UNIVERSIDAD COMPLUTENSE DE MADRID
FACULTAD DE GEOGRAFÍA E HISTORIA

TESIS DOCTORAL

Extreme heat and human health:
The effects of extreme temperatures and pollution on health in Spain

Olas de calor y salud humana:
Efectos en la salud de temperaturas extremas y contaminación en España

MEMORIA PARA OPTAR AL GRADO DE DOCTORA

PRESENTADA POR

Dariya Ordanovich

DIRECTORES

Diego Ramiro Fariñas
Javier Gutierrez Puebla

Extreme heat and human health: The effects of extreme temperatures and pollution on health in Spain

Olas de calor y salud humana: Efectos en la salud de temperaturas extremas y contaminación en España

Author: Dariya Ordanovich

Supervisors: Dr. Diego Ramiro Fariñas and Dr. Javier Gutierrez Puebla

Facultad de Geografía e Historia
Universidad Complutense de Madrid

Programa de doctorado de Geografía

2021

UNIVERSIDAD COMPLUTENSE MADRID

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D./Dña. Dariya Ordanovich,
estudiante en el Programa de Doctorado D9AG - DOCTORADO EN GEOGRAFÍA,
de la Facultad de Geografía e Historia de la Universidad Complutense de Madrid, como autor/a de la tesis presentada para la obtención del título de Doctor y titulada:

Olas de calor y salud humana: Efectos en la salud de temperaturas extremas y contaminación en España.
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To my parents, for their love, support, encouragement and wise advices.

Acknowledgements

En un camino tan largo, como es una tesis doctoral, son muchas las personas, instituciones y proyectos que han hecho posible que esta tesis doctoral se haya podido realizar, y necesitaría muchas más que dos páginas para expresar mi agradecimiento a todos ellos. Desde el punto de vista de la financiación, la posibilidad de acceso a las fuentes de datos empleadas, la oportunidad de conocer al personal más cualificado en diversas áreas del conocimiento, como a las posibilidades de formarme en diferentes cursos y estancias en el extranjero en múltiples áreas, ha sido gracias a las instituciones, grupos de investigación y proyectos en los que me he integrado.

Mi primer paso fue la participación como *Marie Skłodowska-Curie Early Stage Researcher* durante 3 años de intensa formación dentro del Proyecto Europeo *Methodologies and Data mining techniques for the analysis of Big Data based on Longitudinal and Epidemiological Registers* (LONGPOP[1]) que me trajo de Rusia a España en 2016. Dentro de este proyecto, donde estuve contratada en *ESRI España*, desarrollé una intensa formación con cursos y talleres a lo largo de las diferentes instituciones europeas que formaban parte del proyecto. También, mi trabajo en ESRI España supuso mi inmersión en la empresa privada y mi primera experiencia impartiendo cursos de formación durante este período. Quiero agradecer a todo el equipo de ESRI España, su calurosa acogida, su tiempo dedicado a ayudarme en perfeccionar mi trabajo y permitirme sentirme como en mi segunda casa. En especial quiero agradecer a **Paloma Lara**, que siempre estuvo atenta a mis necesidades y me ayudó en todo lo que necesitaba.

La participación en ese proyecto me permitió además realizar estancias de larga duración en el extranjero en centros líderes en temáticas que he tratado en la tesis. Mi estancia en el *Centre for Research on Environment Society and Health (CRESH)* de la *Universidad de Edimburgo* en el Reino Unido, me permitió establecer colaboraciones que aún perduran, y la colaboración con el resto de investigadores del proyecto LONGPOP me ha permitido crear una red de investigación que será muy útil en mi carrera futura. De esa red, querría agradecer de forma muy especial a **Michel Oris** de la *Universidad de Ginebra*, Suiza, **Jamie Pearce** de la *Universidad de Edimburgo* y **Francisco Viciana** del

[1]Contract 676060. Entidad financiadora: European Commission, H2020 Programme, H2020- MSCA-ITN-2015

Instituto de Estadística y Cartografía de Andalucía, su inmensa generosidad y el tiempo que me han dedicado a responder mis dudas, a cualquier hora, cualquier día del año.

Por otro lado, la presencia del proyecto LONGPOP me permitió, iniciar mis colaboraciones en otros proyectos de investigación del *Consejo Superior de Investigaciones Científicas* (CSIC), bajo la dirección de Diego Ramiro, como los proyectos "Supervivencia y salud a lo largo del ciclo de vida y diferencias generacionales en el envejecimiento: un análisis por edad, momento y generación" (RTI2018-097812-B-I00) del Ministerio de Ciencia, Innovación y Universidades, que han subvencionado parte de mis actividades científicas, tales como asistencia a congresos y cursos de formación especializada, y, finalmente, me incorporé con un contrato de investigación, a finales de 2019, al proyecto *ERC Advanced ECHO*[2] dirigido por **Alberto Palloni**, una de las figuras mundiales en el campo de la demografía y la salud, y donde he tenido que formarme y colaborar con un equipo interdisciplinar en áreas nuevas de investigación, que aunque me han supuesto un esfuerzo adicional espero que me permitan abrir nuevas líneas de trabajo y colaboración en el futuro. De este proyecto quiero agradecer la inmensa paciencia y generosidad de Alberto conmigo, por sus ideas brillantes, y mis agradecimientos al resto del equipo del proyecto. Por todo ello, mi más sincero agradecimiento a las instituciones mencionadas y al personal de las mismas.

De manera especial quiero dar las gracias a **Diego Ramiro**, pues sin él, nada de lo anterior hubiera sido posible. Gracias por creer en mí y darme la posibilidad de disfrutar de tantas oportunidades y de guiar mi formación y mi tesis doctoral desde 2016 hasta llegar a este punto, por permitirme acceder a gran número de investigadores e investigaciones y por poner a disposición lo que necesitara para el desarrollo de mi trabajo. Del mismo modo, agradecer a **Javier Gutiérrez Puebla** no sólo su ayuda en esta tesis, sino también su intenso apoyo y confianza en mí. Sus palabras, tan adecuadas, en el momento oportuno han supuesto un gran revulsivo para que esta tesis se haya podido finalizar. Los dos han sido unos directores de tesis envidiables, por lo que debo resaltar mi agradecimiento, por su apoyo y consejo en este largo recorrido que ha supuesto mi tesis doctoral. Me han ayudado a superar importantes baches, especialmente en los últimos momentos. Siempre les estaré agradecida por ello. Agradecer a los miembros del *Grupo de Dinámicas Demográficas y del Instituto de Economía, Geografía y Demografía* del CSIC su compañía durante todos estos años. Especialmente a **Yolanda**, **Begoña**, **Elena**, **Laura**, **Mathias**, a todos los integrantes y compañeros ESR del proyecto LONGPOP, en especial a **Ángela Martínez**, nuestra Project manager que ayudó a resolver todos mis problemas recurrentes administrativos. Y finalmente a **Antonia**, por su apoyo en la distancia.

[2]Early Conditions, Delayed Adult Effects and Morbidity, Disability and Mortality in Modern Human Populations del European Research Council (ERC) Horizon 2020 (grant agreement No 788582)

En el plano personal, mi agradecimiento se extiende a mis amigos, especialmente a **Helvis**, **Lucy** y **Olga**, y a mis queridos padres que en la distancia, sobre todo en mitad de una pandemia, me han acompañado y me han dado ánimos y fuerza. A todos, mi más sincero agradecimiento.

Dariya Ordanovich
Madrid, España
Diciembre 2021

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List of Abbreviations

AMO . . . . . Atlantic Multidecadal Oscillation
AEMET . . . . Spanish State Meteorological Agency
AQI . . . . . Air Quality Index
AR . . . . . IPCC Assessment Report
BI . . . . . Balearic Islands
CI . . . . . Canary Islands
CLC . . . . . CORINE Land Cover
CNIG . . . . . National Center for Geographic Information
CORINE . . . . CooRdination of InfoNmation on the Environment
CSIC . . . . . Spanish National Research Council
DTR . . . . . Diurnal Temperature Range
ECMWF . . . . European Centre for Medium-Range Weather Forecasts
EEA . . . . . European Environmental Agency
ENSO . . . . . El Niño - Southern Oscillation
ESRI . . . . . Environmental Science Research Institute
HC . . . . . Hadley cell
IGN . . . . . National Geographic Institute
INE . . . . . Spanish Statistical Office
INSPIRE . . . . Infrastructure for Spatial Information in the European Community
IP . . . . . Iberian Peninsula
IPCC . . . . . Intergovernmental Panel on Climate Change
JS . . . . . Jet Stream
MMHI . . . . . Minimum Mortality Heat Index
MMT(P) . . . . Minimum Mortality Temperature (Percentile)
MR . . . . . Mediterranean Region
NAO . . . . . North Atlantic Oscillation
NCEI . . . . . National Centers for Environmental Information
NOAA . . . . . National Oceanic and Atmospheric Administration
NWS . . . . . United States National Weather Service
PJS . . . . . Polar Jet Stream
QBO . . . . . Quasi-Biennial Oscillation
RCP . . . . . Representative Concentration Pathway
SMR . . . . . Standardized Mortality Ratio
SNAO . . . . . Summer North Atlantic Oscillation
STJ . . . . . Subtropical Jet Stream

Abstract

Extended abstract

This PhD thesis entitled *Extreme heat and human health: The effects of extreme temperatures and pollution on health in Spain* examines the impacts of heat waves and air pollution on human mortality.

Background. We present this research as a scientific contribution to major societal issues: human impacts on environment, ongoing climate change, population settlements and demographic aging, along with adaptive capacities of our societies, to mention a few. With a clear emphasis on spatial dimensions and a steadfast investment in data collection procedures and statistical methods, we propose a novel perspective on the spatial and temporal geographic, demographic and epidemiological transformations witnessed in Spain during the late 20th and early 21st century. The choice of Spain as a study area is based on the fact that this country as an excellent laboratory in which one could run comprehensive analysis oriented to disentangle complex relationship between changing climate with newly emerging extreme events and human mortality.

Primary objectives and results. Globally, this work pursued two goals: to analyze the exposure to heat from geographical and ecological perspectives, and to explore the relationship between mortality outcomes and temperatures, especially its hotter spectrum, along with air pollution. We started the analysis by identifying episodes of abnormal heat in the Spanish territory in the period from 1979 to 2018 using regular spatial data from climatic reanalysis and custom methodological approach. These episodes were classified by their location, frequency, intensity, duration and other set of characteristics. We study the incidence of heat wave episodes using the systemic approach and consider concomitant factors such as land coverage and levels of air pollution. Overall, our results clearly indicate an upward trend for heat wave frequency and magnitude; however, these episodes of abnormal heat are subject to great spatial variability with northern regions of Spain being affected the most. Air pollution often works in a synergetic tandem with air temperatures, and our results indicated an association between higher concentrations of primary air pollutants and extreme heat, especially in the metropolitan areas. On

the next step, we estimated the excess mortality using individual death microdata for the same period. These estimates were used to model the effects of exposure to the episodes of abnormal heat of different types. Results indicate higher risks of exposure to the episodes with night-time temperatures above 20ºC in adults, especially in elderly woman, irrespective of the location. Further, we deepened the analysis and explored the association between mortality and air temperatures using distributed lag non-linear modelling strategy. Results revealed an overall progressive increase in minimum mortality temperatures (MMTs) over time, with significant heterogeneity in the estimates for individual locations within the country. Mortality curve shifted from a traditional V-shape to a U-shaped curve with a flat bottom. Heat-attributable mortality fraction gradually decreased until 2014, with a slight increment in the last 4 years of observation. As for the intra-state variability, MMTs followed the latitudinal gradient and increased from north to south, being the lowest in the northern landlocked areas of Spain. Generally, risks for exposure to high temperatures were the highest on the same day of exposure with gradual reduction in the following 2 weeks, especially pronounced in the females aged 65+. Rural areas in the South, Center and East of Spain had lower MMTs compared to other regions. More deprived areas had higher risks of mortality when exposed to colder (higher) temperatures in the North (South) of Spain. Lastly, we studied the effects of exposure to air pollution in urban areas of Andalusia in 2000-2017, accounting for potential confounders such as seasonality and air temperatures. The overall net effects for all studied pollutants but ozone were estimated as statistically significant but relatively small.

Conclusions. Using a comprehensive geographic approach, we explored spatial and temporal variations of the effects of exposure to extreme heat on human health. Our findings highlighted the importance of using spatially disaggregated methods, but at the same time illustrated wide range of problems rising from combining data from different domains. The results obtained in this thesis are in line with diverse ongoing international research on heat-mortality associations. Similar to other works performed on the same area, we witnessed an overall adaptation (seen through the increment of the optimum temperatures) to extreme heat. However, these trends were not always positive depending on the location and particular geographic and ecological settings. Flattening of the mortality curves over time suggested an extension of the optimal temperature range, applied to the aggregated national and to a number of individual sites. Ultimately, the association between temperature, air pollution and human health is complex and requires advanced statistical methods to properly understand this relationship which might be confounded by multiple factors, have non-linear dependencies and possess lagged structure.

Resumen ampliado

Esta tesis doctoral titulada *Olas de calor y salud humana: Efectos en la salud de temperaturas extremas y contaminación en España* examina los impactos de las olas de calor y la contaminación del aire en la mortalidad humana.

Introducción. Aportamos con esta tesis una contribución científica a algunos de los problemas sociales más acuciantes: el impacto humano en el medio ambiente, el cambio climático en curso, el asentamiento de la población y el envejecimiento demográfico, junto con las capacidades de adaptación de nuestras sociedades. Con un claro énfasis en la dimensión espacial y en procedimientos de recopilación de datos y métodos estadísticos, proponemos una perspectiva novedosa sobre las transformaciones geográficas, demográficas y epidemiológicas ocurridas en España desde finales del siglo XX. Elegimos España como área de estudio por ser un excelente laboratorio donde se pueden realizar análisis integrales orientados a desentrañar la compleja relación entre el cambio climático, eventos extremos emergentes y la salud y mortalidad humana.

Objetivos principales y resultados. Este trabajo persiguió dos objetivos: analizar la exposición al calor desde perspectivas geográficas y ecológicas, y explorar la relación entre temperaturas, polución del aire y su efecto en la mortalidad. Comenzamos el análisis identificando episodios de calor anormal en el territorio español en el período de 1979 a 2018 utilizando datos de reanálisis climático con metodología personalizada. Estos episodios fueron clasificados por su ubicación, frecuencia, intensidad y duración. Estudiamos la incidencia de las olas de calor utilizando el enfoque sistémico y consideramos factores concomitantes como la cobertura del suelo y los niveles de contaminación del aire. En general, nuestros resultados indican una tendencia al alza en la frecuencia y magnitud de las olas de calor; sin embargo, estos episodios de calor anormal están sujetos a una gran variabilidad espacial, siendo las regiones del norte de España las más afectadas. Además, los resultados indicaron una asociación entre concentraciones más altas de principales contaminantes del aire y el calor extremo, especialmente en las áreas metropolitanas. En el siguiente paso, estimamos el exceso de mortalidad utilizando microdatos de defunciones para el mismo período. Estas estimaciones se utilizaron para modelar los efectos de la exposición a los episodios de calor anormal de diferentes tipos. Los resultados indican mayor riesgo de exposición a los episodios con temperaturas nocturnas superiores a 20^{o}C en adultos, especialmente en mujeres mayores, independientemente de la localización. A continuación, exploramos la asociación entre la mortalidad y las temperaturas utilizando una estrategia de modelado no lineal de retardos distribuidos. Los resultados revelaron

un aumento progresivo de las temperaturas mínimas de mortalidad (MMTs) a lo largo del tiempo, con una heterogeneidad significativa para ubicaciones individuales dentro del país. La curva de mortalidad cambió de una forma de V tradicional a una curva en forma de U con un fondo plano. La fracción de mortalidad atribuible al calor disminuyó gradualmente hasta 2014, con un ligero incremento hasta 2018. En cuanto a la variabilidad espacial, las MMTs siguieron el gradiente latitudinal y aumentaron de norte a sur, siendo las más bajas en las zonas de interior del norte de España. En general, los riesgos de exposición a altas temperaturas fueron más altos el mismo día de la exposición con una reducción gradual en las siguientes 2 semanas. Las áreas más desfavorecidas tenían mayores riesgos de mortalidad cuando estaban expuestas a temperaturas más frías en el norte y más altas en el sur de España. Por último, estudiamos los efectos de la exposición a la contaminación del aire en áreas urbanas de Andalucía de 2000-2017. Los efectos netos generales para todos los contaminantes estudiados excepto el ozono se estimaron como estadísticamente significativos pero pequeños.

Conclusiones. Utilizando un enfoque geográfico integral, exploramos las variaciones espaciales y temporales de los efectos de la exposición al calor extremo en la salud humana. Nuestros resultados destacaron la importancia de utilizar datos y planteamientos espacialmente desagregados, pero al mismo tiempo ilustraron una amplia gama de problemas que surgen de combinar los datos de diferente naturaleza. Los resultados obtenidos en esta tesis están en línea con diversas investigaciones internacionales en curso sobre asociaciones entre el calor y la mortalidad. Al igual que en otros trabajos realizados en la misma zona, observamos una adaptación (medida a través del incremento de las MMTs) al calor extremo. Sin embargo, esta tendencia no siempre fue positiva dependiendo del entorno geográfico. El aplanamiento de las curvas de mortalidad a lo largo del tiempo sugiere una extensión del rango de temperaturas optimas. En última instancia, la asociación entre la temperatura, la contaminación del aire y la salud humana es compleja y requiere métodos estadísticos avanzados para comprender adecuadamente esta relación que puede confundirse debido a dependencias no lineales y efectos retardados.

1 Introduction

1.1 Background

This PhD thesis examines the impacts of heat waves and air pollution on human mortality. This is a fairly brief summary, yet it is sufficient to inscribe this research as a scientific contribution to major societal issues: human impacts on environment, ongoing climate change, population settlements and demographic aging, along with adaptive capacities of our societies, to mention a few. Climate deserves special attention because it has the potential to have a direct impact on biophysical processes that are important to humans, such as crop and animal survival and growth, aquatic life and activity of the microorganisms that cause diseases in plants, animals, and humans (Pozzi and Fariñas 2010). Temperature and rainfall fluctuations have a significant impact on mortality and health, and this impact is magnified for vulnerable groups that are more susceptible to heat, such as children and the elderly. Prolonged excessive heat provokes complications of health conditions, however the direct exposure to extreme temperatures may even result in spontaneous death due to heat stroke.

With a clear emphasis on spatial dimensions and a steadfast investment in data collection procedures and statistical methods, we propose a novel perspective on the spatial and temporal transformations witnessed in Spain during the late 20^{th} and early 21^{st} century. The primary focus of this thesis is made on the episodes of extreme *heat*, although at some stages of our analysis we explore both - hot and cold - edges of the spectrum. Heat waves are not a new phenomenon: episodes of extreme temperature and their direct

and indirect effects on human survival have a long history. Climate, however, was not considered one of the knights of the apocalypse together with wars, famines, and epidemic diseases that devastated human populations over centuries. Instead, climatic conditions stayed hidden behind. Rural societies were deeply embedded in their natural environment since the relation of dependency was simply a matter of life or death. Before storms capable of destroying the harvests came into play, cold spells during the winter presented the major concern (Cabantous 2014). The industrial revolution and urbanization altered the relationship between humans and nature in a gradual, but at the same time a very drastic manner. The development of anthropocentrism not merely implicated the rational exploitation of natural resources for human benefit (Albritton Jonsson 2012). Progresses, both in scientific knowledge and living conditions, were expected to make the humans free from the *"climate dictature"* (Ladurie 2018). At first, this idea seemed rather unrealistic as cholera outbreaks and other gastrointestinal disorders had wreaked havoc on industrial mushroom towns and capital cities, especially during the summer (Fariñas and Oris 2016). Investing in public hygiene infrastructure, on the other hand, was expected to be the definitive solution to these problems. As some might say, *"Prometheus was unbound"* (Landes 2003). When a severe heat wave hit Europe in 1911, causing a cholera epidemic as a side effect in Italy, the Italian government even manipulated the statistical data to prevent the country from seeming as going downhill (Pozzi and Fariñas 2010).

Throughout most of the twentieth century, heat was increasingly associated with leisure, vacation and beach, among other things. Only in the mid-1980s the debates on global warming and its origins in human activities found a genuine echo in the scientific community, public opinion, and, ultimately, the political agenda, as highlighted by Demeritt (2001). In the latter work the author states that *"... the 1988 heat wave and drought in North America were arguably as influential in fostering public concern as any of the more formal scientific advice"*. In Europe, the heat wave of 2003 was unquestionably the most traumatic event. The majority of authors estimated excess deaths to be between 35 000 and 55 000 (Kovats and Jendritzky 2006), with the highest estimate exceeding 70 000 people (Robine et al. 2008). It sounded like a thunderclap. Since that time, heat waves have regularly challenged human technical mastery of nature and the politics of risk management that Beck et al. (1992) describe as a distinctive trait of our "risk societies". As this influential sociologist wrote: *"Modern society has become a risk society in the sense that it is increasingly occupied with debating, preventing and managing risks that it itself has produced."*

Extreme heat events in the late twentieth and early twenty-first centuries revealed vulnerability of humans to anthropogenic climate change. Vulnerability, a term that has

shown an impressive success in many academic disciplines since the 2000-s, encompasses risk, among other components (Hanappi et al. 2015). Schröder-Butterfill and Marianti (2006) have proposed a dynamic model in which the risk exposure (also referred to as latent vulnerability), the risk itself (also known as threat or stress), and the consequent state of vulnerability are differentiated. Since then, many researchers have been inspired by their contribution and relied upon this model in their studies (Yang and Jensen 2017; Sheridan and Allen 2018; Jones et al. 2021). This dissertation contributes precisely to the aforementioned research line. Here, we implement an in-depth analysis of the components of health vulnerability (perceived through the perspective of mortality) to heat waves in the Spanish population from 1979 until 2018.

Why do we choose Spain as a study area? Contrary to popular perceptions of Spain as a stable Mediterranean locality with generally low environmental risks, we see this country as an excellent laboratory in which one could run comprehensive analysis oriented to disentangle complex relationship between changing climate with newly emerging extreme events and human mortality. Located in the far west of Europe on the crossroads of the Atlantic and the Mediterranean, Spain, which spans half a million square kilometers, represents a unique geographic phenomena with diverse orographic, hydrological and climatic conditions. From temperate humid climate in the north, through extensive mountain chains all across the country, regimes drastically change and reach other extremes, represented by arid climate and deserts in the south.

Working on those environmental dimensions, we embed our PhD in a long legacy of natural disaster research and literature on the interactions of climate change and health. As mentioned previously, heat waves have joined tsunamis, earthquakes, volcanic eruptions, droughts, and flooding in the list of natural catastrophes since late 1990-s. However, scientific research on these major events was among the first to use the concept of vulnerability to emphasize that the human costs (e.g. death tolls) were not "natural" at all, but rather depended on both human frailties (such as population clusters, land use, poverty and deprivation) and human strengths (preventive and reactive institutional and societal capabilities) (Paul 2013; Klinenberg 2003).

1.2 Research questions

To unravel the tangle of complex relationships of ever changing climate and mortality answers of the Spanish population to its emerging extremes we formulate a number of research questions presented further below.

Research Question 1

What are the global implications of the warming of air temperatures for humans? What is the position of the issue of heat-related mortality and morbidity in the international and regional interdisciplinary discourse? What are the potential collateral effects of the increasing incidence of the episodes of abnormal heat, both locally and worldwide?

The adverse effects of exposure to extreme heat have been widely discussed in the scholarly and societal literature during several decades. In the Mediterranean context, the issue of heat wave intensification and related impacts was increasingly getting attention from specialists from different fields: climatologists and meteorologists, epidemiologists and demographers, but also economists, human migration experts and even occupational health and safety specialists and technicians. To begin our examination of the problem of heat-related mortality in Spain, we first aim to position the current study in the global landscape of ongoing multidisciplinary debates and scientific research.

Research Question 2

How does the human body react to exposure to extreme heat? What are the physiological mechanisms responsible for thermoregulation in humans, and what are the factors that can tamper and deteriorate the normal physiological response to extreme temperatures? What are the most common illnesses caused or related to the exposure to abnormal heat and air pollution? How large are the risks of exposure, according to the state-of-the-art research?

Exposure to extreme heat can result in a number of health consequences for humans. However, the response to abnormal heat is subject to many concomitant factors and conditions. The exposure itself (its duration, intensity) alters the outcome, while physical and medical conditions of the individual (presence of chronic diseases, age, sex) can act either as exacerbators or as mitigators of the impacts. By asking the aforementioned questions, we prepare the fundamental basis of our research, which helps us to establish the hypothesis to be tested further.

Research Question 3

Is it possible to assert that the number of heat waves in Spain has grown in the past decades? How uniform, spatially and temporally, is the incidence of the episodes of extreme heat in Spain? Are there any exceptions, and if so, where?

The continuous rise of the air temperatures, changes in the climate variability and consequent emergence of the episodes of abnormal heat all across the globe and particularly in Europe undoubtedly take place, and the expected trends are persistently increasing. However, neither across Europe nor within Spain, the recurrence of such events exhibits a uniform pattern. Some areas were and continue being affected less, while some experience a mounting pressure, and these dissimilarities are projected into the future (Masson-Delmotte et al. 2019; Schär et al. 2004). Thus, research question 3 opens a wide discussion on the spatial heterogeneity of heat wave incidence in Spain.

Research Question 4

How does the concentration of air pollutants change depending on the fluctuations of air temperatures in Spain? What are the main clusters of air pollution and where are they located? What are the differences in the concentrations of air pollutants during heat waves depending on the patterns of land use?

Air pollution often "adds fuel to the fire" in terms of worsening the impacts of heat on health. Urban areas are known for its "added heat effects", and are often referred to as *urban heat islands*. In simple terms, metropolitan areas tend to be hotter than their periurban and rural surroundings due to the properties of the build up surfaces (buildings, pavement). Coupled with more intense air pollution from transport and industrial activities, heat wave episodes in the cities can be potentially more devastating due to its sinergetic power, as concentrations of some air pollutants increase as function of the air temperature. State of the art research now combines two threats, extreme heat and air pollution, into a single one (Kalisa et al. 2018; Analitis, Michelozzi, et al. 2014; Sun et al. 2020). The sources of the air pollution, however, not necessarily should be related to the human activity and can be of natural origin. Due to its proximity to the African continent, Spain often experiences the intrusions of Saharan dust in the air masses in the form of particulate matter. If summed to the anthropogenic sources of air pollution, especially in the coastal areas in the south and south-east of the country, it may multiple the health risks for the population (Perez, Tobias, et al. 2008; Jiménez et al. 2010). Air pollution clusters, seasonal fluctuations in air pollutant

concentrations, and their occasional splatters are studied to gain a better knowledge of the Spanish vulnerability context.

Research Question 5

What are the risks of exposure to the episodes of extreme heat in Spain? Is there any difference in mortality answers to the exposure to the episodes of different types? Are the risks equal for men and women, young and old? Is there any trend in mortality answers to extreme heat over time?

As discussed in the introductory part to this chapter, the exposure to heat waves has been proven to have a direct impact on morbidity and mortality of the population. Many authors argue that the ultimate impact of a heat wave is determined by a variety of factors, including the attributes associated with a heat anomaly, such as its duration, intensity or timing in season (Kovats and Hajat 2008; Anderson and Bell 2009; D'Ippoliti et al. 2010). Moreover, a vast amount of studies suggest higher risks related to the exposure to heat waves for elderly female individuals (Conti, Meli, et al. 2005; Benmarhnia, Deguen, et al. 2015; Canouï-Poitrine et al. 2006). The overall risks, however, are subject to reduction over time due to progressive adaptation to new environment. Research Question 5 is formulated to initiate the debate on the temporal changes in the adaptive capacity of the population to abnormal heat.

Research Question 6

What is the association between mortality and air temperature in Spain, considering its knowingly complex non-linear and lagged structure? How large is the attributable fraction of mortality due to heat? What are the optimum temperatures and how do they vary across space? How did these optimum temperatures, and consequently the mortality outcomes, evolve over time and across socioeconomic strata?

With Research Question 6, we focus on the deeper exploration of the heterogeneity of the effects of air temperatures on human health across spaces and time using a comprehensive geographic approach. In 2003, Spain´s closest neighbor, France, has registered up to 18 000 deaths attributed to a devastating heat wave episode that summer. Two consecutive episodes of extreme heat in 2019 had higher magnitude, if compared to 2003, but resulted in 1500 excess deaths, which makes a 10-fold difference with 2003. A simple and simultaneously perplexing inquiry has drawn our attention: is this happening in Spain as well, and if so, why? Changes in the optimum, or minimum mortality temperatures (MMT), are often used to evaluate the process of adaptation to increasing temperatures in populations that vary in vulnerability and resilience capacity. The

geographic variation and evolution of the MMT over time were described using different data in different regions across the globe (Gasparrini Antonio et al. 2015; Gasparrini, Guo, et al. 2015; Guo et al. 2014; Vicedo-Cabrera, Sera, et al. 2018). In Spain, detailed studies of MMT variations were mostly done at the level of provincial capitals (Tobias et al. 2012; Tobías, Armstrong, et al. 2017). As argued by many researchers, incremental changes in the MMT indicate progressive adaptation of the population to the hotter environments. Follos et al. (2020) estimated the increase of MMT in Madrid and Sevilla at 0.58°C and 1.14°C per decade, respectively. The work by Achebak, Devolder, and Ballester (2019) revealed an increase in overall MMT in Spain in 0.7°C from 1980-1994 (19.5°C) to 2002-2016 (20.2°C), and general reduction in risks and attributable fractions of cardiovascular deaths due to heat or cold. Hypothetically, a complete adaptation could be achieved when MMT increases at the same speed as the temperature, i.e. an increase of 1°C MMT for a rise of 1°C of the mean annual temperature (Tobías, Hashizume, et al. 2021). Despite the fact that temperature-mortality associations have been extensively studied in the regional and country-specific contexts, studies involving a thorough retrospective geographical analysis based on the data with fine spatiotemporal resolution are still rare (Jones et al. 2021; Lerch and Oris 2018). Therefore, answering this research question we leverage the opportunity to conduct a large-scale study using precise environmental estimates and explore if the change in mortality responses happen all across the country in a similar manner.

Research Question 7

What are the health risks related to air pollution and temperature in Spain? Is there any effect modification by air pollution when combined with the exposure to temperatures? How long do the risks stay elevated after the exposure?

Air pollution might modify the effects of heat waves on mortality, as was shown in a number of studies (Analitis, Michelozzi, et al. 2014; Breitner et al. 2014; Rainham et al. 2005). It is essential to control for seasonal and long-term trends when modelling short-term associations between exposures to air pollution and health outcomes, at the same time accounting for time varying confounders and delayed effects (Bhaskaran et al. 2013). With the Research Question 7, we aim to investigate the exposure-lag-response relationships between primary air pollutants in the south of Spain and mortality outcomes.

1.3 Specific objectives and structure of the dissertation

The ultimate goal of this dissertation is to study the adverse effects of the exposure to extreme heat on human health, perceived through the lens of all-cause mortality. Endeavoring this task, we developed a series of specific objectives, designed to prepare the ground to consistently answer to all the research questions stated above.

Structurally, this PhD is divided into three main parts in order to cover all the topics and at the same time to ease the navigation through the document.

Foundation

① **Chapter 2**. *Extreme heat and human health*
Chapter 3. *Data: sources, advantages and limitations*

First part pulls together the pieces that make up the foundation of this work. Chapter 2 examines the effects of exposure to heat, particularly in terms of mechanisms of physiological response to heat, post-exposure health complications and eventual mortality outcomes, by reviewing medical and public health literature. In this chapter the reader finds a detailed and structured answer to the **research questions 1 and 2**. Here, we not only compile a theoretical summary, but also perform a systematic review of hundreds of global, regional and national studies published in English and Spanish languages from 1975 to 2021. The specific objectives we establish are as follows:

- To compile a database[1] consisting of scientific publications relevant to the key topics of study, and add custom tags.
- To review the tagged items and extract information of interest (e.g. study estimates and confidence intervals, further reported in the literature review).
- In some cases, to adapt the materials (graphs or tables) to be reused in specific sections.

The data that have been collected and constructed in this dissertation are introduced in Chapter 3. The main goal we pursue at this stage is to compile a unified database and to develop reproducible programmatic code for data retrieval and processing operations. Overall, the steps we follow to construct this database are listed below.

[1]Here we used the *Zotero* open-source reference management software to manage bibliographic data and related research materials and available web-browser plug-ins.

- To identify all data sources of potential interest with the highest possible level of detail.
- To request the data unavailable for public use (includes preparation of the applications).
- To programmatically retrieve the data available publicly (includes familiarization with the data retrieval schema of the provider, writing the code for data download; applies for large time-series such as e.g. temperature estimates on regular grids).
- To download the data available publicly but not designed for programmatic retrieval (includes downloading and organizing the metadata).
- To process all downloaded files in order to eliminate potential bias and normalize the data (includes developing a reproducible code which allows any user to track the whole process from start to end point).
- To develop methodological basis and procedures to establish the linkage between regular and administrative units.
- To prepare final ready-to-use datasets to be leveraged on the following steps of the analysis.

As the reader can see from this list of objectives, the level of analysis is an essential consideration. Our study, like all scientific research, is limited by the data available, which in Spain, as in many other countries, is restricted by privacy laws. As a result, individual demographic data always have to be pooled at a certain administrative unit. Throughout the PhD journey, it has been a constant challenge to find the best trade-off between using regular spatial grids with precise environmental estimates and avoiding too small numbers (population size and number of deaths) that could affect the reliability of the results.

Geographic analysis of heat waves in Spain

② **Chapter 4**. *Heat waves in Spain: factors, definitions and generic characteristics*
Chapter 5. *Spatiotemporal dynamics of heat waves in Spain*
Chapter 6. *Extreme heat, air pollution and land use: accumulation of vulnerabilities*

To answer the **research questions 3 and 4**, it is necessary to conduct a thorough analysis of the incidence of heat waves and concomitant effects of air pollution using the data collected on the previous steps. We discuss the specific objectives established to perform this analysis down below.

In Chapter 4, we examine shifts in the climatic variability seen in Spain over the last few decades, debate plausible causes and develop a bespoke definition of the heat wave episodes, which is further used to identify these events in time and space. The first challenge that this study seeks to address globally is determining the ways to accurately identify episodes of abnormal heat. It may seem straightforward, but there is no universal agreement on a definition. The criteria to declare an episode of excessive heat are usually study-specific: some would work with absolute thresholds (Huynen M M et al. 2001; Tong et al. 2012), while others opt for using relative metrics (Basagaña et al. 2011; de Schrijver et al. 2021). Irrespective of the approach selected, most of the research goes beyond simply defining a time period of exposure to heat, but explores the variety of its quantitative characteristics. To fully understand the effects that extreme heat might have on health of the individuals not only must length and intensity of the episodes be taken into account, but also the predominant climatic regimes of the study area, which determines the point at which population gets accustomed to heat. Therefore, we decide to work in the following order:

- To identify global and local factors "responsible" for the heat wave formation in the Iberian peninsula based on the literature review.
- To provide an overview of the past events of heat stress.
- To explore overall changes and trends of the air temperatures in Spain at the national and regional levels.
- To review a variety of the definition used to identify periods of abnormal heat globally.
- To suggest custom criteria for heat waves to be used further in this study.
- To implement these criteria to identify episodes of abnormal heat in Spain during the period of study (includes the development of a reproducible code for creating a database where episodes of different types with corresponding characteristics are stored).
- To analyze non-spatial attributes of the detected episodes (frequency, duration, absolute and relative magnitudes, amplitudes, curve character).

Generally speaking, by running this analysis we expect to see an overall growth of the temperatures over time, along with an increment of the frequency of the episodes of abnormal heat. At the same time, we do not anticipate to observe a spatially homogeneous picture. Therefore, we focus the Chapter 5 on the spatiotemporal dynamics of the incidence of heat waves in Spain. In this chapter we aim to identify areas

characterized by the highest levels of environmental "pressure" from the standpoint of heat exposure overlaid with the land use background. To achieve this goal we follow the steps listed below:

- To identify heat wave episodes in time at the national level and to describe it with a set of selected characteristics (to be used further as a reference point in the analysis).
- To explore patterns of yearly and monthly incidence of heat wave episodes and to map the phenomena.
- To examine accumulated incidence of the episodes of extreme heat (includes emerging hot spot analysis).
- To describe summary statistics of the heat wave episodes and map the results (includes multivariate mapping).
- To explore the variations in heat wave incidence depending on the land cover settings and map the results.

Land use, air pollution and extreme heat could be all perceived as a penalty or a hazard that increases susceptibility and puts human survival in jeopardy. Chapter 6 investigates how these three components interact and accumulate by completing the following steps:

- To explore the trend levels of air polluting in Spain and visualize the summary statistics.
- To examine the variations in the concentration of air pollution depending on the contextual settings (land cover) and intensity of the heat wave episodes.
- To estimate a combined indicator of air pollution (air quality composite index) and identify and map clusters of air pollution based this composite index.
- To detect and map hot spots of air pollution in Spain.
- To compile a database with air pollution estimates on a regular grid compatible with the grid used for heat wave analysis.

Statistical analysis of mortality due to extreme heat

③ **Chapter 7**. *Excess mortality attributed to heat waves in Spain*
Chapter 8. *Spatiotemporal variations of minimum mortality temperatures in Spain*
Chapter 9. *Adverse effects of air pollution on health in Andalusia*

The third final part explores complex associations between environmental exposure and mortality outcomes. Chapter 7 opens the discussion with a generic analysis of the effects of heat waves of diverse types on mortality, providing the answers to the **research question 5**. Using classical methods of epidemiological analysis, we aim to estimate the excess mortality and focus on its peaks associated with extremely hot conditions since 1982 onwards. In particular, we pursue the following objectives:

- To estimate the excess mortality based on restrictive models of historical averages by sex and age group at the level of autonomous communities for the entire period of study.
- To represent these estimates graphically and examine the peaks of mortality during heat waves.
- To select and, if necessary, re-estimate, specific characteristics of heat waves at the level of autonomous communities to be entered as variables into regression models.
- To run the models, to compare effect estimates between sexes and age groups and to represent the results in a graphical and tabular format.

Broadly speaking, we expect to see an increase in excess mortality on the days with abnormal heat. However, we also anticipate that the intensity and timing of exposure would result in different effects, within and between groups of individuals of different age and sex. In Chapter 8, we make a step forward and examine the exposure-lag-response associations between temperatures and mortality, using series of newly developed methods in the scientific community. To answer the **research question 6**, we use the *Minimum Mortality Temperature* as a measure to explore the changes in the societal capacities to cope with extreme temperatures from 1979 to 2018. To do so, we follow the next steps:

- To establish and justify spatial levels of analysis based on the state-of-the-art research and availability of the data.
- To adjust mortality data to the selected units of analysis, where necessary.
- To execute statistical analysis (includes developing a reproducible programmatic code) in order to estimate minimum mortality temperatures and heat-attributed mortality tolls at established spatial levels.
- To examine cumulative exposure-response and lag-response associations with air temperatures and heat index.
- To explore variations by sex and age groups and represent the results graphically.

- To estimate changes in the minimum mortality temperature and heat index and attributable mortality in Spain at different spatial levels over time.
- To analyze spatial variations in mortality answers within Spain and map the results.
- To explore geographic disparities between different socioeconomic strata.

Here we presume that in general, throughout 4 decades of observation, heat-attributable mortality had experienced a decline, while the minimum mortality temperatures have increased. On the other hand, we suspect that the associations between exposure and mortality are site-specific, thus our findings should indicate significant regional heterogeneity. Moreover, we expect to see the alteration of the estimated effects after introducing an extra dimension of air pollution in our analysis. Hence, we wrap this part with Chapter 9, where we present the results of a pilot study focused on the impacts of air pollution, controlled for seasonality and confounding factors, on mortality in Andalusia from 2000 to 2017. Specific objectives established to pursue the aim of this analysis and answer the **research question 7** are as follows:

- To identify units of analysis and adjust the data where necessary.
- To perform time series regression analysis.
- To explore exposure-response associations and analyze the effects of potentially confounding factors.
- To study and report the delayed effects of air pollution on mortality.

The document contains six appendices with supplementary material and a section where publications, conference presentations and awards are listed. Some of the largest figures were moved from the main body of the text to the corresponding appendices to preserve the original quality of the illustrations.

Extreme exogenous forces such as the climate have become so disastrous partly because the emerging isolation and privatization, the extreme social and economic inequalities, and the concentrated zones of affluence and poverty pervasive in contemporary cities create hazards for vulnerable residents in all seasons

— *Heat wave: a social autopsy of disaster in Chicago*, Klinenberg (2003).

2

Extreme heat and human health

Before the start of our discussion on the key subject of this study, namely, *adverse effects of extreme heat on human health*, we clarify the vocabulary and provide a brief overview of the environmental processes associated with a changing climate. We believe that understanding of the ecological context is essential for deeper comprehension of associated risks for human health and wellbeing.

2.1 Concepts and definitions: towards an interdisciplinary discourse and future forecasts

Today, without a doubt, humans are an integral part of the natural systems they live in. Threats and challenges to these systems, as an inevitable aftermath of warming of the surface temperatures, are numerous and diversified, and often pose latent risks on human health. Figure 2.1, published in the IPCC report on 1.5°C warming, illustrates the implications of global warming - the complex process defined in continuation - for ecosystems, economies and humans.

Climate Change and *Global Warming* are two terms that are often used interchangeably, and have entered the vocabulary of general public and mass media practically as synonyms. However, these are two related but peculiar, specific processes. In the present study, we stick to the terminology introduced by the Intergovernmental Panel on Climate Change[1] (IPCC), which defines climate change as *"a change in the state of the climate*

[1]The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change, for more information see www.ipcc.ch

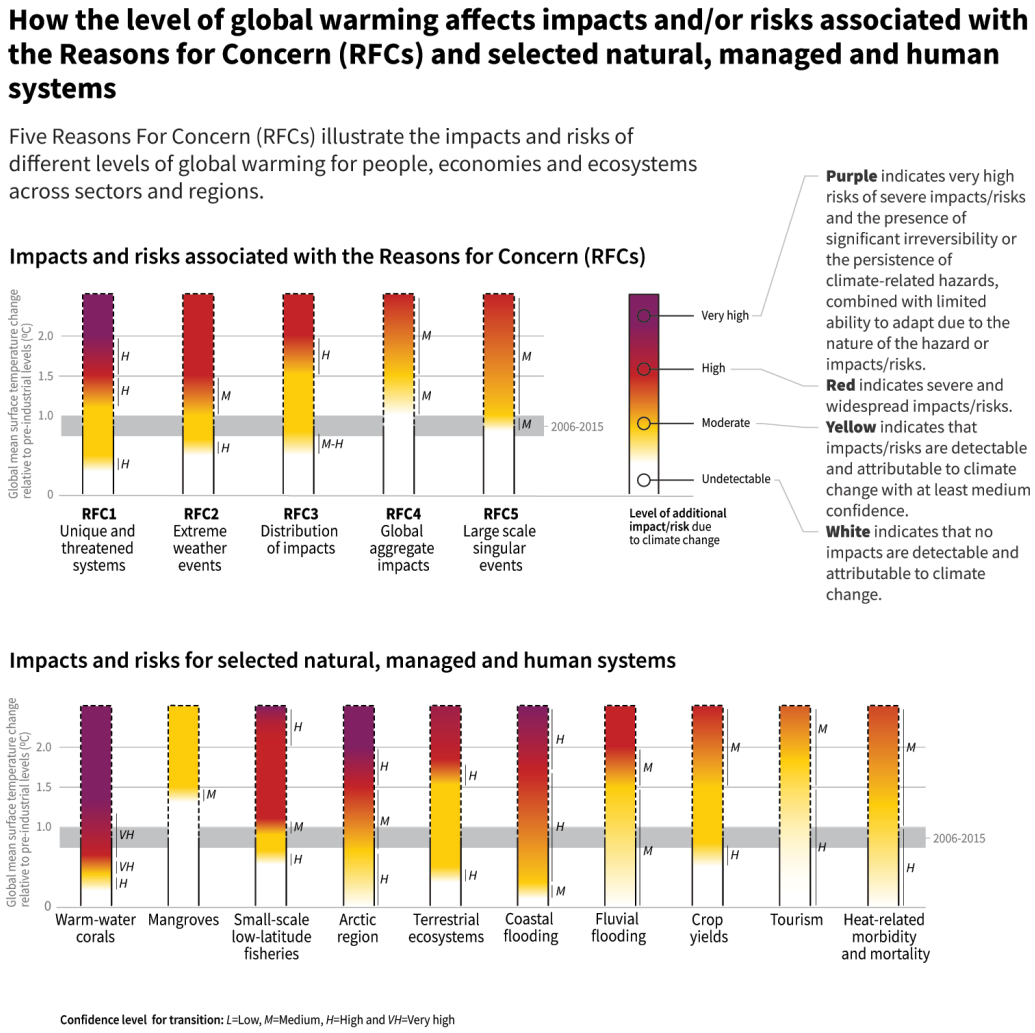


Figure SPM.2 from 2018 IPCC Special Report on the impacts of Global Warming (Masson-Delmotte et al. 2019), access at www.ipcc.ch/sr15.

Figure 2.1: Implications of global warming for people, economies and ecosystems

that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. The Framework Convention on Climate Change makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to

natural causes" (IPCC 2013). Most frequently, the term climate change is discussed in relation to anthropogenic activity, especially energy production and consumption. The force of this activity is, indeed, of an extraordinary scale and continues to gain momentum despite of the global mitigation effort.

The process of *Global Warming* forms part of the *Climate Change* process and is defined by the IPCC as *an estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.* According to the Special Report on the impacts of Global Warming of 1.5°C of the IPCC (Masson-Delmotte et al. 2019), if rates are maintained at the current level it is highly likely that in 2030-2052 global warming will reach 1.5°C with respect to the pre-industrial levels. At high confidence, regional model-based projections point to the increases in mean sea- and land-surface temperatures (SST/LST) along with extreme hot events, especially in densely populated areas. The changes of the regional climates are foreseen not only in regard to the temperatures but also to precipitations which are expected to intensely increase in some regions and severely reduce in others.

Indeed, the regional effect may be disproportionate and will not necessarily follow the global trend in specific places. High latitudes are anticipated to be affected the most during the colder season, whereas mid-latitudes will experience the highest pressure in terms of warming during the warm season. Regions which climates are under the influence of ocean currents, low-lying coastal and hurricane prone regions, along with the high mountain regions, are admittedly the most vulnerable areas to climate change and global warming from biophysical point of view, not to mention the susceptibility of millions of people living in these areas (Balica et al. 2012).

The first integrative reason for concern, as displayed on Fig.2.1, corresponds to the risks associated with unique and threatened systems. As a matter of fact, intensification of the interannual hydroclimate variability results in the habitat destruction and ecosystem collapses. Some geographic areas constrained by specific climatic conditions are especially susceptible for biodiversity loss and extinction of endemic species. Examples of such natural systems are warm-water corals, which are at a very high risk of irreversible damage at current warming levels, or mangroves, which have moderate risks attributable to 1.5°C+ warming. Ocean acidification, fish stock decline, glacial retreat, ice sheet melt, freshwater loss and desertification, sea level rise and coastal submersion are only some of the consequences of the ecosystem perturbations caused by global warming. As humans

make an integral part of the global ecosystem, it is hard to downplay the role of the processes mentioned above as they impose significant sideway[2] threats for people.

Environmental determinants are drivers of vector-, food- and water-borne diseases. As noted by Semenza et al. (2012), changes in climatic conditions might alter the exposure pathways, therefore leading to an increased incidence of infectious diseases in new, different geographic areas. Coping mechanisms and controlling strategies here are directly dependent on the level of economic development of the affected area. For example, there is a much higher risk for water-borne infections outbreak provoked by flooding in the developing countries rather than in the western states (Hunter 2003). As discussed in the latter study, the increased temperature relates to the blooms of planktonic species, and creates a hospitable environment for some harmful algae and other microbes to grow. In conditions of low levels of public education on water sanitation and unsatisfactory state of sanitation facilities, especially in densely populated areas, this might lead to outbreaks of cholera, ascariasis, diarrhea, hookworm infection and eventual increase of diarrhea-specific mortality (Khasnis and Nettleman 2005). Warming temperatures also affect the food chain supply globally. Several studies highlight the importance of adaptation to hotter conditions in terms of food handling, storage, preparation and delivery to consumers. Rising temperatures also might increase the risks for domestically acquired food-borne infections, therefore an early warning system for food-borne disease prevention is a necessity for developing **and** developed countries. (Semenza et al. 2012; Schuster-Wallace et al. 2014; Milazzo et al. 2014).

Emergence and re-emergence of vector-borne diseases imposes a great threat for human health as temperatures keep rising. World Health Organisation (WHO) defines vectors as *living organisms that can transmit infectious pathogens between humans, or from animals to humans* (*Global Vector Control Response 2017–2030* 2017). Most commonly, these vectors are insects - cold-blooded animals (so called ectotherms), which body temperature almost entirely depends on the temperature of surrounding environment. Under warmer conditions the metabolism of these organisms increase, as increases their reproduction, biting activity and the rate at which pathogens mature within them (Epstein 2001). The latter represents a major danger for humans, as the incubation period of such viruses as malaria, dengue and yellow fever becomes much shorter at warmer temperatures (within the survivable range of temperatures for hosts) (Shope R 1991).

[2]Here we separate the events into those that affect human health *directly*, by provoking diseases or death *on-the-spot*, e.g. exposure to extreme heat resulting in a deadly heat stroke; and those that harm through *intermediate* mechanisms, e.g. food safety and security threatening caused by crop failure, flooding of cities and farmland loss.

The geographical areas where vectors are present are limited by temperature thresholds, and as the temperature is changing these areas shift to higher latitudes and expand their coverage. Fluctuations of the ocean currents play an important role for controlling the transmission season in endemic areas. The relationship between El Niño/Southern Oscillation (ENSO) and increased malaria risk was established by Hunter (2003), whereas Rocklöv and Dubrow (2020) highlight the exceptional influence of the temperature conditions related to ENSO and Zika virus transmission in 2015-2016 in South America. In Europe and North America, where diseases like malaria were eradicated in the second half of the past century, the changes in the environmental conditions might lead to the potential expansion of other diseases like encephalitis, as noted by Khasnis and Nettleman (2005). This study also mentions the fact that significant changes in the environment may cause human migration, and this also implies the shift in disease patterns. Not only migration but international travel, allowing individuals to relocate from one side of the globe to another in literally hours, also facilitates the transmission of vector-borne diseases. Although infrastructure of the developed countries will prevent the re-emergence of endemic diseases, the pressure on the health care system of the recipient countries will increase as the incidence on the sender side spikes (Tatem et al. 2017).

Extreme weather events, including heat waves, heavy rain, droughts, wildfires and flooding, are listed as another reason for concern on Figure 2.1. However, as the reader might note, only **heat**-related mortality and morbidity appear within selected impacts for human systems on this figure. The emphasis on heat-related mortality is done as heat waves, in fact, are the most prominent causes of weather-related mortality around the globe, even compared, on the global scale, to catastrophic events such as tropical hurricanes. Heat waves, generally defined as prolonged period of abnormal heat, are predicted to increase in its frequency and magnitude in all the continents. We will repeatedly come back to the discussion of the physics of the process of heat wave formation and regional differences in the following chapters. In the mean time, in this opening part, we would like to provide a summary of the possible future synopsis where heat waves play an increasingly important role. Table 2.1 illustrates 3 potential storylines depending on a chosen scenario[3] with focus on outcomes related to extreme weather events and especially heat waves. Best-case (Scenario 1), mid-case (Scenario 2) and worst-case (Scenario 3) plots include an intensification of heat waves as an inevitable "payoff" irrespective of the mitigation pathway. The severity and extent of these events depend on particular mitigation strategies, as highlighted in the table.

[3]A 'scenario' is an internally consistent, plausible, and integrated description of a possible future of the human-environment system, including a narrative with qualitative trends and quantitative projections (Nakićenović 2000).

Table 2.1: Heat wave storylines resulting from different scenarios

Scenario	Mitigation	Internal climate variability	Possible storyline
Scenario 1[4]	Early move to decarbonization designed to minimize land footprint, coordination and rapid action of the world's nations towards 1.5°C goal by 2100.	Probable (66%) best-case outcome for global and regional climate responses.	Frequent deadly heatwaves whose risks are reduced by *proactive adaptation*, overlaid on a suite of development challenges and limits in disaster risk management.
Scenario 2[5]	Delayed action (ambitious targets reached only after warmer decade in the 2020s due to internal climate variability), overshoot at 2°C, decrease towards 1.5°C afterward, no efforts to minimize the land and water footprints of bioenergy.	10% worst-case outcome (2020s) followed by normal internal climate variability.	Deadly heatwaves in major cities (Chicago, Kolkata, Beijing, Karachi, Sao Paulo), *droughts in southern Europe*, southern Africa and the Amazon region, and major flooding in Asia, all intensified by the global and regional warming, lead to increasing levels of public unrest and political destabilization.
Scenario 3[6]	Uncoordinated action, major actions late in the 21st century, 3°C of warming in 2100.	Unusual (ca. 10%) best-case scenario for one decade, followed by normal internal climate variability.	Major heatwaves on all continents, with deadly consequences in tropical regions and Asian megacities, especially for those ill-equipped for protecting themselves and their communities from the effects of extreme temperaturas. *Droughts occur in regions bordering the Mediterranean Sea*, central North America, the Amazon region and southern Australia, some of which are due to natural variability and others to enhanced greenhouse gas forcing. The world as it was in 2020 is no longer recognizable, with decreasing life expectancy, reduced outdoor labour productivity, and lower quality of life in many regions because of too frequent heatwaves and other climate extremes. Droughts and stress on water resources renders agriculture economically unviable in some regions and contributes to increases in poverty.

Adapted from IPCC special report on the impacts of Global Warming of 1.5°C, Masson-Delmotte et al. 2019.

[4] In 2020, strong participation and support for the Paris Agreement and its ambitious goals for reducing CO_2 emissions by an almost unanimous international community led to a time frame for net zero emissions that is compatible with halting global warming at 1.5°C by 2100.

[5] The international community continues to largely support the Paris Agreement and agrees in 2020 on reduction targets for CO_2 emissions and time frames for net zero emissions. However, these targets are not ambitious enough to reach stabilization at 2°C of warming, let alone 1.5°C.

[6] In 2020, despite past pledges, the international support for the Paris Agreement starts to wane. In the years that follow, CO_2 emissions are reduced at the local and national level but efforts are limited and not always successful.

2.2 Heat waves in the Mediterranean

The Mediterranean Region (MR, includes Southern Europe[7], Northern Africa[8] and Near East[9]) has been identified as one of the most responsive and vulnerable to climate change regions globally (IPCC 2013). The MR region is extremely diverse in demographic and socioeconomic terms. Northern Mediterranean coast is composed by economically developed countries with European aging populations, low fertility rates and high life expectancy. Southern coast, in contrast, is formed by mostly developing, often politically unstable African and Asian countries with lower life expectancy, younger population, overreplacement but slowly decreasing fertility rates; see table 2.2).

Table 2.2: Summary statistics of main indicators of Mediterranean population

	Fertility rate[10]	Ages 0-15	Life Expectancy[11]	Population[12]
Northern Africa	2.6	31.12	76.01	201.79
Near East	2.1	24.69	78.57	117.88
Southern Europe	1.42	15.15	81.78	199.67
Mediterranean	**2.03**	**23.52**	**78.81**	**519.34**

Adapted from Population Reference Bureau World Population data sheet (see https://www.prb.org/collections/data-sheets/)and World Bank country statistics published in 2021; all indicators are weighted by population size in 2020.

The region has experienced a substantial growth of population in the past decades, however this increase was geographically unbalanced. According to the World Bank[13] statistics, European side (12 states) went from 173.7 millions in 1980 to 199.6 millions in 2020 (+14%), mostly driven by migration. In the mean time, southern Mediterranean (9 states) went from 151.5 millions in 1980 to 319.6 millions in 2020. Doubling of the population in 40 years is attributed to sharp declines in mortality and a slower fertility decline, which still compensated an intense out-migration. As highlighted in 2019 report by Mediterranean Experts on Climate and Environmental Change (Cramer, Guiot, and Marini 2019), to date the MR faces a large number of inequalities: uneven distribution of resources, social and political instability, armed conflicts, migration, all against the background of natural predisposition to environmental hazards. The list of challenges the

[7]Albania, Bosnia and Herzegovina, Croatia, Cyprus, France, Greece, Italy, Malta, Monaco, Montenegro, Slovenia and Spain

[8]Algeria, Egypt, Libya, Morocco and Tunisia

[9]Israel, Lebanon, Syria and Turkey

[10]Number of births per woman

[11]Life expectancy at birth, years (total)

[12]Total population in 2020, millions

[13]The World Bank Data Catalogue, for more information see datacatalog.worldbank.org

MR confronts on a regular basis has been recently replenished by climate change-related extreme weather events, namely, heat waves, droughts and wildfires.

Cramer, Guiot, Fader, et al. (2018) stated that observed rates of warming in the MR exceed global trends and are projected to do so, especially during the summer season (up to 40% larger than the global mean). The retrospective analysis performed by Kuglitsch et al. (2010) showed that frequency, intensity and duration of the heat waves have increased by a factor of 6 and above in the MR since 1960s. In the future, hot extremes are projected to warm the most in the MR, and as repeatedly highlighted by IPCC reports the risk of drought intensification in this region is also increasingly high. The variations of the annual maximum daytime temperatures, shown as a function of global warming on Figure 3.5[14] in the IPCC 2018 Special Report, have linear tendencies and are independent of the emission scenarios (Masson-Delmotte et al. 2019).

There is an active debate regarding the mechanisms of heat wave formation across the MR. Generally speaking, MR has a strong soil-moisture-temperature coupling which dictates preferential warming of the hot tail of the daily temperature distribution (Diffenbaugh et al. 2007). Rainfall deficits in Southern Europe during the winter season often precede the exceptionally hot summers, not only affecting the MR itself but embracing areas to the north due to the winds from the south (Vautard et al. 2007).

Most significant changes in heat wave peaks affect Eastern Mediterranean (also referred to as Eastern Mediterranean and Middle East, EMME). There is a large body of studies focusing on the exploration of the origins of the most recent and devastating heat waves in this area. Hochman et al. (2021) concluded that the heat wave of 2010 in EMME was mostly attributed to the displacement of air parcels with westerlies rather than to the in-place air stagnation and heating for a prolonged period. Baldi et al. (2006) explored triggering processes of the heat waves in central MR in relation to Atlantic westerly jet. According to this study, the occurrence of heat waves is associated with the adiabatic warming of the troposphere over the MR under the condition of alignment of Scandinavian and Mediterranean jet branches, which in summer season are at minimum meridional distance. Strong adiabatic heating in the southern EMME provoked by intensified anticyclonic activity is also listed as a potential reason for changes in the heat wave peaks by Zittis et al. (2016). Anticipating the discussion in the following chapters, it is worthy to note that heat wave conditions are often associated with intensified air pollution, as highlighted in another study for EMME by Lelieveld et al. (2014).

[14]Figure 3.5 can be accessed at *Graphics — Global Warming of 1.5 ºC*: www.ipcc.ch/sr15

To examine the changes of heat waves long simulations of the present and future regional climate conditions are needed, as claimed by Planton et al. (2012), a reference reading on the climate of the MR. According to the models developed by the authors, both extreme sides (cold, 5^{th} percentile, and hot, 95^{th} percentile of the temperature distribution) are projected to increase. However, the patterns across the region are not homogeneous, which is an important conclusion to take into account. In particular, Southern parts of the IP and western parts of North Africa show slight decreases of extreme minimum temperatures in winter, whereas hot extremes in summer are projected to slightly decrease over parts of the IP, in contrast to the Central and Eastern Mediterranean where both ends are anticipated to increase. In terms of the changes of temperature extremes, the results for the IP indicate a mixed picture, which implies non-symmetric modifications of the frequency distribution of the MR temperatures and not just a plain positive shift. We will discuss the forecasts and physics of the heat wave formation processes in the Spanish territory in detail in Chapter 4.

In the following paragraphs, we would like to guide the reader through some of the social and economic challenges that Spain as a MR constituent state might face as a consequence of climate change and rise of the temperatures.

2.3 Collateral effects

Human migration and conflicts. The MR region was prone to armed conflicts during many centuries. To date, the waters of the Mediterranean are among the most militarized in the world. With all the latest events[15] in its oriental half it has re-emerged as a focus of geopolitical interest. The climate change, in turn, is a silent but arguably one of the most important exacerbators of the political instability and multiplier of the risks (Scheffran 2020).

As emphasized by Tacoli (2009), extreme events resulting from climate change and global warming (e.g. heat waves, severe droughts, flooding), become authentic disasters when they affect highly vulnerable population. The richer countries have evident advantages as they are better 'equipped' and able to cope with the adverse effects of the changing environment than their low-income counterparts. Population growth, low water availability, decrease in agricultural productivity (e.g. crop failure),

[15]Lebanon conflicts in 2007 and 2008, Islamist insurgency in the Maghreb following the Algerian civil war (onset in 2002, affects Algeria and Morocco); started in 2011 and ongoing Egyptian revolution and aftermath, Lybian and Syrian Civil Wars, Turkey Coup Attempt in 2016; ongoing disputes between Turkey, Greece and Cyprus, and many more.

degradation of the coastal and marine ecosystems, aridization and desertification are the drivers of the increased competition for the land, instability, decrease of living standard and aggravation of food insecurity. The social reponse to these perturbations might eventually lead to the destruction of the infrastructure, threats to health and trigger human mobility, provoking what Tacoli (2009) defined as a *climate-induced distress migration*. The topic of climate-related migrations is highly polemic and difficult to study as there are too many factors that prompt an ultimate decision of relocation. Apart form the environmental drivers, other economic, political, social and demographic factors also play a crucial role (Black et al. 2011).

Globally, climate-change induced migration currently predominates in lower latitudes as the severity of climate impacts is much more palpable in the southern countries with developing economies and geopolitical volatility (Felipe Pérez 2018; Vigil 2017). Nevertheless, this does not mean that northern states stay out of the risk and remain unaffected by these movements. In the Mediterranean settings, there is a large discrepancy between Southern Europe and countries of North Africa and Near East in terms of income and socioeconomic development, which defines the intensity of the south-to-north migratory flows. It is, however, hard to estimate the fraction of the migrants entering the northern coast of the Mediterranean and Spain in particular due to the changes in their living environment that made the relocation inevitable. Worthy to note that the intra-state migrations triggered by the climate change in Spain gain an increasing concern at the governmental level. The risk of land abandonment due to the change in crop yield and production location was included in the Basic Study of Adaptation published by the local government of Andalusia (Méndez Jiménez et al. 2012).

Potential economic impact. Overall increase of the temperatures and intensification of heat waves events imply a significant burden for the economy, which is conditioned by the state of the health- and social care system and effectiveness of the heat prevention plans. A large body of literature has been developed over the years to produce monetary estimates of the health and other costs due to extreme heat, and project these impacts into the future.

We identified 5 groups of studies that touch on the following aspects:

- Heat-attributed mortality costs, retro- and prospective estimations,
- Hospitalization and hospital admission costs,
- Labor loss and occupational health risks,
- Damage of infrastructure,
- Tourism demand.

Globally, annual total impact of climate change on mortality risk is estimated at 3.2% of global GDP under a high emission scenario (Carleton et al. 2018). These estimations account for adaptation costs and benefits and are based on future projections of climate, income, and population. Regional estimates of health costs due to heatwaves represent a notable burden and reach millions of dollars each year (Gronlund, Cameron, et al. 2019; Cheng, Xu, et al. 2018). A study by Carmona et al. (2016) evaluated the effects of the implementation of the heat prevention plan over the period of ten years (2000-2009) in Spain and estimated the total heat-related mortality cost of over €1K million. According to their results, activation of a heat prevention plan could help avoiding 2.04 deaths on a daily basis (assuming an effectiveness of 68% of the plan), in such way saving approximately a quarter of a million €. Another fundamental study by Díaz, Sáez, et al. (2019) explored impacts high temperatures have on mortality under a high-emission scenario[16] with and without adaptation processes. For the period 2021-2050, the annual cost attributable to mortality due to extreme heat was estimated at €6021/€2667 million[17] (scenario without/with adaptation), whereas the economic burden for Spain in 2051–2100 would reach €53,217/€4108 million.

Heat-related morbidity and associated costs (hospitalization, emergency department and clinic visits) have been examined to a smaller extent if compared to the costs associated with heat-related mortality. A study by Liss, Wu, et al. (2017) on heat-related morbidity of elderly during heat waves in the city of Boston, US, has revealed that an episode of extreme heat could lead to a 7-fold increase in hospitalization of older adults (for the period 1991-2006). In terms of medical charges the impacts of hospitalization of elderly due to heat waves were almost equivalent to the entire annual state budget for senior support. Lin Shao et al. (2012) projections of future attributable risks related to extreme heat estimated 2-6 times higher hospital admissions for heat-related respiratory diseases in New York in 2080-2099 (compared to 1991-2004) with an associated economic cost of US$26–$76 million. In addition, Jagai et al. (2017) highlighted that days spent in hospitals due to heat-related causes represent a substantial burden of indirect costs. Last but not least, extreme heat is often associated with intensified air pollution - an issue that we will discuss in details later. Health impacts of air pollution also pose excessive economic costs through hospitalization and visiting emergency rooms (Peel et al. 2013).

That said, perhaps the most frequently studied subject in relation to economic costs associated with extreme heat are the potential health risks and productivity reductions

[16]RCP8.5, the most aggressive Representative Concentration Pathways (RCPs) scenario, for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100. For more information see www.ipcc-data.org

[17]In 2018 € values

of working population. The adverse effects of heat exposure on human function at work are rather 'neglected' and overlooked in classic climate change impact studies, highlights Kjellstrom, Holmer, et al. (2009). Immediate direct deaths from sun exposure are, indeed, rare, and most often occur among individuals wearing protective clothing and performing intense physical work during the hottest hours (Lin and Chan 2009). It was, however, proven that mental performance and psychomotor functions are significantly affected by prolonged heat stress and result in injuries and other health consequences (Rodahl 2003). Heat-induced disorders resulting from excessive exposure to hot environments include dehydration, heat rash, cramps, exhaustion, fatigue and heatstroke, which potentially might lead to death (Schulte and Chun 2009). In some areas, in 2100 a 30-40% loss of daylight working hours is expected due to inadequate temperatures for physical and mental activity under the RCP4.5 scenario. It might eventually result in a 20% forfeit of global productivity (Kjellstrom, Briggs, et al. 2016; Yang, Song, et al. 2019). Under the same scenario 600–2600 million hours of lost labor per year could be avoided in US only, thus saving US$20–78 billion by 2100 (Zhang and Shindell 2021). Insurance claims due to excess work-related injuries tend to significantly increase during the heat wave episodes (Varghese 2019; Ma, Zhong, et al. 2019). In Spain, the annual economic burden of occupational injuries attributable to non-optimal temperatures was estimated at €370 million which constituted 0.03% of country´s GDP in 2018 (Martínez-Solanas, López-Ruiz, et al. 2018). According to the estimates of this study, the majority of the regions revealed higher risks associated with cold extremes, although the effects of heat on injuries in a few southern communities (Cádiz, Badajoz) were more pronounced than the effects of cold. As showed by Martínez (2020), the benefits of introducing heat adaptation plans for the period 2051-2100 in Spain are estimated at 49.1 billion of euros per year.

Extreme heat not only poses a direct societal threat, but is capable of creating a significant damage for basic systems and services such as infrastructure. An Australian study by McEvoy et al. (2012) explored the adverse impacts and associated costs resulting from extra pressure on electricity network, road and rail transport during hot weather. Electricity demand spikes during heat waves due to a sharp increase of air conditioning use and might lead to power outage and shutdowns. High temperatures affect rail network performance, which results in physical damage (buckling of tracks, often resulting in catastrophic derailments) and train delays (Greenham et al. 2020), creating additional and often high economic costs. Extremely hot temperatures can also provoke so-called "bleeding" or "flushing"[18], resulting in the paved surface becoming

[18]Flushing is a pavement surface defect with bituminous (asphalt) binder on the pavement surface, which results in minimal surface texture. For more information see https://www.nzta.govt.nz

sticky and soft and therefore increasing the risk of car accidents. The effects of hot weather on vehicle crashes in Spain was studied by Basagaña Xavier et al. (2015). Results indicate a significant increase of risks of crashes during heat wave episodes which are partially explained by the car equipment, health state of the driver (fatigue, sleepiness due to uncomfortable temperatures in the days prior to the accident) and pavement conditions. The vehicle crashes and infrastructure damage during heat waves contribute to excess costs via ambulance calls, hospitalization, insurance payouts, repairing works and slowdown of support systems.

Last but not least, the impacts of the warming of temperatures on the tourism industry revenue might be of a great scale, especially for a country like Spain with 12.4% of GDP attributed to touristic sector[19]. An econometric study by Barrios and Ibañez (2014) estimated the decrease of tourism income by 0.6-0.8% of GDP in 2100 (no adaptation strategy applied results in fall by 0.73%, holiday timing adaptation - in 0.86%, and holiday duration adaptation - in 0.67% of GDP).

2.4 Physiological basis

The topic of adverse effects of extremely hot temperatures on humans is utterly broad and integrative. Disciplines ranging from physiology, epidemiology, toxicology, neonatal-perinatal medicine to social and environmental demography are closely intertwined here.

We start this chapter with an overview of the fundamental physiological processes responsible for thermal regulation in humans. We believe that understanding of the core mechanisms that are in charge of *normal* functioning of the body is essential for grasping health outcomes resulting in *deterioration* of these mechanisms as a function of extreme heat.

Further, we discuss the most common factors that exacerbate the negative response to high temperatures in different populations. The adverse effects on different organ systems of air pollution, a process highly sensitive to the changes in ambient temperatures, are examined further. This discussion is accompanied by a comprehensive review of the scientific publications on the corresponding topics released in the recent years.

In conclusion to this chapter, we introduce the reader to the primary research questions of our study, set out primary hypothesis and corresponding objectives, and justify logical basis of the work and organizational structure of the following chapters.

[19]Spanish Tourism Satellite, Statistical review 2019 published by the INE. For more information see www.ine.es

2.4.1 Mechanisms of body thermoregulation in humans

Temperature has a significant effect on the course of life processes[20] in the human body and on its physiological activity. Life processes are limited by a relatively narrow temperature range of the internal environment, suitable for the main enzymatic reactions to occur. For an individual, a decrease in body temperature below 25°C and an increase above 43°C is usually fatal.

Life processes in humans are accompanied by continuous heat generation and its release into the environment. The exchange of heat energy between the body and the environment is called *heat exchange*. Human body is a self-regulating system with an internal heat source, in which, under normal conditions, heat production (the amount of heat generated) is equal to the amount of heat given to the external environment (heat transfer or heat loss). The constancy of body temperature is called thermal homeostatis or isothermic state. It ensures the independence of metabolic processes in tissues and organs from fluctuations in ambient temperature, which is the main factor to define the level of heat balance.

When ambient temperatures deviate from the so-called thermoneutral zone - a range of environmental temperatures in which the basal metabolic rate[21] is low and independent of temperature - a new level of heat balance is established, providing thermal homeostatis in new environmental conditions. This constancy of body temperature is provided by the *thermoregulation mechanisms*, which are controlled by the endocrine and nervous system and are responsible for regulating metabolism, blood circulation, sweating and the activity of skeletal muscles.

The normal oral body temperature usually ranges from 36.5°C-37°C, whereas the normal core temperature is slightly higher than the oral and equals to approximately 37.5°C. The temperature at the skin surface varies and is usually slightly above the ambient temperature. Body temperature fluctuates throughout the day following so-called circadian rhythms[22]: it is the highest in the late afternoon and the lowest in the early morning. Female body temperature is subject to monthly fluctuations (around 1°C) according to the menstrual cycle whereas, ceteris paribus, male body temperature remains fairly constant.

[20] Defined as basic important activities achieved by an organism; in humans include such processes as nutrition, respiration, digestion, excretion, reproduction, metabolism and transportation.

[21] Metabolic rate of a resting endotherm at a temperature within the thermoneutral zone

[22] Circadian rhythms, also known as biological or internal clocks, are 24-hour cycles that set the rhythm for all the essential functions and vital processes in the human body. An example of such cycle is a sleep-wake cycle.

The generation of the heat in human body is primarily attributed to metabolic reactions and processes (cellular respiration and other biochemical reactions) and muscular activity. Assimilation of food (absorption of nutrients and its processing in the liver) also contributes to heat generation. Heat loss, on the other hand, is associated with 4 major pathways: conduction (through contact), convection (through air), radiation (through skin) and evaporation (through sweat).

As mentioned earlier, normal body function requires a relatively constant body temperature which is regulated by the hypothalamus[23], which essentially plays the role of a thermoregulatory reflex center. Hypothalamus generates a temperature set point for the body (core temperature of 37°C) and appears to be the major site for the integration of the temperature information. In simple terms, when the body temperature is warmer than this set point, hypothalamus registers this surplus through various thermoreceptors[24] located across the body and sends corresponding "instructions" to various organs to cool the body down. These organs are called *effectors* and are represented by cutaneous blood vessels, sweat glands, skeletal muscle and endocrine glands. When the body gets too cool, hypothalamus commands the body to do the opposite and perform a warming response by activating these effectors. Thermal regulation might be affected by non-thermal signals: dehydration, metaboreceptors[25] or cytokines[26] (Ebi et al. 2021; McGinn et al. 2014; Leon and Helwig 2010; Leon and Bouchama 2015; Conti, Tabarean, et al. 2004).

If the behavioral response to feeling cold or hot is not sufficient to maintain the core temperature stable, the following homeostatic reflexes are activated:

1. Cutaneous vasodilation (increase of blood flow to the surface of the skin to increase radiative heat loss, as result of the change in brain temperature above the set point) or cutaneous vasoconstriction (decrease of blood flow to the surface of the skin to reduce radiative heat loss, when body temperature goes lower than the set point).

2. Sweating (to increase evaporative heat loss when vasodilation is not sufficient to remove excessive heat) or shivering (to increase heat production through muscle

[23]A brain structure that, together with the thalamus, forms the diencephalon, and controls the endocrine and autonomic nervous systems of the body.

[24]Temperature-sensitive nerve cells present in the skin and throughout the body (Ebi et al. 2021).

[25]Peripheral afferent nerve endings that respond to metabolites produced by active muscle. Known to influence cutaneous vascular conductance and sweat rate.

[26]Secreted proteins that mediate intercellular communication in the nervous and immune system. Traditionally known as adverse mediators of the systemic inflammatory response syndrome, which in case of heat stroke may lead to multi-organ failure and death. There is an ongoing debate on the protective role of cytokines in the resolution of inflammation.

friction and increase of cellular respiration, if vasoconstriction is insufficient to increase core temperature). Worthy to note that the process of sweating is strongly affected by the concentration of water vapor in the air: higher humidity prevents the sweat to be transferred from liquid to gas state and therefore impedes heat removal. Havenith and Fiala (2015) highlight the importance of inclusion of humidity parameter into the analysis of temperature-related mortality, especially in relation to hot conditions.

These responses of the human body to the changes in the ambient temperature with respect to the internal body temperature are practically instantaneous as they are mediated by the nervous system "on the spot". However, there is an additional endocrine pathway through which the body temperature might be regulated in the longer run. When humans are repeatedly exposed to hotter (colder) environments, it results in reduction (intensification) of hormonal release from thyroid and adrenal glands. The essential role of thyroxin (secreted by thyroid gland) and adrenalin (secreted by adrenal gland) in the human body is quite different. However, these two hormones are similar because they both affect metabolic rate by decreasing (increasing) the rate of biochemical reactions which eventually decrease (increase) the production of heat. This is part of the **acclimatization** process to new environmental settings. Doubtlessly, the thermal balance of the body is affected not only by the local environmental conditions but also by the individual physiological characteristics such as metabolic rate, height, weight, fat percentage, blood flow rate, gender or skin surface area (Katic et al. 2016).

During an episode of extreme heat stress, the capacity of the human body to thermoregulate can be exceeded. Inability to maintain thermal homeostasis leads to a number of serious and often fatal health consequences. Exposure to extremely high temperatures is often analyzed from two different angles: direct impact on the *health status* of the individuals (i.e. clinical damage to organ function) and reductions in *human performance capacity* (includes reduced work capacity due to cognitive function decline, increased risk of incidence, reduced physical activity and therefore higher risks of obesity, and so on). As the reader might remember from the introductory part, we have touched on the latter topic from the purely economic point of view, discussing potential economic impact resulting from the labor loss and occupational health risks as result of overall warming. In the next sections, we discuss direct impacts on the individual health status. We primarily focus on acute and subacute heat-related diseases and factors that might act as a risk multipliers for the course and ultimate outcome of these diseases.

2.4.2 Heat-related illnesses

As formulated by Lugo-Amador et al. (2004), heat-related illnesses could be seen as a *continuum of disorders* varying from milder syndromes to life-threatening conditions. The International Classification of Diseases[27] lists a number of specific diseases attributed to heat exposure and defines them as *adverse effects resulting from a failure to maintain normal body core temperature on exposure to excessive heat.* There are also a few diseases that are mostly attributed to heat but could be provoked by other types of exposures. We also discuss these diseases further.

Heat stroke[28]

Heat stroke, sometimes referred to as *sunstroke*, is the most severe outcome of exposure to high environmental temperatures, and could be fatal if left untreated. ICD-11 defines heat stroke as an *elevation of the core body temperature above 40.6 degrees centigrade due to environmental heat exposure and a failure of thermoregulation.* If the body core temperature goes above 41°C and stays at this level for a prolonged period of time it results in irreversible cell damage, e.g. heat-induced protein denaturation that leads to cell deaths or necrosis (Jardine 2007). Heat stoke often results in multi-organ dysfunction provoked by a systemic inflammatory response syndrome (Leon and Helwig 2010).

During fever, which is a normal body response to viral or bacterial infections or inflammatory conditions, the hypothalamic set point is elevated whereas core temperature is still controlled by normal thermoregulation mechanisms. In case of the hyperthermia, evaporative, vasomotor, hemodynamic and behavioral responses are insufficient, which leads to substantial rise of core body temperature to critical levels. Nevertheless, hyperthermia and fever might occur in conjunction due to initial presence of infection, as shown by Stéphan et al. (2005). The condition of hyperthermia should be treated immediately with aggressive supportive care, as prognosis is the poorest if treatment is delayed for more than two hours (Yeo 2004).

Heat stroke might be of two types: so-called *classical* and *exertional*. As mentioned by Kilbourne (2011), these two types correspond to two different circumstances under which heat stroke might occur. Exertional heat stroke is a complex disorder that is characterized by inability to thermoregulate during physical activity. It is one of the

[27] International Classification of Diseases for Mortality and Morbidity Statistics, Eleventh Revision ICD-11, WHO. For more information see https://icd.who.int/

[28] **NF01.0** Heat stroke or sunstroke - NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

most frequent causes of sudden death in young athletes and an important occupational hazard, particularly in the military. Classical heat stoke, on the other hand, tends to occur in people with more sedentary lifestyle (most often infants or older patients) who are exposed to longer persistent exposures to extreme heat.

Exertional rhabdomyolysis[29]

Exertional or exercise-induced rhabdomyolysis is associated with exertional heat stroke and is characterized by *increased intramuscular pressure, ischemia, hypoxia and necrosis of striated skeletal muscle as result of abnormally excessive movement, excessive isometric tension by attempted movement against resistance, or coma*, as described in ICD-11. It is a rather uncommon condition seen in athletes and military personnel, however it has severe consequences and might eventually lead to death if it is not managed properly (Knochel 1989; Heytens et al. 2017; Tietze and Borchers 2014).

Heat cramps[30]

Heat cramps usually occur in patients after working or strenuous exercise in hot environment, and is considered as the mildest syndrome in the spectrum of heat-related illnesses. Brief muscle cramps are attributed to the electrolyte imbalance and pass away after supplying salt-enriched fluids.

Heat exhaustion[31]

Heat exhaustion, defined in ICD-11 as *a failure of thermoregulatory sweating on exposure to heat as a result of water deprivation and/or inadequate replacement of fluids lost through sweating or by other means (e.g. severe diarrhea)*, frequently precedes heat stroke, but is a less severe condition *per se* and does not involve major neurologic impairment. Fluid and electrolyte imbalance due to increased perspiration are the most common reasons for this condition (Kilbourne 2011). The tenth edition of ICD classified *heat exhaustion* syndrome into *anhydrotic heat exhaustion* defined as *heat prostration due to water depletion*, and *heat exhaustion due to salt depletion* defined as *heat prostration due to salt (and water) depletion*.

[29] **FB32.20** Idiopathic rhabdomyolysis - FB32.2 Ischaemic infarction of muscle - FB32 Certain specified disorders of muscle - Disorders of muscles - Soft tissue disorders - 15 Diseases of the musculoskeletal system or connective tissue; **8C84** Secondary rhabdomyolysis - Secondary myopathies - Diseases of neuromuscular junction or muscle - 08 Diseases of the nervous system

[30] **NF01.Y** Other specified effects of heat- NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

[31] **NF01.2** Heat exhaustion due to fluid depletion - NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

Heat rash[32]

Heat rash is specific form of miliaria, *a common skin disorder resulting from occlusion of eccrine sweat ducts* as defined in ICD-11. When the sweat ducts are blocked, it prevents sweat from reaching the surface of the skin and evaporating: instead, sweat remains below the skin surface causing a rash. There is a number of additional factors apart from extreme heat exposure (e.g. clothing, use of topical skin products, etc) that might trigger the appearance of heat rash.

Heat syncope[33] **and Heat fatigue**[34]

Heat syncope, defined as *fainting attributable to exposure to heat* in ICD-11, is a relatively mild syndrome related to circulatory instability due to superficial vasodilation in response to the heat. As blood vessels are widening and dehydration and sweating increases with high temperature, the blood pressure might fall, leading to dizziness and fatigue.

Heat oedema[35]

Heat edema (or oedema) is a cutaneous condition resulting from transient peripheral vasodilation from heat and consequent transfer of liquids (orthostatic pooling) to the limbs. Salt imbalance is known as an additional risk factor for this disease.

2.5 Risk multipliers

There is a plethora of factors that could potentially contribute to individual risks of a heat-related illness (Barrow and Clark 1998). These factors range from individual health and medical status to overall socioeconomic status, living and environmental (other than climatic) conditions. Further we discuss four groups of factors affecting health outcomes resulting from exposure to extreme heat: medical pre-conditions, natural processes, socioeconomic considerations and air pollution.

[32]**EE02.Y** Other specified forms of miliaria - EE02 Miliaria - EE02.Y Other specified forms of miliaria - Disorders of eccrine sweat glands or sweating - Disorders of the epidermis and epidermal appendages - Skin disorders involving specific cutaneous structures - 14 Diseases of the skin

[33]**NF01.1** Heat syncope - NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

[34]**NF01.3** Heat fatigue, transient - NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

[35]**NF01.Y** Other specified effects of heat- NF01.Effects of heat - Other or unspecified effects of external causes - 22.Injury, poisoning or certain other consequences of external causes

2.5.1 Medical conditions

Current health status or medical condition is one of the primary factors that may put an individual to a greater risk at the time of exposure of extreme environmental conditions. Presence of ongoing subacute (chronic) conditions and use of medications or abusive substances increases individual susceptibility and significantly alters the outcome of heat exposure. Moreover, the effects of heat exposure may accumulate over time: as discussed by Ebi et al. (2021), cognitive and organ dysfunction can persist over long periods of time after an extreme event and then "discharge" after decades.

Cardiovascular and respiratory diseases

Multiple studies have shown that all-cause cardiovascular illnesses along with heat-derived lung damage and increased pulmonary stress are the two largest sources of morbidity and mortality during heat waves.

The mechanism of the exacerbation of pre-existing heart conditions are based on the increase of the cardiovascular strain that eventually may lead to cardiovascular collapse. Pre-existing cardiovascular conditions may impair vascular responses in order to regulate core temperature. On the other hand, increased blood viscosity may contribute to coronary and cerebral thrombosis (Kenny et al. 2010). Pulmonary oedema, acute respiratory distress syndrome and hyperventilation produce additional damage to the lungs during episodes of high temperatures. Individuals with pre-existing pulmonary and cardiovascular illnesses are put to an higher risk, an issue that is well reflected in the recent scientific publications (Bouchama et al. 2007; Xu, FitzGerald, et al. 2016; Phung et al. 2016).

These diseases are most commonly found in the elderly patients. Here we specifically emphasize that age *itself* acts as a risk multiplier for the adverse heat-related health outcomes. Age with respect to heat will be discussed in the following paragraphs. In the mean time, we note that the relation between increasing death rates in elderly due to respiratory, cardiovascular and often renal illnesses in response to extreme temperatures is well established and appears to be consistent globally (Monteiro et al. 2013; Conti, Masocco, et al. 2007; Oudin Åström, Bertil, et al. 2011; Gronlund, Zanobetti, et al. 2016; Hopp et al. 2018). Further, we review the evidence from the studies performed using the data for Spain only.

Ballester et al. (1997) studied the relation between temperature and cause-specific mortality in Valencia during the period between 1991 and 1993. The authors estimated the relative risks of dying due to a rise of 1°C in the mean temperature above the cutoff

point of 24°C in the city of Valencia at 1.098 (95%CI: 1.024–1.179) for respiratory diseases, which was higher than the relative risk for cardiovascular diseases or neoplasms[36] on the day of exposure. On the consequent days (up to 2 weeks) the risks decreased for the respiratory diseases and neoplasms, whereas for cardiovascular diseases the risks increased in the following week and were the highest at 3-6 days lag (1.029 at 95%CI: 0.986–1.074). SAEZ et al. (2000) focused on the ischaemic heart disease[37] in adults and its association with extreme values of ambient temperature in Barcelona during 1986-1991. Their results indicate an approximately 4% increase of the risks of an ischaemic heart pathology with every 1°C rise above 25°C.

Another study by Fernández-Raga et al. (2010) evaluated the effects of average monthly weather conditions (not only temperature but air humidity and pressure) on cause-specific mortality in the community of Castile-León in 1980-1998. This study shows statistically significant mortality trends during the summer, where extreme heat is more likely to occur in this community, only in the group of respiratory diseases. The authors also argue that among the selected meteorological variables chosen for the analysis, only temperature shows strong connection with mortality. Nevertheless, this study mentions the impact of the variations of air humidity on mortality as humidity affects the evaporative processes (sweating) and, if low, causes dehydration of the nasal cavity which increases the risk for viral and bacterial infections, especially in the winter season. Linares, Diaz, et al. (2015) explored the impact of heat waves on circulatory- and respiratory-cause mortality in the community of Castile-La Mancha in 1975-2008. Their results revealed that 16.5% (95%CI: 15.5-17.4) of summer mortality in the area was attributed to heat, and persistence (prolonged duration) of heat wave episodes was associated with a 3.5% increase in daily natural mortality. At the same time, the risks of mortality due to respiratory causes during heat waves were higher than the risk of mortality due to circulatory diseases. The percentage increase in mortality for 1°C rise of the maximum daily temperatures above the threshold of 37°C was estimated at 16.4% (95%CI: 14.8-18) for respiratory causes whereas for the circulatory causes it equaled to 14% (95%CI: 14.9-15.8). These findings are in line with a study performed by Miron et al. (2015) for the same location using the cause-specific mortality data from

[36] **02 Neoplasms** chapter, defined by ICD-11 as *an abnormal or uncontrolled cellular proliferation which is not coordinated with an organism's requirements for normal tissue growth, replacement or repair.*

[37] Ischaemic heart diseases - 11 Diseases of the circulatory system, include acute (**BA40-BA4Z**) and chronic (**BA50-BA5Z**, defined by ICD-11 as a *chronic heart disease is seen due to the atherosclerosis. of coronary arteries; characterized by angina pectoris and unstable angina*) ischaemic heart diseases, certain current complications following acute myocardial infarction (**BA60**) and unspecified ischaemic heart diseases (**BA6Z**).

1975 to 2008. Same threshold value of 37°C was estimated for heat-related mortality. Adding an additional heat wave day explained the rise of 5.3% (95%CI: 2.6–8.0) and 2.3% (95%CI: 1.6–3.0) in respiratory mortality in the first and last decade of the study period, respectively. Highest impact on both causes was registered in the period 1986-1996, with percentage increase in 30.3% (95%CI: 28.3-32.3) for circulatory mortality for each degree above the threshold, and in 16.3% (95%CI: 14.1-18.4) for respiratory mortality. The 1997-2008 decade showed, however, a shift in the percentage for these causes: circulatory heat-attributed mortality reduced to 7.3% (95%CI: 6.2-8.4) whereas respiratory mortality stayed above the circulatory at the 13.7% (95%CI: 11.5-15.9) level.

Overall trends in mortality due to cardiovascular causes in Spain were explored by Achebak, Devolder, and Ballester (2019). In this study, provincial data for the period 1980-2016 was used to explore the changes in minimum mortality temperature (MMT) and in the heat- and cold-related risks over time. The results show an increase in overall MMT in 0.7°C from 1980-1994 (19.5°C) to 2002-2016 (20.2°C), and general reduction in risks and attributable fractions of cardiovascular deaths due to heat or cold[38]. In particular, relative risks for cardiovascular mortality corresponding to the 99^{th} temperature percentile decreased from 1.97 (95%CI: 1.78–2.17) in 1980-1994 to 1.46 (95%CI: 1.37–1.55) in 2002-2016. The same group of authors examined the trends in the seasonality of temperature-attributable mortality from respiratory diseases (Achebak, Devolder, Ingole, et al. 2020). Interestingly, this study reports a complete reversal of the seasonality patterns of temperature-attributable mortality from respiratory diseases in 1980-2016 in Spain. The maximum monthly attributable fraction of respiratory mortality shifted from colder months to warmer, whereas the minimum fraction moved from summer to winter, with an overall declining trend in the background.

Hospital admissions for respiratory, cardio and cerebrovascular diseases in Spanish provinces during the period 1997-2013 were analyzed by Martínez-Solanas and Basagaña (2019). The authors showed that heat was not associated with the risk of hospital admissions for cerebrovascular diseases (2%, 95%CI: -3%-7%), whereas for respiratory causes the risk was significantly higher and reached 14% (95%CI: 9%-19%). The risk for hospitalization due to respiratory causes significantly increases during longest and

[38]The increase in MMT could be interpreted as an indication of adaptation to extreme heat over time. For example, Follos et al. (2020) estimated the increase of MMT in Madrid and Sevilla at 0.58°C and 1.14°C per decade, respectively.

intense heat waves, according to this study. The incidence of myocardial infarction[39], commonly known as a heart attack, was studied by García-Lledó et al. (2020) in relation to extreme heat in the community of Madrid in the period 2013-2017. According to their results, elevated ambient temperatures did not show an association with the highest incidence (seasonal- and trend-adjusted risks estimated at 1.03, 95%CI: 0.76-1.41) whereas colder temperatures were significantly associated with an increased risk of a heart attack (1.25 at 95%CI: 1.02-1.54).

Iñiguez et al. (2021) explored cardiovascular and respiratory mortality and morbidity records with respect to ambient temperatures for all the provincial capitals of Spain between 1990 and 2014. Heat-attributable risks of mortality due to respiratory causes was estimated at 1.63 (95%CI: 1.45-1.83) and was higher than the risk for hospitalization due to the same cause, estimated at 1.04 (95%CI: 0.97-1.11). Risks for cardiovascular mortality due to extreme heat was lower than for respiratory diseases. According to the results, the risks were estimated at 1.15 (95%CI: 1.08-1.23), which was higher than the risk for hospital admission due to cardiovascular disease, estimated at 1.02 (95%CI: 1.0-1.04). The authors relate a significantly lower effects on hospital admissions for both causes to the fact that extreme heat is more likely to provoke an acute effect resulting in death in the most vulnerable population. The results of another study by Díaz, Carmona, Mirón, Ortiz, and Luna (2020), presented at the 34$^{\text{th}}$ Scientific Conference of the Spanish Meteorological Association, based on the cause-specific mortality data for provincial capitals and municipalities of more than 10 000 inhabitants for the period 2000-2009, are consistent with other works. The authors showed that the relative risks during heat waves that occurred in this period were the highest for respiratory diseases, reaching 1.18 (95%CI: 1.16-1.21). Relative risks for the cardiovascular diseases were slightly lower, 1.11 (95%CI: 1.09-1.13), whereas the overall attributable fraction was estimated at 9.9% for every degree of temperature surplus above the corresponding local threshold.

The effect on daily mortality of droughts, frequently occurring but rarely studied phenomenon characterized by prolonged shortages in the atmospheric, surface and ground water supplies, was explored by Salvador et al. (2020). Heat waves are not necessarily associated with drought conditions, though are often registered simultaneously. Similar to a number of mentioned above studies, cause-specific mortality data covered the

[39]**BA41** Acute myocardial infarction - Acute ischaemic heart disease - Ischaemic heart diseases - 11 Diseases of the circulatory system, recommended as diagnostic by ICD-11 *when there is evidence of myocardial necrosis in a clinical setting consistent with acute myocardial ischemia*; **BA50** Old myocardial infarction - Chronic ischaemic heart disease -Ischaemic heart diseases - 11 Diseases of the circulatory system, defined in ICD-11 as a *past myocardial infarction diagnosed by electrocardiogram or other special investigation, but currently presenting no symptoms.*

period of 2000-2009 and corresponded to the provincial capitals and cities with over 10 000 of inhabitants within the peninsular Spain. Overall natural, circulatory and respiratory mortality were studied in relation to meteorological drought indicators. The results revealed significant risks for respiratory mortality associated with drought events, especially in the southwest, northwest and northeast, whereas circulatory mortality was less associated with this type of hydrological extreme. Moreover, authors defined the respiratory mortality as the group most strongly affected by heatwaves and air pollution under drought conditions, in consideration of the relative risk values.

Obesity, hypertension and diabetes

Obesity[40], hypertension[41] and diabetes mellitus[42], three common chronic and often co-occurring pathologies, pose a significant risk on individual´s health under the conditions of extreme heat. The primary explanation for this lies in the impairments in the control of blood flow in the skin and consequent disturbances of the core temperature regulation. Due to extra deposits of fat and consequent metabolic adjustments, heat production in overweight and obese individuals is higher than in the non-overweight ones. Under normal temperature conditions, this might lead to the elevation of the core temperature and produce an additional cardiovascular strain. Combined with other metabolic, cardiovascular and neurologic complications that all three diseases might provoke, the exposure to extremely high temperatures may result in an acute heat stress. Xu, Zhao, et al. (2019) conclude that 7.3% (95%CI: 3.5-10.9) of hospitalizations due to diabetes in the hot season between 2000 and 2015 in Brazil could be attributed to heat exposure. Meta-analysis by Moon (2021) suggest a rise by 18% in mortality and by 10% in morbidity due to diabetes during heat waves.

The effects of exposure to extreme heat in obese patients is not sufficiently represented in the literature. Prevalence of obesity, on the other hand, was more frequently explored with respect to the ambient temperatures (Voss et al. 2013; Yang, Han, et al. 2015). To

[40] **5B81** Obesity - Overweight or obesity - Overweight, obesity or specific nutrient excesses - Nutritional disorders - 05 Endocrine, nutritional or metabolic diseases, defined in ICD-11 as *a chronic complex disease defined by excessive adiposity that can impair health, in most cases a multifactorial disease due to obesogenic environments, psycho-social factors and genetic variants.*

[41] Hypertensive diseases - 11 Diseases of the circulatory system, include **BA00** Essential hypertension, **BA01** Hypertensive heart disease, **BA02** Hypertensive renal disease, **BA03** Hypertensive crisis, **BA04** Secondary hypertension and **KB45** Neonatal hypertension.

[42] Diabetes mellitus - Endocrine diseases - 05 Endocrine, nutritional or metabolic diseases, defined in ICD-11 as *a metabolic disorder with heterogeneous aetiologies which is characterized by chronic hyperglycaemia and disturbances of carbohydrate, fat and protein metabolism resulting from defects in insulin secretion, insulin action, or both.*

our knowledge, a unique study on association between ambient temperature and obesity in the Spanish population was conducted by Valdés et al. (2014). According to their results, the odds ratio for obesity progressively increases with the increments in the mean annual temperature. These results are in line with Kanazawa (2020), who estimate an increase of the odds of obesity by 12% from 1961 to 2081, under the worst-case scenario. On the contrary, Salehi et al. (2020) have seen a decrease of the impact of BMI[43] with the increase of temperatures. Generally, the existing evidence on the association of obesity and ambient temperature remains quite contradictory and requires further investigation.

Mental health and cognitive function

Mental disorders have been traditionally studied in relation to the environment, especially in context of the variations of the amount of daylight and seasonality patterns. For example, a study performed by Iglesias-Fernández et al. (2021) in Spain revealed that females tend to commit suicides in spring whereas males suicide more often in autumn. Another Spanish study by Henríquez-Sánchez et al. (2014) established an association between the number of daily light hours and mean temperature and the risk of depression in male population: those living in the northern parts of Spain had lower risk for developing depression than those from central and southern regions. With the global increase of heat wave episodes, the attention to psychiatric disorders and general cognitive function in population of young and working age has significantly augmented as well. Mental disorders were shown to have more association with hot, rather than cold, temperatures (Lee, Lee, et al. 2018; Li, Ferreira, et al. 2020).

Individuals suffering from mental disorders often have disturbances in thermoregulation. This malfunction may be attributed to two factors. Xue et al. (2019) argue that patients with mental disorders are unable to properly regulate body temperature due to both emotional and thermal dysfunctions associated with poor neurotransmitter activity. On the other hand, clinical treatment of the most mental disorders implicates the usage of medications that can modify thermoregulation processes. We discuss this particular aspect in the following paragraphs. Age also seems to be a risk modifier for psychiatric patients, however this effect is disease-specific. Hansen Alana et al. (2008) indicates that patients with an early (16-64 years of age) onset of dementia are more susceptible to extreme heat. Naughton et al. (2002) find an increase of such psychiatric illnesses as depression in younger patients during heat waves. Conversely, Oudin Åström, Schifano,

[43] *B*ody *M*ass *I*ndex, a metric derived from the body mass (weight) and height of an individual, frequently used as a proxy to obesity conditions. For more information see www.cdc.gov

et al. (2015) report higher heat-related mortality risks for patients with psychiatric disorders in the age group of 65 years and older.

Individuals diagnosed with mental disorders often are unable to provide an adequate self-care and therefore rely on family members or provided sociosanitary assistance, if applicable. An important consideration by Bark (1998) refers to the fact that the majority of individuals with some kind of psychiatric illness remain outpatients, and will almost entirely depend on the individual socioeconomic conditions (available social support, housing) during heat waves.

Bulbena et al. (2009) focused on psychiatric emergencies in the city of Barcelona during 2003 heat wave, known in Europe for its exceptional intensity and devastating health consequences, and revealed a few interesting associations. According to this study, more hospitalizations were associated with substance (alcohol and drugs) abuse rather than anxiety disorders, as extreme heat, supposedly, suppresses the precipitation of anxiety in patients, and exacerbates the secondary effects of mood stabilizers and drugs for alcoholism and drug addiction treatments. Moreover, this study points out to the association between extreme temperatures and increase in aggression and violence in patients admitted with no record of substance abuse.

The decline in cognitive function during heat waves is also a widely discussed subject since, as highlighted by Laurent et al. (2018), it may lead to significant implications on educational attainment, productivity and workplace safety.

Medication and substance use

As briefly mentioned earlier, patients prescribed with antipsychotics, anticholinergics, tricyclic antidepressants, monoamine oxidase inhibitors, sedatives, amphetamines and mood stabilizers are especially vulnerable during the episodes of extremely hot weather (Kim, Lim, et al. 2015; Schifano et al. 2012). These drugs are frequently used to treat dementia, Alzheimer's disease, psychosis, anxiety and other types of disorders and might affect the evaporative and metabolic functions (Hansen Alana et al. 2008). Some authors emphasize the need to adjust the dosage and replace medication during periods of excessive heat (Bark 1998).

General evidence on pharmacokinetic interactions between heat exposure and drug therapy in humans is limited (Vanakoski and Seppälä 1998; Lomax and Schönbaum 1998). The use of sympathomimetic agents (e.g. hypertension treatment), beta-adrenergic and calcium channel blockers (e.g. arrhythmia, hypertension and migraine treatment), inhaled anesthetics, diuretics, laxatives and antihistamine drugs may worsen the condition of

the patients during exposure to extreme heat. In addition, particular attention should be paid to medication-induced photosensitivity, especially in the context of climate change and increase of UV-radiation (Beggs 2000).

Moreover, the use of alcohol, cocaine, heroin, pencyclidine (PCP) and lysergic acid diethylamide (LSD) are known substances to affect the perception of external temperature and modify thermoregulatory processes in the human body (Cusack et al. 2011; Barrow and Clark 1998).

2.5.2 Natural processes

There is a number of factors that put at greater risk individuals even if their general health state is not confounded by chronic diseases or any other medical conditions discussed in the preceding paragraphs. Thus, in continuation we discuss two most important physical risk modifiers of heat-related health outcomes, namely, the processes of ageing and gestation.

At the edge of the age spectrum

Age, especially its advanced stage, is mentioned as an important consideration to take into account when evaluating heat-related morbidity or mortality. The overwhelming majority of studies find individuals of older ages (usually 65+) at higher risk, and these findings are consistent across regions. Adverse health effect of extreme heat could be analyzed from different angles. Below we discuss the evidence from the studies focusing on *overall effects* due to high temperatures and on *added effects* due to prolonged heat for several consecutive days (also defined as heat waves).

A study using Australian data showed a death increase of 28% (95%CI: 15-42%) in the group of individuals aged 75 years or older (Cheng, Xu, et al. 2018). Nakai et al. (1999) states that half of the heat-related deaths in the period 1968-1994 in Japan occurred on both tails of the age spectrum (children, 4 years and under, and elderly, 70 years and over). A Brazilian study by Gouveia et al. (2003) showed a 2.6% (95% CI: 1.6–3.6%) and 2.5% (95% CI: 2.1–2.8%) increase in all-cause mortality for a 1°C increase in mean temperatures above 20°C in children (under 15) and elderly (over 65), respectively (Gouveia et al. 2003). Basu and Ostro (2008) explored the relationship between environmental temperatures and mortality in California in 1999-2003, and estimated the risks for 5°C rise of mean apparent temperature at 2.2% (95% CI: 0.04-4.0) for individuals aged 65 years or over and at 4.9% (95% CI: -1.8-11.6) for infants under 1 year of age.

Multiple retrospective Chinese studies indicate higher vulnerability of the most advanced age group: relative risks for Shanghai residents aged 65 and over during 2003 were the highest and equaled to 1.13 (95% CI: 1.06–1.21) (Huang et al. 2010); for residents of Guangzhou risks reached 1.49 (1.28, 1.73) for the age group of 75+ during another heat wave in 2005 (Yang, Liu, et al. 2013); heat-attributed mortality risk increased by 20.9% (95% CI: 8.1%, 35.1%) for the elderly (75+) residents of Guangdong province during the period 2006-2010 (Zeng et al. 2014); cumulative excess mortality risks were also the highest for the elderly over 75 years (6.1%, 95% CI: 3.2%–9.1%) living across China and exposed to heat wave during the period 2006-2011 (Ma, Zeng, et al. 2015). A series of studies based on USA data also highlight increasing risks for the elderly: relative risks for heat-related hospitalization of the elderly (65+) were estimated at 10.4 (95%CI: 8.5; 12.3) and 11.4 (95%CI: 9.6; 13.3) for the first and second consecutive heat waves in the US between 1991 and 2006 (Liss and Naumova 2019); mortality hazard ratio for the same age group in 135 US cities ranged from 1.028 (95%CI: 1.013– 1.042) to 1.040 (95% CI: 1.022–1.059) per 1 °C increase in summer temperature standard variation in patients with congestive heart failure and diabetes, respectively (Zanobetti et al. 2012). A prospective study for Beijing by Li, Horton, et al. (2016) highlights that by 2080 heat-related deaths in the age group of 65 and older will see an increase of 265% in comparison with 1980s (under a scenario of medium population and RCP8.5).

A large body of literature focused on heat-mortality and morbidity in elderly population has been developed for the European region as well. Studies based on the French data reported significant increases in mortality in different periods of time. Fouillet et al. (2006) registered a regular increase in mortality ratios with age, rising from 1.3 (95%CI: 1.3-1.4) for subjects aged 35–44 years to 1.7 (95%CI: 1.6-1.8) and 2.0 (95%CI: 1.8-2.2) for subjects aged 75-94 and 95 years and over, respectively, in 2003, a year that put France on the leading positions by total death toll and daily death frequencies, due to an exceptional summer heat that affected the entire region that year (Robine et al. 2008). Laaidi Karine et al. (2012) demonstrated that for a 0.5°C increase in the average minimum temperature for the 6 days preceding death and the day of death the odds ratio was 2.24 (95% CI: 1.03-4.87) for the individuals 65 years old or over residing in the metropolitan area of Paris. A comprehensive study by Baccini et al. (2008) examined the period prior to the Great European heat wave of 2003 (1990-2000) using the data for different sites in Europe, including large cities of France, Italy, United Kingdom, Spain and other countries. This study shows significant differences in between mortality estimates for Mediterranean and North-Continental cities, especially for the ages 65-74 and 75+. Thus, overall

meta-analytic percent changes in natural mortality, associated with a 1°C increase in maximum apparent temperature above the city-specific threshold for the Mediterranean cities (e.g. Athens, Rome, Barcelona) was estimated at 2.13 (95%CI: -0.42-4.74) for 65-74 age group and at 4.22 (95%CI: -1.33-7.2) for individuals aged 75+, whereas in North-Continental cities (e.g. Zurich, Paris, Helsinki) the changes were lower for the same age groups, 1.65 (95%CI: -0.51-3.87) for 65-74 years old individuals and 2.07 (95%CI: 0.24-3.89) for those aged 75+). Another multicountry study by Michelozzi et al. (2009) used the same period of study 1990-2001 and same sites and focused on the estimations of the effects of maximum apparent temperatures on cause specific hospital admissions. Here, Mediterranean cities again showed higher positive percentage changes of +4.5% (95%CI: 1.9-7.3) in admissions for 1°C increase over the 90^{th} percentile of maximum apparent temperature than North-Continental cities with +3.1% (95%CI: 0.8-5.5), but only for respiratory causes in the most advanced age group (75+). According to future forecasts under medium emissions scenario (SRES A1B) developed by Hajat, Vardoulakis, et al. (2014) all age heat-related mortality in the UK is expected to rise by 257% by 2050s, with the highest heat-related death rates in the group of individuals aged 85+.

Age-specific mortality is also well covered in studies based on the data for Spain. Pajares Ortíz et al. (1997) studied mortality patterns in the age group of 45-64 in the Community of Madrid in 1986-1991. The authors argue that MMT in the age group of 45-64 stay above the average value estimated for the entire population, as this threshold value is attributed to the age group of 65+, therefore indicating a better physiological response to extreme temperatures at younger age. A study by Díaz, García, et al. (2002) explored the relationship between summer temperatures and mortality in the advanced age group of the residents of Seville in 1986-1997. The results demonstrate that all-cause mortality in the group of 75 years old and over mortality doubled for a 1°C increase above the 41°C mark. Another study performed by the same group of authors for the same period of 1986-1997 in the city of Madrid showed an increase of 28.4% for a 1°C increase above the 36.5°C in mortality in the group of individuals aged 75+ (Díaz, Jordán, et al. 2002). Another study for the city of Madrid for the same period revealed an increase of 18.36 and 20.1% for 1°C increase above the 36.5°C threshold in natural mortality in the age groups of 65-74 and 75+, respectively (Linares and Díaz 2008). A multivariate analysis performed by Trejo et al. (2005) explored hospital admissions to an emergency hospital unit in Barcelona during the summer of 2003 and reported a higher risk of death in patients older than 70 years. deCastro et al. (2011) studied the mortality answers to heat waves in Galicia in the period 1987-2006 in the group of population aged 65+.

Their results indicate that mortality exceedance in the studied population segment was significantly (3-5 times) higher in heat wave episode in 1990 in comparison with 2003, suggesting local physiological and social adaptation to extreme temperatures.

It is important to note here that an absolute majority of the studies mentioned above indicate that female individuals, especially those of advanced age, are at higher risk of heat-related mortality and hospitalization due to extreme heat in comparison with male population.

Studies discussed in the preceding paragraphs provide a quantitative estimation of risks associated with exposures to extremely hot environmental temperatures at advanced age. However, changes in physiological mechanisms, which are responsible for reaction of the aging body to elevated ambient temperatures, are rarely mentioned in the literature. Ebi et al. (2021) emphasizes that development of the thermoregulatory system in a human body is age dependent. Worfolk (2000) highlights the role of changes in the cardiovascular and evaporative functions that gradually become impaired as a person grows older. Reduced thermoregulatory responses are related to the decline in cardiac reserve and age-related reduction in vascularity affects the efficiency of heat removal. Sweating, on the other hand, may also become weaker due to the change in the functioning of the sweat glands and overall hydration status in older individuals. These conditions, added to the exposure to extreme heat, may trigger thrombosis or other cardiovascular accidents in elderly population, even if no chronic background is present. Moreover, behavioral response plays an important role in risk modification for elderly. Kettaneh et al. (2003) discusses the behavioral changes that took place after the extreme heat wave of 2003 in France where a significant improvement in the prevalence of intracellular hydration disorders was seen.

Simiarly to the elderly, individuals at the opposite edge of the age spectrum - children and infants - are at a higher risk in comparison with young and middle-aged adults exposed to the conditions of extreme heat. It is explained by several traits of a developing organism. Xu, Sheffield, et al. (2014) suggests four groups of factors that exert influence on the particular sensitivity of younger individuals to higher temperatures. In the first place, physiological (1) and cardiovascular (2) conditions of a growing body define the ability to efficiently thermoregulate. Children have higher surface-area-to-mass ratio in comparison with adults, therefore the intensity of a heat exchange with the environment is generally greater. Smaller blood volume and cardiac output add up to the lower capacity to control internal climate in children, especially in infants (Bunyavanich et al. 2003; Basagaña et al. 2011). Children´s basal metabolism (3) is greater, but the functional range is

significantly smaller in comparison with adults, which results in additional sensitivity to extreme environment (Sonkin and Tambovtsev 2012). Lastly, the behavioral (4) modality plays an important role as children can not provide a complete self-care on the one hand, while on the other hand they can be more exposed to environmental heat depending on their developmental stage and levels of physical activity (Xu, Crooks, et al. 2017). However, Díaz, Linares, et al. (2004) argue that exposure of children to extremely high and low temperatures would still be lower in comparison with adult´s exposure.

Indeed, a number of heat-related morbidity and mortality studies reveal significant effects among children, usually defined as individuals under 15 years old. Leonardi et al. (2006) explored the symptomatic emergency calls in England during the period 2001-2004. Their results reveal a significant rise of +2.5 (95%CI:1.8-3.3) in the percentage change in outcome per 10°C degree increase in the mean daily temperature in the group of children aged 0-4 years. Wang, Barnett, et al. (2014) studied the emergency hospital admissions for renal disease for children aged from 0 to 14 years, during the period of 1996-2005 in Brisbane, Australia. The estimated odds ratio for the day of exposure reached 2.94 (95%CI: 1.32-6.53), with an increase up to 3.59 (95%CI: 1.35-9.5) on the next day after the exposure, with consideration of possible confounders like air humidity and air contamination. Knowlton Kim et al. (2009) focused on cause-specific morbidity in California in 2006. Their results show that infants (age 0-4) had greater risks for admissions to the emergency departments due to electrolyte imbalance when compared with other age groups (1.19 at 95%CI:1.1-1.3). As we repeatedly emphasized in the previous sections, extreme heat is a known factor to impede cognitive function and affect educational attainment. An experiment performed by Dapi et al. (2010) showed that adverse symptoms (e.g. fatigue, headache, lower writing speed and perception of educational material) were associated with high indoor air temperatures at schools.

Although early-life conditions (especially, environmental exposures during childhood) are outside of the scope of the present work, they are of great importance for understanding long-terms effects and adverse outcomes in later life. The evidence on the effects of different thermal conditions at the place of birth of individuals is, however, fairly scarce. The ability of humans to function normally in terms of thermoregulation in different and often extreme environmental conditions is the result of various adaptive physiological but also genetic mechanisms. The variations of heat tolerance between different ethnic groups was previously explored (Austin and Ghesquiere 1976). Vigotti et al. (2006) highlight that the ability to tolerate very hot or very cold temperatures arises from the *early acclimatization*. The authors suggest that during early developmental stages

humans reach some *equilibrium with the external environment*, where individuals are *programmed* to spend the rest of their lives. This fact may result in difficulties to adapt to entirely different climatic conditions at later stages in life.

Adverse pregnancy outcomes

Exposure of pregnant woman to high environmental temperatures leads to a number of adverse outcomes. This association was thoroughly studied by many authors, but there is still a number of gaps to fill. Extreme heat exposure may result in serious pregnancy complications, reductions in gestational length, stillbirths and low birth weights.

Arroyo, Díaz, et al. (2016) and Kuehn and McCormick (2017) strengthen physiological aspects responsible for particular sensitivity to increase in ambient temperatures in pregnant woman. Increase of fat deposits and weight gain during pregnancy increments the surface-area-to-mass ratio, therefore enhancing the maternal heat production and overall exchange with the environment. Body composition of the fetus along with fetal and placental metabolism also disturb normal thermoregulatory function of the mother. The most common pregnancy complications studied in association with the environmental temperatures are the hypertensive disorders: gestational hypertension, pre-eclampsia[44] and eclamspia[45]. Beltran et al. (2014) reported higher risks of pre-eclampsia in woman that delivered in the coldest months of the year and conceived during the hottest season. Shashar et al. (2020) concluded that elevated ambient temperatures during 1st and 3rd semester of the pregnancy, where more than half of the gestation occurred during spring-summer period, significantly increased the risks of developing pre-eclampsia. Yet, the evidence of the effects of temperatures on pre-eclampsia and eclampsia remains meager.

The association between gestational length, a key determinant of fetal maturity at birth, and high environmental temperatures has been reported on repeated occasions. Dehydration of the mother during exposure to extreme heat may decrease the uterine

[44] **JA24** Pre-eclampsia - Oedema, proteinuria, or hypertensive disorders in pregnancy, childbirth, or the puerperium - 18 Pregnancy, childbirth or the puerperium. Defined in ICD-11 as a *condition characterised by systolic blood pressure greater than 140mmHg and or diastolic greater or equal to 90mmHg on two occasions 4 hours or more apart in the presence of either proteinuria or other new onset maternal organ dysfunction characterized by one thrombocytopenia, elevated serum creatinine or liver transaminases, or neurological conditions or fetal growth restriction.*

[45] **JA25** Eclampsia - Oedema, proteinuria, or hypertensive disorders in pregnancy, childbirth, or the puerperium - 18 Pregnancy, childbirth or the puerperium. Defined in ICD-11 as a *condition affecting pregnant females, characterized by seizure or convulsions newly arising in pregnancy. The condition is often associated with pregnancy-induced hypertension, convulsions, seizure, anxiety, epigastric pain, severe headache, blurred vision, proteinuria, and oedema that may occur during pregnancy, labour, or the puerperium.*

blood flow which can trigger labour (Carolan-Olah and Frankowska 2014; Kuehn and McCormick 2017). In addition, heat stress leads to the release of specific heat-shock proteins, e.g. HSP-70. The induction of proinflammatory cytokines and the effect of HSP-70 were also linked to preterm births (Dadvand Payam et al. 2011). Among other health complications, reduced gestational period is associated with lower birth weight. Nevertheless, Chersich et al. (2020) argue that associations of environmental heat with preterm birth and stillbirths is stronger and more consistent, opposed to the association between heat and birth weights. The results of their study have shown that higher temperatures were associated with stillbirths in male fetuses. A systematic review performed by Sexton et al. (2021) concluded that an increased risk of stillbirth is associated with exposures to both hot and cold extreme temperatures at any time of pregnancy and in the week prior to delivery. The adverse effects of exposure to heat throughout the pregnancy might have other than physiological (e.g. socioeconomic) explanations. Using short-time observational windows (a few days or a week before the delivery) to explain the reductions in length of gestation due to extreme heat is more cogent and less confounded (Beltran et al. 2014; Kuehn and McCormick 2017).

2.5.3 Socioeconomic factors

A large discrepancy exists between mortality and morbidity answers to extreme heat along the socioeconomic gradient. The effects of such factors as educational attainment, income levels, housing (including possession of air conditioning and fans), social position (marital status, cohabitation, social network) and ethnic background have been widely explored, and several systematic reviews were published (Kenny et al. 2010; Benmarhnia, Deguen, et al. 2015).

Low educational attainment, illiteracy and other similar indicators of general education were shown to imply a greater vulnerability for heat-related mortality (Bai, Woodward, et al. 2016; Xu, Chen, et al. 2019; Voelkel et al. 2018; Chen et al. 2018; O'Neill et al. 2003). Some studies have shown a higher likelihood for death to occur during heat waves in more socioeconomically deprived areas (Kim and Kim 2017; Benmarhnia, Oulhote, et al. 2014), while others have not found a modification effect of area deprivation for heat-related mortality, suggesting greater importance of individual factors (Macintyre et al. 2018; Hajat, Kovats, et al. 2007; Lerch and Oris 2018).

The use of air conditioning or any other type of cooling device is, perhaps, the most commonly studied protective factor, which, along with the heating, is often seen as a proxy for overall socioeconomic conditions for studying weather-related mortality (Curriero

et al. 2002). However, some studies argue that low income alone would serve as a better explanation of variations in adverse health outcomes, as having the cooling device installed does not mean being capable to afford its performance and maintenance costs (Gao et al. 2020; Farbotko and Waitt 2011). Living alone, being a widow/er, separated or divorced significantly increases the mortality risk (Ellena et al. 2020; Stafoggia et al. 2006). Living in nursing and residential homes, or any other type of institution providing day and night care for the elderly, is often seen as an indicator of frailty and dependency, and acts as an important predictor of death during or following heat waves (Brown and Walker 2008). Being more socially active during heatwaves reduces the risk of mortality, especially in the elderly population (Klinenberg 2003; Zhang, Nitschke, et al. 2016). Moreover, service accessibility, also referred to as remoteness, poses a significant dose-response relationship with heat wave intensity (Xiao et al. 2017; Vanhems et al. 2003).

In Spain, there is a wealth of evidence for modification effects of socioeconomic conditions on heat-related health outcomes. López-Bueno et al. (2020) explored the role of income, prevalence of elderly (65+), presence of air conditioning units and green spaces on heat-related mortality in 21 districts of Madrid between 2010 and 2013. According to their results, the effect of heat on mortality showed a declining trend, which is consistent with other studies for the same area (Díaz, Carmona, Mirón, Ortiz, and Linares 2015). The presence of green zones was not shown as statistically significant, whereas the existence of air conditions, prevalence of elderly in the district and the income level modified the impact of heat waves on mortality, with income having the strongest influence. Remoteness from green areas, however, had statistically significant risk on mortality during heat waves (relative risk of 1.29 at 95%CI: 1.01-1.65), along with the proportion of old buildings in the census tracts (1.21 at 95%CI: 1.0-1.46) within the city of Barcelona in 1999-2006 (Xu, Dadvand, et al. 2013). Borrell et al. (2006) focused on studying the effects of socioeconomic position on mortality during the 2003 heat wave in Barcelona. Their results suggest a protective role of completed primary education on mortality.

2.5.4 Air pollution

Ambient air pollution origins from natural and anthropogenic sources, which under certain circumstances may produce a synergetic effect. Due to the peculiarities of the physical and chemical composition of some air pollutants their concentration often changes in function of the variations of meteorological parameters, principally air temperatures. The majority of the studies that explore the relationship between health outcomes and ambient temperatures, especially its hottest band, include concentrations of primary

air pollutants as control variables. We discuss the physics of behavior of several air pollutants in response to the meteorological conditions in Chapter 6. Meanwhile in this section we introduce the reader to the variety of adverse health outcomes related to the intensification of air pollution, especially in the context of climate change. Here we mostly focus on the mechanisms of impact of air pollution on the human body, enriching our discussion with the overview of the recent literature published on this topic.

One of the very important consequences of the climate change globally is the shift in the pollen season. Changes in the distribution, timing and lengthening of the pollen season significantly contribute to allergic or hypersensitivity conditions[46] and asthma[47]. Worthy to note here that in Europe biological air pollution is not yet covered in legislative terms, as it is in the case of the chemical pollutants. Shea et al. (2008) especially highlights the impact of climate change on the variety of allergenic plants: for some plants, higher temperatures stimulate earlier onset and longer duration of the flowering season, whereas an increased production of carbon dioxide leads to the increase in plant biomass and triggers additional pollen production. Excessive exposure of vulnerable populations with milder chronic conditions (e.g. allergic rhinitis[48]) to pollen may result in immunological changes eventually leading to a severe outcome such as asthma. Moreover, meteorological factors may affect biological and chemical components of the interaction between air pollution and allergic respiratory diseases (D'Amato et al. 2014). The synergistic effect of exposure to allergens is widely discussed in the literature. Asthma symptoms and overall allergenicity could be enhanced by increasingly higher levels of aromatic hydrocarbons contained in fine particles, which *per se* causes an increase in pollen production and the allergenicity of the pollen (D'Amato et al. 2015; Sierra-Vargas and Teran 2012).

Another commonly known natural contributor to air pollution is wildfire. Risks for wildfires increment with the increase in temperature and reduction in precipitation. Smoke emissions are transported across large distances with the wind, therefore exposing population to harming compounds, e.g. fine inhalable particles. Exposure to wildfire

[46] Allergic or hypersensitivity conditions - 04 Diseases of the immune system; allergy defined in ICD-11 as *a hypersensitivity reaction initiated by a proven immunologic mechanisms"* and hypersensitivity conditions as *conditions clinically resembling allergy that cause objectively reproducible symptoms or signs, initiated by exposure to a defined stimulus at a dose tolerated by normal subjects.*

[47] **CA23** Asthma - Certain lower respiratory tract diseases - 12 Diseases of the respiratory system; defined in ICD-11 as *a chronic inflammatory disorder of the airways in which many cells and cellular elements play a role, and characterized by an increased responsiveness of the trachea and bronchi to various stimuli and manifested by a widespread narrowing of the airways that change in severity either spontaneously or as a result of therapy.*

[48] **CA08.0** Allergic rhinitis - CA08 Vasomotor or allergic rhinitis - Upper respiratory tract disorders - 12 Diseases of the respiratory system; defined in ICD-11 as *an inflammation of nasal airway triggered by allergens to which the affected individual has previously been sensitized.*

smoke is often associated with eye and respiratory syndromes (Vicedo-Cabrera, Esplugues, et al. 2016), along with adverse psychological effects (Caamano-Isorna et al. 2011).

Fine inhalable particles represent a variety of *particulate matter* (particle pollution) with diameters of 2.5 micrometers and smaller ($PM_{2.5}$), formed by diverse range of substances such as combustion particles, organic compounds or metals. Inhalable particles with diameters of 10 micrometers and smaller are usually referred to as PM_{10} and can be composed by dust, pollen or mold. Particular matter is an air pollutant proceeding from both natural and anthropogenic sources and is perhaps the most studied in relation to adverse health outcomes. Along with the particular matter, there is a number of other chemical compounds known to affect various systems of the human body. Thus, European Environment Agency (EEA) distinguishes 5 major air pollutants associated with the most acute health problems: particulate matter (PM); sulfur dioxide (SO_2), primarily associated with heating, power generation, transport and volcanic emissions; nitrogen dioxide (NO_2), formed during combustion processes; ground level ozone (O_3), triggered by sunlight and formed by chemical reactions during natural gas extraction, landfills, household chemicals or transportation; and Benzo(a)pyrene (BaP), originating from incomplete fuel combustion[49]. Table 2.3 displays the associations between these pollutants and some of the possible health outcomes.

Table 2.3: Potential health impacts from major air pollutants

	PM	NO_2	O_3	SO_2	BaP
Headache and anxiety				+	
Impacts on the central nervous system	+				
Irritation of eyes, nose and throat	+	+	+		+
Asthma and reduced lung function		+			
Chronic obstructuvie pulmonary disease	+				
Lung cancer	+				+
Cardiovascular diseases	+		+	+	
Impacts on liver, spleen and blood		+			
Impacts on the reproductive system	+				

Adapted from EEA Report on *Healthy environment, healthy lives: how the environment influences health and well-being in Europe*, Fig. 4.3.

Exposure to air pollution can provoke a wide range of adverse health outcomes at different stages of person´s life, starting from prenatal phase and continuing to early life and adulthood. Premature birth and hypertensive disorders in pregnant woman were linked to the elevated concentrations of some air pollutants. Arroyo, Linares, et al. (2019) explored daily incidences of premature births in some of the Spanish provinces between 2001 and 2009. Their results show that relative risks for a preterm birth was higher for

[49] *Healthy environment, healthy lives: how the environment influences health and well-being in Europe* (2021)

NO_2 (1.150 at 95%CI: 1.084-1.220) than the risk due to PM_2 (1.071 at 95%CI:1.049-1.093). The authors suggest some of the plausible potential biological mechanisms responsible for preterm birth due to the elevated concentration of particulate matter and nitrogen dioxide. For example, PM particles, that can be potentially deposited in extrathoracic, tracheobronchial and alveolar respiratory compartments, penetrate the alveolar walls and proceed to the bloodstream. This results in pro-inflammatory and pro-thrombotic stresses which can lead to the decrease of placental circulation and result in maternal hypertension, which is a known risk factor for preterm birth.

The effects of air pollution on children were comprehensively studied by many researchers. Perera Frederica P. (2017) highlights the importance of minimization of exposure to air pollution during early developmental stages (including prenatal and neonatal periods) as this is a critical time window when brain, lung and immune system are developed. The authors emphasize that early-life exposure to toxins or extreme environmental conditions may launch a series of adverse effects that may become evident only later in life. An example of such mechanism can be prenatal and early-postnatal exposure to environmental toxins resulting in alterations of lung and immune functions later in life (Cao et al. 2016). Children have a number of physical characteristics that make them more vulnerable to air pollution than adults. Among those features, Bunyavanich et al. (2003) spotlight greater exposure to pollutants per unit mass, resulting from faster breathing speed and longer outdoor stays, and elevated tissue exposure per volume inhaled, which exacerbates airway oxidative stress and airway inflammation. As mentioned by Sierra-Vargas and Teran (2012), oxidative stress plays a key role in the chain of mechanisms responsible for health damage. Exposure to air pollution in children has predominantly respiratory and neurodevelopmental effects, which could be immediate or delayed. In adults, respiratory diseases are the primary morbidity and mortality causes associated with exposure to air pollutants. Indeed, lungs are the major source of interaction between human body with environmental particulates (D'Amato et al. 2015). Particulate matter, especially ultrafine particles, can provoke deleterious effects on lungs, but also other organs like brain, heart or bone marrow, resulting in acute cardiovascular and neurological outcomes. A set of other pollutants ranging from ozone to elemental carbon are also known to impair lung function and lead to severe complications of pre-existing respiratory chronic diseases. The cytotoxicity of ozone, for instance, might cause functional and morphological alterations in the respiratory epithelium, and generate an inflammatory response leading to a bronchial dysfunction and alteration of the immune system.

In Spain, research on the adverse health effects attributed to air pollution is focusing on two major sources of pollution: industrial production and traffic on the one hand, and Saharan dust on the other. During the period between 1993 and 2017 air quality in Spain has significantly improved (meaning a declining trend in the concentrations), except for the tropospheric ozone, as shown in the study by Borge et al. (2019). Their results indicate that emission reduction efforts in Spain directed to minimize air pollution-related mortality were effective despite weather penalties. However, according to this study, these efforts could be even 10% more successful if no climate-change attributable modifications of weather conditions were observed. Another comprehensive analysis of the health impacts due to air pollution by particulate matter, nitrogen oxide and ozone in all Spanish provinces during 2000-2009 was performed by Díaz and Linares (2018). The authors estimated the mortality due to short-term effects of chemical air pollution at 9500 deaths per year level, which is 8 times greater than the mortality due to traffic accidents and 5 times less than the one attributed to tobacco smoking. Nitrogen oxide is leading this list with 6300 NO_2-attributed deaths per year, and is followed by PM_{10} with 2700 deaths/year. The concentrations of these two pollutants express linear relationship with daily mortality, without lower threshold. The lowest estimates of 500 deaths per year are associated with O_3. There is, however, no protective effect of ozone on mortality as its lower concentrations correspond to the peaks of the concentrations of other pollutants. Same group of authors explored the quadratic relationship between ozone concentrations and cause-specific daily mortality (Díaz, Ortiz, et al. 2018). Their results indicate a relative risk of 1.089 (95%CI: 1.058–1.120) for respiratory causes and 1.025 (95%CI: 1.018–1.033) for circulatory causes for every 10 $\mu g/m^3$ increase in ozone concentrations above its 80^{th} percentile.

Dust intrusions, displaced northwards from Sahara-Sahel desert region, are the major natural contributors to air pollution in Spain. Summing with the anthropogenic sources of particulate matter, it significantly increases the risks for adverse health outcomes. Perez, Tobias, et al. (2008) aimed to investigate the effects of $PM_{2.5}$ and PM_{10} on daily mortality in 2003-2004 in Barcelona. Their estimates show an increase of daily mortality by 8.4% (95%C: 1.5%-15.8%) for every 10 $\mu g/m^3$ of $PM_{10\text{-}2.5}$ on the Saharan dust days. The fraction of daily mortality during non-Saharan dust days was estimated at 1.4% (95%C: -0.8%-3.4%). The results of another study for Barcelona in 2003-2007 provide an evidence of statistically significant effects of short-term exposure to coarse fraction of particulate matter during Saharan dust days on cardiovascular and respiratory mortality (Perez, Tobías, et al. 2012). The coarse PM fraction (PM_{10}) was also associated

with higher mortality risks in elderly population residing in Madrid during days with Saharan intrusion (Jiménez et al. 2010). In addition, Dominguez-Rodriguez et al. (2020) reported elevated concentration of PM_{10} during Saharan dust events as an independent predictor of heart failure in-hospital mortality in Tenerife, Canary Islands. The results of an ecological study by de Keijzer et al. (2017) reveal a reduction of ten months of life due to a 5 µg/m^3 increase in PM_{10}.

Weather and climate variability do not fit well the conventional research model. The biggest challenge is scale. Both the geographical spread of climate-related health problems and the much elongated time spans that often apply, are largely unfamiliar to public health researchers.

— *Looking to the future: challenges for scientists studying climate change and health*, Woodward and Scheraga (2006).

3

Data: sources, advantages and limitations

One could think of a task to model relationships between ambient heat and health outcomes in simple terms. The reader could even suggest that only surface air temperatures and mortality estimates would be enough to run this kind of analysis. That would not be a wrong assumption: it is, indeed, sufficient to have these two variables at the same spatiotemporal resolution to get a glimpse on this association. In fact, the overwhelming majority of the demographic studies rely only upon *aggregated* climatic data at the level of *administrative units*. It is completely understandable, as in a very rare case it is possible to produce a demographic variable with a regular uninterrupted spatial coverage. However, this simplistic approach becomes problematic if we think of it from a more realistic geographic perspective.

Summary plot represented on Figure 3.1 highlights the variety and complexity of the sources used in the present study. The set of sources shown on the graph is reduced to the items of primary importance. Data used for validation or cross check are described in the text but not displayed on the graph. As the reader might note, not all the sources coincide temporarily and spatially, which leaves us no choice but to make a series of arbitrary decisions for processing and aggregation in order to unify these datasets and proceed to modelling.

In this chapter, we provide a fundamental description of the input data, mostly focusing on the structure and features of the original data and caveats related to the retrieval and processing, whereas exact methods applied to transform the data for a particular objective are described in corresponding paragraphs in Chapters 4-9. The primary data domains are represented in different colors on Figure 3.1 and consist of:

1. **Environment** (meteorological and air quality data, contextual geographic data),
2. **Infrastructure** (administrative division, health care facilities, transportation network),
3. **Population** (deaths registers, reference population),
4. **Socioeconomic context** (census data, combined indicators and other metrics).

Each dataset is constructed for a specific mapping unit (marked with a corresponding symbol): it might be a ground point measurement taken from a particular station with known coordinates (e.g. meteorological station), or estimated value for a regular spatial unit (e.g. grid cell), or an indicator based on the census data collected for administrative units (e.g. census tracts). Spatial coverage also varies depending on the source. The prevailing majority of the providers produce datasets with continuous regular (grid) or irregular (administrative units) coverage for the entire country The exception are data on population and air quality of Andalusia: in this case, we refer to the local governmental institutions that generate data only for this autonomous community.

In this chapter, we provide a description of all data sources that were explored and treated along the PhD journey. Most of the data sources were used to produce the principal results of this work, while some of the datasets and estimates generated throughout the analysis would be addressed in future studies. The remainder of this chapter contains a description of each data domain mentioned earlier.

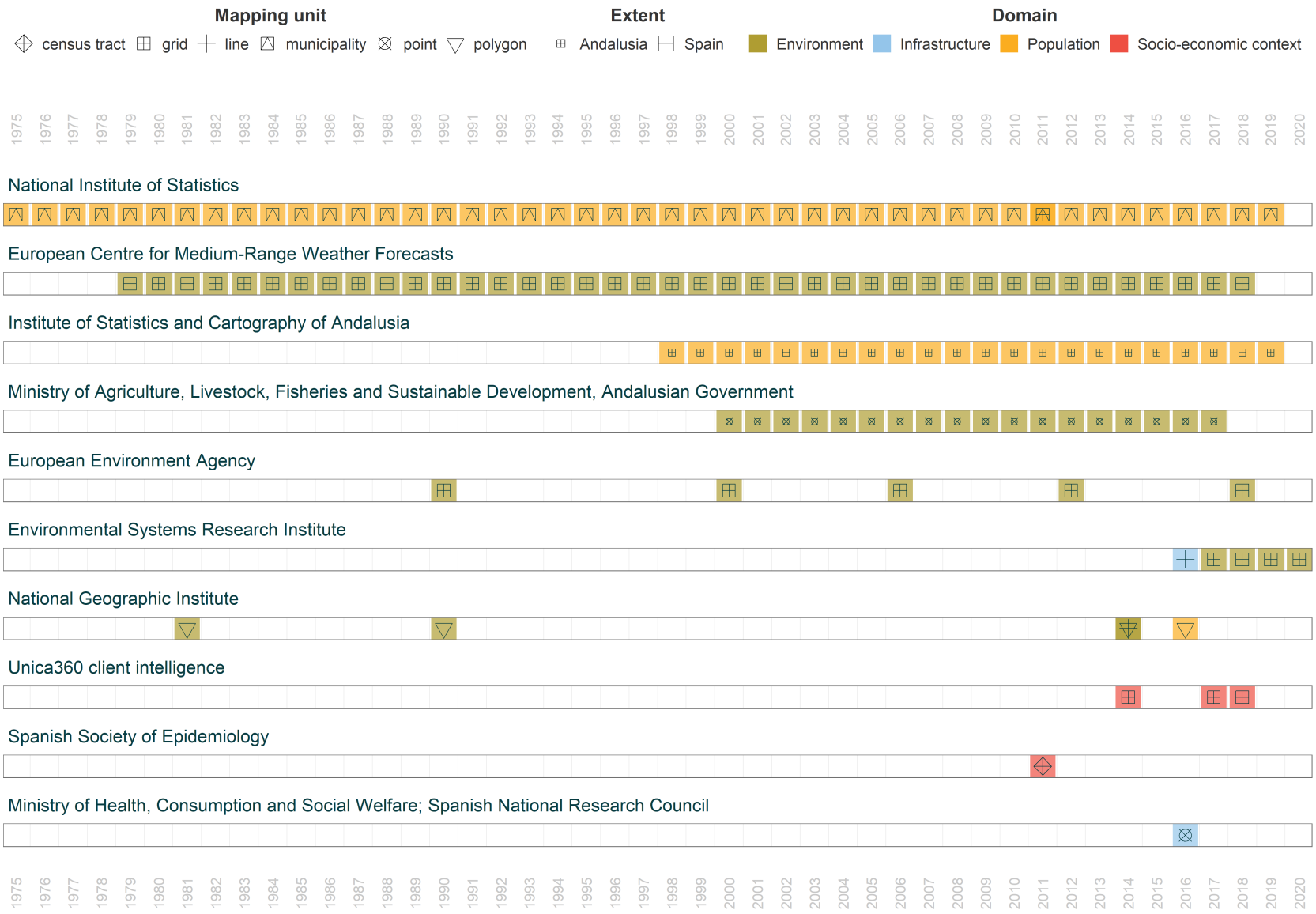


Figure 3.1: Types, coverage and extent of the data used in the study

3.1 Environment

The environmental data used in this study are multifarious as cover various facets of natural and anthropogenic settings. As a primary source for meteorological data we choose pre-modelled datasets which represent a blend of observations with past short-range weather forecasts rerun with modern weather forecasting models produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The choice in favor of the pre-modelled data (as opposed to the ground point measurements collected from meteorological stations) is made mainly due to a seemingly lower overall estimation error of the atmospheric reanalysis. Howbeit, the pre-modelled data are cross-checked against the discrete stationary data (retrieved from the National Centers for Environmental Information (NCEI for NOAA) local climatological data archives, from 1930 onward; and obtained from the Spanish State Meteorological Agency (AEMET) from 2000 onward) via aggregation over relatively large areas in order to capture possible under- and overestimation.

3.1.1 Essential climatic variables

The global atmospheric reanalysis datasets ERA-Interim from the ECMWF are the key data for this study and are available from 1979 onward at 0.125°x 0.125°resolution. ERA-Interim uses a fixed version of a numerical weather prediction system (Integrated Forecasting System CY31r2) to produce reanalyzed data, and is known for capturing monthly, seasonal and annual trends with high accuracy (Zhao, Gao, et al. 2020). The results of the multivariate atmospheric reanalysis contained in the ERA-Interim datasets have passed through quality control and multiple bias correction in comparison with the preceding reanalysis datasets as highlighted by Dee et al. (2011). However, the seasonal and local biases of these estimates should be also taken into account when interpreting the results (Wang, Graham, et al. 2019; de Leeuw et al. 2015). Relying on the work by Royé, Íñiguez, et al. (2020), where authors compared the mortality-temperature association using weather station temperature and ERA-5 reanalysis, we considered the reanalysis data suitable for the key purposes of this work.

The parameters at the surface level retrieved from the ECMWF data server using Web API in NetCDF format cover the period from 1979-01-01 until 2018-12-31 and include:

- 2 meter temperature,
- 2 meter dewpoint temperature

- 10 m U and V wind components,
- Total precipitation.

The data are processed and transformed where necessary (e.g to obtain wind speed and directions, or to calculate heat index as per the equations from the US National Weather Service (NWS), with all the necesarry adjustments). The results are then passed from the original spatial grid to the core study grid of 10km x 10km created according to the Infrastructure for Spatial Information in Europe (INSPIRE) technical guidelines on geographical grids. The centroid of the core grid is assigned the hourly values from the closest spatial neighbor from the ERA-Interim grid (average distance between points is estimated at 4.7 km). The final dataset we use for the study includes daily mean, maximum and minimum values for air temperature, heat index, wind speed and direction and total daily precipitation.

3.1.2 Air pollution variables

In case of the air pollution, we primarily rely on the continuous surfaces provided by the third party[1], although despite their ultimate accuracy these data have a limited temporal extent. To cover this gap, we also involve the ground point measurements in the analysis. Aiming to minimize the estimation error we do not proceed with spatial interpolation[2] of these data but make aggregations for the small administrative units within urban settings.

This study uses 10 air pollutants: non-methane volatile organic compounds, peroxyacetyl nitrate, ammonia, carbon monoxide, nitrogen monoxide and 5 components of European Air Quality Index (AQI) (ozone, particulate matter (coarse and fine), sulfur and nitrogen dioxides). Spatial resolution of the ENSEMBLE modelling dataset, provided as a set of the NetCDF cubes, is identical to the core grid of the study (10km x 10km). The configuration of two grids, however, is different, therefore we apply a similar recalculation approach as described for the essential climatic variables, and estimate a weighted[3] average value for centroids of every cell in the INSPIRE core grid. This

[1]Data provided by ESRI Spain on commercial basis. Sourced from The Weather Partner, for more information see www.theweatherpartner.com

[2]Here we assume that using any custom interpolation method of ground measurements of air pollution without including an appropriate air circulation model by default brings in larger estimation error when compared to the ENSEMBLE modelling output (sourced from the Copernicus Atmosphere Monitoring Service).

[3]by the neighborhood rank, where 1^{st} is the closest pair of coordinates, at an average distance of 3.7 km, and has the highest weight, and 5^{th} is the farthest pair (up to 11 km distance) with the lowest weight given.

dataset covers only Spanish territory of the Iberian peninsula (Canary Islands excluded) and only 3 years (from July 2017 until June 2020).

The stationary data are provided by the Local Spanish Administration and are available only for the Andalusian community (135 stations, January 2000 to July 2017). Geographic location of these stations is strongly associated with the urban areas, and we use these data in the aggregated form to explore the association between air pollution and mortality in Andalusia only. We select components of the AQI to be used in the analysis: ozone, atmospheric particulate matter, sulfur dioxide and nitrogen dioxide.

3.1.3 Geographic context

Furthermore, to comprehensively and adequately represent and explain the phenomena of heat waves, we rely on the overall geographic context (digital elevation models, hydrological network, climatic, phytoclimatic and biogeographic zonification). These data are retrieved from the National Center for Geographic Information[4] in form of raster and vector spatial layers.

3.1.4 Land cover and land use

Apart from solely biophysical environment, this study uses the data on land cover and land use proceeding from the Corine Land Cover (CLC) inventory as a proxy for urban settlement and human activity allocation. We consider sufficient the minimum mapping unit of 25 hectare for areal phenomena used by the CLC for the purpose of our study. These data have uninterrupted coverage and several snapshots over time (1990, 2000, 2006, 2012 and 2018). We also acknowledge two additional sources provided by IGN: SIOSE[5] and Urban Atlas[6]. As spatial resolution of these datasets is significantly more refined than the core study grid, we stick to the CLC at 1:100 000 scale for the analysis, whilst frequently consulting the latter two sources as supplementary material.

The final set of variables covering the environmental domain is composed by **core climatic** variables (temperature, dew point temperature, wind and precipitation) available for 1979-2018 on a regular grid of 10km x 10km with national coverage; **air pollution** variables (ozone, sulfur oxides, nitrogen oxides, suspended particles, carbon monoxide, ammonia, non-methane volatile organic compounds and peroxyacetyl nitrates) available

[4]Centro Nacional de Información Geográfica (CNIG), managed by the National Geographic Institute of Spain (IGN), for more information see www.ign.es

[5]Database on land use in Spain at 1:25 000 scale for 2005, 2011 and 2014

[6]Land cover and land use maps for urban areas in Spain at 1:15 000 scale, for 2012

for 2017-2020 on a regular grid of 10km x 10km covering continental Spain and Balearic islands, and for 2000-2017 as ground point measurements in metropolitan areas of Andalusia; **land cover** variables available for 1990, 2000, 2006, 2012 and 2018 on a regular grid of 10km x 10km with national coverage; and a series of vector layers of diverse spatiotemporal resolution covering various aspects of biophysical context.

3.2 Infrastructure and administrative geometry

Health care services and efficiency of transport infrastructure are among the key elements for mitigating the adverse effects of extreme heat and air pollution on human health. Driving times to nearest hospital might be crucial for acute patients, whereas general accessibility (measured, for example, by walking times to health centers or health care facilities for elderly people) defines the overall effectiveness of facility location and road network configuration.

3.2.1 Health care infrastructure

The location data for 912 national hospitals, 12 859 health centers and 8 623 elderly care centers was sourced from the Social Resources for Elderly SigMayores database to generate time-constrained driving and walking zones towards each facility [7]. These estimations were then passed to the core grid to classify the area according to different levels of accessibility to the resources. Due to the scope of this thesis we do not include these health care indicators in the primary analysis, however we look forward to leverage these data in future studies. One of the deliverables of the Longpop project, where author was employed during several years of the PhD program, was the Portal for Health and Population in Spain. This portal includes multiple products developed by the author including the Catalogue of Health Care resources in Spain, interactive applications to explore the Accessibility to Health Care Resources and a number of methodological guides

Another dataset of great potential was provided by the third party[8] and consisted of series of indices of economic activity and commercial offer, developed on a discontinuous grid of 100 m. In particular, we use two indices: public transport index and health

[7] To do so, we use Network Analyst Toolset, ArcGIS PRO 2.2, and StreetMap Premium network dataset (last updated in 2019). This dataset is based on commercial street reference data from leading global and local street data suppliers (HERE and INCREMENT P) and was provided by ESRI within the frames of Longpop project)

[8] Unica360 client intelligence, commercial indices by microzones. Data provided by ESRI Spain to CSIC on commercial basis.

care index. Originally, these indices are built by the provider using the information on locations on points of interest of diverse types in 2017. This information is acquired from administrative sources or independent data projects, or retrieved from online repositories of various establishments. The possible range of values is from 0 to 1, where 0 indicates lowest level of commercial effort in corresponding category and 1 indicates the highest offer. To create public transport index, following points of interest were used: transport stations, train, metro, bus and taxi stops (parking for private transport and car rental not included). The index of health care is based on the locations of hospitals, pharmacies and medical establishments including general therapy, physiotherapy and dental centers. We also believe it would be highly beneficial to include these data in the future analysis to identify the most vulnerable to heat areas.

3.2.2 Reference nomenclature

The reference grid nomenclature, as mentioned on multiple occasions before, corresponds to the INSPIRE standard. The minimum available cell size for this system is 1 km^2. For the purpose of this study we stick to the 10km x 10km resolution grid. The source GIS data can be retrieved from the European Environmental Agency (EEA) reference grid homepage.

As highlighted in the preamble to this chapter, at some point of the analysis the necessity to have the ambient data aggregated to the level of administrative units is practically inevitable as otherwise the inclusion of the demographic variables becomes impossible due to spatiotemporal incompatibility. The reference administrative data in Spain are provided by IGN and INE[9]. The reader may consult the map with administrative division of Spain presented in the Figure A.1 in Appendix. Here we use several layers of geographic information: municipal, provincial and autonomous boundaries along with the geographical location and geometric shape of the population settlements. The latter, along with the Urban land cover data, serves as a sufficiently precise proxy for population scattering, and helps to transfer all the environmental estimates from the regular structure to artificially defined boundaries. Figure 3.2 represents an illustration of the process of matching grid cells with municipalities.

Population settlement layer is shown in blue on the map, whereas municipality boundaries are highlighted in red. As an example we randomly choose two municipalities in Tenerife, Canary islands: Granadilla de Abona (34053838017) and San Miguel de

[9]Instituto Nacional de Estadística, Spanish Statistical Office since 1946, for more information see www.ine.es

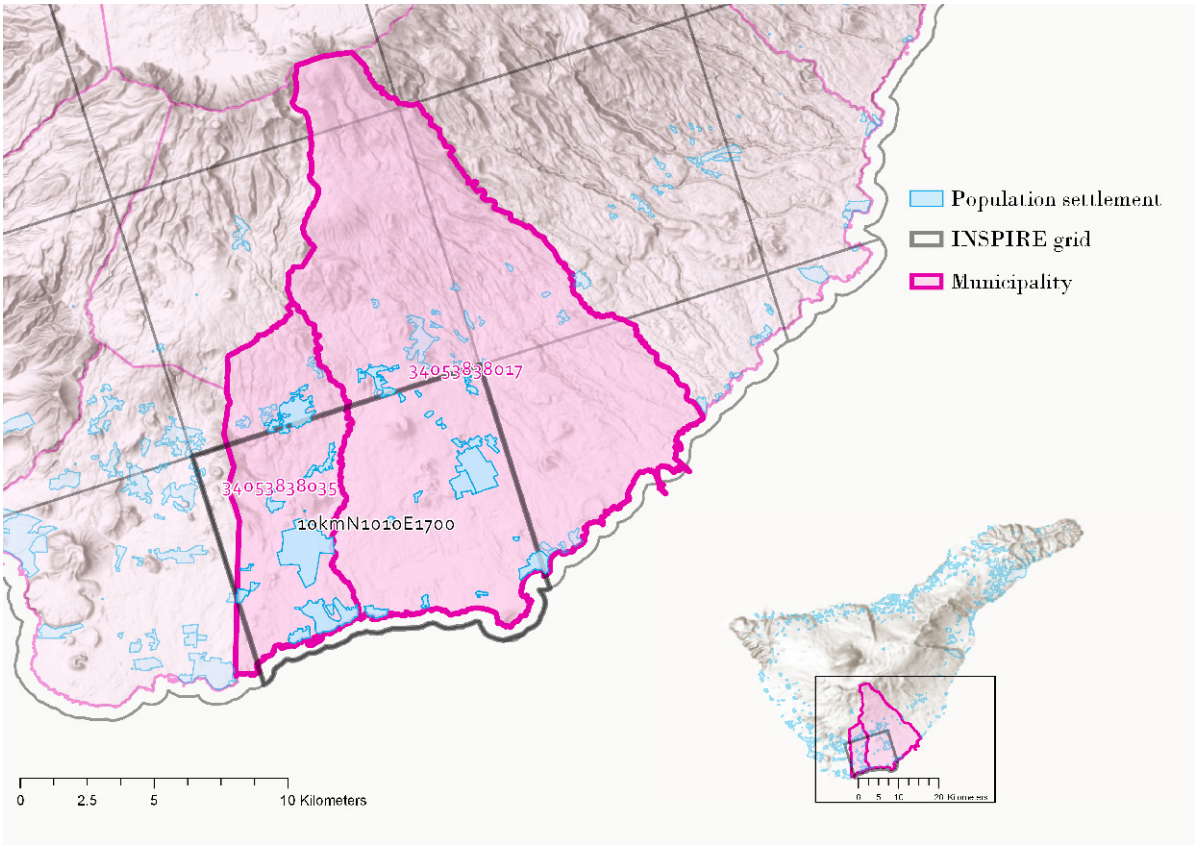


Figure 3.2: Methodological illustration of cell-to-municipality assignment process

Abona (34053838035). The settlement of these municipalities is disperse and generally tends to cluster towards the coastal areas. Granadilla de Abona is intersected by 6 different cells, San Miguel de Abona is crossed by 3 cells, two of which coincide with the ones intersecting its neighbor. Now the reader might ask a logical question: which one of the cells should be assigned to these municipalities? The answer we opt for in this study is "where most of the population of the municipality lives". The cell identified 10kmN1010E1700 and outlined by thick black line happens to be this location for both of the municipalities, as major part of the human settlements falls into this cell. There are, however, some concerns related to the decision of cell-to-municipality assignment based solely on the population spread. Municipalities in Spain differ in spatial extent quite substantially (61 sq. km. on average, with standard deviation of 91 sq. km.), and potentially variation of environmental characteristics within a municipality might be very different. We chose temperature as key indicator to test this hypothesis. In an absolute majority of the cases (98%) the variations of minimum and maximum temperature within

a single municipality do not exceed 2 degrees Celsius[10].

There are some rare exceptions when the difference of maximum temperatures within the same municipality reaches 13 degrees on the same day. The 24 hour variation of such magnitude is hard to explain if there is no impedance of exceptional scale within the municipality. If we look at the Figure 3.3 we make sure that this is exactly the case: the municipality of Almeria is composed by in-land territory and isle of Alborán, administratively belonging to the same municipality.

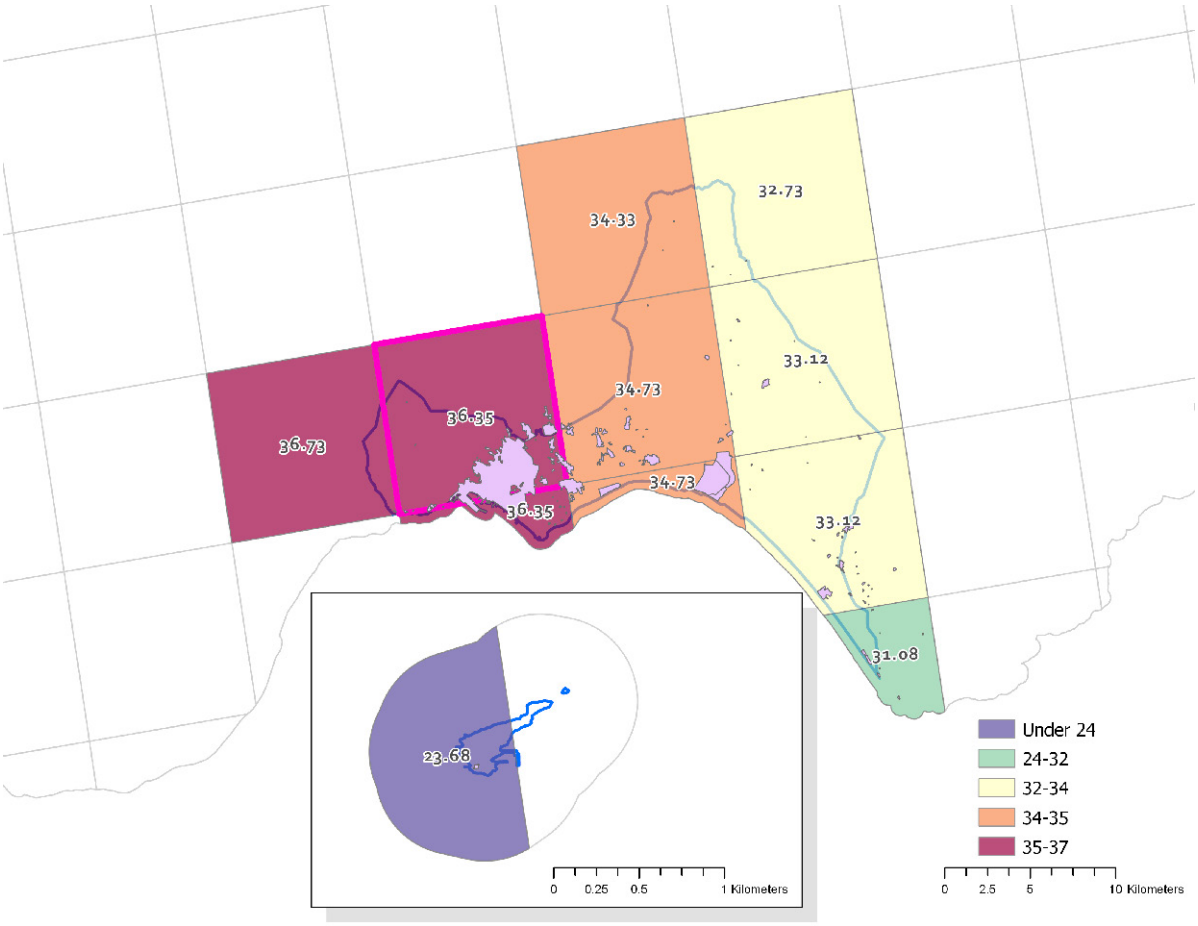


Figure 3.3: Intra-municipality variations of maximum temperatures on a given day

This isle is located at roughly 140 km distance from the city of Almeria, center of the municipality and capital of eponymous province, in the middle of Alborán sea (western part of the Mediterranean).This explains the difference of over 10 degrees on the same day within the same municipality. This case is the only exception when

[10]To estimate variations of temperatures in municipalities we use grid of 10km x 10km developed in the previous steps of the analysis.

intra-municipality variations of temperature exceed 75th percentile. Therefore, we assume it appropriate to proceed with the proposed method of cell-to-municipality value transfer. The position of the final set of cells assigned on one-to-one basis to the municipalities is displayed on the Figure 3.4.

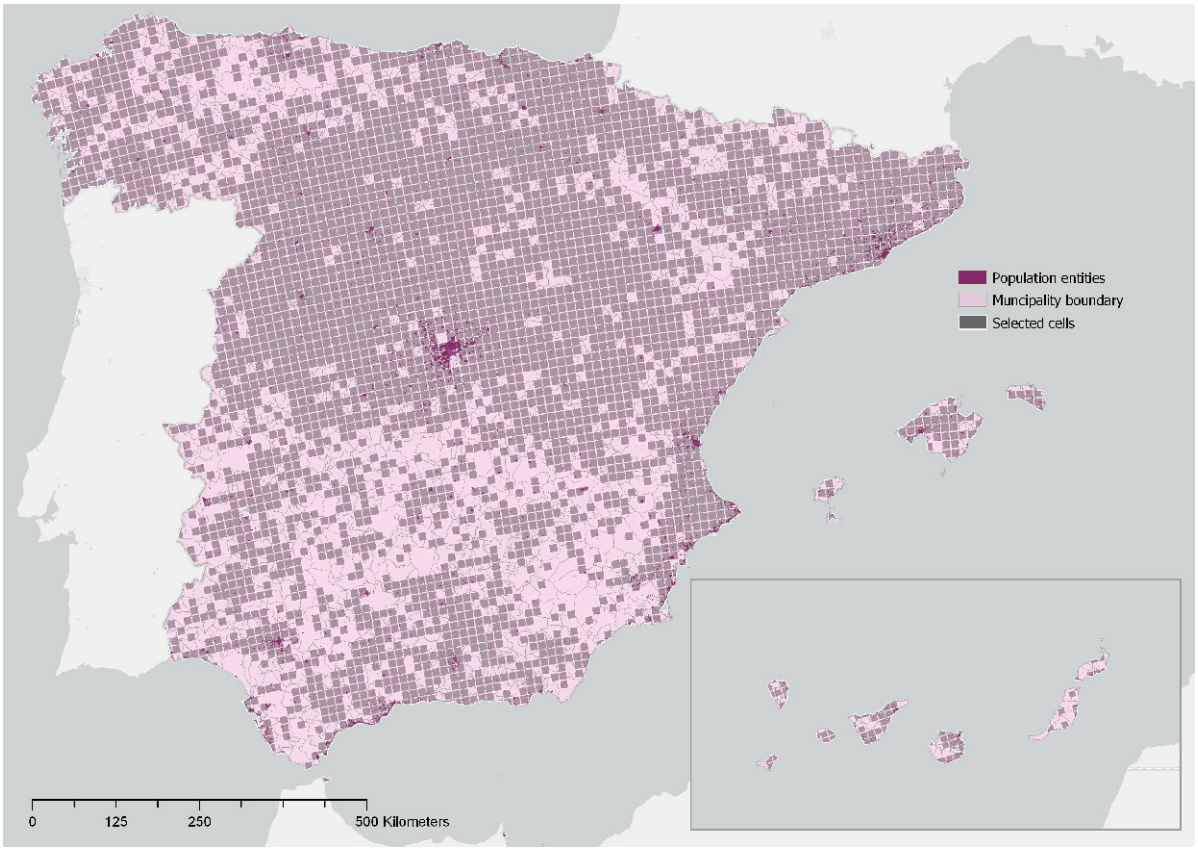


Figure 3.4: Cells assigned to Spanish municipalities on one-to-one basis

The domain of infrastructure is then represented by three groups of datasets: **health care facilities** (hospitals, health care centers and elderly care facilities), available as a spatial layer updated in 2016; **transportation network**, last updated in 2016; 2017 indices of commercial offer (public transport, health care), spatial layers with **administrative division** and **reference nomenclature**.

3.3 Population

In this study, we use two population databases that differ in nature, coverage and set of available variables. First dataset to be used in this study are the Death Statistics, covering the entire national territory and available for the period from 1975 to 2019.

Second dataset we involve in the analysis is the data derived from the Longitudinal Database of Population of Andalusia for the period from 1998 until 2019.

3.3.1 Death and population statistics

Death statistics form part of the Vital Statistics[11], which is a traditional statistical operation executed by INE. Statistical concept of death covers all deaths of individuals born alive (includes infant death of those who lived less than 24 hours).

The data was provided by INE on request for CSIC as a series of microdata[12] files, which were imported, tabulated and recoded per register design guidelines. Missing data statistics are shown in Table A.1. There are 4 main groups of variables available:

1. Death "coordinates": exact date of death, available in 100% of the cases, and death location (either residence, hospital, workplace etc), available from 2012 onward.
2. Socio-demographic characteristics: age at the time of death, sex and civil status of the individual, available for all the records; education (full availability from 2012 onward) and occupation (years 2012-2018 missing).
3. Nationality by country: this information starts to be recorded by the register from 2009 onward.
4. Geographic reference:
    - Place of Registration (municipality and province), available for the entire period;
    - Place of Birth (municipality, province, country), available since 1999;
    - Place of Residence (municipality, province, country), which is used as the proxy for *place of death* further in the analysis and available for the entire period from 1975 until 2019.

By including the date of death and birth, the resolution of the geographic data had to be reduced by the provider according to the privacy and legal regulations. Therefore, individuals which place of residence corresponded to the municipalities with less than 10 000 inhabitants, were assigned only the province of residence. This is why the percentage in the columns corresponding to the municipalities in Table A.1 never reaches

[11] Vital Statistics refer to births, deaths and marriages that take place within Spain. In administrative terms, Vital Statistics are based on the Civil Register. For more information on the methodology of Vital Statistics see www.ine.es

[12] For more information on Vital and other Statistics provided as microdata see www.ine.es

100%. Needless to say, this fact affects all the posterior steps of the analysis as all the municipalities under 10 000 of inhabitants are aggregated into a single area.

In order to correctly estimate the mortality indicators for the period 1975-2019 using the deaths statistics at different spatial levels, it is essential to acquire the data on the population of reference in a particular year and location. Here we rely on the data coming from the so-called *Continuous Register Statistics* (*Padrón continuo*). This Continuous Register was initially created to coordinate all the municipal registers in Spain. The term *municipal register* refers to an administrative registry where residents of a municipality are listed. In other words, the data from municipal register constitutes proof of residence in the municipality of an individual. Indeed, it is compulsory by law to sign in the corresponding municipal register for all Spanish residents. Formation, maintenance, revision and custody of the municipal registry corresponds to the respective town council. The latter sends all the updates of the variations in their respective registers to INE on a monthly basis in order to avoid duplication and ease the overall coordination between official data holders.

We programmatically retrieve the data from the Continuous Register available in different formats depending on the administrative unit for which the data is provided. In the first place, we obtain microdata for the period 2003-2020, which provide us with the population estimates for the 1stof January of each year disaggregated[13] to the level of municipalities. Then, we add the detailed definitive data (not microdata but yearly estimates by sex, age group and municipality) for municipalities for the period 1998-2002. Additionally, we access population estimates at the level of autonomous community as these data are available from 1970 onward. All mentioned data are publicly available and could be consulted at www.ine.es. All operations related to programmatic retrieval and processing of these data can be provided on request by the author in the form of R scripts.

After retrieval and processing of described statistics derived from the INE repositories, we construct a custom database with daily estimates of deaths and population of reference by sex, age and additional socioeconomic parameters by municipality for the period 2000-2019, and by autonomous community for the period 1975-2019. This set of variables constitutes first dataset in the population domain.

[13]Data for municipalities with less than 10 000 inhabitants are censored, as in case of death statistics.

3.3.2 Longitudinal Database of Population of Andalusia

The Longitudinal Database of Population of Andalusia[14] (BDLPA) was developed by the Institute of Statistics and Cartography of Andalusia (IECA) and integrates the information of the municipality registers of Andalusia, statistical bulletins of the *Natural Movement of the Population* (births, deaths and marriages) and population and housing censuses. The idea behind the creation of statistical source of such kind is to obtain vital trajectories that not only reflect current situation of individuals but also include longitudinal or historical perspective, changes in residence or sociodemographic characteristics over time. The data are publicly disseminated via 3 types of statistical products: tables, maps and microdata. Here, we have the privilege to leverage the data derived from the BDLPA and pre-processed according to custom criteria on request.

Since 1996, the core of the BDLPA is the information derived from the city councils, INE and other administrative registers such as Civil Registry. The quality of the official data received in 1996-1998 was not satisfactory, therefore Andalusian register claims its onset in 1998, when the issue of data inconsistency was successfully solved. INE sends to IECA data on municipal variations accumulated over a six-month period in a single file. This file includes births, deaths, changes of residence and management incidents that have been incorporated in the form of additions, cancellations or modifications during this period. For example, a semestral data flow consists, on average, in an update on around 8 million individuals; 1 million of entries, exists and modifications of the data; over 100 000 of new vital event registries (births, deaths, marriages), etc.

Figure 3.5 illustrates an example of individual life trajectories followed in the BDLPA. Here we see the trajectories of 3 family members: member 1 (father), born in 1965 and registered in a new location in 1984 at age 19; member 2 (mother), born in 1970, changed residence in 1988 at age 18, married to member 1 in 1990 and given birth to a child (member 3) in 1992. In 1998 these individuals entered the BDLPA and all the vital events in the following years (joint family migration in 2002, emancipation in 2010 and marriage in 2018 of the child, death of the mother in 2015) were recorded in the database. Some of the events that happened before the register onset was also possible to reconstruct and add to the database (e.g. partial linkage to the census of 1991). The information received from the censuses of 2001 and 2011 was also incorporated in the register in this way adding substantial socio-demographic details to these profiles.

To summarize, the statistical sources that are currently being used to reconstruct vital biographies of the Andalusians are the following:

[14]Base de Datos Longitudinal de Población de Andalucía, for more information see www.juntadeandalucia.es/institutodeestadisticaycartografia/longevidad

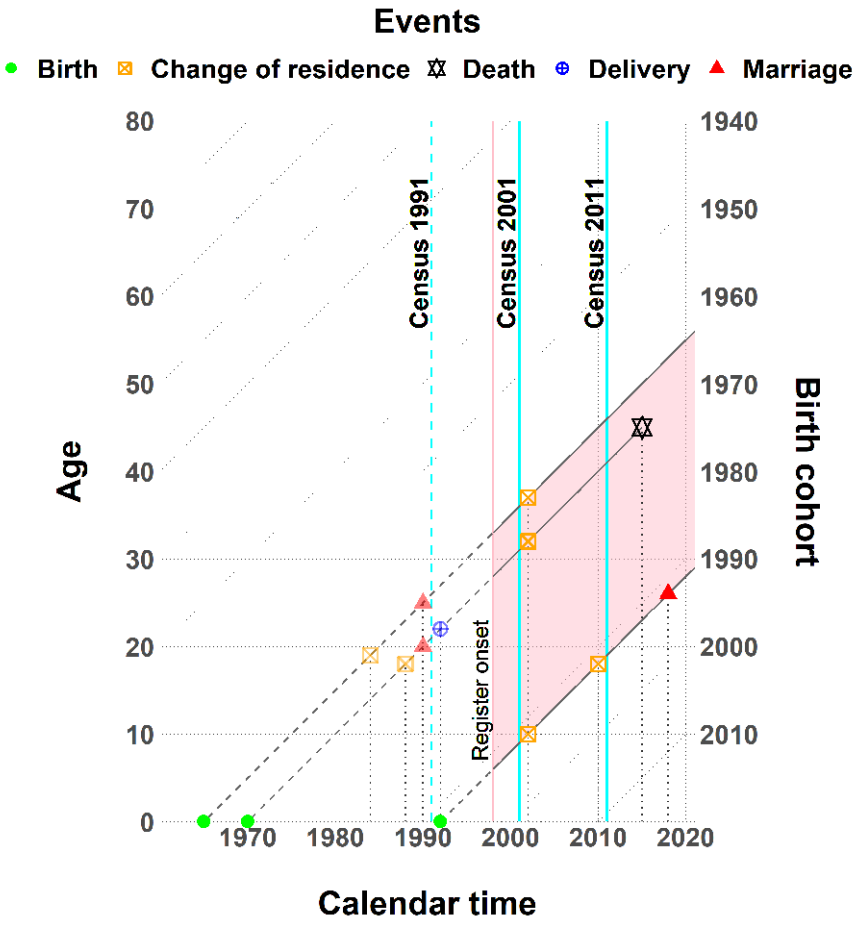


Figure 3.5: Organization of sources of demographic information in BDLPA shown on a Lexis diagram

1. Information of the last registry renewal in 1996.
2. Events collected in the *Natural Movement of the Population* circuit: births, deaths and marriages.
3. Variations that have occurred in the Andalusian registers since the operational start of the system.
4. Socio-demographic information collected in 2001 and 2011 censuses.

The richness and preciseness of the information of the BDLPA enable estimations of mortality indicators for small areas. A publicly available example of a small area indicator is published on the official IECA webpage and represents a Smoothed Standardized Mortality Ratio (SMR) indicator estimated for a regular spatial unit (cell) of residence of

individuals in 2001[15].The indicators of SMR by age group, sex and cause of death are *standardized* and therefore are not affected by differences in the structures of population, which allows for comparison of these indicators between populations with distinct structures.

The second dataset in the population domain is formed by variables derived from the BDLPA register which were estimated on a regular 10km x 10km grid delimited by Andalusian borders for the period 1998-2018. Variables include weekly death counts, population of reference, demographic and socioeconomic attributes. Unfortunately, the analysis based on these data did not enter in the main body of present dissertation. Nevertheless, in the Appendix we place a poster work (Fig.F.1), based on the results of the study based on the BDLPA register, which received an award as a best poster work at the British Society for Population Studies conference in 2018 in Winchester, UK.

3.4 Socioeconomic context

One of the important tasks of this study is to estimate the degree of vulnerability to extreme heat of different groups of population. To implement this objective, the information on (1) exposure and (2) socioeconomic conditions is required. As we will be discussing it in the upcoming chapters, the exposure is estimated using the observations on environment and population described in the preceding paragraphs. The socioeconomic context, in turn, is seen as a more static characteristic, a "reflector" of patterns and trends (e.g. an accumulation of disadvantages over time). Here we rely on two groups of indicators: deprivation index, a complex metric based on the data from 2011 census and estimated at the level of census tracts, and series of economic activity indices developed on a discontinuous regular grid.

3.4.1 Socioeconomic deprivation

The deprivation index (IP2011) developed by the Spanish Epidemiological Society[16] is a measure of the degree of the socioeconomic deprivation of the population residing in Spain as per the 2011 census. The IP2011 blends six socioeconomic indicators, estimated for each census tract using the data from the Population and Housing Census of 2011. These components are: population of manual workers, population of temporary workers, unemployed population, adult and young population with low

[15]SMR at 250m x 250m resolution, available at www.juntadeandalucia.es; SMR at 1km x 1km resolution available at www.juntadeandalucia.es

[16]Sociedad Española de Epidemiologia, for more information see www.seepidemiologia.es

level of education, dwellings without Internet access, all six expressed as percentage of total population of a corresponding census tract. The deprivation index was constructed using the principal component analysis to maximize the variance of the first component, which was standardized to have 0 as average value and standard deviation of 1. Thus, the IP2011 can be interpreted only in relative terms: a value of a particular census tract can not be interpreted directly unless related to other census tracts. As it is a standardized index, value close to zero would indicate the mean level of deprivation in Spain (Duque et al. 2021).

In our study, we scale up these data to the municipality level so it matches minimal resolution of the population data, which is a required component for estimating heat vulnerability. Re-estimation of the index to the level of municipality is based on the original values at the level of census tracts, re-weighted by the population size of each census tract (Fig.3.6 a, b). The generic picture becomes smoother, as intra-municipality variations, which in some cases are large, are now hidden (Fig.3.6 c). However, this step is necessary in order to reach comparability in the data.

3.4.2 Economic activity

As a proxy for economic activity we use another two indicators from the third party provider mentioned in the preceding paragraphs referring to Infrastructure. The general commercial index reflects overall intensity of economic activity and is based on locations of points of attraction of all types: shops, banks, pharmacies, medical assistance, hotels, religious establishments, public transport, public administration, leisure centers etc. The index of tourism, in turn, reflects the potential offer generated by mostly cultural and leisure points of interest: museum, art galleries, zoo, airports, train stations, accommodation etc. This index excludes hotels and beaches from its model. Both indices are generated on a regular discontinuous grid of 100 m and ranges from 0 (low offer) to 1 (high offer). These indicators have been pre-processed and rescaled to match the core grids used in this study, however were not leveraged to produce the primary results. We believe that these data have a great potential, especially in terms of vulnerability aspects, and therefore plan to use these data in the future research.

The domain of socioeconomic context is represent by two datasets: **deprivation index** of 2011, estimated at the level of municipalities, and **indices of economic activity**, estimated for 2017 and provided on a discontinuous regular grid of 100 m.

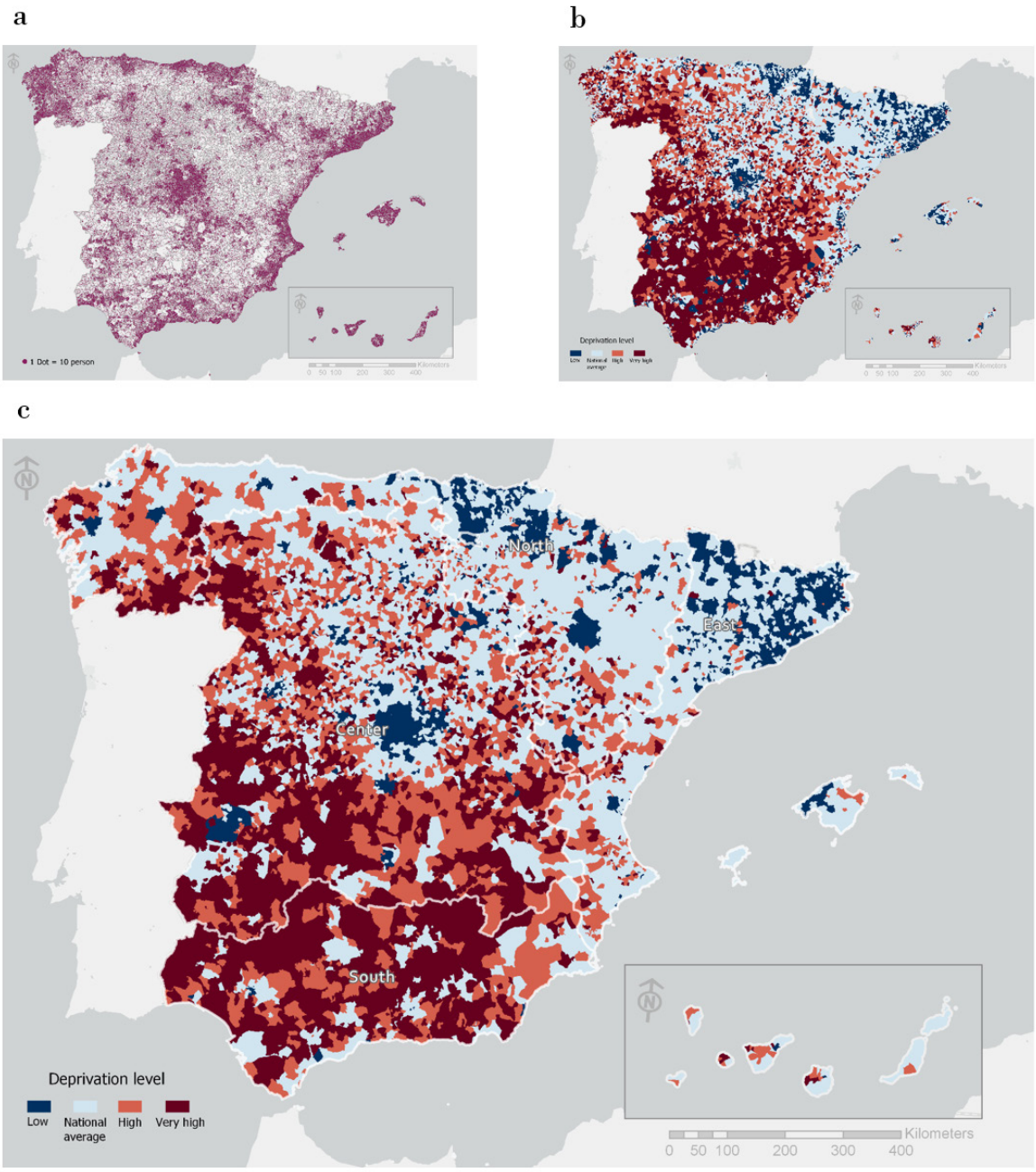


Figure 3.6: Index of deprivation estimated for Spanish municipalities

3.5 Legal terms

The majority of the datasets used in this study are publicly available with an exception of:

- Air quality dataset obtained by CSIC on commercial basis,

- Air pollution stationary measurements from national agencies provided through a special request to CSIC on non-commercial basis,
- Socioeconomic indices on regular grids provided to CSIC on commercial basis,
- Transportation network provided by ESRI Spain and used to perform accessibility estimations within the frames of Longpop Project which author formed part of.

European summer climate might experience a pronounced increase in year-to-year variability in response to greenhouse-gas forcing. Such an increase in variability might be able to explain the unusual European summer 2003, and would strongly affect the incidence of heatwaves and droughts in the future. It would represent a serious challenge to adaptive response strategies designed to cope with climate change.

— *The role of increasing temperature variability in European summer heatwaves*, Schär et al. (2004).

4

Heat waves in Spain: factors, definitions and generic characteristics

Why, when and where do heat waves happen? These questions are of extreme importance for understanding their effects on human health since patterns of their distribution are subject to continuous change as a function of many environmental and anthropogenic factors of global, regional and local scales. What are the physical triggers for these anomalies? Where and when are they most likely to occur? How often will they happen in the future? What is the predicted geographic pattern of its incidence? Yet this study does not pretend to explain the physics of the process of heat wave formation, we make an attempt to gather the evidence on the most apparent factors that prompt the emergence of thermal anomalies on surface in Iberian Peninsula (IP) and Canary islands (CI).

In this chapter, we embark upon a detailed analysis of the environmental data at our disposal (description provided in Chapter 3) in order to estimate the trends and analyze spatial patterns of the incidence and distribution of heat waves in Spain in the last 4 decades. We start with a descriptive analysis of the general trends of temperature variations over time. On the next step, we estimate temperature anomalies in Spain using a custom definition of a heat wave adapted from multiple sources. The chapter is then wrapped up with a comprehensive analysis of the spatiotemporal patterns of the incidence of heat waves in IP and CI.

4.1 Global thermodynamic factors

The thermodynamic factors affecting both mid-term regimes and synoptic situation in the IP can be divided into two large groups: air circulation in higher altitudes, so called *jet stream* (JS), and air circulation on the surface. Additionally, two important actors known to affect the IP climate and potentially trigger heat waves are the ocean currents (energy conveying water streams with their own characteristics and fluctuation cycles) and land surface thermal conditions (such as soil moisture variations), as emphasized by Zhang, Sun, et al. (2020).

The JS is a tubular geostrophic wind stream that circulates at the limit of the troposphere in west-to-east direction in meandering paths, shifting positions and speed seasonally. These oscillations produce a great climatic variability in the temperate zone in the Northern Hemisphere: depending on the shifts of the jet stream warm tropical air masses might reach higher latitudes, or, in other years, polar masses can extend to North Africa. The Mediterranean region (MR), roughly located between 30N and 45N parallels, is affected by two substreams: the Polar Jet Stream (PJS), related to the Polar front and circulating at 9-12 km at around 60N, and somewhat weaker Subtropical Jet Stream (STJ), which lies above the subtropical high-pressure belt and acts as a limit between tropical and mid-latitudes air masses, circulating at higher altitudes, 10-16km, on the 30N. In the "normal" situation when the polar jet circulates at its highest speed and is therefore more uniform, the cold air concentrates in the north of Europe thus "feeding" the formation of the cyclones (e.g. Icelandic low, a semi-permanent center of low atmospheric pressure).

The warm air then is located near the IP strengthening the anticyclone of the Azores which blocks the cold air. The anticyclone of the Azores is an important center of action located in direct proximity to the IP and represents an extensive almost stationary area of high pressure, which partially explains why summers in the Mediterranean climate are so poor in precipitations. The excessive heating of the Arctic during the summer period might debilitate the PJS and thus the Azores anticyclone becomes weaker and northern cyclones shift southwise and hotter tropical air moves towards the pole. The more oriental part of the anticyclone of Azores transforms into the Saharian anticyclone which brings in very hot and dry air masses (often with high dust content).

The STJ, in turn, is strongly associated with the tropical Hadley cell (HC) circulation processes and also with its recent shift poleward (especially in the July and August in the Northern Hemisphere) (Abish et al. 2015). The HC circulation per se can significantly affect the temperatures in the mid-latitudes (Brikas et al. 2006), and as shown by the

authors an anomaly in downward air movement resulting from the shifts of HC and STJ and consequent strong adiabatic heating can lead to formation of warm anticyclones above the Mediterranean and trigger heat waves.

The variability in the nature and intensity of the general atmospheric circulation in the North Atlantic is primarily attributed to the North Atlantic Oscillation (NAO) (Hurrell and Deser 2009). It is characterized by the NAOI (NAO index), which is the pressure difference between the Icelandic minimum and Azores maximum, and is used to estimate the intensity of the westerly winds over the North Atlantic, the axis position of the North Atlantic JS and the trajectories of the northbound cyclones. A large amount of studies focuses on the impacts of NAO in Spain (mostly in terms of precipitation, but also cold waves) during winter months (Muñoz-Díaz and Rodrigo 2004; García, Gimeno, et al. 2005; Prieto et al. 2002). The Summer North Atlantic Oscillation (SNAO) is well known for controlling summer heat, droughts and floodings in the northwest Europe; however Southern Europe seems to experience the effects of the SNAO to a much lower extent and mostly in terms of precipitations in the MR (Folland, Knight, et al. 2009).

A third part of the surface air temperature anomalies and Mediterranean Sea surface temperature anomalies can be attributed to the variations of the Atlantic Multidecadal Oscillation (AMO) during summer months in the MR, as asserted by Mariotti and Dell'Aquila (2012). Cassou et al. (2005) confirms that the anomalous peaks of Sea Surface Temperature (SST) along the European coast are known contributors to the heat intensification over the land. In particular, the AMO warm phases have been linked to the temperature anomalies and droughts over the IP in the summer months (Palter 2015; Ting et al. 2014; Sutton and Dong 2012). There is less evidence on the direct impact of El Niño - Southern Oscillation (ENSO) on the European climate in general (Scaife 2010), however Schneidereit et al. (2012) relate the ENSO-to-la Niña shift in summer 2010 to the eastern European blocking (which resulted in the 2010 Russian heat wave as explained further).

4.2 Regional geographic conditions

Sketch of orography of IP. As reader might suggest from the fact that so-called continental Spain is located on the Iberian *peninsula*, the proximity to large water masses is a crucial factor defining its climate. When this is true if we approach this assumption from the macro scale (general prevalence of Atlantic air masses at these longitudes and dominance of the westerly winds (anti-trades) on these latitudes), when looking at Spain as part of the IP we can argue that the influence of the sea is rather scarce, or at the

very least does not have great penetration towards the interior (opposed to neighbouring Portugal, for instance). This peculiarity is linked to several characteristics:

1. Solid shape of the landform with very regular shore (significantly less indented coastline in comparison with other Mediterranean countries, which naturally limits the penetration of the marine influence);
2. Perimetral mountainous relief (Cantabrian range, Iberian and Baetic mountain chains) which on many occasions acts as an insurmountable barrier for marine air masses to reach the Central Plateau.

This generates a fundamental difference in between a narrow humidified strip of the coastal areas that are open to the sea (mostly flat areas of the Murcian, Andalusian or Valencian Mediterranean coasts, cliffy Galician Atlantic coast and Cantabrian coast where cliffs alternate with beaches), with respect to the dry continental climate of the interior parts of the IP. The orientation of the slopes with respect to the prevailing winds has great importance as it facilitates or hinders the marine influence. Apart from the perimetral character that mountain chains have within the IP, these also have predominantly east-to-west extension (e.g. Cantabrian and Penibaetic range, Catalan coastal chain that all go in parallel to the coastline) which inhibits the south-to-north air displacement. This configuration itself defines the dominant type of the air masses that are most likely to enter from the Atlantic side to the inner parts of the country as there is no physical limit with longitudinal extension that would prevent the penetration of the westerlies. However, considering the distances that air has to pass before reaching the central parts of the peninsula, these masses arrive rather weakened and bring significantly less precipitation. Figure 4.1 displays seasonal windroses for the IP (two top rows) and CI (two bottom rows). Indeed, on average, winds within the IP have predominantly south-west (during the summer) and west (rest of the seasons) direction, whereas the maximum wind speeds in the IP are associated with the north-west directions in winter reaching the whole gale category on the Beaufort wind scale (26 m/s). Prevailing winds in the CI throughout all seasons are strongly associated with the north-east direction with the maximum wind speed of slightly over 19 m/s (fresh gale on the Beaufort scale) during winter and spring.

Climatic diversity. In this study, we stick to the climatic classification of Köppen-Geiger (Köppen 1900; Kottek et al. 2006) based on the patterns of average precipitation, temperature and natural vegetation. According to this classification, approximately 40% of the IP is under the hot-summer Mediterranean Cs_a climate with dry summers and cold and wet winters (in the CI this type of climate is only present in 5% of the

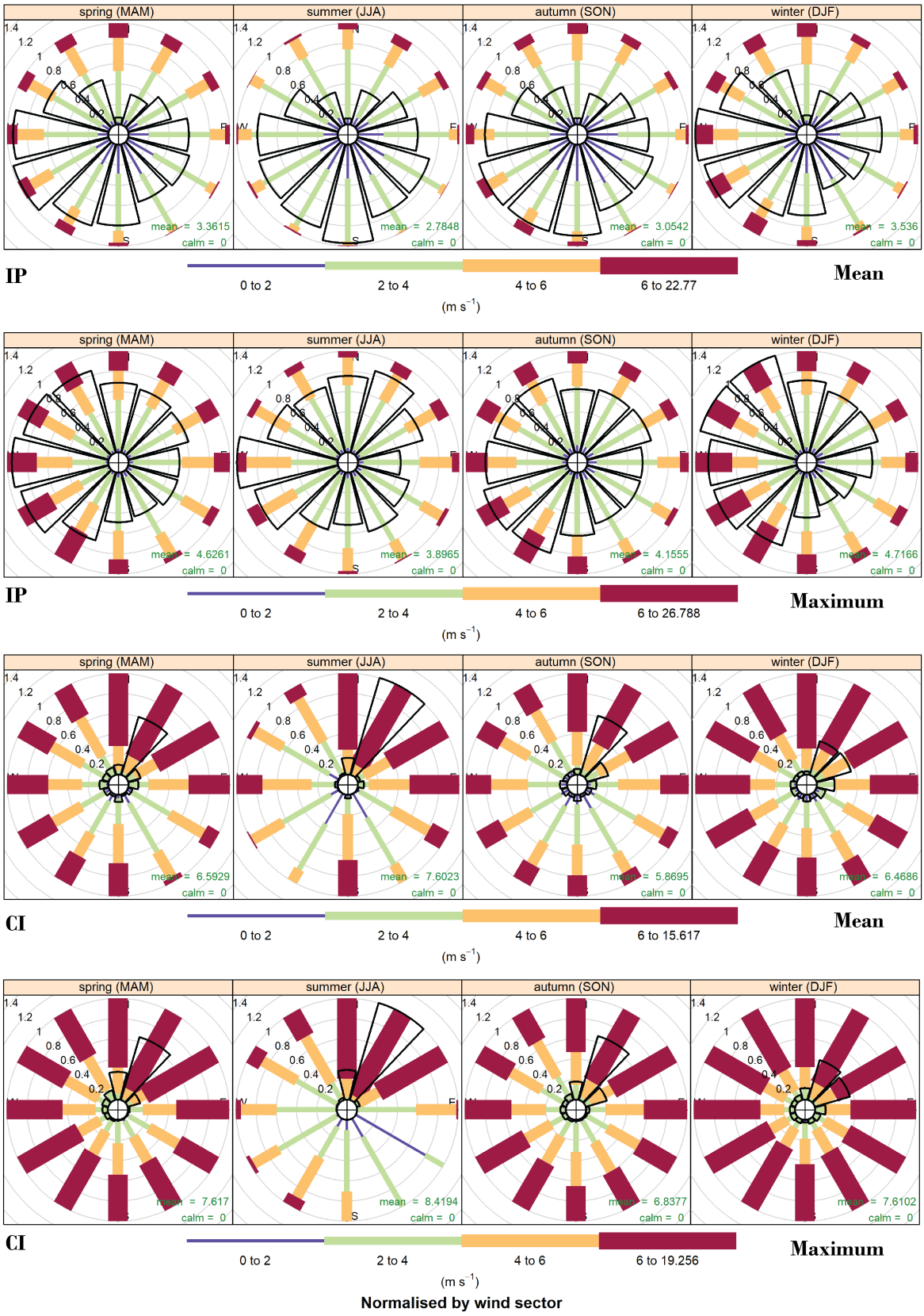


Figure 4.1: Seasonal windrose for IP and CI

territory). Milder warm-summer Mediterranean climate Cs_b is present in 20% of the land (both within the IP and in CI). Thus the peninsula has almost 60% of its land covered by the typical Mediterranean dry climate which is strongly dominated by the subtropical anticyclones with clear skies and high temperatures during the summer season. In the continental settings the Mediterranean climate borders the cold semi-arid BS_k climate (17% of the land): here an important role imposes the mentioned coastal proximity. Eastern part of the Central Plateau, Baetic mountain chain and Ebro depression are "trapped" in between mountain chains and are characterized by exceptional aridity. For instance, the city of Zaragoza - the capital of Aragón - is located in the river Ebro depression equidistantly between Mediterranean Sea and the Biscay Bay. For the precipitations to be formed in the city, the humid marine air masses should squeeze into a gorge between Iberian mountain chain, the Pyrenees and Catalan coastal chain and pass over 200 km in almost a straight line. Alternatively, the wet air masses can come from the northwest, although they also reach Zaragoza almost dried out as the major part of the rainfall is being left on the Basque coast. The amount of precipitation to reach the city might not be even a tenth part of the volume entering the land. The relief thus determines the greater aridity of similar interior closed basins. Another important feature of this climatic type is that unlike the semi-arid climate BS_h (1.5% and 16% of the land on IP and CI, respectively), the BS_k type tends to have warm to hot summer and also quite cold winter (continentality factor).

The most extreme arid climates in Spain are present by the Hot desert BW_h and cold desert BW_k types, which are localized within the peninsula in the south-eastern coast of Andalusia (less than 1% of coverage) whereas in CI the hot desert climate is the predominant one (57% of the islands are hot, sunny and dry year-round). Quite the opposite to these conditions is the temperature oceanic climate – typical maritime climate of the west coasts in higher middle latitudes – which is present in the northern part of the peninsula and covers around 17% of the territory. Approximately 1% of the IP is covered by the continental climatic types of the D group, which is present primarily in the mountainous regions (Pyrenees, Baetic chain).

It is clear that the overall geographic conditions predispose the IP to experience prolonged hot and dry periods almost across the entire territory as the result of long-term regime formed on these latitudes, altitudes and conditioned by the regional orography. However, on a smaller scale, there are dozens of factors that can exacerbate already extreme seasonal conditions and result in a temperature anomaly. Here we list some of the factors that might have the greatest impact.

Local wind systems. A well known atmospheric phenomena occurring in almost all mountain regions is a warm, dry, downslope wind called Foehn (or föhn). The windward slopes experience abundant precipitation and orographic cloud formation whereas the dehydrated hot air descends on the leeward slope. Within the IP foehns are likely to affect the eastern areas, so-called *zona de Levante* (Valencia and Alicante) with dominant winds coming from the west, Cantabrian mountain chain with south winds and Cadiz area (Alboran sea) with south-east wind.

Slope aspect. Aspect of the slope (or, in other words, the direction that a slope faces, its exposure) strongly affect the physical and biotic features (so-called slope effect). Within the IP the main latitudinal mountain chains will have its S, SW and SE slope receiving more solar radiation than the northern shady ones.

Anthropogenic influence. Continuous urbanization resulting in a rapidly expanding built-up areas, excessive traffic and industrial production contributes to the skewness of the land surface heating towards cities, if compared to the rural areas. An Urban Heat Island (UHI) effect is a well studied phenomena which is practically always associated with the heat wave phenomena and vice versa (Zhao, Oppenheimer, et al. 2018; Founda and Santamouris 2017). Senciales-González et al. (2020) have estimated the difference in daily minimum temperatures in August in Malaga city with the surrounding areas to be 2.3 degrees Celsius (maximum weighted average), while in Madrid the average difference in nocturnal temperatures might reach 6 degrees Celsius (García and Álvarez 2008). The UHI is a rather dynamic phenomena: Vicente-Serrano et al. (2005) claims that spatial patterns of the UHI of Zaragoza are subject to fluctuation over time as a function of prevailing winds.

4.3 Historical heat waves

Abnormal heat was a well known threat for human health for many decades (Pozzi and Fariñas 2010), though it was mostly treated as an 'environmental accident' without any implications at the governmental level and for public policies until recently. A serious public concern related to the adverse health effects of the emerging heat wave phenomena starts to gradually arise from the end of the 1980-s as more evidence comes in. The 1988 North American drought caused by a large-scale quasi-stationary Rossby-wave pattern in response to the anomalous sea-surface temperatures in the tropical Pacific which, in turn, was attributed to a strong la Niña event (Trenberth, Branstator, et al. 1988), was perhaps one of the first occasions to cause a serious public health consideration at a country-scale

at that time. The scientific community followed with the investigation on the role of land-surface processes, such as role of evapotranspiration for the surplus heating and heat-wave formation, or alterations in the soil-moisture-atmosphere feedback and its effects on the atmospheric circulation (Oglesby and Erickson 1989). In the 1995 another heat wave hit the Midwest and cities along the East Coast in the US: Karl and Knight (1997) estimated the return period of temperature registered in July 1995 as 23 years (meaning that an exceedance of meteorological parameters of such scale might be expected every once in 23 years). Provoked by a large high pressure system that trapped heat on the surface, the 1995 Chicago heat wave was characterized not only by extreme daily temperatures but also night-time extremes and very high humidity. This heat wave episode has already manifested an extent and danger that such events impose on health (Klinenberg 2003), however the literature on both social and physical aspects of the phenomena remained rather scarce up until 2003, when an extraordinary heat wave struck on Europe. This episode was called Great European heat wave because of its spatial spread but more importantly because of its 'abnormality': the return period surpassed a thousand years for central European summers as estimated by Schär et al. (2004). Large areas of southern France experienced an anomaly of 10 degrees Celsius with respect to 2001. At the same time, while northern parts of the IP were also affected by strong anomalies, the eastern coast of Spain registered even cooler temperatures than in 2001 (figure 4.2).

A comprehensive paper published by García-Herrera et al. (2010) lists atmospheric blocking (anticyclonic anomaly with longitudinal direction), soil moisture deficit (preceding long-lasting droughts earlier in 2003 with enhanced evapotranspiration leading to reduction of latent cooling during the summer, as additionally highlighted by Fischer, Seneviratne, et al. (2007)) and unusually high sea surface temperatures (SST)[1].

The 2003 heat wave resulted in a burst of scientific literature of diverse disciplines as the detrimental outcomes represented an undeniable piece of evidence. Seven years later, in 2010, eastern parts of the European continent (particularly central Russia) experienced another temperature anomaly exacerbated by the air pollution from wildfires. The mechanism of the formation of this heat wave was linked to the strong dominance of the high-pressure atmospheric system in western Russia, lack of precipitation earlier in the year and consequent soil moisture deficit (Barriopedro et al. 2011). Wildfires and consequent air pollution were of an unprecedented magnitude that year: Konovalov et al. (2011) estimated that in summer 2010 the European part of Russia almost doubled

[1]Still quite arguable, as exceptionally high Mediterranean SST are rooted in the PJS displacement northwards (Feudale and Shukla 2007), which triggered the anticyclonic activity in this area in the first place) within the primary factors responsible for the Great European heat wave.

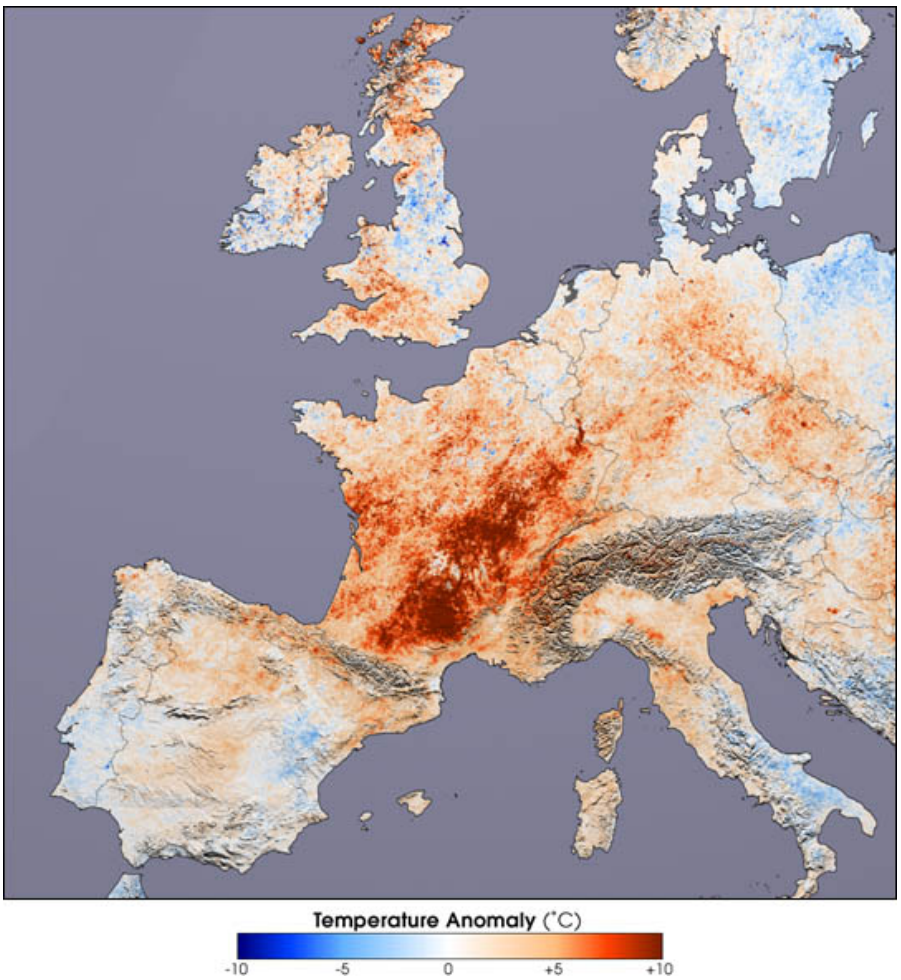


Figure 4.2: Temperature anomaly in July 2003 (Terra MODIS derived LST), sourced from visibleearth.nasa.govI

its total annual anthropogenic emissions of carbon monoxide. The *Mega* heat wave of 2003 (term used by Barriopedro et al. (2011)) and concurrent droughts were also associated with extensive wildfires (Ruffault et al. (2018)), which are projected to increase in frequency and intensity in the nearest future, gripping not only Europe but Northern Africa, North America and Australia (Liu et al. 2016; Trenberth, Overpeck, et al. 2004; Abram et al. 2021).

While past events have served to identify the role of the large-scale dynamics and land-surface atmosphere feedbacks, several recent events could not fit into the statistics of the past due to their 'extreme abnormality'. It is then of unquestionable importance to understand the mechanisms that will trigger heat waves in the future and will be in charge of establishing a new environmental reality. We discuss more thoroughly future climatic scenarios and predicted heat wave patterns for Spain in the concluding part of the thesis.

4.4 Overall changes and trends in Spain

In order to quantify the change of the temperatures in Spain during the period of observation we run two types of analysis. First, we estimate the *overall change* in the temperatures by comparing the last two decades with the preceding ones. This, indeed, might seem to be a rather simplistic approach, however it captures some general tendencies and justifies the necessity to run a more specific analysis to account for seasonal variations and overall incremental trend. Thus, on the subsequent steps we introduce the *time series analysis* to evaluate separately the components of the daily temperatures series.

It is worth mentioning that the variability hypothesis is fundamental for explaining the shifts in the incidence of temperature anomalies. Following the idea of Katz and Brown (1992) that future extreme events will be primarily dependent on the change of the climatic variability, Folland, Karl, et al. (2001) explain different hypothesis and scenarios of the combined effects of the shifts in temperatures (and precipitation) and increase in its variability. The researches find it rather hard to attribute the increase in frequency of the very extreme events to the shifts in mean values and therefore come to the conclusion that the changes in variability ('tale extensions') are the key factors for modelling heat wave incidence in the future.

The simulations from the Regional Climate Model (RCM) performed by Schär et al. (2004) for Europe highlight a clearly pronounced longitudinal gradient in the future mean temperature change (scenario period, 2071-2100, compared to the control period, 1961-1990) and change in the temperature variability. Particularly, the variability of the summer temperatures is expected to dramatically increase in the continental parts of the central Europe (France, Germany, Switzerland) rather than in the Western Mediterranean where IP is located. These findings then suggest that the increase in the frequency of heat waves in Spain will be mostly attributed to the overall increase of the temperatures, as clearly shown by the simulations performed by Fischer and Schär (2008). The mean summer warming in the interior of the IP is expected to be the strongest in the MR while the increase of the extremes (95th and 99th percentiles) is shifted up north to this strongest mean warming (Fischer and Schär 2010; Kjellström et al. 2011). In other words, in case of the IP the change in the variability will not be the main factor to induce heat waves in the area in the future, but the increase in the mean values will.

Here we have attempted to represent the changes in the probability distributions of the mean temperatures retrospectively. Figure 4.3 displays the changes in the mean temperatures (January to December) in the IP and CI for the past 2 decades (2000-2018) versus 2 preceding ones (1979-1999). The general character of the curve has

not changed over time, however the shifts of the absolute values seem to be quite significant: +0.8 degrees to mean (50thpercentile) and maximum (97.5thpercentile) temperatures in IP (+0.2/+0.7 in CI).

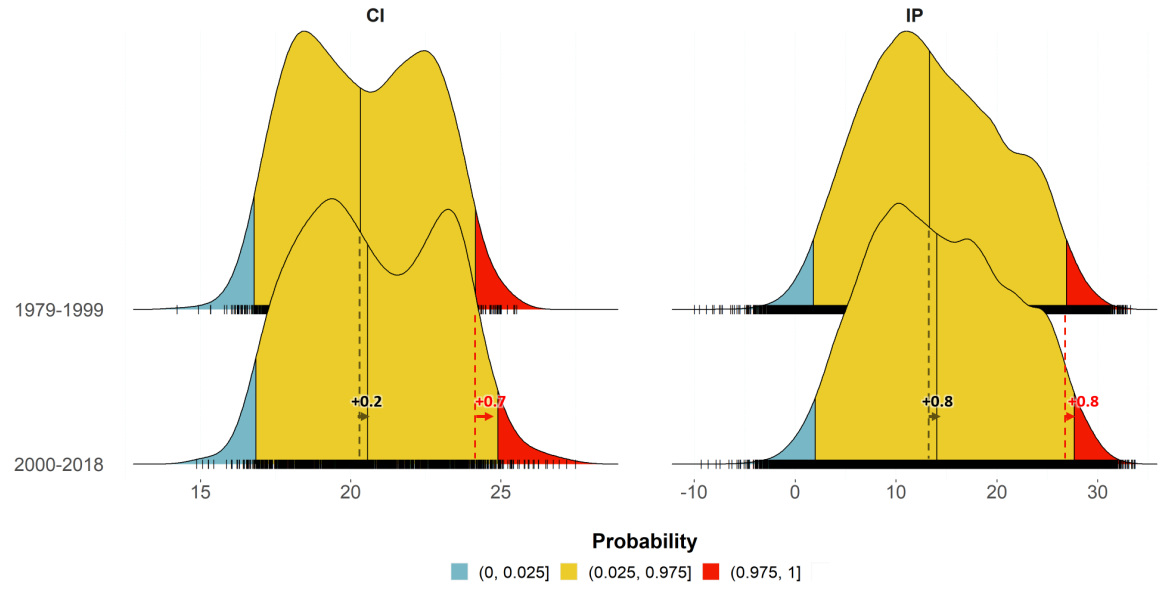


Figure 4.3: Change in probability distribution of all-year mean temperatures in IP and CI

In case of the summer (May to September) temperatures the observed increase of 50thpercentile equals to 0.8 degrees and 97.5thpercentile to +0.9 degrees in the IP while in CI the values are slightly lower, 0.5 for 50thpercentile and 0.6 for 97.5thpercentile (Fig. 4.4). Even though the temporal window used in this study might seem limited for making substantial inferences on the change of the climate of the area, small incremental shifts are clearly visible.

4.4.1 Inter-regional contrasts

On the following step, we compare 18 years of observations (2000-2018) with two preceding decades (1979-1999) by aggregating maximum (Fig. 4.5) and minimum (Fig. 4.6) temperatures by month and year all across IP and CI. Further, the aggregation is done at monthly step for each autonomous community in Spain: changes in the maximum and minimum temperatures are displayed in Fig. 4.7 and Fig. 4.8, respectively. There are two striking features manifested by the graphs below: (**a**) a clearly pronounced increase in both maximum and minimum temperatures in the summer months (+2 degrees in June) reflected across all the study area, and (**b**) an evident polarization of the seasons, especially in the late fall, and the beginning of the winter with minimum

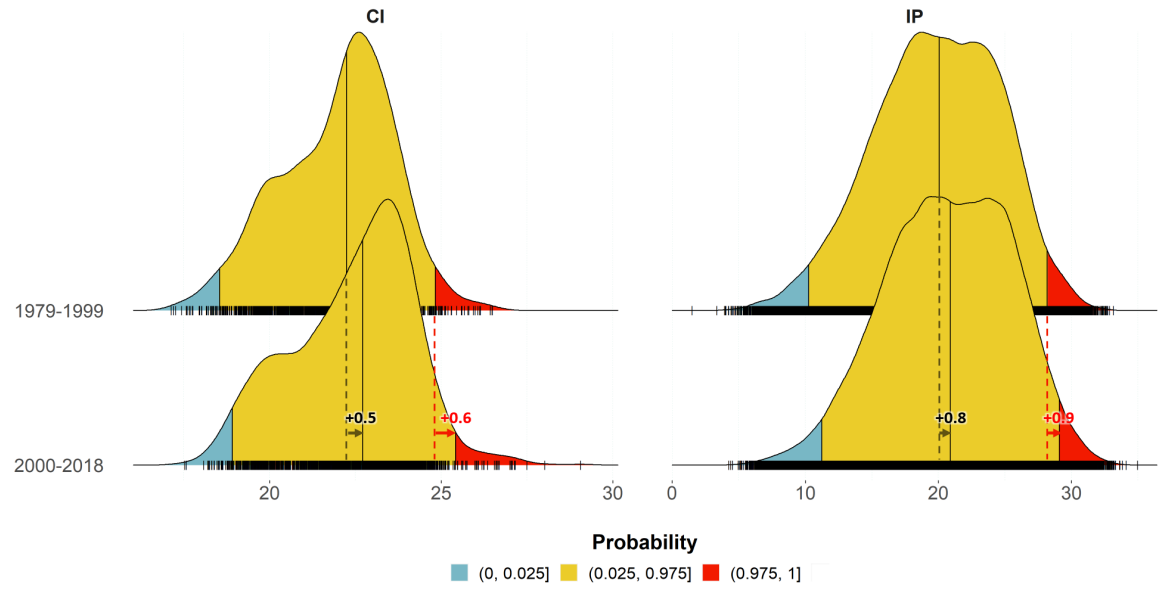


Figure 4.4: Change in probability distribution of summer mean temperatures in IP and CI

temperatures dropping by 0.1-0.8 degrees Celsius and maximum temperatures going upwards (+0.6ºC). Interestingly, both minimum and maximum values for October have a significant increase comparable with the one seen in the late spring. During the summer months, most increase in the maximum temperatures is seen in the more continental areas (e.g. Castilla-la Mancha, Madrid) in contrast to the coastal Northern and Eastern areas, a result matching the highlights of the report by Moreno et al. (2005) on the impacts of climate change in Spain. The highest overall increase in the maximum temperatures if compared to the period 1979-1999 is seen in Andalucia (+1.1 degree) and Castilla-La Mancha (+1 degree) whereas the lowest increase is registered in the northern Spanish communities (+0.4 degrees in Asturias, Cantabria, Galicia and País Vasco). Except for Ceuta, an autonomous city located in Northern Africa, the minimum temperatures across almost the entire territory of Spain show an increase up to 0.5 degrees, remaining unchanged in Melilla (another enclave in Africa) and two northern communities, namely Asturias and Galicia.

Oñate and Pou (1996) classify the territory of Spain into 3 large groups according to the secular temperature trends (1901-1989) characteristics: areas with smaller temperature extremes (lower maximum and higher minimum; e.g. Cantabrian coast and southern Pyrenees), areas with higher maximum and minimum values and increase in daily amplitude (e.g. South-West of IP, CI) and areas with overall more extreme temperatures (higher maximum and lower minimum, e.g. East, South East and Central areas of IP). These findings go in accordance with our results: South region (Andalucía, Murcia, Ceuta

and Melilla) have the highest increase in maximum and lowest in minimum temperatures, followed by Central (Madrid, Castilla y León, Castilla-La Mancha, Extremadura) and Eastern (Catañuña, Comunidad Valenciana, Balearic Islands) regions with medium increase in maximum and highest in minimum temperatures, Canary islands (medium and low increase in maximum and minimum temperatures, respectively) and Northeast (País Vasco, Navarra, Rioja, Aragón) and Northwest (Galicia, Asturias, Cantabria) regions, where maximum temperatures have the lowest increase and minimum are at medium level. A similar spatial pattern was identified by Brunet et al. (2007): this study divides Spain into Southwestern Spain (where annual temperature variability trends are at the highest rate), Southeastern and Eastern Spain and Northern Spain where these trends are less significant.

Another characteristic frequently used to quantify seasonal contrasts and intensity of temperature fluctuations is the diurnal temperature range (DTR) or amplitude. The graph shown in figure 4.9 illustrates the DTR in the starting period of observation (1979-1999) while the figure 4.10 corresponds to the closing period (2000-2018). Generally speaking, the higher the DTR the more continental the climate is, which is clearly seen in case of Extremadura, Comunidad de Madrid and both Castillas, which are the more centrally located areas within the IP. The lower amplitude usually corresponds to the milder climates located next to large water bodies: the examples of Balearic and CI clearly illustrate this concept. When we compare the two periods for all the country we discover another exemplification of the augmentation of the extremes: the amplitudes add up to 1 degree of more in the 2000-2018, which is especially visible in the more continental areas.

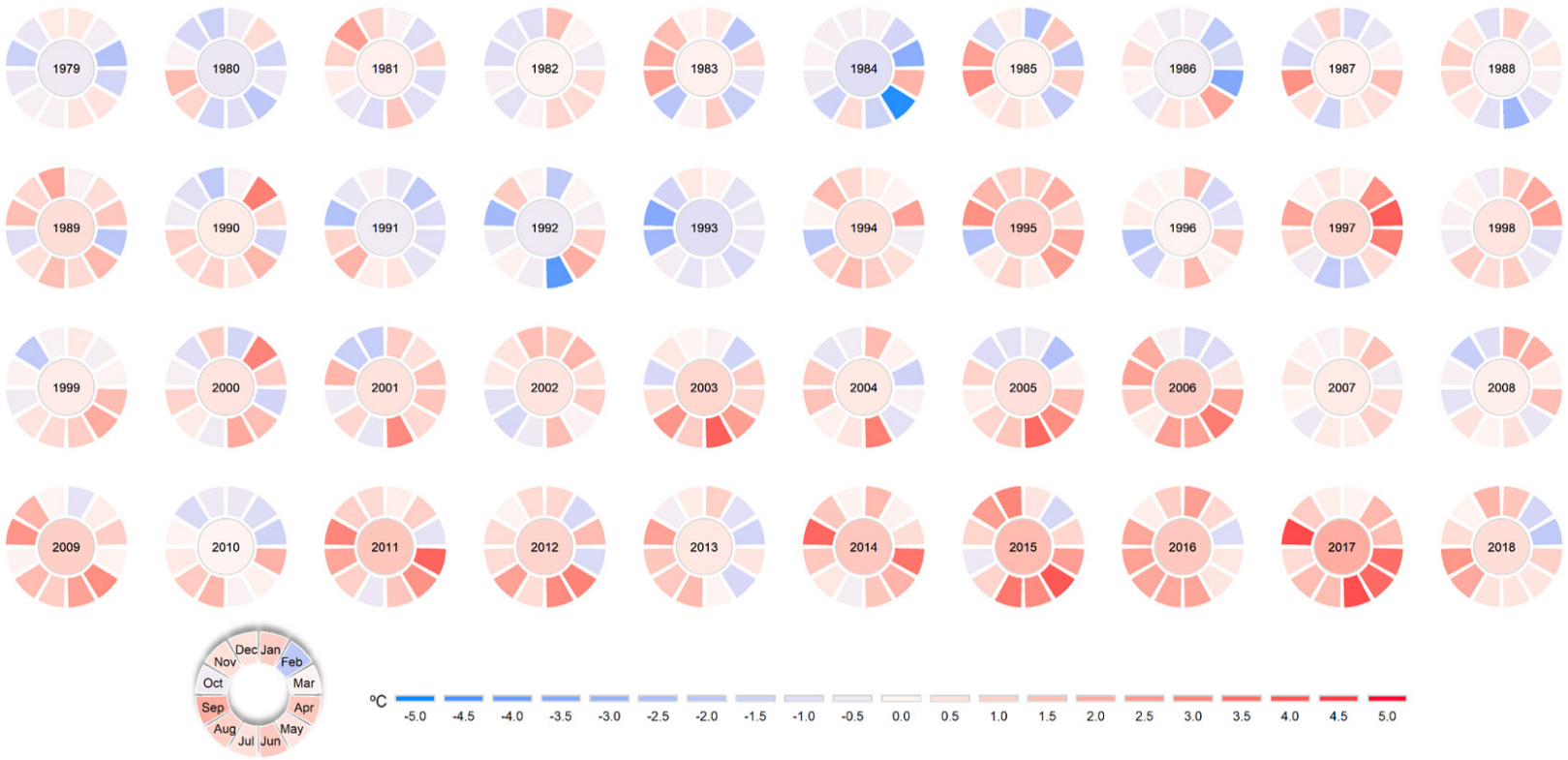


Figure 4.5: Change in maximum monthly temperatures over time (reference period 1979-1999)

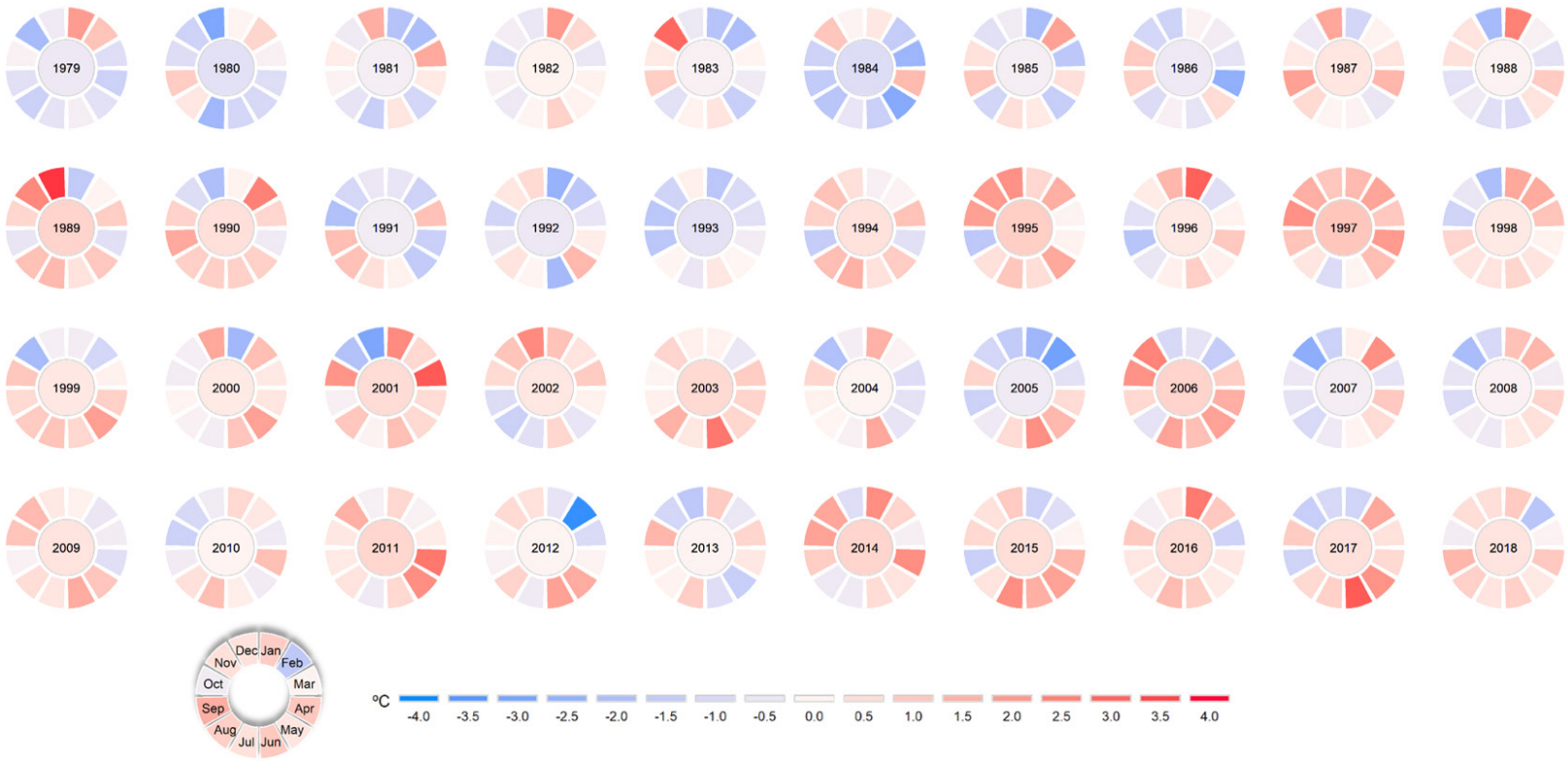


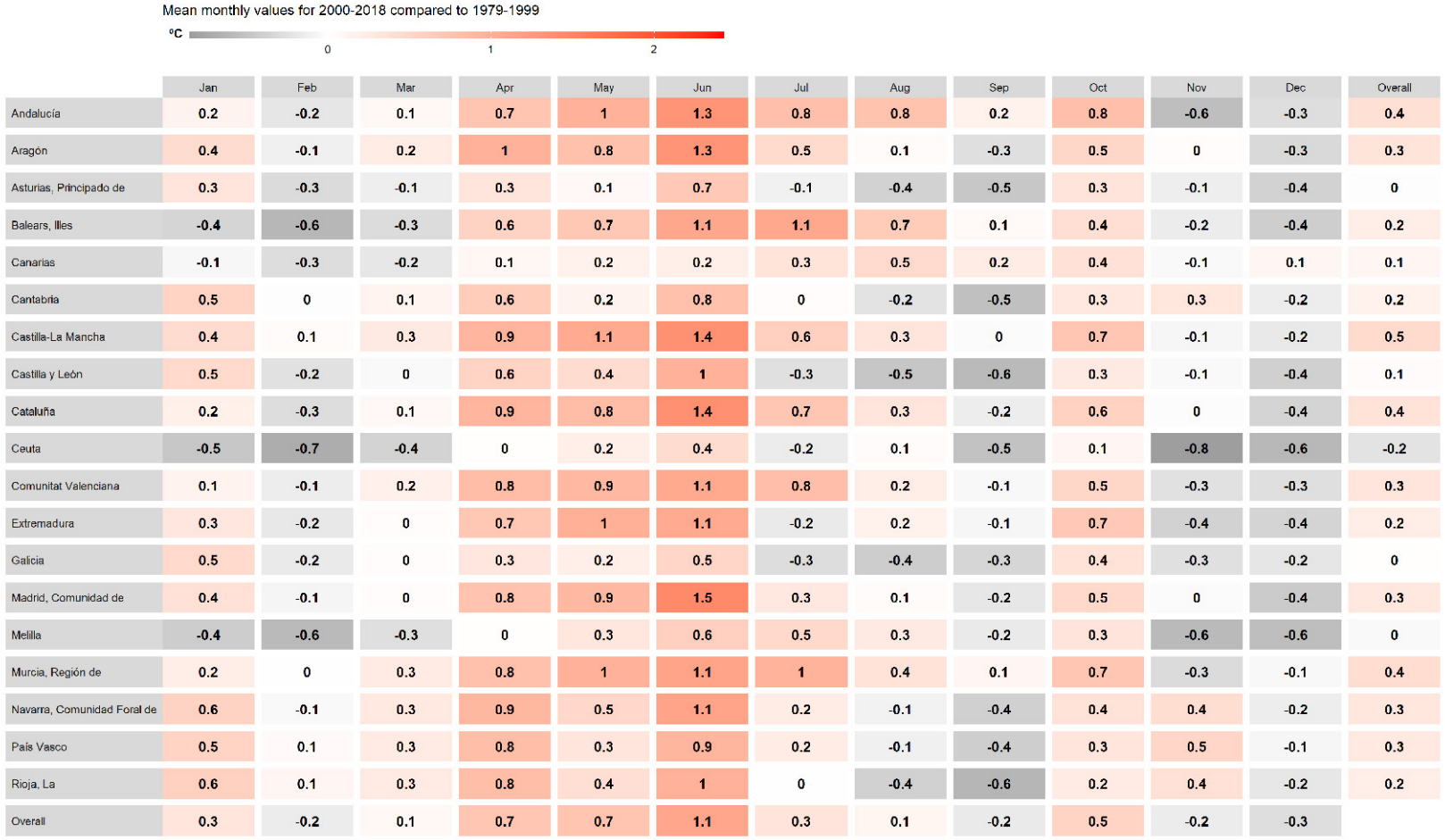
Figure 4.6: Change in minimum monthly temperatures over time (reference period 1979-1999)

Mean monthly values for 2000-2018 compared to 1979-1999

ºC 0 1 2

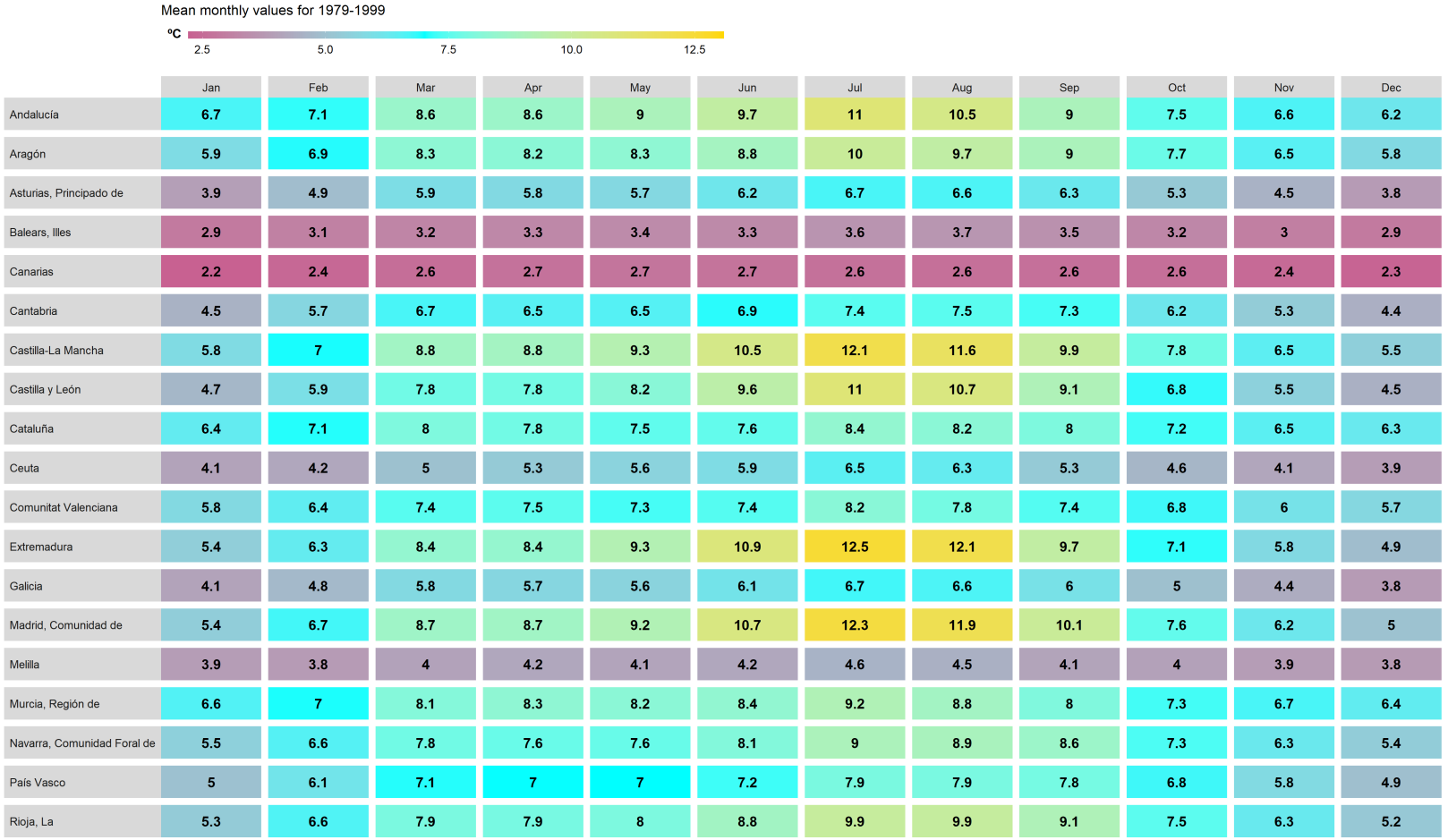
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
Andalucía	0.5	0.3	0	1.2	1.8	2.4	1.7	1.7	0.9	1.6	0.2	0.4	1.1
Aragón	0.8	0.1	0.5	1.6	1.4	2.3	0.9	0.9	0.6	1.5	0.4	0.3	0.9
Asturias, Principado de	0.2	-0.2	0	0.9	0.8	1.3	0.2	0.4	0.7	1.1	-0.2	0	0.4
Balears, Illes	0.3	0	0.5	1.2	1.1	1.7	1.3	0.9	0.6	1.1	0.4	0.3	0.8
Canarias	0.5	0.2	0.4	0.7	0.8	0.9	1	1	0.8	1	0.4	0.6	0.7
Cantabria	0.4	-0.3	0.1	1	0.6	1.2	0.1	0.3	0.3	1	0	0.1	0.4
Castilla-La Mancha	0.6	0.2	0	1.4	1.8	2.3	1.2	1.1	0.8	1.6	0.3	0.5	1
Castilla y León	0.4	-0.1	-0.2	1.1	1.4	1.9	0.4	0.6	0.7	1.2	-0.1	0.1	0.6
Cataluña	0.6	0.1	0.6	1.5	1.4	2.2	0.8	1	0.5	1.2	0.6	0.2	0.9
Ceuta	0.3	0.2	0.2	0.7	1.1	1.6	1.1	1.1	0.5	1.1	0.1	0.2	0.7
Comunitat Valenciana	0.7	0.3	0.5	1.2	1.3	1.7	0.9	0.6	0.4	1.2	0.3	0.3	0.8
Extremadura	0.4	0.2	-0.5	0.9	1.7	1.8	0.4	0.9	0.6	1.3	0	0.2	0.6
Galicia	0.3	0	0.1	0.9	1	1	-0.1	0.3	0.8	1.2	-0.2	0.1	0.4
Madrid, Comunidad de	0.6	0.2	-0.1	1.4	1.8	2.4	1	1.1	0.9	1.4	0.2	0.4	0.9
Melilla	0.2	0.1	0.5	0.8	1.1	1.5	1.3	1.1	0.7	1.2	0	0.2	0.7
Murcia, Región de	0.7	0.3	0.6	1.2	1.4	1.9	1.2	0.8	0.5	1.3	0.2	0.4	0.9
Navarra, Comunidad Foral de	0.6	-0.2	0.4	1.3	0.8	1.6	0.2	0.3	0.2	1.2	0.3	0.2	0.6
País Vasco	0.5	-0.3	0.2	1.1	0.5	1.3	0.1	0.2	0.1	1	0.2	0.2	0.4
Rioja, La	0.6	-0.2	0.2	1.3	1	1.6	0.2	0.3	0.3	1.2	0.1	0.3	0.6
Overall	0.5	0.1	0.1	1.2	1.5	2	0.8	0.9	0.7	1.3	0.2	0.3	

Figure 4.7: Change in maximum temperatures across Spain



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Overall
Andalucía	0.2	-0.2	0.1	0.7	1	1.3	0.8	0.8	0.2	0.8	-0.6	-0.3	0.4
Aragón	0.4	-0.1	0.2	1	0.8	1.3	0.5	0.1	-0.3	0.5	0	-0.3	0.3
Asturias, Principado de	0.3	-0.3	-0.1	0.3	0.1	0.7	-0.1	-0.4	-0.5	0.3	-0.1	-0.4	0
Balears, Illes	-0.4	-0.6	-0.3	0.6	0.7	1.1	1.1	0.7	0.1	0.4	-0.2	-0.4	0.2
Canarias	-0.1	-0.3	-0.2	0.1	0.2	0.2	0.3	0.5	0.2	0.4	-0.1	0.1	0.1
Cantabria	0.5	0	0.1	0.6	0.2	0.8	0	-0.2	-0.5	0.3	0.3	-0.2	0.2
Castilla-La Mancha	0.4	0.1	0.3	0.9	1.1	1.4	0.6	0.3	0	0.7	-0.1	-0.2	0.5
Castilla y León	0.5	-0.2	0	0.6	0.4	1	-0.3	-0.5	-0.6	0.3	-0.1	-0.4	0.1
Cataluña	0.2	-0.3	0.1	0.9	0.8	1.4	0.7	0.3	-0.2	0.6	0	-0.4	0.4
Ceuta	-0.5	-0.7	-0.4	0	0.2	0.4	-0.2	0.1	-0.5	0.1	-0.8	-0.6	-0.2
Comunitat Valenciana	0.1	-0.1	0.2	0.8	0.9	1.1	0.8	0.2	-0.1	0.5	-0.3	-0.3	0.3
Extremadura	0.3	-0.2	0	0.7	1	1.1	-0.2	0.2	-0.1	0.7	-0.4	-0.4	0.2
Galicia	0.5	-0.2	0	0.3	0.2	0.5	-0.3	-0.4	-0.3	0.4	-0.3	-0.2	0
Madrid, Comunidad de	0.4	-0.1	0	0.8	0.9	1.5	0.3	0.1	-0.2	0.5	0	-0.4	0.3
Melilla	-0.4	-0.6	-0.3	0	0.3	0.6	0.5	0.3	-0.2	0.3	-0.6	-0.6	0
Murcia, Región de	0.2	0	0.3	0.8	1	1.1	1	0.4	0.1	0.7	-0.3	-0.1	0.4
Navarra, Comunidad Foral de	0.6	-0.1	0.3	0.9	0.5	1.1	0.2	-0.1	-0.4	0.4	0.4	-0.2	0.3
País Vasco	0.5	0.1	0.3	0.8	0.3	0.9	0.2	-0.1	-0.4	0.3	0.5	-0.1	0.3
Rioja, La	0.6	0.1	0.3	0.8	0.4	1	0	-0.4	-0.6	0.2	0.4	-0.2	0.2
Overall	0.3	-0.2	0.1	0.7	0.7	1.1	0.3	0.1	-0.2	0.5	-0.2	-0.3	

Figure 4.8: Change in minimum temperatures across Spain



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Andalucía	6.7	7.1	8.6	8.6	9	9.7	11	10.5	9	7.5	6.6	6.2
Aragón	5.9	6.9	8.3	8.2	8.3	8.8	10	9.7	9	7.7	6.5	5.8
Asturias, Principado de	3.9	4.9	5.9	5.8	5.7	6.2	6.7	6.6	6.3	5.3	4.5	3.8
Balears, Illes	2.9	3.1	3.2	3.3	3.4	3.3	3.6	3.7	3.5	3.2	3	2.9
Canarias	2.2	2.4	2.6	2.7	2.7	2.7	2.6	2.6	2.6	2.6	2.4	2.3
Cantabria	4.5	5.7	6.7	6.5	6.5	6.9	7.4	7.5	7.3	6.2	5.3	4.4
Castilla-La Mancha	5.8	7	8.8	8.8	9.3	10.5	12.1	11.6	9.9	7.8	6.5	5.5
Castilla y León	4.7	5.9	7.8	7.8	8.2	9.6	11	10.7	9.1	6.8	5.5	4.5
Cataluña	6.4	7.1	8	7.8	7.5	7.6	8.4	8.2	8	7.2	6.5	6.3
Ceuta	4.1	4.2	5	5.3	5.6	5.9	6.5	6.3	5.3	4.6	4.1	3.9
Comunitat Valenciana	5.8	6.4	7.4	7.5	7.3	7.4	8.2	7.8	7.4	6.8	6	5.7
Extremadura	5.4	6.3	8.4	8.4	9.3	10.9	12.5	12.1	9.7	7.1	5.8	4.9
Galicia	4.1	4.8	5.8	5.7	5.6	6.1	6.7	6.6	6	5	4.4	3.8
Madrid, Comunidad de	5.4	6.7	8.7	8.7	9.2	10.7	12.3	11.9	10.1	7.6	6.2	5
Melilla	3.9	3.8	4	4.2	4.1	4.2	4.6	4.5	4.1	4	3.9	3.8
Murcia, Región de	6.6	7	8.1	8.3	8.2	8.4	9.2	8.8	8	7.3	6.7	6.4
Navarra, Comunidad Foral de	5.5	6.6	7.8	7.6	7.6	8.1	9	8.9	8.6	7.3	6.3	5.4
País Vasco	5	6.1	7.1	7	7	7.2	7.9	7.9	7.8	6.8	5.8	4.9
Rioja, La	5.3	6.6	7.9	7.9	8	8.8	9.9	9.9	9.1	7.5	6.3	5.2

Figure 4.9: Average diurnal temperature amplitudes across Spain in 1979-1999

Mean monthly values for 2000-2018

°C 2.5 5.0 7.5 10.0 12.5

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Andalucía	7	7.6	8.5	9.1	9.9	10.8	11.9	11.5	9.8	8.3	7.4	6.9
Aragón	6.2	7.2	8.6	8.9	9	9.8	10.4	10.5	9.9	8.6	6.8	6.4
Asturias, Principado de	3.9	4.9	6.1	6.4	6.5	6.8	7	7.4	7.4	6	4.5	4.2
Balears, Illes	3.5	3.6	3.9	3.9	3.8	3.9	3.8	3.9	4	3.9	3.5	3.6
Canarias	2.8	2.9	3.2	3.3	3.4	3.4	3.3	3.2	3.2	3.2	2.9	2.8
Cantabria	4.4	5.4	6.6	6.9	6.9	7.3	7.5	8	8.1	6.9	5	4.7
Castilla-La Mancha	6	7.1	8.5	9.3	10	11.4	12.6	12.4	10.7	8.6	6.8	6.2
Castilla y León	4.6	6.1	7.6	8.4	9.1	10.4	11.6	11.8	10.4	7.8	5.5	5
Cataluña	6.8	7.5	8.5	8.4	8.1	8.4	8.4	8.9	8.7	7.9	7.1	6.8
Ceuta	4.8	5.1	5.5	6	6.5	7	7.8	7.4	6.3	5.6	5.1	4.7
Comunitat Valenciana	6.3	6.8	7.7	7.9	7.7	8.1	8.2	8.2	7.9	7.5	6.6	6.3
Extremadura	5.5	6.7	7.9	8.7	10	11.6	13.1	12.8	10.4	7.7	6.2	5.4
Galicia	3.9	5	5.8	6.2	6.3	6.6	6.9	7.4	7.2	5.7	4.5	4.1
Madrid, Comunidad de	5.6	7	8.5	9.4	10.2	11.7	13	12.9	11.2	8.5	6.4	5.8
Melilla	4.5	4.5	4.8	4.9	4.9	5.1	5.4	5.4	4.9	4.9	4.5	4.5
Murcia, Región de	7	7.4	8.4	8.8	8.6	9.1	9.4	9.2	8.4	7.9	7.2	6.8
Navarra, Comunidad Foral de	5.5	6.4	7.9	8.1	8	8.6	8.9	9.4	9.2	8.1	6.1	5.8
País Vasco	5	5.8	7.1	7.2	7.2	7.6	7.7	8.3	8.4	7.4	5.5	5.2
Rioja, La	5.3	6.3	7.9	8.3	8.5	9.4	10.2	10.6	10	8.4	6	5.7

Figure 4.10: Average diurnal temperature amplitudes across Spain in 2000-2018

4.4.2 Trend analysis

The aggregated analysis shown in the latter paragraphs provides us with the justification for running time series analysis to obtain a more comprehensive estimation of the temperature change that accounts for seasonal variations. To do so, we created two daily time series for (A) CI and (B) IP and BI, as these are two essentially (geographically) distinct areas. The temperatures are therefore aggregated for each area by day. These time series are further decomposed into seasonal, trend and irregular components using moving averages by applying the additive approach as the seasonal variation remains constant throughout time. Here we use the *decompose* function from the base ***stats*** R package as described by the following equation (4.1):

$$Y_t = T_t + S_t + \epsilon_t \tag{4.1}$$

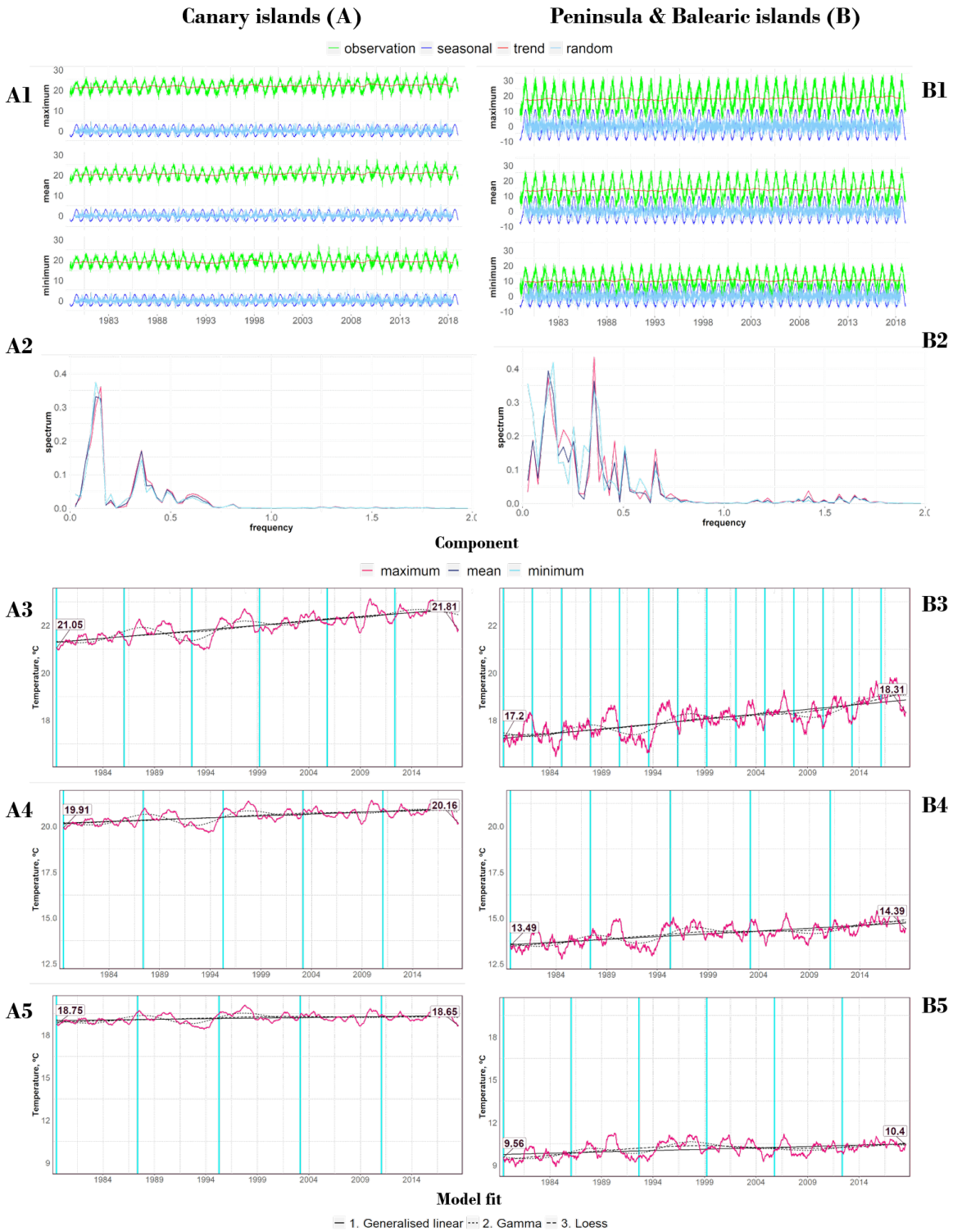
where T_t being the trend component determined using a moving average (in this case, a symmetric window with equal weights), which is further removed from the series; S_t being a centered seasonal figure computed by averaging, for each time unit, over all periods; and ϵ_t being an error component determined by removing trend and seasonal figure (recycled as needed) from the original time series.

The result of this decomposition is displayed on figure 4.11 which consists of three parts: the top row (*A1-B1*) shows the daily observations with three additive components, whereas second row (*A2-B2*) displays the results of the estimations of the spectral density of the trend component by fitting a smoothed periodogram, and the third to fifth rows represent only the trend component for maximum (A3 and B3), mean (A4 and B4) and minimum (A5 and B5) temperatures with 3 different fitted models to highlight the tendency of the trend. To estimate spectral density we use the *spectrum* function from the ***stats*** package: the periodogram is calculated using a fast Fourier transformation and the results are presented as vectors of approximate Fourier frequencies for which the spectral densities are estimated. The period (T) then is defined as

$$\mathcal{T} = \frac{1}{f} \tag{4.2}$$

For example, the main period - corresponding to the frequency (f) of the highest spectrum - for the trend in maximum temperatures for the CI (A3) is equal to 1/0.152 which is approximately 6.57 years).

The red line on sub-figures A3 and B3 on Fig. 4.11 represents the trend curve itself whereas blue vertical cut-off lines correspond to the period estimated through



1. Decomposed time series 2. Frequencies at the highest spectrum 3. Change in trend component for maximum temperatura 4. Change in trend component for mean temperatura 5. Change in trend component for minimum temperature

Figure 4.11: Decomposition of temperature time series and spectrum analysis of trend component

Fast Fourier transformation and spectral density estimation. Quantifying the trend is though somewhat tricky: for the simplicity sake we fit a generalized linear, gamma and loess models to each trend primarily to highlight the ever growing character of the curve. Moreover, to give a certain numerical evaluation of how much the estimated trend changed over the period of observation we calculate the differences between the start and end periods. The change is overwhelmingly positive, for both geographical zones and for all temperatures: overall, the maximum temperatures are 0.94 degrees warmer than at the start of the record (0.8 in CI and 1.1 within IP); minimum temperatures are 0.37 warmer[2], and lastly the mean temperatures are 0.58 degrees warmer with CI adding 0.25 degrees in the end of the period and peninsula and BI reaching +0.9 degrees.

An important and thought-provoking feature of the trend curves is the periodic character of its fluctuations. The period is significantly different in case of the maximum temperatures within the IP: here it equals to 2.8 years, while for the rest of the curves the period makes 6.5-7.9 years. Commonly the periodic fluctuations of the temperatures are related to the solar magnetic activity cycle (11 years), although some research suggest that smaller period in fluctuations might be related to different processes in the atmosphere or hydrosphere (ocean). As shown by Pereira de Souza Echer et al. (2007) a period of 3-7 years of temperature series might be related to the El Niño–Southern Oscillation (ENSO), however this phenomena is proved to affect the climates mostly in tropical and subtropical latitudes. The periods estimated in our study slightly surpass the upper limit and we suggest that it might be a weak echo effect from the lower latitudes to the 36-44ºN where the continental Spain is located. Pereira de Souza Echer et al. (2007) also indicate that the periods of 2 years may be associated with the so-called Quasi-Biennial Oscillation (QBO), which is a a quasi-periodic oscillation of the equatorial zonal wind in the tropical stratosphere with a mean period of 28 to 29 months.

4.5 Defining a heat wave: common criteria, metrics and approaches

Since the Great European heat wave of 2003 there has been a whopping amount of research developed on association of ambient temperatures and morbidity and mortality where diverse weather-related and bioclimatic indices, complex and simple, were involved.

[2]For CI the slope of the fitted model indicates the increase, however chosen value at the end of the period is 0.1 degree colder when compared to the start of the period; in case of IP it is 0.84 degrees warmer

There is no standard definition of a heat wave, and to our knowledge almost all of the studies referenced in this work provide a discussion on the method selected to identify abnormal heat episodes for the *specific* purposes of the study. As noted by Smith et al. (2013), this diversity of definitions is reasonable due to the number of applications as it introduces a plethora of approaches and therefore frames of references. At the same time it might be somewhat puzzling to navigate through dozens of custom criteria. Howbeit, generally speaking, a heat wave episode is considered a prolonged period when the ambient temperatures are *unusually* high. The term *unusual* frequently refers to a deviation from a long-term trend, but the period of reference is not established on official terms either (the rule of thumb here is to use a sufficiently extensive time period that allows for pulling statistically significant inferences).

Kostopoulou and Jones (2005) argue that there are two ways to assess extreme climatic events: either by using absolute thresholds, mostly derived from physiological concerns (Jones et al. 2021; Kovats, Hajat, and Wilkinson 2004; Huynen M M et al. 2001; Tong et al. 2012), or by using statistics of (climate) variables i.e. percentiles (Basagaña et al. 2011; de Schrijver et al. 2021; Kim, Park, et al. 2021; Issa et al. 2021). A number of systematic reviews on the comparison of different heat wave definitions, either applied to the mortality research (Xu, FitzGerald, et al. 2016), or to assessment of the effectiveness of heat plans (Toloo et al. 2013), was published during the past decade. Overall, it is considered that the usage of the relative locality-specific thresholds has more extended application as it enables to make comparisons in between different conditions and across areas. With rapid expansion of adaptive measures like climate control systems it became relatively easy to protect from extreme thermal conditions, which in some cases led to the increase of socially accepted thresholds: Robinson (2001) distinguished the physiological and sociological thresholds where sociological depend on the adaptation (i.e. selected activities, indoor conditions) and can be higher than purely physiological limits.

Depending on the type of data and scope of the investigation researchers use either only temporal extent (episode duration) and threshold exceedance[3], like most of the

[3]Wet-bulb globe temperature, an integrated measure of the heat intensity and influence of sun exposure, air temperature, humidity and wind speed (Grundstein et al. 2015), was used in several studies (Heo et al. 2019; Ma, Zhong, et al. 2019; Cheng, Lung, et al. 2019); Apparent temperature, a perceived outdoor temperature (sometimes also referred to as a measure of human discomfort) caused by the combined effects of air temperature, relative humidity and wind speed (Steadman 1979; Steadman 1984), implemented in another group of studies (Basara et al. 2010; Kershaw and Millward 2012; Henderson et al. 2013); or heat index, a measure of how a human body perceives the heat when relative humidity is factored in with the actual air temperature (Rothfusz 1990), applied by Kim, Ha, et al. (2006), Bai, Ding, et al. (2014) and Heo et al. (2019)

mortality- and morbidity-focused research, or also add spatial extension (Stefanon et al. 2012) and use more elaborated indices for inter-definition comparisons (Fenner et al. 2019).

Certain studies consider the minimum (usually night-time) temperatures particularly important for exploring the adverse effects on health and therefore involve both maximum and minimum temperature in the definition of a heat wave (He et al. 2019). The concept of *hot nights* or *tropical nights* recently began to gain 'popularity' for health-related research as it is assumed that the elevated temperatures during night-time impedes proper sleep and resting (Ren et al. 2020; Lee, Kim, et al. 2019; Royé 2017).

Another recently developed metric frequently used for heatwave monitoring and forecasting is the Excess Heat Factor (EHF), originally developed by Australian Bureau of Meteorology (Nairn and Fawcett 2015; Langlois et al. 2013). The EHF is a bicomponent index: it measures the intensity of the deviation of the 3-day-averaged temperatures and also includes the approximation of human physiological adaptation by comparing the 3-day-averaged temperatures with the recent past (30 preceding days). Mostly the research using this metric was performed at the national scale in Australia (Hatvani-Kovacs et al. 2016; Borg et al. 2019; Varghese 2019; Wondmagegn et al. 2021), though recently it began to gain "popularity" and was adopted in several European studies (Fenner et al. 2019; Royé, Codesido, et al. 2020).

It is important to explicitly highlight that all the criteria for identification of an extreme heat episode explained above, along with the custom definition that we will use in this study, are based on purely climatic characteristics, and do not derive from the thresholds that trigger the negative responses in terms of human health in a particular area (like it was done by García and Álvarez (2008) for the metropolitan area of Madrid). In this study, we aim to reduce the ambiguity of interpretations and also stick to the national heat-policy vocabulary. Therefore the base definition used to declare Heat Wave Episodes (HWE) is derived from the one declared by the State Meteorological Agency of Spain (Agencia Estatal de Meteorología, AEMET) with custom modifications.

4.5.1 Towards a custom definition

AEMET defines a heat wave episode as an episode of at least 3 consecutive days (1) in which at least 10% of the considered stations (2) register maximums above the 95% percentile (3) of their series of maximum (4) daily temperatures for the months of July and August (5) for the period 1971-2000 (6) (AEMET 2020). As can be clearly seen from this definition the selection of the threshold temperatures, reference months and years along with the episode duration will strongly affect the result. This approach can be

considered as essentially *local*: temperatures registered at a single location (meteorological station) are compared to the temperatures registered at the same location during the years before (and *not* to the average temperatures across surrounding areas, or across the entire country, which, in turn, could be then described as a zonal approach for anomaly detection). To declare a heat wave episode over a larger area the Agency observes the situation at multiple locations and uses 1/10 of all the sites as a lower limit for spatial extent to release the alert.

We use this official definition as a basis and introduce some changes in the parts labelled above in order to make further analysis more flexible:

1. At least 1 day over the corresponding threshold is considered.
2. Spatial extent is removed from the definition as we are not interested in establishing alerts on large areas but on a single location (cell).
3. Both 90^{th} and 95^{th} percentiles are used, for both single location (cell) and larger areas (climatic/phytoclimatic zones).
4. Maximum (day-time) and minimum (night-time) temperatures are considered.
5. Selection of reference hottest months is adjusted to the geographic location.
6. Reference period is amplified to 1979-2018.

In addition to the air temperatures, heat index (an indicator derived from air temperature and dew point temperature or relative humidity as described earlier) is used to identify heat wave episodes:

$$\begin{aligned} HI = &- 42.379 + 2.04901523 \times T + 10.14333127 \times RH - .22475541 \times T \times RH \\ &- .00683783 \times T^2 - .05481717 \times RH^2 + .00122874 \times T^2 \times RH \\ &+ .00085282 \times T \times RH^2 - .00000199 \times T^2 \times RH^2 \end{aligned} \tag{4.3}$$

where **T** is temperature in degrees Fahrenheit and **RH** is relative humidity in percent. Depending on a particular combination of temperature and relative humidity the coefficients change, which is reflected in work by Rothfusz (1990).

Overall, we define 8 different types of heat wave episodes: half registered by air temperatures and half by heat index.

1. **Temperature**-derived episodes
    - Defined with respect to the **zonal** settings using:

  - 90^{th} percentile of the temperature series for a particular climatic type where an individual cell is located;
  - 90^{th} percentile of the temperature series for a particular phytoclimatic subtype where an individual cell is located;
- Defined with respect to the **local** settings using:
  - 90^{th} percentile of the temperature series for an individually taken cell;
  - 95^{th} of the temperature series for an individually taken cell.

2. **Heat index**-derived episodes

- Defined with respect to the **zonal** settings using:
  - 90^{th} percentile of the heat index series for a particular climatic type where an individual cell is located;
  - 90^{th} percentile of the heat index series for a particular phytoclimatic subtype where an individual cell is located;
- Defined with respect to the **local** settings using:
  - 90^{th} percentile of the heat index series for an individually taken cell;
  - 95^{th} of the heat index series for an individually taken cell.

As we see, in each of these two groups 50% of episodes are so-called **local**: for every location we use the corresponding 90th and 95th percentiles of their series of maximum and minimum temperatures or heat index for the hottest moths at this location for the period 1979-2018. Taking individual thresholds and hottest months for every single cell allows us to capture heat anomalies with respect to the local settings throughout the entire period of observation. The other 2 types of the episodes are classified as **zonal**: we use the 90th percentile of the series of maximum and minimum temperatures within the same climatic and phytoclimatic zone for July and August within the IP and August and September in CI for the period 1979-2018. Further we provide a detailed description of the aforementioned components (selection of the hottest months to be used as a reference, identification of the threshold values) used to define a heat anomaly.

4.5.2 Reference periods

Selection of the top two hottest months was performed for a single location, climatic zone and phytoclimatic subtype. An emphasis is done on importance of selecting a period where highest temperature are registered in the real geographic settings. Indeed, an assumption that July and August are necessarily the hottest months across the area of over 500k sq.km. with over 10 different climatic zones and complex orography might be false for some areas. We analyze the entire time-series of maximum (Fig. B.5 in the Appendix) and minimum (Fig. B.6) temperatures and maximum (Fig. B.3) and minimum (Fig. B.4) heat index within the peninsula and islands to identify the two months that are most likely to register the highest values.

Both temperatures and heat index reach its highest values in different times during the 40 year observation window, however as can be seen from the maps, July and August are the most likely to be the hottest months for the IP (in some years July shifting to June and August to September) and August and September for the CI (occasionally shifts to September and October). The summary graph on Fig. 4.12 shows the portion of the national territory registering its highest values for temperatures and heat index in certain months.

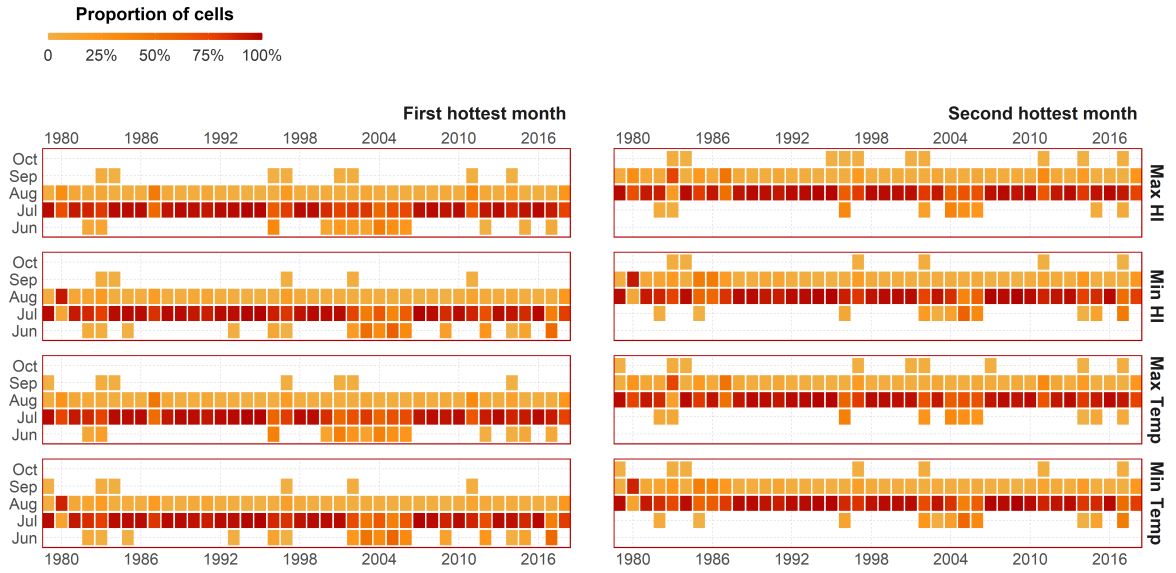


Figure 4.12: Most frequent months for registering highest temperatures: evolution by month and year

An interesting feature to note is that there was an overall persistent shift to earlier months in 2000-2006 where almost half of the country recorded highest values in June and

July. To define local heat wave episodes we use the statistics for the most frequent months for every cell to account for the geographic variability of the area and local settings.

Spain is characterized by high climatic and phytoclimatic diversity due to its landscape variability and overall transitional position between Mediterranean and Atlantic. In the previous section we have described a diverse range of climatic types present in IP and CI according to the Köppen-Geiger classification. Thus, Spain falls into three major climatic groups: the largest part is covered by the temperate climate (group C: humid subtropical, temperate oceanic and hot- and warm-summer Mediterranean), the driest areas correspond to the dry climates (group B: hot and cold semi-arid, hot and cold deserts) and mountains have continental climate (group D: warm-summer humid continental, Mediterranean-influenced warm-summer humid continental and subarctic climates). If we look at the distribution of the temperatures (Fig. 4.13) throughout the period of study across different climatic groups we could notice a clearly pronounced summer period (except the hot desert climate localized on CI, where annual temperature variation is generally smoother than elsewhere within the IP) with significant inter- and intra-temperature variations. With some exception, the top two hottest months appear to be July and August.

The Fig. 4.14 illustrates the probability of a month appearing amongst the two hottest months during the period of observation (each bar represents month incidence proportion from 40 years of measurements). For instance, maximum and minimum temperatures in September in hot semi-arid climate were registered only in 5% and 10% of all cases, whereas August was one of the two hottest months for temperatures for almost all of the cells (97.5% for maximum values and 100% for minimum) followed by July when 97.5% and 90% of all cells in Spain reported this month being one of the two hottest for maximum and minimum temperatures, respectively.

The phytoclimatic types combine the information on temperatures and precipitation (de Zulueta 1990), which are the leading factors to define the distribution of the species. Overall, there are 20 subtypes of vegetative formations according to this classification present on IP and BI. The CI are not included in this schema since its differential biogeoclimatic essence requires the use of a resolution power less than 1 sq.km. In this study we treat Canary archipelago as a segregated phytoclimatic unit. We also tend to associate spatial patterns of the heat index distribution to the phytoclimatic outline of the area since both strongly rely on the humidity or precipitation. Fig. 4.15 highlights the heat index dissimilarities between 20 phytoclimatic subtypes.

Seasonal heat index variation with peak in the summer season clearly stands out: the curve is smoother in case of CI (same behavior as temperatures) and in some subtypes of Nemoral regions (e.g. N-5 and N-7). At a glance the highest values of heat index are most frequently reached in July and August in peninsula and BI and in August and September in CI, which is later confirmed by statistical calculations (Fig. 4.16, each bar represents month occurrence proportion from 40 years of measurements).

From the Fig. 4.16 the reader grasps the following: In Arid and Mediterranean phytoclimatic regions it is unlikely for the heat index to reach its highest marks in September or June, thus leaving July and August the top two hottest month. In case of Nemoral and Oroboreal regions, the variation is rather more ample: in some subtypes up to 20% of these areas register highest heat index values in September (e.g. N-6). However, statistically the months of July and August appear to be the hottest two within the peninsula, and August and September in the CI, for both minimum and maximum values and across all phytoclimatic subtypes. The same applies to the climatic zone and temperatures.

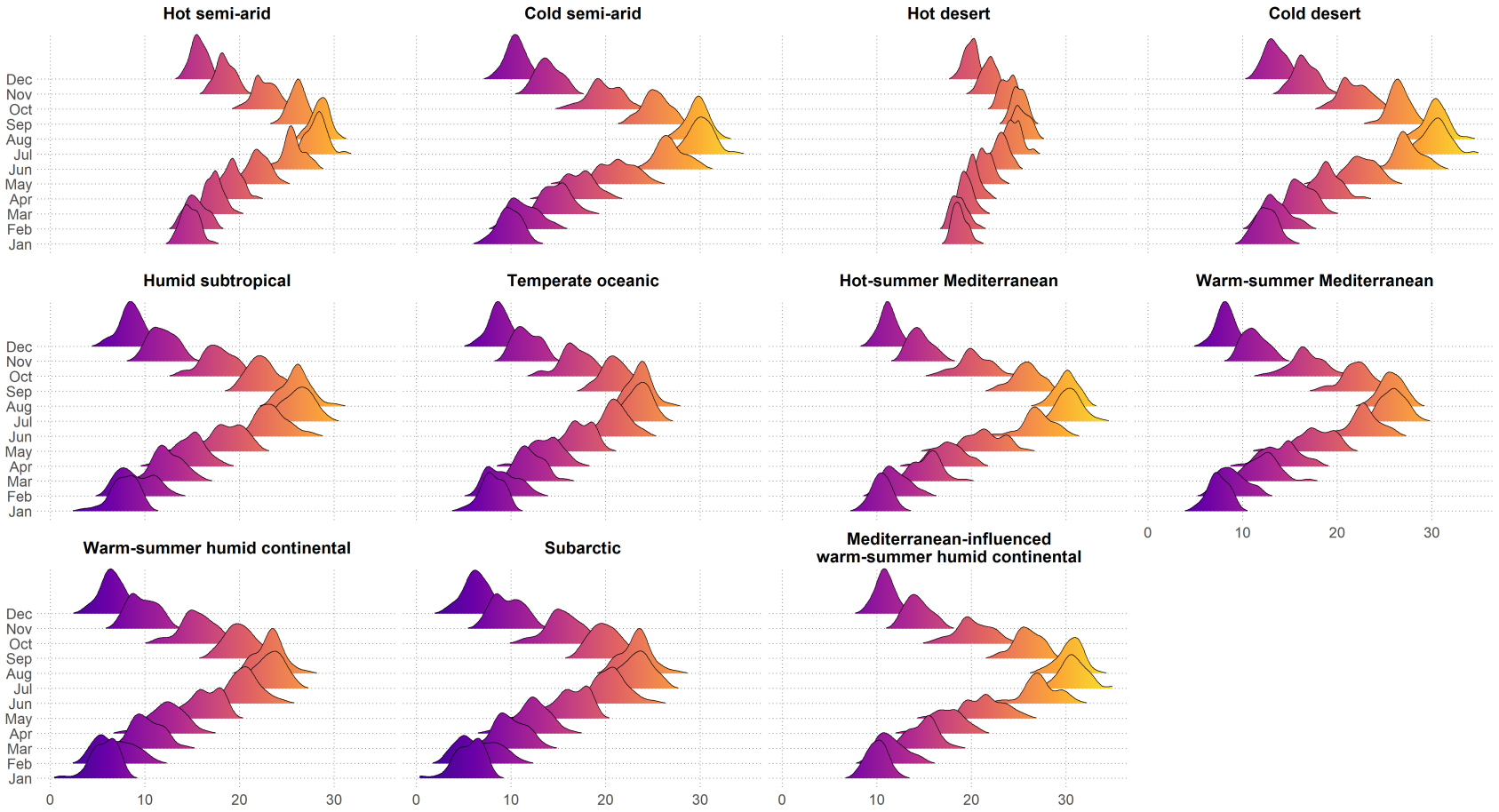


Figure 4.13: Monthly temperature variations by climatic types

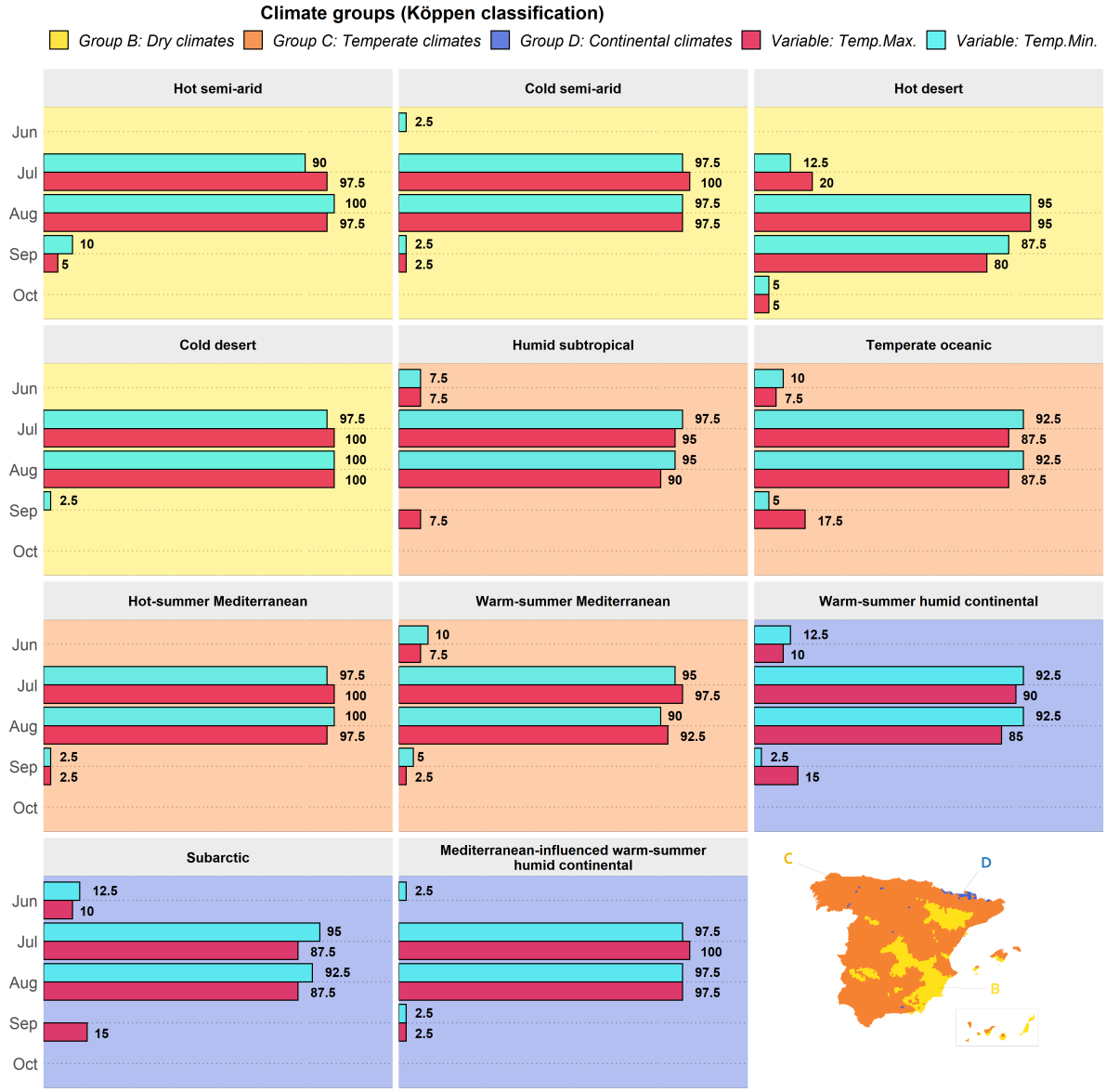


Figure 4.14: Frequency of maximum values of maximum and minimum temperatures in Spain by climatic zones in 1979-2018

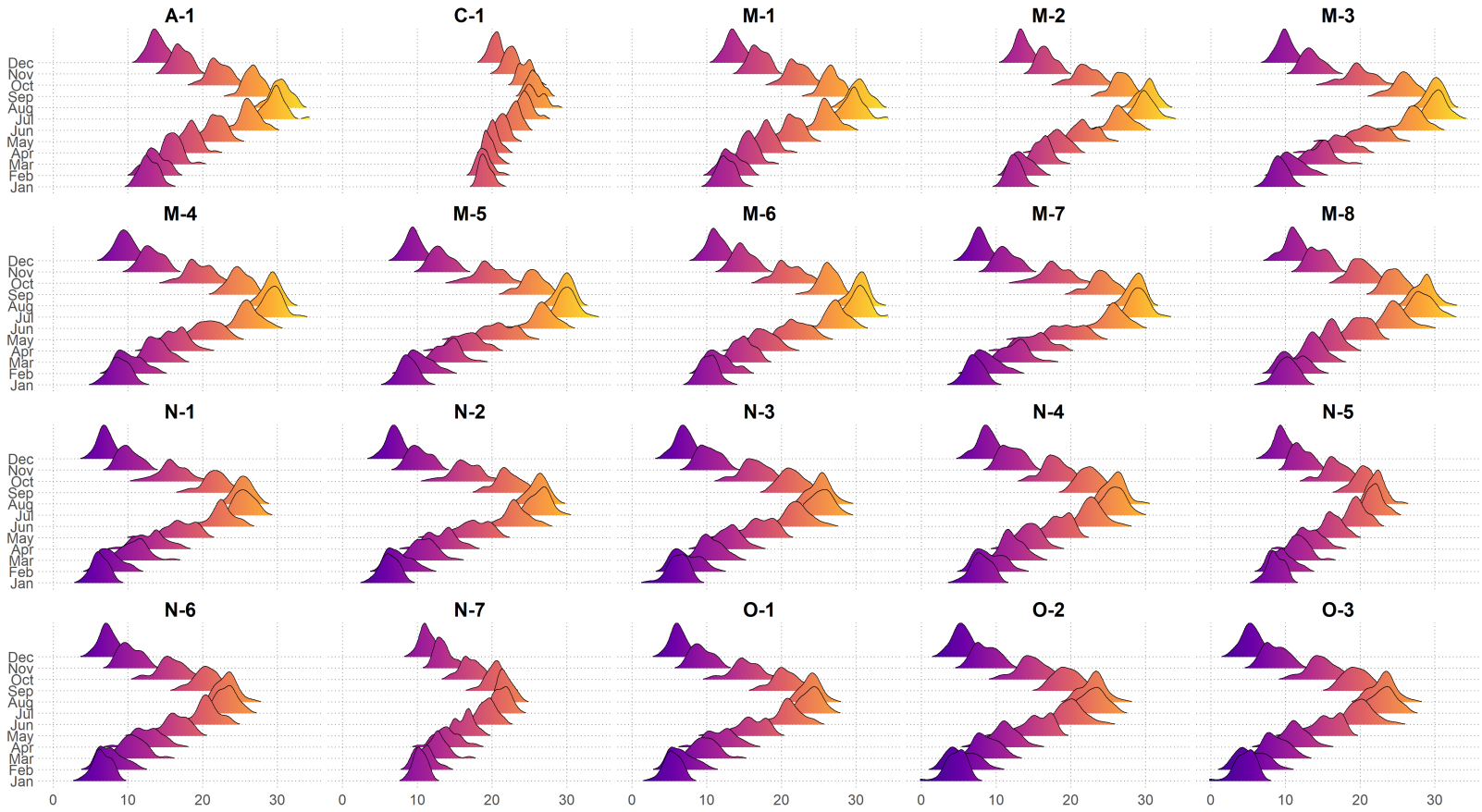


Figure 4.15: Monthly variations of heat index by phytoclimatic subtypes

Arid (III (IV) Saharian submediterranean A-1); **Nemoral** (VI (IV) 2 Nemoromediterranean genuine N-1, VI (IV) 1 Nemoromediterranean subnemoral N-2, VI (VII) Nemoral substeppe N-3, VI (IV) 4 Nemoromediterranean submediterranean N-4; VI (V) Nemoral genuine N-5, VI Nemoral genuine N-6, VI (IV) 3 Nemoromediterranean genuine N-7); **Oroboreal** (VIII (VI) Oroborealoid nubnemoral O-1, X (VIII) Oroborealoid genuine O-2, X (IX) 1 Oroborealoid termoaxeric O-3,); **Mediterranean** (IV (III) Mediterranean subsaharian M-1, IV2 Mediterranean genuine M-2, IV4 Mediterranean genuine M-3, IV1 Mediterranean genuine M-4, IV3 Mediterranean genuine M-5, IV (VII) Mediterranean substeppe M-6, IV (VI) 1 Mediterranean subnemoral M-7, IV (VI) 2 Mediterranean subnemoral M-8); **CI** (C-1).

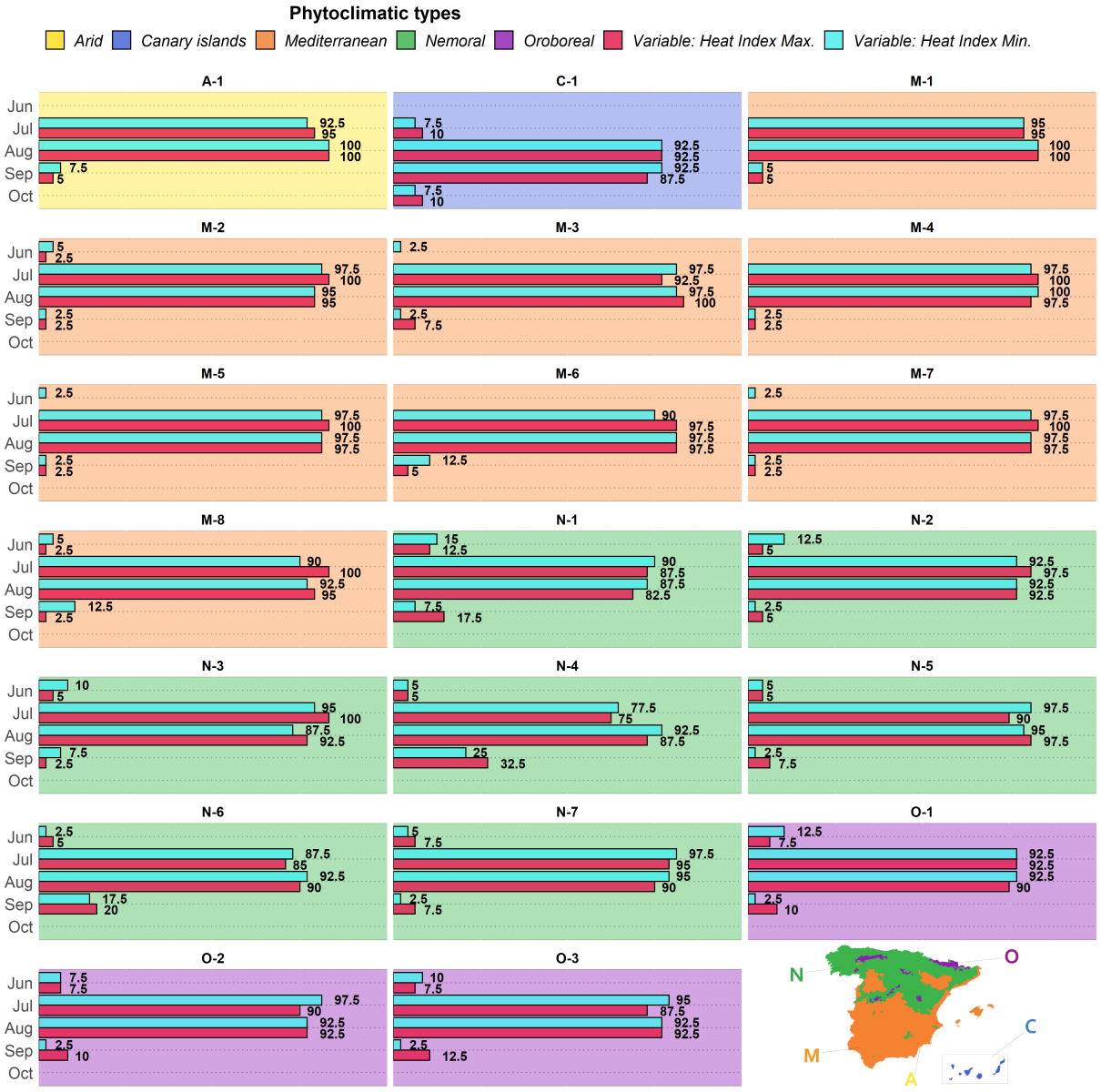
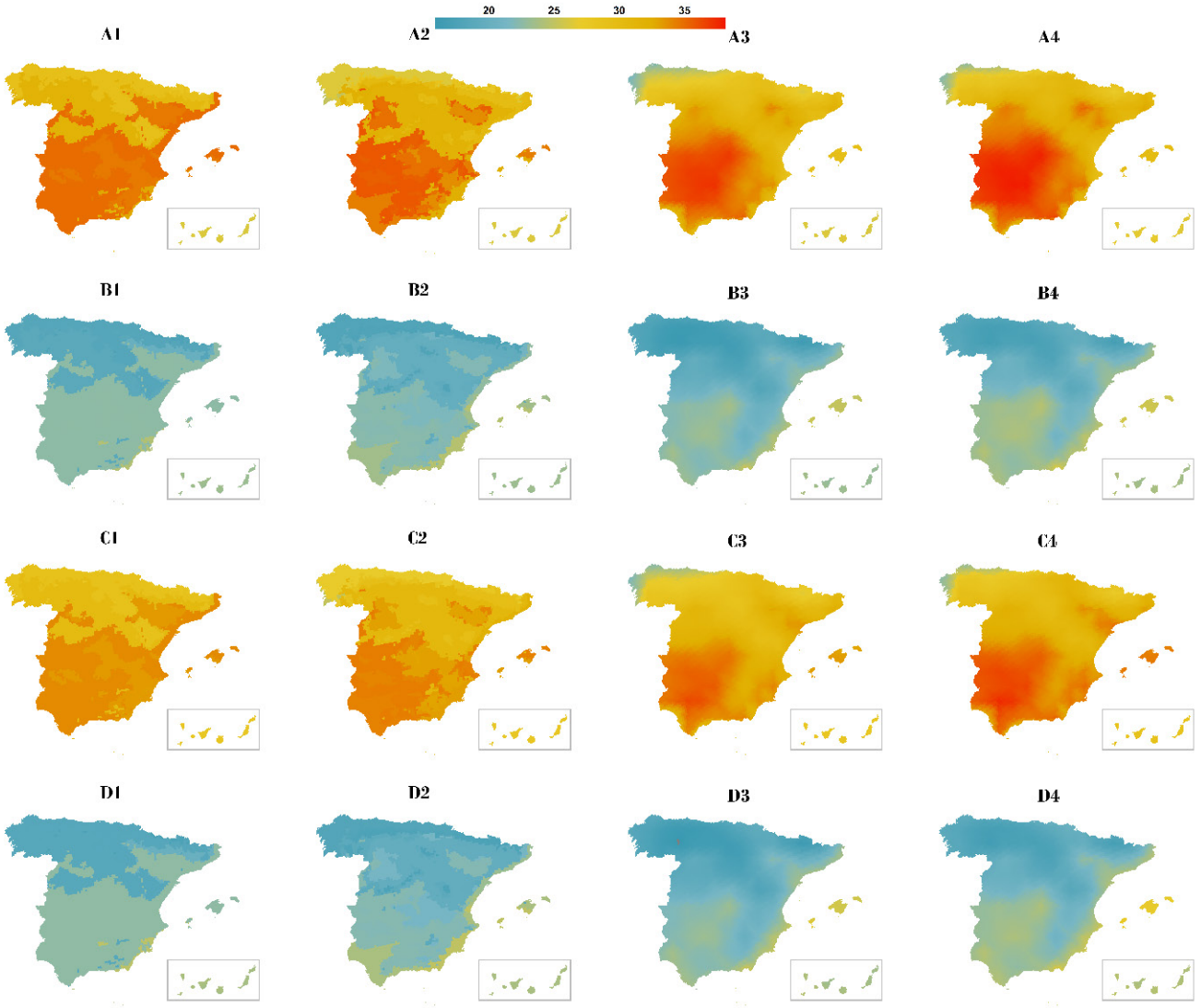


Figure 4.16: Frequency of maximum values of maximum and minimum Heat Index in Spain by pythoclimatic subtypes during 1979-2018

4.5.3 Threshold temperatures

Using selected months in local and zonal settings, we are now able to calculate the corresponding thresholds, which will be further used to detect heat wave episodes (Fig. 4.17). As previously mentioned, we estimate the 90th and 95th percentile of temperature series for individually selected months for all of the 5.5K cells (A3-4 for maximum and B3-4 for minimum temperatures) and for heat index (C3-4 and and D3-4 for maximum and minimum values respectively). The latitudinal gradient is observed as expected with threshold temperatures over 35 degrees Celsius located to the south of Central System and Ebro depression with a slight decrease in the coastal areas; whereas in the northern part of the country thresholds are lower than 30 degrees falling down to 20 degrees as approaching the Atlantic coast. In case of the heat index, threshold values exceed the 30 degrees limit more towards the south in comparison with the temperatures. Limiting values established for climatic zone (A1, B1, C1 and D1) and phytoclimatic subtypes (A2, B2, C2 and D2) are generally lower than those estimated at individual locations, which is explained by large spatial extent of the reference areas (and therefore the aggregation gives smoother values). The delimitation of the threshold zones is somewhat sharp which then find its reflection in the spatial patterns of the zonal heat anomalies.



A. Temperature, maximum. B. Temperature, minimum. C. Heat Index, maximum. D. Heat Index, minimum.
1 – 90th percentile for climatic zone, 2 – 90th percentile for phytoclimatic subtype, 3 – 90th percentile for a single cell, 4 – 95th percentile for a single cell.

Figure 4.17: Threshold values used for heat wave episode detection

4.5.4 Identification of the episodes

The estimation of 16 different threshold values for every cell (8 for minimum and maximum temperatures and 8 for minimum and maximum heat index) allows us to analyze the entire period of observation and detect the days where these threshold were exceeded. Note that in this study heat wave episodes are declared only if minimum and maximum values of temperature or heat index are **simultaneously** above their corresponding limits. Temperature and heat index are analyzed independently. The subsequent section describes the process of defining heat wave episodes using examples of 2 different cells intentionally located across the study area so they represent entirely different geographic settings under the same climatic regime. Randomly selected local heat wave episode for a site in Andalusia is illustrated in Figure 4.18, and for Balearic islands - on Figure B.1, presented in the Appendix. The top part of each graph contains area locator, monthly temperature and heat index variation diagrams and 4 density estimates where 90th and 95th percentiles are displayed for better understanding. At the bottom of the graph a randomly selected heat wave episode is visualized and each phase of the episode is explained (comments are color-coded with respect to the graph).

Figure 4.19 illustrates zonal (based on phytoclimatic subtypes) heat wave episode in Andalusia on the same dates as shown on Figure 4.18. In general terms, the idea to use zonal thresholds in addition to the local ones is based on the need to compare cells located in very similar geographic context between each other. Thus, the cell located in Jaen province of Andalusia (Figure 4.19) is characterized by resembling biomes and overall conditions as the north-east areas of Guadalquivir depression, large portion of Extremadura and the southern shore of Valencian gulf coast, and therefore we assume that in order to compare cells within this phytoclimatic subtype the same threshold should be used. Moreover, using zonally detected heat anomalies might help to better explain the differences in ecological pressure between the sites as these events occur in the same natural conditions. The Appendix B contains additional illustrations for zonal heat wave episodes in Balearic islands (Figure B.2).

Now that 8 types of episodes are identified, in the following sections we embark upon the quantitative description of these events. Starting with the general descriptive statistics of the incidence and duration, we then move to the analysis of the absolute and relative magnitudes of the episodes, curve types and last, but not least, to the analysis of the spatial patterns of heat anomalies in Spain.

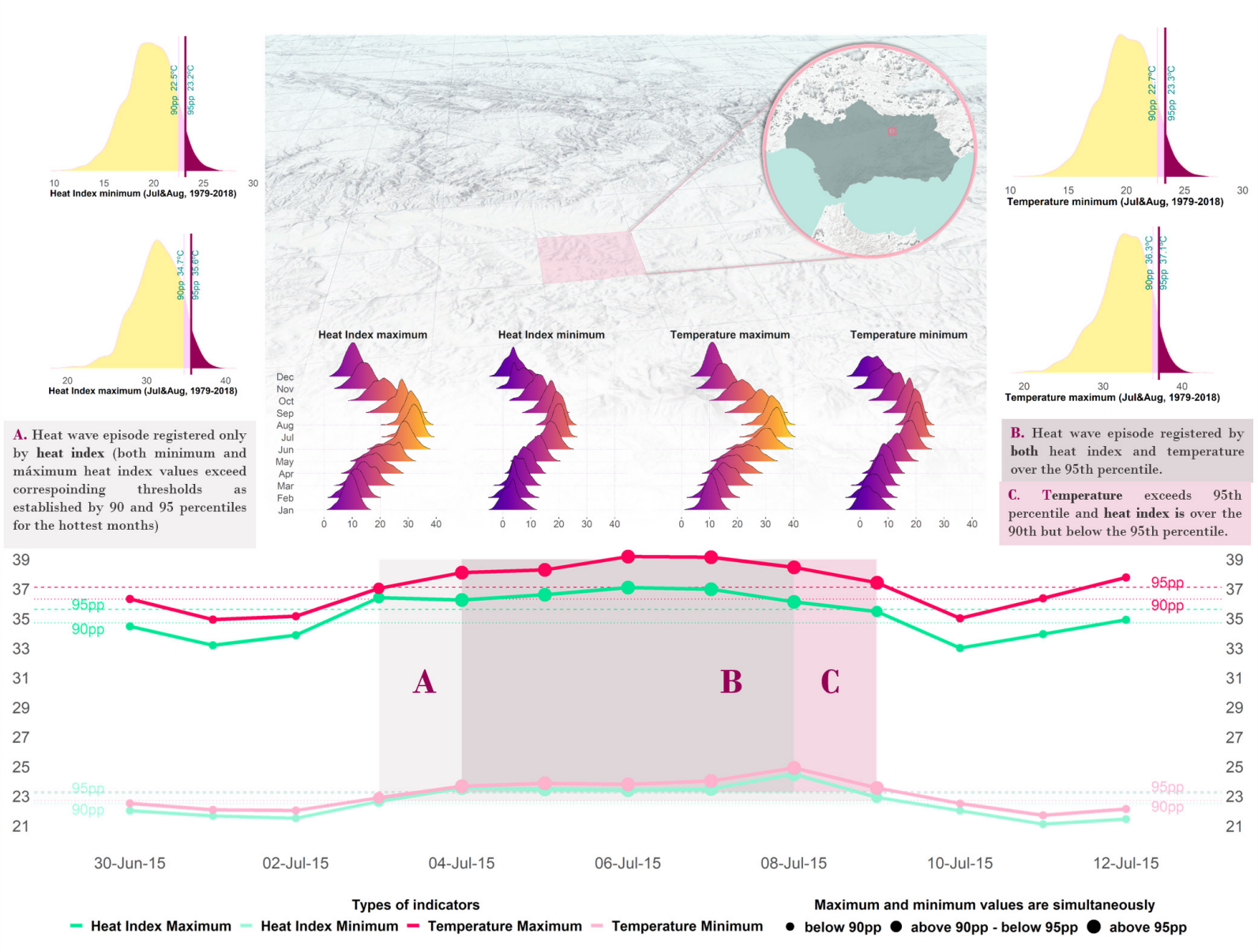
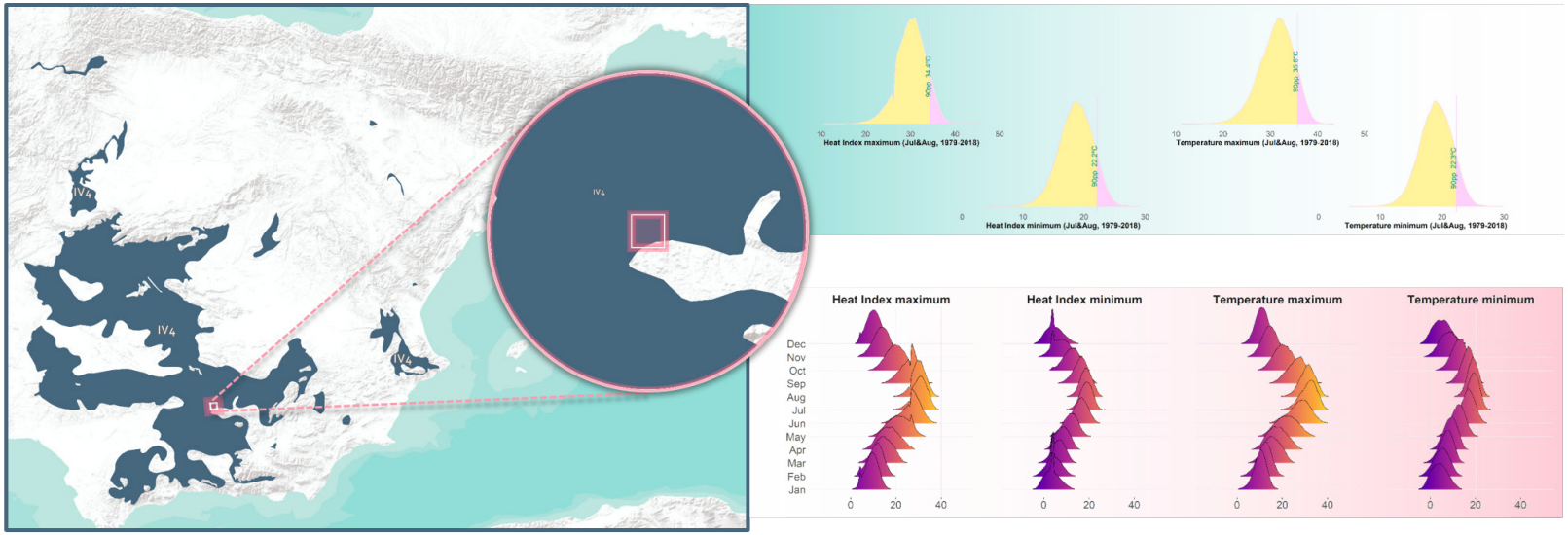


Figure 4.18: Local heat wave episode in Andalusia: methodological illustration



Type: Mediterranean
Subtype: *Mediterranean genuine (IV_4)*

A. Heat wave episode registered by both **heat index** and **temperature:** both mínimum and máximum values go over the 90th percentile for the Mediterranean genuine phytoclimatic type (IV_4).

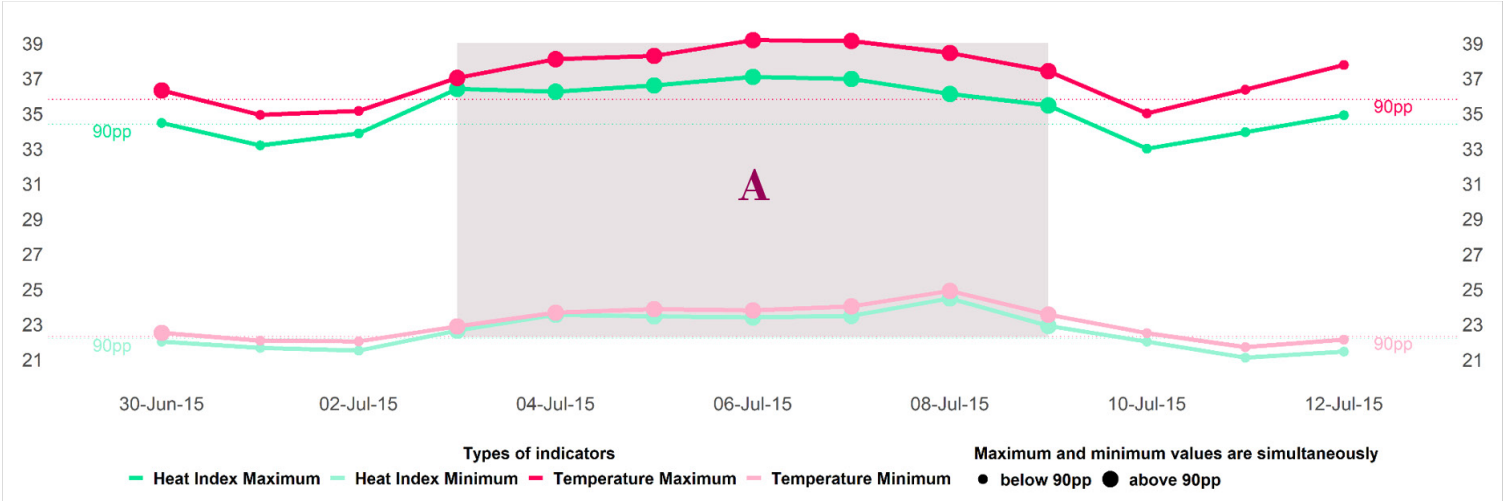


Figure 4.19: Zonal (phytoclimatic subtype) heat wave episode in Andalusia: methodological illustration

4.6 Frequency and intensity of detected episodes

Heat wave incidence. Out of all episodes captured by different methods (thresholds) approximately 19% and 8% correspond to the 90th and 95th percentiles established at individual location, and 11% and 12% to the 90th percentile of the series within the climatic types and phytoclimatic subtypes, respectively (equally for temperatures and heat index).

Heat wave episode incidence varies significantly depending on the threshold used to detect the episode. On average, cells recorded 30 incidences during 40 years of observation (detected with 95th percentile) whereas 90th percentile for temperature and heat index series gives almost a doubled result of 70 episodes per cell. Average incidence in case of zonal episodes is slightly lower, around 60 episodes per cell, but there is a significant number of outliers accounting for over 300 episodes per cell (fig. 4.20).

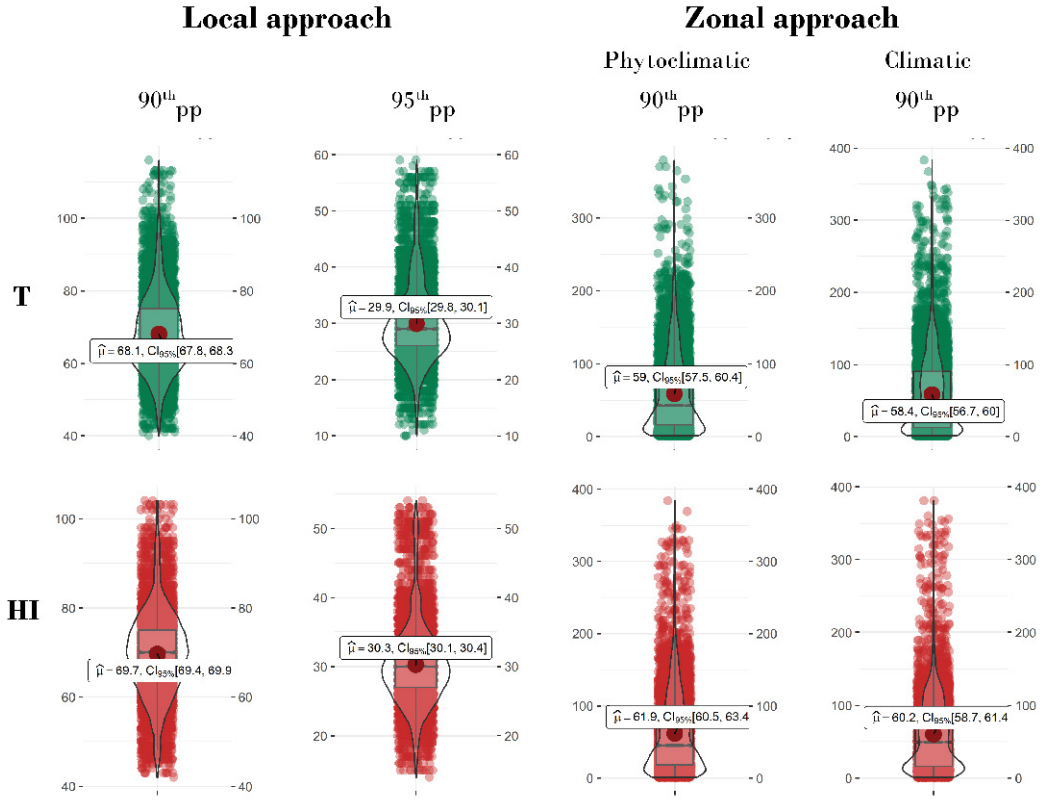


Figure 4.20: Incidence of heat wave episodes in Spain: descriptive statistics

Such a high value usually corresponds to the cells located in spatially extensive zone (climatic or phytoclimatic) in a specific area where geographic settings differ from the background (relieve, closeness to the water bodies, urban surfaces etc). The duration of the episodes also varies depending on the detection method (Table 4.1). On average, heat

wave episodes lasted for 1.5 days when using 95th percentile threshold for individual cell, 1.7 days when using the 90th percentile for the local area and 1.9 days when using 90th percentile either for phytoclimatic subtype or climatic type. The maximum duration was reached by heat wave episodes detected using the 90th percentile for the climatic type (up to 49 days, for both heat index and temperature), followed by the episodes registered using the 90th percentile for the corresponding phytoclimatic subtype (42 days). Local heat anomalies reached 28 (29) and 11 (12) days when using 90th and 95th percentiles for the series of temperatures (heat index), respectively.

Table 4.1: Number of days reached by episodes of different type

	Heat Index		Temperature	
	Mean	Maximum	Mean	Maximum
90pp for climatic type	1.93	1.94	49	49
90pp for individual cell	1.75	1.73	29	28
90pp for phytoclimatic subtype	1.98	1.93	42	42
95pp for individual cell	1.59	1.56	12	11

When it comes to the regional differences within climatic types (Table 4.2), we note a large gap in extreme values whereas average duration of the episodes stays within the 1.6-2.1 days range. Maximum duration of 49 day is reached by the temperature- and heat index derived episodes in the Warm-summer Mediterranean climate (large areas in Castilla-La Mancha, Castilla y Leon, Galicia, eastern Andalusia and south-western Murcia), followed by 32 (28) days of temperature (heat index) derived episodes in hot deserts (primarily CI) and 32 (30) days of heat anomalies in Temperate oceanic climate (northern coast of Spain, Aragón, Rioja and large part of Pyrenees).

The statistics for duration of heat episodes detected by temperature and heat index using the 90th percentile for phytoclimatic subtypes also reveal significant differences (Table 4.3). The maximum duration of the episode detected by temperature within the Arid type (narrow area along the south-eastern coast of Spain) equals to 6 days only, whereas the maximum duration of the episode detected by the heat index within the same phytoclimatic type goes up to 25 days. The maximum time of duration, however, is similar for the episodes detected by both heat index and temperature, and is reaching 28 (32) and 42 (42) days in CI and within the Nemoral phytoclimatic type (northern parts of Spain).

Evolution of the incidence over time. An important observation made from the Fig. 4.21 is the clear positive growth of the incidence rate (number of heat wave episodes registered in the same cell) over time. This finding is consistent with the results

Table 4.2: Heat wave episode duration by climatic types, in days

	Heat Index		Temperature	
	Mean	Maximum	Mean	Maximum
Cold desert	1.84	1.62	6	5
Cold semi-arid	1.82	1.86	26	21
Hot desert	2.05	1.95	28	32
Hot semi-arid	2.04	1.74	26	26
Hot-summer Mediterranean	1.87	1.96	26	16
Humid subtropical	1.89	1.85	24	17
Mediterranean-influenced warm-summer humid continental	1.80	1.83	6	6
Subarctic	1.70	1.68	12	12
Temperate oceanic	1.85	1.83	30	30
Warm-summer Mediterranean	2.16	2.08	49	49
Warm-summer humid continental	1.73	1.68	18	15

Table 4.3: Heat wave episode duration: between-groups statistics by phytoclimatic types, in days

	Heat Index		Temperature	
	Mean	Maximum	Mean	Maximum
Arid	2.13	1.51	25	6
Canary islands	2.02	1.97	28	32
Mediterranean	1.98	1.98	27	22
Nemoral		1.87	42	42
Oroboreal		2.06	23	27

of fundamental studies on heat wave trends, e.g. Della-Marta et al. (2007) claims the long-term linear trend in IP to be the largest in Europe. However, some studies show that projected (A2-SRES emission scenario, PROMES-RCM) changes in the frequency of heat wave events in the interior parts of IP is negative and does not correlate with the overall increase in the "hottest" temperatures (Sánchez et al. 2004).

Thick pink line on the graph below represents a local polynomial regression model fitted to the series of estimated yearly incidence of heat episodes per cell. The slope of the curve differs from type to type, flattening in the beginning of the XXI century and sharply spiking in the end of the observation window.

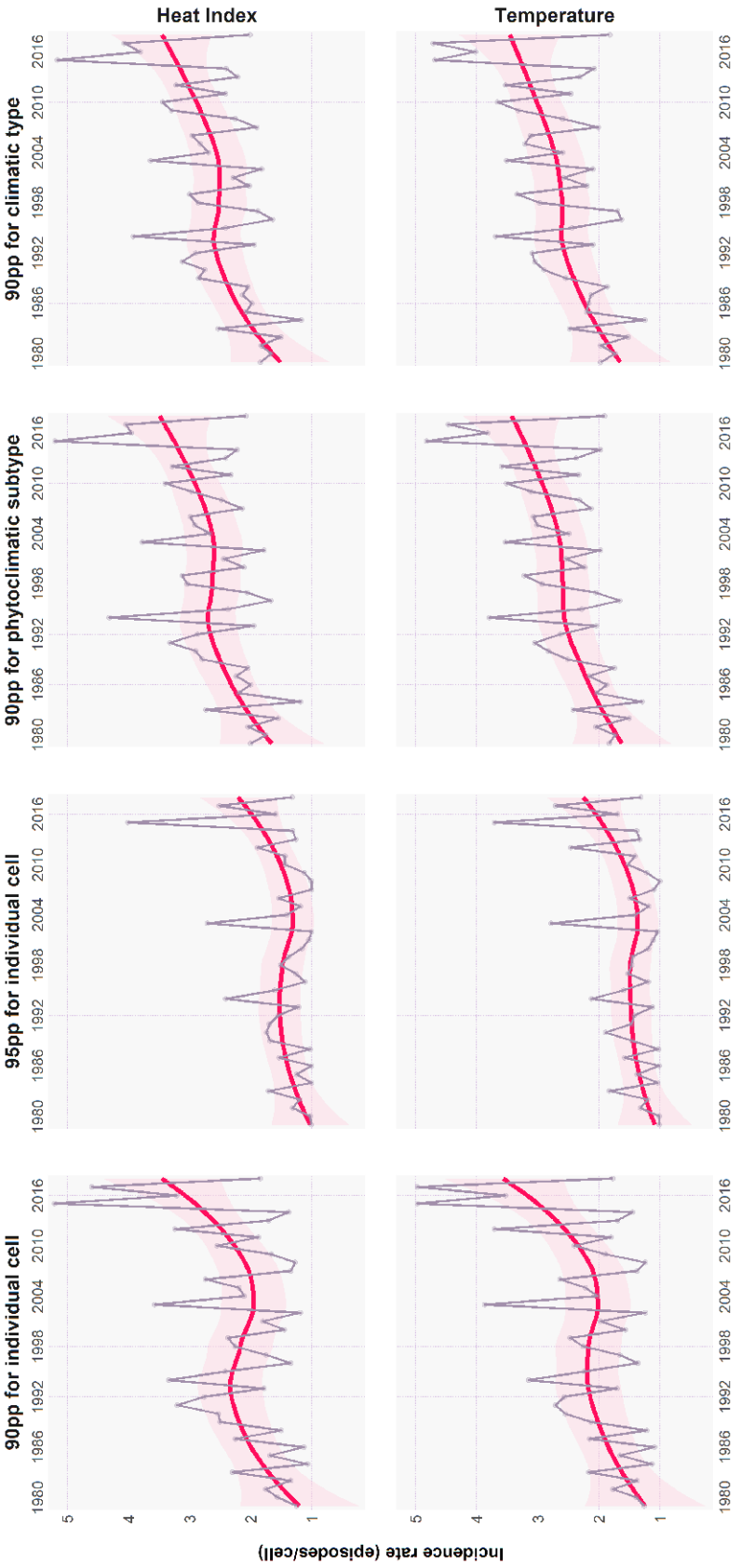


Figure 4.21: Evolution of heat wave episode incidence rate in Spain over time

Further, we decompose the time series of the incidence using an additive model to analyze the trend component. Here, instead of yearly aggregations, we use the time series of accumulated daily incidence of heat wave episode scaled by regional coverage (i.e. sum of all cells with an episode registered on a single day divided by the total number of cells in IP and CI, respectively), which allows us to make inter-zonal comparisons. We then proceed to the estimation of the spectral density of these time series.

Figure 4.22 shows changes in episode incidence rates over time by month. While color intensity increase in time stresses the same behavior shown on fig. 4.21, we note that heat anomalies tend to happen in a wider season in the end of the observation period compared to the starting point. In other words, it is more likely for a heat wave episode to happen at any point between March and November in 2018, while before 1990 it was more probable for the heat anomaly to occur only from June to September.

Figure 4.22: Change in heat wave episode incidence rate by month and year

Figure 4.24 displays the evolution of the trend estimated for the incidence of the temperature-derived heat waves while Figure 4.25 corresponds to the heat-wave derived episodes. Bold green and dotted black lines on the graphs show, respectively, the primary and secondary periods, estimated for the trends. Blue spiky line is the trend itself and the smoothed curves show the gamma (orange), loess (red) and generalized linear (neon

green) models fitted to the data. For both locally- and zonally-defined temperature-based episodes the primary period is 2.8 years for CI and slightly bigger for IP where it reaches 3-4.4 years. The secondary period is predominantly 13.2 years. These estimates are practically identical for the episodes detected using heat index. The trend of the incidence of heat waves is positive across-the-board.

Another non-spatial representation of monthly and yearly incidence of heat wave episodes is presented on Fig. 4.26. Here, pink bars represent the average proportion of territory covered by cells with heat wave episodes detected by any of the 8 existing methods (100% would mean that all of the cells in the country had a heat anomaly). Beige bars, in turn, reflect the proportion of methods that captured the episodes (0% means that none of the methods captured an episode and 100% mean an episode was captured by all 8 methods). Most commonly, heat wave episodes are produced during the summer months and these events have extensive spatial coverage (on average half of the country is registering at least 1 heat wave episode detected by any method in July and August). The fact that outside of the summer period beige bars are approaching 100% while the pink bars are almost at the zero level illustrates the local character of these episodes. In other words, all of the methods might register a heat anomaly simultaneously but these events tend to be restrained in space (i.e. detected by only a few cells).

One of the most important characteristics of heat wave episodes appears to be its intensity, or magnitude, as we refer to it further in the text. Here we define the magnitude as a quantitative measure of excess of either temperature or heat index above the established thresholds or a certain value which reflects a long-term baseline.

Absolute magnitude. The term "absolute" placed next to the magnitude refers to the absolute number of degree Celsius that a cell may register above one of its 4 threshold values for each indicator. For example, if maximum daily temperature in one particular cell reaches 35 degrees on a given day, and the 90th and 95th percentiles of the 40 year-long series of the maximum temperatures for the two hottest months at this location are 30 and 32 degrees respectively, absolute magnitude of the episode detected by the 90th percentile will be 5 degrees and absolute magnitude of the episode detected by the 95th percentile will be 3 degrees Celsius. The first row on the graph 4.27 portrays change in the average absolute magnitude of temperature-derived episodes over time whereas the second row on the same figure shows the evolution of this parameter for the heat index-derived episodes.

Mean absolute magnitude is slightly lower for local heat anomalies (up to 1 degree on average) whereas zonal heat wave episode exceed the corresponding threshold in 1 degree or more (applies to both temperature- and heat index-derived episodes). The growth

of the absolute magnitudes over time is rather weak in case of the temperature-derived anomalies and stronger for heat index-based episodes. Monthly change in the absolute magnitudes for minimum and maximum temperature of heat waves over the period of study is displayed on Figure 4.28. Magnitudes tend to be generally higher for maximum values and the gradient towards higher values increase over time.

Diurnal Temperature Range. Diurnal temperature range (DTR) or temperature amplitude is a common metric of the temperature variability during the day. Its reduction is also frequently associated with an increased heat stress on humans as the night-time (minimum daily) temperatures are coming closer to the maximum day-time temperatures, therefore making it less comfortable for a human body to cool down and rest during the night.

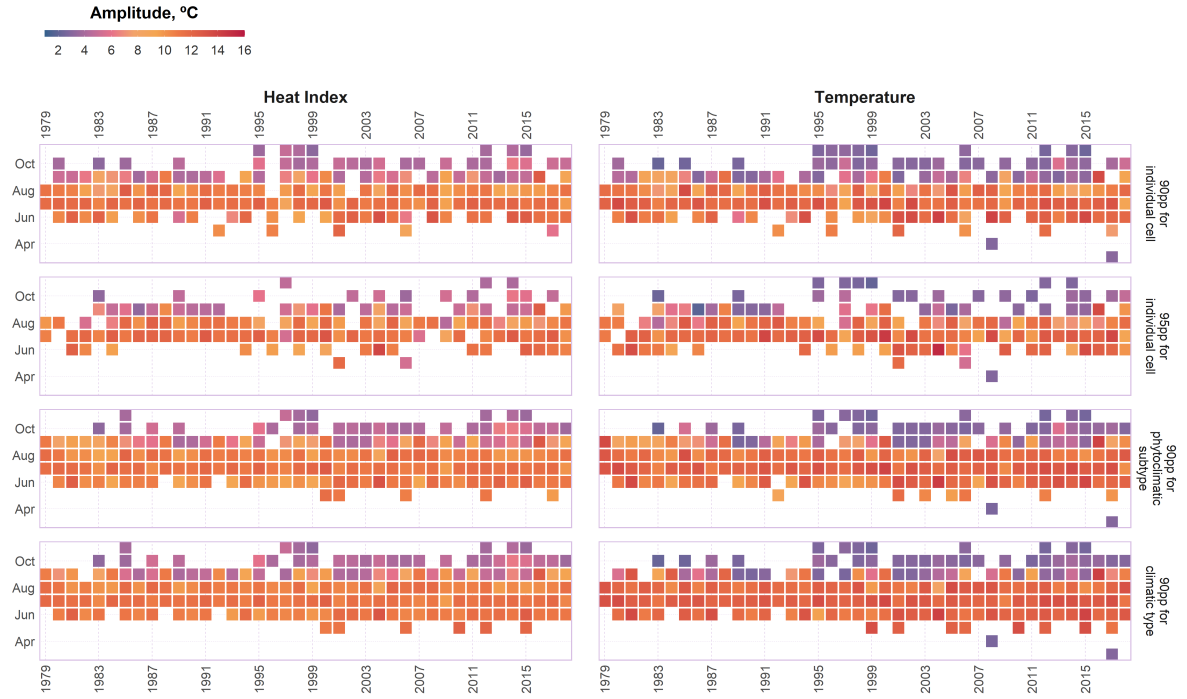


Figure 4.23: Change in the diurnal temperature range of the heat episodes by month and year

On average, the DTR during hot spells in Spain stays at the level of 10 degrees Celsius (both for heat index- and temperature-derived episodes) as shown in Figure 4.29. Over time we note a certain constriction in the amplitudes for all the types of heat anomalies: both local and zonal events decrease their daily variation in almost 1 degree Celsius (last decade of the observation period compared to the first one). Monthly

DTR variation evolves over time as well: the amplitude tends to be narrower outside of the summer period, which has to do with the overall decrease in solar heating, however, a reduction tendency becomes more pronounced in the last years of observation in the summer months as well (Fig.4.23).

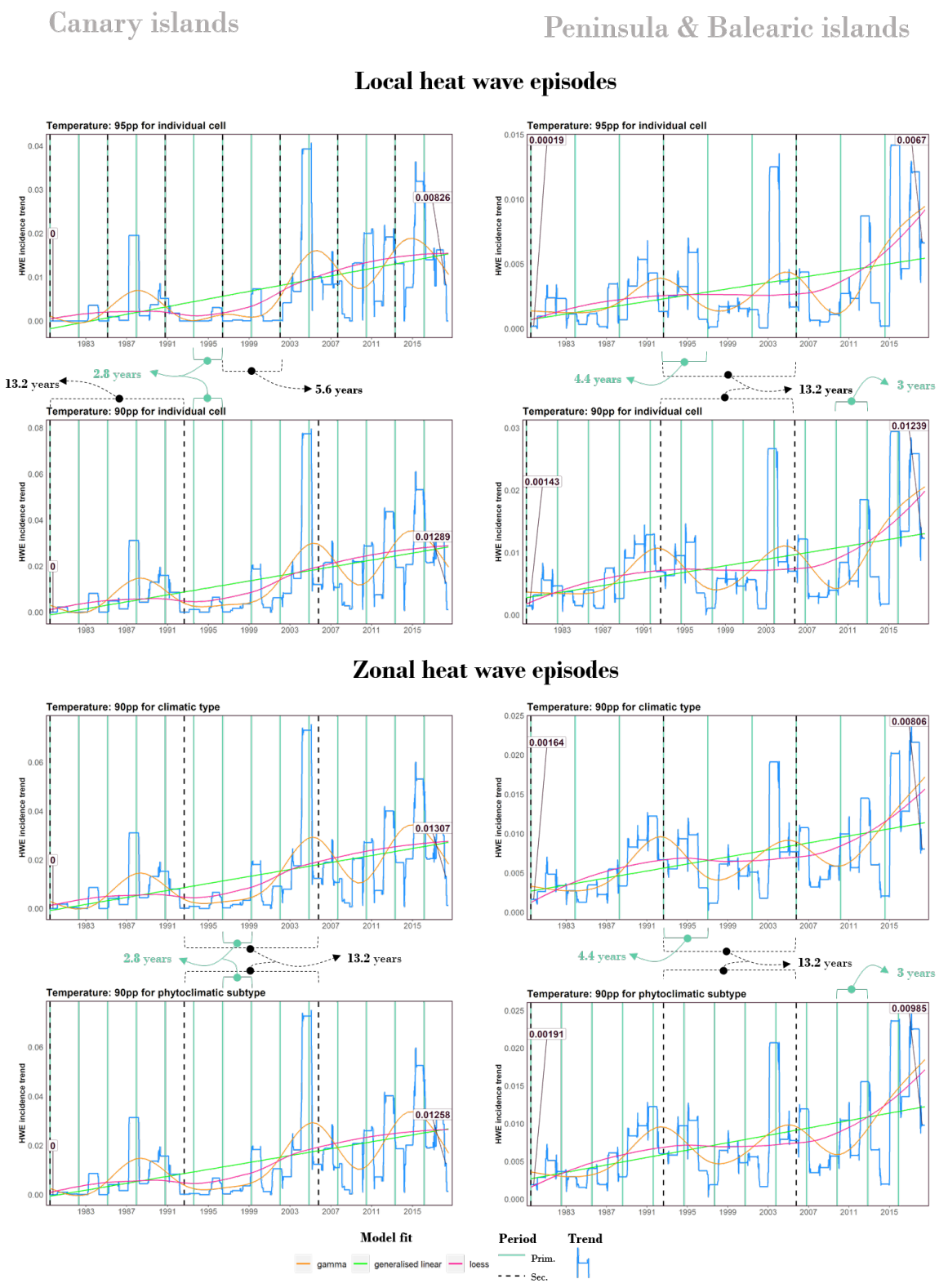


Figure 4.24: Evolution of the trend estimated for the incidence of the temperature-derived heat wave episodes

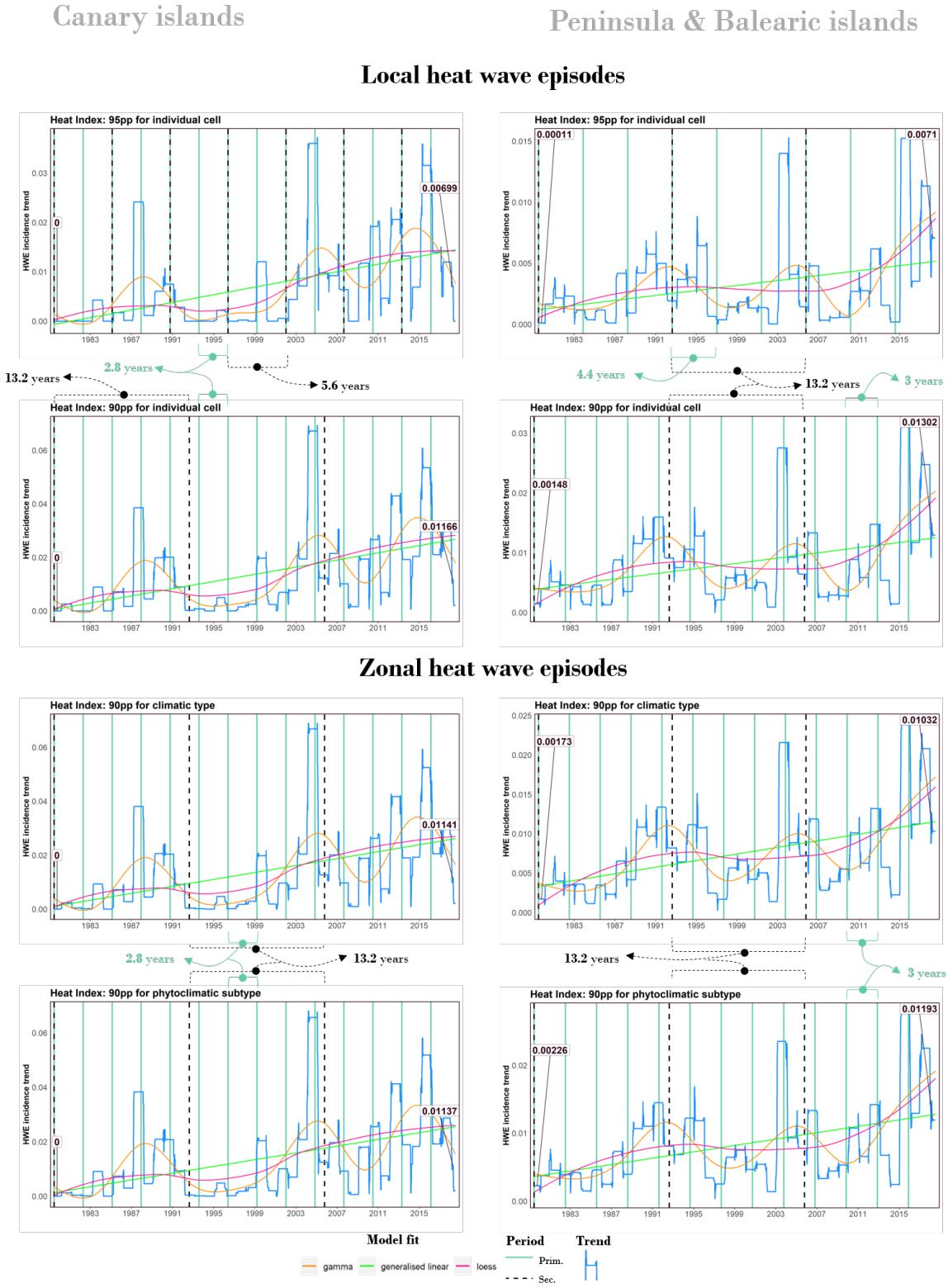


Figure 4.25: Evolution of the trend estimated for the incidence of the heat index-derived heat wave episodes

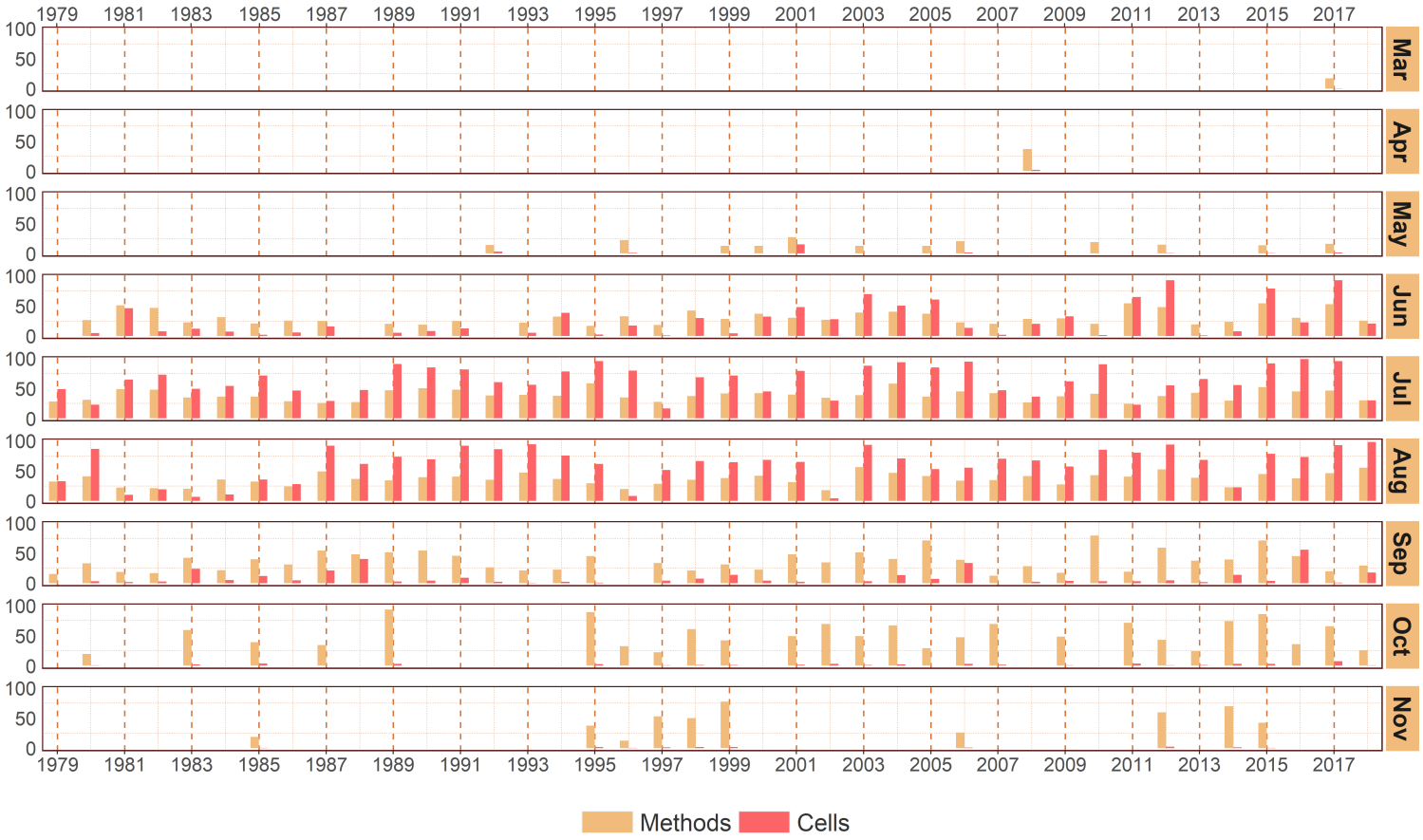


Figure 4.26: Monthly variations in HWE definition sensitivity

Methods responsible for capturing episode, mean proportion of all available methods; **Cells** which registered episode by at least one method, proportion from total coverage.

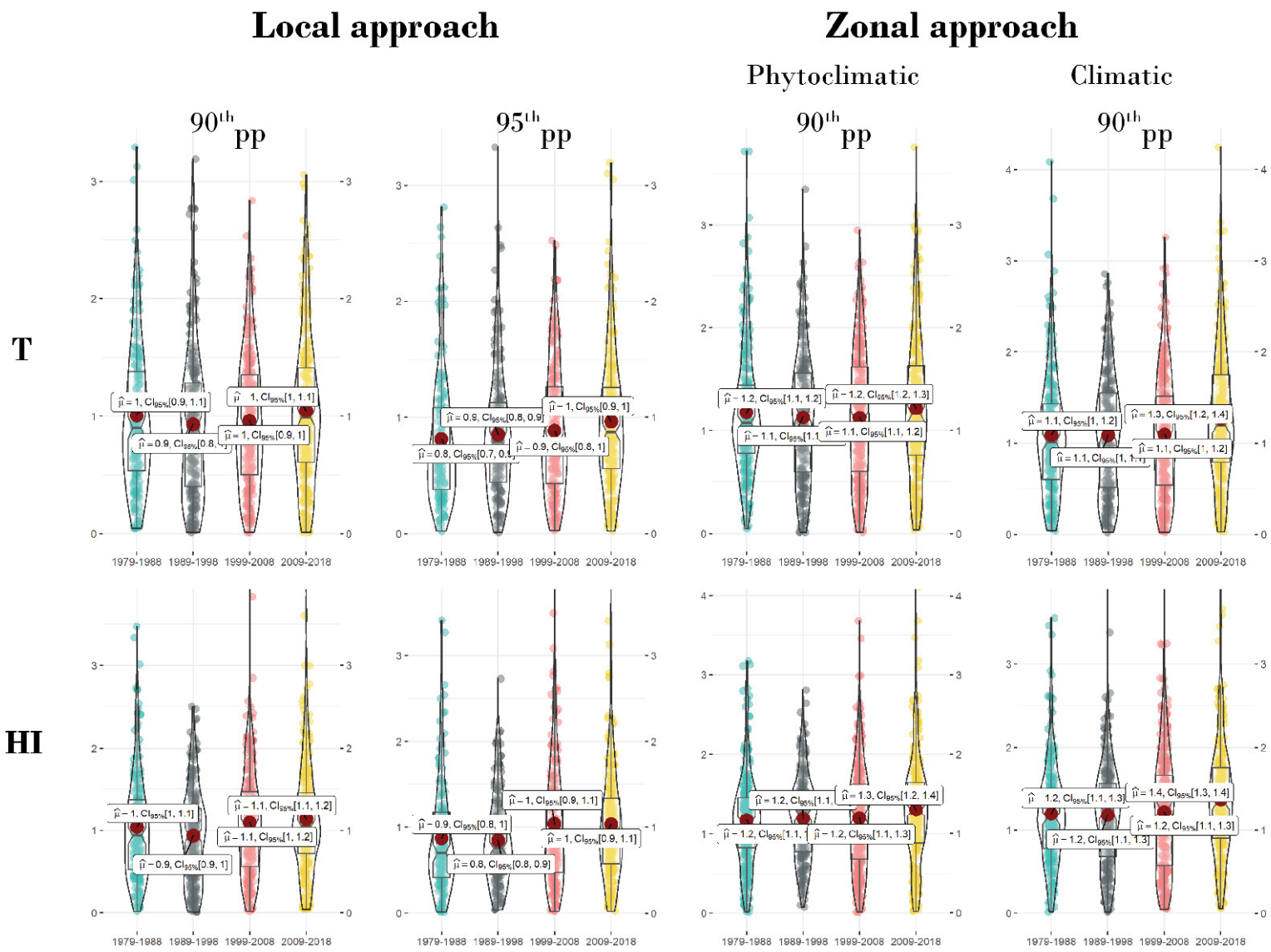


Figure 4.27: Change of the mean absolute magnitude of heat episodes over time

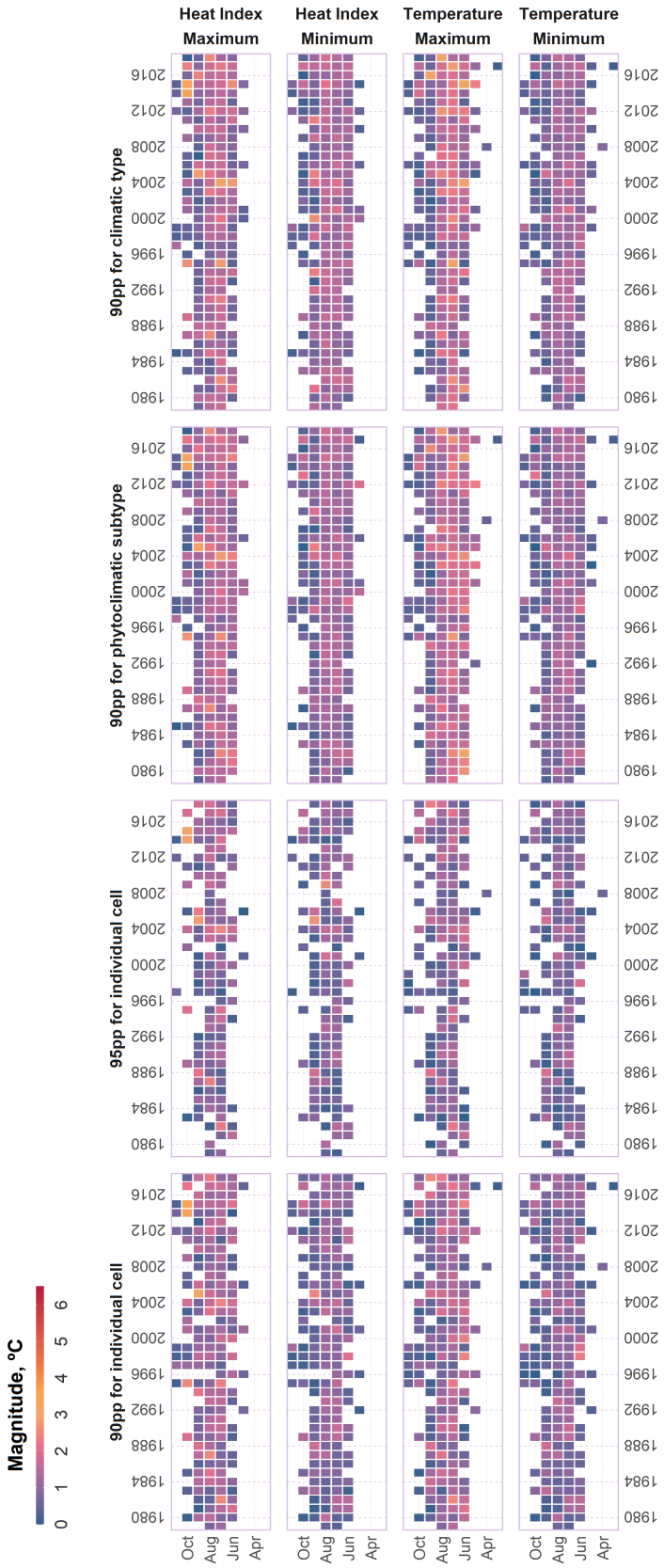


Figure 4.28: Change in the mean absolute magnitude of the heat episodes by month and year

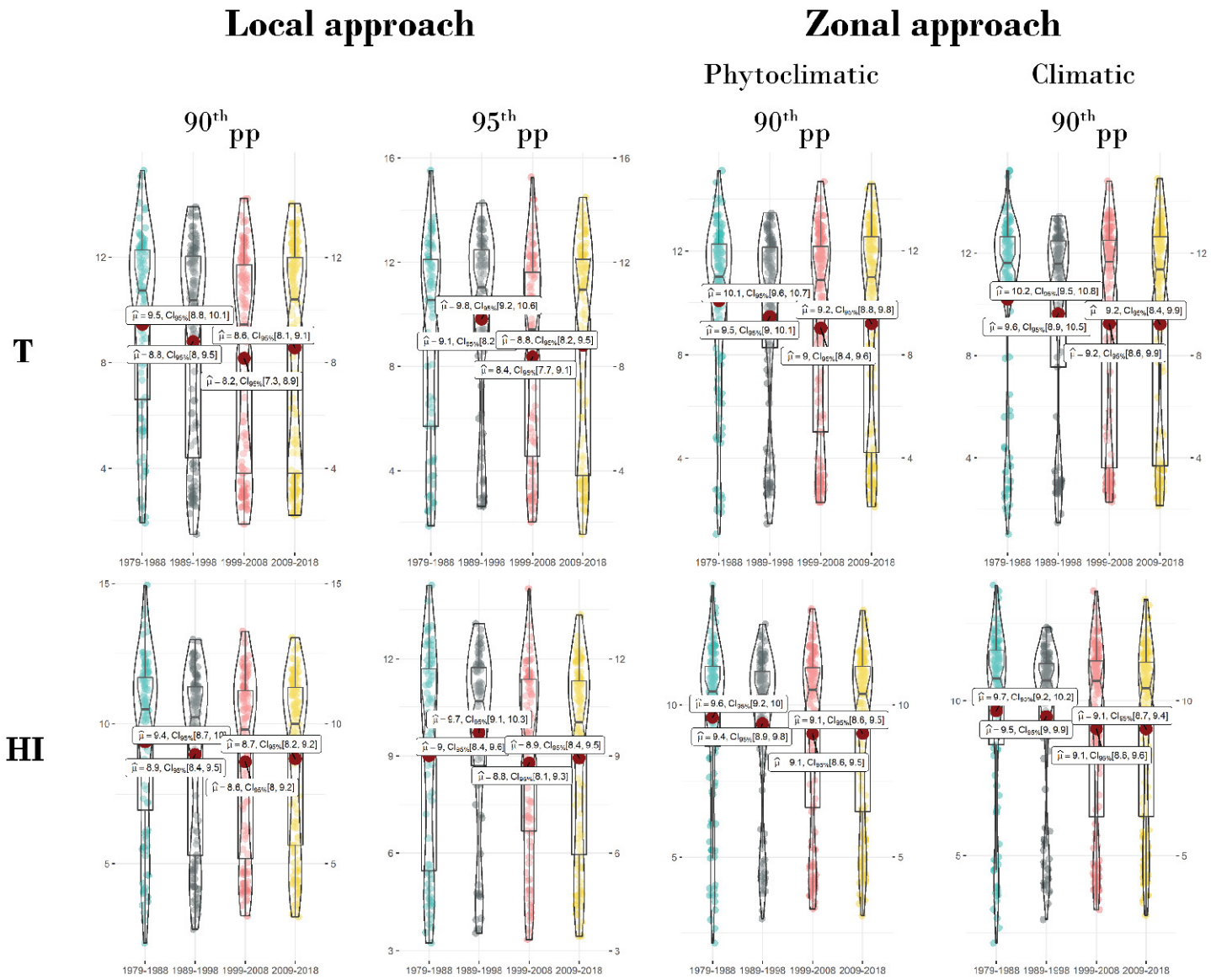


Figure 4.29: Change in the diurnal range of heat episodes over time

Relative intensity. Following the approach suggested by Russo et al. (2015) we quantify the hot spells with the so-called magnitude index based on the inter quartile range (IQR) of the temperatures within the reference period 1979-2018 as shown in the equation (4.4).

$$MI_d(T_d) = \begin{cases} 0, & \text{if } T_d \leq T_{40y25p} \\ \frac{T_d - T_{40y25p}}{T_{40y75p} - T_{40y25p}}, & \text{if } T_d > T_{40y25p} \end{cases} \tag{4.4}$$

with T_d being the maximum daily temperature on day d of the heatwave, T_{40y25p} and T_{40y75p} are, the 25th and 75th percentile values, respectively, of the time series composed of 40 year annual temperatures and heat index values within the reference period 1979–2018.

In contrast with the absolute magnitude which shows a stark excess with respect to a "maximum" threshold (either 90th or 95th percentile, established locally or zonally), the use of the IQR allows us to compare the extremes with the "middle fifty" (in other words, where the bulk of the measurements area) of the temperatures (heat index values) over a large period of time. As can be inferred from the formula, a magnitude index with value over 1 indicates that temperature anomaly on a given day is over the IQR of the 40 year long period. The variation in the magnitude index for both temperature and heat index derived indicators increases with time, as clearly display Figure 4.30. The average values of the magnitude index augment in 0.1-0.2 units whereas the maximum outlier spikes in almost 1 unit for the last decade of the study period in comparison with the start of the observation.

Change of the magnitude index by phase of the episode. An important characteristic of a heat wave episode is the change in its intensity according to the temporal phase. Schematically we can represent any hot spell of duration of 3 days or more as a three-phase event which should start with an opening phase (start of the hot spell), main phase with a mid point, and a closing phase (end of the episode). The figure 4.31 illustrates the change in the magnitude index of the maximum and minimum values of the temperature and heat index derived episodes according to the phase of the episode and its evolution through time during the 4 decades of the observations. Overall, the behavior of the maximum and minimum magnitude index curves reflects the general logic: an episode starts when both minimum and maximum values simultaneously exceed its local or zonal thresholds with the minimum (nighttime) values having lower magnitudes with respect to the maximum (day-time) magnitudes. As time passes by and daytime magnitude increases or remains unchanged in the mid-phase of the episode, the nighttime temperatures (heat index values) gradually increase with a certain inertial

time lag, reaching its peak in the closing phase of the episode, when the maximum magnitude most likely has already dropped down. The same behavior is seen in all the decades with an exception of the 1999-2008 (the period containing the most intense heat wave registered in 2003). Interestingly, this period is characterized by heat anomalies where minimum and maximum magnitudes follow the same behavior: a clear bell-shaped curve with a highest point in the mid-phase.

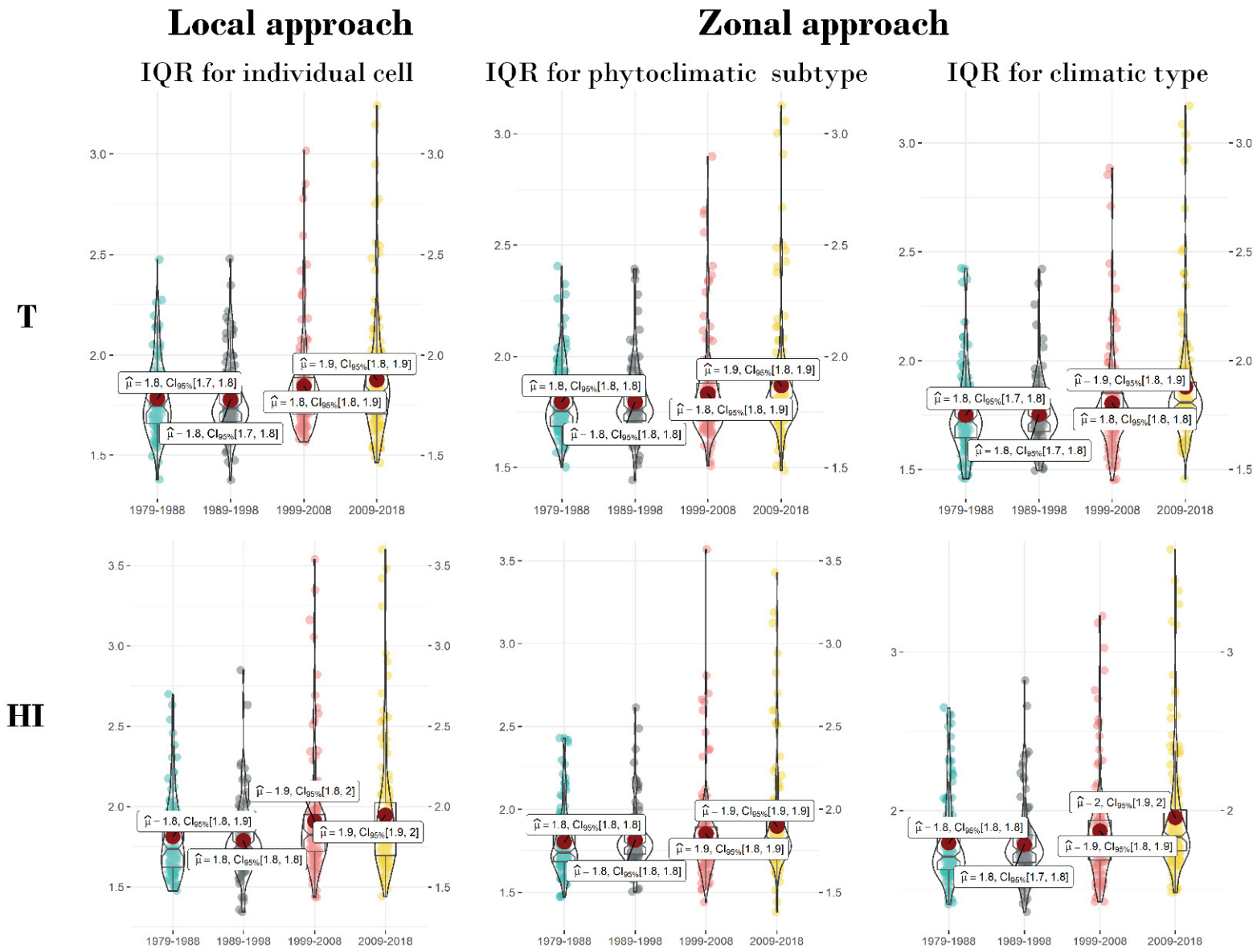


Figure 4.30: Change in magnitude indices with respect to the IQR for 1979-2018 over time

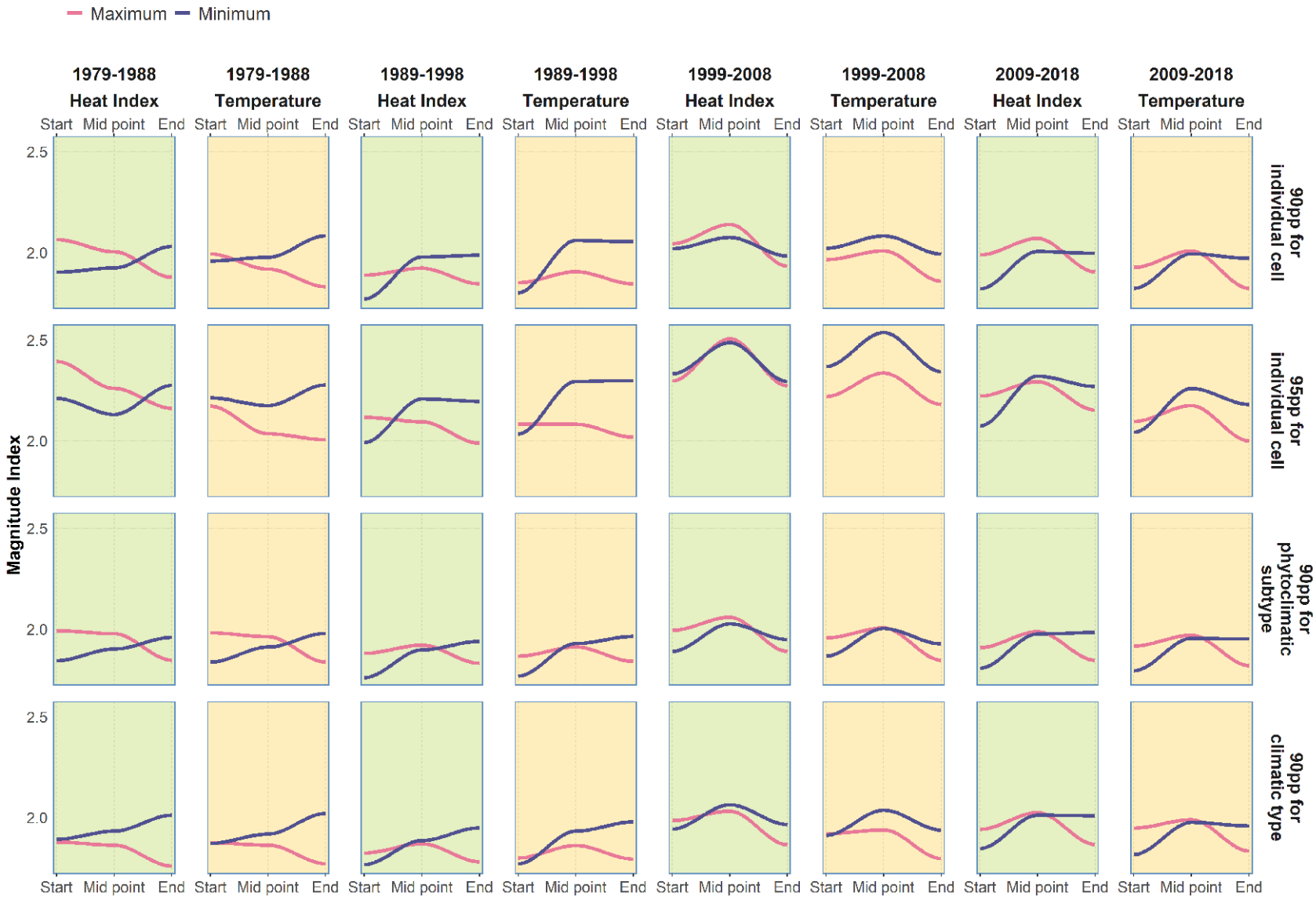


Figure 4.31: Change in the magnitude index by episode phase over time

Although the clearest and most general atmospheric heat wave situation with temperatures of over 40°C is due to advection of air from the Sahara in the lower layers of the troposphere, in some parts of Spain this threshold has been reached in other situations, e.g. föhn winds on the Valencian and Basque coasts. (...) In the results of projections of climate extremes at the end of this century for emission scenario SRES-A2 obtained by @sanchez_future_2004 an increase in the frequency of heat waves in spring and autumn can be appreciated, and this seems to be in consonance with what was previously established.

— *A Preliminary Assessment of the Impacts in Spain due to the Effects of Climate Change, ECCE project, 2005.*

5 Spatiotemporal dynamics of heat waves in Spain

Literature on the characteristics of spatial patterns and future trends of heat wave distribution and incidence in IP and CI is fairly scarce. There is a number of coarse-resolution fundamental studies revealing regional patterns (discussed in detail in the previous chapter), whereas fine-grained retrospective and prospective research on heat waves in Spain remains a singularity.

In this study, we refer to the official report by AEMET (2020) as the core retrospective analysis of the heat waves in Spain from a purely climatological point of view. Due to the differences in the methodological approaches we can not fully rely on the statistics provided in this report for comparative purposes. Tables B.1 - B.8 in the Appendix list heat wave episodes of 8 different types at the **national level** (for both IP and CI) for the entire period of observation. Here, we make an arbitrary decision to declare a heat anomaly in the entire country if the areal coverage[1] is above 0, meaning that there is at least one populated cell (0.01% of the total inhabited national territory) affected by a heat anomaly. The minimum duration of the episode in this case is limited to 3 consecutive days.

Anticipating the discussion of the peculiar properties of the human settlement in Spain, historical background and changes (depopulation of the rural areas) over the past decades, we illustrate general patterns of the population proliferation on Figure

[1]Proportion of the inhabited cells affected by an episode of a particular type from the total number of inhabited cells in the 10x10 km continuous grid used in this study

5.1[2], as we take it into consideration for estimations performed in this chapter. As the reader can observe on this map, spatial distribution of the population in Spain is very heterogeneous and is severely skewed towards provincial capitals with somewhat more equal spread along the Mediterranean and Atlantic coasts.

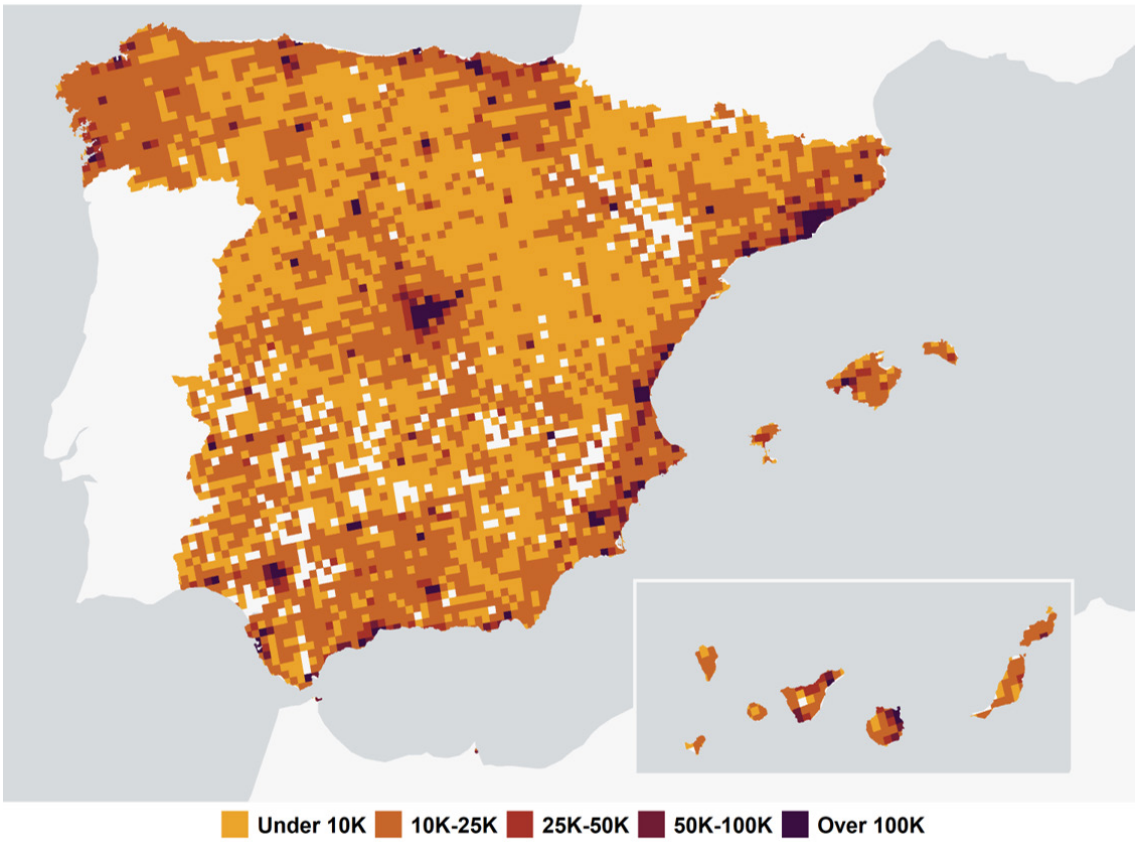


Figure 5.1: Distribution of the population in Spain in 2011

There are also cells (marked in white on the map) which did not have any registered population in 2011 (either areas of agricultural production, wetlands, natural reserves or unused land, altogether corresponding to 8.5% of the national coverage). These cells were excluded from the grid used to declare heat wave episodes at the national level. The Tables B.1 - B.8 in the Appendix provide the following information on the listed episodes:

- Date of the start and date of the end of the episode,

[2]Here we used the data from the Spanish Census 2011, provided by INE on a 1x1 km discontinuous grid with diverse estimations of the population, including the total count of inhabitants per cell, which we then aggregated to 10x10 km cells by summing the total population up and grouping the cells into 5 categories: **Under 10K**, which includes all the cells where total population is not exceeding 10 000 inhabitants including censored cells, **10K-25**, **25K-50K**, **50K-100K** and **Over 100K**.

- Duration in days,
- Proportion of affected spatial coverage (mean value with a standard deviation estimate; absolute maximum reached on any of the day of the episode),
- Absolute values of the indicator[3] during the day (mean value with a standard deviation estimate; absolute maximum reached on any of the day of the episode),
- Absolute values of the indicator during the night (mean value with a standard deviation estimate; absolute maximum reached on any of the day of the episode),
- Average daily indicator with a standard deviation estimate,
- Magnitude Index during the day (average value with a standard deviation estimate),
- Magnitude Index during the night (average value with a standard deviation estimate).

Each descriptive table is accompanied by a summary heat map (Figures B.7-B.14 placed in the Appendix) which illustrates the evolution of the proportion of affected territory by year (1979-2018).

5.1 Geographic patterns in the distribution of heat waves

We will now focus on the general yearly and monthly geographic patterns of the heat waves in Spain, and then proceed to the discussion of the summary characteristics of the episodes: their cumulative incidences, time steps, average duration, absolute and relative metrics of intensity of the episodes, and so on.

5.1.1 Seasonal incidence

Spatial distribution of heat wave episodes in Spain varies from year to year. The figures C.1-C.4) in the Appendix display accumulated incidence of heat waves in each year, from 1979 until 2018. The reader can visually track the sprawl of the spatial extent over time. The overwhelming expansion becomes especially clear in the last years of the observation period (Fig. C.4). Interestingly, as was noted in the previous sections, the Great European heat wave of 2003 has resulted in a high number of accumulated episodes (13 per cell in a year in case of local, and 17 in case of zonal episodes) in the north and north-east of Spain, whereas the Eastern coast remained unaffected by heat anomalies that year.

[3]Temperature or heat index depending on the method used to detect episode, as specified in the table header

As for the spatial patterns of the incidence of the heat anomalies by month, there are a few peculiarities. The maps shown on Figure 5.2 represent the yearly proportion of the incidence of episodes in a given month[4]. In general terms, irrespective to the method of detection, the set of cells within the IP tends to register heat waves mostly in July and August, whereas CI have a one month delay and record the majority of the episodes in August and September. This pattern is predominantly homogeneous, however there are particular areas in the southern part of the Valencian gulf and in some sporadic locations in the north of Spain that concentrate all their zonal heat anomalies in July. Eastern Galicia, in turn, is receiving the prevailing fraction of the zonal heat waves in August.

The DTR during heat wave episodes, as shown on Figure 5.3, has a pronounced south-to-north and shore-to-interior gradient. In July and August western and central parts of the IP reach 15-20 degrees Celsius. The amplitudes gradually shorten with the decrease of the continentality: practically all the coastal areas reach around 10 degrees of DTR during heat waves. Western and northern Galician coast, Balearic islands and Canary islands have the lowest DTRs (1-5 degrees), meaning that during heat wave episodes in these areas the change between diurnal and nocturnal temperatures is minimal.

[4]In other words, each column sums up to 100%, which corresponds to the total number of episodes detected using a particular method

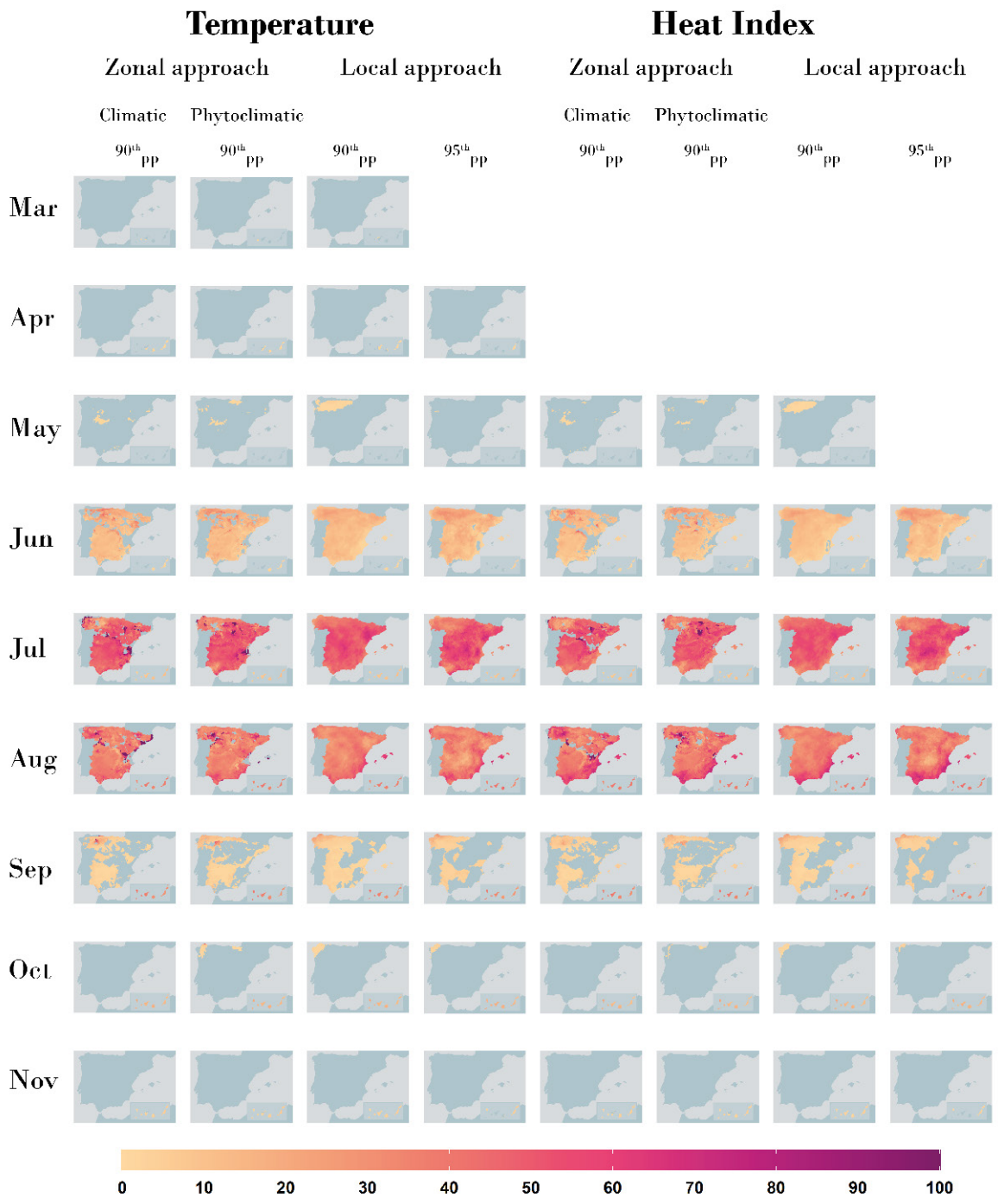


Figure 5.2: Monthly incidence of heat wave episodes in Spain (1979-2018), yearly proportion

5.1.2 Accumulated incidence

We now proceed to the discussion of the overall patterns of the accumulated incidence, average frequency, duration and variations in the absolute values and magnitudes of the heat anomalies in Spain. Figure 5.4 displays several important characteristics of the heat waves. The illustration is organized so that columns correspond to a particular method used for detecting episodes, and each of the four rows demonstrates the following parameters: **A**. Accumulated number of the episodes per cell during 40 years of observation (heat anomaly footprint), **B**. Accumulated number of years with episodes (ranges from 1 to 40), **C**. Average time step[5] between years with heat wave episode, and **D**. Average duration of an episode in a cell, measured in days.

We invite the reader to focus on the column 4 (maps A_T4-D_T4) of the Figure 5.4 which corresponds to the characteristics of heat wave episodes detected using the 95$^{\text{th}}$percentile of the temperature series established as a threshold for an individual cell. The total number of episodes accumulated in every cell across the grid is shown on the map A_T4. The distribution of this parameter is relatively homogeneous in the interior of the IP with some deviations in the western part of the country, southern Almeria and Valencian gulf. Both archipelagos have higher accumulated incidence in comparison with continental Spain: CI register the highest overall number (over 50 episodes per cell in total). Northern coast of Spain also clearly stands out by significantly higher accumulated incidence in comparison with the rest of the IP. If we now take a look at the accumulated incidence of the temperature-derived zonal episodes (maps A_T1 and A_T2), the patterns are quite different. Some areas are shown in grey as they do not register any episodes when thresholds for large climatic/phytoclimatic zones are used. Galicia, for instance, when using the 90$^{\text{th}}$percentile of the corresponding climatic type (map A_T1), does not register any anomalies in the coastal areas, whereas when using the local methods of detection the incidence in this area is very high. This is happening because the locally defined thresholds in this area are significantly lower in comparison with the zonal thresholds (4.17).

Another important feature to note for zonal incidence is the differences in the range of estimates if compared to the local. Indeed, when using a threshold for a very extensive area (for example, Cs_a climatic type, which occupies approximately half of the national territory), some locations, especially those located at the edges of the area bounding box, or separated from the main land by large water masses, would clearly stand out against the overall background in terms of the incidence count. This is exactly what we see in case

[5]Average frequency of the incidence, in years, e.g. 2.5 years would mean that at least one episode is registered in a particular cell every 2.5 years.

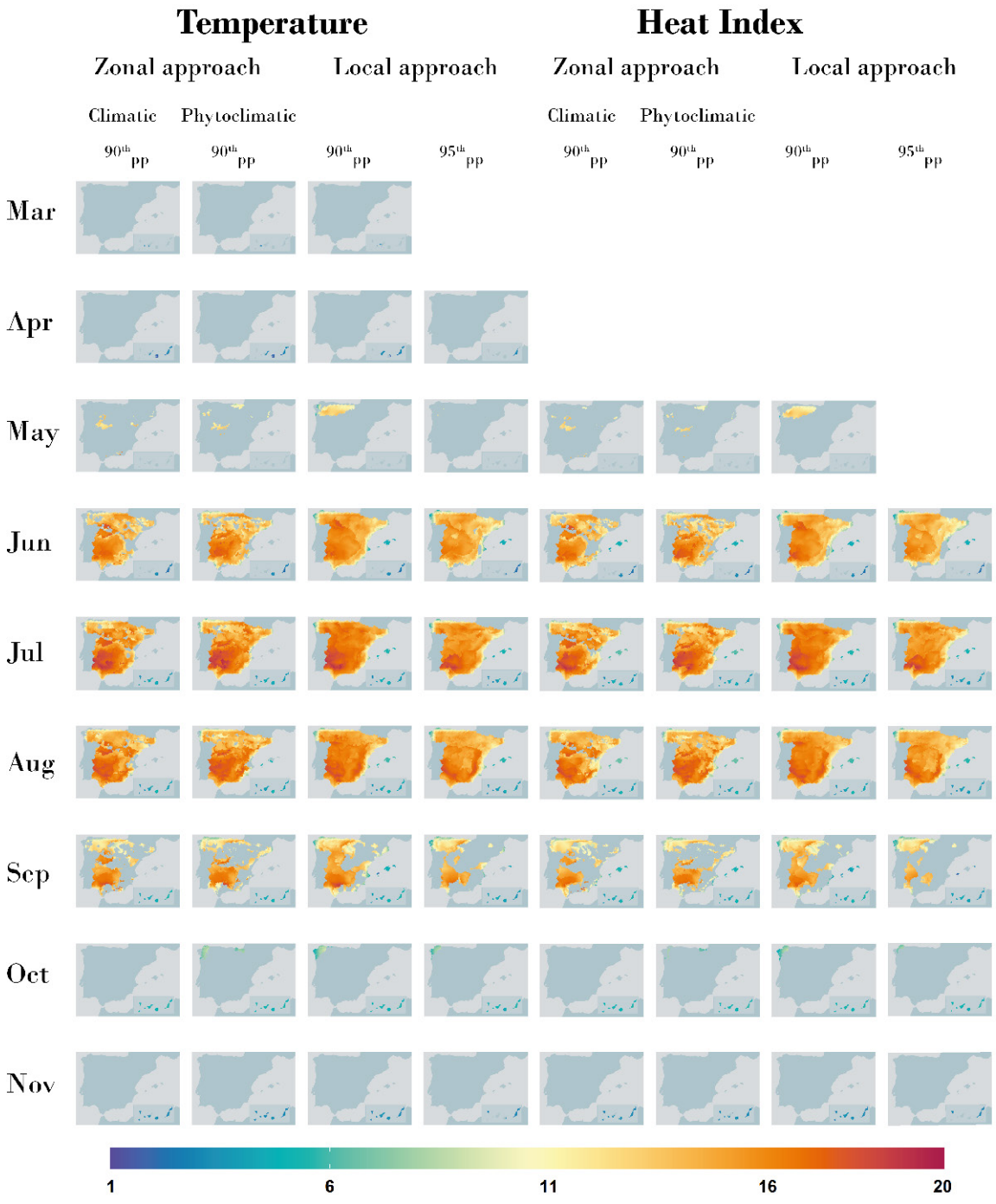


Figure 5.3: Spatial variations of diurnal temperature range during heat wave episodes in Spain by month (1979-2018)

of the Balearic islands and southern part of the Valencian gulf: although both locations are classified with Cs_a climate, the local conditions are much milder than in the interior of the peninsula. It sets higher thresholds for this climatic type, which, in turn, can not be reached by these two coastal areas. On the other hand, south-west part of Aragón, classified as Cf_b climatic type, has the highest incidence counts (up to 380 episodes in 40 years) of the zonal temperature-based anomalies. This peculiarity roots in the fact that the major part of this climatic type is present along the northern coast of Spain and in the Pyrenees, which have similar precipitation and temperature regimes (and therefore belong to the same climatic type), but much lower absolute values in comparison with more continental areas with the same climate. Therefore, abrupt thermal conditions in Aragón lead to a very high incidence of heat anomalies when compared to the other Cf_b type locations. The same areas in Aragón have medium incidence of heat wave episodes (70-80 episodes per cell accumulated over 40 years) when local methods of detection are implemented. At a glance, it might seem somewhat counterintuitive that the north of Spain along with the Mediterranean and Atlantic islands, which are all characterized by generally milder conditions in comparison with the rest of the IP, tend to be more affected by heat anomalies rather than the interior or even the south. The graph shown on the Figure 5.5 is designed to highlight regional differences in the temperature surplus, i.e. an absolute value (in degrees Celsius) needed to pass from the mean (50^{th}percentile) or the upper bound of the IQR (75^{th}percentile) to the extreme range (90^{th}percentile and 95^{th}percentile). Here several comparisons are made. Some areas of Galicia and Aragón belong to the same Temperate Oceanic type of climate (Cf_b). The density plots of the minimum temperatures of these two areas are clearly different: Galicia has generally lower values and quite a narrow range (IQR = 2.8) while in Aragón the IQR equals to 4.7 degrees and the distribution has much longer tales. Therefore, in absolute terms, for the minimum temperatures in Galicia to "jump" from the mean value of 15.5 degrees to the "extreme zone" of 17.7 degrees where the 90^{th}percentile is exceeded, an increase in 2.2 degrees is required. At the same time in Aragón this value has to be 1.7 times higher than in Galicia: the surplus needed in this case is 3.7 degrees Celsius. For the maximum temperatures the pattern is similar: under similar climatic regimes it has to be much hotter in Aragón than in Galicia for a heat wave to occur. Thus, to pass from the mean value of 20.3 degrees to a "very extreme" value of 25.3 degrees (95^{th}percentile) a surplus of 5 degrees is required for Galicia and 6.5 degrees in Aragón.

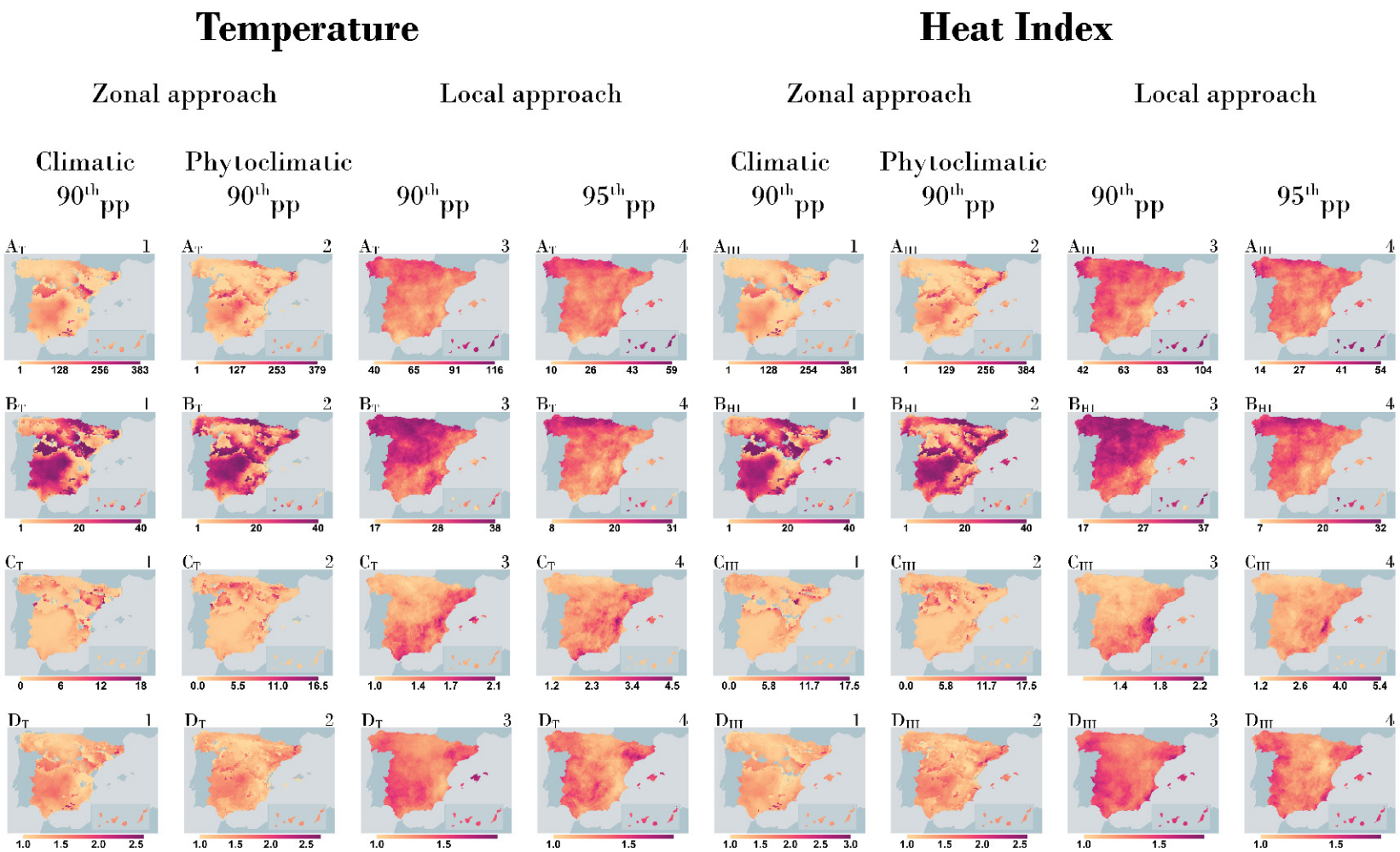


Figure 5.4: Spatial patterns of heat wave incidence, frequency and duration in Spain

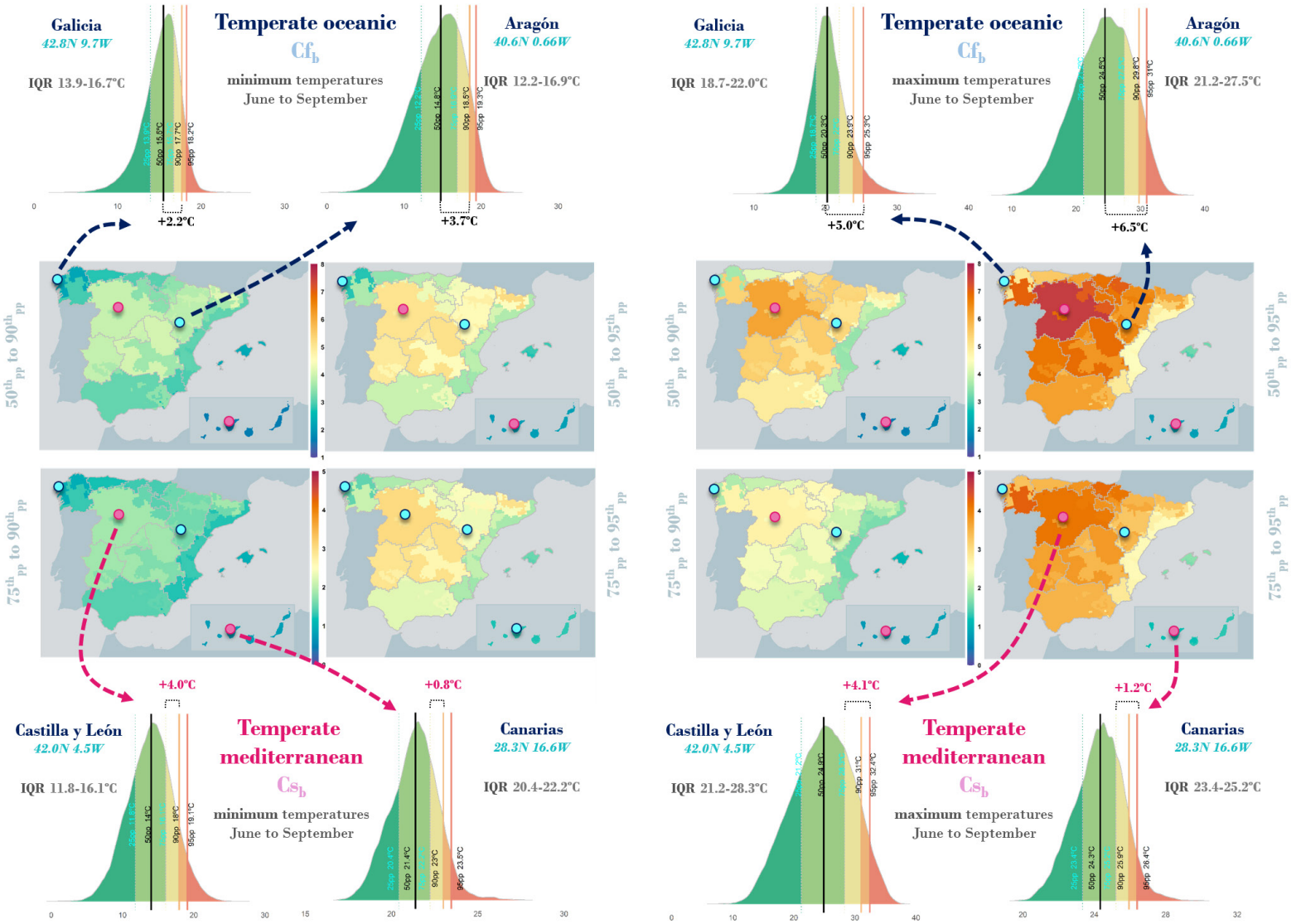


Figure 5.5: Spatial variations in temperature surplus required for normal-to-extreme transition

Another example with even more striking distinctions can be found at the bottom of the Figure 5.5. Here we are looking at two areas which fall into the same Temperate Mediterranean type (Cs_b) but are located 2000 kilometers apart. The selected location in Castille and Leon has generally more continental and therefore austere conditions in comparison with Tenerife island which climate is strongly influenced by the Atlantic. Thereby, to pass from the 75^{th}percentile to the 90^{th}percentile less than 1 degree is required in Tenerife, whereas in the Castille and Leon, under the same climatic regime, a surplus of 4 degrees is needed for the minimum temperatures to reach the extreme. In case of maximum temperatures, the difference of 2.9 degrees is observed in the surpluses required for the temperatures to transition from the 75^{th}percentile to the 95^{th}percentile in these two locations (1.2 and 4.1 in Tenerife and Castille and Leon, respectively).

Our finding that northern Atlantic coast of the IP and coastal Mediterranean areas experience a more intense local heat stress in comparison with the interior of the IP is consistent with the discussion on peculiar future trends[6] for the IP published in several experimental studies. Thus, absolute warming of the maximum temperatures is expected to be more intense in the interior IP rather than in the coastal areas. However, when it comes to the prediction of the summer heat wave frequency and duration changes, some parts of the IP (Cataluña, Extremadura, western Andalusia and Castille and Leon) might experience a decrease in heat wave frequency and intensity (Yagüe et al. 2006). The areas that will experience the highest positive changes (A2-SRES versus control run) in heat wave duration are anticipated to be Northern Spain (Galicia, Pais Vasco) and Spanish Mediterranean coast (Sánchez et al. 2004).

Now we return to the Figure 5.4 to discuss frequency of the heat wave incidence. Map B_T4 represents the accumulated number of years when heat anomalies were registered. As darker the color, the more the accumulation of years is. Map C_T4 provides an additional information to the map B_T4 and shows the average[7] time step in between years with heat anomalies. The northern coast of the IP sharply stands out against the overall background. The total number of "abnormal" years is reaching 25-30 out of 40, with an average time step of less than two years. The coastal areas of southern Andalusia and eastern La Mancha (interior areas in between southern parts of Iberic system and northern Baetic system) have the slowest pace and register heat waves every 3.5-4.5 years.

For detailed geographic analysis performed in this study, we have declared heat episodes as those above the corresponding threshold for at least 1 day, as was highlighted

[6] A2-SRES (IPCC Special Report Emission Scenario) emission scenario (2070-2100)

[7] Adjusted to the total number of years with heat anomalies in a particular cell.

previously in the text. This contrasts with the commonly used criteria of 3 consecutive days. Here, we do not distinguish between "spells" and "waves" as was done by Robinson (2001) as we are interested in continuous analysis of the phenomena. On average, according to the custom criteria used in this study, heat waves tend to last around 1.5 days all across the country. Western parts of the IP, Southern Subplateau, river Ebro basin, eastern Pyrenees and both archipelagos have longer episodes (up to 2 days, on average). If we compare duration of the temperature-derived episodes with the duration of the episodes detected using heat index ($D_{HI}4$), the pattern is different in the coastal areas. While the Mediterranean coast has short temperature-derived episodes, the duration of the heat index-derived is longer in the same locations.

Generally speaking, distribution patterns of the temperature-derived episodes are similar to the heat index-derived heat waves. However, there are some locations that result to be under heat stress when heat index zonal thresholds are used to detect heat anomalies (maps $A_{HI}1$ and $A_{HI}2$), and are stress-free when using temperature only (maps A_T1 and A_T2). This mainly applies to the Balearic islands and coastal zones of Valencian community and Cataluña: whereas temperature-derived methods do not capture heat anomalies in these locations.

Figure 5.6 displays spatial variations in maximum and minimum temperature and heat index values during heat wave episodes across Spain. This graphic is organized in a similar manner to the Figure 5.4: columns match the detection method, while rows correspond to different indicators. First row (row **A**) displays 8 maps of the variation of the average values of maximum temperatures and heat index; row **B** shows absolute maximum values; rows **C** and **D**, respectively, depict average and absolute minimum temperature and heat index value during heat anomalies. Following the strategy used before, we will focus primarily on the column 4 (maps A_T4 - D_T4) which illustrates variations in the attributes of the local heat anomalies identified using the strictest criteria (95^{th}percentile for a single location).

On average, maximum values during heat waves gradually increase from 24-28 degrees in the north-west of the IP and central Pyrenees to 32-35 degrees in the Ebro valley and western parts of the Central Plateau, sharply rising at lower latitudes and with the increase of the continentality. Eastern sides of Guadiana and Guadalquivir depressions, Sierra Morena, La Mancha and Southern Subplateau exceed 35 degrees for their maximum daily temperatures during heat wave days, on average. In case of the CI, Fuerteventura and Lanzarote have the lowest average values, around 26-28 degrees, while the rest of the islands in the archipelago surpass 30 degrees, with southern coasts of Tenerife and

north-west of Gran Canaria reaching 35 degrees. The pattern of the spread of the average maximum values of heat index (map $A_{HI}4$) mimics the dispersion of the temperatures, however the role of continentality factor here is slightly weakened. Guadalquivir river basin stands out by the maximum heat index values reaching 40 degrees.

As for the absolute maximums in the IP, there is a clear shift to the lower latitudes for both temperatures (map B_T4) and heat index (map $B_{HI}4$). For the temperatures, the overall pattern is similar to the distribution of the maximum values on average. The maximum values of the heat index are generally higher: the absolute maximum (50 degrees) in the IP during the heat anomaly is reached in the Guadalquivir river depression. Interestingly, patterns of the spread of absolute maximum values in the CI differ from the distribution of the values on average. Whereas mean maximum temperature in Fuerteventura is one of the lowest in Spain, when it comes to the absolute extremes the eastern coast of the island marks values exceeding 40 degrees. In case of the heat index maxima, Gran Canaria beats the record, approaching 50 degrees.

Maps shown on the Figure 5.7 reveal variations in the absolute magnitude of heat wave episodes in IP and CI. The strategy to organize the maps on this figure is identical to the one used in Figure 5.6. Maps A_T3 and A_T4 (local approach based on temperatures) depict a clearly pronounced latitudinal gradient: Northern coast of Spain (especially the coastal areas of the Basque Country) shows up as a region with the highest exceedance of day-time temperatures (up to 2.5 degrees on average for maximum temperatures, and 7-9 degrees for absolute maximums). The distribution of the absolute magnitude of the minimum temperatures is more homogeneous: on average, minimum values tend to surpass locally-defined thresholds in 1.0-1.5 degrees (Maps C_T3 and C_T4), gradually decreasing to under 1 degree in the extreme north of Galicia and all along Mediterranean coast. In CI, absolute magnitudes for minimum temperatures do not exceed 1.2 degrees, on average, being higher in the east of the archipelago and lowering to the west. The absolute minimum magnitudes are the highest in the north-west and south-west of Spain (7-8 degrees). The Mediterranean coast and interior Spain stays within 1-5 degree limit. The magnitude of maximum night-time temperatures in CI is around 5 degrees for locally-defined episodes.

As for the heat index, the pattern is quite similar for the distribution of the magnitudes of the average day-time and night-time heat index values (isolated areas in the extreme north and south of Spain in case of maximum heat index, north-west to south-east gradient in case of minimum heat index). The main difference is observed in both archipelagos: whereas temperature-based magnitudes are quite low (especially in BI, around 1 degree during the day and less than 1 degree in the night, on average), absolute

mean day-time magnitudes based on heat index (maps $A_{HI}3$ and $A_{HI}4$) reach 1.5-2 degrees in BI and stay around 1.2-1.4 in CI. During the night both archipelagos register the highest exceedance of the heat index (1-3-1.7 on average, maps $C_{HI}3$ and $C_{HI}4$, and up to 6 degrees in the extreme cases, maps $D_{HI}3$ and $D_{HI}4$).

The patterns of the distribution of the absolute magnitude of the episodes identified with a zonal method have a number of differences from those accentuated by the local approach. The spread of the magnitudes of locally-defined temperature-based episodes is more similar to the magnitudes of the episodes based on the 90^{th}percentile for climatic type. In case of the magnitudes of the heat index-based episodes more similarities are seen with the spread of the magnitudes of the episodes based on the 90^{th}percentile for phytoclimatic subtype.

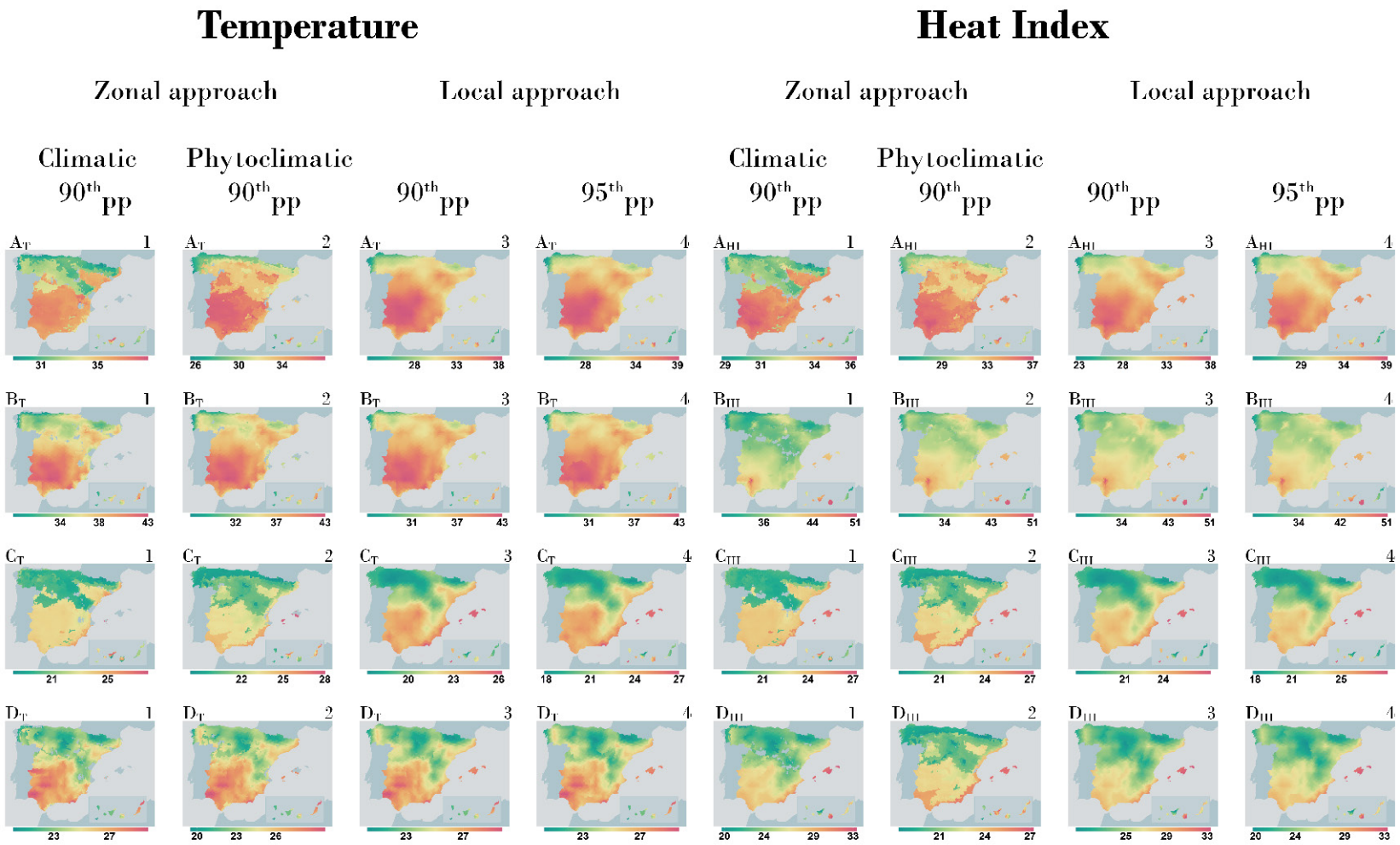


Figure 5.6: Spatial variations in minimum and maximum values of temperature and heat index during heat wave episodes in Spain (1979-2018)

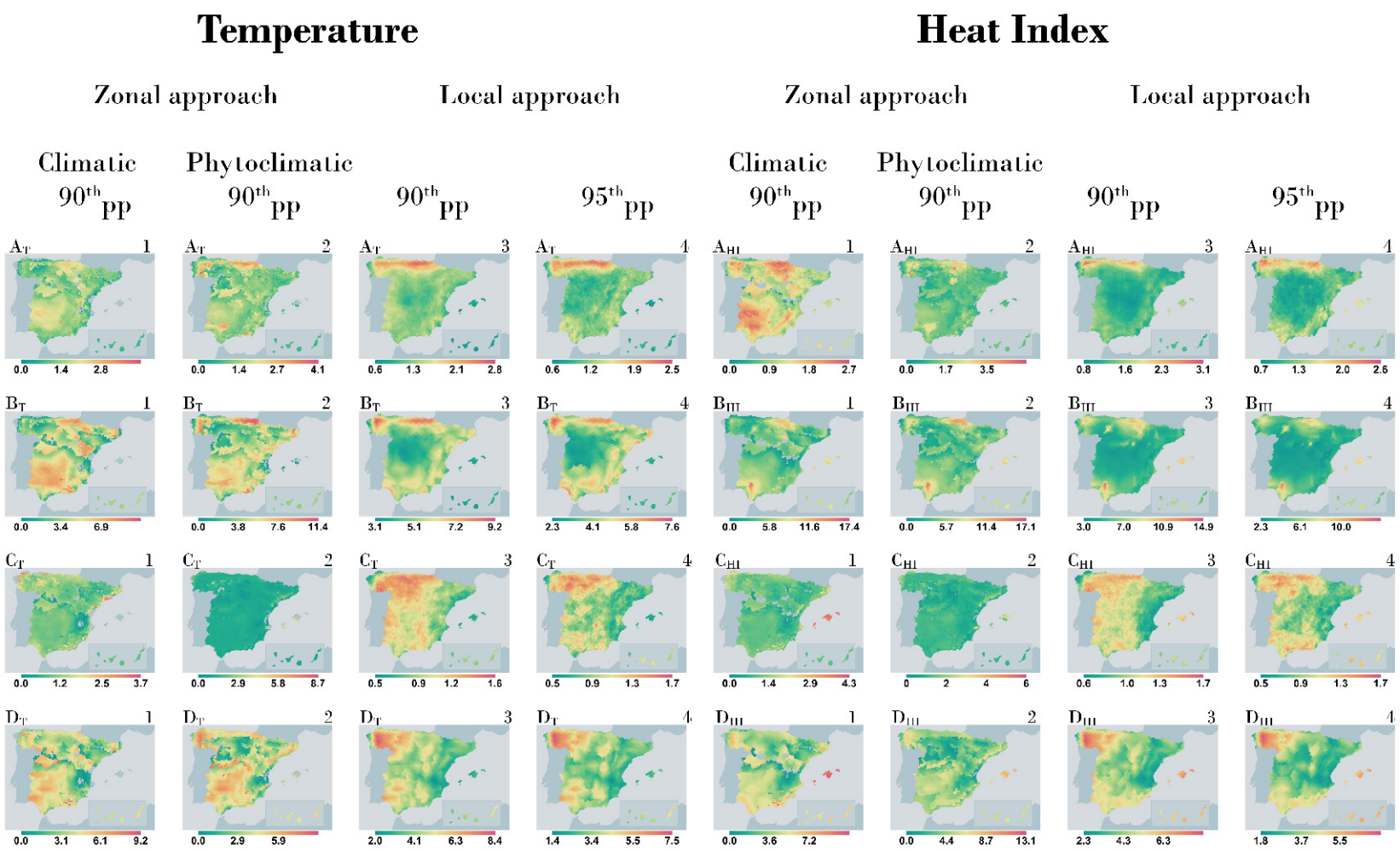


Figure 5.7: Spatial variations of absolute magnitude of heat wave episodes in Spain (1979-2018)

5.2 Tropical nights in Spain

There is no officially established definition for the term **tropical night**, but most commonly it is applied for the days when minimum night-time temperatures exceed 20 degrees. Some studies also apply this term for the days when nocturnal temperatures are even higher and surpass 25 degrees (Park et al. 2012), others proceed to the development of more complex indices like *hot night hours* and *hot night degree* indices, which allow for relativization and interzonal comparison (Royé 2017). The latter paper suggest the usage of a so-called *tropical night index* which is based on the 95$^{\text{th}}$percentile of the daily minimum temperatures throughout the year. In the present study, this tropical night index could be regarded as identical to the 95$^{\text{th}}$percentile of the minimum temperatures for the corresponding hottest month. For the sake of simplicity, this study uses an absolute threshold of 20 degrees to define tropical nights.

Within the IP the prevailing number of tropical nights occurs in July and August, while in the case of BI the incidence is equal throughout the entire summer (June to August). In the CI the period of incidence of tropical nights extends from July to October in equal proportions. Heat maps shown on Figure 5.8 (a) represent the change in the overall proportion of tropical nights from 1979 until 2018. We grouped tropical nights by their duration into the following categories: **under 3 days**, if minimum nocturnal temperature is above 20 degrees for 1 or 2 days; **3 to 5 days** for uninterrupted periods of 3-5 days with night-time temperatures over 20 degrees; followed by **6 to 10 days**, **11 to 14 days** and **15 to 21 days** periods. Period when nocturnal temperatures exceeding 20 degrees lasted for more than 21 days were classified as **over 3 weeks**, and periods when night-time temperatures stayed below 20 degrees are marked as **none** on the Figure 5.8 (a).

As the reader can see, the overall pattern of incidence is quite homogeneous. In the IP, tropical nights tend to last for up to 3 days. Tropical nights extend to more than 21 days only in 6% of the cases within the peninsula. In the CI and BI once the nocturnal temperatures reaches 20 degrees, it usually stays on top of this threshold for more than 3 weeks. The absolute maximum night-time temperature (heat index) for both CI and BI does not surpass the mark of 28 (33) degrees.

In continental Spain, tropical nights are more of a "Mediterranean" rather than an "Atlantic" phenomena. 40 maps displayed on Figure 5.8 (b) show the locations that are colour-coded with respect to the maximum number of days classified as tropical nights reached in each year. For instance, the Mediterranean coast of Spain and BI are marked in red (category of **over 3 weeks**) as this area always has tropical nights lasting for

more than 3 weeks at some point during the year. Northern coast of Spain almost never exceeds 20 degrees for more than 2 days, with only one exception. A few locations in the extreme north-east (coastal areas of the Basque Country) experienced tropical nights for up to 10 days in 2003. The maximum duration of the tropical nights in the interior parts of the IP extends to 2 weeks, gradually increasing to the coastal areas. The CI are not shown on this figure as the maximum category reached each year is **over 3 weeks**.

5.3 Spatiotemporal variations by land cover type

As we discussed in the previous sections, heat waves are often linked to the Urban Heat Island (UHI) effect. The UHI effect, or, in other words, the elevation of the temperature in the metropolitan areas with respect to the surrounding areas, results from the heat retention and heat absorption by pavement and construction materials (houses, roofs etc), along with the excessive heat generation from human activity, all against the background of usually scarce vegetative cover. The phenomenon of UHI and heat waves might work in tandem: a study by Founda and Santamouris (2017), which focused on the coastal areas in Greece, is using the term *synergy* to highlight the multiplication of the UHI effect by extreme heat. The objectives of our study do not include a detailed exploration of the UHI-heat wave relationship. Nevertheless, we consider it essential to account for the variation in the land cover across space in our debate. On the following pages we focus on the analysis of the incidence of heat waves in different land cover settings.

The Corine Land Cover (CLC) used in this study (details in Chapter 3) has 5 temporal slices, or snapshots, for years 1990, 2000, 2006, 2012 and 2018. We then estimate the mean accumulated incidence of local and zonal heat wave episodes by cell for the following groups of years: 1979-1989, 1990-1999, 2000-2005, 2006-2011 and 2012-2018. Each cell is then assigned its corresponding land use type for the reference year. For the generalization purposes, we match each cell with the land cover type which occupies 50% or more of the total area of the cell.

The generic change of the land cover in Spain from 1990 to 2018 was not dramatic[8]. Overall, 88% of the national territory remained unchanged in terms of the land cover in 28 years (1990-2018), as shown on Figure 5.9 (a). Among those cells that experienced any kind of transition during this period (remaining 12% of the territory), the Agricultural-to-Forest and Forest-to-Agricultural shift was observed in 90% of the cases. The transition

[8]The proportion in between Agricultural areas/Artificial surface/Forest and semi natural areas/Water bodies/Wetlands went from 52.5/0.8/46.1/0.4/0.2 in 1990 to 51.4/1.4/46.5/0.4/0.2 in 2018

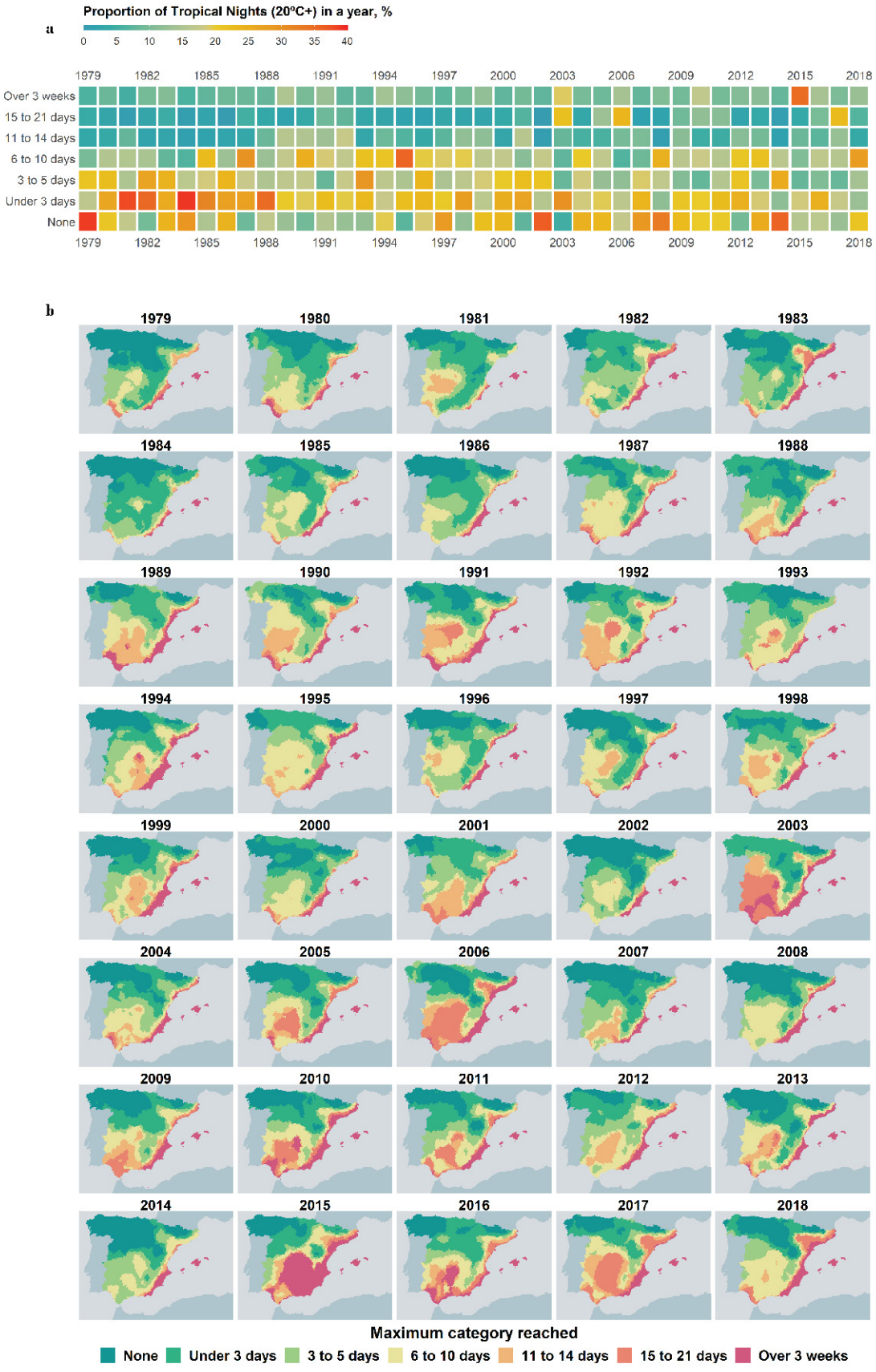


Figure 5.8: Tropical nights in Spain

from Agricultural areas to Artificial surfaces affected 3.4% of Spain, which is slightly above 17.000 sq. kilometers. The graphic shown on the Figure 5.9 (b) represents the summary of the mean incidence rate of heat waves by method of detection and land cover class[9]. For either local and zonal methods agricultural (permanent crops) and forest (open spaces with no or little vegetation) land classes stand out for their higher values of incidence rate, with the last time period (2012-2018) notably having the highest overall incidence. The affected by heat anomalies artificial surfaces (mostly represented by urban fabric and industrial, commercial and transport units) experience a sharp increase in the last period of observation as well. The incidence rates are doubling with respect to the previous period.

[9]Names and codes of the land cover classes are provided on the left side of the same graph

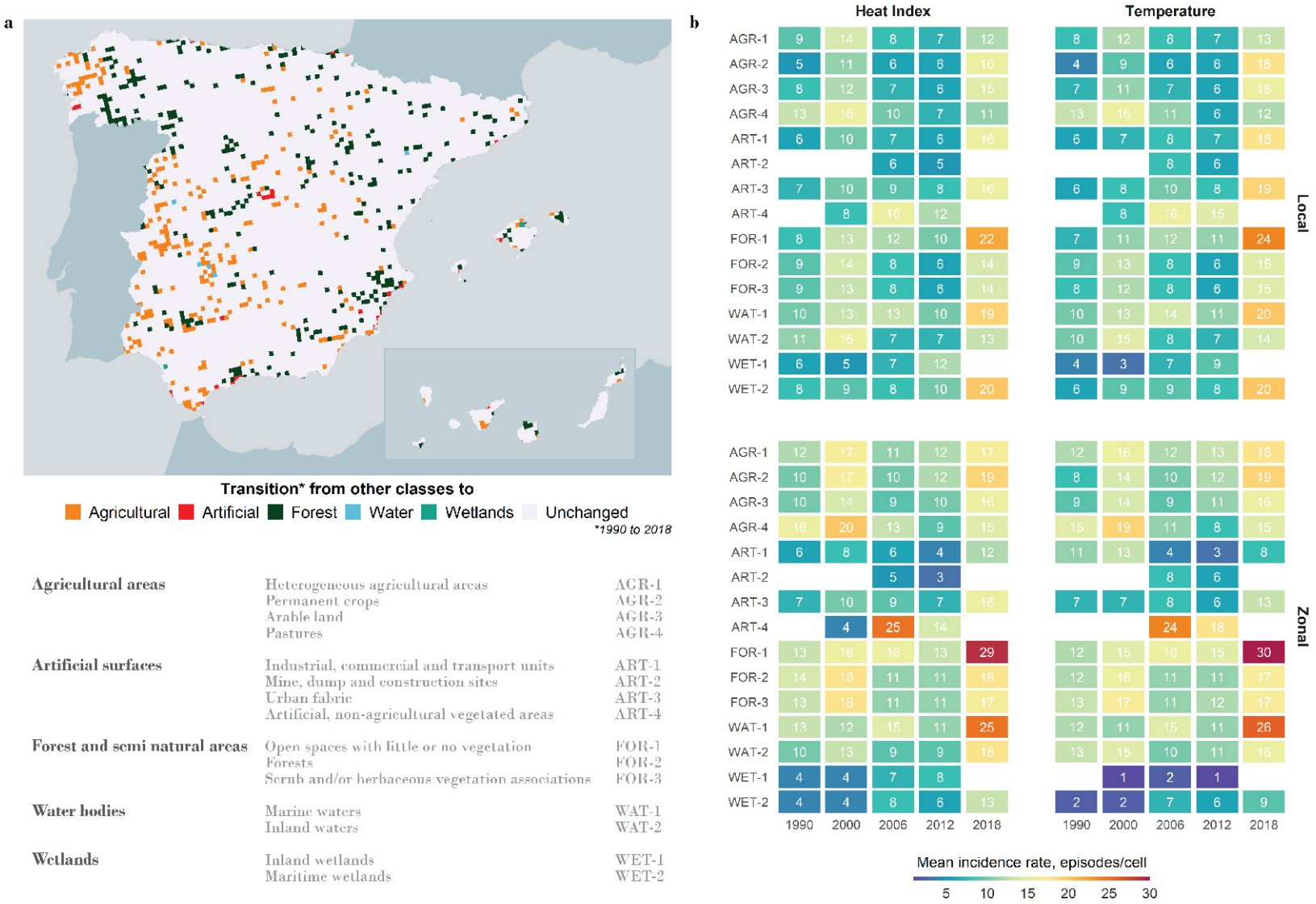


Figure 5.9: Land cover transitions from 1990 to 2018

Spatial variations of the heat wave incidence, accumulated over each time period, are portrayed on the Figure C.5 in the Appendix (CLC codes and names are listed on the Figure 5.9). Here, the color matches the land cover class[10] and the size of the dot inside the cell shows the amount of accumulated episodes, on average by method and time period. Smaller the dot, lower the accumulated incidence, and vice versa. Visually, the intensity of the color highlights the land cover class affected by heat anomalies the most.

The dominating colors in all the maps are red, orange and greens, which correspond to the agricultural and forest classes. As we discussed earlier, settlement in Spain has very irregular pattern, and the overwhelming majority of the land in the country is taken by agricultural and semi natural lands. The proportion of purely artificial areas (composed by urban fabric, infrastructural and industrial units) is slightly over 1%. By 2018, average incidence of the locally (zonally)-defined temperature- and heat index-based heat wave episodes reached 16 (15) and 18 (12) episodes per cell, respectively. The results vary significantly depending on the location. Thus, the highest mean incidence rate on the artificial areas is registered in Canary islands, and equals to 30 (28) episodes per cell in case of temperature (heat index)-based anomalies. Artificial surfaces in Melilla, País Vasco, Cataluña and Comunitat Valenciana form the second highest group with average rates between 16 (15) and 23 (24) temperature (heat index)-based episodes per cell. Artificial areas of Community of Madrid and Murcia register 14 and 14 (11 and 17) temperature (heat index)-based episodes per cell, on average. The incidence of temperature-based episodes in Balearic islands is lower than in Madrid and Murcia (13 episodes per cell), however average incidence of the heat index-based episodes is one of the highest and goes up to 23 episodes per cell. Andalusia and Asturias are characterized by an average incidence of 10 episodes (either temperature- or heat index-based) per cell. Artificial areas in Galicia have the lowest incidence of temperature- (9 episodes/cell) and heat index-(7 episodes/cell)-based heat anomalies.

5.4 Emerging Hot Spot Analysis

We now proceed to the final step of spatial analysis of the distribution of heat waves across Spain. To wrap our discussion on the generic patterns of heat wave incidence, we perform the emerging hot spot analysis[11] to identify overall trends in our data. We first create a so-called *Space Time Cube* from defined locations, which in this case are the

[10]Highest in the Corine hierarchy, see land.copernicus.eu for more information

[11]EHSA, one of the commonly used tools within *Space Time Pattern Mining* toolset in ArcGIS PRO

10x10 km grid cells. For every unit of time (1 year) we calculate accumulated incidence by indicator and threshold, which is then considered as the primary variable of analysis. When the necessary 3-dimensional structure is created, we parametrize the EHSA as follows: global window set to the entire cube (so all the trend estimations are done against 40 years of observation), conceptualization of spatial relationship set to *k nearest neighborhood* and number of neighborhoods (adjacent cells) set to 8.

Table 5.1 contains summary of the EHSA results, whereas Figure 5.10 displays spatial patterns of the emerging hot and cold spots. The trends for all 8 methods of detection were estimated as *increasing* (trend statistics[12] and corresponding significance levels[13] are shown at the two bottom rows of the table). Numeric values displayed elsewhere in the table represent the proportion of the territory identified as a certain type of hot or cold spot. For example, 77.8 % of the national territory is classified as an oscillating hot spot when accumulated yearly incidence of heat wave episodes detected using the 90$^{\text{th}}$percentile of the temperature distribution at a single location is considered. No cold spots are identified. 22.2% of the territory is classified as having no trend for the incidence of episodes of this particular method.

We will now focus on the 4$^{\text{th}}$ and 5$^{\text{th}}$ columns of the Table 5.1, which correspond to the proportion of the national territory classified as either hot or cold spot of heat anomalies detected using the strictest temperature threshold of 95$^{\text{th}}$percentile for an individual cell. Here, both hot and cold spots emerge, however the predominant pattern stays very similar to the case of "looser" threshold of 90$^{\text{th}}$percentile. 77.5% of the area is an oscillating hot spot, 0.4% is a newly emerged hot spot, while 0.6% of the territory is classified as oscillating and sporadic cold spots of the heat wave incidence. The area under the latter three categories is located in the extreme south of Andalusia (Figure 5.10, 2$^{\text{nd}}$ map on first row, area in the zoom circle). Thus, coastal areas from Tarifa to Estepona (extreme south) show a downward trend (oscillating and sporadic cold spots). At the same time, an isolated area to north-east of Ronda is marked with intense red color and reveals a new hot spot. During the last time step of the analysis these cells showed an upward trend for the first time during the 40 years of observation. As for the rest, 21.9% of Spain remains in the "no trend" category. Patterns of the hot and cold spot emergence of the local episodes based on heat index are very similar to the described above.

Columns 6-9 and 14-17 in the Table 5.1 as well as the bottom row on the Figure 5.10 represent the results of EHSA for the trends in the incidence of the heat wave episodes

[12]Getis-Ord Gi* statistic z-score, designed to measure the intensity of high value (hot spot) and low value (hot spot)

[13]Getis-Ord Gi* statistic p-value

detected using zonal approaches. In case of zonally detected episodes, slightly larger proportion of the national territory stays out of any trend, if compared to the locally-defined episodes (34% versus 21-22% for temperature-based methods, 38-39% versus 23-32% for heat wave-based methods). The overall variation of the emerging patterns of the incidence of zonal episodes is more pronounced. Here, in case of the zonal episodes based on both indicators, the interior southern and central parts of the peninsula and CI archipelago belong to the oscillating hot spot category. South-east areas of Castille and Leon, Southern Aragón, northern Castille la Mancha, north-east Cataluña and extreme east of the Basque Country are classified as either intensifying or persistent hot spots.

The areas under any subcategory of cold spots are quite extensive for the zonal methods of detection based on both temperature and heat index, however the distribution varies from method to method. Heat anomalies detected using climatic type thresholds classify into intensifying and persistent cold spots in the extreme north-west of Galicia and in some isolated areas in the interior of Castille and Leon. In case of the temperature-based climatic thresholds the coastal areas of Valencian Gulf and the BI archipelago also belong to the category of intensifying and persistent cold spots, whereas when using thresholds based on the heat index Valencian gulf shows no trend and the BI pass from cold spot to oscillating hot spot.

Spatial patterns of the EHSA based on the episodes detected using thresholds for phytoclimatic subtypes resemble the climatic type-based patterns. However, in this case, larger portion of the territory falls into "no trend" category (34.8% for temperature-based methods and 39.6% for those based on heat index). Persistent cold spots are shifted southward in the Northern Spain, when compared to the methods based of climatic thresholds. In the extreme north-east of the country, the coastal zone of the Basque country and the adjacent mountain areas of Navarra stand out for being categorized as intensifying and persistent hotspots. Remember, that for the zonal approach of episode detection the thresholds are set for extensive areas similar by their temperature and precipitation regimes, which allows us to identify anomalies against the zonal background and compare distant areas with similar conditions (long-term regimes). As we are using global window for the EHSA, the results indicate the trends of the zonal heat anomalies considering the overall picture i.e. the trends of the incidence of zonal anomalies across the country. Therefore, if a certain area is categorized as a e.g. persistent hot spot, it would mean the the upward trend of the incidence of the zonal heat anomaly in this particular cell is statistically significant considering local neighbors and the trends elsewhere in the study area.

Table 5.1: Emerging Hot Spot Analysis details

	Temperature								**Heat Index**							
	90^{th}pp		95^{th}pp		$90^{th}pp_{climatic}$		$90^{th}pp_{phytoclimatic}$		90^{th}pp		95^{th}pp		$90^{th}pp_{climatic}$		$90^{th}pp_{phytoclimatic}$	
Category	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold	Hot	Cold
New[1]			0.4		0.5		0.6						0.3		0.5	
Consecutive[2]					0.5		0.4						0.7		0.2	
Intensifying[3]					2.5	3.2	2.4	1.7					2.1	1.6	2.3	1.6
Persistent[4]					0.2	6.2	0.2	6.5					0.9	3.2	0.2	6.2
Diminishing[5]						1.3		1.3						2.3		0.6
Sporadic[6]				0.1	9.0	9.0	7.8	4.7					8.0	6.0	7.8	5.0
Oscillating[7]	77.8		77.5	0.5	32.6	0.4	38.6	0.2	67.7		75.6	0.8	36.4	0.5	34.1	0.4
Historical[8]						1.5		1.8						1.0		1.5
No trend	22.2		21.9		34.3		34.8		32.3		23.5		38.7		39.6	
Trend statistic	*2.7*		*2.4*		*3.2*		*3.2*		*2.2*		*1.7*		*2.8*		*2.7*	
Trend p-value	*<0.01***		*<0.05**		*<0.001****		*<0.001****		*<0.05**		*0.05-0.1*		*<0.01***		*<0.01***	

[1] The most recent time step interval is hot (cold) for the first time.
[2] A single uninterrupted run of hot (cold) time step intervals, comprised of less than 90% of all intervals.
[3] At least 90% of the time step intervals are hot (cold), and becoming hotter (colder) over time.
[4] At least 90% of the time step intervals are hot (cold), with no trend up or down.
[5] At least 90% of the time step intervals are hot (cold), and becoming less hot (cold) over time.
[6] Some of the time step intervals are hot (cold).
[7] Some of the time step intervals are hot (cold), some are cold (hot).
[8] If the last time step is not hot (cold), at least 90% of the time step intervals are hot (cold), but the most recent time step interval is not.
[9] Proportion of the national territory under correspondong hot (cold) spot category, expressed in %.

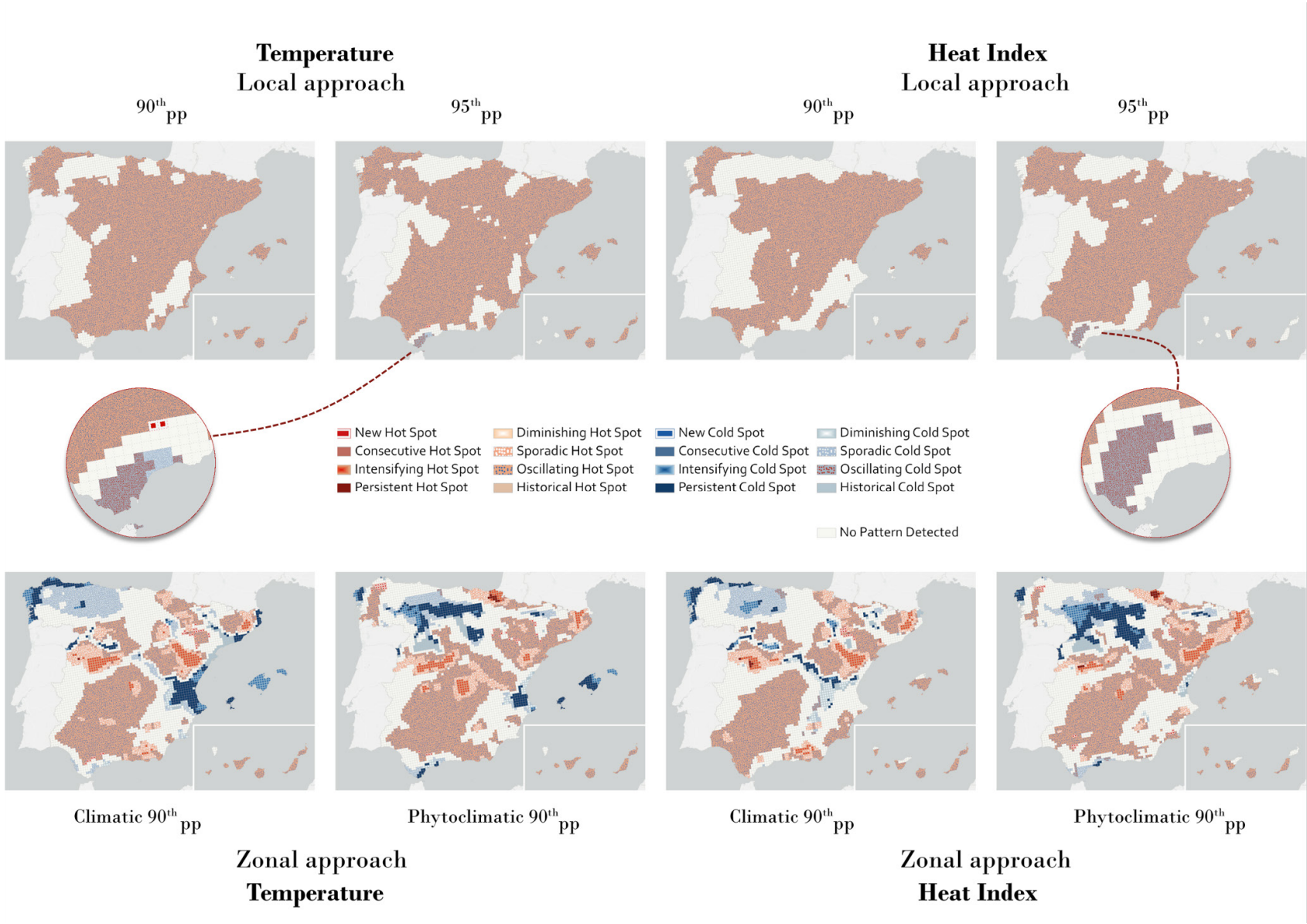


Figure 5.10: Emerging hot spot analysis of heat anomalies in Spain

5.5 Multivariate mapping

In order to see spatial variations of the combined effect of two variables a so-called *bivariate mapping* technique could be applied. Figures below represent the results of bivariate mapping performed for two different combination of variables: 1) incidence of heat wave episodes and their duration (Fig. 5.11), and 2) diurnal and nocturnal magnitude indices of the episodes (Fig. 5.12). The legend for bivariate maps is shown in the center of each figure. Two maps on the top row correspond to the characteristics of the local episodes, while the bottom row displays maps covering the zonal episodes. The incidence and duration of the episodes for each group of methods was averaged, and the limits of the color scale are adjusted to all four sets of data (local temperature-based, local heat index-based, zonal temperature-based, zonal heat index-based) independently. To ease the interpretation of these maps, some areas on the maps are highlighted with the arrows and the commentary is given[14].

We will start with the discussion of the combined effects of incidence and duration of heat episodes displayed on the Figure 5.11. The lightness of each color shows the increase in intensity of one of the two variables. When both variables (incidence and duration) reach their maximum values the color becomes the darkest as the result of the overlay of maximum lightness and saturation of the two independent colors. The lightest of the 9 colors characterizes the simultaneously low incidence and duration. Local and zonal patterns are essentially different, however the inter-indicator differences are not that significant. Locally, heat anomalies tend to be frequent and last longer in the CI. Western coast of Galicia and eastern coast of the Basque country receive frequent but short episodes, on average. Northern interior Spain tends to have short and frequent episodes as well, however the frequency of heat anomalies in these areas is lower than of those affecting the Atlantic coast. South-west, interior south regions and BI tend to register long episodes but with less frequency, when compared to the North of Spain. Mediterranean coast is characterized by short and rare heat wave episodes, if analyzed against the overall country background.

Northern Spain, Mediterranean coast and large interior areas along the coastline have weaker heat "footprint" when zonal anomalies are analyzed. Interior areas of central Spain, Ebro river valley, north-east Cataluña and Basque country coast receive longer and frequent episodes, while the duration and incidence of heat wave episodes in CI is average in relation to the overall picture.

[14]The color of both arrows and commentary text corresponds to the color (bivariate class) of the cell where the arrow starts.

Maps shown on the Figure 5.12 are designed to show day- and night-time intensity of heat anomalies. The darker the color, the higher are both diurnal and nocturnal magnitudes. In the group of locally defined episodes, Atlantic coast and CI clearly stand out with the highest overall magnitudes. In other words, these areas tend to have episodes of exceptional local deviation from their IQR of values. Western interior parts of the IP tend to have larger deviations of the magnitude during the night rather than during the day time. At the same time, extensive interior areas in the east of the country and along with Mediterranean coast lean towards having low and medium diurnal and nocturnal combination of magnitudes. As for the zonally-detected episodes, CI show the highest values of day- and night-time magnitudes, similarly to the locally-defined anomalies. North-west of Atlantic coast, as well as BI, south and north-east of Mediterranean coast have high nocturnal and low diurnal magnitudes, when compared to the rest of the territory. On the contrary, ample interior areas in central Spain and north-east of the Atlantic coast have the highest diurnal magnitudes whereas during the night the magnitude is low to medium, with respect to the rest of the country.

Reader can explore more bivariate combinations of heat waves in Spain in maps shown in the Appendix C: figure C.6 (a) combines incidence of the episodes with the diurnal magnitudes, figure C.6 (b) merges the frequency and nocturnal magnitudes, figure C.6 (c) and figure C.6 (d) blend duration and diurnal and nocturnal magnitudes, respectively.

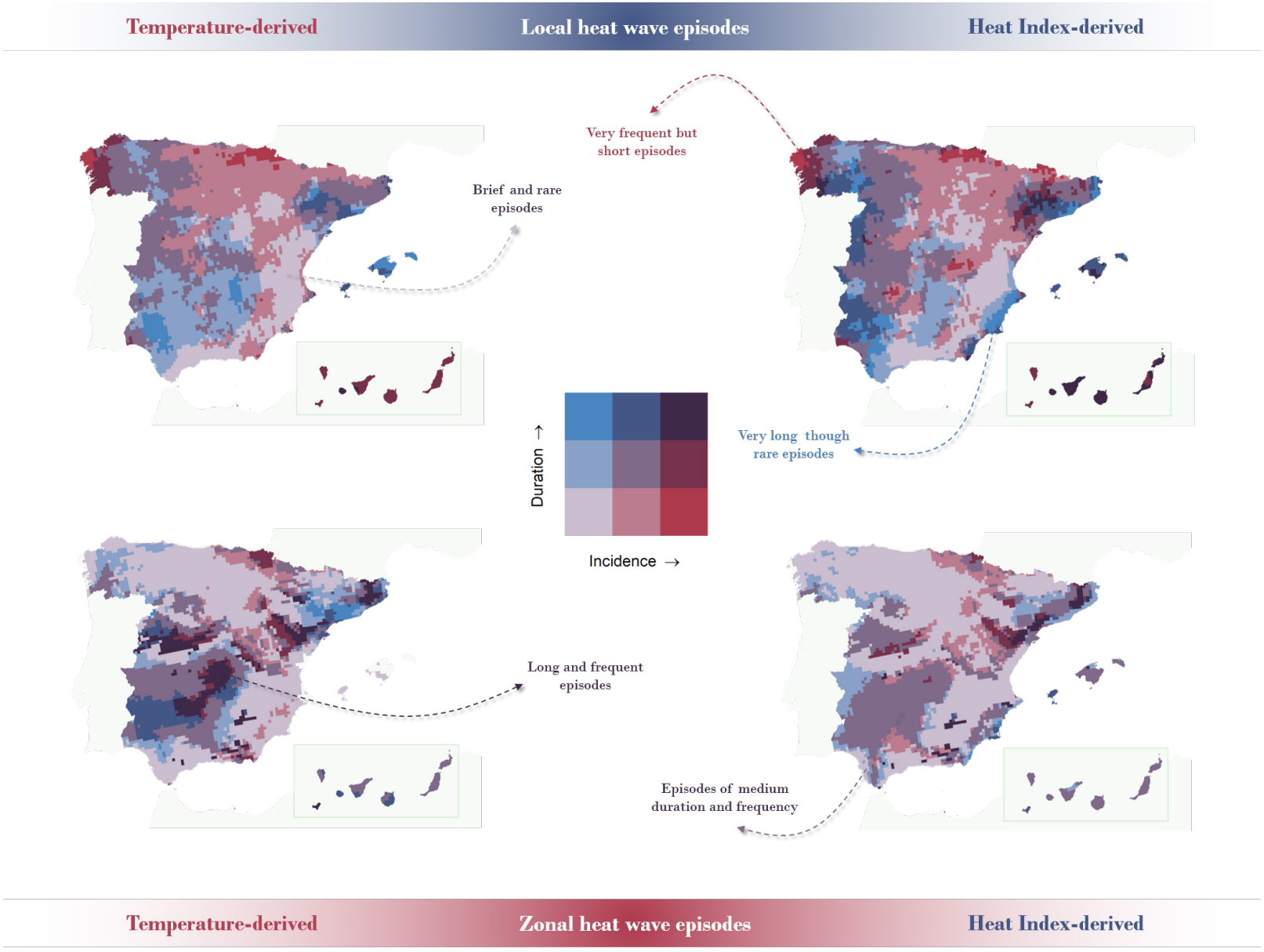


Figure 5.11: Bivariate map: incidence of heat wave episodes and their duration

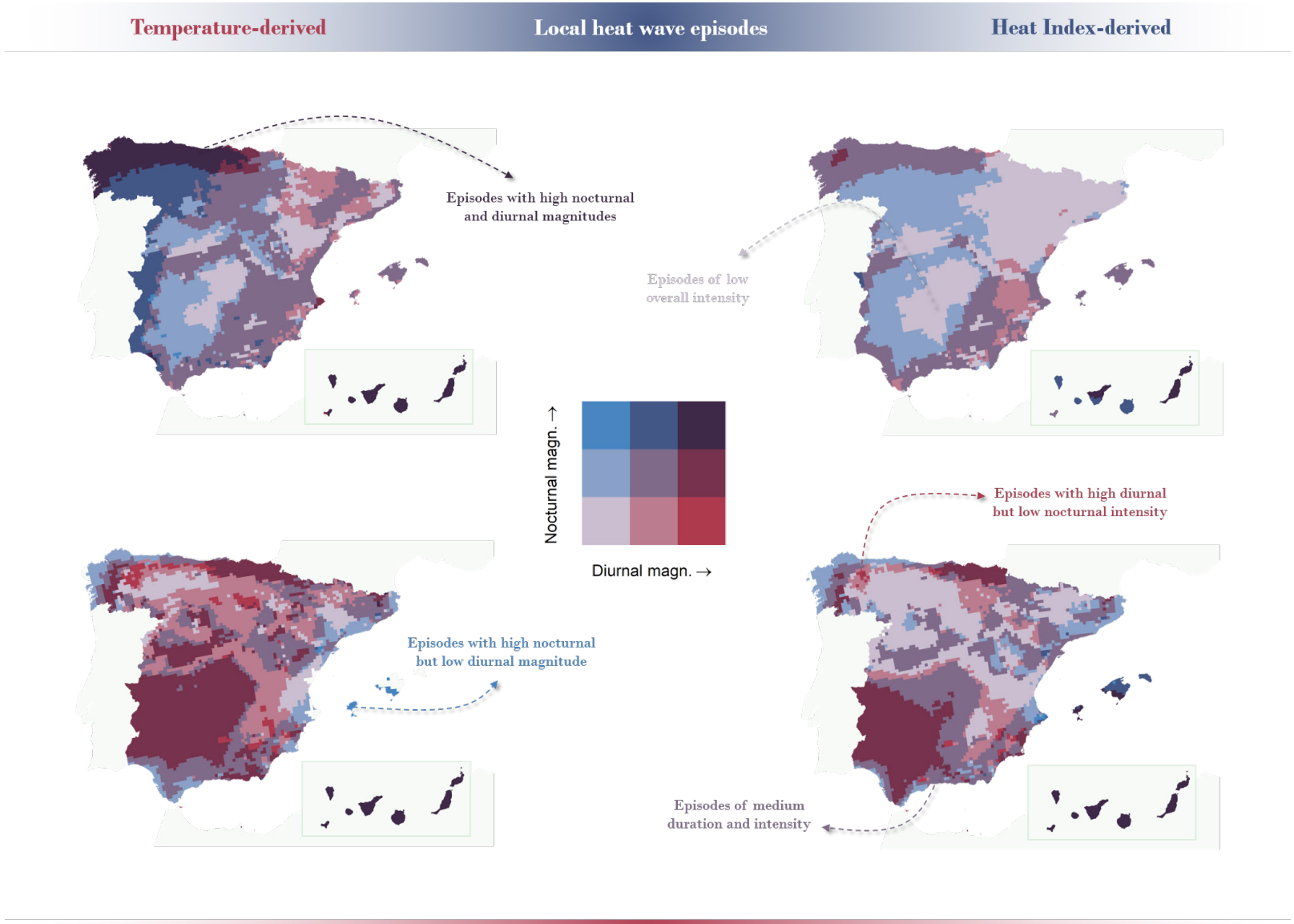


Figure 5.12: Bivariate map: diurnal and nocturnal magnitude indices of heat wave episodes

Climate change can affect local to regional air quality directly through changes in chemical reaction rates, boundary layer heights that affect vertical mixing of pollutants, and changes in synoptic airflow patterns that govern pollutant transport. Energy demand could also increase, and as we continue to rely on the combustion of fossil fuels, this could lead to an increase in particulate matter (PM) and NOx levels. Additionally, some particles are products of photochemical reactions and will be higher at higher temperatures at any given precursor emission level.

— *Synergistic Effects of Ambient Temperature and Air Pollution on Health in Europe: Results from the PHASE Project*, Analitis, De' Donato, et al. (2018).

6

Extreme heat, air pollution and land use: accumulation of vulnerabilities

The relationship between atmospheric conditions and air pollution is well established and was studied in different contexts for many decades. Most commonly, air pollution is defined as the presence in the air of substances or particles that imply risk or damage for the human health, flora or fauna. The main source of atmospheric pollution are ozone gases (O_3), sulfur oxides (SO and SO_2), nitrogen oxides (NO and NO_2) and suspended particles (PM). These are mainly derived from emissions from burning of fossil fuels (including emissions from transportation), industrial processes, forest burning, use of aerosols and radiation. Other potentially harmful for human health substances include carbon monoxide (CO), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs) and peroxyacetyl nitrates (PANs). We remind to the reader that particular mechanisms of interactions between human body and air pollution were discussed in details in Chapter 2.

In terms of the atmospheric conditions, air quality is mostly affected by temperature, humidity, solar radiation and air pressure. One of the main actors to define the distribution of air pollutants across space is *wind*. Depending on its speed, wind can spread the pollution over large distances. Air stagnation, usually associated with high pressure systems, which are also often responsible for heat wave formation, leads to the concentration of pollutants over certain areas. In particular, urban areas located in the low-lying landforms might experience high levels of air pollution. The majority of the studies on heat-related mortality and morbidity controls for the air pollution

in the analysis, as most of the studies are done for metropolitan areas, which are a priori predisposed to more intense air contamination.

Variations in temperature are linked to the variations in the concentration of such pollutants as O_3, NO_2 and PM. For instance, on cloud-free days the increase in temperatures triggers an intense photochemical formation of ground level ozone (Saini et al. 2014; Castell et al. 2008). The temperature can also affect the formation of particles: high temperature can promote the photochemical reaction between precursors (Wang and Ogawa 2015). Moreover, pollutants tend to interact and function as catalysts for each other. Often to describe the relationship between air pollutants specific proportions are used, e.g. ratio between nitrogen dioxide and monoxide (NO_2/NO) and O_3 (Hagenbjörk et al. 2017; Han et al. 2011).

There are pronounced seasonal and daily fluctuations in the course of the ground level O_3 concentration. In the northern hemisphere, the annual cycle of O_3 has its main minimum in the cold season and the maximum, often bimodal, in the warm season (period of maximum photochemical activity). In Spain, the peak of O_3 concentration is registered in June-July, whereas the secondary maximum occurs in April-May. As shown by García, Sánchez, et al. (2005) both temperature and synoptic weather patterns are an important controlling factor and make the highest contribution in maximum O_3 concentration.

Ozone and nitrogen oxides are inversely related: the peak concentration of O_3 in summer corresponds to the minimum concentration of nitrogen oxides concentration, and vice versa (Roberts–Semple et al. 2012). Lower concentrations of NO_2 in summer can also be attributed to the fact that this compound contributes to the O_3 formation under the increased influence of solar radiation and intensified photochemical reaction during summer months (Cichowicz et al. 2017). In Spain, higher concentrations of NO_2 are observed in metropolitan (large cities) and industrial (north and east coasts) areas with pronounced peaks in winter season (Cuevas et al. 2014).

The seasonal cycle of SO_2 is similar to the nitrogen oxides' annual behavior: it reaches the maximum in the lower troposphere during the winter (Rasch et al. 2000). Higher concentrations of sulfur dioxide are attributed to the emission sources, and while in Spain there has been a progressive reduction in the sulfur-reach fuels in the last decades, the SO_2 hot spots are still linked to the metropolitan areas (Escudero et al. 2016).

In Spain, concentration of particular matter in the air peaks in the summer season, and is related to the increase of photochemical activity (as function of the temperature) and to the occurrence of African dust storms. Despite being of *natural origin*, the latter source of PM poses a great concern for human health, especially in highly populated

areas along the Mediterranean coast, and was studied in relation to mortality by several researchers (Jiménez et al. 2010; Perez, Tobias, et al. 2008; Perez, Tobías, et al. 2012; Dominguez-Rodriguez et al. 2020).

Industrial air pollution in Spain was always more intense in the regions of historically established manufacturing: Andalusia, Aragon, Basque country, Asturias, Castile la Mancha, Catalonia and Galicia (García-Pérez et al. 2007). Since the adoption of the Gothenburg Protocol[1] in 1999, Spain implemented a number of programs designed to control and reduce the environmental pollution (Vedrenne et al. 2015). As the result, the concentrations of main air pollutants in the past two decades were gradually decreasing.

According to the latest report on the air quality issued by the Spanish Ministry of Environment in 2020 (*Evaluación de La Calidad Del Aire En España* 2020), none of the regions exceeded the hourly threshold of NO_2. Only the area of Madrid surpassed the annual threshold for nitrogen dioxide (41 µg/m^3 against the 40 permitted by the European air quality standards[2]). The levels of PM_{10} air pollution are naturally high in Spain due to the proximity of the African continent; therefore some "discounts" are applied to increase the permitted threshold levels locally. According to this adjusted normative, daily limits of PM_{10} (50 µg/m^3) in Spain were exceeded only in one location (Galicia), whereas the yearly limit (40 µg/m^3) was not exceeded at all. The average annual concentrations of $PM_{2.5}$ stayed within permitted ranges (25 µg/m^3) as well. All of the aforementioned statistics show positive dynamics with respect to the preceding years. The maximum daily 8 hour mean concentrations limits of O_3 (120 µg/m^3 threshold) were exceeded in 21% of the zones that were evaluated in the report (primarily in Andalusia, Extremadura, Madrid). However, in comparison with the preceding decade, the ozone concentrations also show a downward trend. The limits of the hourly (350 µg/m^3) and daily (125 µg/m^3) concentrations of SO_2 were not reached anywhere in the country.

For the monitoring and forecasting purposes, the EEA has developed an Air Quality Index[3](AQI), which we rely on to in our analysis. This index is based on five key pollutants (O_3, NO_2, SO_2, $PM_{2.5}$ and PM_{10}). For each pollutant, a certain range of values defines an index level (e.g. if the concentration of O_3 stays below 50 µg/m^3, the AQI level of this pollutant is considered to be *good*, if it falls into the range of 50-100 µg/m^3, the AQI level passes to the *fair* category, if the concentration of O_3 exceeds 100 µg/m^3 but stays below 130 µg/m^3 it places ozone into the *moderate* category, and so on). The overall

[1] 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone (Gothenburg Protocol), for more information see unece.org/gothenburg-protocol

[2] For more information visit ec.europa.eu

[3] To access the visualization tool updated on an hourly basis visit www.eea.europa.eu

level of AQI at a given point of time is defined by the maximum concentration of any of the five elements. In other words, if concentrations of O_3, NO_2, SO_2 and $PM_{2.5}$ place each one of the elements into the *moderate* category, and PM_{10} occasionally exceeds the 150 µg/m^3 threshold mark (limiting value for PM_{10} to pass from *very poor* to *extremely poor* category), the overall level of AQI would be considered as being *extremely poor*.

Further in this chapter we embark upon the discussion of the results of the analysis of air pollution in 2017, 2018 and 2019 in IP and BI. The data for CI was not provided, as previously highlighted in the previous chapter. In the first place, we show overall spatiotemporal distribution of primary (O_3, NO_2, SO_2, $PM_{2.5}$ and PM_{10}) and secondary (NO, CO, NH_3, NMVOCs and PANs) pollutants. Further, we perform a comparative analysis of the variations in concentrations and spread of the main air pollutants on non-heat wave days and heat wave days. In addition, we estimate the AQI, explore its variations over time and space and compare the results in urban and rural settings. On the last step, we proceed to the multivariate clustering analysis in order to classify the territory into spatial clusters similar by average concentrations of primary air pollutants.

6.1 Trend levels of pollution in 2017-2019 in continental Spain

Figure D.5 in the Appendix shows temporal variations in the concentrations of primary air pollutants by month and wind directions, whereas Figure D.6, also presented in the Appendix, displays the pollution trend levels for the group of secondary pollutants. First column on both figures corresponds to the maximum concentrations and the second one covers the average values. Monthly variations in spatial distribution of average concentrations of all ten air pollutants are presented on Figure D.1 in the Appendix.

Plots D.5 a, f and D.5 b, g illustrate the inverse relationship of ozone and nitrogen dioxide discussed before. While peak concentrations of O_3 are associated with spring and summer months and south, south-east and east winds, maximum concentrations of NO_2 in Spain are reached in the late autumn and during the winter and are associated with winds coming from north, north-east and east. Nitrogen monoxide concentrations follow the variations of nitrogen dioxide, peaking in winter and staying at its lowest in the rest of the seasons (Figure D.6 d, i). Spatially, O_3 has relatively homogeneous spread across the country with pronounced south-to-north incremental gradient in summer months. In the colder months, concentration of ozone is lower in urban areas (Madrid, Barcelona, Gijon, Sevilla) in comparison with agricultural areas and natural vegetation

in the rest of IP and BI. Spatial distribution of NO_2 and NO concentrations practically mimics the infrastructure and settlement pattern of the country, in such way highlighting the anthropogenic nature of highest concentrations.

Monthly variations of sulfur dioxide are less pronounced (plots D.5 c, h): SO_2 occasionally peaks throughout the entire season, wheres on average the concentrations tend to be higher during the winter. Mostly, higher concentrations of SO_2 are associated with winds from the east. In Spain, SO_2 concentrations are notably high in the area of Gijon, Asturias, a historical center for steel and naval industry, as well as in the cities of Santander, Madrid, Huelva and Algeciras. Spatial pattern is persistent throughout the year.

Concentrations of particular matter (plots D.5 d, i for $PM_{2.5}$, plots D.5 e, j for PM_{10}) start increasing in spring, and stay at their maximum during the summer. However occasional peaks, often related to the intrusion of air masses rich in suspended material, are possible throughout the year. Seasonal changes of $PM_{2.5}$ concentrations are generally more gradual in comparison with the variations of PM_{10}. In the period of observation (2017-2019) highest concentration of both $PM_{2.5}$ and PM_{10} was reached in April 2018 and was associated with eastern winds. On average, summer peaks of PM usually couples with south-east, south and south-west winds. During the summer, $PM_{2.5}$ and PM_{10} show a clear north-to-south incremental gradient, whereas in the colder months higher concentrations are persistently seen in the large cities and along the river basins (Ebro, Guadalquivir).

Fluctuations of carbon monoxide in Spain show strong seasonality: it peaks during the winter season and sharply declines in hotter months (Figure D.6 d, i, shown in the Appendix). The interannual variations are quite significant: during 2018 winter the concentrations were 20% higher than in the 2019, on average. The main source for CO emissions is anthropogenic activity, such as combustion of fossil fuels and oxidation of hydrocarbons (Khalil and Rasmussen 1990). Analysis performed for other regions in the northern hemisphere relates the interannual variability in CO to the El Niño-La Niña transitions, while seasonal fluctuations are mostly attributed to free tropospheric processes (Sheel et al. 2014). Hot spots of CO concentrations during the winter period unsurprisingly correspond to the largest urban settlements in Spain, whereas in the warmer months the area to stand out by significantly higher values of CO is Gijon.

Peroxyacetyl nitrate (PAN[4]) is formed by oxidation of non-methane volatile organic compounds (NMVOCs) in the presence of NO_x with a springtime maximum in the Northern Hemisphere (Fischer, Jacob, et al. 2014). In IP and BI in 2017-2019 the average concentrations of PANs were the highest in March and April with ocassional peaks

[4]also known as Acyl peroxy nitrates or APN

from February to May, mostly associated with winds coming from north, north-east and east (Figure D.6 e, j in the Appendix). Seasonal variations of NMVOCs show less clear pattern. Higher concentrations are more likely to occur in the end of the summer season. Winds associated with elevated NMVOCs concentrations are of south, south-west and south-east directions (Figure D.6 c, h in the Appendix). While PAN concentrations, with an overall homogeneous distribution, show a clear south-to-north incremental gradient, especially in the summer and early autumn months, the NMVOCs hot spots are tightly linked to the large cities in Spain and this pattern is stable throughout the year.

Gaseous ammonia (NH_3) is causing special concern for human health due to its known ability to form fine inhalable particles ($PM_{2.5}$) (Meng et al. 2014). During the observed period in Spain, NH_3 showed maximum concentrations during the spring season in 2019 with no clear association of wind direction, whereas in the rest of the months the pattern was somewhat random. Generally speaking, during the warm season the volatility of NH_3 is higher; however the increase during the colder seasons might be related to human activity e.g. vehicular emissions or soil fertilization (Nguyen et al. 2021). Geographically, notably higher concentrations of ammonia during the period of 2017-2019 were seen in the north-east of river Ebro depression with a very clear distinction from the rest of IP and BI in the colder months.

6.2 Air pollution as function of heat intensity and land cover

We now granulate our analysis in order to explore variations in the concentrations of primary air pollutants with respect to heat anomalies in Spain. We start by examining differences in the concentrations of O_3, NO_2, SO_2, $PM_{2.5}$ and PM_{10} on heat wave days and days without thermal[5] anomalies in urban, agricultural and other land cover settings. Figure D.2 presented in the Appendix represents one of the results of this analysis and is organized in the following manner: first two columns correspond to the days classified as heat waves, whereas the last two columns show the results for the normal days (days without heat waves). In each pair, first column corresponds to the day-time magnitude index, and the second one to the night-time magnitudes. Each row matches one of the five analyzed pollutants. Each graph, labeled by a letter, is formed by three rows

[5]We explored the relationship between maximum concentrations of primary air pollutants and magnitude indices of heat waves detected exclusively using temperature. The values of magnitude indices for local and zonal methods were averaged.

corresponding to Urban, Agricultural and Other (not urban nor agricultural) land cover class. The columns of this graph correspond to the level of magnitude index, and the number of the columns depends on particular subset of data. The smallest graphical element of the Figure D.2 is a so-called *pollution rose* - a more sophisticated version of a *wind rose*, which is a meteorological diagram depicting distribution of wind direction and speed at a location over a period of time. Pollution rose allows to combine information on the wind directions in association with pollution levels. Additionally, it enables conditioning by additional characteristics such as land cover type and level of magnitude of heat anomaly. The colors on the warmer spectrum (yellow to red) indicate higher concentrations, while colors on the colder spectrum (green to blue) mark lower values. Each pollution rose is normalized by wind sector for unification and display purposes.

The overall impression the reader might get from looking at this graph is that there is a persistent top-to-bottom and left-to-right incremental color gradient. Indeed, the majority of analyzed pollutants tend to have significantly higher concentrations in urban areas (top row in all the graphs) at higher values of magnitude index (far right columns). Nevertheless, these associations change depending on the pollutant.

During heat waves in 2017-2018, peak concentrations of nitrogen dioxide (from 10 $\mu g/m^3$ up to 63 $\mu g/m^3$) in IP and BI were strongly associated with urban areas. The variation of maximum concentrations depending on the magnitude of heat anomaly was less pronounced. During heat episodes of highest diurnal (Fig. D.2 a) and nocturnal (Fig. D.2 b) magnitudes there was a notable contribution of NO_2 from south and south-east. During non-heat wave days the difference in peak concentrations between urban areas and other land cover classes was even more dramatic. Maximum NO_2 concentration (up to 132 $\mu g/m^3$[6]) at lower diurnal (Fig. D.2 c) and nocturnal (Fig. D.2 d) heat intensity are mostly associated with west and north-west winds all across Spain, whereas in urban setting and under more intense heat conditions higher NO_2 concentrations are associated with south, south-east and east winds.

Maximum ozone concentrations throughout the entire period of analysis (2017-2018) in Spain equal roughly to 90 $\mu g/m^3$ and overall variation in between land cover classes is less pronounced in comparison with e.g. the variations of nitrogen or sulfur dioxides. In the course of heat anomalies, O_3 reached its peak concentration in urban areas during episodes of highest day-time (Fig. D.2 e) and night-time (Fig. D.2 f) magnitude index. Higher ozone concentrations in other land cover classes were also associated with more intense

[6]As reader might remember from the previous discussion, higher concentrations of NO_2 are generally associated with winter season when there are no heat wave days.

episodes and south winds. During the days without heat episodes significantly higher O_3 concentrations were observed on hotter days (Fig. D.2 g): here, peak ozone concentrations within urban settings (up to 232 µg/m^3) were associated with south-east wind directions whereas in agricultural and other non-urban areas more contribution of O_3 was seen from north-east. On the normal colder days, lower O_3 concentration was associated with north-west and west direction, while higher concentration was attributed to south-east winds. Variations of sulfur dioxide as a function of land cover and intensity of heat anomalies were clearly manifested. During heat anomalies, concentrations of SO_2 were significantly higher in urban areas and gradually increased with diurnal (Fig. D.2 i) and decreased with nocturnal (Fig. D.2 j) magnitudes. At its peak, SO_2 concentration shows association with mainly south-east winds. On normal days (Fig. D.2 k, l), urban areas clearly stood out by higher SO_2 concentrations primarily associated with south-east winds.

Patterns of the distribution of particulate matter on heat wave and non-heat wave days deserve a particular attention. Overall variations of $PM_{2.5}$ and PM_{10} are practically identical, with some minor deviations. During heat anomalies, PM concentrations are higher in non-urban areas, which exhibits a distinct pattern as opposed to the rest of primary air pollutants. As the reader might recall from our previous discussion, one of important natural sources of fine inhalable particles in Spain, especially in the summer, are the dust storms originating in the African continent. These storms mostly affect the interior south and Mediterranean coast of the country, which are predominantly agricultural areas. Another important natural contributor of particular matter are the sea spray aerosols and wild-land fire particles. In the north of Spain, open coastal areas, receiving strong winds from Atlantic and being traditionally used for eucalyptus (highly flammable tree) plantations, have favorable conditions for higher concentrations of finely dispensed particles.

On the hottest days of heat wave episodes in 2017 and 2018 higher concentrations of $PM_{2.5}$ (Fig. D.2 m, n) and PM_{10} (Fig. D.2 q, r) were mostly associated with north and north-east winds. As we will see in the following paragraphs, the areas with peak concentrations of particular matter during heat anomalies in these years were located in the north-west and west of Spain, suggesting higher contribution of sea salts (Atlantic ocean) and wildfire particles (Galicia and neighboring Portugal) in these areas. Higher concentrations of PM during heat waves along the southern Mediterranean coast could be attributed to wind-blown desert dust particles (originating from arid zones in North Africa). On the contrary, during non-heat wave days, peak concentrations of $PM_{2.5}$ and PM_{10} were reached in the urban areas and did not show significant association with

any particular wind direction (Fig. D.2 o, p, t, u). It suggests that the main source for particulate matter outside of periods of abnormal heat is of non-natural origin. To summarize non-spatial part of the analysis of the concentrations of air pollutants during heat waves, we will now focus on the correlation matrices visualized on Figure 6.1.

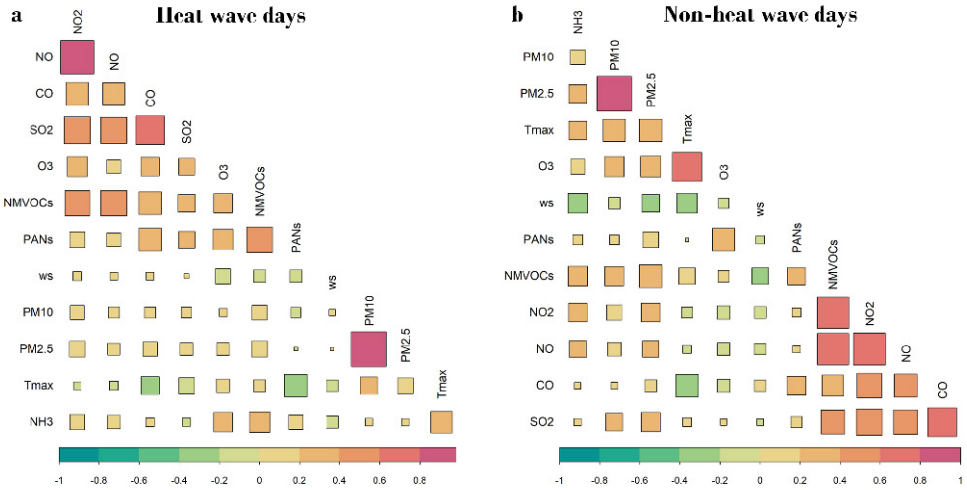


Figure 6.1: Correlation plot for maximum day-time temperatures and concentrations of air pollutants on heat wave and non-heat wave days

Each correlation plot is hierarchically clustered. The size of the square corresponds to the correlation coefficient (at 0.01 significance level), whereas color indicates the direction of the correlation (either positive, in red, or negative, in green). At the time of heat anomalies during the period of observation, all the studied air pollutants except ammonia and particulate matter were positively correlated with each other (Fig. 6.1 a). Maximum daily temperature had the highest correlation with NH_3 (0.34), PM_{10} (0.23) and $PM_{2.5}$ (0.18). Slightly lower but still positive correlations were seen in between maximum temperature and O_3 (0.13) and NMVOCs (0.11). The rest of the pollutants showed negative correlations with the temperature.

On the normal days, a cluster of high positive correlations is formed by nitrogen oxides, carbon monoxide, sulfur dioxide and non-volatile organic compounds (Fig. 6.1 b). Another positive cluster is formed by maximum temperature and ozone (correlation coefficient of 0.64, p-value 0.01), particulate matter (0.38 for both $PM_{2.5}$ and PM_{10}) and ammonia (0.25). Positive correlation between maximum temperatures also applies to NMVOCs maximum concentrations (0.2), whereas the rest of the pollutants reveal negative correlation with temperature.

6.3 Spatial variations of air pollution on heat wave days

Figure D.3 shown in the Appendix pictures spatial variations in the mean and maximum concentrations of primary air pollutants in 2017 and 2018, by season and type of the day (either a heat wave day, top row on all the figures, or a normal, non-heat wave, bottom row). The figure is organized in a similar to Figure D.2 manner.

As can be noted at a glance, there is a significant difference between concentrations on heat wave and non-heat wave days of ozone and particulate matter with respect to the rest of pollutants. In summer months, during heat anomalies ozone tends to peak in large urbanized areas (cities of Madrid, Valencia, Barcelona; Guadalquivir and Ebro river valleys; western Galicia) (Fig. D.3 a). On average, during the summer south of Mediterranean coast stands out by its higher concentration of O_3, with particularly high values during heat anomalies, and lower values during normal days, especially along the Atlantic coast (Fig. D.3 b).

As discussed previously, the origin of particulate matter is heterogeneous (natural and anthropogenic). Therefore seasonal and spatial variations of $PM_{2.5}$ and PM_{10} in Spain frequently reflect irregular atmospheric processes (e.g. intrusion of air masses enriched with sea salts, sand or other substances of non-anthropogenic nature). Overall, the maximum and average concentrations of PM on abnormal (heat wave) days in summer and autumn at the same locations are much higher than on normal days (Fig. D.3 d, j, e, k). Especially high $PM_{2.5}$ and PM_{10} heat-associated concentrations were reached in the north-west and west of Spain. The increase in these areas could be linked to the proximity of Atlantic ocean and frequent wildfires. Peak concentration of PM_{10} in sub-coastal area in Galicia in the summer months corresponded to lower wind speeds (stagnation after entering Meridiana depression at a higher speed, fig. D.3 f, l).

There were no essential differences between seasonal variations in the distribution of maximum and average concentrations of nitrogen (Fig. D.3 b, h) and sulfur (Fig. D.3 c, i) dioxides, which is attributed to the fact that peak concentration of both pollutants occur in the winter season.

6.4 Air quality composite index and pollution clusters

A useful metric to evaluate overall quality of the air is the European Air Quality Index (AQI), which methodology we have discussed in the preceding sections. Depending on the

highest concentration of any of the five primary pollutants, air quality is being classified into one of the six classes: good, fair, moderate, poor, very poor and extremely poor. We estimated daily AQI using maximum concentrations of primary air pollutants for the period of observation for every 10km x 10km cell. We then compared the estimated results between urban and non-urban areas on heat wave days and days without heat anomalies (Figure 6.2). Circular plots used to visualize these results are designed to link the AQI classes and the air pollutant to be "blamed" for the air quality.

Plots displayed on Figure 6.2 a, b correspond to the AQI variations in the urban areas whereas plots on the bottom row (Figure 6.2 c, d) show the variations in other non-urban land cover settings. During heat waves, the air quality in IP and BI varied from *fair* to *poor* in artificial areas, whereas in agricultural, semi-natural and natural settings AQI ranged from *fair* to *very poor*. The fact that urban areas have not reached *very poor* or *extremely poor* category as expected, might be related to a particular selection of dates used for this analysis (July 2017 - Dec 2018). *Poor* AQI in urban areas was associated with high concentrations of ozone and particulate matter. In non-urban areas *poor* AQI was also attributed to $PM_{2.5}$, PM_{10} and O_3, whereas *very poor* AQI was associated exclusively to particulate matter.

On non-heat wave days AQI varied from *good* to *very poor* in urban areas, and from *good* to *extremely poor* in non-urban zones. Half of the time, AQI in urban areas was *moderate* and worse, while in non-urban areas the quality of the air was predominantly *fair*. The poorest AQI all across IP and BI was associated with the concentrations of $PM_{2.5}$ and PM_{10} on non-heat wave days.

On the final step of the analysis of air pollution in relation to extreme heat, we evaluated the overall distribution of average concentrations of primary and secondary air pollutants with an ultimate goal to divide the territory of IP and BI into pollution clusters. Figure 6.3 portrays hot and cold spots of the average concentrations of air pollutants based on Getis-Ord Gi* statistic[7] for each cell. With minor exceptions, hot spots of air pollution in Spain correspond to the urban sprawl: practically all air pollutants (except O_3) have their hot spots in the cities of Madrid, Gijon, Santander, Ferrol and la Coruña, areas around Valencia, Barcelona, Ebro and Guadalquivir river depressions. Cold spots of air pollution in Spain are present in the interior center and north of the country.

Finally, we use spatially constrained multivariate clustering technique[8]] in order to classify the territory into clusters based on average concentrations of primary air

[7]Hot Spot Analysis tool (Mapping Clusters toolset), ArcGIS Pro 2.2

[8]Spatially Constrained Multivariate Clustering tool (Mapping Clusters toolset), ArcGIS Pro 2.2

pollutants (AQI components). We construct a spatial weights matrix[9] to measure how each cell in the dataset spatially relates to each other. As a conceptual model for spatial relationship we chose the contiguity edges corners (Euclidian distance method without row standardization). Further, we use these estimated spatial weights as spatial constrains for the multivariate clustering based on average concentrations NO_2, O_3, SO_2, $PM_{2.5}$ and PM_{10} in each cell. We let the optimum number of clusters to be estimated based on the highest pseudo F-statistic. The number of permutations to calculate membership probabilities was set to 1000. The results of this spatially constrained multivariate clustering are presented on Figure 6.4.

Based on the model of spatial relations and variable values there were 27 clusters identified. This number could have be reduced if we decided to group all the areas separated from the mainland into a single category. However, in order to highlight the heterogeneity of the territory we maintain 4 separate clusters for the islands of Balearic archipelago and 2 for autonomous cities of Ceuta and Melilla. Each cluster is characterized by a particular combination of average concentrations of primary air pollutants. These clusters should be interpreted as categorical classification of the territory. Cells are aggregated based on the maximum likelihood of the neighbors to have similar values; so one cluster will not necessarily have all concentrations *high* or all concentrations *low*.

On the map displayed on the left hand side on Figure 6.4 clusters are labeled with a numeric id, which corresponds to the codes column in the colorcoded table on the right of the same graph. Apart from the numeric code, each cluster is characterized by two parameters: geographic location[10] and predominating land cover class[11]. We use these parameters to describe particular ambient conditions corresponding to a particular combination of concentrations of primary air pollutants. For instance, cluster 19 intersects the territory of two NUTS1 regions: Center and Community of Madrid. Cells that are located in the Center region are predominantly occupied by non-irrigated arable lands and vineyards. The rest of the cells belonging to the Autonomous Community of Madrid are mostly covered by non-irrigated arable land and agro-forestry areas. The total territory of this cluster is 4500 sq.km., so even taking in consideration the fact that the largest metropolitan area of the country is located within this cluster, the average land cover class is still non-urban. Average concentration of NO_2 in the cluster 19 ranges from 8 to

[9]Generate Spatial Weights Matrix tool (modeling Spatial Relationships toolset), ArcGIS Pro 2.2

[10]Here, we use NUTS1 regional classification, for more information see ec.europa.eu/eurostat

[11]We estimate the proportion of the prevailing land cover class in each cell, then summarize these values for each cluster and NUTS1 region, and select the top-two values for final representation.

23 µg/m^3, O_3 is within 53-64 µg/m^3 limit, SO_2 varies from 1.4 to 4.7 µg/m^3, and average concentrations of $PM_{2.5}$ and PM_{10} equal to 7.5-9.6 µg/m^3 and 11-13.8 µg/m^3, respectively.

Overall, cluster 22 (*East, industrial or commercial units, continious urban fabric*), mostly the metropolitan areas of Barcelona) stands out by the highest values of NO_2 (11-22 µg/m^3) and $PM_{2.5}$ (10-12 µg/m^3). Cluster 1 (*Melilla, continious urban fabric, pastures*) is characterised by the highest overall O_3 (up to 87 µg/m^3) and PM_{10} (up to 20 µg/m^3). Lastly, cluster 26 (*Northwest, complex cultivation patterns, non-irrigated arable land*), metropolitan area of Gijon) shows up as having the highest concentrations of SO_2 (5-17 µg/m^3, on average).

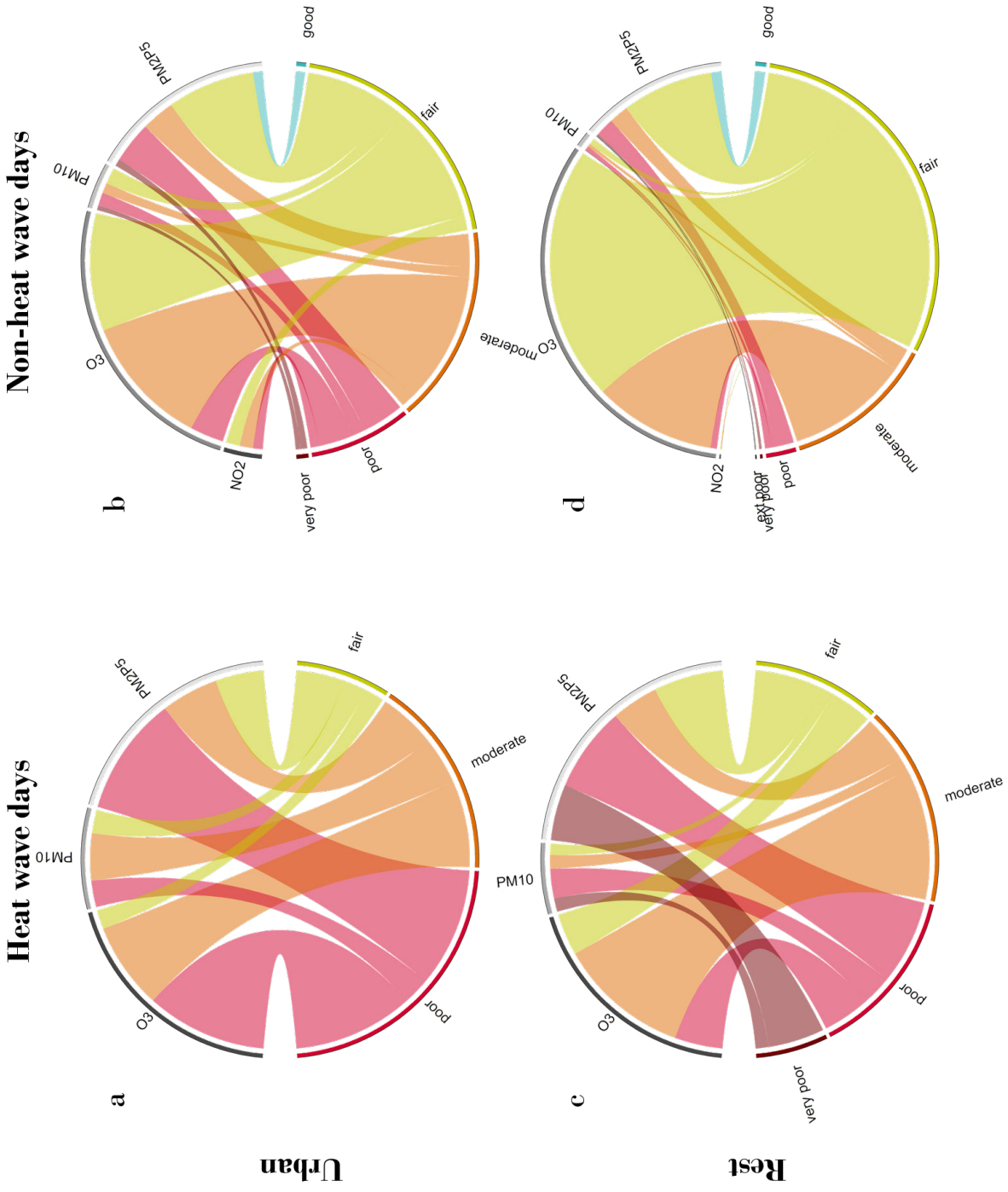


Figure 6.2: AQI levels - pollutant associations by season and land cover

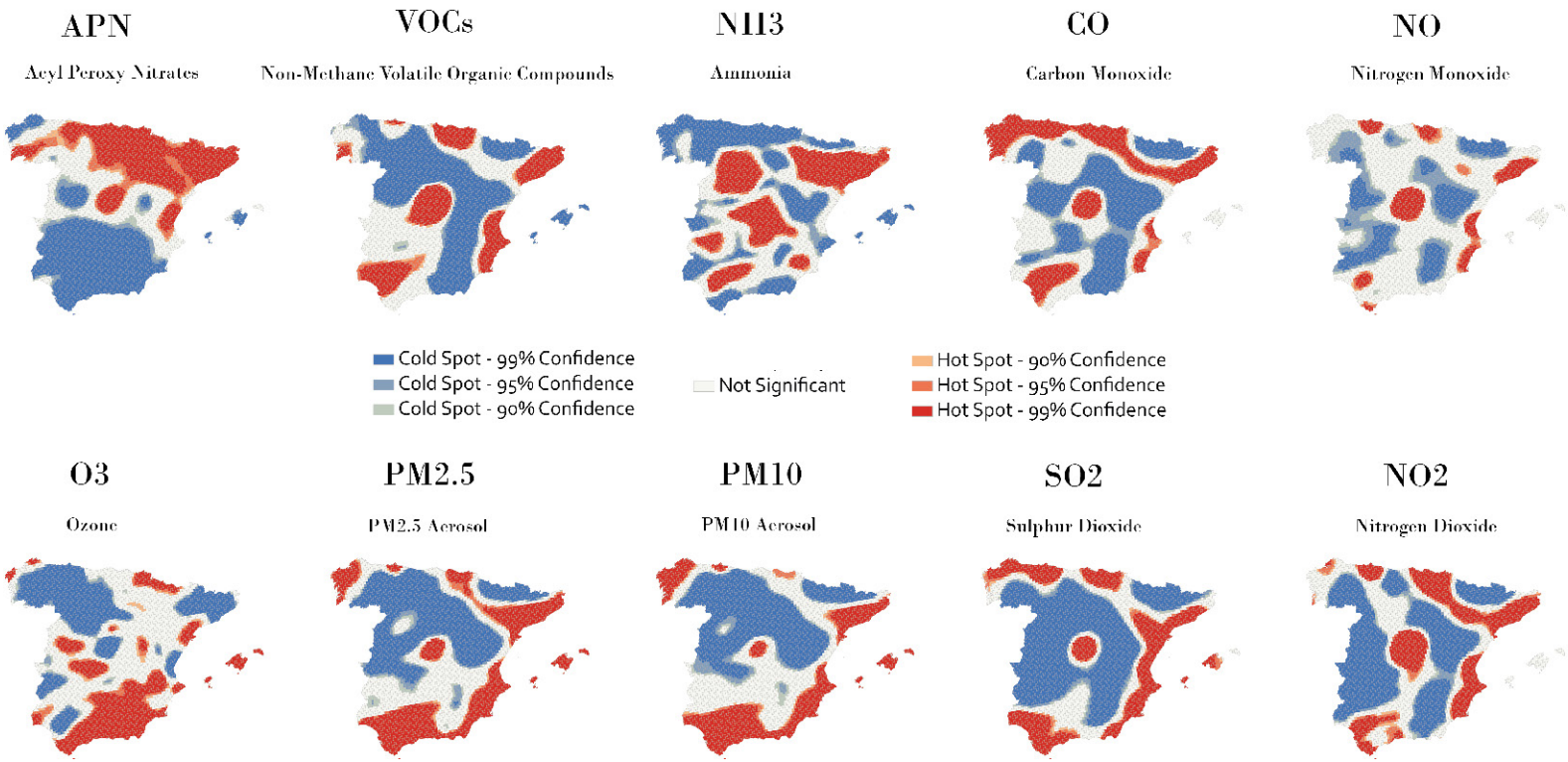
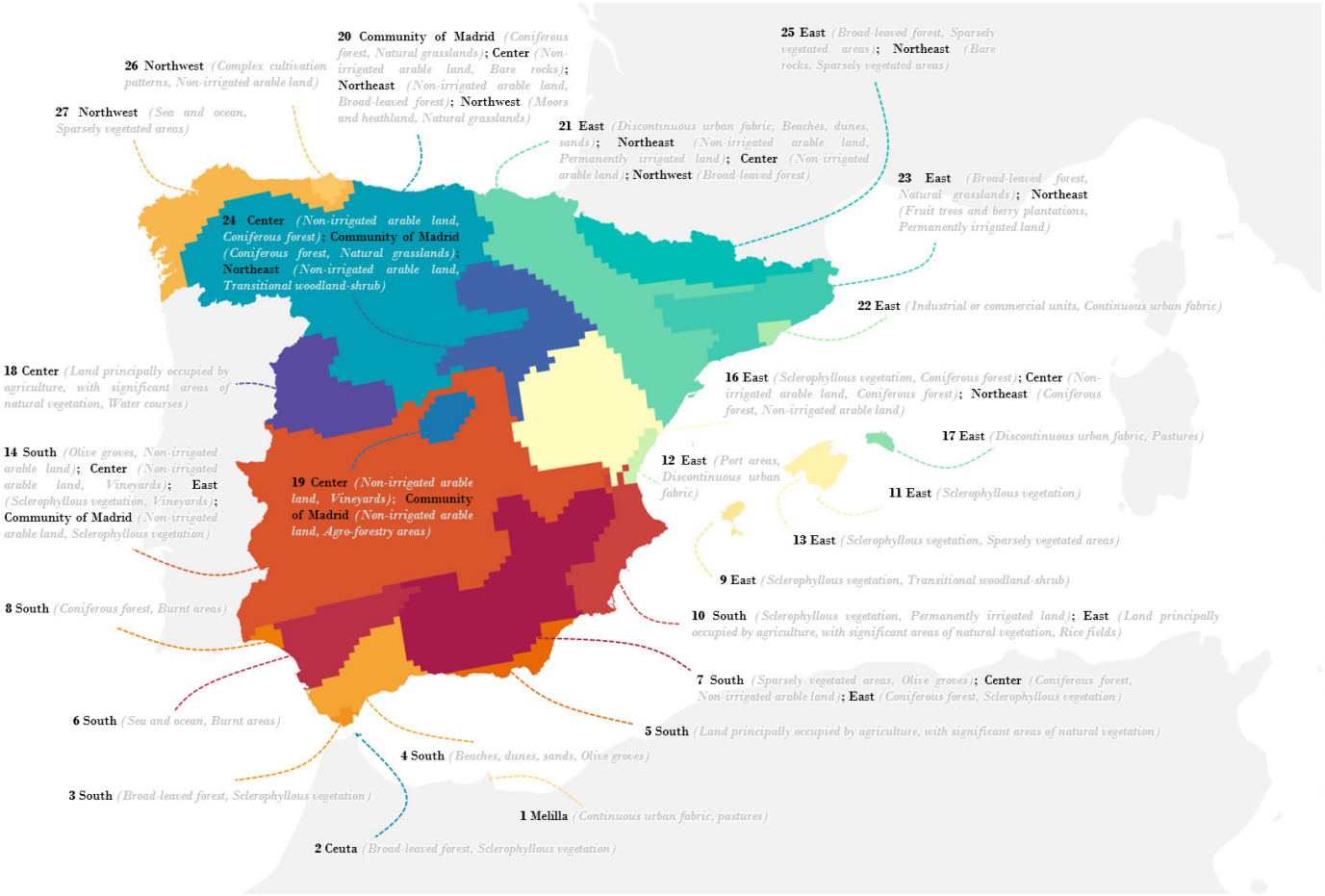


Figure 6.3: Hot spots of air pollution



Average concentrations of primary air pollutants by cluster

Code	NO_2	O_3	SO_2	$PM_{2.5}$	PM_{10}
18	1.04-2.9	65.37-73.1	0.27-0.5	5.01-6.4	7.75-9.6
24	1.28-4.6	63.65-72.6	0.39-1.5	4.7-6.7	6.97-9.9
19	8.43-23	53.16-64.9	1.41-4.7	7.55-9.6	11.05-13.8
2	9.5-9.7	75.83-76.4	5.38-5.6	9.97-10.1	17.55-17.9
20	0.88-6.5	56.5-71.9	0.29-2.8	4.33-7.2	6.51-11.6
15	2.25-2.3	85.07-85.1	1.29-1.3	7.58-7.6	14.27-14.3
25	0.69-3.8	57.49-73.5	0.16-0.9	4.41-6.4	6.45-9.2
23	2.47-13.6	57.09-76.6	0.5-4	5.94-10.8	8.42-15.9
21	1.52-11.9	59.96-78.4	0.36-4.3	5.77-8.6	8.38-13.2
17	2.25-2.8	78.1-83	0.8-1.1	8.08-8.3	15.94-17
22	11.42-22.4	51.5-60.3	2.08-4.7	10.4-12.2	14.96-17.6
12	5.52-15	57.45-66.2	1.95-3.9	6.98-8.6	10.44-13.1
11	1.68-1.7	83.98-84.8	0.97-1	8.06-8.1	16.52-16.8
16	0.92-6.8	62.7-71.9	0.37-1.9	4.89-7.5	7.36-11.3
13	2.11-6	69.03-82.6	0.91-1.8	7.56-8.2	14.08-16.1
9	2.16-4.5	78.06-84.1	1.25-2	7.82-8.3	14.53-17
1	2.62-2.6	87.13-87.2	1.75-1.8	9.86-9.9	20.72-20.8
26	6.74-14.5	51.54-64.2	5.44-17	7.56-9.8	11.5-14.5
27	2.01-8.9	53.66-75.9	0.78-5.4	5.95-8.7	8.79-16.4
4	1.59-9.5	69.69-77.3	0.86-3.2	7.06-9.8	11.71-16.1
3	5.36-11.4	71.43-74.8	3.32-6.7	9.09-10.5	15.42-17.7
8	2.95-6.1	66.93-72.6	2.82-9.3	7.45-8.6	12.22-14
5	2.49-6.4	72.54-83.3	1.17-3.6	7.33-9.4	11.57-16.2
14	1.35-9.7	61.56-74.6	0.39-2	5.64-7.6	8.71-12.5
10	3.77-11.4	60.5-80.7	1.1-3.1	6.98-9.3	10.41-16
6	2.78-9.8	58.56-75.6	0.98-3.2	7.25-9.3	11.41-15.6
7	0.93-6.6	67.62-81	0.39-1.7	5.75-8.7	9.11-13.8

Spatial Weights constructed based on polygon contiguity *(edges of corners)*

Percentage of spatial conectivity: 0.14
Average number of neighbors: 7.65

Figure 6.4: Pollution clusters

Global warming is connected to heat waves, heavy rains and severe droughts (...) It is especially crucial in Spain since the number and duration of heat waves have increased dramatically in the previous decade, posing a major threat to human health. According to the latest estimations from the Carlos III Health Institute, approximately 1800 individuals die each year as a result of severe heat in the summer.

— *Report on the climate state in Spain in 2020*, Agencia Estatal de Meteorología (2021).

7

Excess mortality attributed to heat waves in Spain

Chapter 7 focuses on the analysis of the effects of exposure to heat waves in Spain in the past 4 decades. Here, we leverage the results primarily produced in Chapters 4 and 5. However, the finest resolution of the indicators of environmental exposure developed in those chapters is not directly usable in the mortality analysis due to multiple issues that arise if spatio-temporal resolution of mortality data is increased. The main complication here is the sample size and consequent zero-inflation of the models, which may compromise the reliability of the results. Therefore, we choose *autonomous community* as a spatial unit and *week* as a time step.

7.1 Statistical analysis

We start the analysis by implementing a series of generic predictive models in order to eventually estimate excess mortality for selected units. Similarly to the approach developed by the Spanish National Epidemiology Center (so-called *MOMOTemp*[1]), we estimated the expected deaths based on restrictive models of historical averages. For each point of time a Poisson generalized linear model with overdispersion was fitted

[1]MOMOTemp is a monitoring system for daily mortality associated with temperature, which has been implemented in the National Epidemiology Center, with the aim of contributing preventive actions against the effects of excess temperatures on health proposed by the National Plan of the Ministry of Health. For more information see Vigilancia de la Mortalidad Diaria (MoMo) - MoMoTemp

to predict an upper bound on the number of death counts, according to the procedure developed by Farrington et al. (1996) and Noufaily et al. (2013). These models take into account historical trends of mortality. We further parametrize these models by setting up custom windows: 6 years for the years back in time to include when forming the base counts, and 4 weeks as window's half-size (number of weeks to include before and after current week in each year). The estimates of expected deaths are done by sex, large age groups (under 15 years old, 15-54 years old and over 65 years old) and five-year groups. Overview of the weekly variations of observed and expected deaths (presented in the form of crude death rates per 1000 of inhabitants) from 1982[2] to 2018 at the national level is displayed on the Figure 7.1.

Largest variations are seen in the youngest ages, where an overall decline of mortality over time is clearly seen. The mortality curve remains rather constant for the mid-ages, being generally lower in females than in males. In case of the elderly individuals, the trend is incremental, which reflects structural changes over time due to overall aging of the population. At the bottom part of each panel is displayed the *Standardized Mortality Ratio* (*SMR*), which is essentially the ratio between observed and expected deaths and is frequently used in epidemiological studies to quantify the increase or decrease in mortality with respect to the general population. When $SMR = 1$, it signifies that the number of observed fatalities is equal to the number of predicted cases. It would be then logical to assume that if $SMR < 1$ the mortality is lower than expected, and, conversely, it is higher if $SMR > 1$. For instance, *SMR* of 1.25 registered on a particular week in the group of females aged 65+ should be interpreted as a 25% increase in mortality with respect to expected number of deaths in the same group based on the previous 6 years of observations. In the following paragraphs, we work with this relative indicator to estimate the magnitude of excess mortality in response to heat waves.

7.2 Exploring excess mortality during heat waves

In general terms, mortality during summer months tends to be lower in comparison with other seasons, and occasional peaks are associated with exposure to extreme temperatures (Gil Bellosta et al. 2018). Table 7.1 shows variations in excess mortality at the national level during summer months in selected years[3] for adults (aged 15-64) and elderly (aged

[2]Here, 1982 is the onset year, as 6 first years in the 1975-2018 time series had to be removed due to the custom window size used for predictions.

[3]Here, a cut-off of 4 years was chosen in order to provide an overview of the entire observation window and include years with the highest heat wave "pressure"

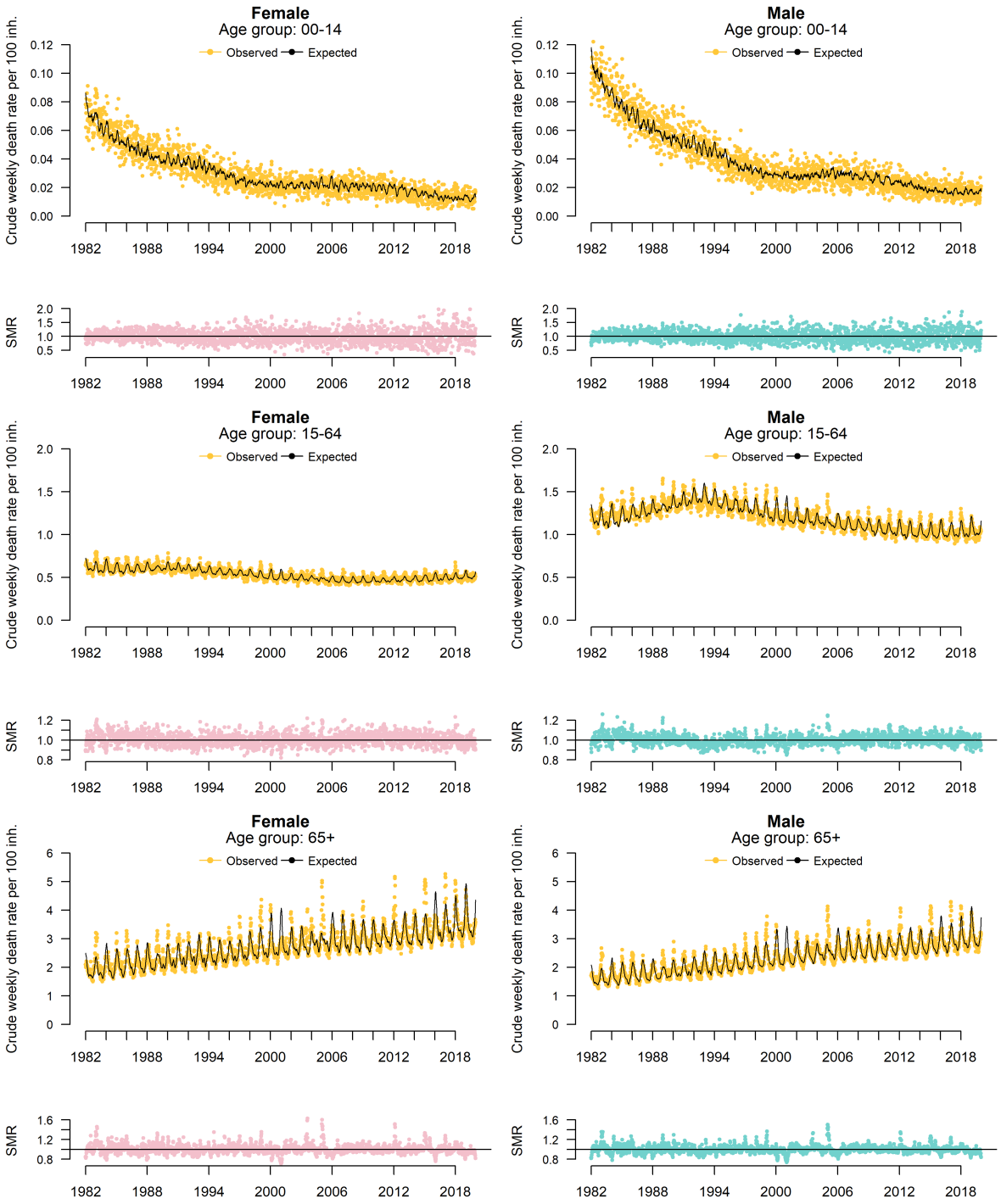


Figure 7.1: Observed and expected deaths estimated at weekly step by age group and sex

over 65). At a glance, the reader might note the peaks in excess deaths in both age groups in August 2003 and July 2015. For adults, it resulted in an added value of 8% in 2003 and 2015, whereas for older individuals 29% and 14% surplus of mortality was

registered in 2003 and 2015, respectively. However, these results exhibit a spatially heterogeneous pattern as we will see further.

Table 7.1: Differences between expected and observed deaths by age during summer months in different years in Spain

		Adults (15-64)				Elderly (65+)			
		Observed	Expected	Excess	SMR	Observed	Expected	Excess	SMR
1983	June	8710	8642	**68**	1.00	16379	16417	**-38**	0.99
	July	7193	6902	**291**	1.04	13342	12876	**466**	1.03
	August	6974	6724	**250**	1.03	11895	12288	**-393**	0.96
	September	8608	8229	**379**	1.04	15284	15146	**138**	1.00
1987	June	7341	7151	**190**	1.02	13766	14197	**-431**	0.96
	July	9221	9053	**168**	1.01	17619	17571	**48**	1.00
	August	7628	7276	**352**	1.04	14620	13641	**979**	1.07
	September	7358	7207	**151**	1.02	13619	13376	**243**	1.01
1991	June	7717	7758	**-41**	0.99	15247	15605	**-358**	0.97
	July	7967	7996	**-29**	0.99	16783	16704	**79**	1.00
	August	9736	9977	**-241**	0.97	19325	20066	**-741**	0.96
	September	7650	7813	**-163**	0.97	14009	15021	**-1012**	0.93
1995	June	9020	9114	**-94**	0.98	20169	20509	**-340**	0.98
	July	7707	7388	**319**	1.04	18271	16735	**1536**	1.09
	August	9178	9077	**101**	1.01	20683	20321	**362**	1.01
	September	7237	7265	**-28**	0.99	15752	16300	**-548**	0.96
1999	June	6555	6742	**-187**	0.97	17208	18275	**-1067**	0.94
	July	8540	8469	**71**	1.00	22487	23168	**-681**	0.97
	August	6775	6716	**59**	1.00	18141	18190	**-49**	0.99
	September	8160	8204	**-44**	0.99	21361	22054	**-693**	0.96
2003	June	6538	6493	**45**	1.00	22772	19936	**2836**	1.14
	July	8228	8122	**106**	1.01	26996	24115	**2881**	1.11
	August	6876	6310	**566**	1.08	23819	18427	**5392**	1.29
	September	6235	6290	**-55**	0.99	19095	18486	**609**	1.03
2007	June	6205	5985	**220**	1.03	20434	20238	**196**	1.00
	July	6074	6000	**74**	1.01	20399	20409	**-10**	0.99
	August	7669	7459	**210**	1.02	25100	24697	**403**	1.01
	September	5947	5988	**-41**	0.99	19422	19388	**34**	1.00
2011	June	7459	7351	**108**	1.01	26985	27251	**-266**	0.99
	July	5936	5903	**33**	1.00	20837	21566	**-729**	0.96
	August	5808	5806	**2**	1.00	21607	20890	**717**	1.03
	September	7115	7228	**-113**	0.98	25684	26065	**-381**	0.98
2015	June	5722	5749	**-27**	0.99	22672	22401	**271**	1.01
	July	7790	7152	**638**	1.08	31759	27626	**4133**	1.14
	August	5961	5702	**259**	1.04	21867	21531	**336**	1.01
	September	5759	5692	**67**	1.01	20823	21425	**-602**	0.97

Note:
Cities of Ceuta and Melilla excluded from estimations

Figure 7.2 is designed to highlight differences in mortality answers during summer months in years 2003 and 2015 in three particular communities: Andalucía, on the left, Cataluña, in the middle, and Madrid, on the right. Each row shows variations in *SMR* by week during selected years by 10 year age groups and by sex. Vertical lines on the background mark the weeks when heat waves of local type[4] were registered

[4]Here, we focus on the heat wave episodes identified using thresholds of $P_{90\%}$ of temperatures in an

anywhere within the community. What can be noticed right away is the reduction of *SMR* in 2015 in comparison with 2003 in Cataluña and Andalucía. Community of Madrid did not experience a sharp drop down of excess deaths and some age groups had higher estimates of *SMR* in 2015 than in 2003. Among these three communities, the highest overall *SMR* of 2.8 estimated during heat wave weeks was reached in Cataluña in August of 2003, followed by Andalucia with *SMR* of 2.2 in the same year and month. Nevertheless, on average Andalucia had higher *SMR* estimates (1.5) during heat wave weeks in 2003 than Cataluña (1.39). In Madrid, highest *SMR* during weeks with heat wave alerts in August of 2003 was generally lower and reached 1.9. Heat wave weeks of August in 2015 had maximum *SMR* two times lower than in 2003 in Andalucía and Cataluña, whereas Madrid did not experience heat waves of selected type in August 2015 (maximum SMR during non heat wave weeks was estimated at 1.5). In terms of the distribution by sex and age, females aged over 80 in all three communities had the highest *SMR* estimates, with Cataluña ranked the highest.

individual 10x10 km cell.

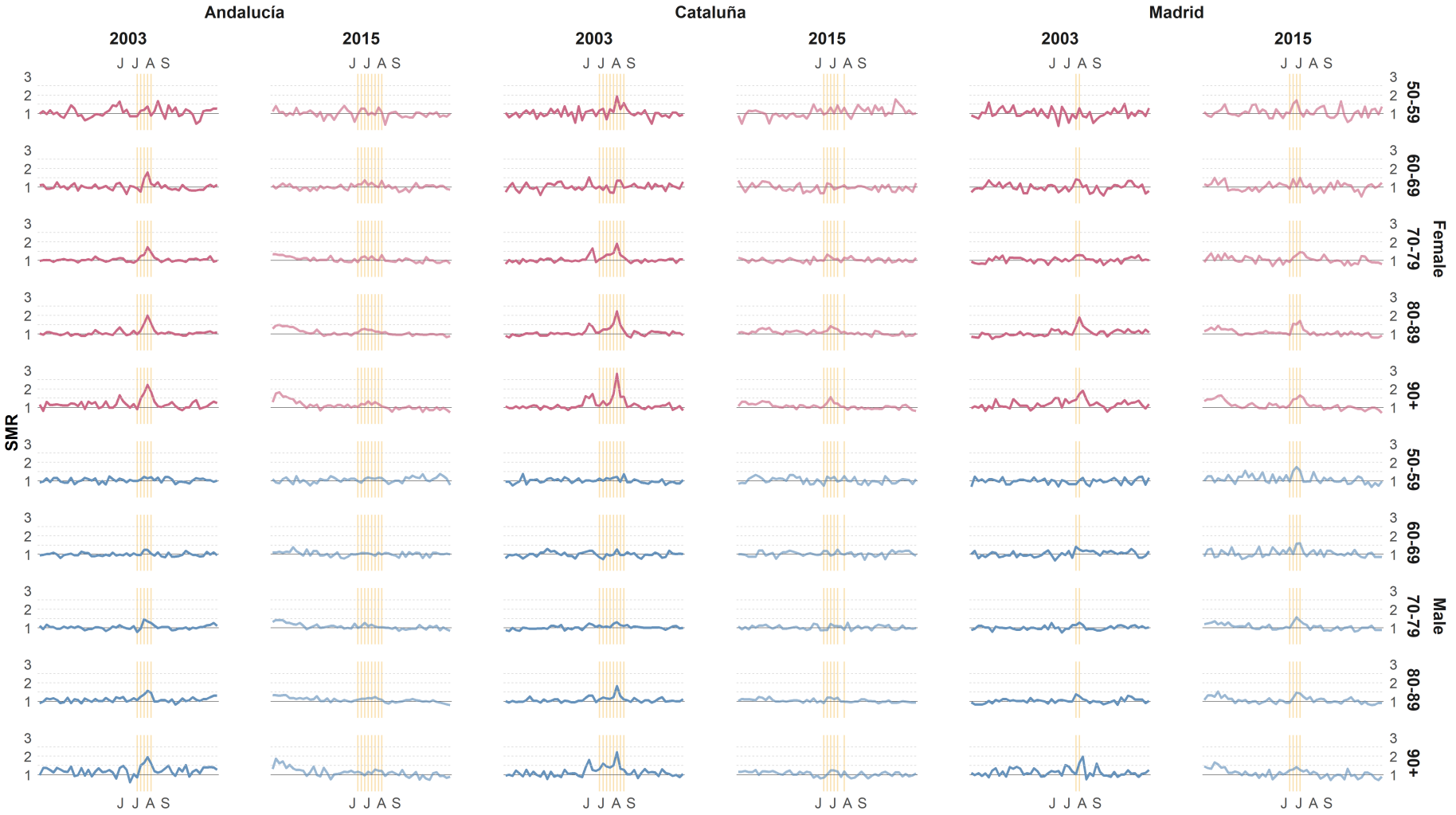


Figure 7.2: Variations in SMR by age group and sex in Andalucía, Cataluña and Madrid in 2003 and 2015

7.2.1 Spatiotemporal variations in excess mortality

One of the most important research questions in this study is whether a heat-attributed mortality decline over time occurs. Radar plot displayed on Figure 7.3 shows changes in average *SMR* estimates during weeks with (in pink) and without (in green) heat waves in the summer period at the national level. Summer weeks without heat wave alerts tend to have lower excess mortality ($SMR = 0.99$, on average), whereas *SMR* during summer weeks with heat waves has shown a persistent decline over time: 15% in 1982-1992, 8% in the following decade, 6% - in 2002-2012 and 1.05 after 2012. This could potentially indicate an overall adaptation to warming environment over time.

However, spatially the picture is somewhat patchy. Among all the communities, only Castilla-La Mancha and Balearic islands showed a persistent decline in *SMR* during heat waves from 1982 to 2018. The rest of the communities experienced an increase in the second or third decade of the studied period, and the major part showed a lower *SMR* estimates during heat wave weeks in the summer in the last decade in comparison with the first one. The exceptions are the communities of Galicia, Castilla y León, Murcia and Madrid which have the *SMR* higher after 2012 than before 1992. None of the latter two communities revealed a consistent increase but a fluctuation from decade to decade.

In order to better understand this spatiotemporal diversity, we take a step further and proceed to a more detailed analysis which aims to quantify mortality responses to exposure to heat waves from 1982 to 2018 within 17 Spanish communities.

7.2.2 Selecting indicators of exposure to heat waves

Measuring the exposure at the level of autonomous community could be tricky. As the reader remembers from the previous chapters, we derived a series of indicators on a regular 10x10 km grid at daily time step. In order for these data to be "digestible" by regression models, it needs to be transformed in a way that each row in the dataset plugged into the models has variables that correctly represent environmental exposure and mortality response. First, we limit heat wave episodes only to those that were identified using local approaches with a more relaxed criteria ($P_{90\%}$ of the temperature distribution). Additionally, we place an arbitrary threshold of 3 days on the minimal duration of the episodes so all the episodes of only 1 and 2 consecutive days are not considered. Consequently, we estimate the total number of cells[5] within each community which had

[5]Cells that did not have any population in the 2011 Census (see Fig.5.1) were excluded from the estimations.

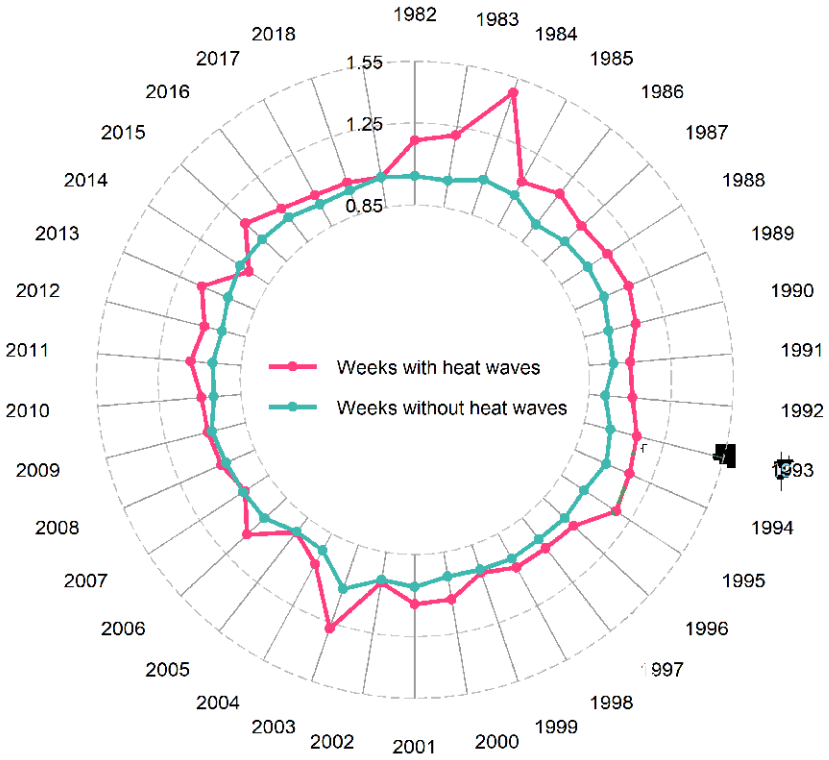


Figure 7.3: Average SMR during weeks with and without heat waves during summer months, 1982-2018

registered episodes during each week. Further, we calculate the proportion of the territory of the community "affected" by heat waves by week. If at least 10% of the cells have a heat wave alert on a particular week, we then declare that this community was *exposed* to heat waves, while the rest of the weeks in this community are classified as having *no exposure*.

Next, we classify the weeks with exposure by the intensity of this exposure during the night and during the day. The reader might recall from Chapter 5 that *tropical nights* (those with minimum nocturnal temperature above 20ºC) is a frequent phenomena in Spain, which most intensely affects the Mediterranean coast (Fig.5.8). For individuals living in a temperate climate, going through prolonged periods of nocturnal temperatures that are more characteristic of a different climatic area (as the name suggests, to subtropical and tropical climates), on top of being exposed to elevated temperatures during the day, might pose additional risks for health. To account for this, we classify the weeks with heat wave episodes by average night-time temperature during the episodes. To classify the weeks with exposure to heat waves by the value of intensity of exposure

during the day, we used relative intensity index $MI_d(T_d)$ described in Chapter 4. Here the average day-time magnitude index estimated for weeks with heat wave exposure was cut into two intervals, with the lower interval referred to as *moderate heat*. In turn, the values of the $MI_d(T_d)$ corresponding to the upper interval indicated the exposure to *extreme heat*.

Figure 7.4 summarizes these two final variables of day- and night-time exposure to heat waves, which are independently entered in the models later. The size and color of the dot corresponds to the day-time exposure, while the opacity level marks the weeks with and without tropical nights. Moreover, apart from the exposure to heat waves of any of the aforementioned types, we believe that it is essential to introduce past exposure into the analysis. In other words, excess mortality on a current week might not reflect the current but also prior exposures to heat waves. Thus, for each week we introduce two additional variables that indicate the lag terms for nocturnal and diurnal exposure. However, the lag perspective will be analyzed in a more comprehensive way using a different approach in Chapter 8.

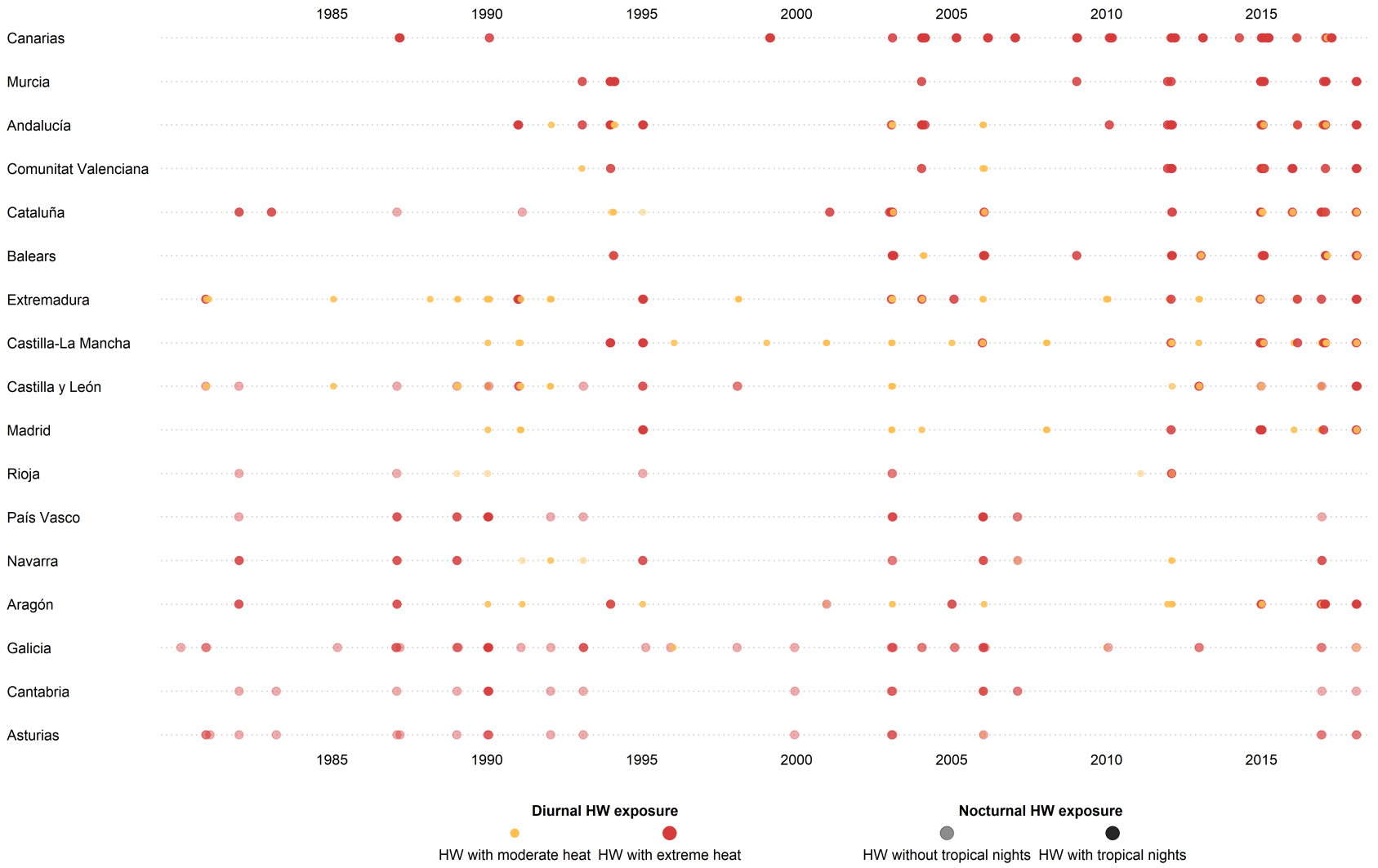


Figure 7.4: Variables used to represent day- and night-time exposure to heat waves in regression models, by week, year and autonomous community

7.2.3 Effect estimates

On the last step, we create a series of linear regression Poisson models with log link function for two large age groups, adults (15-64) and elderly (65+). Here, we use the *observed* deaths as dependent variable, and *expected* deaths, estimated at the previous step, as an offset, i.e. an a priori known component to be included in the linear prediction during fitting. Therefore, the results should be interpreted from the angle of *excess* mortality. We create five independent models for two age groups. These models differ by the complexity, i.e. the number of variables included. After adding a new set of variables we perform tests for significance based on the change of the deviance after adding new predictors to the null model. The most complex model based on nocturnal exposure could be formalized as shown in the equation below ((7.1)).

$$\begin{aligned}\log(E(\text{deaths}_{\text{observed}})) = \alpha &+ \beta_1(\text{sex}_{\text{Male}}) + \beta_2(\text{ccaa}_{\text{AR}}) + \beta_3(\text{ccaa}_{\text{AS}}) + \ldots + \beta_{17}(\text{ccaa}_{\text{VC}}) \\ &+ \beta_{18}(\text{expNight}_{\text{Regular}}) + \beta_{19}(\text{expNight}_{\text{Tropical}}) \\ &+ \beta_{20}(\text{expLagNight}_{\text{Regular}}) + \beta_{21}(\text{expLagNight}_{\text{Tropical}}) \\ &+ (\text{offset} \rightarrow \text{deaths}_{\text{expected}})\end{aligned} \tag{7.1}$$

where *expNight* denotes the current exposure and *expLagNight* corresponds to the past exposure. In the upcoming chapters, we will use a distinct approach to explore the lagged exposure-response relationships through the *distributed lag non-linear* modelling approach. The results of the regression models run for the age group of 65+ are displayed in the Table 7.2.

Figure 7.5 illustrates the effect estimates for both age groups for two types of models: with and without lag terms. Variables are color-coded to ease the interpretation[6]. Plots 7.5 a (current exposure) and b (with lag term) show the exponentiated regression parameters[7] derived from the models based on night-time exposure, whereas plots 7.5 c and d correspond to the models based on day-time exposure.

[6]In blue: sex (ref. *Female*); in green: autonomous communities (ref. *Andalusia*); in red: current exposure (ref. *No exposure*); in orange: past exposure (ref. *No exposure*)

[7]Estimated effects presented as relative odds ratios or OR, which are computed by taking an exponent of the estimated coefficients e^{β_x}. Essentially, the OR compares the chances of an event occurring in the absence of a certain exposure against the odds of that outcome occurring in the presence of that exposure. If OR equals to 1, the exposure does not affect the odds of an outcome. The OR above 1 implies the higher odds of an outcome due to the exposure, while OR below 1 signifies that the exposure is associated with lower odds of an outcome.

Table 7.2: Regression results (age group: 65+)

	Dependent variable:				
	Observed deaths (offset by expected deaths)				
	Default	Nocturnal exposure		Diurnal exposure	
	(1)	(2)	(3)	(4)	(5)
Male	−0.004***	−0.004***	−0.004***	−0.004***	−0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Aragón	−0.001	0.003	0.004	0.003	0.004
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Asturias	−0.007*	0.0002	0.002	−0.001	−0.0001
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Cantabria	−0.007	0.0004	0.002	−0.001	0.0004
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
Castilla y León	−0.002	0.002	0.003	0.001	0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Castilla-La Mancha	−0.001	−0.001	−0.001	−0.001	−0.0002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Canarias	0.0003	0.0002	0.0005	0.00001	−0.0002
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Cataluña	0.0001	0.002	0.002	0.001	0.002
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Extremadura	0.001	0.002	0.002	0.002	0.003
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Galicia	−0.003	0.0005	0.002	−0.002	−0.002
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Balears	−0.005	−0.003	−0.003	−0.003	−0.003
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Murcia	0.0002	0.005	0.006	0.005	0.005
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
Madrid	−0.002	0.002	0.003	0.002	0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Navarra	−0.001	0.006	0.008	0.005	0.007
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
País Vasco	−0.005*	0.002	0.004	0.002	0.003
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Rioja	−0.006	0.003	0.005	0.002	0.004
	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
Comunitat Valenciana	−0.002	0.003	0.004*	0.002	0.003
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
This week: regular nights		0.110***	0.100***		
		(0.006)	(0.006)		
This week: tropical nights		0.140***	0.110***		
		(0.003)	(0.003)		
Last week: regular nights			0.031***		
			(0.006)		
Last week: tropical nights			0.063***		
			(0.003)		
This week: moderate heat				0.130***	0.100***
				(0.004)	(0.004)
This week: extreme heat				0.140***	0.110***
				(0.003)	(0.003)
Last week: moderate heat					0.045***
					(0.004)
Last week: extreme heat					0.065***
					(0.003)
Constant	0.004***	−0.006***	−0.009***	−0.006***	−0.008***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Observations	21,930	21,930	21,930	21,930	21,930
Akaike Inf. Crit.	184,591.000	181,822.000	181,410.000	181,841.000	181,423.000

Note: *p<0.1; **p<0.05; ***p<0.01

The effects corresponding to the geographic variables are not statistically significant in any of the models, implying that there is no significant inter-regional difference. The effects for sex are significant. The risk of excess death for male individuals were estimated to be lower than those for females, which is consistent with findings from other studies (Yu et al. 2010; Borrell et al. 2006; Lerch and Oris 2018). The effects corresponding to current exposure are statistically significant for both adults and elderly, unsurprisingly being more pronounced in elderly individuals. The odds of excess death due to the exposure to heat waves with tropical nights are generally higher (for 65+ age group OR = 1.15, 95%CI: 1.14-1.15; for 15-64 age group OR = 1.06, 95%CI: 1.05-1.07) than those corresponding to the exposure to heat waves with regular (below 20°C) nights (for elderly, OR = 1.11, 95%CI: 1.10-1.12; for middle ages, OR = 1.04, 95%CI: 1.02-1.06).

After adding lagged exposure to the models, the risks of current exposure were dragged down, however remained elevated for both age groups. For individuals aged 65+, the exposure to heat waves with tropical nights resulted in OR of 1.11, 95%CI: 1.11-1.12, while being exposed to these heat waves on the week before had the odds of 1.06, 95%CI: 1.05-1.07. Exposure to heat waves with average night temperature below 20°C on a given week had generally lower risks for the elderly (OR = 1.10, 95%CI: 1.09-1.11), while the odds for prior exposure to heat waves of this type were estimated at 1.03, 95%CI: 1.02-1.04, for this age group. For younger individuals aged 15-64 the current exposure to heat waves with and without tropical nights had the OR of 1.05, 95%CI: 1.04-1.07, and 1.04, 95% CI1.02-1.06, respectively. Past exposure to heat waves with tropical nights had slightly lower effects (OR = 1.01, 95%CI: 1.00-1.03), while past exposure to heat waves with temperatures below 20°C in the age group of 15-64 was associated with even lower odds of the outcome (OR = 0.98, 95%CI: 0.96-1.00).

In terms of the day-time exposure to heat waves, the odds of excess deaths were slightly lower in comparison with the results derived from the models based on night-time exposure. Thus, for elderly individuals being exposed to extreme heat during the day resulted in OR of 1.14, 95%CI: 1.14-1.15, while for the younger adults the OR were of 1.07, 95%CI: 1.05-1.08. Exposure to moderate heat was associated with lower odds of the outcome: OR = 1.13, 95%CI: 1.12-1.14, for those aged 65+, and OR = 1.04, 95%CI: 1.03-1.05, for those aged 15-64. Similarly to the models based on the nocturnal exposure, the introduction of the lag term shifted the OR towards the null, though OR for both age groups were associated with higher odds of excess deaths. For elderly, the exposure to extreme heat on the same week was associated with OR of 1.12, 95%CI: 1.11-1.2, while the exposure to extreme heat on the previous week had the odds of 1.06,

95%CI: 1.06-1.07. For adults, current exposure to extreme heat resulted in OR of 1.06, 95%CI: 1.05-1.07, while past exposure to extreme heat did not affect the outcome (OR = 1.008, 95%CI: 0.996-1.02). Interestingly, past exposure to moderate heat in adults aged 15-64 had an increased OR of 1.01, 95%CI: 1.00-1.03, an effect not observed for the exposure to extreme heat. Current exposure to moderate heat in the same age group in the models with the lag term included had the OR of 1.03, 95%CI: 1.02-1.05, while for the individuals aged 65+ the odds were estimated at 1.10, 95%CI: 1.09-1.11.

Our findings demonstrate that preventive public health initiatives oriented to mitigate the effects of exposure to heat in Spain should focus on adults, particularly elderly women, everywhere across the country. Moreover, the attention should be paid not only to the days with extreme abnormal heat, but also to the episodes of excessive heat of moderate magnitude, either during the day or at night-time.

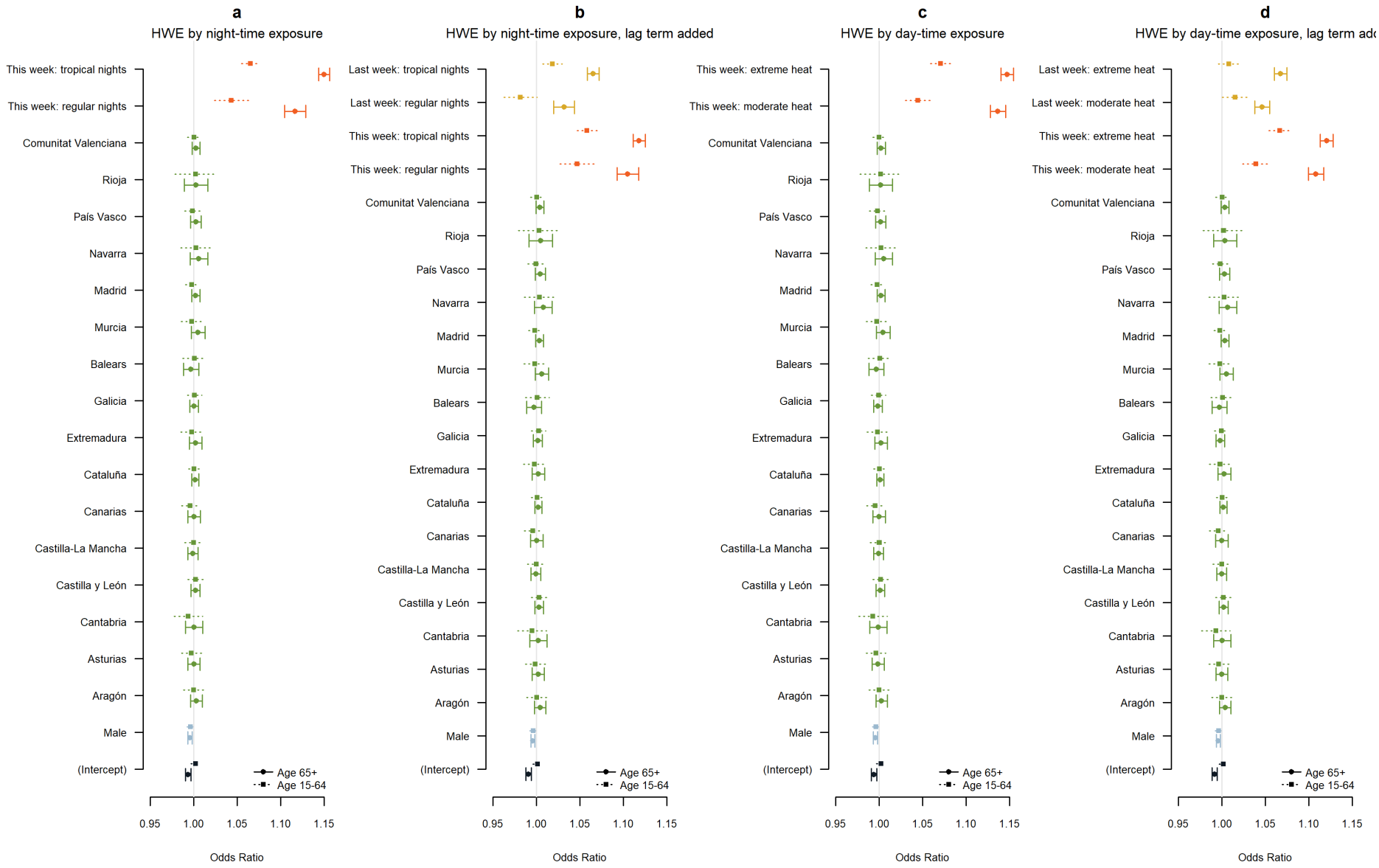


Figure 7.5: Estimated effects from regression models

The rate of adaptation that was obtained in the studied period has helped avoid greater mortality due to heat as a consequence of registered temperature increases does not guarantee that the same will occur in the future. The challenge lies in continuing with adaptation. From the perspective of "planned" (institutional) adaptation, this includes continuing to progress in terms of implementation, evaluation and improvement in prevention plans, greater governance and stakeholder involvement, interventions at the urban and health care level, and improvements in infrastructure and population education.

— *The evolution of minimum mortality temperatures as an indicator of heat adaptation*, Follos et al. (2020).

8

Spatiotemporal variations of minimum mortality temperatures in Spain

In this chapter, we introduce the reader to the recently developed concept of the *Minimum Mortality Temperature*. We see the indicator of minimum mortality temperature as a measure of adaptation to a continuously changing environment. The objective of the analysis presented below is to explore geographic and temporal variations of the minimum mortality temperatures and attributable mortality fractions in Spain at different spatial levels during the period 1979-2018 using individual death records and refined environmental data.

In general terms, the relationship between air temperatures and mortality exhibits a U or J-shaped non-linear dependency, where the most extreme ranges of the temperature are associated with a sharp increase in mortality. The point where the health effects (mortality, in this case) is at its minimum is called the *optimum temperature*, or *minimum mortality temperature* (further reported as *MMT*), thus putting the edges of the temperature in the non-optimum spectrum, suggesting greater risks for human health. There is a plethora of factors that could potentially contribute to individual risks of a heat-related illness, in this way making some individuals more vulnerable than the others. These factors range from individual health, e.g. advanced ages (Linares and Díaz 2008; deCastro et al. 2011), and medical status, e.g. chronic cardiovascular, respiratory diseases, obesity (Iñiguez et al. 2021; Díaz, Carmona, Mirón, Ortiz, and Luna 2020; Fernández-Raga et al. 2010; Valdés et al. 2014) to overall socioeconomic status (poverty, low educational levels), living (housing) and environmental (air pollution) conditions (Xu, Chen, et al. 2019;

Voelkel et al. 2018; Gao et al. 2020; Farbotko and Waitt 2011). We remind the reader that the theoretical basis was discussed in details in Chapter 2.

The geographic variation and evolution of the MMT over time were described using different data in different regions across the globe (Gasparrini Antonio et al. 2015; Gasparrini, Guo, et al. 2015; Guo et al. 2014; Vicedo-Cabrera, Sera, et al. 2018). In Spain, detailed studies of MMT variations were mostly done at the level of provincial capitals (Tobias et al. 2012; Tobías, Armstrong, et al. 2017). As argued by many researchers, incremental changes in the MMT indicate progressive adaptation of the population to the hotter environments. Follos et al. (2020) estimated the increase of MMT in Madrid and Sevilla at 0.58°C and 1.14°C per decade, respectively. The work by Achebak, Devolder, and Ballester (2019) revealed an increase in overall MMT in Spain of 0.7°C from 1980-1994 (19.5°C) to 2002-2016 (20.2°C), and a general reduction in risks and attributable fractions of cardiovascular deaths due to heat or cold. Hypothetically, a complete adaptation could be achieved when MMT increases at the same speed as the temperature, i.e. an increase of 1°C MMT for a rise of 1°C of the mean annual temperature (Tobías, Hashizume, et al. 2021).

Considering the work that has already been done, the objective of this chapter is to offer a new perspective on the geographic and temporal variations of the MMT and attributable mortality fractions across Spain, during the period between 1979 and 2018. The novelty of our study is to work at different spatial levels and to use individual death records as well as refined environmental data.

8.1 Challenges of the geographical approach: combining environmental and demographic data

As discussed previously, one the most challenging tasks in any analysis based on wide observational windows and essentially different data domains (e.g. meteorological and demographic data), is to find a compromise to preserve the resolution for all the domains and guarantee sufficient sample sizes. Thus, to perform a comprehensive and scalable analysis of the association between mortality, temperature, heat index and air pollution we established three levels of spatio-temporal aggregation:

1. **Macro level**: national and regional aggregated.

Here, we estimated daily mean and maximum temperatures and heat index for a) national territory b) large regions. In the latter case, we opted for a custom aggregation of NUTS1 regions into five larger units: North (Northwest **ES1**, includes *Asturias*, *Cantabria* and *Galicia*; Northeast **ES2**, includes *Aragón*, *Navarra*, *País Vasco* and *Rioja*), East (East **ES5**, includes Baleares, Cataluña and Comunidad Valenciana), Center (Center **ES4**, includes *Extremadura*, *Castilla-La Mancha*, *Castilla y León*; Community of Madrid **ES3**, includes *Comunidad de Madrid*), South (South **ES6**, includes *Andalucía*, *Murcia*, *Ceuta* and *Melilla*) and Canary Islands (Canarias **ES7**). In case of splitting regions further by contextual characteristics (either population size or socioeconomic characteristic of municipality) we used the municipality-to-cell linkage (method of assignment explained in Chapter 3). This linkage between administrative units (municipalities) and regular units (10x10 km cells) allowed us to estimate temperatures and heat index in different contextual settings within regions in a more precise way.

When working at the national aggregated level, deaths were aggregated by day, sex and large age groups[1] for entire observational window (1979-2018). Further, in order to aggregate municipalities by their population size, the reference data on the population were required. Here we relied upon the Continuous Register Statistics which provides estimates of the population in each municipality since 1998. As a result of the shorter time period (going from 40 down to 20 years), the sample size was lowered. On the other hand, in order to group municipalities by degree of deprivation, we used only municipalities of more than 10K inhabitants (as references are not available for censored units), which also led to the reduction in sample sizes. Such data limitations are explicitly acknowledged along the discussion, and have to be kept in mind when interpreting the results.

2. **Meso level**: municipalities of 52 provincial Spanish capitals.

Average and maximum daily values of temperature and heat index were estimated for each of the 52 municipalities corresponding to provincial capitals for the entire period from 1979 to 2018. To work at the so-called meso level, we revised the cell-to-municipality linking procedure used to work at other levels. To avoid, on one hand, averaging temperatures over large and often sparsely inhabited areas of municipalities (e.g. municipalities of Badajoz and Cáceres shown on Fig.8.1), and capture better the intra-municipality dispersion pattern of human settlement, on the other hand, we used the following algorithm. First, only those 10 km cells that contain at least one population

[1]Here we work with three large divisions: under 15 years (children), 15-65 years (adults) and over 65 years (elderly).

entity polygon and are not entirely censored[2] were pre-selected. Then, cells were ordered by the populated area within an individual cell[3]. Further, using a stepwise algorithm we compiled a list of 10km x 10km cells that altogether accounted for at least 75% (custom threshold) of total populated area of the municipality, as illustrated on Fig.8.1 (b). When this condition was satisfied, we stopped adding new cells. Final selection of cells for the analysis at meso level in 52 provinces are displayed on Fig.8.2. Later we estimated daily average and maximum values of temperature and heat index in selected subset of cells within each of the 52 capital municipalities.

As municipalities corresponding to the provincial capitals did not change their configuration during the observational window, we were able to use the entire period and estimate daily deaths in each of the 52 municipalities from 1979 to 2018.

3. **Micro level**: provinces disaggregated by municipality size.

As explained earlier, in order to include population size in the analysis at the municipal level, it is necessary to reduce the observational window from 1979 to 1998 due to the availability of the population estimates at this level. Each province was then classified by the municipality size into two groups: those having less than 50K of inhabitants (further used as a proxy for rural settings) and those having over 50K of inhabitants (proxy for urban settings). This classification was performed for each year individually to account for temporal changes. For visual representations we used the geometry corresponding to the end of the study period. Map shown on Figure 8.3 highlights variations in municipal sizes within national territory in 2018[4]

Further, using the municipality-to-cell linkage (Fig.3.4) we estimated daily average and maximum temperatures and heat index in the groups of selected cells corresponding to urban and rural classes within each province for the period from 1998 to 2018.

[2]In order to identify cells which should be excluded from the analysis we used the reference grid of 1km x 1km used provided by INE to disseminate statistical information on population according to Eurostat guidelines (for more information visit www.ine.es). Here, we identified 10km x 10km cells which contain only censored cells of 1km x 1km and excluded them from further consideration as shown on Fig.8.1 (a).

[3]To obtain an aerial estimate of populated surface, we spatially intersected 10 km grid with the layer of population entities.

[4]Here we present a map with 3 classes: *Over 10K* in dark violet color (municipalities corresponding to provincial capitals are highlighted in cyan), *10K-50K* (in brick red) and *Under 10K* (in yellow). The latter two classes are further grouped into a single class of *Under 50K*. The purpose of this map is to demonstrate to the readers an overall latitudinal and longitudinal gradient of "rurality". The bar chart on the left hand side of the figure is intended to show the composition within each autonomous community. The chart is sorted from those communities with the highest percentage of rural (Castilla y León, Aragón, Rioja) to the lowest.

For the same period of time and classes within each province we estimated daily death counts. In order to avoid zero-inflation problem while modelling we did not lower the level of spatial detalization any further neither stratified the dataset by available variables.

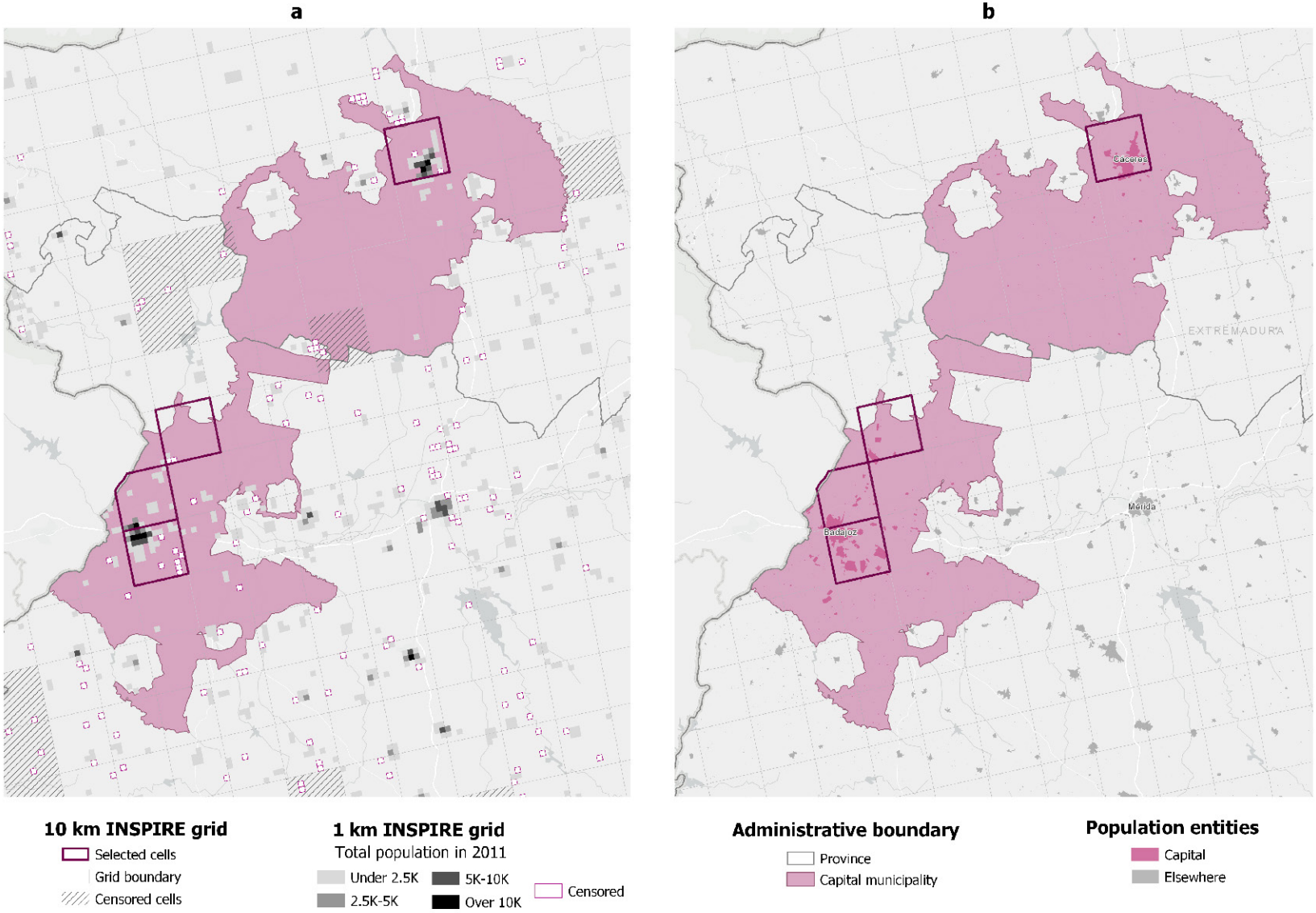


Figure 8.1: Cells selected to work with individual municipalities corresponding to provincial capitals. Methodological illustration

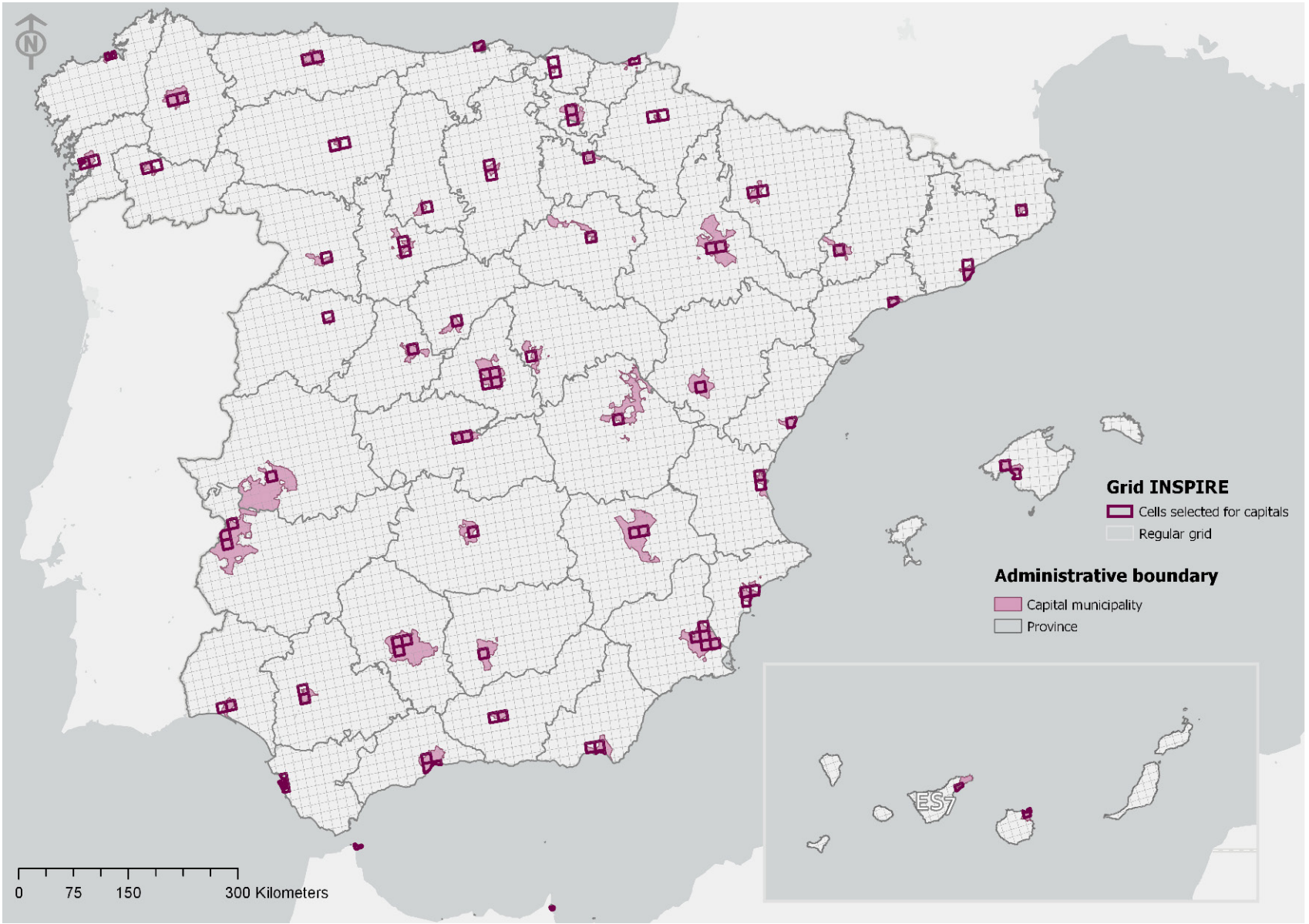


Figure 8.2: Macro grouping: cells selected to match capital municipalities

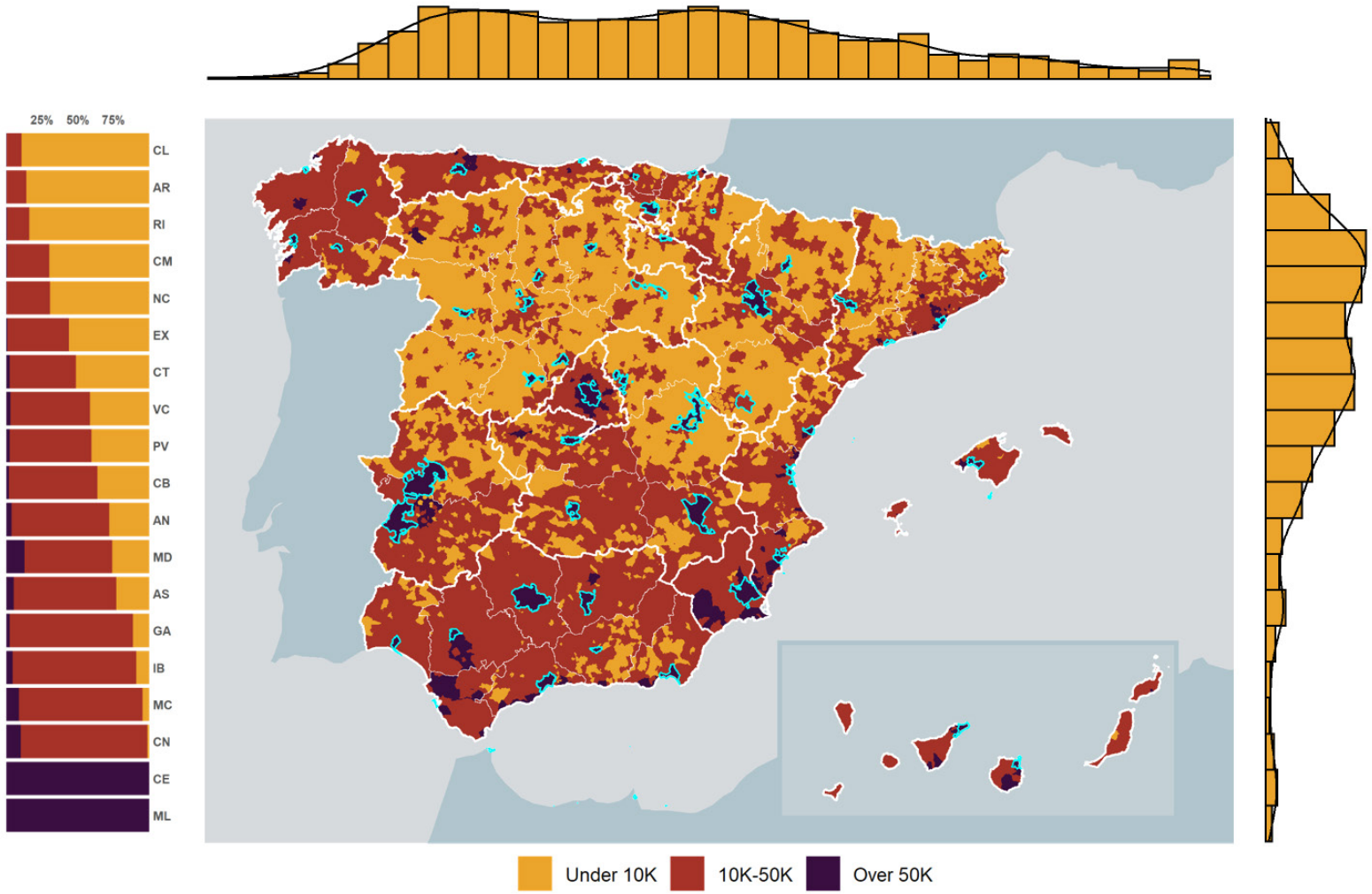


Figure 8.3: Spanish municipalities by population size in 2018

8.2 Statistical analysis

Delayed exposure effects is an issue that raised a progressive interest in environmental epidemiology since 2000 (O'Neill et al. 2003; Michelozzi et al. 2009; Conti, Meli, et al. 2005). This interest triggered the development of sophisticated methods to account for *lags* between the onset of unfavorable environmental conditions and eventual death of the individuals. Not only the presence of the delayed effect but its actual duration represents an important factor for understanding the underlying behavior (harvesting or long-term) of the observed effects.

The *distributed lag non-linear models* (DLNMs) represent an extension of the conventional *distributed lag models* (DLM), designed to describe lag structure of linear effects, proposed in econometrics some decades ago (Almon 1965). Some authors attempted to relax the linearity assumptions and explored the non-linear relationship between exposure and outcome (Schwartz 2000-004-28; Braga et al. 2001; Roberts and Martin 2007-003-17) The *DLNM* class of models is designed to simultaneously represent the exposure–response relationship and its temporal structure in a flexible manner (Gasparrini, Armstrong, et al. 2010), what is perfectly coherent with the vulnerability approach we rely on. Modelling strategy developed by Gasparrini and colleagues is fundamental for the analysis performed in this chapter. The statistical analysis was executed entirely in R software (v.4.0.4) using *dlnm* package (Gasparrini 2011).

Following the methodology suggested by these authors, we modeled the exposure-response association and lag-response association with selected indicators using a distributed lag non-linear model. For each chosen unit of analysis (either a single municipality or a group of municipalities, at different time steps) a time-series quasi-Poisson regression was applied to derive a site-specific temperature-mortality association, reported as relative risks (RR). RR is a standard measure used in demography and epidemiology *to compare the risk of a health event (death, in our case) in one group with the risk in another group*, as defined by the CDC[5]. Rephrasing another definition by Vicedo-Cabrera, Scovronick, et al. (2021), the RR of death over selected lag periods for each indicator value in the observed range can be interpreted as *change in mortality risk at a given value of temperature/heat index compared with a reference temperature/heat index*. The reference value used in our study corresponds to the site-specific MMT/MMHI[6] (or, in other

[5]See Centers for Disease Control and Prevention (CDC), Principles of Epidemiology in Public Health Practice - Measures of Risk - Measures of Association for more information, access via www.cdc.gov

[6]Minimum Mortality Heat Index (MMHI), an equvalent of the MMT metric based on the heat index values.

words, the value of the indicator for which the risks of death are the lowest). The results reported in the following sections are shown as an estimate with a 95% empirical confidence interval, which is derived from the bootstrap simulation performed during computation. Moreover, following the approach suggested by Tobías, Armstrong, et al. (2017), we apply a series of constrains to the range of values used for computing MMT to account for potential problems in the small areas (especially, when working at meso level). Thus, we estimated MMT using an entire range of values (further, we refer to this estimates as *Unrestricted* or *Uncontrained*), and also constraining the range of values to 1^{th}-99^{th}, 5^{th}-95^{th} and 10^{th}-90^{th} centile ranges.

Location-specific model could be formalized as follows (8.1).

$$\begin{aligned} Y_s &\sim Poisson(\mu_{\text{s}}) \\ \log E(\mu_{\text{s}}) &= \alpha + \text{cb} + ns(\text{time}, 8df \times \text{year}) + DoW \end{aligned} \tag{8.1}$$

where Y_s denotes the observed daily death count in a specific site s, α is the intercept, *cb* is the cross-basis matrix for the bi-dimensional functional space of predictor and lags produced by distributed lag non-linear model, *ns* stands for the B-spline basis matrix for a natural cubic spline with 8 degrees of freedom per year to control for seasonal and long-term trends, and *DoW* represents an indicator of the day of the week. The exposure function included 3 internal knots placed at the 10^{th}, 75^{th}, and 90^{th} percentiles of site-specific indicator distribution. The lag period was extended to 3 weeks (21 days) to account for the long delayed effects of cold temperatures (in case of estimating all-year MMT). For the summer season (June to September) the lag period was reduced to 7 days, and the *time* argument was adjusted accordingly.

Daily average temperature and heat index were selected as primary exposure indices in this study (estimation schema depended on the choice of spatial unit as explained earlier). The choice of exposure metric was evaluated in sensitivity analysis, where we replaced the mean with maximum daily values.

We also estimated the attributable numbers *AN* and fractions *AF* of mortality due to cold and heat using *backward* (current burden, denoted with *b*-) and *forward* (future burden, denoted with *f*-) perspectives, deriving it from the models created on the previous step. As explained in detail by Gasparrini and Leone (2014), from a forward standpoint future risks are associated with the current exposure whereas from a backward standpoint current risks are seen from the perspective of the past exposures. A conceptual model of the backward and forward perspectives is displayed on Figures 8.4 (a) and (b) as it was displayed in the original work by Gasparrini and Leone (2014).

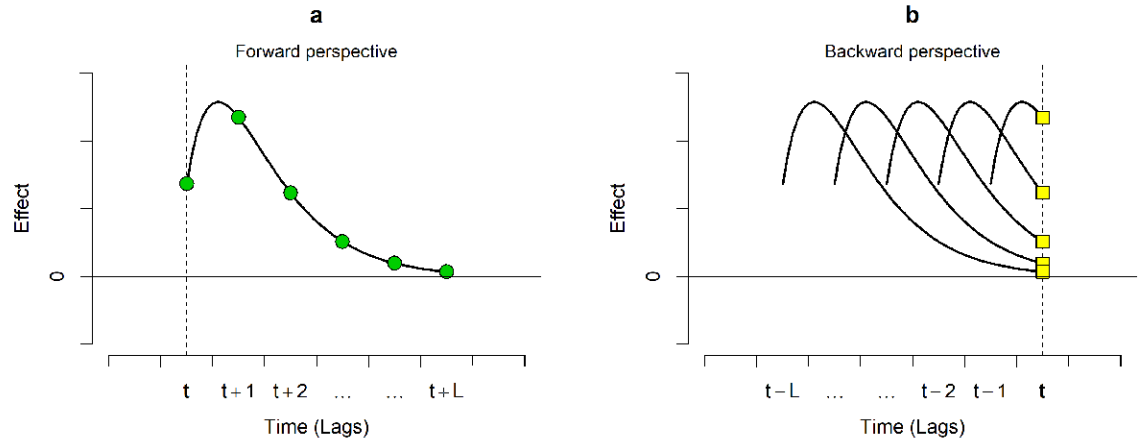


Figure 8.4: Forward and backward perspectives of exposure-lag-response associations

The attributable risk from DLNMs were computed using a custom function suggested by the same group of authors. The uncertainty intervals were computed empirically through Monte Carlo simulations (here, we arbitrarily chose a 5000 simulations per estimation). The empirical confidence intervals for $b(f)$-AN and $b(f)$-AF for overall and separated components were computed by simulating 5,000 samples from the assumed multivariate normal distribution. There were 4 components considered: extreme cold (temperature/heat index below 5^{th} percentile), cold (below MMT), heat (above MMT) and extreme heat (above 95^{th} percentile).

Additionally, to evaluate changes in the MMT we split the period into equal ranges[7] and compared last period with the initial one. At the meso level, we estimated MMT using moving average windows of 10 years in order to achieve smoother estimates for small areas.

8.3 Spatial and temporal variations of MMT in Spain since 1979

We start by exploring the overall cumulative exposure-response association in Spain at the national aggregated level. Further, we focus on the delayed responses to exposure to edges of the temperature and heat index spectrum and reveal common consistent patterns. Further we proceed to the analysis disaggregated by large age groups and sex and focus on the dose-response and lag-response associations in each group. We wrap

[7] 5,10 and 20 years were tested, and 10 years were selected as the most appropriate period for comparison.

our discussion on the national level by estimating temperature-attributable fractions and numbers (overall and for cold/heat components).

8.3.1 Cumulative exposure-response associations

Figures 8.5 - 8.8 reveal exposure-response associations as best linear unbiased predictions (with 95% empirical confidence interval, displayed in shaded grey) with related mean temperature (Fig.8.5 a), maximum temperature (Fig.8.6 a), mean heat index (Fig.8.7 a) and maximum heat index (Fig.8.8 a) distributions. Solid vertical black lines in the upper part of these plots show corresponding MMT/MMHI, whereas dotted red and blue lines represent cutoffs to define extreme values ($P_{1\%}$ and $P_{5\%}$ for cold, $P_{95\%}$ and $P_{99\%}$ for hot spectrum). Histograms at the bottom of these subgraphs intend to highlight the proportion of extremely cold and hot days. In case of Spain, cold temperature range consists of lower proportion of days in comparison with the hot "tale", whereas relative risks are equally high at both ends in case of mean temperature and heat index. In case of the maximum values of temperature and heat index, the risks for the hot spectrum increase in a clear non-linear fashion (especially in case of maximum daily heat index), whereas for the colder spectrum risks increase at a slower path and approximate to a more linear dependency.

MMT and MMHI based on mean values were both estimated at 21.9°C at 95%CI: 21.7°C-22.1°C. In terms of the temperature/heat index distributions, this value corresponds to $P_{81.1\%}$ at 95%CI: $P_{80.1\%}$-$P_{82.2\%}$, for temperature and to $P_{81.9\%}$ at 95%CI: $P_{80.8\%}$-$P_{82.8\%}$ for heat index. For the maximum values, MMT was estimated at 31.8°C at 95%CI: 30.2°C-32.4°C and MMHI at 29.3°C at 95%CI: 27.6°C-31.1°C. For temperatures this value corresponds to the $P_{78.2\%}$ at 95%CI: $P_{72.8\%}$-$P_{80.2\%}$ of maximum temperature distribution, and for heat index it corresponds to $P_{72.1\%}$ at 95%CI: $P_{65.3\%}$-$P_{78.7\%}$ of maximum heat index distribution. Relative risks corresponding to the extreme cut-off values of mean and maximum temperature and heat index are displayed in Table 8.1.

Hottest ($P_{99\%}$) temperature of 38.9ºC was associated with the highest overall RR of 1.32 at 95%CI: 1.3-1.34. The metric of RR in this case could be interpreted as an added risk of 32% with respect to the reference state, i.e. MMT or heat index, where risks are equal to 1. Highest RR for heat index were associated, on the contrary, with the lowest values. Thus, $P_{1\%}$ of the mean heat index distribution, which corresponds to 3.6ºC, was associated with the RR of 1.3 at 95%CI: 1.28-1.32. Milder cold values ($P_{5\%}$) of mean temperature and heat index had generally lower risks (1.19 at 95%CI: 1.17-1.21), whereas milder heat ($P_{95\%}$) was associated with the lowest overall risks (1.09 at 95%CI: 1.08-1.1)

Table 8.1: Relative risks associated with extreme cold and hot cut-off values of minimum and maximum temperature and heat index

		Temperature		Heat Index	
		°C	RR	°C	RR
Maximum	$P_{1\%}$	18.3	1.18 (1.16-1.2)	17.9	1.17 (1.15-1.19)
	$P_{5\%}$	19.2	1.14 (1.12-1.16)	18.9	1.13 (1.12-1.15)
	$P_{95\%}$	36.6	1.12 (1.11-1.14)	35.7	1.09 (1.08-1.1)
	$P_{99\%}$	38.9	1.32 (1.3-1.34)	38.3	1.25 (1.23-1.27)
Mean	$P_{1\%}$	4.3	1.3 (1.28-1.33)	3.6	1.3 (1.28-1.32)
	$P_{5\%}$	6.4	1.19 (1.17-1.21)	5.6	1.19 (1.17-1.21)
	$P_{95\%}$	24.5	1.09 (1.09-1.1)	24.6	1.09 (1.08-1.1)
	$P_{99\%}$	26.0	1.25 (1.24-1.27)	26.1	1.24 (1.23-1.26)

Note:
Estimated relative risk (RR) with 95% confidence intervals shown in parenthesis. P1%, P5%, P95%, P99% stand for corresponding percentile of mean and maximum temperature and heat index distribution.

in the group of mean daily values. For the milder cold values ($P_{5\%}$) in the maximum daily distribution group the RR were estimated at 1.14 at 95%CI: 1.12-1.16 for temperature (19.2ºC) and at 1.13 at 95%CI: 1.12-1.15 for heat index (18.9ºC). Milder heat ($P_{95\%}$) was associated with the lowest risks in this group which were estimated at 1.12 at 95%CI: 1.11-1.14 for temperature (36.6ºC) and at 1.09 at 95%CI: 1.08-1.1 for heat index (35.7ºC).

Absolute maximum value of mean heat index/temperature (28.9ºC/28.1ºC) were associated with the RR of 1.61/1.64 at 95%CI: 1.57/1.59-1.66/1.68 whereas absolute minimum value of mean heat index (-0.7ºC/-0.5ºC) had RR of 1.63/1.68 at 95%CI: 1.58/1.63-1.67/1.73. Absolute maximum values of maximum heat/index temperature (51.1ºC/43ºC) were associated with RR of 4.28/1.93 estimated at 95%CI: of 3.72/1.85 - 4.93/2-02. Absolute minimum value of maximum heat index (15ºC) had RR of 1.3 at 95%CI: 1.26-1.34, whereas absolute minimum of maximum temperature (15.7ºC) was associated with the RR of 1.28 estimated at 95%CI: of 1.24-1.32.

We now invite the reader to focus on graphs displayed at the bottom of Figures 8.5 - 8.8. Subgraphs labeled as *b*, *c*, *d* and *e*, *f*, *g* correspond, respectively, to exposure and lag perspectives of the complex exposure-lag-response associations. Three dimensional surfaces are designed to highlight variations across exposure and lag dimensions at once. A common feature that the reader could notice at a glance are the highest RR for hotter values and lower RR for colder spectrum at shorter lags. As time passes by after exposure, RR for hotter values sharply decreases from the first week after exposure. For the colder values, RR is low with respect to the optimum temperature on the day of exposure and the following day, and increases on the second and following days after exposure.

8.3.2 Lag-response associations

Blue lines of subgraphs *c* match the blue lines highlighted on 3-D surface on subgraphs *b* and correspond to the one of the lowest values of mean/maximum temperature/heat index. Same applies to the red lines corresponding to one the highest values shown on subgraphs *d*, which also match the red line on the *b* plots. For the mean temperature and heat index general character of curves *c* and *d* is similar. For example, on the day of exposure to daily mean temperature of 1ºC (Fig.8.5 c) RR are 13% lower in comparison with the RR on days with MMT (21.9ºC). On the next day after exposure RR are 0.5% lower, while on the second, third and fourth days after being exposed to 1ºC RR are 4.95%, 5.34% and 5.1% higher with respect to the MMT. The effects are present from 2nd (Fig.8.5 f) until the 21st day after exposure and are higher on longer lags than those corresponding to the highest temperatures. The RR on the days of exposure to average daily temperature of 27ºC are 8.8% higher with respect to the days with MMT (Fig.8.5 d). RR remain higher than the reference value up until 18th day, however on the 10thday after exposure RR are only 1% higher (Fig.8.5 g). Exposure-lag-response associations based on the average heat index value exhibit similar behavior. However, for the value of 50ºC of maximum daily heat index the RR are 11% higher with respect to the days with MMHI estimated at 29.3ºC (Fig.8.8 d), but overall highest RR are not reached on the day of exposure but on the next and following exposure days (added value of 12%, Fig.8.8 f). From the third and until the end of the third week RR are up to 2% higher with respect to the days with MMHI. Detailed illustration of the the dose-response and lag-response relationships is represented on Fig.E.1 in Appendix E[8].

[8]First row demonstrates dose-response relationship between mortality and average daily heat index (Fig.E.1 a for minimum mean heat index, Fig.E.1 b for lower quartile, Fig.E.1 c for median or 50thpercentile, Fig.E.1 d for upper quartile and Fig.E.1 e for the maximum mean heat index. Second row visualizes the lag-response relationship between mortality and average heat index at the lags of 1 day (Fig.E.1 f), 3 days (Fig.E.1 g), 1 week (Fig.E.1 h), 10 days (Fig.E.1 i) and 3 weeks (Fig.E.1 j). Third row, similarly to the first row, highlights the dose-response relationship between mortality and mean temperature quartiles. Bottom row, similarly to the second row, displays the lag-response association between mortality and mean temperature at lags of 1, 3, 7, 10 and 21 days.

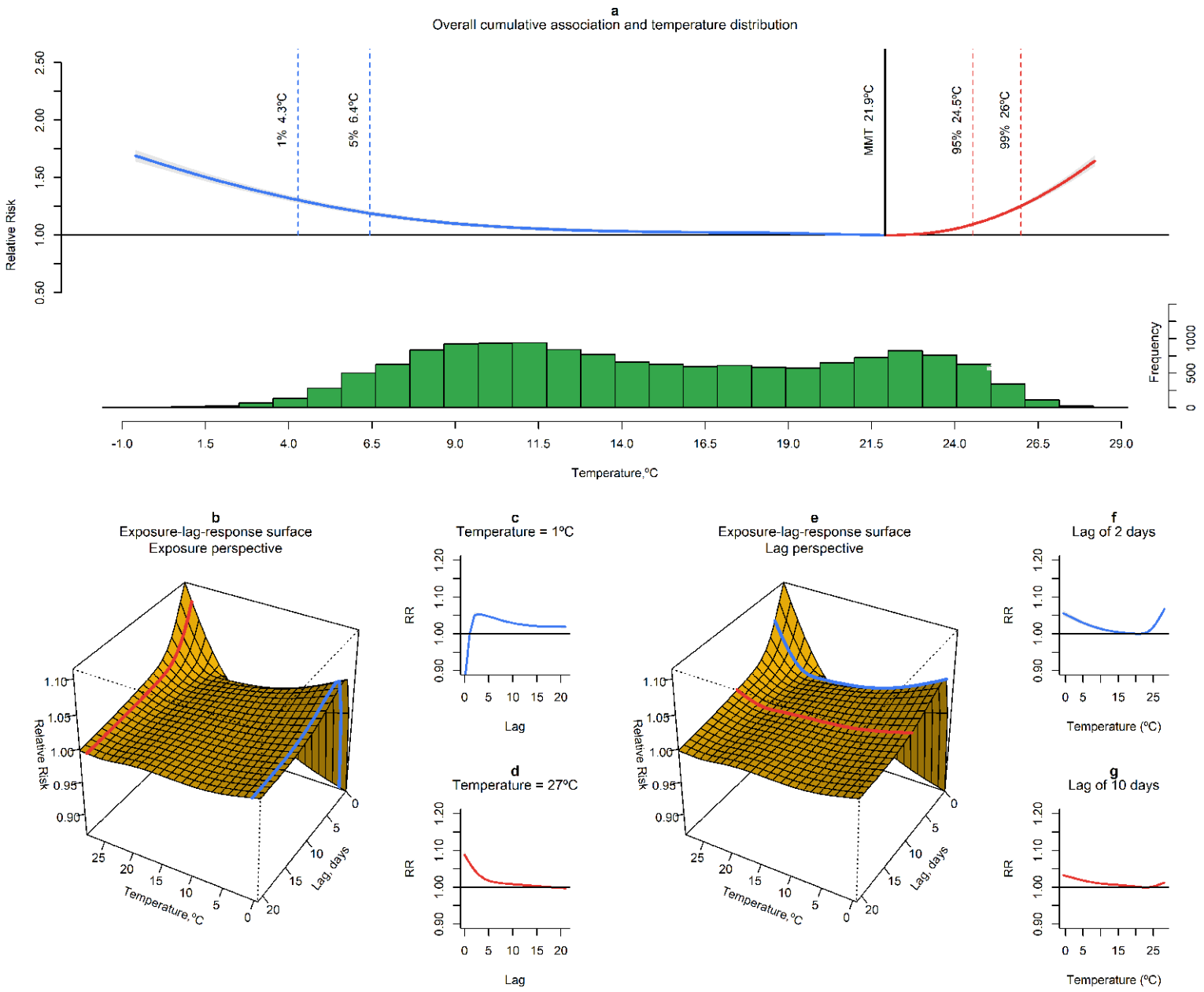


Figure 8.5: Exposure-lag-response associations between daily mortality and mean temperature at national level

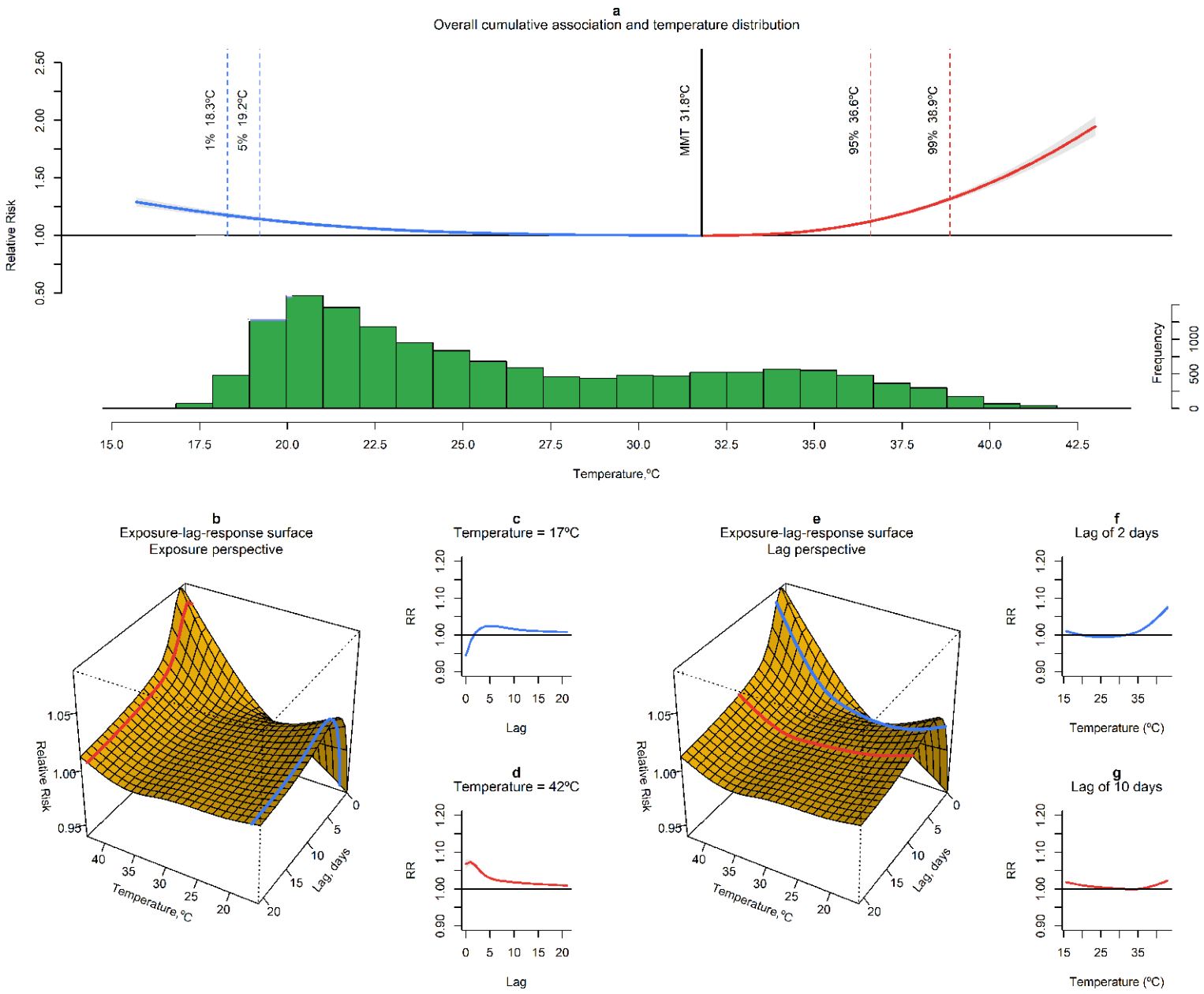


Figure 8.6: Exposure-lag-response associations between daily mortality and maximum temperature at national level

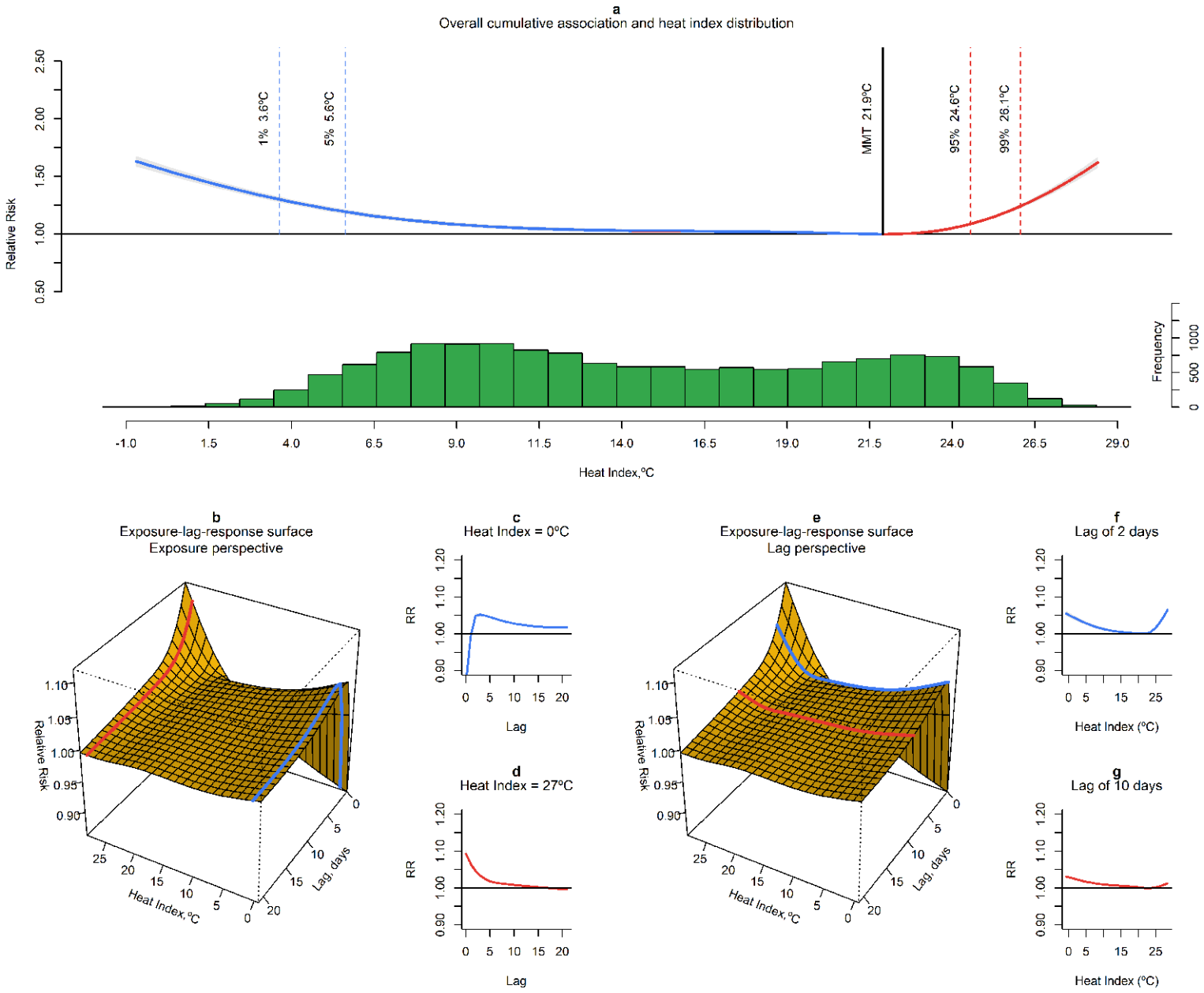


Figure 8.7: Exposure-lag-response associations between daily mortality and mean heat index at national level

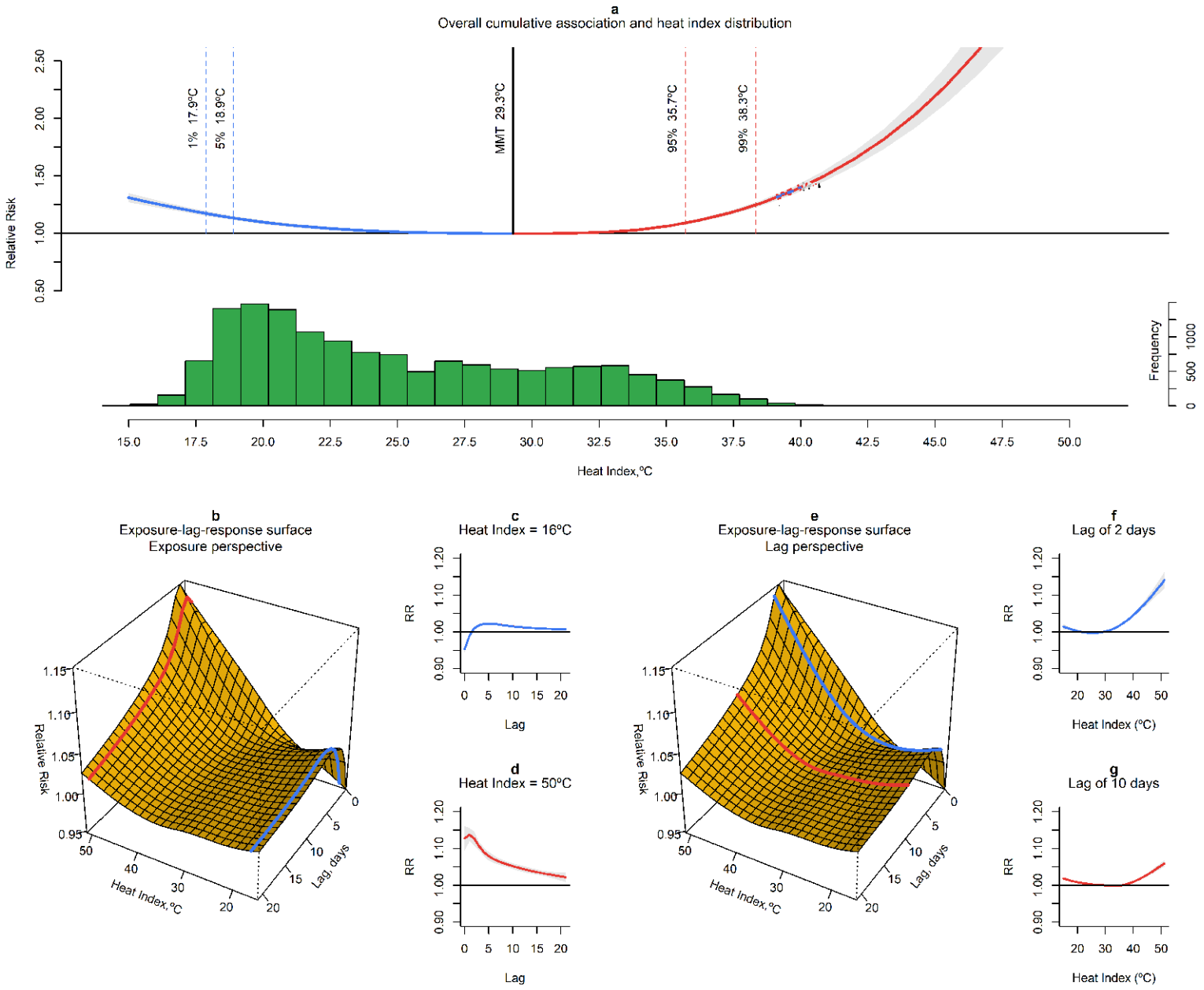


Figure 8.8: Exposure-lag-response associations between daily mortality and maximum heat index at national level

8.3.3 Variations by large age group and sex

We refine the analysis, disaggregating the mortality data by three large age groups (under 15 years old, 15-65 years old and those aged 65 or over) and sex of the individuals. Based on differences in the physiological responses across the age spectrum and between male and female individuals (biological mechanisms reviewed in detail in Chapter 2), we expect the differences in exposure-response associations between the groups to be significant. Figure 8.9 provides an illustration of such variations. The graph is organized in the following way: 1st column corresponds to the *Under 15* age group, 2nd column to those in the *15-65* years old range, while the 3rd column shows the associations for those aged *65+*. Each row, in turn, relates to a different type of indicator: average heat index, average temperature, maximum heat index and maximum temperature, listed from top to bottom.

Highest uncertainty is unsurprisingly associated with the youngest age. The number of deaths (roughly 1.5% of all deaths) in this age group is incomparably smaller with respect to other ages. We use subplots 8.9 a, d, g and j specifically to illustrate the size effect issues in this age group. The group of adults (15-65) and elderly (65+) individuals exhibit much more consistent patterns. For adult females, MMT and MMHI based on mean daily values were estimated at 22.3ºC (Fig.8.9 e) and 22.2ºC (Fig.8.9 b), respectively. For male population, the estimates were practically equal, but still slightly higher: 22.4ºC for MMT and 22.3ºC for MMHI. MMT based on the maximum values was estimated at 32.8ºC for both sexes (Fig.8.9 k). In case of the MMHI based on maximum heat index values the estimates were 0.6ºC lower for female (30.8ºC) than for male individuals (31.5ºC) ((Fig.8.9 h). The risks at the ends of the temperature/heat index spectrum were almost identical for the cold, and higher in females at the hotter edge.

MMT based on mean values was estimated at 21.6ºC for elderly females and at 22.2ºC for males aged over 65 (Fig.8.9 f). For woman, the RR for the coldest value of -0.6ºC were computed as 1.82 at 95%CI: 1.75-1.89, whereas mean daily temperature of 28.2ºC was associated with RR 2 times higher in comparison with the optimum temperature (2.01 at 95%CI: 1.92-2.08). For man, the same extreme values had lower associated risks: RR of 1.79 at 95%CI: 1.72-1.86 for coldest temperature and RR of 1.5 at 95%CI: 1.44-1.56. Similarly to the temperature, MMHI based on mean heat index values was lower for older females (21.5ºC) and 0.7ºC higher for males (Fig.8.9 c). RR were generally lower than those for mean temperature. Thus, coldest value of -0.7ºC of mean daily heat index was associated with 1.74 at 95%CI: 1.67-1.8 for females and with 1.73 95%CI: 1.66-1.8 for males. The highest mean daily heat index of 28.4ºC had higher RR for females (1.97 at 95%CI: 1.89-2-05) than for males (1.49 at 95%CI: 1.43-1.55).

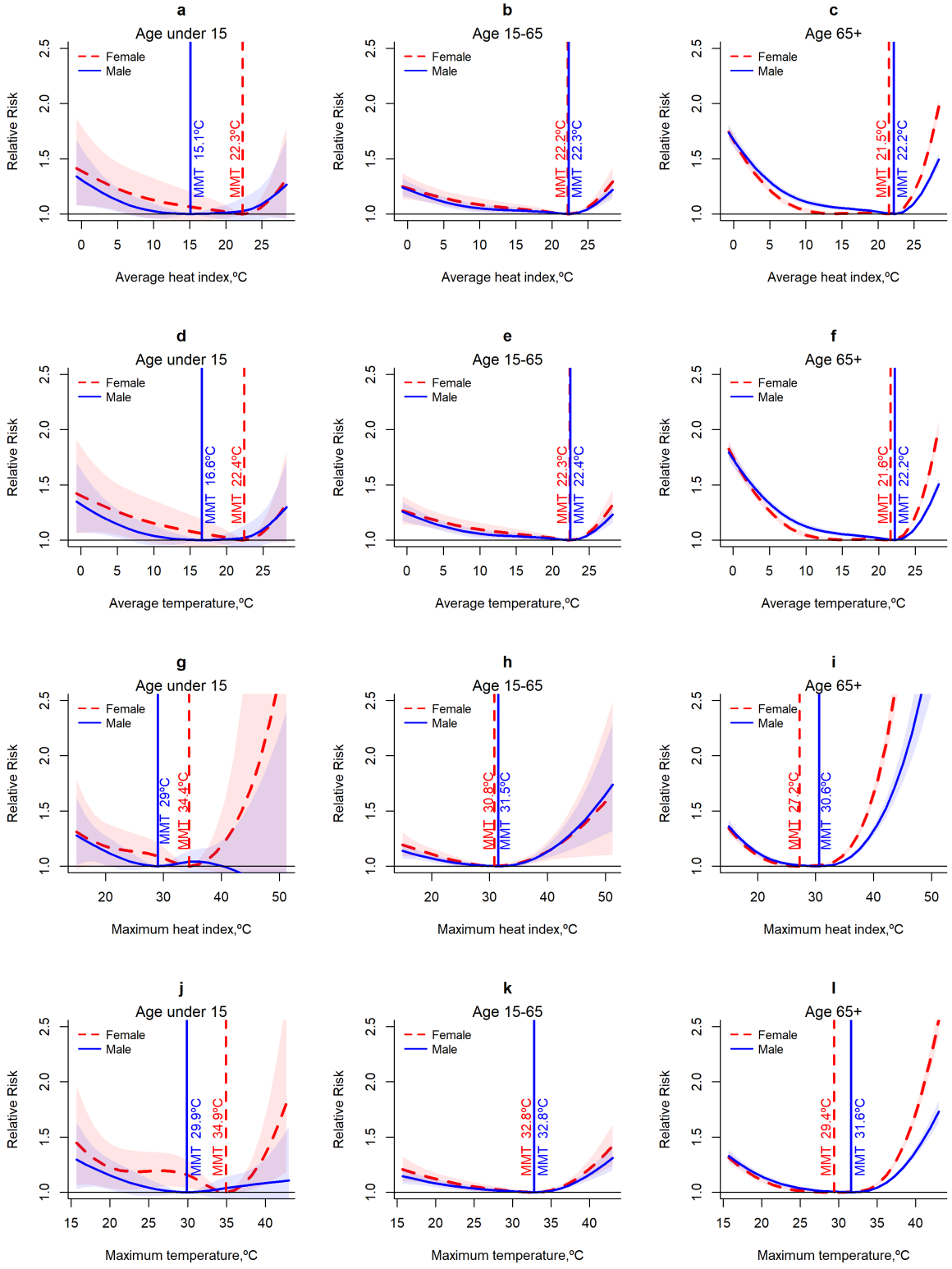


Figure 8.9: Cumulative exposure-response associations with mean and maximum temperature and heat index by sex and age group

In case of the maximum daily values, MMT/MMHI was significantly lower for females (29.4ºC/27.2ºC) than for males (31.6ºC/30.6ºC), in this way suggesting higher vulnerability of elderly woman for peak values of temperature and heat index. The RR for males at 15.7ºC (minimum value of maximum daily temperature) were estimated at 1.32 (95%CI: 1.27-1.38). The risks at the same temperature for females were almost equal (1.31 at 95%CI: 1.26-1.36). At 43ºC (maximum value of maximum daily temperature), the risks for males were estimated at 1.72 (95%CI: 1.63-1.82) whereas for females they were 2.55 times higher in comparison with the optimum temperature (2.55 at 95%CI: 2.41-2.7).

It is important to point out to the potential limitations of the model we used to estimate the risks by age group and sex. The population as such was not entered in the model as an offset, which might have led to the biased estimations at older ages due to the population structure. Indeed, women outnumber males among the "oldes old" (those aged 80 and up), who are believed to be the frailest. Despite this, our findings are clear and consistent with the international literature.

In the following paragraphs, we explore the variations in exposure-lag-response associations between sexes and age groups. Figure 8.10 visualizes these associations with average daily heat index (top two rows) and temperatures (bottom rows). First and third rows cover the entire lag period of 21 days while the second and the fourth rows zoom in only on the first week after exposure. Here, we will focus only on the age groups of 15-65 and over 65 years old.

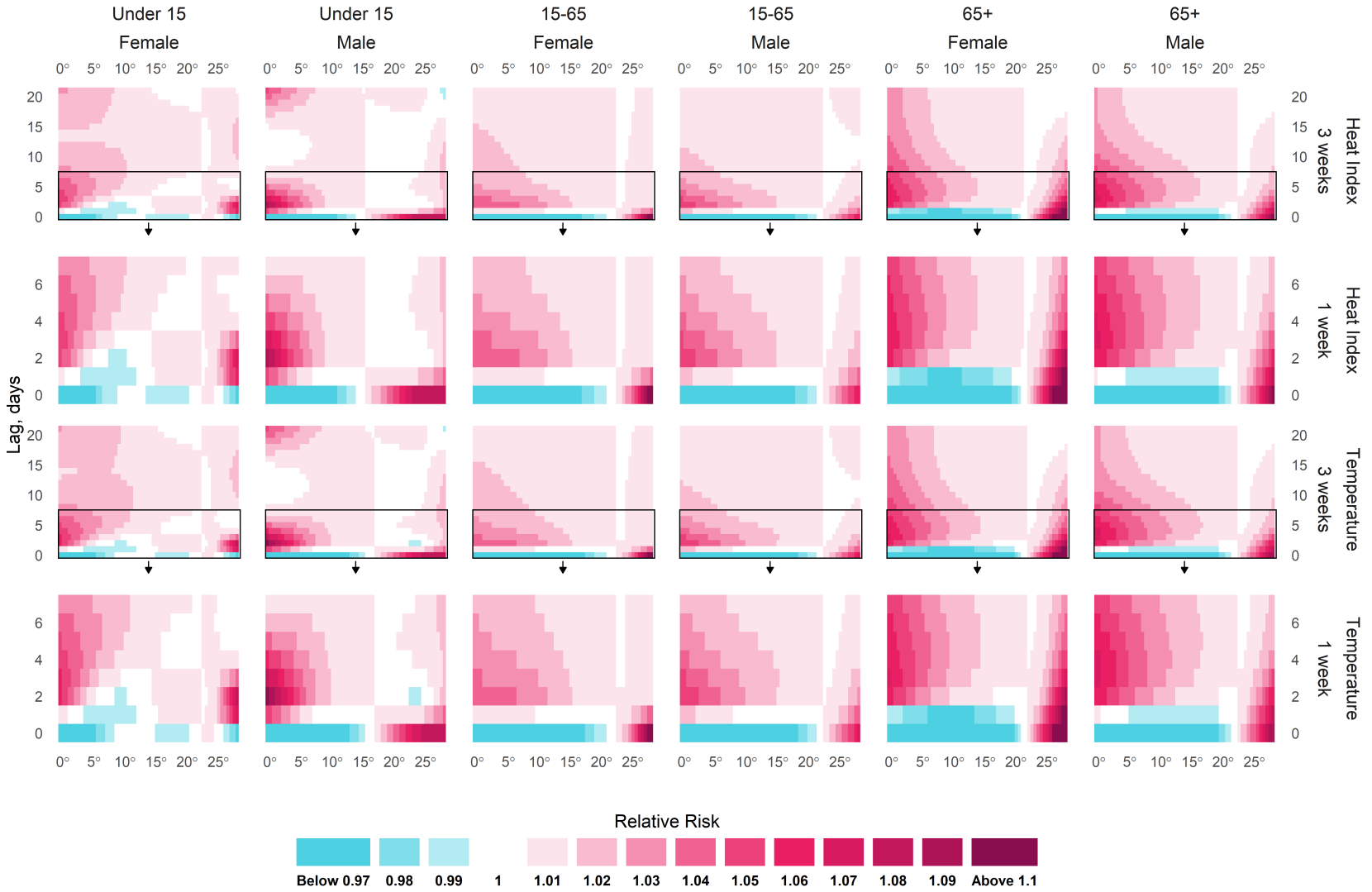


Figure 8.10: Exposure-lag-response association between daily mortality by sex and large age groups and average temperature and heat index at the national level

The general pattern clearly seen on the presented graph could be summarized as following: lower risks on shorter lags for colder temperatures, and inverse picture for the hotter temperatures - lower risks on longer lags, with generally stronger effects for elderly individuals. For adult females, the exposure to the temperature of 0°C has increased mortality risks on the second (RR of 1.03 at 95%CI: 1.01-1.06) and the following days. By the end of the third week this effect disappears. The exposure to the temperature of 28°C of the females in the same age group results in the highest risk of 1.11 at 95%CI: 1.07-1.16. The next day after exposure shows a decrease of 8% (RR of 1.03 at 95%CI: 1.01-1.05), whereas from the third day onward the effect gradually disappear during the 1st week. For males aged 15-65 the lag-response association is similar. However, the RR of exposure to colder (hotter) temperatures are slightly higher (lower) in males in comparison with females. Thus, the exposure to 0°C on the second day after exposure in males has the risk of 1.04 at 95%CI: 1.2-1.06 with respect to the optimum temperature. In turn, being exposed to the mean daily temperature of 28°C has the relative risk of 1.06 at 95%CI: 1.03-1.08 for adult males. The effect also gradually reduces with time. Compared to the association with the daily heat index, the RR are consistently similar with the same delayed patterns.

Generally, the risks for extreme temperature exposure of elderly population are the highest. In females aged 65+ and exposed to mean daily temperature of 0°C the RR of dying are low on the day of exposure (0.83 at 95%CI: 0.82-0.85) as well as on the following day (0.98 at 95%CI: 0.97-0.99). In comparison with the days with optimum temperature, the risks of exposure to cold temperature of older females start to increase from the second day after exposure (1.05 at 95%CI: 1.04-1.06) remaining high until the end of the third week (1.02 at 95%CI: 1.02-1.03 on the 21st day). The RR of exposure to cold in older males are similar to those of females.

The RR of exposure to mean daily temperatures of 28°C were estimated at 1.14 (95%CI: 1.12-1.16) for older females and at 1.08 (95%CI: 1.07-1.1) for older males. For males, the elevated risks were seen during two weeks post-exposure whereas for females the effects were present until the 17th day after exposure.

Table 8.2 displays the attributable mortality fractions and numbers by sex, age group, indicator and approach (perspective) used for estimations. Rows highlighted in bold correspond to the total (both sex and all ages combined) attributable fractions (AF) and numbers (AN). The AF/AN were calculated globally and as separated components caused by cold, extreme cold (below $P_{5\%}$), heat and extreme heat (above $P_{95\%}$). We will start by analyzing the estimates for both sexes and all ages. In total, 15 810 237

deaths were included in the analysis. The total backward temperature-based $b\text{-}AN_T$ was estimated at 913 845 deaths which represents a $b\text{-}AF_T$ of 6.43% estimated at 95%CI: 5.51-7.34%. The alternative estimation using forward perspective $f\text{-}AN_T$ was lower and equaled to 896 290 deaths ($f\text{-}AF_T$ of 6.31% at 95%CI: 5.38-7.25%). As highlighted by the authors of the method, the forward estimating strategy is more likely to create an underestimation because contributions are linked to risks calculated at different times (Gasparrini and Leone 2014). Heat index-based total $b\text{-}AN_{HI}$ was estimated at 920 237 deaths ($b\text{-}AF_{HI}$ of 6.48% at 95%CI: 5.55-7.45%) whereas using the forward approach the $f\text{-}AN_{HI}$ was 17K lower (903 068 deaths, $f\text{-}AF_{HI}$ of 6.36% at 95%CI: 5.41-7.31%).

Most of the total AF_T and AF_{HI} were related to the cold component (temperature and heat index below the optimum (minimum mortality) values). For heat index the fraction was slightly higher ($b\text{-}AF_{HI}^{cold} = 5.39\%,\ 95\%\ CI\ 4.44 - 6.37\%,\ ;\ f\text{-}AF_{HI}^{cold} = 5.33\%,\ 95\%\ CI\ 4.31 - 6.25\%$) in comparison with the temperature based contributions ($b\text{-}AF_{T}^{cold} = 5.28\%,\ 95\%\ CI\ 4.33 - 6.23\%,\ ;\ f\text{-}AF_{T}^{cold} = 5.22\%,\ 95\%\ CI\ 4.25 - 6.15\%$). The extreme cold component accounted for approximately 1.2% for temperature and heat index attributable deaths. Hot temperatures (above the minimum mortality value) accounted for considerably smaller fractions in comparison with cold components, with temperature-based estimates being higher ($b\text{-}AF_{T}^{heat} = 1.16\%,\ 95\%\ CI\ 1.08 - 1.24\%,\ ;\ f\text{-}AF_{T}^{heat} = 1.09\%,\ 95\%\ CI\ 1.01 - 1.17\%$) than those of heat index ($b\text{-}AF_{HI}^{heat} = 1.09\%,\ 95\%\ CI\ 1.01 - 1.17\%,\ ;\ f\text{-}AF_{HI}^{heat} = 1.03\%,\ 95\%\ CI\ 0.96 - 1.11\%$). Exposure to extremely hot temperatures and heat index (above $P_{95\%}$ of the corresponding distribution) accounted for approximately 0.8% of all deaths.

We will now focus on the variations of AF_T and AF_{HI} in between large age groups and sexes. The age group of *Under 15* is shown in the Table 8.2 to illustrate the uncertainty ranges discussed in the preceding paragraphs. Further we will discuss only the *15-65* and *65+* age groups. The global fractions for older males were generally larger than for females of the same age. Thus, the $b\text{-}AF_{T,male\,65+}$ was estimated at 8.47% (95%CI: 7.17-9.8%) whereas for older females the fraction was smaller ($b\text{-}AF_{T,female\,65+} = 5.45\%,\ 95\%\ CI\ 4.13 - 6.69\%$). Conversely, for younger male adults aged 15-65, the total $b\text{-}AF_{T,male\,15-65}$ of 4.08 (95%CI: 1.8-6.2) was lower in comparison with adult females ($b\text{-}AF_{T,female\,15-65} = 6.1\%,\ 95\%\ CI\ 2.95 - 9.11\%$), however the empirical confidence intervals were also significantly larger. In both male and female individuals of older ages, the highest contribution was due to the cold component ($b\text{-}AF_{T,female\,15-65}^{cold} = 3.72\%,\ 95\%\ CI\ 2.34 - 5.06\%;\ b\text{-}AF_{T,male\,15-65}^{cold} = 7.59\%,\ 95\%\ CI\ 6.28 - 8.95\%$). Hot temperatures were responsible for small fractions in both sexes, however in older females

the fraction ($b\text{-}AF^{heat}_{T,female\,15-65} = 1.74\%$, 95% CI $1.62 - 1.86\%$) was 2 times larger than in males ($b\text{-}AF^{heat}_{T,male\,15-65} = 0.89\%$, 95% CI $0.78 - 0.99\%$). This pattern is consistent across indicators and perspectives used for estimation.

Our findings are in line with other studies for Spain. Gasparrini, Guo, et al. (2015) estimated the total AF_T of 6.52% (95%CI: 5.82-7.16%), AF^{cold}_T of 5.46% (95%CI: 4.79-6.07%) and AF^{heat}_T of 1.06% (95%CI: 0.96-1.16%) for Spain in 1990-2010 using ~3.5 millions of deaths. Another study by Carmona et al. (2016) based on a different approach for estimating the attributable fractions, reveals a similar pattern: the mortality attributable to cold in Spain is higher than mortality due to heat. Vicedo-Cabrera, Sera, et al. (2018) estimated the change in mortality fractions attributed to heat and cold in Spain: according to their results, AF^{cold}_T went from 6.58% (95%CI: 5.76-7.3%) in 1990-1994 to 3.89% (95% 3.22-4.51%) in 2005-2009. As for the heat component, authors report a reduction in ~0.5% from $AF^{heat}_T = 1.39\%$, 95% CI $1.1 - 1.65\%$ in 1990-1994 down to $AF^{heat}_T = 0.93\%$, 95% CI $0.84 - 1.01\%$ in 2005-2009.

Further, we proceed to the analysis of the temporal changes in mortality answers to temperatures and heat index at the national level.

Table 8.2: Temperature-attributable mortality by sex and age group in Spain (1979-2018)

				Global		Cold		Extreme cold		Heat		Extreme heat	
Indicator	Perspective	Sex	Age group	Deaths	Fraction	Deaths	Fraction	Deaths	Fraction	Deaths	Fraction	Deaths	Fraction
Heat Index	Backward	Female	Under 15	5901	8.19 (-1.78-16.63)	5554	7.71 (-2.03-16.4)	874	1.21 (0.2-2.11)	348	0.48 (-0.18-1.09)	257	0.36 (-0.08-0.75)
			15-65	46537	5.84 (2.71-8.73)	42294	5.31 (2.21-8.31)	5943	0.75 (0.43-1.06)	4263	0.54 (0.29-0.78)	3198	0.4 (0.24-0.56)
			65+	322311	5.45 (4.17-6.72)	225355	3.81 (2.49-5.08)	76205	1.29 (1.15-1.42)	97578	1.65 (1.53-1.77)	68981	1.17 (1.1-1.24)
		Male	Under 15	3313	3.37 (-0.25-6.76)	2169	2.21 (-1.14-5.2)	718	0.73 (0.16-1.27)	1146	1.17 (-2.15-4.23)	414	0.42 (-0.19-0.99)
			15-65	74680	4.06 (1.9-6.15)	67348	3.66 (1.46-5.81)	11065	0.6 (0.39-0.81)	7365	0.4 (0.24-0.56)	5635	0.31 (0.19-0.42)
			65+	475791	8.68 (7.38-9.98)	430314	7.85 (6.48-9.14)	86526	1.58 (1.44-1.71)	45833	0.84 (0.74-0.94)	34663	0.63 (0.57-0.7)
Heat Index	**Backward**	**Both**	**All ages**	**920237**	**6.48 (5.55-7.45)**	**766055**	**5.39 (4.44-6.37)**	**180354**	**1.27 (1.17-1.37)**	**155151**	**1.09 (1.01-1.17)**	**113117**	**0.8 (0.75-0.84)**
Heat Index	Forward	Female	Under 15	5877	8.16 (-1.88-16.5)	5539	7.69 (-2.33-16.38)	823	1.14 (0.24-1.89)	338	0.47 (-0.18-1.03)	247	0.34 (-0.06-0.71)
			15-65	46315	5.82 (2.69-8.75)	42180	5.3 (2.12-8.25)	5802	0.73 (0.45-1)	4134	0.52 (0.28-0.75)	3070	0.39 (0.23-0.53)
			65+	309958	5.24 (3.99-6.51)	219373	3.71 (2.36-4.99)	74228	1.25 (1.14-1.37)	90585	1.53 (1.42-1.64)	62040	1.05 (0.99-1.11)
		Male	Under 15	3258	3.32 (-0.35-6.69)	2140	2.18 (-1.06-5.21)	685	0.7 (0.2-1.15)	1118	1.14 (-2.17-4.06)	401	0.41 (-0.18-0.92)
			15-65	74263	4.03 (1.95-6.14)	67097	3.64 (1.43-5.91)	10863	0.59 (0.39-0.78)	7166	0.39 (0.23-0.55)	5455	0.3 (0.19-0.4)
			65+	469554	8.57 (7.25-9.86)	426082	7.78 (6.42-9.07)	81163	1.48 (1.36-1.59)	43472	0.79 (0.7-0.89)	32427	0.59 (0.53-0.65)
Heat Index	**Forward**	**Both**	**All ages**	**903068**	**6.36 (5.41-7.31)**	**756543**	**5.33 (4.31-6.25)**	**173083**	**1.22 (1.14-1.3)**	**146525**	**1.03 (0.96-1.11)**	**104705**	**0.74 (0.69-0.78)**
Temperature	Backward	Female	Under 15	6293	8.73 (-0.92-17.16)	5935	8.24 (-1.98-16.99)	903	1.25 (0.23-2.22)	359	0.5 (-0.13-1.13)	262	0.36 (-0.06-0.76)
			15-65	48541	6.1 (2.95-9.11)	43949	5.52 (2.43-8.52)	6139	0.77 (0.45-1.07)	4613	0.58 (0.33-0.82)	3450	0.43 (0.27-0.59)
			65+	322395	5.45 (4.13-6.69)	219935	3.72 (2.34-5.06)	76975	1.3 (1.17-1.44)	103110	1.74 (1.62-1.86)	72296	1.22 (1.15-1.29)
		Male	Under 15	3316	3.38 (-0.7-7.28)	2296	2.34 (-1.54-6.14)	716	0.73 (0.13-1.3)	1021	1.04 (-1.87-3.71)	424	0.43 (-0.14-0.96)
			15-65	75170	4.08 (1.8-6.2)	67275	3.65 (1.44-5.78)	11148	0.61 (0.39-0.81)	7931	0.43 (0.27-0.59)	5982	0.32 (0.22-0.43)
			65+	464020	8.47 (7.17-9.8)	415697	7.59 (6.28-8.95)	86341	1.58 (1.44-1.72)	48679	0.89 (0.78-0.99)	36403	0.66 (0.6-0.73)
Temperature	**Backward**	**Both**	**All ages**	**913845**	**6.43 (5.51-7.34)**	**750362**	**5.28 (4.33-6.23)**	**181488**	**1.28 (1.18-1.38)**	**164472**	**1.16 (1.08-1.24)**	**118731**	**0.84 (0.79-0.88)**
Temperature	Forward	Female	Under 15	6269	8.7 (-1.23-17.12)	5921	8.22 (-1.69-17.06)	849	1.18 (0.25-1.96)	348	0.48 (-0.14-1.08)	251	0.35 (-0.06-0.71)
			15-65	48310	6.07 (2.97-9.07)	43837	5.51 (2.44-8.63)	5978	0.75 (0.47-1.02)	4473	0.56 (0.32-0.79)	3306	0.42 (0.27-0.56)
			65+	309745	5.23 (3.95-6.45)	213887	3.61 (2.27-4.88)	74863	1.26 (1.15-1.38)	95858	1.62 (1.5-1.73)	65031	1.1 (1.04-1.16)
		Male	Under 15	3262	3.32 (-0.75-7.09)	2268	2.31 (-1.74-5.95)	686	0.7 (0.11-1.22)	994	1.01 (-1.92-3.72)	411	0.42 (-0.15-0.89)
			15-65	74740	4.06 (1.87-6.18)	67025	3.64 (1.39-5.69)	10947	0.59 (0.39-0.78)	7715	0.42 (0.26-0.57)	5783	0.31 (0.21-0.42)
			65+	457692	8.35 (7.03-9.65)	411488	7.51 (6.12-8.81)	81013	1.48 (1.36-1.59)	46203	0.84 (0.75-0.94)	34054	0.62 (0.56-0.68)
Temperature	**Forward**	**Both**	**All ages**	**896290**	**6.31 (5.38-7.25)**	**740872**	**5.22 (4.25-6.15)**	**173950**	**1.22 (1.14-1.31)**	**155418**	**1.09 (1.01-1.17)**	**109871**	**0.77 (0.73-0.82)**

Note:

Fractions shown as estimate with 95% confidence intervals in parenthesis.

8.3.4 Changes in optimum temperature and heat index and attributable mortality in Spain over time

To analyze changes in the MMT over time we split the period of study into 4 decades and run estimations for each period separately. The results are summarized in Table 8.3, whereas Figure 8.11 illustrates the evolution of the MMT and MMHI constrained to their corresponding 1st-99st percentiles. The estimations were done using mean and maximum daily temperatures and heat index.

At a glance, the reader might notice the change in the temperature-(heat index-) mortality curve from V- to U-shaped as shown on graphs 8.11 a, b, c and d (8.11 i, j, k, l). As pointed out by Tobías, Armstrong, et al. (2017), this character of the curve suggests a minimum mortality *range* rather than a single value, in this way expanding the concept of the optimum temperatures. To compensate for the increase in the variability of the temperatures in the last two decades, we limit the range of the temperatures (to their 75th percentile) to estimate the minimum mortality value. The uncertainty ranges of the MMT (MMHI) based on the maximum values are larger than those based on the mean values. With the constrains applied, the overall increase of the MMT (MMHI) values can be observed. The only exception are the MMHI values based on the maximum daily heat index which slightly declined in the last decade of the observation (Fig.8.11 p). On average, MMT (MMHI) based on the mean temperatures (heat index) increased at +0.3ºC per decade rate, which corresponded to the +0.28ºC decadal increase in the mean temperatures (heat index). For the maximum temperatures, the average rate for the MMT increase was estimated at 0.43ºC per decade, which matches the average rate of increase in the maximum temperatures (+0.42ºC per decade). In case of the MMHI based on the maximum heat index values, the overall decadal change was estimated at -0.26ºC due to the increased variability in the last decade of observation. The average change rate for the maximum heat index itself was estimated at 0.38ºC per decade. Decadal changes in the MMT (MMHI) estimated for the summer months are shown in the Figure E.10 in the Appendix.

Changes in the attributable fractions of mortality due to temperature and heat index exhibit a non-uniform pattern. Generally, all types of AF reduce over time from roughly 11% in 1979-1983 to 5% in 2014-2018. However, the trend is not monotonous. The maximum $b, f\text{-}AF_{T,HI}^{global}$ was estimated in 1989-1993 with sharp reduction in the following 5 years. Since 2009, the fractions increased and reached the level of 5% similar to 1994-1998. Interestingly, in the last 5-year observational period the $b, f\text{-}AF_{T,HI}^{cold}$ was the lowest of approximately 1.5% (decrease of ~8% since the first period), whereas the

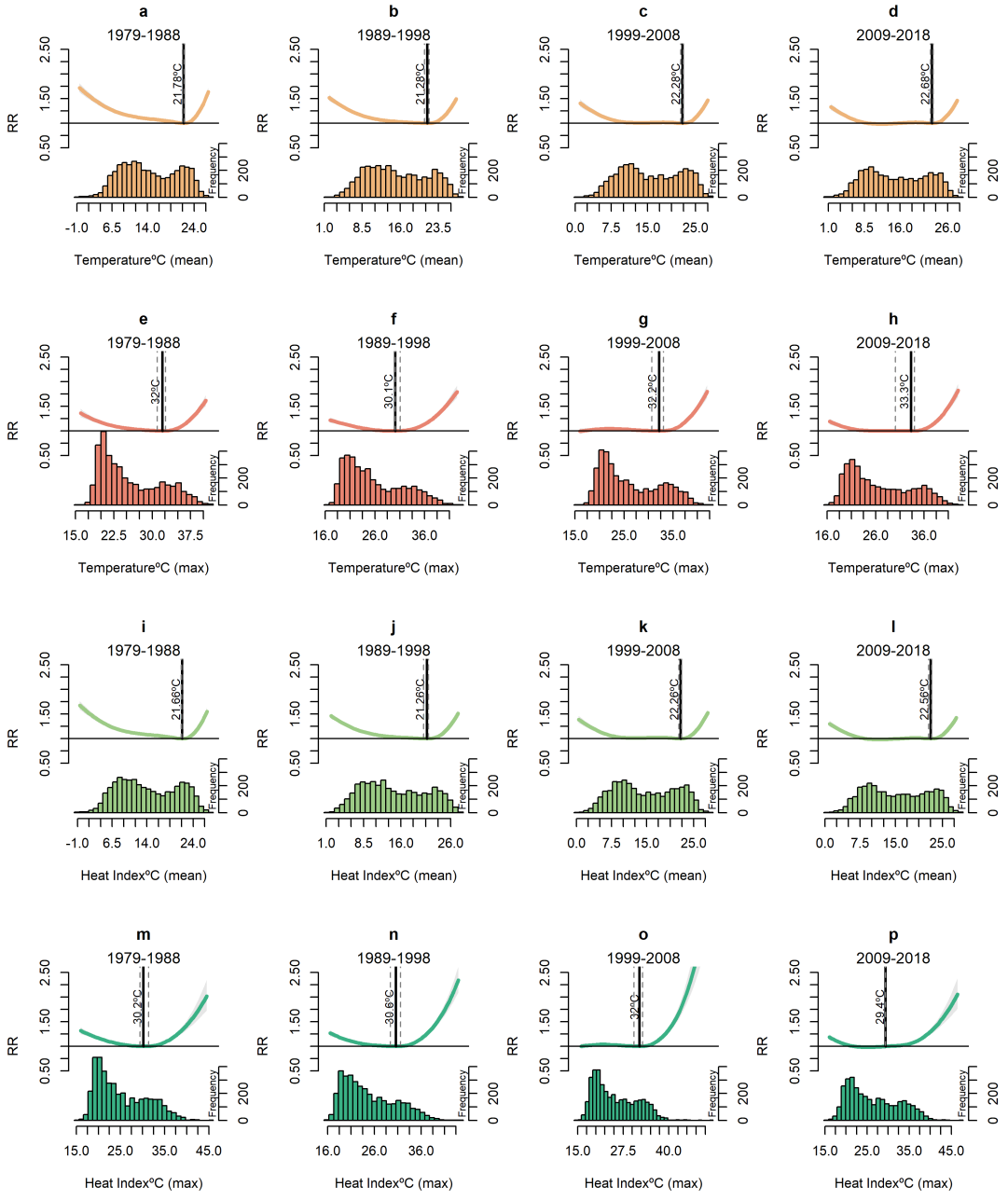


Figure 8.11: Change in MMT (constrained to 1-99 centile range) by decade at national level for maximum and average all-year temperature and heat index

fraction attributable to hot temperature sharply increased (+3%) since 2009-2013. As the reader might recall from the discussion in Chapter 5, years 2015-2018 showed the highest incidence of heat waves in that decade.

Table 8.3: Change in all-year MMT and MMHI in Spain over time

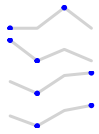
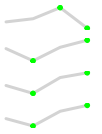
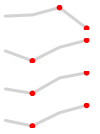
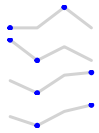
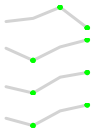
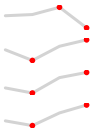
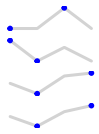
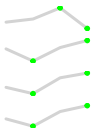
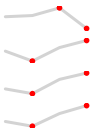
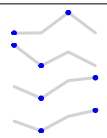
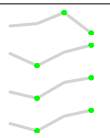
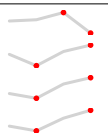
							Overall change		
			1979-1988	1989-1998	1999-2008	2009-2018	Lower bound	Estimate	Upper bound
Unconstrained	Maximum	Heat Index	30.2 (29.4-31.4)	30.6 (29.4-31.6)	32 (30.4-32.8)	29.4 (29.4-29.4)			
		Temperature	32 (31-32.6)	30.1 (30.1-31.2)	32.2 (30.6-33.1)	33.3 (30.1-34.1)			
	Mean	Heat Index	21.7 (21.5-21.9)	21.2 (20.6-21.6)	22.2 (21.9-22.5)	22.5 (22.1-22.8)			
		Temperature	21.8 (21.5-22)	21.3 (20.7-21.6)	22.3 (21.9-22.5)	22.7 (22.3-23)			
1st–99th centile range	Maximum	Heat Index	30.2 (29.4-31.4)	30.6 (29.4-31.6)	32 (30.5-32.8)	29.4 (29.4-29.4)			
		Temperature	32 (31-32.6)	30.1 (30.1-31.1)	32.2 (30.7-33.1)	33.3 (30.1-34)			
	Mean	Heat Index	21.7 (21.5-21.9)	21.3 (20.6-21.6)	22.3 (21.9-22.5)	22.6 (22.1-22.8)			
		Temperature	21.8 (21.5-22)	21.3 (20.8-21.7)	22.3 (21.9-22.5)	22.7 (22.4-23)			
5th-95th centile range	Maximum	Heat Index	30.2 (29.4-31.4)	30.6 (29.4-31.6)	32 (30.5-32.9)	29.4 (29.4-29.4)			
		Temperature	32 (31-32.6)	30.1 (30.1-31.2)	32.2 (30.7-33.1)	33.3 (30.1-34.1)			
	Mean	Heat Index	21.7 (21.4-21.9)	21.3 (20.7-21.6)	22.3 (21.9-22.5)	22.6 (22.1-22.9)			
		Temperature	21.8 (21.5-22)	21.3 (20.7-21.7)	22.3 (21.9-22.5)	22.7 (22.4-23)			
10th-90th centile range	Maximum	Heat Index	30.3 (29.4-31.4)	30.6 (29.4-31.6)	32 (30.4-32.8)	29.4 (29.4-29.4)			
		Temperature	32 (31-32.7)	30.1 (30.1-31.1)	32.2 (30.7-33.1)	33.3 (30.1-34)			
	Mean	Heat Index	21.7 (21.5-21.9)	21.3 (20.7-21.6)	22.3 (21.9-22.5)	22.6 (22.1-22.9)			
		Temperature	21.8 (21.5-22)	21.3 (20.7-21.7)	22.3 (21.9-22.5)	22.7 (22.4-23)			

Table 8.4: Change in temperature- and heat index-attributable mortality in Spain over time

			1979-1983	1984-1988	1989-1993	1994-1998	1999-2003	2004-2008	2009-2013	2014-2018
Heat Index	Backward	Cold	10.46 (6.71-14.03)	8.84 (6.5-11.08)	13.48 (11.47-15.45)	3.69 (2.71-4.6)	2.3 (1.83-2.77)	2.99 (-0.4-6.24)	3.82 (1.33-6.27)	1.63 (1.26-2.01)
		Heat	0.88 (0.68-1.06)	1.01 (0.82-1.21)	1.85 (1.56-2.14)	1.87 (1.13-2.59)	1.92 (0.59-3.22)	0.85 (0.66-1.03)	0.76 (0.58-0.94)	3.77 (2.1-5.4)
Heat Index	**Backward**	**Global**	**11.32 (7.64-14.87)**	**9.85 (7.55-12.08)**	**15.32 (13.36-17.24)**	**5.56 (4.49-6.62)**	**4.22 (2.93-5.5)**	**3.83 (0.47-7.04)**	**4.58 (2.09-6.99)**	**5.4 (3.77-6.96)**
Heat Index	Forward	Cold	10.38 (6.67-13.87)	8.74 (6.43-10.98)	13.42 (11.41-15.38)	3.62 (2.66-4.56)	2.28 (1.81-2.75)	2.9 (-0.45-6.12)	3.81 (1.32-6.21)	1.59 (1.2-1.95)
		Heat	0.81 (0.63-0.98)	0.95 (0.77-1.13)	1.73 (1.45-2)	1.79 (1.05-2.5)	1.83 (0.47-3.16)	0.81 (0.63-0.98)	0.72 (0.55-0.89)	3.71 (2.03-5.34)
Heat Index	**Forward**	**Global**	**11.18 (7.46-14.64)**	**9.7 (7.41-11.92)**	**15.15 (13.18-17.02)**	**5.41 (4.32-6.46)**	**4.11 (2.8-5.36)**	**3.71 (0.43-6.84)**	**4.53 (1.97-6.9)**	**5.29 (3.71-6.83)**
Temperature	Backward	Cold	10.47 (6.63-14)	9.65 (7.28-11.93)	12.62 (10.64-14.6)	3.59 (2.63-4.51)	2.19 (1.7-2.66)	1.71 (1.22-2.19)	3.61 (1.14-5.98)	1.51 (1.16-1.86)
		Heat	0.95 (0.75-1.13)	1.06 (0.87-1.26)	2.01 (1.7-2.31)	1.87 (1.12-2.59)	1.71 (0.32-3.01)	1.46 (-0.35-3.19)	0.82 (0.63-1.01)	3.98 (2.24-5.7)
Temperature	**Backward**	**Global**	**11.4 (7.63-14.88)**	**10.71 (8.42-12.93)**	**14.62 (12.67-16.49)**	**5.45 (4.41-6.48)**	**3.89 (2.58-5.13)**	**3.16 (1.43-4.79)**	**4.42 (1.95-6.73)**	**5.49 (3.81-7.14)**
Temperature	Forward	Cold	10.39 (6.54-13.92)	9.55 (7.23-11.82)	12.57 (10.55-14.57)	3.51 (2.56-4.43)	2.17 (1.7-2.62)	1.64 (1.16-2.1)	3.59 (1.11-6.01)	1.47 (1.13-1.8)
		Heat	0.87 (0.7-1.04)	1 (0.82-1.18)	1.88 (1.58-2.16)	1.78 (1.04-2.51)	1.62 (0.27-2.94)	1.4 (-0.41-3.16)	0.78 (0.6-0.96)	3.91 (2.18-5.58)
Temperature	**Forward**	**Global**	**11.26 (7.45-14.82)**	**10.55 (8.2-12.74)**	**14.45 (12.55-16.31)**	**5.29 (4.25-6.32)**	**3.79 (2.5-5.02)**	**3.04 (1.3-4.71)**	**4.37 (1.89-6.77)**	**5.37 (3.74-6.96)**

8.4 Inter-municipality variations in mortality answers to temperatures and heat index

We now move from macro to meso level of our analysis and focus on the municipalities corresponding to 52 provincial capitals of Spain. Table 8.5 provides descriptive death and temperature statistics for each municipality by season. Municipalities of provincial capitals vary drastically by population size and therefore the total number of deaths vary from over a million in Madrid to slightly above 12K in Teruel.

Table 8.5: Descriptive statistics for variables used for minimum mortality temperature estimation at meso level

	Winter			Spring			Summer			Autumn		
	Deaths	Temperature		Deaths	Temperature		Deaths	Temperature		Deaths	Temperature	
	Total	Avg	Max	Total	Avg	Max	Total	Avg	Max	Total	Avg	Max
Oviedo	22413	6.8	19	19574	10.4	27	17914	17.2	31	19010	12.9	31
Santander	19944	7.9	19	17634	11.4	27	16070	18.2	32	16895	14.2	31
Coruña	24464	9.8	20	21951	12.3	26	19824	18	32	20591	14.9	28
Lugo	9671	6.9	20	8655	10.8	29	7636	17.7	34	8069	13	31
Ourense	11223	6.7	19	9811	11.1	31	8917	18.4	35	9353	13.1	32
Pontevedra	7030	9.8	19	6346	12.5	26	5816	18.3	30	5783	14.9	28
Huesca	5174	4.4	18	4632	10.7	31	4435	20.5	36	4256	12.7	32
Teruel	3285	4.2	18	3161	10.1	30	2755	20.5	37	2828	12.3	32
Zaragoza	61046	6.2	18	53780	12.7	33	51299	22.9	39	51734	14.6	34
Pamplona/Iruña	17175	5.7	20	15451	11.2	31	14671	19.2	36	14849	13.1	33
Bilbao	39544	7.4	20	35159	11.8	30	32330	18.7	35	33537	14.1	32
Donostia/San Sebastián	19050	7.3	20	16912	12	30	15709	19.2	35	15942	14.3	32
Vitoria-Gasteiz	17361	5.8	20	15169	10.9	31	14424	18.5	36	14758	12.9	34
Logroño	11777	4.8	18	10659	10.3	30	9978	18.5	34	10170	12.2	34
Madrid	289924	5.4	19	256486	12.2	33	242549	23.7	39	242550	14.4	37
Burgos	15661	4.2	17	14288	9.6	30	13808	18.4	35	13996	11.6	35
León	14069	4.3	16	12808	9.5	30	11710	18.1	34	12115	11.6	33
Palencia	8320	4.8	17	7635	10.5	32	7081	20.1	36	7084	12.6	34
Salamanca	15484	5.6	18	14136	11.5	32	13306	21.6	37	13239	13.6	35
Segovia	5191	4.4	17	4812	10.8	32	4570	21.5	37	4558	12.9	35
Soria	3337	4.1	18	3118	9.7	29	2858	19.1	34	2882	11.8	34
Valladolid	27325	5.2	17	24676	11.2	32	23026	21.1	37	23476	13.2	35
Zamora	6545	5.7	17	5934	11.6	33	5547	21.5	37	5492	13.6	36
Ávila	4974	4.7	17	4472	11.1	32	4365	22	37	4274	13.3	35
Albacete	11526	6.5	19	10506	12.7	34	9666	23.3	39	9532	14.7	36
Ciudad Real	5753	7.2	21	5098	14.2	36	5076	25.7	41	4642	16.2	39
Cuenca	5088	5.1	18	4475	11.4	32	4311	22.6	38	4236	13.6	36
Guadalajara	5538	5	18	5074	11.6	32	4758	22.8	38	4708	13.8	37
Toledo	5715	6.2	20	5250	13.3	35	4970	25	40	4781	15.4	38
Badajoz	11674	9.4	22	10286	15.1	35	9514	24.3	41	9251	17.3	39
Cáceres	6929	8.5	22	6057	14.6	35	5770	24.6	40	5515	16.7	39
Palma	32742	12.5	21	29113	15.4	26	26745	24.1	33	26459	19.8	30
Barcelona	188481	8.1	19	163200	13.1	28	153498	22.5	34	151534	16	32
Girona	7399	7.6	19	6304	13.3	30	6063	22.7	38	5893	15.7	32
Lleida	11743	6.5	19	10199	12.7	32	9629	22.4	37	9803	14.7	34
Tarragona	9995	9.2	21	8803	14.4	30	8401	23.5	37	8406	17.1	33

Table 8.5: Descriptive statistics for variables used for minimum mortality temperature estimation at meso level *(continued)*

	Winter			Spring			Summer			Autumn		
	Deaths	Temperature		Deaths	Temperature		Deaths	Temperature		Deaths	Temperature	
	Total	Avg	Max	Total	Avg	Max	Total	Avg	Max	Total	Avg	Max
Alicante/Alacant	27665	11	22	24078	15.9	33	22383	24.7	37	22057	18.8	35
Castelló de la Plana	13669	9.5	20	12066	14	30	11075	22.8	34	10874	17	32
València	81390	9.7	20	70374	14.2	31	65246	23.1	35	64991	17.2	33
Almería	15324	10.7	23	13318	16.3	35	12236	26.1	41	12133	19	37
Cádiz	14392	13	22	12596	16.7	32	11571	24	38	11295	19.6	35
Córdoba	28303	8.5	21	23949	15.1	36	22920	25.9	43	21938	17.4	41
Granada	24443	7.9	21	21681	14.4	36	19601	25.3	41	19620	16.8	38
Huelva	12780	12.2	21	10826	16.5	32	10295	24.3	39	9853	19.2	36
Jaén	9463	7.6	21	8451	14.1	36	7970	25.3	42	7483	16.5	39
Málaga	49602	10	21	42692	15.2	33	40157	24.4	38	39000	17.8	37
Sevilla	66922	10.5	22	56749	16.1	34	52566	25.3	41	52280	18.5	40
Ceuta	5515	12.9	22	5009	16.1	30	4691	23.2	36	4531	19	33
Melilla	4723	13.2	24	4120	16.3	27	3971	23.6	34	3936	19.5	32
Murcia	31154	10.7	21	26233	15.7	33	24939	24.6	37	24524	18.5	35
Palmas de Gran Canaria	29755	18.5	25	27903	19.1	26	25647	22.6	30	25168	22.5	30
Santa Cruz de Tenerife	17219	18	25	16282	18.7	26	14694	22.3	30	14877	22.1	30

Tobías, Armstrong, et al. (2017) suggested to constrain the estimates to exclude temperatures on the extreme tails to compensate for impreciseness of the spline curves in the smallest units. Following their indications, we estimated MMT and MMHI using entire range of values (so-called unconstrained category) and values constrained to 1st-99th, 5th-95th and 10th-90th percentile ranges of corresponding distributions of mean and maximum daily values. Detailed results for each indicator and type of constrain are listed in the Table E.1 and series of maps. Figure E.11 in the Appendix represents estimates based on mean daily values of temperature and heat index for all seasons, whereas Figure E.13 corresponds to the estimates limited to summer only. Figures E.12 and E.14 correspond to the estimates based on maximum values for all seasons and summer only, respectively.

Overall, 75% of the capitals had their MMT in the 15ºC-25ºC range, 3.8% - above 25ºC, 17% - between 5ºC and 15ºC, and 3.8% had optimum temperatures below 5ºC. As for the heat index, the majority (76%) of the capitals falls within the 15ºC-25ºC range, followed by 5ºC-15ºC interval (15% of the capitals), under 5ºC and over 25ºC (3.8% of the capitals each category). MMT (MMHI), based on the unconstrained range of mean daily values (Fig.8.13, Fig.8.15), varied from -7.6ºC, (-2.7ºC) in Pamplona, Navarra (Toledo, Castilla-La Mancha) ($P_{0\%}$ for both temperature and heat index) to 26ºC (25.7ºC) in Almeria, Andalusia ($P_{85\%}$ for temperature, $P_{84\%}$ for heat index). Lowest minimum mortality values based on maximum daily temperature (heat index) were

also estimated for Pamplona (-4.3ºC, $P_{0\%}$), while the highest estimate corresponded to Almeria (30.5ºC, $P_{87\%}$ for temperature, 29.9ºC, $P_{86\%}$ for heat index).

Cities such as Teruel, Toledo or Segovia, with their minimum mortality estimates at the minimum edges of the distribution and large confidence intervals, are among the cities with the lowest population numbers. When we constrain the ranges to the 1st-99th centile ranges in this way removing the most extreme temperatures (heat index) for a particular location, the minimum mortality estimates shifts to more central values (Fig.8.14, Fig.8.16). For example, after applying the 1st-99th constrains for Pamplona, the minimum mortality estimate went from $P_{0\%}$ to $P_{85\%}$, however the width of the confidence intervals remained practically unchanged.

Figure 8.12 intends to illustrate the effects of the application of constrains for estimating optimum mortality temperatures in capital municipalities of different size (selected communities of Cataluña, Galicia, Aragón and Madrid, capitals are sorted from left to right based on the cumulative number of deaths). Here, the reader can clearly see that the largest cities such as Madrid and Barcelona have narrow confidence intervals, whereas smaller municipalities tend to have their estimates at the edge of the range.

Figures 8.13-8.16 demonstrate geographic variations in the MMT and MMHI estimated for the entire year, while figures 8.17-8.20 show the estimations for the summer (June to September) period. Estimates based on the unconstrained range of summer temperatures vary from 6.3ºC in the city of Palencia to 35.1ºC in Almería. When constrained to the 1st and 99th centile range the MMT in Almería was estimated at more than 15ºC lower at 18.9ºC. Overall, the majority (55%) of the provincial capitals had MMT constrained to 1st-99th centile in the range of 15-20ºC, whereas 23% of the capitals had lower estimates (10-15ºC range) and 11 capitals had the MMT above 20ºC. Interestingly, three provincial capitals with the highest estimates of MMT constrained to 1st-99th centile range are located in the islands: Palmas de Gran Canaria with MMT of 22.7ºC at 95%CI: 21.8ºC-24.5ºC, Santa Cruz de Tenerife with MMT of 22ºC at 95%CI: 21.3ºC-22.9ºC, and Palma de Mallorca with MMT of 21.8ºC at 95%CI: 18.6ºC-23.3ºC. MMT based on the mean daily heat index constrained to to 1st-99th centile represents a similar overall distribution: 50% of the capitals falling into the 15ºC-20ºC interval, 30% with optimum heat index between 10ºC and 15ºC, 17% - between 20ºC and 25ºC and the rest with MMHI below 10ºC.

Generally, MMT and MMHI for summer months show an overall north-to south incremental gradient, however, there is a great spatial variation in the interior parts of the country. The highest MMT and MMHI constrained to 1st and 99th centile range correspond to four capitals with dry climate (hot semi-arid BSh type) and equals to

20.5ºC, on average. 9 capitals with cold semi-arid BSk climate had lower MMT (MMHI) of 17.6ºC (16.5ºC). Slightly higher estimates of 18ºC correspond to 15 capitals with hot-summer Mediterranean climate Csa. Rest of the capitals of temperate climate had, on average, lower MMT (MMHI) going from 16.2ºC (15.8ºC) in 3 cities with humid subtropical climate Cfa, to 15.1ºC (14.7ºC) in 10 capitals with temperate oceanic climate Cfb down to 14.5ºC (13.6ºC) in 9 capitals with warm-summer Mediterranean climate Csb. In terms of the distributions, percentiles of the corresponding minimum mortality estimates in different climatic settings were restricted to $P_{61\%}$-$P_{68\%}$ range for temperatures and $P_{60\%}$-$P_{68\%}$ for heat index, with overall increasing trend from arid to subtropical climates.

Our results are similar to those obtained by Tobías, Hashizume, et al. (2021) in a comprehensive study of global geographic variations of MMT and their corresponding percentiles. Authors reveal an increase of MMT from temperate to arid and tropical climates, which is in line with our results. The percentiles corresponding to minimum mortality estimates in our case make reference only to the respective climates within Spain only. Tobías, Hashizume, et al. (2021) use as the reference climatic division worldwide, which explains differences in the percentile estimates in our results.

The task to estimate temporal changes in the MMT and MMHI is fraught with hindered obstacles. These difficulties are mostly related to the size effects due to the partitioning of the data, especially for less populated sites. We tested several grouping methods such as estimating MMT and MMHI for 5-, 10- and 20-year intervals. In addition, we used moving average windows with the same intervals in order to smooth out potential peaks in individual years. Map presented on Figure 8.21 shows geographic variations in the changes of the MMT based on mean daily temperature constrained to the 5^{th}-95^{th} centile range. Figure 8.22 displays spatial variations of changes in the MMT based on the maximum daily temperature with the same constrains applied. Both maps are focused on the summer period only. Here, we define *change* as an absolute difference between last observation window (here, the last 10 year interval, 2009-2018) and the first interval (1979-1988). Red color marks the positive changes (i.e. increment of the MMT with respect to the start of the observation) whereas blue color shows negative changes. Size of the dot corresponds to the magnitude of the change.

From both graphs could be clearly seen that most of the interior and coastal capitals experienced a decreased in the MMT, while the rest of the capitals, and especially those located in the large river valleys (e.g. Ebro or Guadalquivir), experienced an increase. This increase suggest a progressive adaptation to heat over time. The absolute values of

these changes vary across the country, however the estimates, especially in the smaller cities and based on short time intervals could have high degree of uncertainty. Figure 8.23 illustrates the changes in the MMT based on the mean daily all-year temperatures estimated for selected provincial capitals using 20-years moving windows. For all of the selected capitals the change in the upper bound of the estimation is consistently positive. For some of the capitals the uncertainty range is expanding with time (Fig.8.23 c, d, i, j, l), for some - stays fairly constant (Fig.8.23 b, h, k), and for some - reduces with time (Fig.8.23 e). The estimates are subject to greater variation in a number of locations (Fig.8.23 e, h, k), however for the major part of the selected capitals the pattern is generally more stable. Overall, temporal changes in the MMT in individual municipalities reveal great heterogeneity.

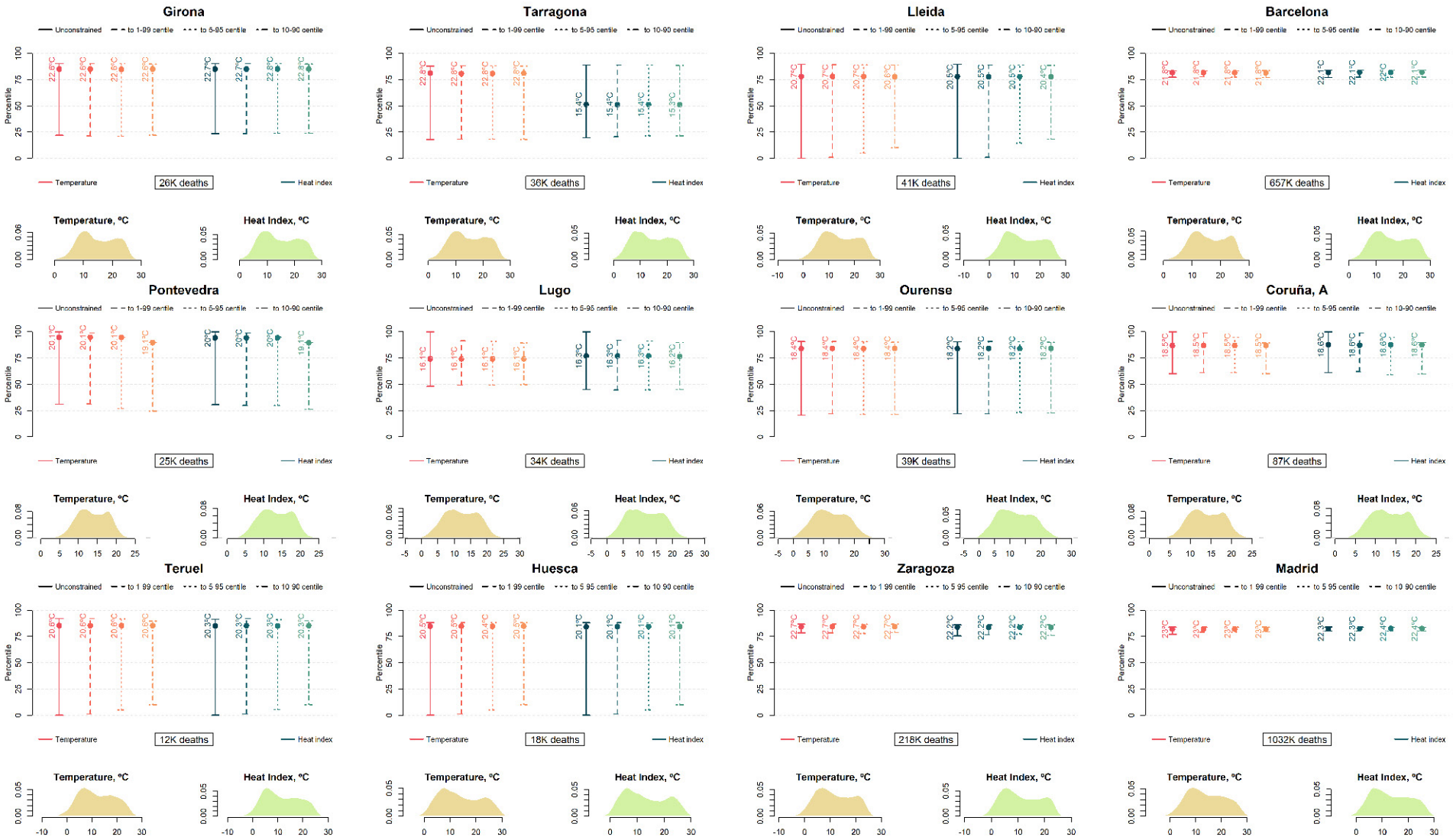


Figure 8.12: Variations in MMT and MMHI based on mean daily values in selected municipalities of provincial capitals by type of constrain

We then perform an aggregated analysis of the changes in the MMT by grouping capital municipalities by their corresponding type of climate. Table 8.6 displays changes in the MMT and MMHI based on all-year mean and maximum daily temperature and heat index at different constrains in the 50 provincial capitals (Ceuta and Melilla excluded), grouped by climatic types.

Table 8.6: Overall changes in MMT and MMHI in 50 provincial capitals in Spain grouped by climate

			Dry climates		Temperate climates			
		Constrains	BSh	BSk	Cfa	Cfb	Csa	Csb
Heat Index	Average	None	2.72	-1.72	10.17	0.11	6.81	-1.68
		1-99 centile	1.73	-0.78	5.62	1.7	1.33	-2.19
		5-95 centile	-0.19	0.97	1.85	-0.95	0.57	-0.44
		10-90 centile	-0.12	1.17	-0.17	-0.82	0.74	0.25
	Maximum	None	2.6	2.77	5.97	0.91	5.4	-6.11
		1-99 centile	2.26	-1.56	4.5	1.33	-0.79	-5.71
		5-95 centile	-1.53	0.09	1.25	-0.22	0.39	-2.21
		10-90 centile	-1.23	1.01	1.18	-1.66	0.24	-1.29
Temperature	Average	None	1.87	-0.89	8.6	1.64	5.67	-0.93
		1-99 centile	1.05	-0.07	4.95	1.55	0.75	-3.15
		5-95 centile	-0.8	0.2	1.77	-0.84	0.05	-1.31
		10-90 centile	-0.71	0.57	0	-0.35	0.97	-0.46
	Maximum	None	10.08	1.9	12	-0.07	1.51	-3.9
		1-99 centile	1.95	0.92	4.43	3.17	-0.23	-7.09
		5-95 centile	-1.33	0.32	1.22	-0.26	0.37	-2.06
		10-90 centile	-1.07	1.23	2.38	-1.69	0.63	-1.04

Note:
Comparison performed for 50 capital municipalities (Ceuta and Melilla excluded) using first decade (1979-1988) and last decade of observations (2009-2018). Estimations averaged for climatic type.

Cities with temperate warm-summer Mediterranean (Csb) climate in Galicia and Castilla and León, on average, have experienced a decline in the MMT and MMHI. Rest of the capitals mostly showed an increase it the estimates. Detailed graphs of the temporal changes in the MMT based on mean daily temperature constrained to the 5^{th}-95^{th} centile range using 20-year moving windows are shown in Appendix on Figure E.15.

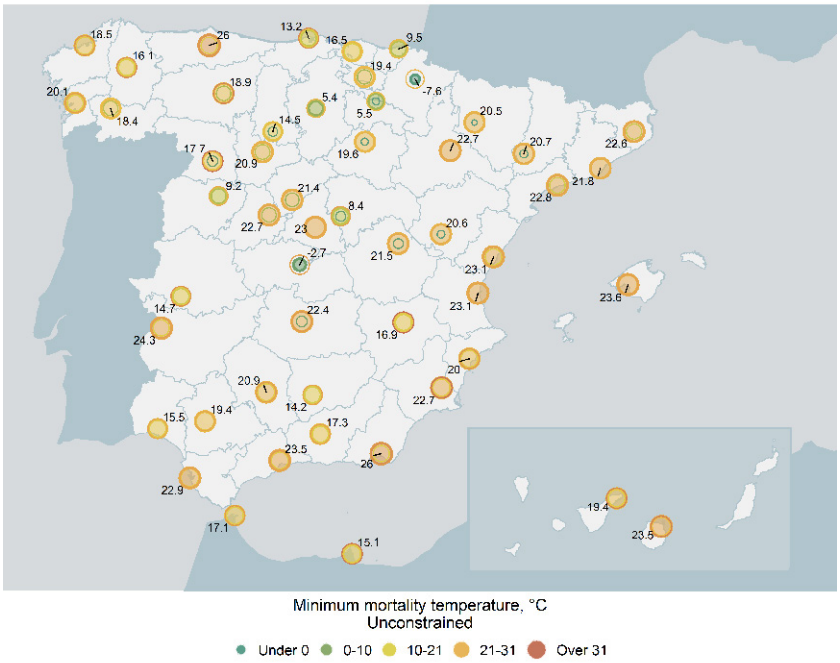


Figure 8.13: MMT based on unconstrained all-year mean daily temperature in 52 municipalities of provincial capitals

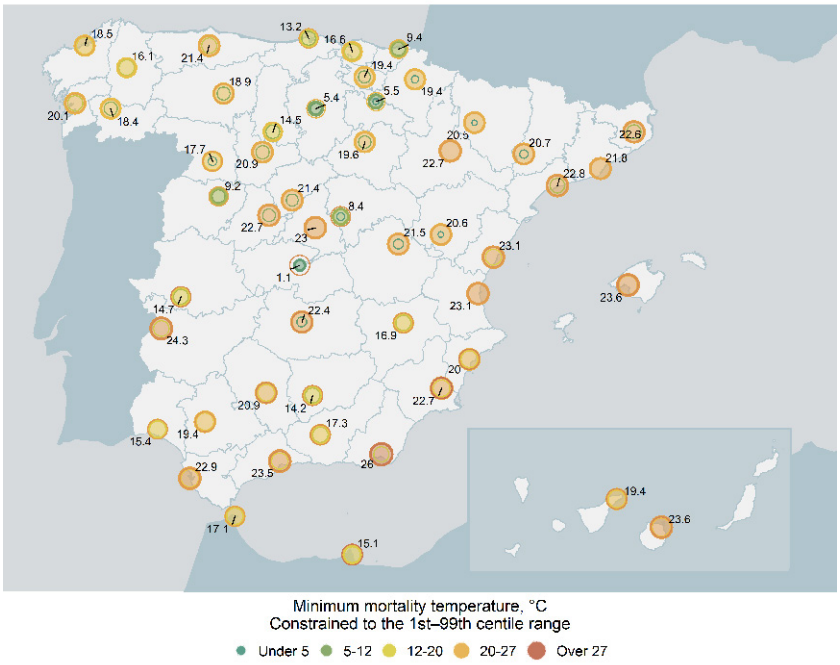


Figure 8.14: MMT based on all-year mean daily temperature constrained to 1st-99th centile range in 52 municipalities of provincial capitals

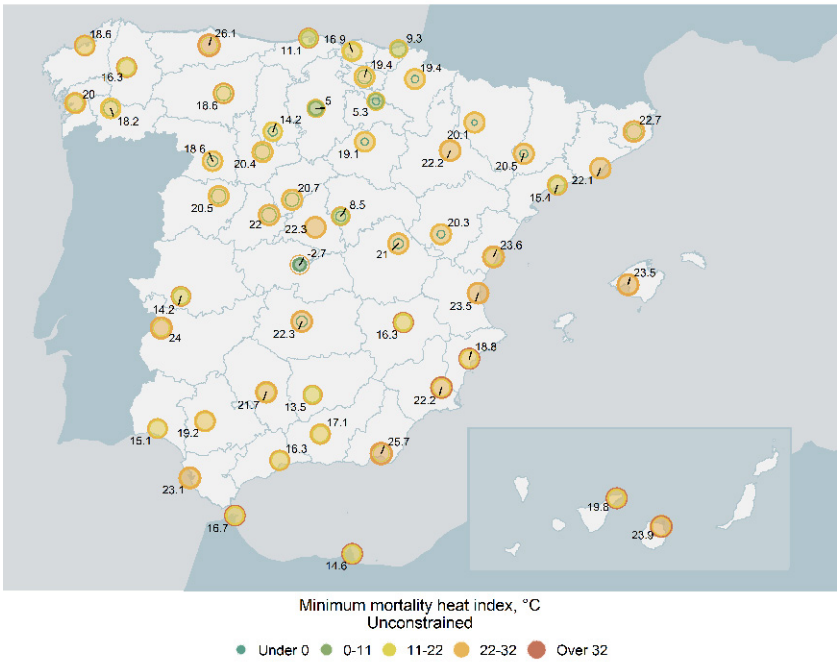


Figure 8.15: MMHI based on unconstrained all-year mean daily heat index in 52 municipalities of provincial capitals

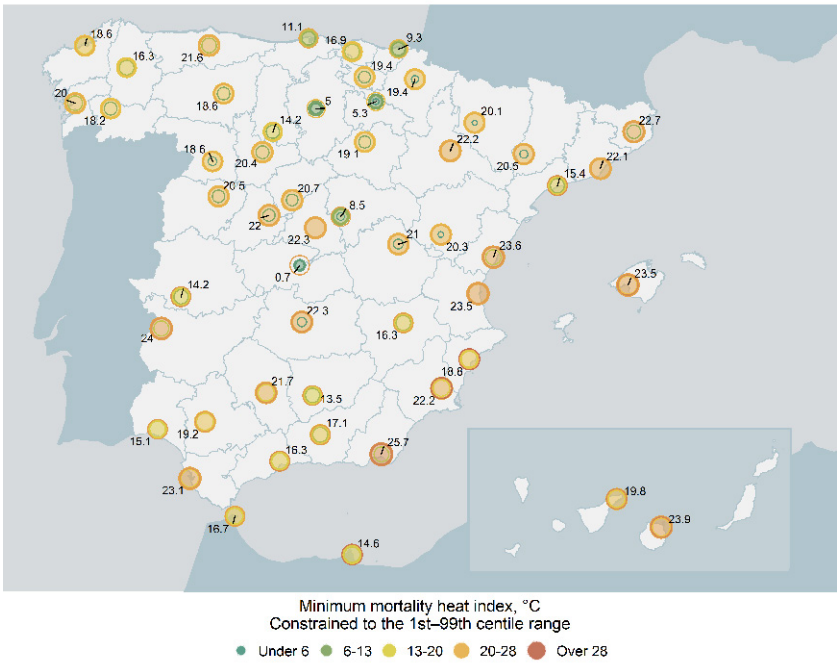


Figure 8.16: MMHI based on all-year mean daily heat index constrained to 1st-99th centile range in 52 municipalities of provincial capitals

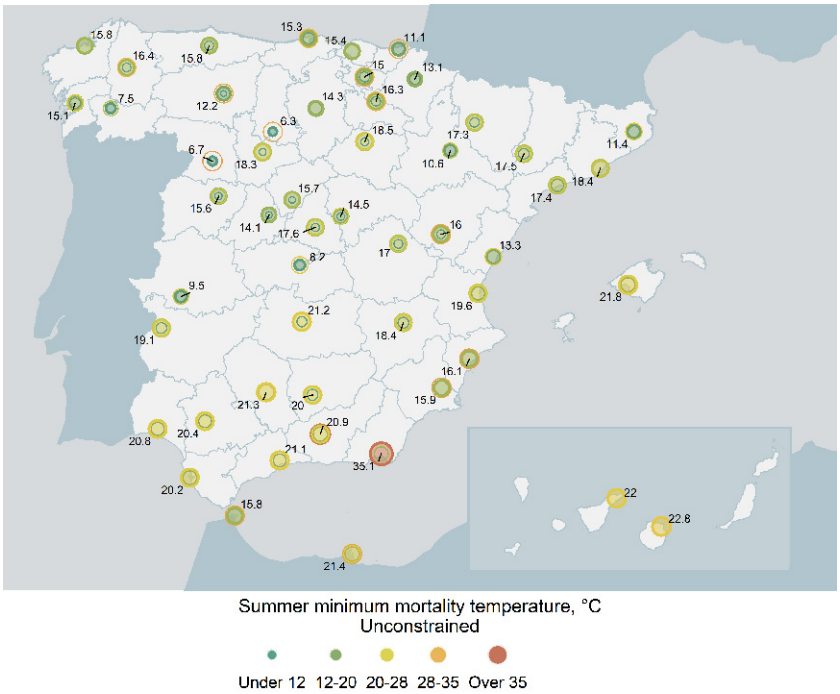


Figure 8.17: MMT based on unconstrained summer mean daily temperature in 52 municipalities of provincial capitals

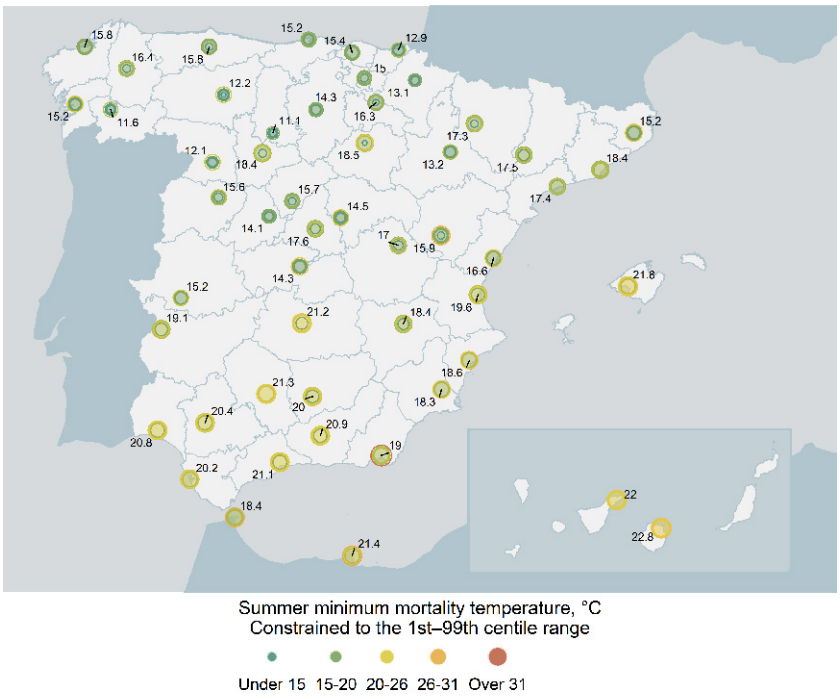


Figure 8.18: MMT based on summer mean daily temperature constrained to 1st-99th centile range in 52 municipalities of provincial capitals

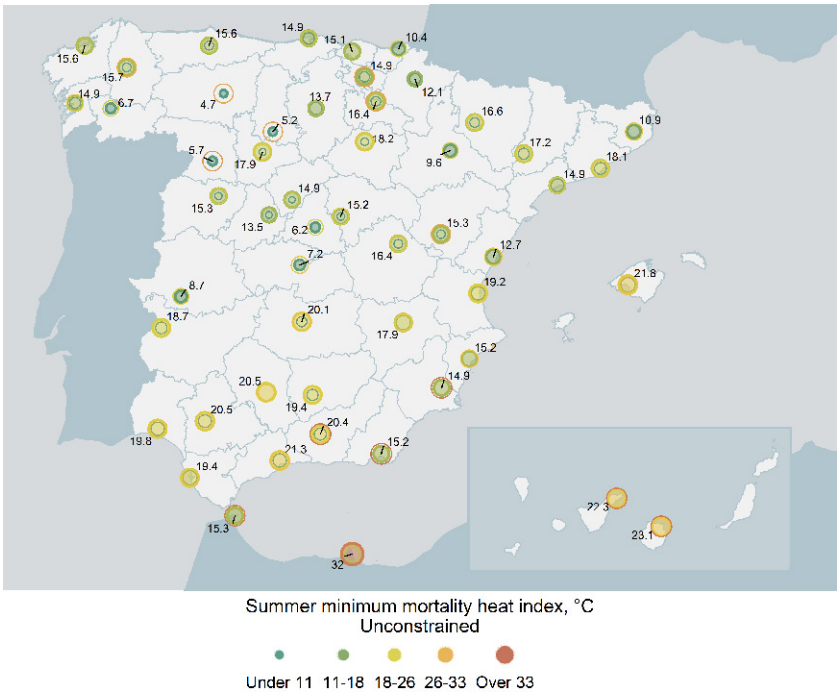


Figure 8.19: MMHI based on unconstrained summer mean daily heat index in 52 municipalities of provincial capitals

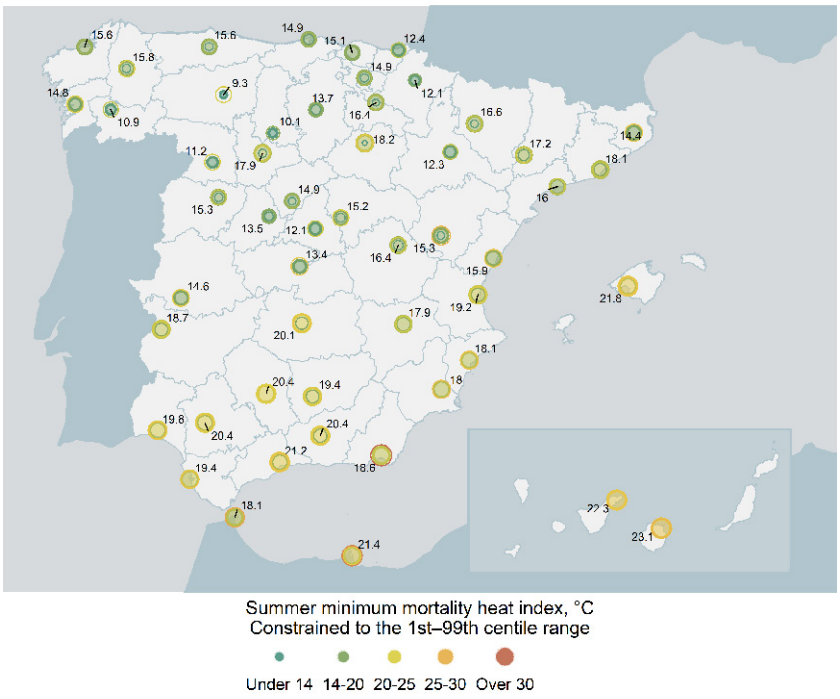


Figure 8.20: MMHI based on summer mean daily heat index constrained to 1st-99th centile range in 52 municipalities of provincial capitals

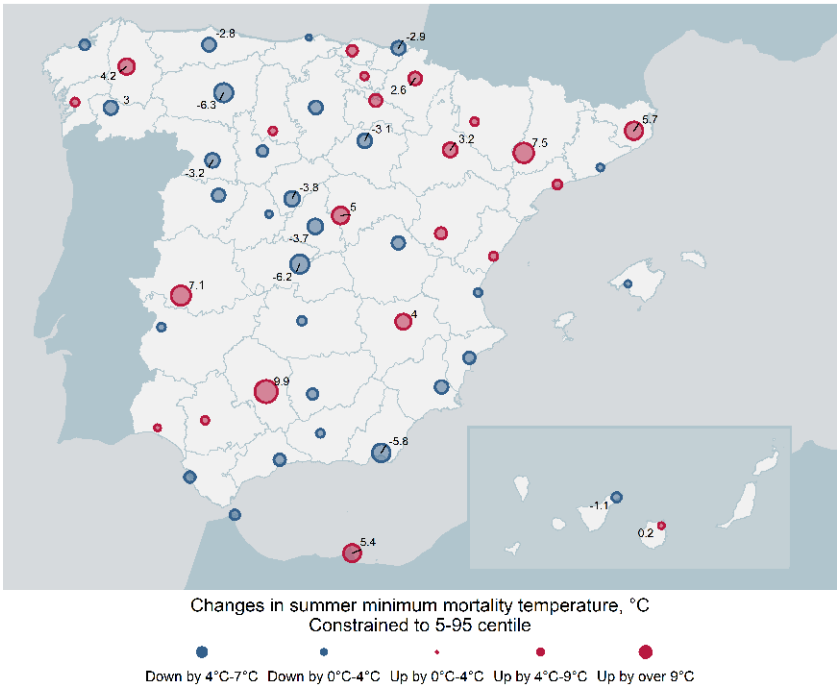


Figure 8.21: Yellow dot indicates the estimate, horizontal yellow line corresponds to the lower bound and red thick lines marks the upper bound of the confidence interval.

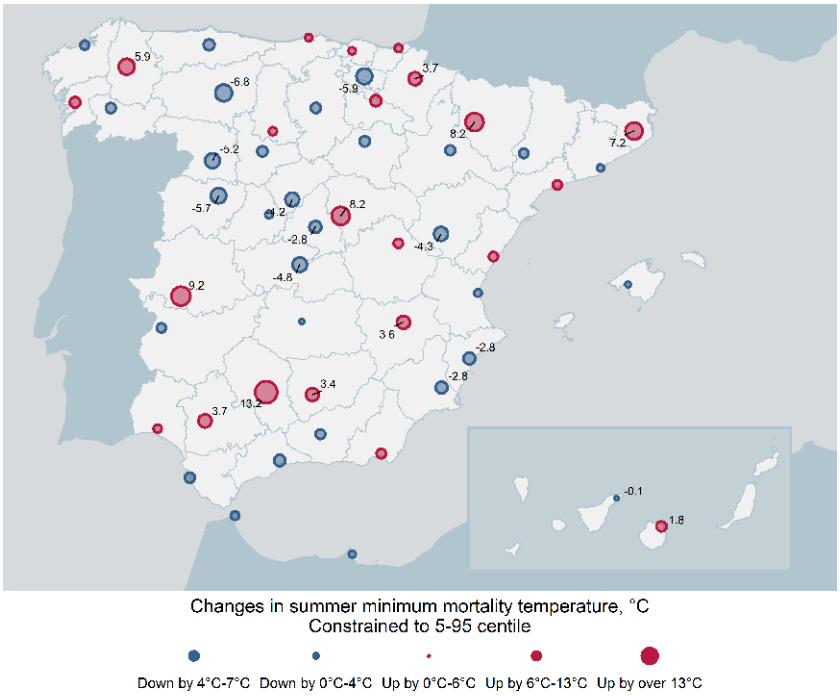


Figure 8.22: Changes in MMT (maximum temperature constrained to the 5-95th centile range) in largest provincial capitals of Spain from 1979 to 2018 (first decade compared to last)

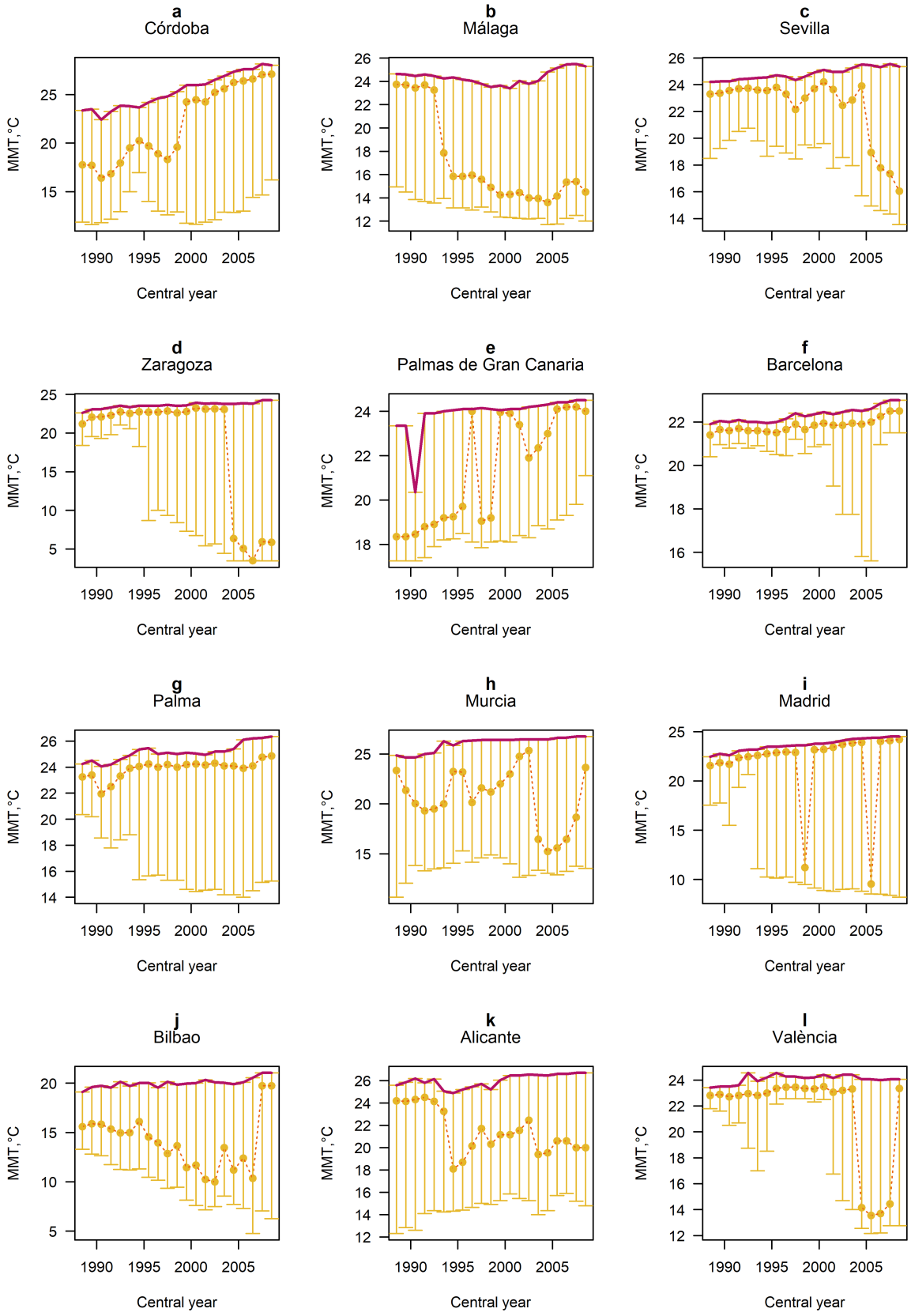


Figure 8.23: Changes in MMT (mean temperature constrained to the 5-95th centile range) in largest provincial capitals of Spain from 1979 to 2018 (moving average windows of 20 years)

8.5 Estimating MMT and MMHI in urban and rural municipalities across Spain

We now scale down our analysis to the micro level and estimate MMT and MMHI in municipalities of different sizes (under and above 50K inhabitants) in each province. As mentioned earlier, in order to disaggregate municipalities by population size it was necessary to reduce the observation window from 40 years down to 20, from 1998 to 2018. Spatially, the distribution of less and more populated municipalities is unequal as more populated municipalities tend to cluster in a certain area (most likely, in proximity to the provincial capital), with the rest of provincial area being occupied with sparsely populated municipalities. The threshold of 50K inhabitants was selected in order to maintain the balance in terms of the sample sizes, however, the aggregation of temperatures was done across large areas.

Figure 8.24 illustrates geographic distribution of the MMT based on the mean all-year temperatures constrained to the 1^{st}-99^{th} centile range, while Figure 8.25 focuses only on the summer period. Detailed maps showing MMT/MMHI (based on mean and maximum summer and all-year temperatures/heat index) variations are presented in Appendix on Figures E.16-E.19.

Overall, 32% of the rural municipalities (less than 50K inhabitants) had their MMT based on the mean all-year temperatures constrained to the 1^{st}-99^{th} centile range in the 15ºC-20ºC degree range, followed by 30% of the municipalities with the MMT between 20ºC and 25ºC and only 4% having their MMts in the 25ºC-30ºC interval. Rest of the rural municipalities had their MMT below 15ºC (18% between 10ºC and 15ºC, 16% between 5ºC and 10ºC). Half of the urban municipalities had their MMT in the 15ºC-25ºC interval, with only a few having their estimates above 25ºC. The rest of the urban municipalities had their MMTs below 15ºC (22% in the 10ºC-15ºC range, 16% in the 5ºC-10ºC and 8% had their MMT below 5ºC). In terms of the geographic distribution, there is a pronounced longitudinal gradient with eastern coastal provinces having higher estimates in comparison with their western counterparts.

Spatial distribution of the MMT based on the mean daily temperatures from June to September, constrained to their respective 1^{st}-99^{th} centile range, shows a clearer latitudinal gradient with highest (up to 31.4ºC) estimates in the southern provinces and the lowest (10.6ºC) in the central-northern parts. In summer, 52% of the rural municipalities in Spain had their MMT in the range of 15ºC-20ºC, whereas 28% had it in between 10ºC to 15ºC and 20% - between 20ºC and 25ºC. Interestingly, urban municipalities reached

highest MMT in the summer, however the number of the units with the MMT between 25ºC and 35ºC was low (4%). 26% of the urban municipalities had their MMT in the 20ºC to 25ºC interval, followed by 40% of the municipalities with the MMT in the 15ºC-20ºC interval and 30% - in the 10ºC-15ºC range. We will discuss intra-provincial variations and protective effects of urban and rural settings in the last section of this chapter.

The general character of the exposure-lag-response association in the groups of urban and rural municipalities in each province follows the national trend discussed earlier. Here, longer lags are associated with an increased risk for the exposure to colder temperatures, while shorter lags have higher risks for the hotter spectrum (similar to the previous analysis, we use the mean daily temperatures restricted to the 1^{st}-99^{th} centile). Figure 8.26 shows the exposure-lag-response associations for the groups of urban (over 50K inhabitants) municipalities in 50 Spanish provinces (as provinces of Soria and Teruel have total population below 50K threshold).

Overall, highest risks on the day of exposure (1.89 at 95%CI: 1.22-1.93) were associated with the temperature of 31ºC in the urban municipalities in Cuenca, Castilla-La Mancha. 7 days after being exposed to 31ºC in the same group of municipalities the risks are still the highest (1.09, 95%CI: 1.02-1.16). The days with slightly lower temperatures of 29.5ºC in the city of Melilla had the risks of 1.7, 95%CI: 1.12-2.6. Urban municipalities in the province of Tarragona, Cataluña, had the third highest risks of 1.56, 95%CI: 1.16-2.09, on the days of exposure to 31ºC. In 2 weeks post-exposure, highest risks were associated with the lowest temperatures. 14 days after being exposed to -5.5ºC, urban municipalities in Huesca, Aragón, had risks 9% higher (1.09, 95%CI: 1.02-1.16) with respect to the days of MMT (21ºC, in this case). In 3 weeks post-exposure, both sides of the spectrum revealed greater risks. For instance, Albacete, Castilla-La Mancha, had the risk of 1.07, 95%CI: 1-1.14 associated with the exposure to 31ºC 3 weeks back. Same lags in the same group of municipalities had the risk of 1.11, 95%CI: 1.06-1.17, associated with the exposure to -3ºC. Generally, lag-response association exhibit a consistent pattern across Spanish provinces with the highest overall risks corresponding to the hotter range of temperatures on the day of exposure and the day after.

To conclude the analysis at the micro-level, we invite the reader to explore Figure 8.27. On this graph, we represent density plots of the mean daily temperature distribution in urban (in pink) and rural (in green) municipalities in each province. Opaque color marks temperatures above the percentile corresponding to the MMT. Provinces are sorted by the value of the percentile of the MMT in the rural area, from highest to lowest. Rural areas in the northern provinces have the highest MMTPs: $P_{85\%}$ in case

of Zamora, $P_{73\%}$-$P_{78\%}$ in Lugo, Cantabria, Burgos, Teruel and Asturias. The lowest percentile of the MMT was estimated at $P_{45\%}$ for Las Palmas, Canary islands. The urban counterparts, on the other hand, tend to have significantly lower MMTPs. For example, MMT in municipalities with over 50K of inhabitants in Zamora corresponds to $P_{51\%}$, in Cantabria - to $P_{59\%}$, in Burgos - to $P_{48\%}$. In case of the Canary island, the percentile of the MMT estimated for the urban municipalities in Las Palmas was higher in the rural areas ($P_{79\%}$). The highest overall MMTP in urban municipalities was estimated for the city of Melilla and urban agglomeration of Almería ($P_{99\%}$).

Largest difference between urban and rural municipalities in terms of the MMTPs were found in Canary islands, with urban municipalities having their MMTP 19% higher than those of rural municipalities ($P_{73\%}$ versus $P_{54\%}$, respectively). Urban municipalities in the South also had their $MMTP_{urban}$ higher than $MMTP_{rural}$ ($P_{69\%}$ versus $P_{63\%}$). Provinces in the East of Spain had generally lower MMTPs but similar distribution with $MMTP_{urban}$ of $P_{64\%}$ and $MMTP_{rural}$ of $P_{59\%}$. Conversely, rural municipalities in the Center of Spain had MMTPs above those of the urban areas ($MMTP_{rural}$ of $P_{62\%}$, $MMTP_{urban}$ of $P_{57\%}$). Rest of the provinces in the Northeast, Northwest and in the community of Madrid had their $MMTP_{rural}$ and $MMTP_{urban}$ practically equal with the lowest absolute values in Madrid ($MMTP_{rural}$ of $P_{52\%}$, $MMTP_{urban}$ of $P_{53\%}$) and the highest in the Northwest ($MMTP_{rural}$ of $P_{68\%}$, $MMTP_{urban}$ of $P_{66\%}$).

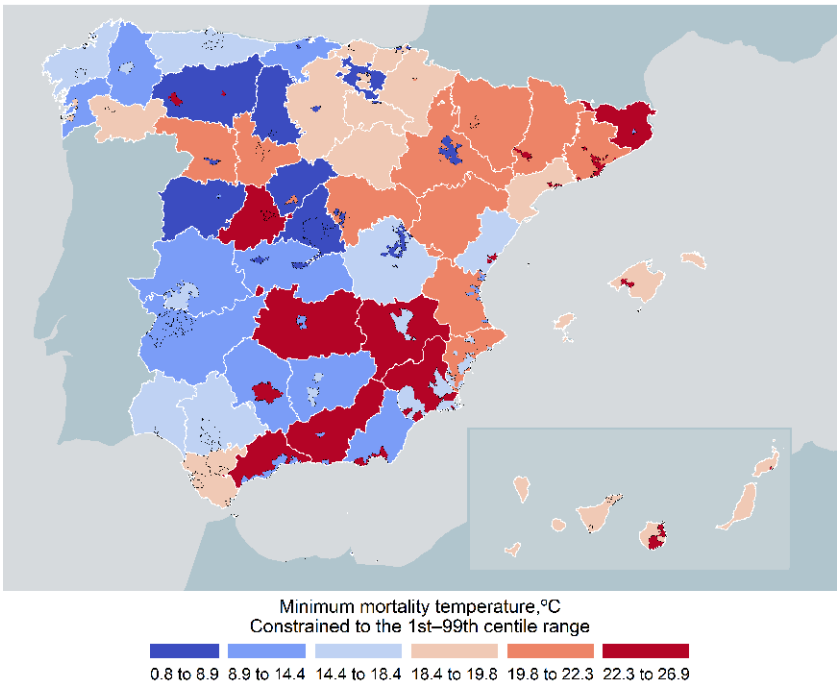


Figure 8.24: Geographic variations of the MMT based on mean daily all-year temperatures constrained to the 1st-99th centile range in urban and rural municipalities in Spain

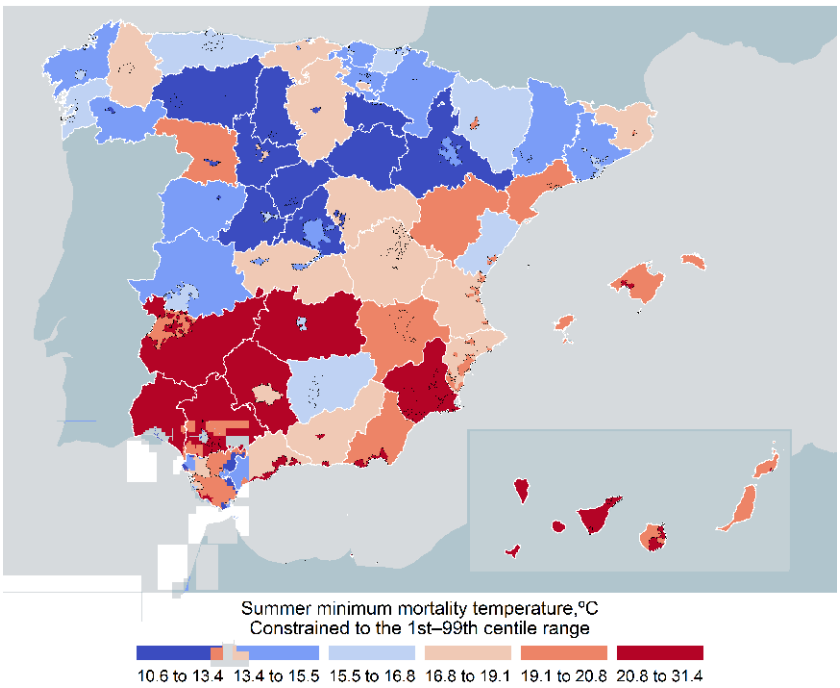


Figure 8.25: Geographic variations of the MMT based on mean daily summer temperatures constrained to the 1st-99th centile range in urban and rural municipalities in Spain

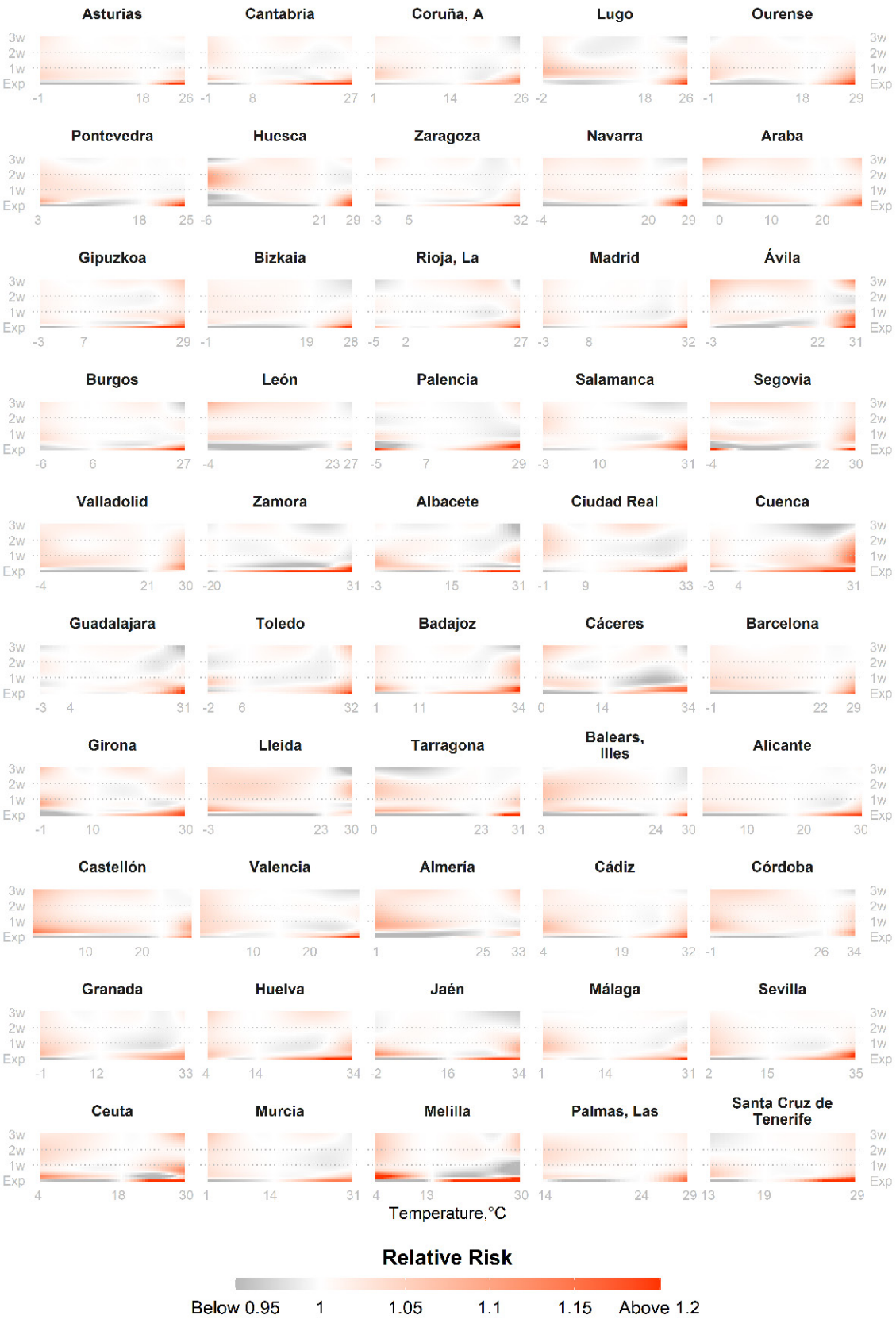


Figure 8.26: Exposure-lag-response association between daily mean temperature constrained to 1st-99th centile range and daily mortality in urban (over 50K inhabitants) municipalities in Spanish provinces

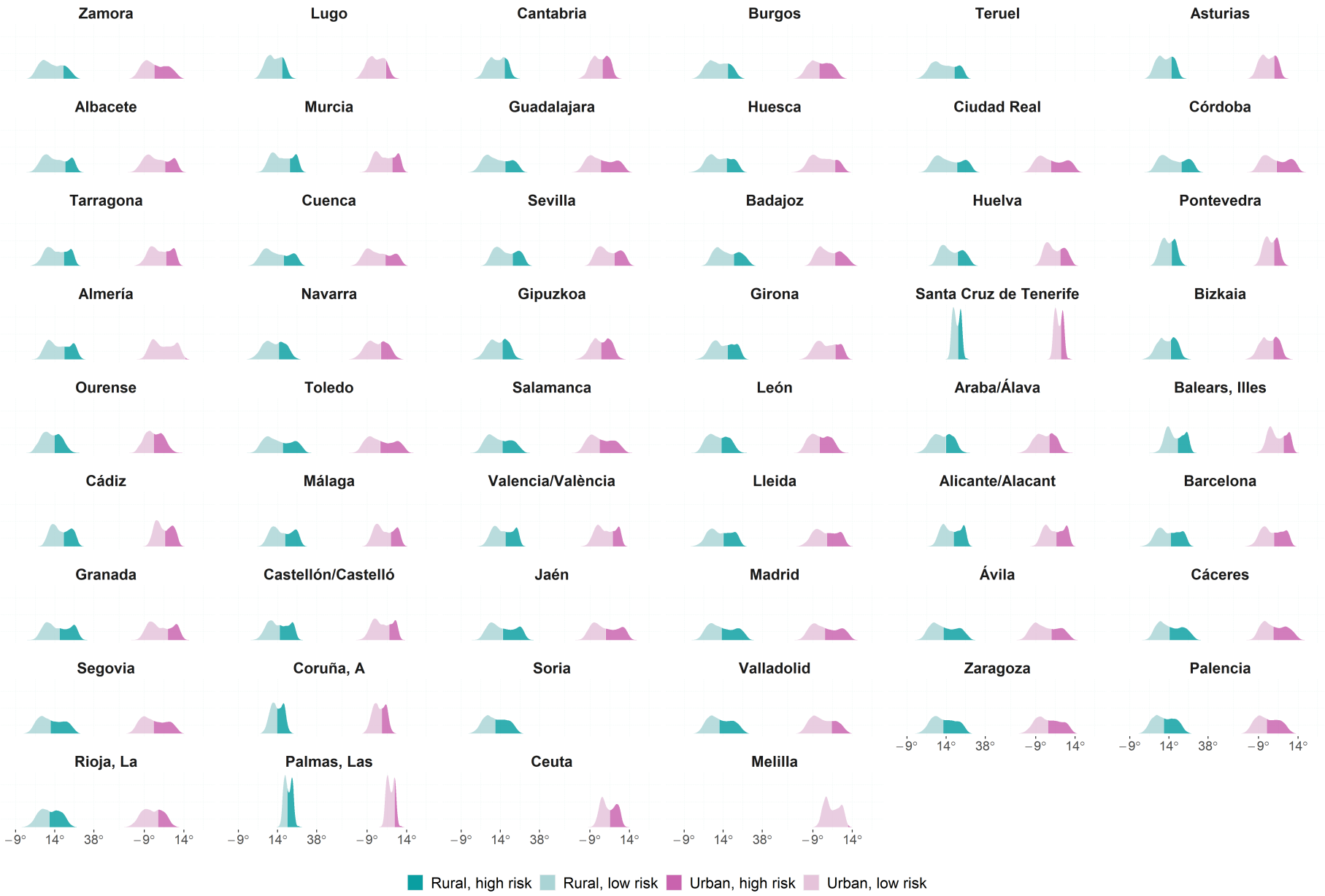


Figure 8.27: Risk temperatures in rural and urban municipalities in Spain

8.6 Geographic disparities in mortality answers between socioeconomic strata

To conclude the analysis focused on the variations of the MMT/MMHI within Spain, we introduce new dimensions representing socioeconomic and ecological environments individuals live in. To cover the socioeconomic dimension, we rely on the index of deprivation estimated at the municipal level. We remind the reader that fundamentals of this indicator were discussed in Chapter 3. Here, the ecological environment refers to the urbanization component, which is approximated by the population size. We will start our discussion with the latter one.

Before, when working at the micro level, we estimated MMT and MMHI for groups of urban (over 50K of inhabitants) and rural (below 50K) municipalities. We then compare these estimates in between urban and rural counterparts in order to identify whether urban environment has protective effects in terms of mortality, or vice versa. By the protective effect here we understand higher values of MMT/MMHI, as it would potentially indicate an increased resistance to summer temperatures (heat index) of the population. Figure 8.26 shows ratio between MMT_{urban} ($MMHI_{urban}$) and MMT_{rural} ($MMHI_{rural}$), estimated using average temperatures (heat index) during summer months. On this graph, category *Rural* would contain estimates for the provinces which do not have municipalities of more than 50K of inhabitants (such as Teruel and Soria), whereas *Urban* category would represent units without rural municipalities (such as autonomous cities of Ceuta and Melilla). The rest of the provinces would be located between two extremes, and as closer the province is located to the category *Equal*, more similar are the MMT/MMHI estimated in its rural and rural municipalities. For the temperature, the protective effect of urban settings is seen in the provinces located in the East and Northeast of the country, and also in the Canary islands and community of Madrid. There is practically no difference between urban and rural settings in terms of the MMT in the Northwestern region, and major part of the South. Nevertheless, the Andalusian provinces exhibit greater variability with province of Cordoba having higher MMT estimates in the rural municipalities and Almeria located at the other edge with urban municipalities having the MMT significantly higher than rural ones. Provinces located in the Central Spain (Castilla and León, Castilla-La Mancha) have higher values of MMT in the rural settings, in comparison with the urban municipalities. However, there are some exceptions, such as provinces of Valladolid or Ávila, where urban settings play a protective role against summer temperatures. The general pattern for heat index is

similar, with less variability noted in the Southern provinces and greater differences revealed in the Center and Northwest of Spain. Figure E.20 displays variations in the MMT_{urban}/MMT_{rural} ($MMHI_{urban}/MMHI_{rural}$) based on the estimates done using maximum summer temperature (heat index).

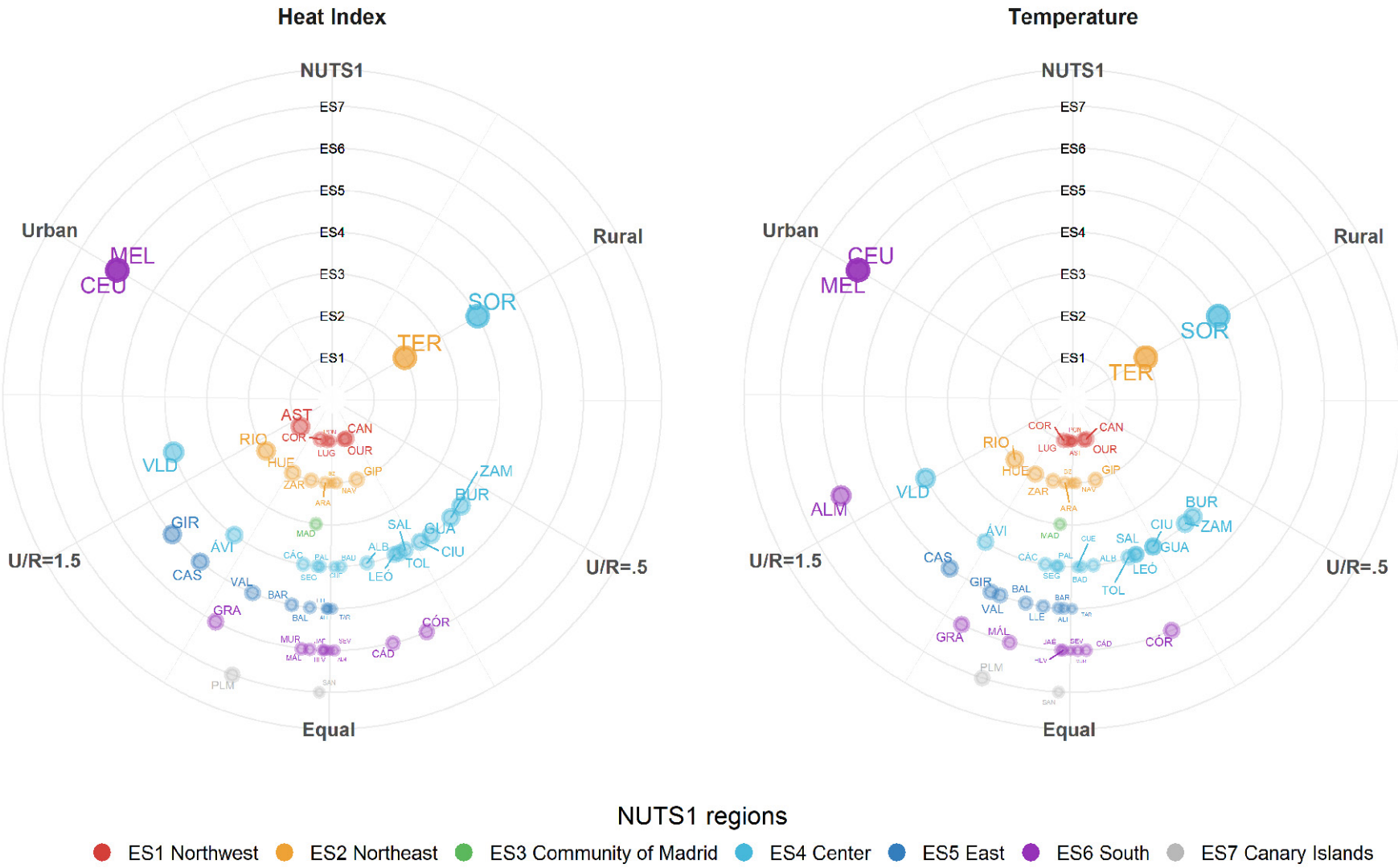


Figure 8.28: Regional variations in urbanicity as protective factor for summer mortality due to heat (average temperatures and heat index)

Additionally, we explored the mortality associations with average and maximum values of all-year temperature and heat index in rural and urban municipalities in large regions[9] Figure 8.29 demonstrates the exposure-response associations in urban and rural settings within each region. Values shown in the legend correspond to the estimated value of MMT/MMHI for each category. The character of the curves is similar from indicator to indicator. In rural municipalities in the Center and in the South the risks for hotter temperatures are higher, if compared to the urban areas. In case of the northern and eastern provinces, the risks are practically identical for the hotter spectrum of average temperatures. In case of the higher values of average heat index, the risks are equal in urban and rural communities in the North of the country, while in the East, Center and in the South the risks for rural areas are higher than those for urban municipalities. In case of the Canary Islands, urban areas have higher risks for exposure to hotter temperatures and heat index. Nevertheless, the uncertainty intervals estimated for this region are also larger.

Lastly, we analyze variations in exposure-response associations with average and maximum temperatures and heat index by degree of deprivation. To do so, we examine the exposure-response relationship in three groups of municipalities (higher, lower and average deprivation) region-wise[10]. Figure 8.30 represents the results of these estimations graphically. Numbers placed in the legend next to each category correspond to the estimated MMT/MMHI value, similarly to the representation on Figure 8.29. At a glance, reader can note greater disparities between municipalities with different levels of socioeconomic deprivation in the North and in the South. In case of the northern municipalities with higher levels of deprivation, the risks are significantly higher for the exposure to colder temperatures and heat index, when compared to those municipalities with average or lower deprivation. Southern municipalities higher deprivation exhibit an opposite pattern: risks for the less deprived municipalities in response to the exposure to colder temperatures/heat index are higher than those estimated for more deprived municipalities. However, more deprived municipalities in the South show higher risks in response to the exposure to hotter temperatures, in contrast to the deprived municipalities in the North. In the rest of the regions the differences between municipalities of higher an lower deprivation in terms of the response to hotter or colder temperatures/heat index are minimal.

[9]Here, we grouped NUTS1 regions into five larger units: *North*, consisting in Northeast ES2 and Northwest ES1, *Center*, formed by Community of Madrid ES3 and Center ES4, *East*, *South* and *Canary Islands*, coinciding with original NUTS1 nomenclature.

[10]More deprived municipalities are formed by the municipalities where deprivation index overpassed 0.5 units. Less deprived municipalities consist in those with deprivation index below -0.5. Average deprivation was formed by those with average level of deprivation between -0.5 and 0.5

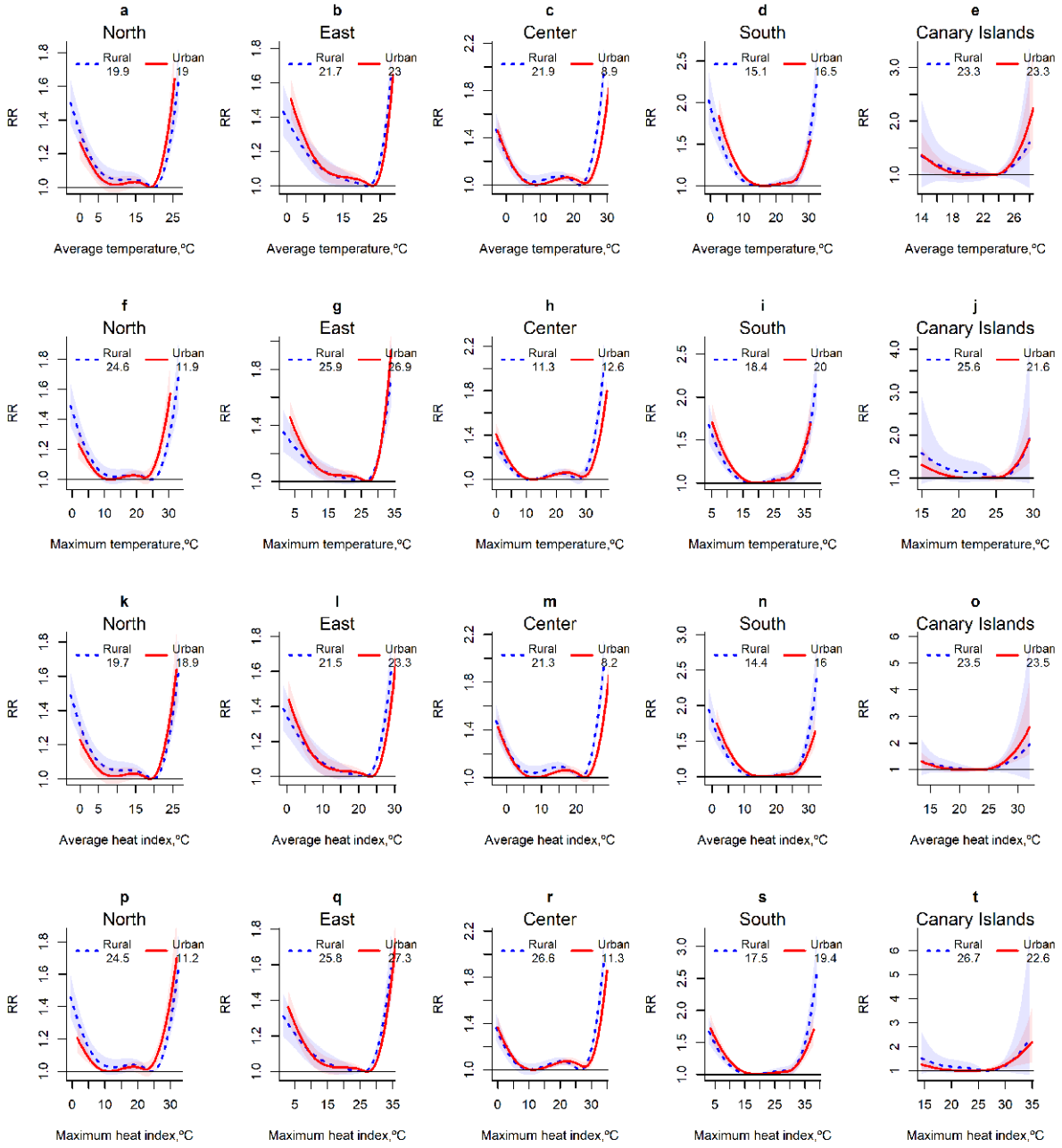


Figure 8.29: Exposure-response associations between daily mortality and mean and maximum temperature and heat index (unconstrained), by municipality size within large regions

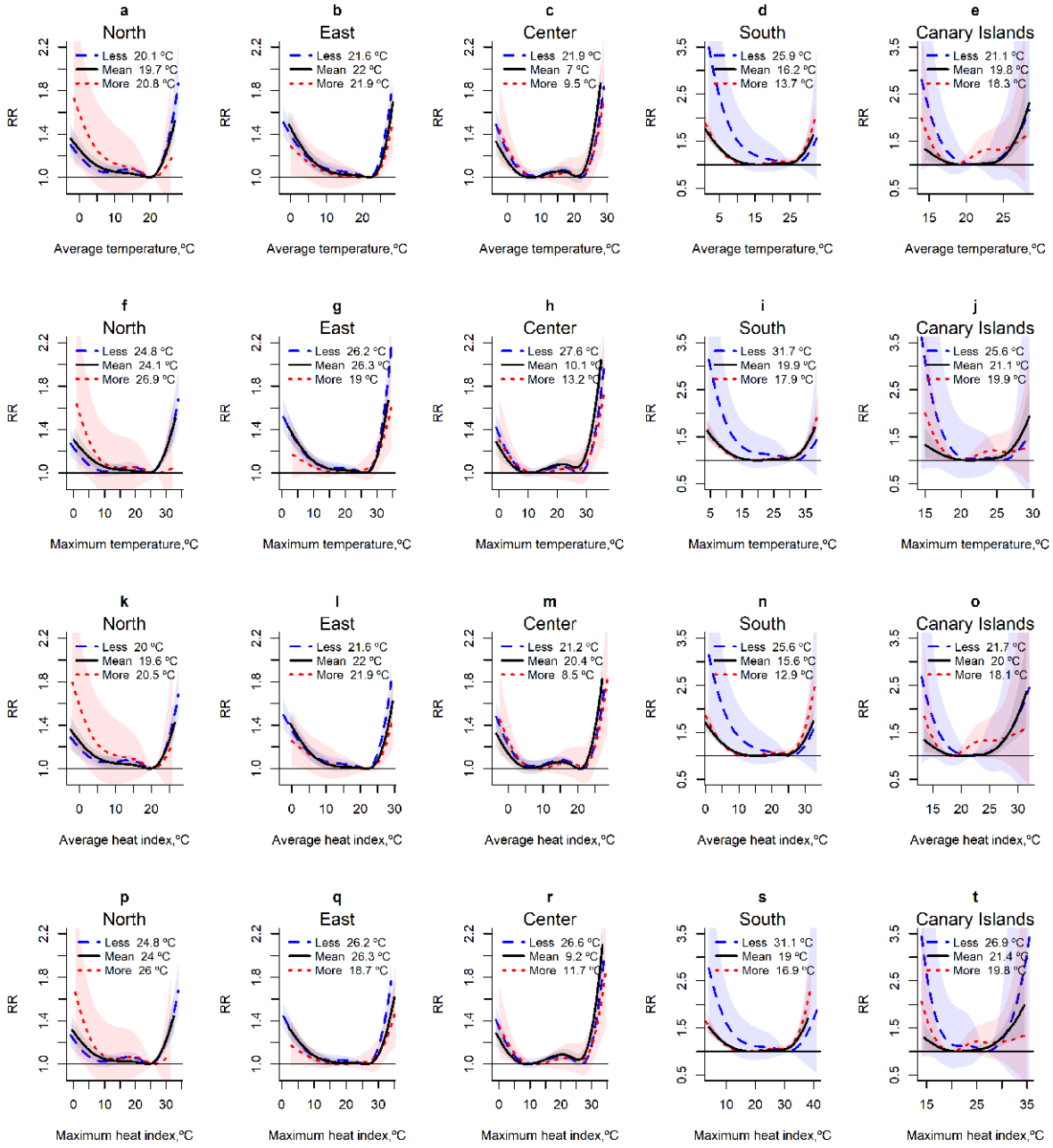


Figure 8.30: Exposure-response associations between daily mortality and mean and maximum temperature and heat index (unconstrained), by degree of deprivation and large regions

The research question of the effect modification induced by air pollution in the temperature-mortality relationship is worth considering (...), therefore the study of the potential modification has a greater public health relevance especially since heat response plans are in place in many cities but virtually none includes information on air pollution.

— *Short-Term Effects of Heat on Mortality and Effect Modification by Air Pollution in 25 Italian Cities*, Scortichini et al. (2018).

9

Adverse effects of air pollution on health in Andalusia

In this chapter, we explore the association between day-to-day variations in concentrations of different air pollutants and daily risk of death, while controlling for seasonality and confounding factors like air temperature. This seemingly straightforward task is non-trivial in terms of methodological approximation because the association between air pollution and health risks can be obscured by a variety of confounding factors. Nevertheless, we consider the analysis presented in this chapter as a somewhat *pilot* study, as there is a number of limitations, especially in terms of the data availability and spatial coverage, that hamper a more comprehensive analysis.

As the reader might recall from the discussion in Chapter 6, we explored in details spatial and temporal variations in daily concentrations of primary air pollutants using the gridded dataset covering continental Spain and Balearic islands with estimations from mid-2017 to mid-2020. Unfortunately, the overlap with the mortality dataset did not reach a year, making time-series analysis practically impossible. To help us tackle this problem we use an alternative source of data - ground point measurements. However, here we do not spatially interpolate these stationary data but use aggregated variables due to the overall purpose of this exploratory analysis. Due to the data constraints, the emphasis of this pilot study is on the autonomous community of Andalusia.

9.1 Study design and statistical analysis

The estimations of the daily air pollution levels were derived from the stationary data in the community of Andalusia. 115 measurement stations are located predominantly in close proximity to large cities. Figure 9.1 represents the location of the stations in each province, 10x10 km cells "containing" these stations and corresponding municipalities. To create a unified dataset usable for modelling, we combine pollutant´s concentrations, air temperature and death statistics into a single structure. Air temperatures in selected cells and concentrations of air pollutants measured at individual stations were aggregated in the chosen municipalities and mean and maximum daily values were computed.

Measurement stations in Andalusia did not operate equally in terms of the data collection. Only 31% of the stations have data measurements available for the entire observation window. 16% of the stations in Andalusia covered more than 75% of the period with observations. 20% of the stations had data available for 50-75% of the interval, while 33% of the stations possessed the data for less than half of the study period.

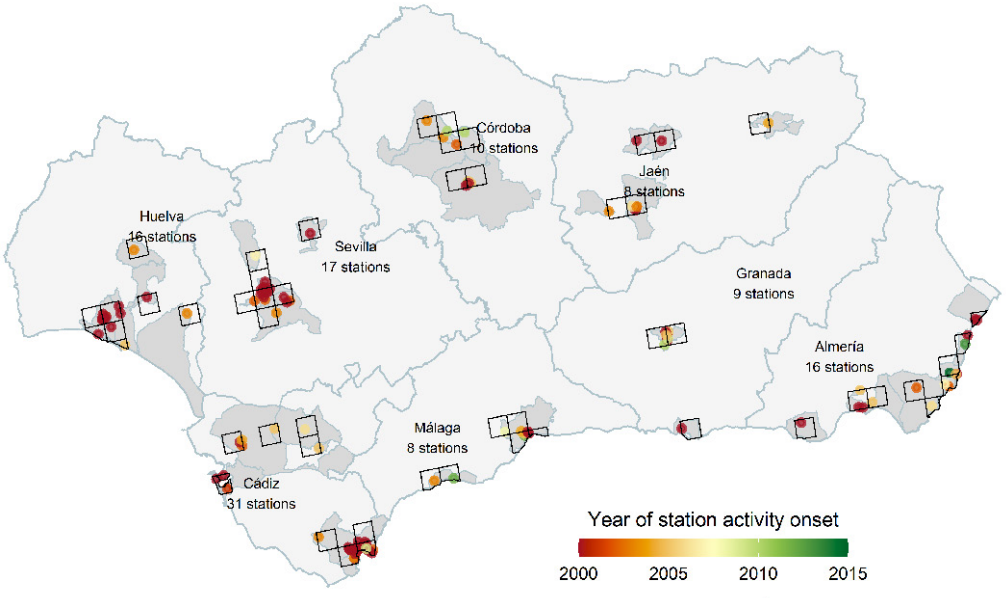


Figure 9.1: Location of air quality measurement stations in Andalusia

For the analysis explained in the following paragraphs, we selected the pollutants with the highest availability across the stations. Figure 9.2 gives an overview of the daily fluctuations of mortality data along with temperatures, ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and coarse particulate matter (from bottom to top),

with main statistics displayed inside each graph[1]. Right panel of the figure shows a histogram of the corresponding data.

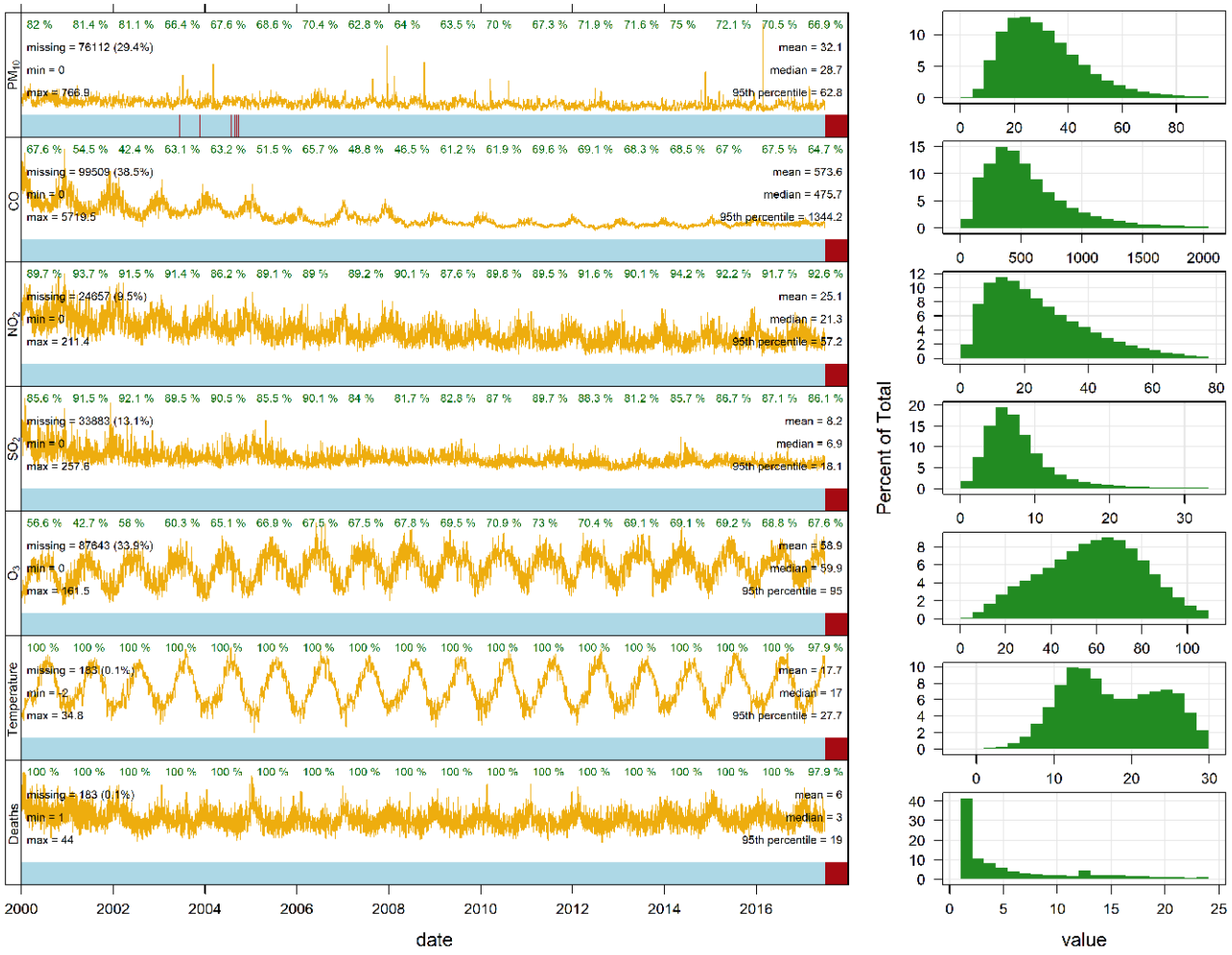


Figure 9.2: Overview of outcome and exposure data in Andalusia, 2000-2017

The final dataset consisted of total daily death counts (overall, 500K records), average and maximum temperature values, and average and maximum air pollution concentrations, aggregated for all selected municipalities in Andalusia from January 2000 until July 2017. Seasonal variations in the average values are highlighted in Table 9.1. Scaling down the analysis even to the provincial level (which would consist in a few municipalities only) was not feasible due to the sample size issues.

[1]Note that missing data proportion is calculated using all stations with at least one measurement of the corresponding variable. As some of the stations had 100% of the interval covered and some just a small portion, the overall missing percentage could reach up to 30% in the stationary data.

Table 9.1: Seasonal variations in air quality and mortality statistics in Andalusia in 2000-2017

		Winter	Spring	Summer	Autumn
ºC	Temperature	11.07	16.28	25.31	18.71
$\mu g/m^3$	O_3	44.12	70.04	72.66	52.84
	SO_3	8.54	8.46	9.13	8.56
	NO_3	25.24	20.39	19.48	22.74
	CO	723.34	563.88	501.91	575.71
	PM_{10}	30.08	29.21	37.69	31.37
Total N	Deaths	148780	131133	116505	112901

Further, relying on the workflow suggested by Bhaskaran et al. (2013), we proceed to the time series regression analysis. The overall aim of this regression analysis is to investigate short-term variability in mortality outcomes owing to environmental exposure (i.e. concentrations of air pollutants) changes. An important step to include in this analysis is explicitly controlling for the seasonal patterns and long-term trends, as our primary interest is in the short-term association between exposure (threat) and vulnerability outcome (death). To achieve this, we fit a spline function of time with 8 degrees of freedom per year (Fig.9.3 a[2]). The residual variation in daily deaths after eliminating seasonal and long-term trend exhibits a fairly random pattern (Fig.9.3 b), allowing us to examine the remaining short-term variability.

9.2 Exposure-response associations and confounding factors

We now proceed to exploring exposure-response associations and confounding by season and time-varying variables, namely temperatures and heat index. Second to sixth rows on Figure 9.3 represent the exposure-response curves for ozone, coarse particulate matter (PM_{10}), sulfur dioxide, nitrogen dioxide and carbon monoxide, after fitting an unadjusted (first column) and adjusted for confounding factors (second and third columns) models.

A simple linear regression quasipoisson model, *unadjusted to any potential confounders* and fitted to ozone (Fig.9.3 c), particulate matter (Fig.9.3 f) and sulfur dioxide (Fig.9.3 i) data suggests that higher concentrations of these pollutants are associated with lower health risks, which appears to be suspicious as generally known to be inverse. Thus, maximum daily O_3 concentration of 120 µg/m^3 were estimated to have a risk of 1.006,

[2]Here, grey dots represent observed daily death counts, whereas thick red line represents the spline function applied to the data.

95%CI: 1.006-1.007, whereas the concentration of ozone of 14 µg/m^3 resulted in a RR of 1.48, 95%CI: 1.44-1.53. Maximum daily PM_{10} concentration of just 10 µg/m^3 had a RR of 2.55, 95%CI: 2.29-2.83, while concentrations of 260 µg/m^3 resulted in two-times lower risks of 1.102, 95%CI: 1.011-1.014. Similarly to unadjusted model estimates of O_3 and PM_{10}, low concentrations of SO_2 of 6 µg/m^3 had RR of almost 50% (1.48, 95% 1.39-1.58) higher compared to the risks corresponding to the highest SO_2 concentration of 39 µg/m^3. Associations for NO_2 (Fig.9.3 l) and CO (Fig.9.3 o) display a more expected pattern with the highest concentrations corresponding to the highest risks. 10 µg/m^3 increase in NO_2 daily maximum concentration supposed a 4% increase in the RR, while for CO the RR increased more gradually (+0.04% per every added 10 µg/m^3).

We then create a second series of models adjusted for seasonal fluctuations and long-term trends using spline function described earlier. The exposure-outcome associations for ozone, particulate matter and sulfur dioxide have been inversed, as shown on Figures 9.3 d, g, and j. Using the adjustment for seasonality now results in +0.8%, +0.3% and +9.8% increase in risks to every added 10 µg/m^3 of O_3, NO_2 and SO_2, respectively. As for the NO_2 and CO, risks increased with respect to unadjusted estimations (+5.4% per 10 µg/m^3 increase in NO_2, Fig.9.3 m, and + 0.3% per 10 µg/m^3 increase in CO, Fig.9.3 p).

Previously, we closely discussed possible synergistic effects between air pollution and temperature (Chapter 6). As a result, we consider temperature to be one of the extra confounding variables that might affect the exposure-response relationship with air pollution. Indeed, after adding the temperature[3] to the model adjusted for seasonality, we observe some changes in the exposure-response associations. After adjustment for the temperature, the effect for O_3 disappeared (maximum concentration of 120 µg/m^3 corresponding to the RR of 1.046, 95%CI: 0.988-1.108, Fig.9.3 e). In case of SO_2 the adjusted effect remained statistically significant (maximum concentration having RR of 1.25, 95%CI: 1.11-1.42), while for the PM_{10} the effects have disappeared similarly to the ozone. Thus, initially present risks for O_3 and PM_{10} were confounded by the maximum daily temperature. After controlling for the temperature, RR remained elevated for NO_2 (1.18, 95%CI: 1.11-1.2, for 63 µg/m^3 concentration) and CO (1.44, 95%CI: 1.25-1.65, for 2600 µg/m^3 concentration). Adjusting the models for the heat index instead of the temperature did not reveal significant differences therefore we do not present the results here.

[3]Cross-basis matrix with 21 days lag and 3 knots, based on maximum daily temperature.

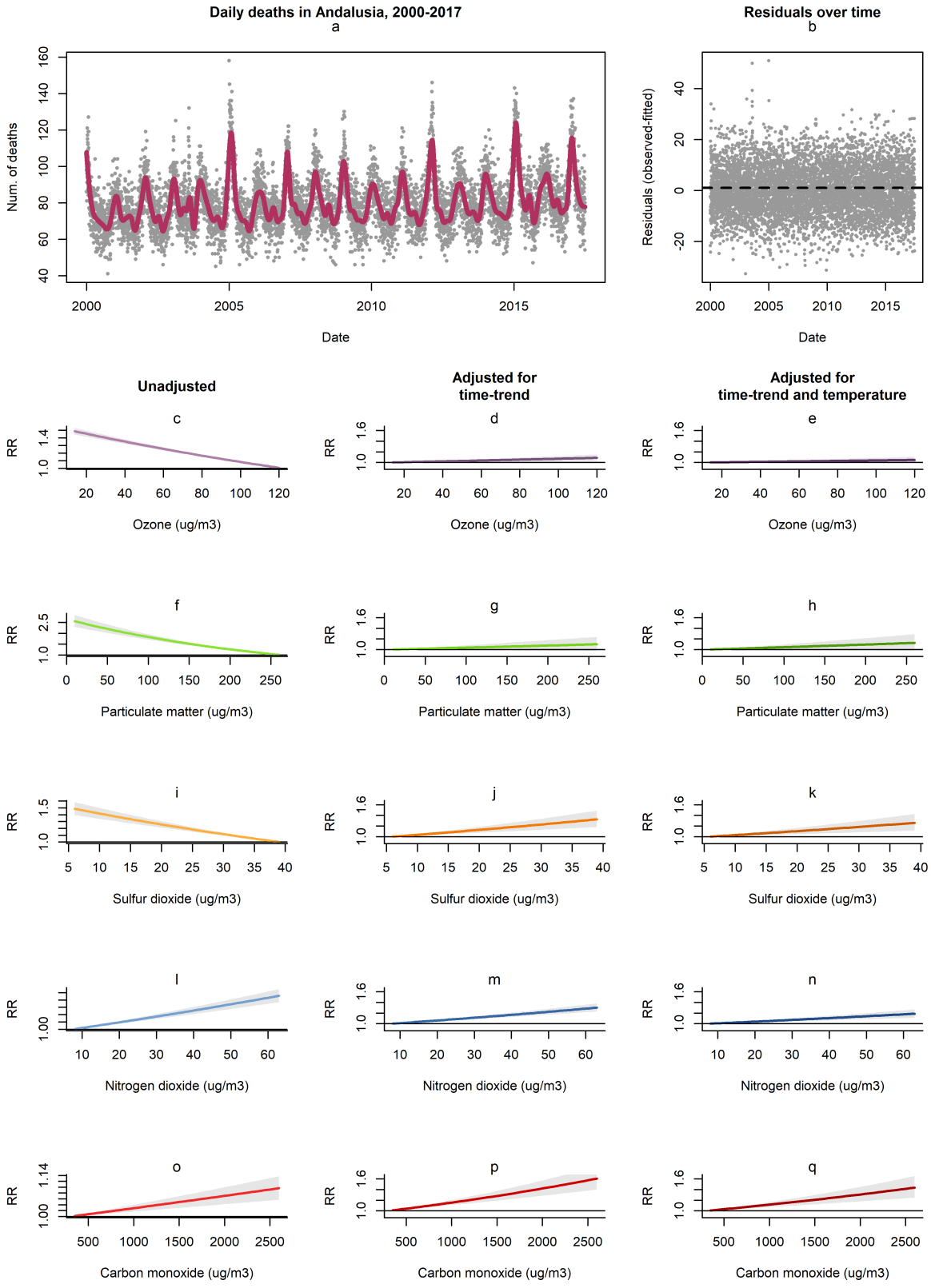


Figure 9.3: Primary air pollutants and mortality: exposure-outcome associations and confounding (maximum concentrations)

9.3 Delayed effects of air pollution

Figure 9.4 illustrates the lag-response relationship with daily mortality and maximum concentrations of ozone. Three dimensional plot shows predictor-lag associations (Fig.9.4 a). Cumulative exposure-response association, which we also discussed in the preceding paragraph, is shown on the Figure 9.4 b. Bottom row displays distributed lags for the first week post-exposure. This example illustrates the fact that the exposure to elevated concentrations of O_3 2 days earlier results in higher risks of mortality 2 days after, whereas exposure to the high concentrations of O_3 on the same day does not pose an immediate risk on health but rather a delayed one. However, the task to properly estimate the delayed effect of exposure to air pollution is not a rudimentary one.

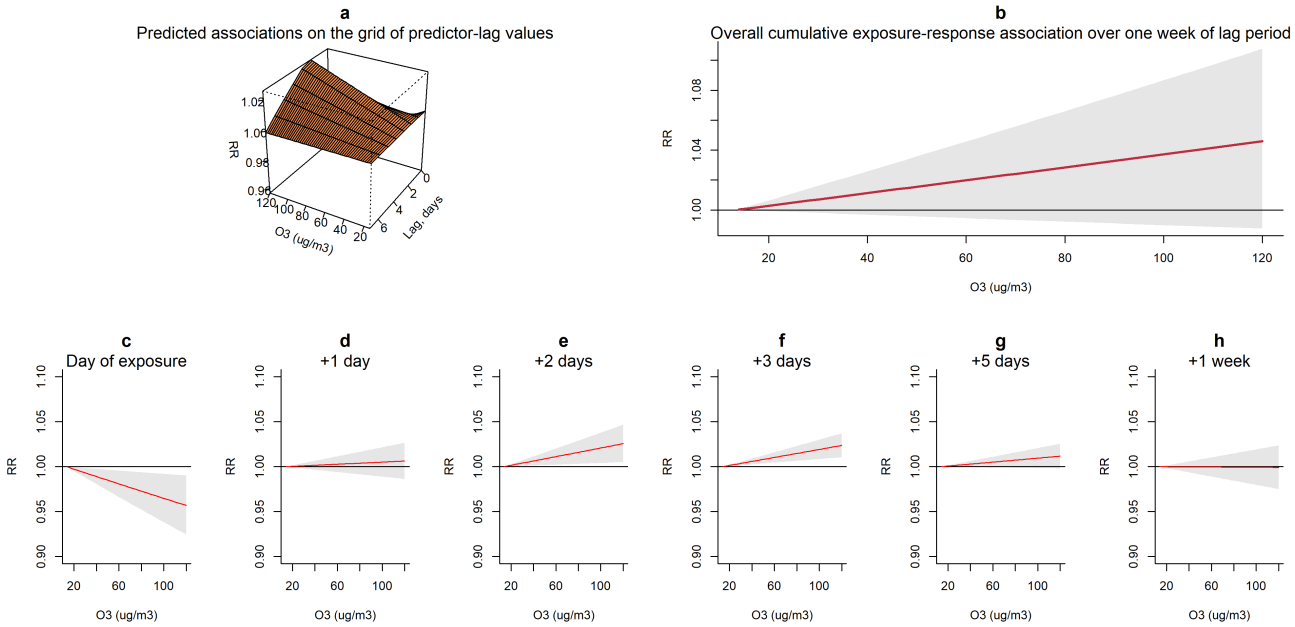


Figure 9.4: Distributed lagged effects of exposure to maximum daily ozone concentrations in Andalusia, 2000-2017

First column on the Figure 9.5, shows the lag terms (0 to 7 days) modelled *independently* with adjustment for temperature for ozone (Fig.9.5 a), coarse particulate matter (Fig.9.5 d), sulfur dioxide (Fig.9.5 g), nitrogen dioxide (Fig.9.5 j) and carbon monoxide (Fig.9.5 m). The delayed response pattern changes depending on the variable, however common feature for all air pollutants except carbon monoxide is that the risks are generally higher on the days following the exposure. To reiterate, the lag terms are entered in the model independently, i.e. they are not adjusted for each other, however

using the *DLNM* approach we can incorporate them in our models *all at once*. The results of this adjustment are present in the second column of the Figure 9.5. For all the pollutants this adjustment resulted in the effect estimates shifting towards the null, except for CO and NO_2, on the seventh day post-exposure. The cumulative net effects for O_3 were estimated at 1.003, 95%CI: 0.998-1.009, for PM_{10} - at 1.006, 95%CI: 1.001-1.012, for SO_2 - at 1.081, 95%CI: 1.041-1.123, for NO_2 - at 1.04, 95%CI: 1.028-1.053, and for CO - at 1.002, 95%CI: 1.001-1.003.

As highlighted by Bhaskaran et al. (2013), the collinearity between lag terms represents an issue for this kind of models and eventually results in imprecise estimates. It is therefore recommended to introduce some constrains for the effect estimates. The third column on the Figure 9.5 represents the results of running a *constrained* distributed lag model, where we use stratification of the lag structure with first and third day as arbitrary cut-offs (right open intervals). In other words, we declare that the effects for the 1-2 days and 3-7 should have equal weights in the esimation. In this way, we overcome the issue of the collinearity between lag terms and produce more precise overall estimates.

Thus, for nitrogen dioxide (Fig.9.5 l) and carbon monoxide (Fig.9.5 o) the effects are statistically significant since the day of exposure throughout the entire week post-exposure. The net effect for NO_2 was estimated at 1.039, 95%CI: 1.027-1.052 and for CO at 1.002, 95%CI: 1.001-1.003. For sulfur dioxide, the effects revealed on the day after exposure and lasted for 7 days (Fig.9.5 i). The cumulative effect of exposure to SO_2 over the period of 1 week was estimated at 1.082, 95%CI: 1.042-1.124. In case of ozone, the effects revealed on the third day post exposure and were small (Fig.9.5 c), while for particular matter the general trend was decremental from the onset until the end on the 1st week, however estimates were not statistically significant (Fig.9.5 f). The net effect for O_3 was estimated at 1.004, 95%CI: 0.999-1.009, and for PM_{10} at 1.006, 95%CI: 1.001-1.012.

In this chapter, we explored an additional source of vulnerability, air pollution, by examining the associations between concentrations of five primary air pollutants and human survival in Andalusia between 2000 and 2017. We controlled our models for seasonality and air temperature and estimated the risks of exposure to maximum daily concentrations of ozone, coarse particulate matter, sulfur dioxide, nitrogen dioxide and carbon monoxide. For some of the mentioned pollutants higher concentrations were associated with moderate net effects (CO, NO_2, SO_2), while for the others the overall net effect was small (PM_{10}) or not significant (O_3), after adjustment for confounders. These results highlight the importance of considering both temperatures and air pollution when analyzing the effects on mortality. The lag perspective was identified as crucial

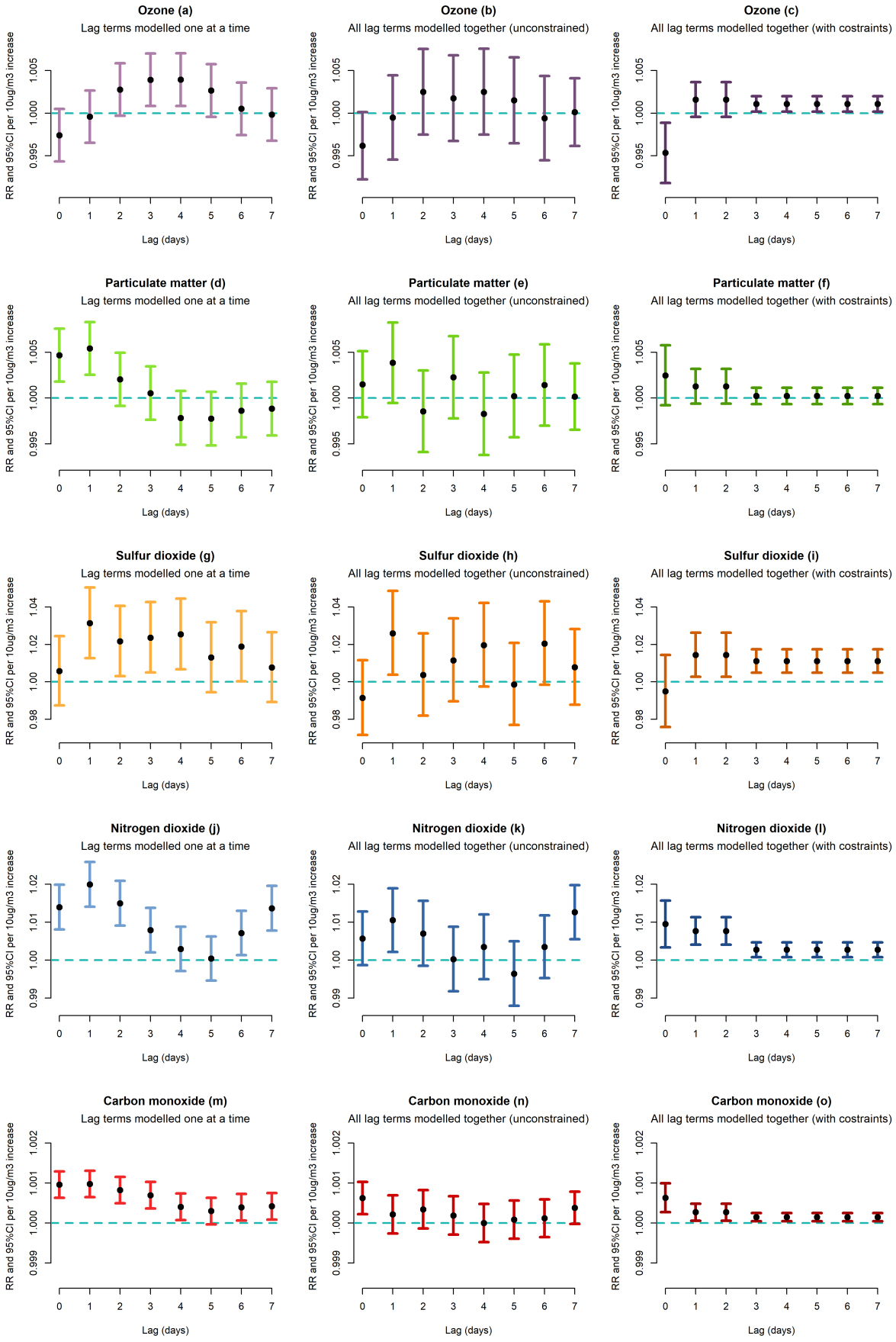


Figure 9.5: Lagged effects of primary air pollutants (maximum concentrations)

to be considered in such type of analysis, as only some of the air pollutants have the highest risks associated with the exposure to elevated concentrations on the same day, while others have the highest risks on the days following the exposure. For all the studied contaminators the risks remained elevated during the entire week post-exposure, which clearly indicates that considering the lagged structure of these effects for designing public health interventions is vital.

10 Conclusions

The main results of the dissertation are discussed in this closing chapter, as well as the limits and future prospects. Each chapter did not merely report the results, but also featured a discussion regarding the findings, as the reader may have noticed along the way. Therefore, in the following paragraphs we will present a concluding discussion of the analysis performed in Chapters 2-9.

10.1 Concluding remarks with respect to research questions

In this work, we explored the environmental and demographic processes in Spain in a retrospective way using a holistic analytic approach. We organized our work into three large thematic sections: the first one consisted in Chapters 2 and 3 and contained the answers to research questions 1 and 2; the second one was formed by Chapters 4, 5 and 6 and corresponded to the research questions 3 and 4; the final third one was made of Chapters 7, 8 and 9 and matched the research questions 5, 6 and 7.

As the reader might remember from the introductory part of this thesis, we first asked ourselves two essential questions. With **research question 1** we intended to place the whole topic of concern into the global panorama of scientific research and name the most important implications of the warming of air temperatures for individuals.

To do so, we studied hundreds of articles, books and reports. This thorough literature review presented in the first part of the Chapter 2, revealed a great diversity of the direct and latent effects of global warming on natural and human systems. Heat-related mortality appears among the most deadly and alarming consequences of the warming of air temperature for human health, as shown by multitude of scientific studies. These repercussions, however, are not limited to deaths due to the exposure to extremely hot temperatures, but extend to the vector-, food- and water-borne diseases, which may emerge and re-emerge in direct response to the warming of the environment. Changing environment, rise in the ambient temperatures and intensification of the extreme events, like episodes of abnormal heat, also bring a number of collateral or latent effects. Extreme heat poses a direct societal threat thorough the escalation of territorial conflicts and accelerated human migration due to land degradation, aridization and depletion of water resources. Economic costs, estimated through the hospital admission costs, labor loss, damage of the infrastructure or declines in tourism demand, reach millions of euros each year, often in prejudice of the planned state budget.

Research question 2 focused on the review of pathophysiology of the outcomes due to the exposure to extreme heat and air pollution in humans, mechanisms and conditions responsible for deterioration of the adverse effects attributed to this exposure and associated risks. To answer the research question 2 implied performing a systematic literature review, which was presented in the second half of Chapter 2. During an episode of extreme heat stress, the capacity of the human body to thermoregulate can be exceeded. Failure to uphold thermal homeostasis has a variety of dangerous and sometimes deadly health implications. Heat-related illnesses range from the most severe outcome of direct exposure to high environmental temperatures such as heat stroke to milder ones such as heat exhaustion or heat fatigue. Deaths resulting from heat stroke are relatively rare, and more often are seen in athletes and individuals working in inadequate conditions. Nevertheless, individual risks of heat-related illnesses can be modified and multiplied by a number of factors such as individual health, medical status and socioeconomic status, living and environmental conditions. Current health status may put an individual to a greater risk at the time of exposure of extreme heat. Individual vulnerability to heat exposure is increased by the presence of chronic conditions (e.g. cardiovascular and respiratory diseases, obesity, hypertension, diabetes) and the use of drugs or abuse substances. Even if individuals do not possess chronic illnesses, some of the natural conditions (e.g. advanced or younger ages, pregnancy) may play a crucial role in exacerbating the effects of exposure. Moreover, socioeconomic conditions

(educational attainment, income level, housing conditions, social position and ethnic background) often modify the effects of heat-related health outcomes. Last but not least, air pollution acts as an additional risk factor for human health, especially during the episodes of abnormal heat. Against the background of international research on all these topics, Spain follows regional trends and patterns with no significant deviations along the demographic and socioeconomic strata.

The **research question 3** opened the section of the geographic analysis of heat waves in Spain. Here we sought the answers to the following queries: *Spain of today, is it hotter than Spain 4 decades ago? Episodes of abnormal heat, is this a common phenomena in this country? Where are the areas that are most impacted by heat waves? And, last but not least, does Spain experience more heat waves today than it did before?* Certainly, our results revealed a global increase of the temperatures in Spain since 1979. However, it would be unwise to assume that this rise would follow a geographically homogeneous pattern throughout a half-million-square-kilometer area. Indeed, as expected initially, geographic variability of the changes of the air temperatures is substantial, with southern and central regions of the country leading the list. Surprisingly, not only a plain seasonally-uniform increment of the temperatures was seen. Our findings showed that temperatures increased the greatest in late spring and early summer, but also in the early fall, suggesting that the warm season is expanding overall. Winter temperatures in some areas revealed a slight decrease, indicating more pronounced *polarization* of the seasons.

Heat wave frequency in Spain has been steadily increasing since 1980-s, with a notable acceleration since the turn of the XXI century. Similarly to many European countries, the heat wave of 2003 marked the onset of a *new reality*. In Spain, this infamous heat wave affected large parts of the country and was exceptionally intense in terms of its magnitude. Previously, the episodes of abnormal heat tended to be more sporadic and spatially isolated, while in the last decade of the observations we saw a considerable expansion and more spatial homogeneity in their occurrence. As the mean temperature kept increasing, more local heat waves were seen in the areas with generally milder climates, especially in the northern regions of the country.

These results fit into ongoing debate on the future predictions of the changes in the climate variability in this area. In absolute terms, it is expected that an average hottest day in the Iberian peninsula would be warmer by 3.5 degrees by the end of the 21st century), similarly to the northern Mediterranean region, parts of northern

Middle East and northern states in the US[1]. Changes in the interannual temperature variability within the Iberian peninsula are estimated to be rather low, from 10% to 25% under different emission scenarios, with only *northern* parts of the peninsula being affected (Masson-Delmotte et al. 2019). Modelling results from Fischer and Schär (2010) show a dramatic increase of temperatures in low-altitude Mediterranean, mostly river basins and coasts. According to their predictions, Guadalquivir river basin and inner parts of the peninsula would have 25 days per summer or more with apparent temperature over 40ºC by 2071-2100.

The next point of interest in this study was to see if there was any relationship between extreme heat and air pollution in different contextual settings. Particularly, with the **research question 4** we aimed *to examine the variations in the concentrations of air pollutants depending on the geographic position, fluctuations of air temperatures and contextual environmental settings.* We hypothesized that there would be a synergetic effect between air temperatures and concentrations of air pollutants, particularly in locations with high anthropogenic activity. Due to the restricted availability of data on air pollution, our inferences should be applied to continental Spain and a narrow period between 2017 and 2019. Nonetheless, our findings are consistent with those of other research on the same topic. We examined the concentrations of such air pollutants as ozone, particulate matter, nitrogen and sulfur dioxide, to name a few, during the episodes of abnormal heat in Spain. Our results suggest an association with elevated concentrations of major air pollutants with heat waves of medium and high intensity, especially in the metropolitan areas.

Having established a solid foundation from the environmental point of view, we moved on to the next step of our analysis. *What can we say about the impact of extreme heat on population if we know when and where heat waves were happening in Spain during the last 40 years?* We sought the answer to the **research question 5** through the analysis

[1]2071-2100 vs 1976-2005, CMIP5/AR5, Scenario RCP4.5. *IPCC's Fifth Assessment Report (AR5)* strongly relies on the results from the Fifth phase of the Coupled Model Intercomparison Project (CMIP5), available at `https://www.wcrp-climate.org/wgcm-cmip` models. *Representative Concentration Pathway (RCP) 4.5*, in turn, is an intermediate stabilization pathway in which radiative forcing is stabilized at approximately 4.5 W m^{-2} and 6.0 W m^{-2} after 2100, available at `https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html`. The estimations from RCP8.5 scenario, a high pathway for which radiative forcing reaches greater than 8.5 W m^{-2} by 2100 and continues to rise for some amount of time, available at `https://www.ipcc-data.org/guidelines/pages/glossary/glossary_r.html`, for this increase are reaching 7 degrees Celsius across all Mediterranean region, large areas in Middle East, North and South Americas.

of excess mortality in Spain from 1982 to 2018. The results revealed a clear effect of exposure to heat waves in adults, especially in woman of older ages. The risks for younger individuals were lower, but still significant. Exposure to the episodes of abnormal heat of different intensity also acted as an important differentiating factor. Thus, episodes with night-time temperatures above 20ºC had the highest risks of excess death, even in comparison with the episodes of extreme heat during the day. We should acknowledge, however, a rather simplistic approach that we chose to perform this exploratory analysis of the associations. For future research, we believe it is necessary to strengthen the suggested models statistically and to incorporate a number of additional control variables related to the socioeconomic status of the individuals.

The adverse effects of extreme heat were clearly evident from the exploratory analysis of excess mortality. However, the process of adaptation to newly emerging extreme climatic conditions remained a source of concern for us. We raised a series of queries grouped into **research question 6**: *What is the association between mortality and air temperature in Spain and how can we describe it? How large are the risks at different exposures and temporal delays? At which temperature the mortality starts to sharply increase? How do these threshold temperatures vary across space?* To approximate to these problems we chose to use a recently developed distributed lag non-linear modelling approach. By implementing these models, we were able to estimate an indicator of minimum mortality temperature, which we used as a proxy for the *balance with environment* or *optimum conditions*. We thoroughly explored the variations in these optimum temperatures across time and space in Spain. Our findings matched the results from the fundamental studies based on the same method, however, in our study we use finer spatial resolution and wider temporal window which exceed the extension of the datasets used in other studies.

At the national level, we see an increase in the optimum temperature during the first decades of the observation. In the subsequent years, the variability of the estimates significantly increases. Along with a progressive increase in the minimum mortality temperature, we witness a change in the mortality curve, which shifts from a traditional V-shape to a U-shaped curve with a flat bottom, suggesting an extension of the optimal temperature range. The heat-attributable mortality fractions showed a general decrease over time, although our findings imply a minor rise since 2014. Spain has experienced a number of intense heat waves since 2014, which might partially explain this result. On the other hand, the uncertainty range of the optimum temperatures increased over time, which might have affected this estimate as well.

Minimum mortality temperature varies dramatically across the country, generally following the latitudinal gradient with lower optimum temperatures in the north and higher in the south. Estimating minimum mortality temperatures in smaller units (e.g. small provincial capitals) was the biggest challenge due to the uncertainty concern. On average, minimum mortality temperatures increased in the Spanish provincial capitals, while capitals located in the temperate warm-summer Mediterranean climate revealed a decrease. Intra-provincial variations in terms of the minimum mortality are pronounced. Rural areas in the South, Center and East of Spain were identified to have lower optimum temperatures, and therefore accumulating more vulnerability, in comparison with their urban counterparts. More deprived areas were estimated to have higher risks of mortality when exposed to colder temperatures in the North, and to higher temperatures in the South. Interestingly, in other regions the exposure to hotter temperatures did not show significant differences in areas with different levels of socioeconomic deprivation. We believe it would be of great interest to involve other socioeocnomic and ecological characteristics of the neighborhoods to explore the geographic disparities in optimum temperatures further.

Lagged structure of the association between temperature and mortality poses a crucial importance for understanding the effects of exposure. Here, we asked ourselves a question: *what will have the highest risk of mortality, the exposure to hotter temperatures today, yesterday or a week before? Moreover, will this risk be equally high for man and woman, young and old?* Our results reveal a lag-response association structurally similar for all groups of individuals. Risks for exposure to high temperatures were the highest on the same day of exposure, and gradually reduced during next 10 to 14 days. However, female individuals aged 65+ showed a much higher risk estimates on the first days after being exposed, in comparison with males of the same age group. In the group of younger females the risks of mortality were also higher than in males, but remained elevated only on the day of exposure and the following one.

Last question we raised in this work touched the topic of adverse effects of air pollution, coupled with the effects of air temperatures. By asking the **research question 7** we aspired *to estimate the health risks related to combined exposure to air pollution and temperatures in Spain*. Our major concern here was the *confounding* issue: whether the estimated effects of exposure to air pollution are confounded by air temperatures, and vice versa. We refer to this analysis as a *pilot* study due to the limitations in temporal coverage and spatial discreetness. Despite these restrictions, we were able to estimate the effects for the exposure to ozone, particulate matter, carbon monoxide, nitrogen

and sulfur dioxides in Andalusia over the period of 17 years, from 2000 to 2017. Our results confirm that controlling for potential confounders such as seasonality and air temperature is essential to precisely estimate the effect attributed to air pollution. The overall net effects for all studied pollutants but ozone were estimated as statistically significant, however, in absolute terms, risks were small. Even so, this finding highlights the importance of considering a combined effect of air pollution and temperatures for development of more effective intervention strategies by public health agencies.

10.2 Study limitations and future research lines

This dissertation provided a comprehensive overview on the topic of the interaction between human health and ever changing climatic conditions in Spain from different angles. Objectives stated in the introduction were successfully achieved, however we should acknowledge a number of limiting factors for this study.

First and perhaps the most challenging constrain was the availability of the data, its resolution and compatibility between domains. Each stage of the analysis required rigorous revision and often re-estimation of the indicators in order for them to be usable for statistical analysis. In reality, this issue does not merely proceed from specific objectives stated in this particular work but rather from the nature of the data itself. The format and resolution of demographic and epidemiological data is usually confined to technical and organizational procedures of the providing institutions, that are, in turn, regulated by the laws and normatives from the parent organizations (e.g. governmental bodies). On the other hand, the data covering natural domains do not have to be initially restricted by any kind of administrative limit, which results in a more flexible output products.

However, even though there are plenty of open source environmental data available for the researchers worldwide, which, without a doubt, make the analysis easier and faster, all these products have to be used with precaution and should be justified for the use for each particular purpose. Reanalysis datasets of air pollution, for instance, have proved its usability for small- and medium-scale analysis as generic patterns are reflected properly, but at a larger scale the uncertainty of the estimates significantly increases and affects the interpretation of the results (*WHO Expert Meeting: Methods and Tools for Assessing the Health Risks of Air Pollution at Local, National and International Level* 2014). Keeping the highest possible spatiotemporal resolution of the data of different nature while completing the stated objectives was one of the primary concerns in this work.

On the other hand, while working on this dissertation we prepared a fundamental scalable database with diverse indicators of exposure from both environmental and demographic sides. A number of indicators we developed while working with the data have not entered in the final analysis presented in this dissertation. One example of such indicators is the *Excess Heat Factor* (EHF), which applicability was discussed in Chapter 4. As the reader might remember, the EHF is a measure of intensity of heat exposure, which is based on a three-day averaged daily value, with respect to the 95th percentile of long-term average trend, and values observed in the recent past (30 previous days), as illustrated on the Figure 10.1, based on the temperature and heat index values in a particular location on selected dates.

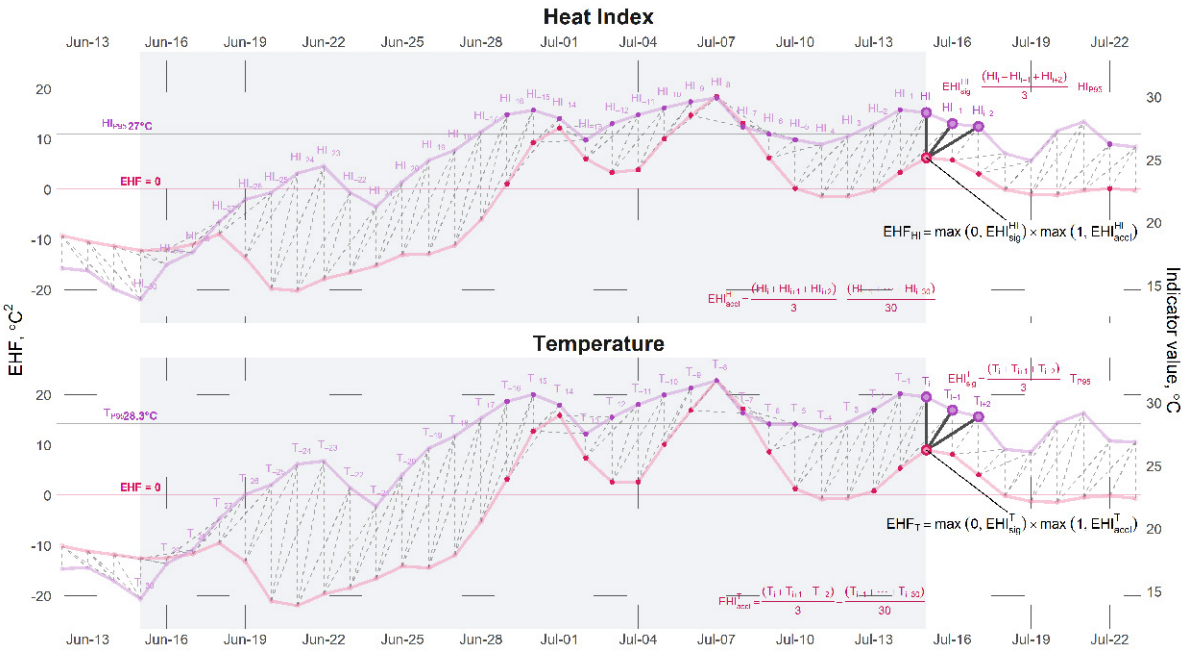


Figure 10.1: Methodological illustration of Excess Heat Factor estimation procedure

This indicator is increasingly used for modelling heat-health relationship, as it reflects not only the exposure in a given moment but prior conditions. Therefore involving the EHF in forthcoming works on adaptation to extreme heat has a great potential. We firmly believe that the effort made to elaborate this ample set of exposure indicators would help us to develop a series of geographic, demographic and epidemiologic studies focused on the analysis of the associations between environment and human health in the future.

Another set of caveats that must be addressed here are the methods implemented to study the variations in mortality answers to the exposure to extreme heat and air pollution. Overall, we focused on investigating the process of adaptation to extreme

heat over time, and therefore major attention was placed on studying the evolution of optimum temperatures and heat-attributed mortality applying the distributed lag non-linear modelling framework. However, studying excess mortality in response to heat waves of different type, duration, magnitude and their combined characteristics, along with exploring spatial variations using geostatistical methods, could offer up a window of new opportunities. Furthermore, dissagregating the mortality data by cause of death could refine the analysis and provide new insights into the temperature-mortality associations. We initiated our analysis with a simplistic approach, presented and discussed in Chapter 7, although additional tests directed to improve the statistical models and introduce new dimensions were also tested and presented in the form of pilot studies throughout the PhD journey (see Appendix F). Moreover, there are various points in the analysis presented in Chapters 8 and 9 that the authors plan to explore and improve in the future. In particular, we will focus on verification of the estimates of the minimum mortality temperatures at different sites in Spain using alternative alternative approaches published in environmental epidemiology studies. Specifically, our objectives are to obtain the minimum mortality temperatures and their standard errors for each site and conduct the meta-analysis, followed by the meta-analysis of all temperature-mortality curves for each site and estimation of the minimum mortality temperature of the combined curve.

Globally, this work highlighted the importance of using interdisciplinary data sources to investigate research problems that include both humans and nature. We are confident that the foundations built in this work would open new possibilities for the authors to explore potential mitigation buffers further, and study the processes of the development of resistance to extreme heat over the life-course in the future.

Appendices

A

Appendix for Chapter 3

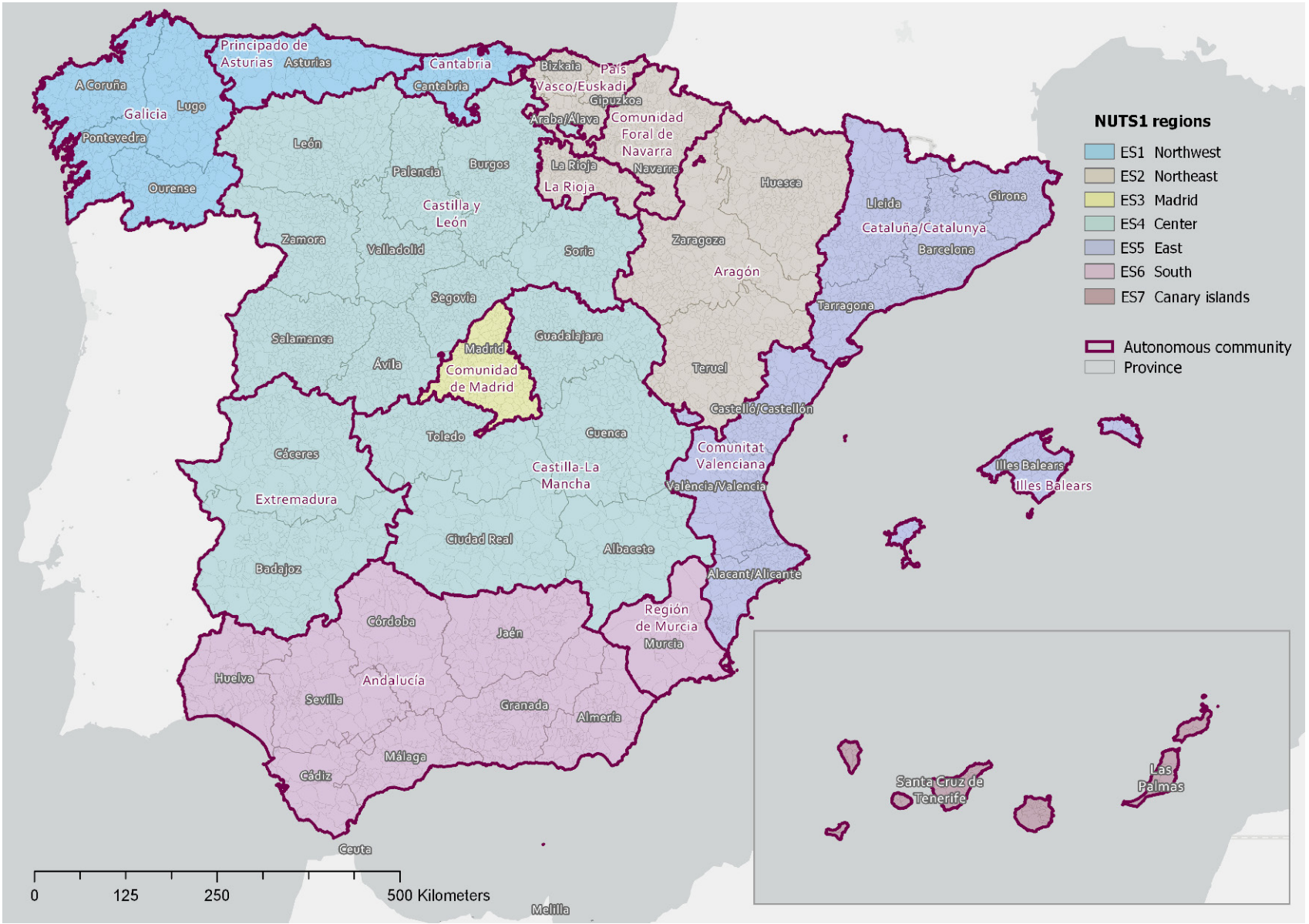


Figure A.1: Administrative division of Spain

Table A.1: Death Statistics: overview of missing data.

Death		Socio-demographics					Nationality		Registration		Birth				Residence			
Year	Place[1]	Age	Sex	Civil status	Educ.	Occup.	Type[2]	Cntr.	Mun.	Prov.	Mun.	Prov.	Cntr.	Type[a]	Mun.	Prov.	Cntr.	Type[b]
1975	0	100	100	100	0	100	0	0	67	100	0	0	0	0	65	100	0	0
1976	0	100	100	100	0	100	0	0	68	100	0	0	0	0	65	100	0	0
1977	0	100	100	100	0	100	0	0	69	100	0	0	0	0	66	100	0	0
1978	0	100	100	100	0	100	0	0	69	100	0	0	0	0	66	100	0	0
1979	0	100	100	100	0	100	0	0	70	100	0	0	0	0	66	100	0	0
1980	0	100	100	100	0	100	0	0	71	100	0	0	0	0	68	100	0	0
1981	0	100	100	100	0	100	0	0	72	100	0	0	0	0	69	100	0	0
1982	0	100	100	100	0	100	0	0	72	100	0	0	0	0	69	100	0	0
1983	0	100	100	100	0	100	0	0	72	100	0	0	0	0	68	100	0	0
1984	0	100	100	100	0	100	0	0	72	100	0	0	0	0	68	100	0	0
1985	0	100	100	100	0	100	0	0	73	100	0	0	0	0	68	100	0	0
1986	0	100	100	100	0	100	0	0	75	100	0	0	0	0	69	100	0	0
1987	0	100	100	100	0	100	0	0	76	100	0	0	0	0	69	99	0	0
1988	0	100	100	100	0	100	0	0	76	100	0	0	0	0	69	99	0	0
1989	0	100	100	100	0	100	0	0	77	100	0	0	0	0	69	100	0	0
1990	0	100	100	100	0	100	0	0	77	100	0	0	0	0	69	100	0	0
1991	0	100	100	100	0	100	0	0	78	100	0	0	0	0	70	100	0	0
1992	0	100	100	100	0	100	0	0	78	100	0	0	0	0	70	100	0	0
1993	0	100	100	100	0	100	0	0	79	100	0	0	0	0	70	100	0	0
1994	0	100	100	100	0	100	0	0	79	100	0	0	0	0	70	99	0	0
1995	0	100	100	100	0	100	0	0	80	100	0	0	0	0	70	99	0	0
1996	0	100	100	100	0	100	0	0	80	100	0	0	0	0	71	99	0	0
1997	0	100	100	100	0	100	0	0	80	100	0	0	0	0	71	99	0	0
1998	0	100	100	100	0	100	0	0	81	100	0	0	0	0	71	99	0	0
1999	0	100	100	100	0	100	0	0	81	100	46.1	97.1	0	0	71	99	0	0
2000	0	100	100	100	0	100	0	0	82	100	46.3	96.9	0	0	71	99	0	0
2001	0	100	100	100	0	100	0	0	82	100	46.4	96.7	0	0	72	99	0	0
2002	0	100	100	100	0	100	0	0	83	100	46.6	96.6	0	0	72	99	0	0
2003	0	100	100	100	0	100	0	0	83	100	46.9	96.4	0	0	72	99	0	0
2004	0	100	100	100	0	100	0	0	83	100	47.2	96.3	0	0	72	99	0	0
2005	0	100	100	100	0	100	0	0	84	100	47.5	96.2	0	0	73	99	0	0
2006	0	100	100	100	0	100	0	0	84	100	48	96	0	0	73	99	0	0
2007	0	100	100	100	0	100	0	0	84	100	48.2	96	0	0	73	100	0	0
2008	0	100	100	100	0	100	0	0	85	100	48.6	95.9	0	0	74	99	0	0
2009	0	100	100	100	0	100	100	99.9	85	100	49.1	96.1	3.7	100	73	100	0.4	100
2010	0	100	100	100	0	100	100	99.8	85	100	49.2	96	3.7	100	73	100	0.4	100
2011	0	100	100	100	0	100	100	99.9	85	100	49.2	95.9	3.8	100	74	100	0.4	100
2012	100	100	100	100	100	0	100	99.9	85	100	49.3	95.9	3.8	100	73	100	0.4	100
2013	100	100	100	100	100	0	100	99.9	85	100	49.3	95.8	3.9	100	73	100	0.4	100

Table A.1: Death Statistics: overview of missing data. *(continued)*

Death		Socio-demographics					Nationality		Registration		Birth				Residence			
Year	Place[1]	Age	Sex	Civil status	Educ.	Occup.	Type[2]	Cntr.	Mun.	Prov.	Mun.	Prov.	Cntr.	Type[a]	Mun.	Prov.	Cntr.	Type[b]
2014	100	100	100	100	100	0	100	99.9	85	100	49.3	95.5	4.2	100	74	100	0.5	100
2015	100	100	100	100	100	0	100	99.9	85	100	49.3	95.8	4	100	73	100	0.5	100
2016	100	100	100	100	100	0	100	99.9	86	100	49.4	95.4	4.4	100	73	99	0.5	100
2017	100	100	100	100	100	0	100	99.9	86	100	49.3	95.2	4.5	99.9	73	99	0.5	100
2018	100	100	100	100	100	0	100	99.9	86	100	49.4	95	4.7	0	74	99	0.5	0
2019	100	100	100	100	100	100	100	99.9	86	100	49.4	94.7	5	99.9	74	99	0.6	100

Note: Values are expressed in % and reflect proportion of available data with 100 meaning full completeness and 0 full incompleteness.

[1] Place of death: Residence, Hospital, Socio-sanitary unit, Workplace, Other, Unknown; [2] Nationality: Spanish, Foreign, Not specified;

[a] Place of birth: Spain, Other; [b] Place of residence: Spain, Other.

B

Appendix for Chapter 4

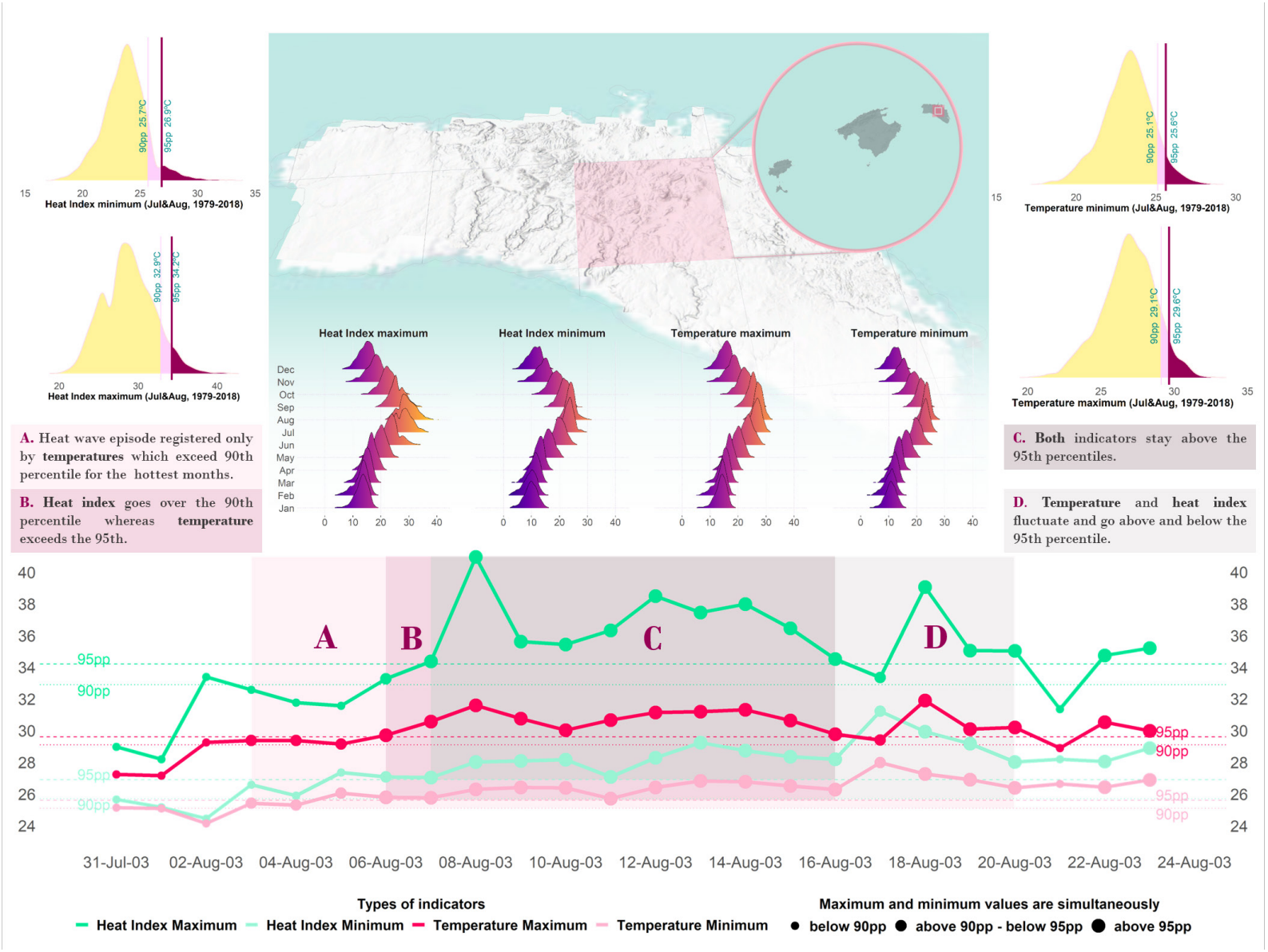


Figure B.1: Local heat wave episode in Balearic islands: methodological illustration

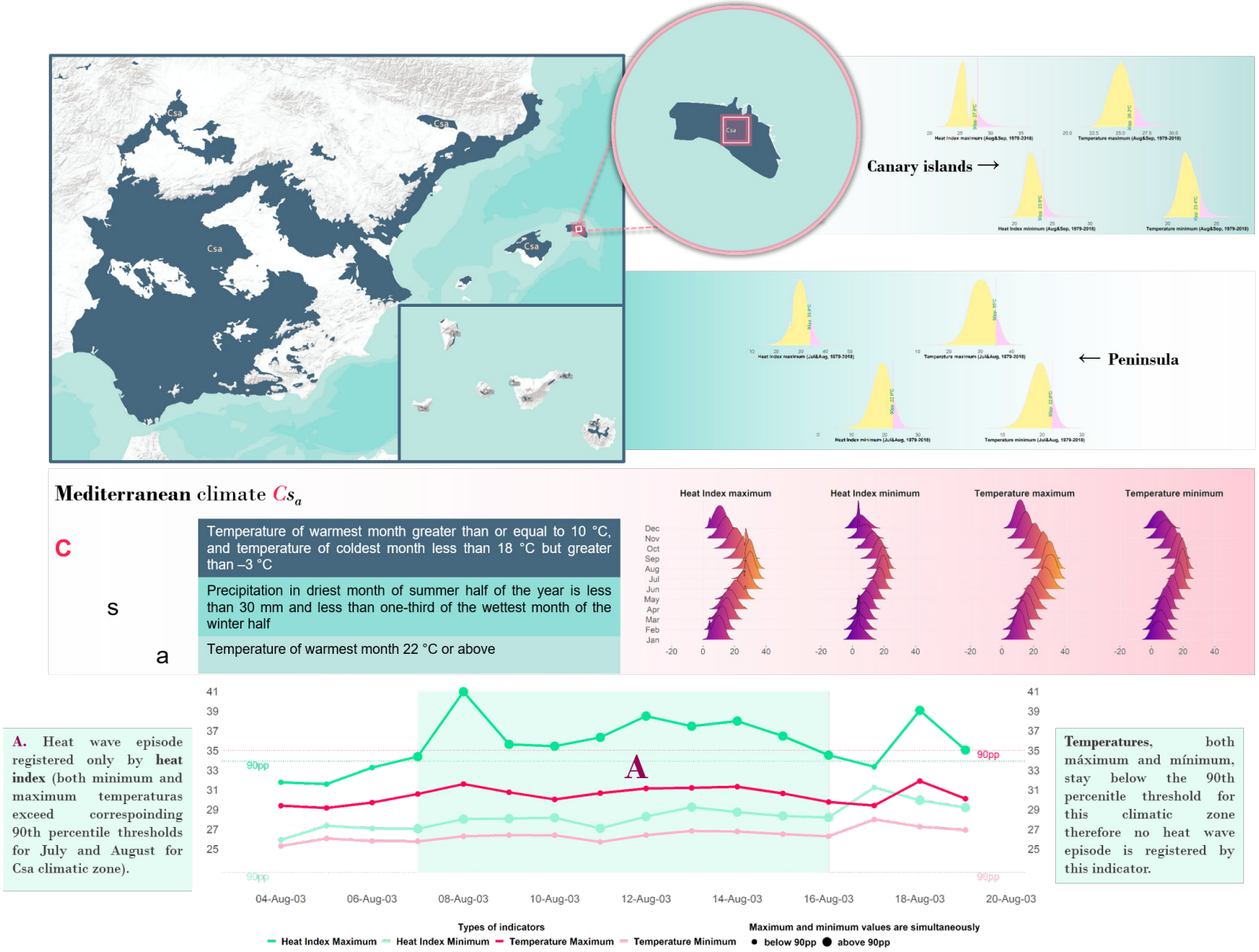


Figure B.2: Zonal (climatic type) heat wave episode in Balearic islands: methodological illustration

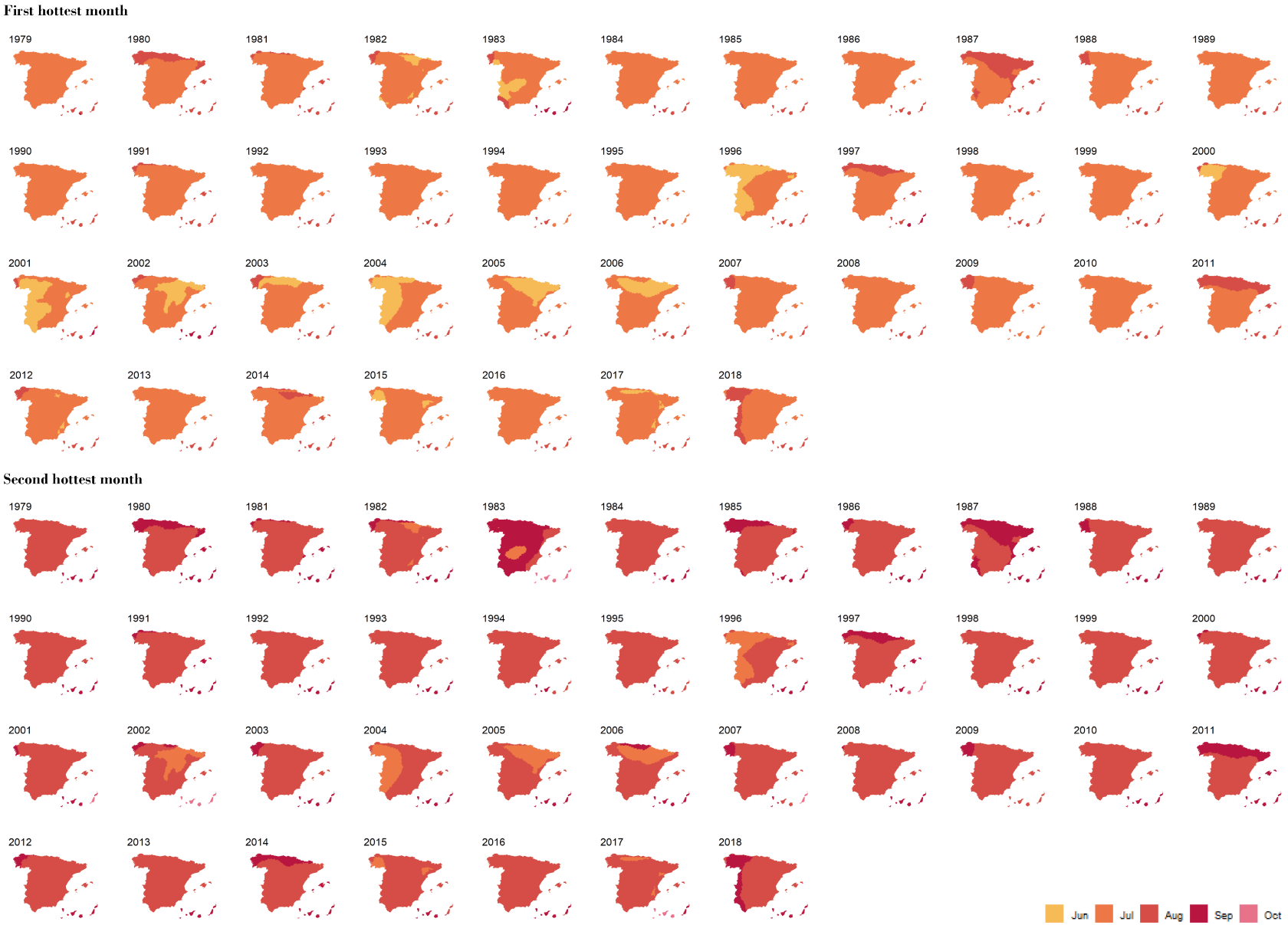


Figure B.3: Top two hottest months for maximum values of temperature

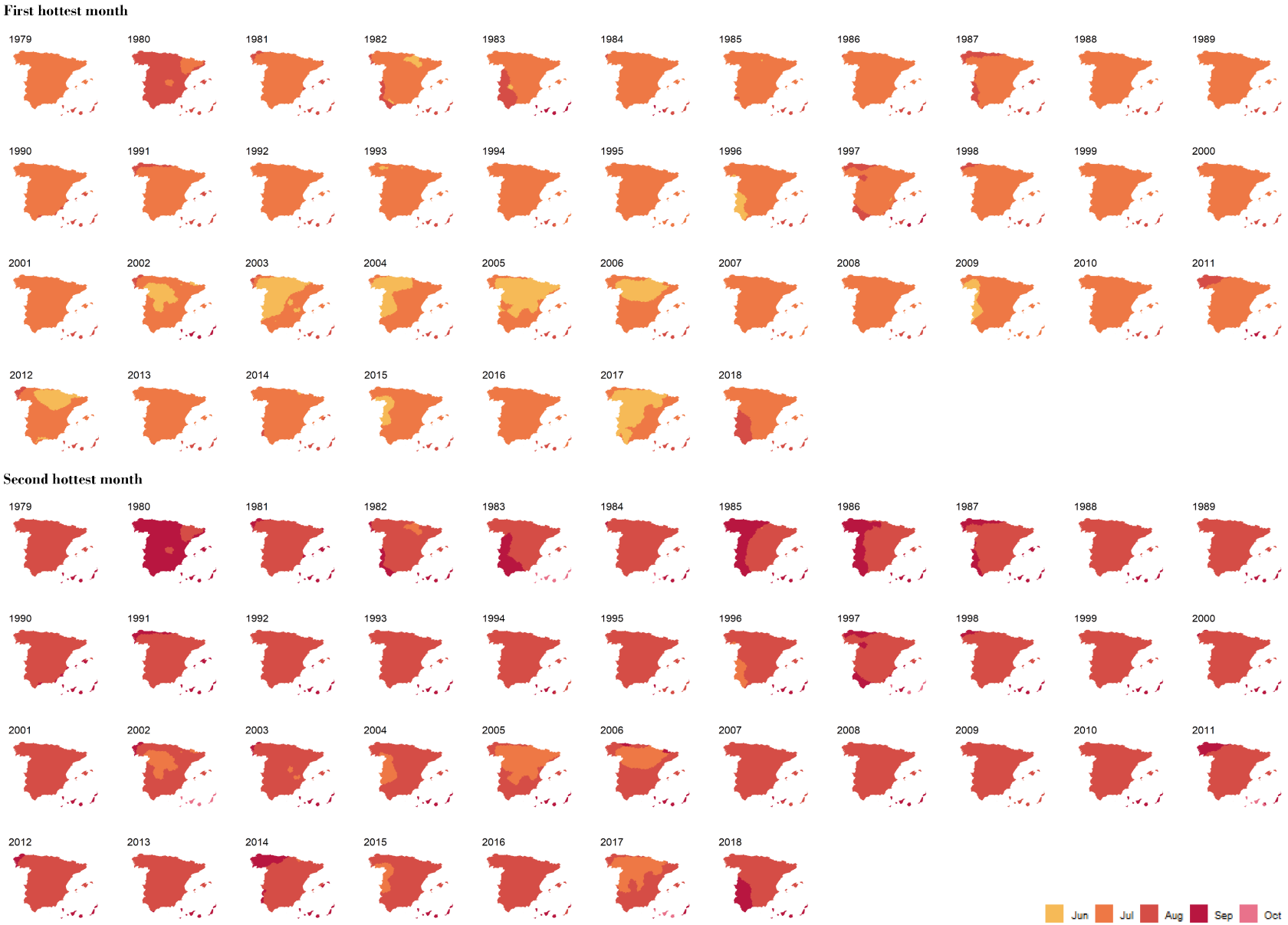


Figure B.4: Top two hottest months for minimum values of temperature

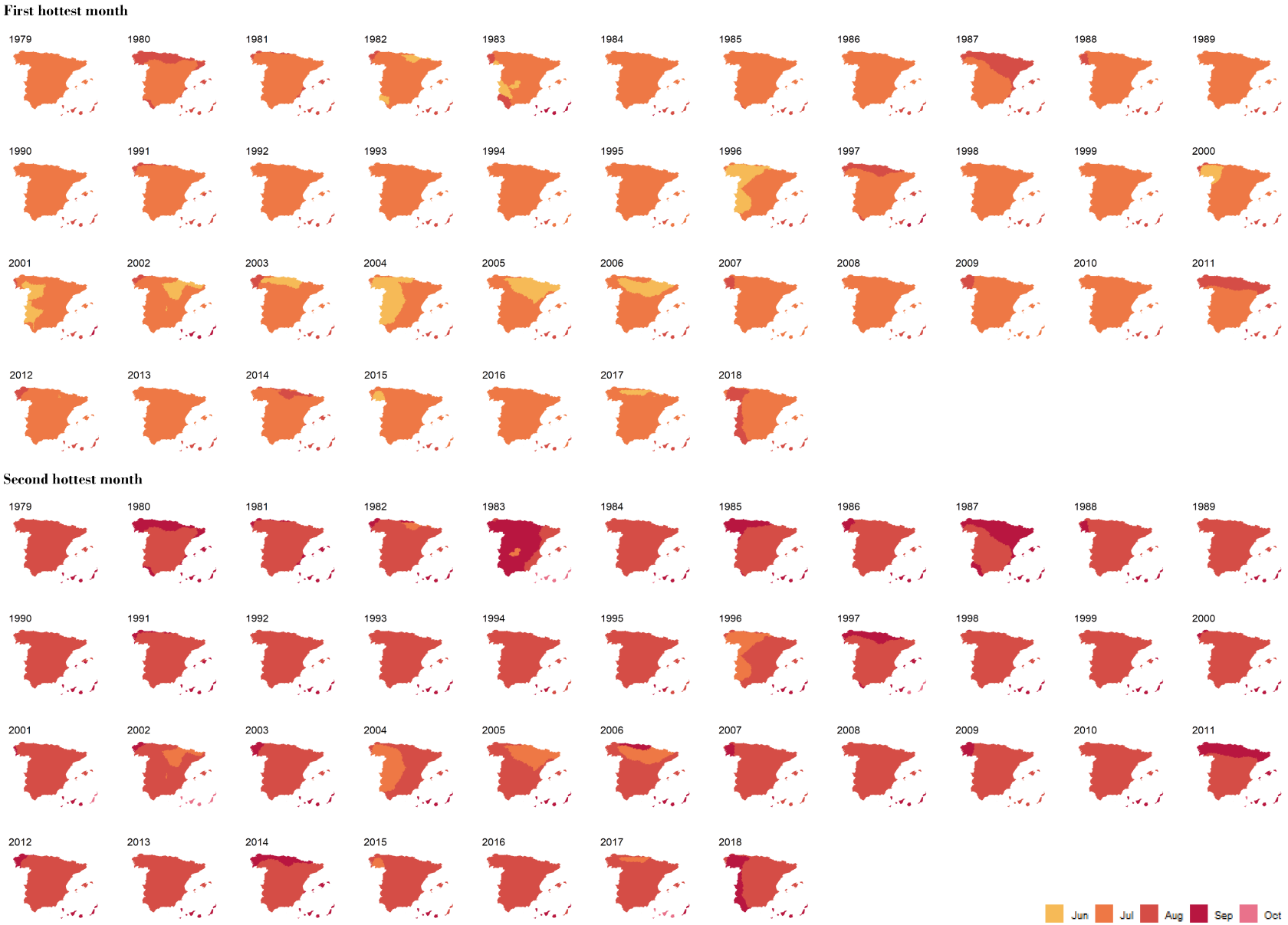


Figure B.5: Top two hottest months for maximum values of heat index

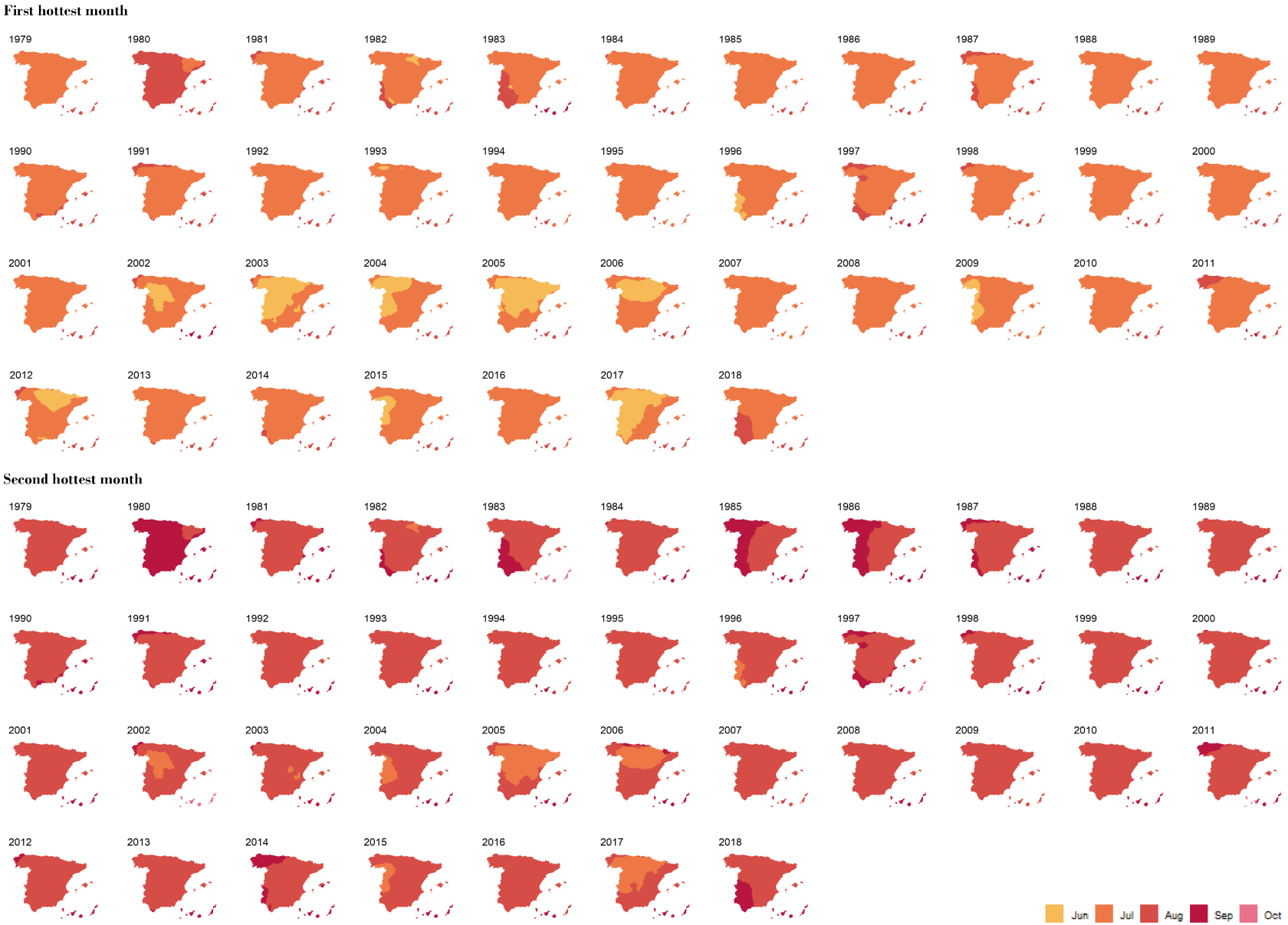


Figure B.6: Top two hottest months for minimum values of heat index

Table B.1: Summary statistics for heat wave episodes identified by temperature using 90pp for individual cell

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1980	1980-08-21	1980-08-23	3 days	2.90 ± 0.00	2.90	37.75 ± 0.57	38	26.92 ± 1.73	28	25.79 ± 0.52	2.13 ± 0.36	2.45 ± 0.23
1981	1981-06-12	1981-06-18	7 days	6.74 ± 5.33	12.12	39.01 ± 1.38	41	25.04 ± 1.66	28	24.18 ± 1.39	1.81 ± 0.19	1.86 ± 0.26
	1981-07-13	1981-07-16	4 days	2.77 ± 1.42	3.48	37.83 ± 0.76	38	24.64 ± 1.10	26	23.24 ± 0.46	1.58 ± 0.10	1.92 ± 0.17
	1981-07-28	1981-07-30	3 days	1.19 ± 0.00	1.19	39.37 ± 1.59	40	24.50 ± 2.55	27	25.06 ± 1.03	2.10 ± 0.35	1.59 ± 0.07
1982	1982-07-05	1982-07-11	7 days	11.00 ± 9.40	21.49	37.25 ± 2.19	40	24.96 ± 0.95	26	25.46 ± 0.93	1.77 ± 0.31	1.76 ± 0.37
	1982-08-09	1982-08-11	3 days	0.04 ± 0.00	0.04	35.90 ± 1.00	37	23.91 ± 0.33	24	23.05 ± 0.65	1.72 ± 0.18	1.84 ± 0.10
1983	1983-07-09	1983-07-11	3 days	0.10 ± 0.00	0.10	35.10 ± 0.54	36	22.52 ± 0.52	23	23.83 ± 0.42	1.49 ± 0.09	1.56 ± 0.23
	1983-07-13	1983-07-15	3 days	0.08 ± 0.00	0.08	36.40 ± 1.10	37	24.93 ± 0.70	26	25.22 ± 0.51	1.58 ± 0.19	1.56 ± 0.16
	1983-07-21	1983-07-23	3 days	0.56 ± 0.00	0.56	33.81 ± 0.80	35	25.59 ± 0.49	26	23.85 ± 0.54	1.73 ± 0.21	1.45 ± 0.08
	1983-07-25	1983-08-01	8 days	1.42 ± 1.75	3.52	34.17 ± 2.16	37	26.02 ± 1.14	28	23.84 ± 0.97	1.84 ± 0.39	1.77 ± 0.24
	1983-09-23	1983-09-27	5 days	2.15 ± 1.83	3.58	34.11 ± 1.11	36	24.23 ± 1.39	26	23.38 ± 0.95	2.08 ± 0.23	2.28 ± 0.38
1984	1984-07-23	1984-07-25	3 days	0.50 ± 0.00	0.50	37.85 ± 0.79	39	24.82 ± 0.71	25	25.17 ± 0.92	2.00 ± 0.09	1.66 ± 0.20
1985	1985-07-22	1985-07-25	4 days	5.01 ± 2.27	6.68	38.39 ± 1.34	40	23.95 ± 0.21	24	25.68 ± 0.51	1.59 ± 0.13	1.80 ± 0.22
	1985-09-08	1985-09-12	5 days	0.66 ± 0.42	0.95	33.17 ± 0.85	34	23.86 ± 0.69	25	23.28 ± 0.13	2.00 ± 0.38	1.81 ± 0.48
	1985-09-29	1985-10-01	3 days	0.24 ± 0.00	0.24	30.72 ± 1.18	32	24.26 ± 0.21	24	21.99 ± 0.33	1.65 ± 0.21	1.89 ± 0.16
1986	1986-07-15	1986-07-17	3 days	0.06 ± 0.00	0.06	36.29 ± 2.21	38	22.86 ± 0.15	23	23.05 ± 0.94	1.61 ± 0.04	1.65 ± 0.13
1987	1987-07-08	1987-07-10	3 days	0.60 ± 0.00	0.60	35.37 ± 1.18	37	24.04 ± 0.46	25	24.03 ± 0.35	1.58 ± 0.12	1.73 ± 0.18
	1987-08-01	1987-08-04	4 days	1.55 ± 0.85	1.99	37.28 ± 1.42	38	23.66 ± 0.74	25	23.68 ± 1.25	1.89 ± 0.19	1.94 ± 0.29
	1987-08-12	1987-08-17	6 days	18.58 ± 12.98	30.29	37.28 ± 1.73	40	25.56 ± 0.53	26	25.81 ± 0.65	1.98 ± 0.23	1.90 ± 0.32
	1987-09-07	1987-09-20	14 days	2.27 ± 1.03	4.00	34.47 ± 2.03	37	25.14 ± 0.68	26	23.67 ± 0.57	2.06 ± 0.21	2.57 ± 0.64
1988	1988-09-06	1988-09-09	4 days	0.89 ± 0.33	1.07	37.30 ± 0.78	38	25.06 ± 0.89	26	25.03 ± 0.82	1.53 ± 0.09	1.88 ± 0.29
1989	1989-07-11	1989-07-14	4 days	0.38 ± 0.13	0.44	36.80 ± 0.87	38	24.55 ± 0.17	25	23.77 ± 0.44	1.87 ± 0.12	1.82 ± 0.27
	1989-07-18	1989-07-22	5 days	12.07 ± 5.79	19.22	37.55 ± 2.00	40	25.71 ± 1.56	28	26.27 ± 0.66	2.08 ± 0.16	2.09 ± 0.31
	1989-07-25	1989-08-02	9 days	7.38 ± 3.76	11.51	37.40 ± 1.24	39	25.71 ± 0.87	27	25.31 ± 0.53	1.80 ± 0.10	2.04 ± 0.28
	1989-08-09	1989-08-11	3 days	0.28 ± 0.00	0.28	34.16 ± 1.05	35	25.96 ± 0.18	26	24.65 ± 0.44	1.79 ± 0.17	1.86 ± 0.39
	1989-08-21	1989-08-26	6 days	1.19 ± 0.60	1.75	35.23 ± 0.98	36	25.99 ± 0.63	27	25.09 ± 0.58	1.75 ± 0.11	1.92 ± 0.31
1990	1990-07-09	1990-07-11	3 days	4.02 ± 0.00	4.02	38.08 ± 0.55	39	24.89 ± 0.21	25	24.07 ± 0.31	1.64 ± 0.09	1.90 ± 0.12
	1990-07-16	1990-07-26	11 days	14.96 ± 12.72	34.21	36.98 ± 1.49	39	25.42 ± 1.26	28	25.56 ± 0.99	2.00 ± 0.27	2.15 ± 0.40
	1990-08-01	1990-08-08	8 days	7.97 ± 6.56	17.97	36.50 ± 1.84	39	25.33 ± 0.61	26	25.00 ± 1.37	1.91 ± 0.31	2.16 ± 0.66
	1990-08-26	1990-08-28	3 days	0.04 ± 0.00	0.04	32.58 ± 0.43	33	24.85 ± 0.37	25	23.14 ± 0.50	1.58 ± 0.13	2.65 ± 0.51
1991	1991-07-12	1991-07-20	9 days	9.91 ± 6.19	16.74	39.05 ± 2.09	41	26.55 ± 1.42	29	25.44 ± 0.50	1.77 ± 0.14	1.97 ± 0.19
	1991-08-04	1991-08-07	4 days	8.33 ± 3.49	11.11	37.82 ± 1.33	39	25.71 ± 0.45	26	25.74 ± 0.46	1.64 ± 0.11	1.60 ± 0.09
	1991-08-11	1991-08-18	8 days	4.17 ± 3.51	9.28	36.73 ± 2.28	41	24.52 ± 1.38	27	24.66 ± 1.26	1.72 ± 0.17	1.81 ± 0.16
	1991-08-25	1991-08-29	5 days	1.89 ± 0.89	2.60	34.81 ± 0.63	36	26.41 ± 0.30	27	25.06 ± 0.24	1.56 ± 0.10	1.44 ± 0.10
	1991-09-17	1991-09-19	3 days	0.08 ± 0.00	0.08	35.44 ± 0.39	36	23.90 ± 0.23	24	23.63 ± 0.05	1.86 ± 0.27	1.82 ± 0.22

Table B.1: Summary statistics for heat wave episodes identified by temperature using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1992	1992-07-26	1992-08-02	8 days	5.93 ± 3.05	10.30	35.35 ± 1.49	37	25.20 ± 0.83	27	25.31 ± 0.55	1.72 ± 0.24	1.79 ± 0.18
	1992-08-04	1992-08-06	3 days	4.09 ± 0.00	4.09	37.79 ± 0.38	38	25.72 ± 0.26	26	25.94 ± 0.39	1.51 ± 0.07	1.75 ± 0.20
1993	1993-08-04	1993-08-08	5 days	5.58 ± 3.09	8.61	37.42 ± 0.44	38	26.78 ± 0.59	28	25.22 ± 1.21	1.83 ± 0.11	1.92 ± 0.14
	1993-08-17	1993-08-21	5 days	9.92 ± 5.70	14.63	34.88 ± 2.45	38	24.87 ± 0.78	26	25.39 ± 1.06	2.23 ± 0.20	2.03 ± 0.55
1994	1994-06-30	1994-07-07	8 days	6.87 ± 5.25	13.46	38.94 ± 2.22	43	26.84 ± 1.73	29	25.02 ± 1.07	2.21 ± 0.52	1.78 ± 0.29
	1994-07-15	1994-07-20	6 days	0.43 ± 0.43	0.83	36.29 ± 1.89	38	26.06 ± 0.70	27	24.89 ± 0.72	1.64 ± 0.25	1.71 ± 0.22
	1994-08-05	1994-08-11	7 days	1.51 ± 1.26	3.00	35.74 ± 1.69	38	26.55 ± 1.01	28	24.28 ± 1.50	1.61 ± 0.20	1.78 ± 0.45
	1994-08-17	1994-08-19	3 days	1.25 ± 0.00	1.25	37.08 ± 0.61	38	26.30 ± 0.75	27	24.69 ± 0.34	1.68 ± 0.04	1.83 ± 0.18
	1994-08-21	1994-08-24	4 days	2.25 ± 1.17	2.84	36.39 ± 0.78	38	26.94 ± 1.16	28	24.54 ± 1.38	1.79 ± 0.22	1.91 ± 0.39
1995	1995-07-16	1995-07-24	9 days	23.35 ± 15.15	42.85	40.02 ± 1.53	42	25.93 ± 1.13	27	26.32 ± 0.96	1.85 ± 0.24	1.87 ± 0.29
	1995-07-28	1995-07-30	3 days	0.04 ± 0.00	0.04	37.41 ± 1.42	38	25.04 ± 0.14	25	25.76 ± 0.65	1.71 ± 0.33	1.84 ± 0.29
	1995-08-13	1995-08-16	4 days	0.49 ± 0.09	0.56	37.17 ± 1.49	39	25.45 ± 0.93	27	24.86 ± 0.47	1.81 ± 0.08	1.66 ± 0.06
	1995-08-22	1995-08-28	7 days	0.60 ± 0.08	0.70	33.77 ± 2.29	36	23.87 ± 0.37	25	22.34 ± 0.46	1.86 ± 0.15	1.95 ± 0.27
	1995-11-18	1995-11-20	3 days	0.02 ± 0.00	0.02	26.70 ± 0.28	27	24.08 ± 0.54	25	15.09 ± 0.41	1.82 ± 0.32	2.08 ± 0.42
1996	1996-06-13	1996-06-16	4 days	2.49 ± 1.04	3.04	34.09 ± 0.91	35	22.81 ± 0.23	23	23.59 ± 0.14	2.06 ± 0.36	1.92 ± 0.21
	1996-07-12	1996-07-19	8 days	1.04 ± 1.09	2.54	35.20 ± 1.28	37	22.91 ± 0.86	25	23.81 ± 0.99	1.67 ± 0.17	1.69 ± 0.21
	1996-07-22	1996-07-24	3 days	2.72 ± 0.00	2.72	36.81 ± 0.67	37	25.33 ± 0.97	26	25.34 ± 0.34	1.48 ± 0.03	1.90 ± 0.42
1997	1997-07-26	1997-07-29	4 days	0.32 ± 0.16	0.40	35.88 ± 1.13	38	23.86 ± 0.22	24	24.54 ± 0.16	1.78 ± 0.12	1.76 ± 0.27
	1997-07-31	1997-08-02	3 days	0.04 ± 0.00	0.04	36.96 ± 0.58	38	24.46 ± 0.51	25	24.78 ± 0.28	1.73 ± 0.09	1.87 ± 0.33
	1997-08-18	1997-08-20	3 days	0.02 ± 0.00	0.02	35.06 ± 0.64	36	24.48 ± 0.50	25	24.51 ± 0.26	1.55 ± 0.09	1.66 ± 0.17
1998	1998-07-18	1998-07-20	3 days	0.06 ± 0.00	0.06	36.30 ± 2.20	38	24.86 ± 0.29	25	25.18 ± 0.75	1.44 ± 0.13	1.53 ± 0.18
	1998-08-05	1998-08-11	7 days	2.75 ± 1.40	4.37	37.04 ± 0.61	38	24.31 ± 0.31	25	25.11 ± 0.85	1.90 ± 0.15	1.73 ± 0.16
	1998-08-22	1998-08-25	4 days	1.24 ± 0.36	1.51	37.42 ± 0.50	38	24.77 ± 0.49	25	24.71 ± 0.30	1.44 ± 0.02	1.73 ± 0.13
1999	1999-07-02	1999-07-04	3 days	1.23 ± 0.00	1.23	38.56 ± 0.62	39	26.22 ± 0.15	26	24.67 ± 1.53	2.03 ± 0.41	1.81 ± 0.22
	1999-07-08	1999-07-10	3 days	0.04 ± 0.00	0.04	38.66 ± 1.87	40	24.30 ± 0.95	25	24.55 ± 0.31	1.81 ± 0.39	1.57 ± 0.19
	1999-07-21	1999-07-24	4 days	2.48 ± 1.15	3.14	37.96 ± 0.79	38	24.89 ± 0.20	25	24.64 ± 0.87	1.58 ± 0.13	1.64 ± 0.09
	1999-08-05	1999-08-08	4 days	0.14 ± 0.07	0.18	34.35 ± 0.73	35	26.39 ± 0.83	27	23.63 ± 0.68	1.88 ± 0.39	1.83 ± 0.20
	1999-08-26	1999-09-01	7 days	1.53 ± 0.93	2.52	33.51 ± 1.80	36	25.66 ± 1.10	28	24.23 ± 0.50	2.13 ± 0.32	2.41 ± 0.42
2000	2000-06-14	2000-06-18	5 days	4.95 ± 3.46	8.21	34.36 ± 1.22	36	22.47 ± 0.77	23	23.21 ± 1.34	2.30 ± 0.22	2.09 ± 0.46
	2000-07-30	2000-08-02	4 days	1.12 ± 0.71	1.49	38.27 ± 1.48	40	25.46 ± 1.16	26	25.23 ± 0.53	1.67 ± 0.10	1.78 ± 0.26
	2000-08-20	2000-08-22	3 days	0.02 ± 0.00	0.02	34.86 ± 2.40	37	26.43 ± 1.53	28	22.59 ± 1.40	1.99 ± 0.50	1.74 ± 0.27
2001	2001-06-23	2001-06-25	3 days	3.48 ± 0.00	3.48	38.27 ± 1.12	40	25.21 ± 1.28	26	25.12 ± 0.25	1.81 ± 0.15	1.64 ± 0.13
	2001-07-29	2001-08-02	5 days	3.11 ± 1.79	4.37	35.26 ± 1.89	38	26.66 ± 1.55	29	25.48 ± 1.35	1.87 ± 0.28	1.70 ± 0.31
	2001-08-25	2001-08-27	3 days	0.12 ± 0.00	0.12	33.22 ± 1.33	34	25.54 ± 0.63	26	25.09 ± 0.43	1.52 ± 0.02	1.97 ± 0.16

Table B.1: Summary statistics for heat wave episodes identified by temperature using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2003	2003-06-19	2003-06-22	4 days	0.94 ± 0.40	1.25	37.23 ± 0.68	38	24.21 ± 0.53	25	25.38 ± 0.57	2.17 ± 0.63	1.91 ± 0.27
	2003-07-11	2003-07-13	3 days	1.85 ± 0.00	1.85	36.17 ± 2.46	39	25.45 ± 0.46	26	25.65 ± 0.58	1.93 ± 0.07	1.44 ± 0.03
	2003-07-19	2003-07-27	9 days	1.90 ± 1.98	4.89	36.70 ± 0.93	38	26.73 ± 0.86	28	24.67 ± 0.38	1.73 ± 0.24	1.90 ± 0.30
	2003-07-29	2003-08-30	33 days	17.92 ± 18.85	49.63	36.36 ± 2.91	42	26.68 ± 0.57	28	25.43 ± 1.67	1.93 ± 0.28	1.91 ± 0.24
	2003-09-01	2003-09-03	3 days	0.06 ± 0.00	0.06	31.88 ± 1.66	34	25.01 ± 0.28	25	20.92 ± 0.49	1.92 ± 0.32	2.00 ± 0.38
2004	2004-06-28	2004-07-01	4 days	2.98 ± 1.34	3.92	38.74 ± 1.87	40	24.72 ± 0.40	25	25.29 ± 0.70	1.73 ± 0.15	1.54 ± 0.08
	2004-07-23	2004-07-29	7 days	13.15 ± 9.31	23.87	37.70 ± 3.08	41	27.70 ± 1.47	30	25.59 ± 1.44	2.32 ± 0.23	2.72 ± 0.47
	2004-08-01	2004-08-03	3 days	0.22 ± 0.00	0.22	34.55 ± 1.89	37	24.70 ± 0.59	25	25.14 ± 1.07	1.76 ± 0.24	1.50 ± 0.21
	2004-08-09	2004-09-03	26 days	2.22 ± 1.67	6.98	33.80 ± 2.29	39	25.84 ± 0.95	28	23.01 ± 1.03	2.08 ± 0.57	2.28 ± 0.98
	2004-09-10	2004-09-12	3 days	0.24 ± 0.00	0.24	32.78 ± 0.36	33	24.96 ± 0.19	25	22.95 ± 0.36	1.63 ± 0.08	1.84 ± 0.27
2005	2005-07-13	2005-07-18	6 days	3.19 ± 1.71	5.11	37.65 ± 0.92	39	25.86 ± 1.69	28	25.17 ± 0.76	1.75 ± 0.20	1.79 ± 0.35
	2005-08-04	2005-08-09	6 days	1.10 ± 0.89	1.93	37.93 ± 2.36	40	24.81 ± 1.19	26	24.93 ± 0.92	1.89 ± 0.29	1.66 ± 0.07
	2005-08-13	2005-08-16	4 days	0.74 ± 0.42	0.95	36.91 ± 2.26	39	24.42 ± 0.98	25	24.58 ± 0.25	2.19 ± 0.38	1.74 ± 0.22
	2005-09-03	2005-09-06	4 days	1.90 ± 1.11	2.46	34.08 ± 2.85	36	25.88 ± 1.07	27	22.95 ± 1.93	2.67 ± 0.83	3.23 ± 1.14
2006	2006-06-29	2006-07-02	4 days	0.02 ± 0.00	0.02	33.89 ± 0.50	34	23.67 ± 0.25	24	23.71 ± 0.59	1.65 ± 0.16	1.54 ± 0.07
	2006-07-09	2006-08-03	26 days	5.81 ± 3.63	13.77	37.40 ± 1.53	40	26.08 ± 0.78	29	25.76 ± 0.57	1.81 ± 0.22	1.85 ± 0.26
	2006-08-05	2006-08-11	7 days	1.03 ± 0.61	1.63	36.98 ± 1.12	38	24.35 ± 0.38	25	23.99 ± 0.22	2.10 ± 0.15	1.79 ± 0.21
	2006-09-03	2006-09-12	10 days	1.26 ± 0.62	1.87	34.49 ± 2.97	39	24.89 ± 0.97	26	23.91 ± 1.34	2.25 ± 0.67	2.36 ± 0.82
2007	2007-07-28	2007-07-31	4 days	1.53 ± 0.04	1.55	39.61 ± 1.05	40	26.14 ± 1.37	27	25.88 ± 0.09	2.55 ± 0.49	3.25 ± 1.34
	2007-08-26	2007-08-28	3 days	1.81 ± 0.00	1.81	35.75 ± 1.16	37	24.71 ± 0.97	26	25.10 ± 0.44	1.99 ± 0.20	1.64 ± 0.10
2008	2008-08-03	2008-08-06	4 days	3.37 ± 1.82	4.49	37.57 ± 1.21	39	25.13 ± 0.55	26	25.96 ± 0.37	1.67 ± 0.16	1.57 ± 0.17
2009	2009-07-03	2009-07-06	4 days	0.26 ± 0.03	0.28	36.62 ± 0.74	37	25.91 ± 0.59	27	24.19 ± 0.82	1.78 ± 0.18	1.67 ± 0.23
	2009-07-22	2009-08-02	12 days	2.03 ± 0.74	2.86	37.22 ± 1.65	39	26.17 ± 1.06	27	24.41 ± 0.87	2.37 ± 0.52	2.43 ± 1.10
	2009-08-12	2009-08-14	3 days	0.10 ± 0.00	0.10	35.97 ± 1.13	37	24.32 ± 0.31	25	24.91 ± 0.22	1.68 ± 0.20	1.80 ± 0.10
2010	2010-07-04	2010-07-08	5 days	4.43 ± 3.73	7.33	38.34 ± 1.14	39	25.26 ± 1.01	26	25.24 ± 0.73	1.63 ± 0.11	1.86 ± 0.19
	2010-07-25	2010-07-31	7 days	5.36 ± 4.54	9.78	37.75 ± 0.60	38	24.83 ± 0.50	25	24.57 ± 0.63	1.69 ± 0.24	1.82 ± 0.24
	2010-08-09	2010-08-13	5 days	5.38 ± 3.19	8.25	37.27 ± 2.31	39	26.76 ± 1.10	28	24.49 ± 1.74	1.97 ± 0.28	2.26 ± 0.33
	2010-08-25	2010-08-30	6 days	1.78 ± 0.76	2.54	38.24 ± 0.94	40	25.94 ± 0.91	27	24.87 ± 1.40	2.18 ± 0.31	2.54 ± 1.20
	2010-09-14	2010-09-16	3 days	1.17 ± 0.00	1.17	32.26 ± 3.05	35	24.49 ± 0.61	25	22.21 ± 0.24	2.16 ± 0.53	2.31 ± 0.49
2011	2011-08-06	2011-08-08	3 days	0.42 ± 0.00	0.42	36.91 ± 1.38	38	25.83 ± 0.54	26	24.10 ± 0.35	2.10 ± 0.29	1.73 ± 0.20
	2011-08-19	2011-08-21	3 days	2.50 ± 0.00	2.50	37.43 ± 2.02	39	26.60 ± 1.32	28	26.31 ± 0.68	1.62 ± 0.09	1.56 ± 0.15
2012	2012-06-25	2012-06-30	6 days	8.32 ± 4.71	14.93	38.42 ± 1.69	41	25.74 ± 1.25	27	25.21 ± 1.94	1.88 ± 0.20	1.70 ± 0.20
	2012-07-17	2012-07-19	3 days	4.09 ± 0.00	4.09	39.02 ± 0.38	39	24.51 ± 0.52	25	25.41 ± 0.35	1.73 ± 0.10	1.62 ± 0.06
	2012-08-01	2012-08-03	3 days	1.77 ± 0.00	1.77	38.29 ± 1.05	39	26.23 ± 1.51	28	24.75 ± 0.31	1.96 ± 0.22	1.79 ± 0.26
	2012-08-09	2012-08-13	5 days	15.28 ± 10.20	24.03	40.12 ± 2.35	42	26.68 ± 0.93	28	26.17 ± 1.92	2.05 ± 0.24	1.83 ± 0.19
	2012-08-18	2012-08-25	8 days	16.25 ± 9.30	29.42	37.42 ± 1.44	40	26.41 ± 0.46	27	25.93 ± 1.25	1.83 ± 0.23	1.78 ± 0.20
	2012-09-18	2012-09-20	3 days	0.64 ± 0.00	0.64	30.78 ± 0.27	31	24.20 ± 0.06	24	21.53 ± 0.46	1.93 ± 0.23	1.78 ± 0.30
	2012-09-23	2012-09-27	5 days	1.29 ± 0.50	1.63	28.67 ± 2.40	33	24.30 ± 0.37	25	18.80 ± 2.47	1.84 ± 0.13	2.07 ± 0.17

Table B.1: Summary statistics for heat wave episodes identified by temperature using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2013	2013-07-04	2013-07-12	9 days	9.49 ± 5.97	15.76	38.03 ± 1.55	40	24.55 ± 0.81	26	25.03 ± 0.41	1.98 ± 0.32	1.89 ± 0.18
	2013-07-25	2013-07-29	5 days	1.05 ± 0.80	1.75	34.22 ± 1.11	36	25.89 ± 1.22	27	23.74 ± 1.18	1.74 ± 0.14	1.71 ± 0.31
	2013-08-14	2013-08-17	4 days	1.24 ± 0.41	1.45	35.66 ± 0.55	36	25.97 ± 1.17	27	24.44 ± 0.36	2.85 ± 0.41	2.63 ± 1.11
	2013-08-19	2013-08-24	6 days	2.18 ± 0.53	2.78	37.26 ± 1.70	39	25.30 ± 0.67	26	24.61 ± 0.63	2.11 ± 0.44	2.50 ± 0.78
2014	2014-09-16	2014-09-19	4 days	0.02 ± 0.00	0.02	30.13 ± 0.55	31	24.77 ± 0.24	25	21.20 ± 0.27	1.60 ± 0.07	1.75 ± 0.18
	2014-10-22	2014-10-24	3 days	1.65 ± 0.00	1.65	29.61 ± 1.90	32	24.91 ± 0.77	26	18.25 ± 1.11	3.08 ± 0.62	2.36 ± 0.71
2015	2015-06-19	2015-06-21	3 days	0.08 ± 0.00	0.08	35.73 ± 0.87	37	22.06 ± 0.66	23	22.93 ± 0.55	2.16 ± 0.51	1.69 ± 0.12
	2015-06-27	2015-07-01	5 days	11.25 ± 3.76	16.50	39.27 ± 1.32	40	25.24 ± 0.90	26	26.13 ± 0.52	1.79 ± 0.20	1.72 ± 0.24
	2015-07-03	2015-07-31	29 days	16.14 ± 11.30	38.78	38.06 ± 1.61	41	26.22 ± 0.95	29	25.96 ± 0.92	1.79 ± 0.22	1.84 ± 0.23
	2015-08-02	2015-08-14	13 days	5.57 ± 4.24	13.20	36.35 ± 1.50	38	27.26 ± 1.11	29	24.88 ± 1.22	1.83 ± 0.28	2.32 ± 0.49
	2015-08-29	2015-08-31	3 days	0.02 ± 0.00	0.02	34.52 ± 2.72	36	25.71 ± 0.59	26	24.98 ± 0.82	1.72 ± 0.23	1.79 ± 0.27
	2015-09-11	2015-09-14	4 days	0.38 ± 0.17	0.46	29.18 ± 0.62	30	24.41 ± 0.10	25	20.51 ± 0.71	1.98 ± 0.37	1.94 ± 0.19
	2015-09-22	2015-09-25	4 days	1.42 ± 0.29	1.57	30.56 ± 2.32	34	24.73 ± 0.01	25	19.30 ± 0.67	2.14 ± 0.61	2.33 ± 0.15
	2015-10-03	2015-10-07	5 days	1.87 ± 0.92	2.46	28.68 ± 1.32	30	25.18 ± 1.15	27	19.18 ± 1.55	2.50 ± 0.79	2.58 ± 0.90
2016	2016-07-05	2016-07-12	8 days	2.66 ± 2.89	6.14	36.94 ± 1.48	39	25.08 ± 0.74	26	25.13 ± 0.92	1.66 ± 0.12	1.70 ± 0.17
	2016-07-24	2016-08-08	16 days	2.06 ± 3.06	8.09	37.78 ± 0.87	39	25.21 ± 1.29	28	25.23 ± 0.49	1.79 ± 0.35	1.78 ± 0.33
	2016-08-18	2016-08-21	4 days	0.04 ± 0.01	0.04	36.60 ± 0.75	37	25.56 ± 0.37	26	23.99 ± 0.51	1.77 ± 0.19	1.85 ± 0.23
	2016-08-28	2016-08-31	4 days	2.17 ± 0.38	2.44	35.20 ± 2.02	37	24.89 ± 0.77	26	23.92 ± 0.85	2.16 ± 0.53	2.41 ± 0.50
	2016-09-03	2016-09-07	5 days	5.91 ± 3.60	9.30	39.30 ± 1.61	41	25.19 ± 1.07	26	26.11 ± 0.53	1.90 ± 0.31	1.69 ± 0.10
2017	2017-06-11	2017-06-24	14 days	17.66 ± 14.31	43.29	37.84 ± 1.22	40	25.48 ± 1.29	28	25.83 ± 0.66	1.75 ± 0.23	1.84 ± 0.15
	2017-07-12	2017-07-19	8 days	7.30 ± 6.29	15.17	38.94 ± 3.06	43	25.75 ± 1.03	28	25.91 ± 0.61	1.98 ± 0.47	1.90 ± 0.22
	2017-07-28	2017-08-09	13 days	8.54 ± 6.83	23.65	37.42 ± 2.05	41	26.85 ± 1.16	29	25.29 ± 1.58	1.85 ± 0.20	1.97 ± 0.32
	2017-08-15	2017-08-29	15 days	1.00 ± 0.90	2.66	35.95 ± 2.16	39	25.35 ± 0.60	26	24.66 ± 1.10	1.63 ± 0.14	1.74 ± 0.37
	2017-10-13	2017-10-16	4 days	1.68 ± 0.71	2.15	30.98 ± 1.55	32	25.41 ± 1.28	27	20.52 ± 0.67	2.65 ± 0.52	2.71 ± 1.09
2018	2018-07-08	2018-07-11	4 days	0.06 ± 0.03	0.08	35.48 ± 0.28	36	24.79 ± 0.22	25	24.73 ± 0.54	1.66 ± 0.26	1.50 ± 0.14
	2018-07-25	2018-08-13	20 days	14.39 ± 19.41	51.56	36.89 ± 2.75	42	26.35 ± 1.30	29	25.39 ± 1.60	1.78 ± 0.29	1.82 ± 0.25
	2018-08-20	2018-08-22	3 days	0.14 ± 0.00	0.14	34.08 ± 0.29	34	25.30 ± 0.38	26	24.45 ± 0.16	1.90 ± 0.19	1.68 ± 0.29

Abbreviations [a] Magnitude Index

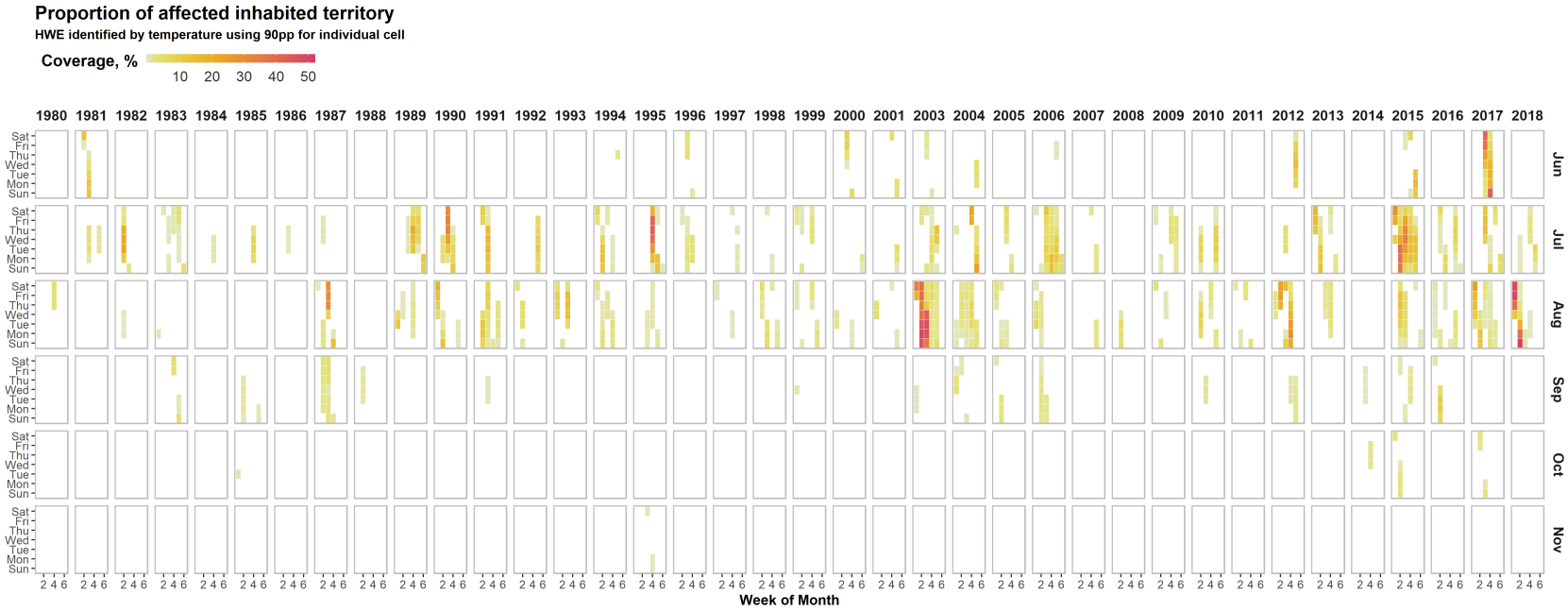


Figure B.7: Proportion of national territory affected by heatwaves identified using temperature (90pp for individual cell)

Table B.2: Summary statistics for heat wave episodes identified by temperature using 95pp for individual cell

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1980	1980-08-21	1980-08-23	3 days	0.22 ± 0.00	0.22	37.75 ± 0.57	38	26.92 ± 1.73	28	25.79 ± 0.52	2.34 ± 0.39	2.52 ± 0.23
1981	1981-06-13	1981-06-18	6 days	2.08 ± 1.52	3.40	38.90 ± 1.48	41	25.44 ± 1.41	28	24.14 ± 1.52	1.84 ± 0.13	2.10 ± 0.16
	1981-07-14	1981-07-16	3 days	0.58 ± 0.00	0.58	38.19 ± 0.22	38	25.15 ± 0.54	26	23.45 ± 0.23	1.73 ± 0.06	2.20 ± 0.26
1982	1982-07-05	1982-07-08	4 days	3.29 ± 2.00	4.39	38.28 ± 1.64	40	24.90 ± 1.20	26	25.90 ± 0.95	2.01 ± 0.36	2.05 ± 0.27
1983	1983-07-29	1983-07-31	3 days	0.52 ± 0.00	0.52	36.30 ± 1.35	37	25.33 ± 0.60	26	24.79 ± 0.84	2.14 ± 0.27	1.71 ± 0.08
	1983-09-23	1983-09-25	3 days	0.64 ± 0.00	0.64	33.47 ± 0.57	34	23.29 ± 0.66	24	23.58 ± 0.40	2.30 ± 0.12	2.00 ± 0.25
1987	1987-08-02	1987-08-04	3 days	0.52 ± 0.00	0.52	37.88 ± 0.90	38	23.93 ± 0.63	25	24.16 ± 0.99	1.98 ± 0.19	2.23 ± 0.17
	1987-08-12	1987-08-16	5 days	8.23 ± 5.79	12.42	37.64 ± 1.66	40	25.67 ± 0.50	26	26.05 ± 0.30	2.02 ± 0.22	2.08 ± 0.25
	1987-09-07	1987-09-20	14 days	1.27 ± 0.62	2.15	34.47 ± 2.03	37	25.14 ± 0.68	26	23.67 ± 0.57	2.14 ± 0.15	2.69 ± 0.57
1989	1989-07-18	1989-07-22	5 days	2.32 ± 1.14	3.88	37.55 ± 2.00	40	25.71 ± 1.56	28	26.27 ± 0.66	2.25 ± 0.43	2.20 ± 0.27
	1989-07-26	1989-08-02	8 days	1.21 ± 0.74	2.17	37.63 ± 1.09	39	25.82 ± 0.87	27	25.44 ± 0.39	1.96 ± 0.17	2.35 ± 0.24
	1989-08-21	1989-08-24	4 days	0.09 ± 0.02	0.10	35.77 ± 0.39	36	26.19 ± 0.71	27	25.42 ± 0.24	1.77 ± 0.05	1.99 ± 0.28
1990	1990-07-09	1990-07-11	3 days	0.52 ± 0.00	0.52	38.08 ± 0.55	39	24.89 ± 0.21	25	24.07 ± 0.31	1.77 ± 0.11	2.16 ± 0.10
	1990-07-17	1990-07-25	9 days	9.38 ± 7.37	19.40	37.31 ± 1.35	39	25.49 ± 1.25	28	25.94 ± 0.53	2.41 ± 0.22	2.55 ± 0.43
	1990-08-02	1990-08-05	4 days	3.73 ± 1.44	4.97	37.47 ± 1.52	39	25.39 ± 0.70	26	25.81 ± 0.24	2.14 ± 0.31	2.07 ± 0.08
1991	1991-07-12	1991-07-18	7 days	5.78 ± 2.00	7.69	40.05 ± 0.69	41	26.26 ± 1.07	28	25.42 ± 0.45	1.89 ± 0.05	2.03 ± 0.16
	1991-08-15	1991-08-17	3 days	1.09 ± 0.00	1.09	38.73 ± 1.84	41	25.31 ± 0.82	26	25.61 ± 0.34	1.77 ± 0.19	2.06 ± 0.18
	1991-08-27	1991-08-29	3 days	0.36 ± 0.00	0.36	34.51 ± 0.64	35	26.42 ± 0.41	27	24.95 ± 0.14	1.87 ± 0.18	1.84 ± 0.23
1993	1993-08-04	1993-08-08	5 days	1.20 ± 0.81	2.01	37.42 ± 0.44	38	26.78 ± 0.59	28	25.22 ± 1.21	1.92 ± 0.13	2.08 ± 0.24
	1993-08-18	1993-08-20	3 days	6.52 ± 0.00	6.52	36.04 ± 2.54	38	24.97 ± 0.89	26	25.91 ± 1.03	2.33 ± 0.08	2.49 ± 0.77
1994	1994-07-02	1994-07-06	5 days	4.48 ± 2.14	6.60	39.95 ± 2.02	43	27.83 ± 1.35	29	25.37 ± 0.93	2.51 ± 0.50	2.12 ± 0.26
	1994-08-07	1994-08-09	3 days	0.06 ± 0.00	0.06	37.31 ± 0.95	38	26.94 ± 1.06	28	24.86 ± 1.20	2.01 ± 0.21	2.20 ± 0.52
	1994-08-17	1994-08-19	3 days	0.14 ± 0.00	0.14	37.08 ± 0.61	38	26.30 ± 0.75	27	24.69 ± 0.34	1.72 ± 0.00	1.85 ± 0.21
	1994-08-21	1994-08-23	3 days	0.14 ± 0.00	0.14	36.46 ± 0.94	38	27.36 ± 1.00	28	25.17 ± 0.66	1.82 ± 0.14	2.31 ± 0.77
1995	1995-07-17	1995-07-24	8 days	13.73 ± 13.05	30.39	40.40 ± 1.07	42	26.19 ± 0.87	27	26.53 ± 0.77	1.94 ± 0.21	1.99 ± 0.27
1996	1996-06-13	1996-06-15	3 days	0.74 ± 0.00	0.74	34.34 ± 0.93	35	22.70 ± 0.07	23	23.52 ± 0.06	2.14 ± 0.25	2.03 ± 0.22
1998	1998-08-09	1998-08-11	3 days	0.10 ± 0.00	0.10	37.28 ± 0.85	38	24.23 ± 0.31	25	25.71 ± 0.15	1.63 ± 0.05	1.70 ± 0.18
1999	1999-07-02	1999-07-04	3 days	0.14 ± 0.00	0.14	38.56 ± 0.62	39	26.22 ± 0.15	26	24.67 ± 1.53	2.14 ± 0.40	1.84 ± 0.20
	1999-08-27	1999-08-30	4 days	1.19 ± 0.52	1.45	34.44 ± 1.44	36	25.36 ± 0.43	26	24.28 ± 0.41	2.28 ± 0.28	2.67 ± 0.41
2000	2000-06-15	2000-06-18	4 days	2.82 ± 1.10	3.76	34.61 ± 1.25	36	22.77 ± 0.41	23	23.75 ± 0.65	2.25 ± 0.17	2.35 ± 0.42
2001	2001-06-23	2001-06-25	3 days	0.26 ± 0.00	0.26	38.27 ± 1.12	40	25.21 ± 1.28	26	25.12 ± 0.25	1.75 ± 0.17	1.78 ± 0.19
	2001-07-30	2001-08-02	4 days	1.27 ± 0.35	1.57	35.80 ± 1.69	38	27.12 ± 1.33	29	25.85 ± 1.24	1.94 ± 0.22	1.89 ± 0.28
2003	2003-07-30	2003-08-27	29 days	7.23 ± 7.11	20.57	36.65 ± 2.82	42	26.66 ± 0.56	28	25.76 ± 1.41	2.08 ± 0.29	2.10 ± 0.21

Table B.2: Summary statistics for heat wave episodes identified by temperature using 95pp for individual cell *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2004	2004-07-23	2004-07-29	7 days	7.27 ± 4.59	13.36	37.70 ± 3.08	41	27.70 ± 1.47	30	25.59 ± 1.44	2.66 ± 0.48	3.14 ± 0.77
	2004-08-17	2004-08-20	4 days	0.20 ± 0.00	0.20	33.02 ± 0.81	34	26.07 ± 0.33	26	22.63 ± 0.71	2.30 ± 0.29	2.15 ± 0.24
	2004-08-24	2004-09-01	9 days	2.01 ± 0.95	3.34	34.70 ± 2.72	39	26.49 ± 1.03	28	23.18 ± 0.80	2.70 ± 0.59	3.30 ± 1.13
2005	2005-08-13	2005-08-15	3 days	0.40 ± 0.00	0.40	37.93 ± 1.22	39	24.08 ± 0.85	25	24.66 ± 0.23	2.35 ± 0.08	1.90 ± 0.08
	2005-09-04	2005-09-06	3 days	2.46 ± 0.00	2.46	33.70 ± 3.36	36	26.32 ± 0.73	27	22.43 ± 1.99	3.05 ± 0.40	3.74 ± 0.57
2006	2006-07-12	2006-07-28	17 days	1.71 ± 1.50	4.07	36.75 ± 1.28	39	25.98 ± 0.57	27	25.70 ± 0.58	2.11 ± 0.44	2.03 ± 0.39
	2006-07-30	2006-08-03	5 days	0.34 ± 0.13	0.56	38.13 ± 0.84	39	26.37 ± 0.49	27	25.77 ± 0.31	1.76 ± 0.11	1.99 ± 0.28
	2006-08-08	2006-08-11	4 days	0.54 ± 0.28	0.68	36.53 ± 1.14	38	24.23 ± 0.46	25	23.88 ± 0.22	2.22 ± 0.16	1.97 ± 0.12
	2006-09-04	2006-09-06	3 days	0.02 ± 0.00	0.02	35.91 ± 2.67	39	25.53 ± 1.34	26	25.05 ± 0.37	2.85 ± 0.36	3.05 ± 1.01
2007	2007-07-28	2007-07-31	4 days	0.69 ± 0.24	0.81	39.61 ± 1.05	40	26.14 ± 1.37	27	25.88 ± 0.09	2.37 ± 0.55	3.70 ± 1.11
2009	2009-07-22	2009-07-24	3 days	0.06 ± 0.00	0.06	38.51 ± 0.26	39	26.61 ± 0.79	27	24.85 ± 0.56	1.89 ± 0.19	1.96 ± 0.50
	2009-07-28	2009-08-02	6 days	1.74 ± 0.80	2.46	36.14 ± 1.70	38	26.37 ± 1.14	27	24.00 ± 1.02	2.79 ± 0.40	3.21 ± 1.12
2010	2010-07-05	2010-07-07	3 days	1.81 ± 0.00	1.81	38.92 ± 0.33	39	25.95 ± 0.23	26	25.14 ± 0.44	1.71 ± 0.07	2.03 ± 0.10
	2010-07-26	2010-07-29	4 days	0.52 ± 0.17	0.62	37.99 ± 0.41	38	25.02 ± 0.28	25	24.80 ± 0.67	2.21 ± 0.26	2.16 ± 0.15
	2010-08-09	2010-08-12	4 days	1.60 ± 0.69	1.95	38.23 ± 0.97	39	27.14 ± 0.82	28	25.24 ± 0.52	2.19 ± 0.17	2.41 ± 0.15
	2010-08-26	2010-08-30	5 days	0.74 ± 0.14	0.81	38.29 ± 1.05	40	26.15 ± 0.85	27	24.83 ± 1.56	2.23 ± 0.38	2.94 ± 0.92
	2010-09-14	2010-09-16	3 days	0.40 ± 0.00	0.40	32.26 ± 3.05	35	24.49 ± 0.61	25	22.21 ± 0.24	2.26 ± 0.44	2.59 ± 0.45
2012	2012-06-25	2012-06-30	6 days	0.56 ± 0.23	0.78	38.42 ± 1.69	41	25.74 ± 1.25	27	25.21 ± 1.94	2.07 ± 0.33	1.91 ± 0.26
	2012-08-01	2012-08-03	3 days	0.30 ± 0.00	0.30	38.29 ± 1.05	39	26.23 ± 1.51	28	24.75 ± 0.31	1.96 ± 0.17	1.96 ± 0.30
	2012-08-09	2012-08-12	4 days	6.57 ± 2.83	8.33	41.15 ± 0.52	42	26.76 ± 1.06	28	26.82 ± 1.45	2.43 ± 0.23	1.97 ± 0.12
	2012-08-18	2012-08-25	8 days	3.23 ± 2.28	6.24	37.42 ± 1.44	40	26.41 ± 0.46	27	25.93 ± 1.25	2.06 ± 0.36	2.29 ± 0.56
	2012-09-23	2012-09-25	3 days	0.64 ± 0.00	0.64	29.48 ± 2.99	33	24.38 ± 0.26	25	20.26 ± 1.96	1.95 ± 0.06	2.16 ± 0.11
2013	2013-07-04	2013-07-09	6 days	4.20 ± 1.75	6.38	38.91 ± 0.61	40	24.89 ± 0.77	26	25.15 ± 0.43	2.37 ± 0.41	2.24 ± 0.26
	2013-07-27	2013-07-29	3 days	0.87 ± 0.00	0.87	33.62 ± 0.45	34	26.76 ± 0.26	27	22.89 ± 0.19	2.00 ± 0.22	2.04 ± 0.05
	2013-08-15	2013-08-17	3 days	0.93 ± 0.00	0.93	35.58 ± 0.65	36	26.39 ± 0.99	27	24.44 ± 0.44	3.01 ± 0.56	3.21 ± 1.01
	2013-08-21	2013-08-24	4 days	1.20 ± 0.16	1.31	36.27 ± 0.94	37	25.39 ± 0.70	26	24.39 ± 0.66	2.25 ± 0.45	3.04 ± 0.52
2015	2015-06-27	2015-07-01	5 days	2.36 ± 1.36	3.74	39.27 ± 1.32	40	25.24 ± 0.90	26	26.13 ± 0.52	1.85 ± 0.17	1.78 ± 0.13
	2015-07-03	2015-07-30	28 days	6.51 ± 6.83	22.38	38.22 ± 1.37	41	26.22 ± 0.97	29	26.05 ± 0.79	1.91 ± 0.22	1.96 ± 0.25
	2015-08-04	2015-08-14	11 days	1.69 ± 1.03	3.28	36.23 ± 1.51	38	27.46 ± 1.08	29	24.81 ± 1.31	2.09 ± 0.34	2.59 ± 0.54
	2015-09-11	2015-09-13	3 days	0.02 ± 0.00	0.02	29.21 ± 0.75	30	24.40 ± 0.11	25	20.79 ± 0.51	2.14 ± 0.30	2.03 ± 0.05
	2015-09-22	2015-09-25	4 days	0.19 ± 0.06	0.22	30.56 ± 2.32	34	24.73 ± 0.01	25	19.30 ± 0.67	2.29 ± 0.47	2.27 ± 0.16
	2015-10-03	2015-10-06	4 days	2.02 ± 0.51	2.46	29.19 ± 0.78	30	25.47 ± 1.11	27	19.64 ± 1.34	2.74 ± 0.69	2.84 ± 0.81
2016	2016-07-08	2016-07-11	4 days	1.66 ± 0.80	2.11	37.77 ± 0.91	39	25.49 ± 0.69	26	25.89 ± 0.63	1.90 ± 0.23	1.85 ± 0.14
	2016-07-26	2016-08-01	7 days	0.70 ± 0.82	1.61	37.77 ± 0.97	39	25.82 ± 1.42	28	25.47 ± 0.51	1.92 ± 0.37	2.06 ± 0.44
	2016-08-18	2016-08-20	3 days	0.02 ± 0.00	0.02	36.86 ± 0.65	37	25.50 ± 0.42	26	24.24 ± 0.03	2.11 ± 0.18	2.11 ± 0.24
	2016-08-29	2016-08-31	3 days	0.91 ± 0.00	0.91	34.84 ± 2.31	37	25.15 ± 0.68	26	23.53 ± 0.42	2.39 ± 0.47	2.68 ± 0.45
	2016-09-04	2016-09-07	4 days	1.36 ± 0.54	1.81	39.81 ± 1.31	41	25.61 ± 0.60	26	26.29 ± 0.40	2.07 ± 0.12	1.93 ± 0.08

Table B.2: Summary statistics for heat wave episodes identified by temperature using 95pp for individual cell *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2017	2017-06-12	2017-06-24	13 days	6.43 ± 6.92	18.45	37.82 ± 1.26	40	25.57 ± 1.29	28	25.91 ± 0.62	1.88 ± 0.23	1.86 ± 0.20
	2017-07-12	2017-07-16	5 days	5.92 ± 2.90	8.75	40.86 ± 1.75	43	26.18 ± 1.06	28	26.11 ± 0.48	2.28 ± 0.46	2.01 ± 0.28
	2017-07-31	2017-08-09	10 days	4.59 ± 4.41	11.43	37.25 ± 2.33	41	27.35 ± 0.76	29	25.10 ± 1.78	1.98 ± 0.21	2.26 ± 0.28
	2017-08-19	2017-08-21	3 days	0.04 ± 0.00	0.04	38.22 ± 0.73	39	25.19 ± 0.63	26	25.18 ± 0.34	2.08 ± 0.34	2.05 ± 0.08
	2017-10-13	2017-10-15	3 days	0.91 ± 0.00	0.91	31.72 ± 0.59	32	25.88 ± 1.04	27	20.68 ± 0.72	3.06 ± 0.27	3.24 ± 0.88
2018	2018-07-25	2018-07-27	3 days	0.04 ± 0.00	0.04	34.94 ± 0.22	35	24.86 ± 0.33	25	24.60 ± 0.12	1.84 ± 0.20	1.65 ± 0.10
	2018-07-30	2018-08-09	11 days	14.14 ± 13.46	34.29	38.21 ± 3.06	42	26.92 ± 1.39	29	26.24 ± 1.66	2.11 ± 0.29	2.14 ± 0.26

Abbreviations [a] Magnitude Index

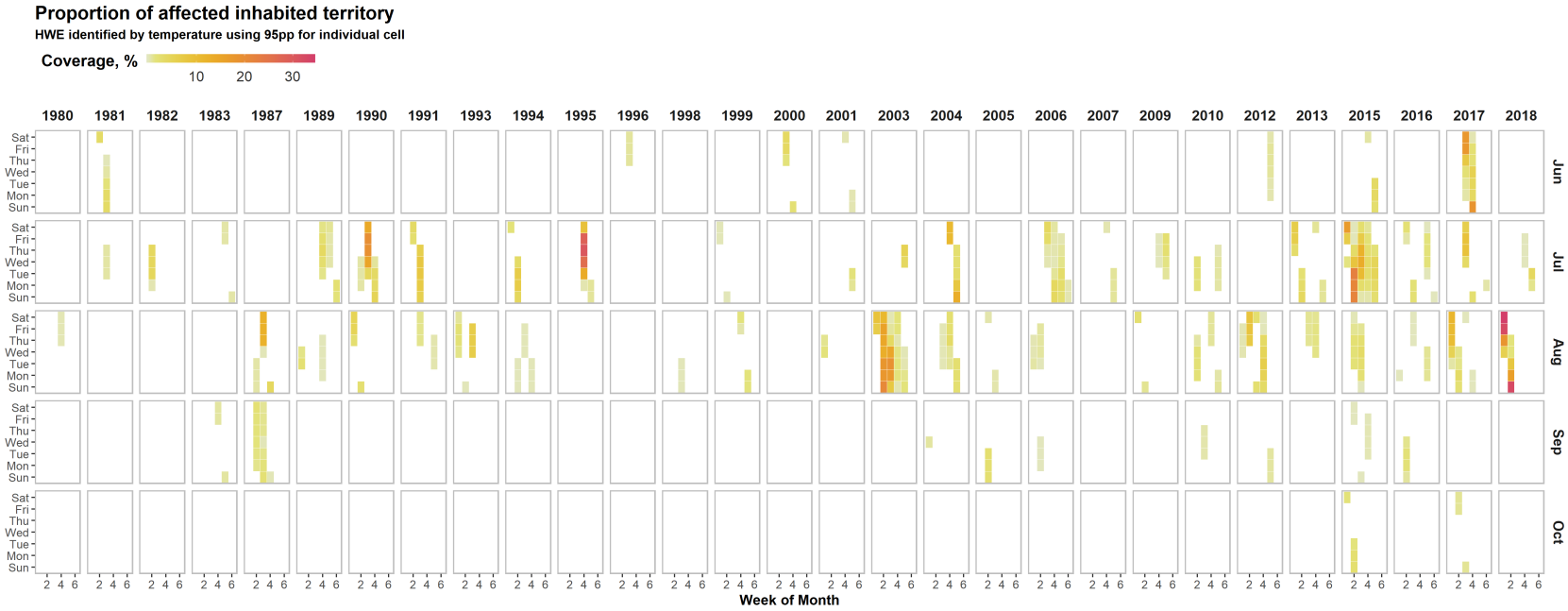


Figure B.8: Proportion of national territory affected by heatwaves identified using temperature (95pp for individual cell)

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1979	1979-07-09	1979-07-12	4 days	0.10 ± 0.01	0.10	34.01 ± 4.04	39	23.79 ± 1.30	25	23.20 ± 1.85	2.20 ± 0.53	1.83 ± 0.42
	1979-07-14	1979-07-19	6 days	0.13 ± 0.06	0.22	35.39 ± 1.50	37	22.84 ± 0.39	23	23.16 ± 1.05	1.90 ± 0.32	1.78 ± 0.26
	1979-07-24	1979-08-07	15 days	0.68 ± 0.84	2.37	36.03 ± 1.71	39	23.96 ± 0.89	26	24.07 ± 0.93	1.86 ± 0.20	1.82 ± 0.12
	1979-08-10	1979-08-14	5 days	0.79 ± 0.59	1.25	36.94 ± 0.60	38	23.87 ± 0.76	24	24.08 ± 0.57	1.66 ± 0.07	1.64 ± 0.09
1980	1980-07-21	1980-07-24	4 days	0.27 ± 0.14	0.34	37.13 ± 0.96	39	23.50 ± 0.64	24	23.48 ± 1.31	1.92 ± 0.10	1.84 ± 0.32
	1980-08-01	1980-08-07	7 days	0.22 ± 0.16	0.38	36.07 ± 1.19	38	24.30 ± 0.76	26	24.36 ± 0.60	2.02 ± 0.22	1.69 ± 0.16
	1980-08-11	1980-08-13	3 days	0.02 ± 0.00	0.02	35.81 ± 0.32	36	22.96 ± 0.34	23	23.98 ± 0.13	1.70 ± 0.08	1.62 ± 0.12
	1980-08-20	1980-08-24	5 days	1.36 ± 1.12	2.21	36.45 ± 1.85	38	26.16 ± 1.67	28	25.01 ± 1.14	1.99 ± 0.58	2.30 ± 0.42
	1980-08-28	1980-08-30	3 days	0.02 ± 0.00	0.02	35.60 ± 2.31	37	23.47 ± 0.29	24	23.85 ± 0.81	1.53 ± 0.13	1.89 ± 0.10
1981	1981-06-11	1981-06-20	10 days	4.97 ± 4.28	9.48	38.11 ± 2.13	41	24.20 ± 1.96	28	23.44 ± 1.77	1.87 ± 0.27	1.75 ± 0.22
	1981-07-13	1981-07-17	5 days	4.33 ± 2.08	5.88	37.51 ± 0.96	38	24.67 ± 0.95	26	23.30 ± 0.41	1.64 ± 0.15	1.80 ± 0.16
	1981-07-26	1981-07-31	6 days	0.68 ± 0.50	1.29	36.92 ± 2.93	40	23.95 ± 2.06	27	23.67 ± 1.91	2.05 ± 0.60	1.94 ± 0.49
	1981-08-10	1981-08-17	8 days	0.09 ± 0.03	0.12	34.41 ± 0.91	36	22.78 ± 0.43	23	23.11 ± 0.51	1.57 ± 0.15	1.72 ± 0.16
	1981-08-24	1981-08-28	5 days	0.11 ± 0.04	0.14	34.71 ± 0.55	36	23.25 ± 0.69	24	22.58 ± 0.29	1.59 ± 0.07	1.68 ± 0.11
1982	1982-07-01	1982-07-15	15 days	3.04 ± 4.61	11.77	34.98 ± 3.29	40	25.02 ± 0.89	27	23.89 ± 1.95	1.88 ± 0.27	1.88 ± 0.32
	1982-08-09	1982-08-14	6 days	0.24 ± 0.12	0.40	35.42 ± 1.07	37	23.88 ± 0.68	25	23.50 ± 0.67	1.81 ± 0.17	1.74 ± 0.11
	1982-08-19	1982-08-21	3 days	0.06 ± 0.00	0.06	35.68 ± 3.34	39	25.26 ± 1.56	27	23.66 ± 1.63	1.63 ± 0.25	2.00 ± 0.72
1983	1983-06-05	1983-06-07	3 days	0.48 ± 0.00	0.48	32.23 ± 1.08	33	21.07 ± 0.06	21	21.69 ± 0.14	2.38 ± 0.37	1.65 ± 0.20
	1983-06-10	1983-06-12	3 days	0.02 ± 0.00	0.02	35.98 ± 0.57	36	23.62 ± 1.84	25	23.53 ± 0.40	1.63 ± 0.19	1.82 ± 0.29
	1983-07-08	1983-08-01	25 days	1.46 ± 1.12	3.42	34.25 ± 1.78	37	24.83 ± 1.55	28	23.86 ± 0.88	1.90 ± 0.31	1.85 ± 0.24
	1983-08-03	1983-08-06	4 days	0.06 ± 0.00	0.06	33.86 ± 0.62	34	24.00 ± 0.86	25	22.94 ± 0.42	1.57 ± 0.10	1.93 ± 0.31
	1983-09-05	1983-09-08	4 days	0.32 ± 0.15	0.40	35.88 ± 1.02	37	24.25 ± 0.89	25	23.35 ± 0.38	1.55 ± 0.09	1.86 ± 0.29
	1983-09-23	1983-09-27	5 days	0.63 ± 0.36	1.05	34.11 ± 1.11	36	24.23 ± 1.39	26	23.38 ± 0.95	2.07 ± 0.12	2.28 ± 0.53
1984	1984-07-10	1984-07-13	4 days	0.05 ± 0.02	0.06	35.33 ± 1.41	37	23.43 ± 1.08	25	22.65 ± 0.91	1.92 ± 0.09	1.63 ± 0.18
	1984-07-15	1984-07-25	11 days	0.23 ± 0.22	0.58	36.02 ± 1.58	39	23.29 ± 1.17	25	23.86 ± 1.16	1.80 ± 0.25	1.74 ± 0.17
	1984-07-27	1984-07-30	4 days	0.02 ± 0.00	0.02	36.20 ± 1.90	39	23.64 ± 0.31	24	24.23 ± 0.30	2.18 ± 0.30	1.51 ± 0.07
1985	1985-06-26	1985-07-01	6 days	0.06 ± 0.03	0.08	34.50 ± 0.66	35	22.02 ± 0.39	23	22.52 ± 0.68	1.50 ± 0.10	1.76 ± 0.13
	1985-07-05	1985-07-29	25 days	1.72 ± 2.93	9.18	35.85 ± 1.92	40	23.86 ± 0.66	26	24.11 ± 0.99	1.83 ± 0.12	1.76 ± 0.24
	1985-08-02	1985-08-05	4 days	0.14 ± 0.05	0.16	37.14 ± 2.27	40	24.56 ± 1.69	27	24.09 ± 1.18	1.76 ± 0.28	1.80 ± 0.54
	1985-08-14	1985-08-16	3 days	0.02 ± 0.00	0.02	33.90 ± 0.26	34	23.68 ± 0.15	24	22.97 ± 0.24	1.83 ± 0.17	1.65 ± 0.23
	1985-08-19	1985-08-24	6 days	0.08 ± 0.03	0.10	35.66 ± 1.51	37	24.12 ± 0.55	25	24.09 ± 0.74	1.93 ± 0.16	1.74 ± 0.21
	1985-09-09	1985-09-12	4 days	0.34 ± 0.16	0.42	33.18 ± 0.98	34	24.02 ± 0.69	25	23.25 ± 0.14	2.06 ± 0.28	1.83 ± 0.35
	1985-09-29	1985-10-01	3 days	0.50 ± 0.00	0.50	30.72 ± 1.18	32	24.26 ± 0.21	24	21.99 ± 0.33	1.66 ± 0.19	2.10 ± 0.14

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1986	1986-07-02	1986-07-06	5 days	0.42 ± 0.31	0.64	35.95 ± 1.00	37	23.39 ± 1.07	25	23.85 ± 0.80	1.77 ± 0.10	1.74 ± 0.19
	1986-07-08	1986-07-11	4 days	0.48 ± 0.16	0.56	36.47 ± 0.65	37	23.46 ± 0.36	24	23.80 ± 0.19	1.81 ± 0.24	1.64 ± 0.16
	1986-07-15	1986-07-18	4 days	0.24 ± 0.09	0.30	36.68 ± 1.97	38	22.87 ± 0.12	23	23.08 ± 0.77	1.83 ± 0.22	1.81 ± 0.24
	1986-07-28	1986-08-04	8 days	0.32 ± 0.21	0.62	35.19 ± 1.67	38	24.27 ± 1.00	26	23.94 ± 0.96	2.09 ± 0.26	1.82 ± 0.16
	1986-08-06	1986-08-11	6 days	0.07 ± 0.02	0.08	32.99 ± 1.40	35	24.40 ± 0.90	26	23.12 ± 0.46	2.07 ± 0.32	1.70 ± 0.22
	1986-08-14	1986-08-18	5 days	0.40 ± 0.24	0.60	34.64 ± 0.82	36	25.26 ± 0.81	26	24.06 ± 0.76	2.14 ± 0.12	1.88 ± 0.35
	1986-09-03	1986-09-08	6 days	0.11 ± 0.10	0.20	32.05 ± 1.55	34	23.71 ± 0.84	25	22.36 ± 0.56	1.71 ± 0.22	2.03 ± 0.53
	1986-09-13	1986-09-15	3 days	0.20 ± 0.00	0.20	30.56 ± 0.48	31	23.92 ± 0.16	24	22.06 ± 0.13	1.86 ± 0.14	1.99 ± 0.47
1987	1987-06-26	1987-06-28	3 days	0.22 ± 0.00	0.22	35.86 ± 1.44	37	22.15 ± 0.74	23	23.10 ± 0.80	1.83 ± 0.16	1.74 ± 0.14
	1987-07-01	1987-07-12	12 days	0.37 ± 0.31	0.87	34.10 ± 1.45	37	23.59 ± 0.78	25	23.78 ± 0.47	1.67 ± 0.20	1.78 ± 0.12
	1987-08-01	1987-08-05	5 days	0.87 ± 0.66	1.41	36.94 ± 1.44	38	23.95 ± 0.90	25	23.79 ± 1.11	2.04 ± 0.29	1.95 ± 0.27
	1987-08-10	1987-08-22	13 days	5.37 ± 5.99	16.16	36.64 ± 1.77	40	25.12 ± 0.64	26	25.38 ± 0.93	1.96 ± 0.38	1.89 ± 0.31
	1987-09-07	1987-09-21	15 days	1.35 ± 0.90	2.50	34.15 ± 2.31	37	25.10 ± 0.67	26	23.57 ± 0.69	2.11 ± 0.22	2.39 ± 0.61
1988	1988-07-11	1988-07-14	4 days	0.05 ± 0.01	0.06	36.21 ± 0.58	37	23.84 ± 1.17	26	23.65 ± 0.74	1.82 ± 0.10	1.85 ± 0.20
	1988-07-18	1988-08-03	17 days	0.33 ± 0.37	1.15	36.05 ± 2.15	40	24.13 ± 0.91	26	24.12 ± 0.84	1.90 ± 0.32	1.80 ± 0.31
	1988-08-07	1988-08-19	13 days	0.22 ± 0.07	0.30	33.67 ± 1.07	35	24.55 ± 0.65	26	23.97 ± 0.46	1.92 ± 0.26	1.67 ± 0.17
	1988-09-05	1988-09-09	5 days	1.80 ± 1.09	2.64	37.25 ± 0.68	38	24.89 ± 0.86	26	24.78 ± 0.91	1.59 ± 0.13	1.73 ± 0.19
1989	1989-06-16	1989-06-18	3 days	0.02 ± 0.00	0.02	31.21 ± 1.91	33	22.36 ± 0.42	23	22.59 ± 0.66	1.73 ± 0.12	1.56 ± 0.14
	1989-07-10	1989-07-23	14 days	3.94 ± 5.34	15.50	36.99 ± 1.64	40	24.81 ± 1.26	28	24.84 ± 1.27	1.96 ± 0.27	1.83 ± 0.38
	1989-07-25	1989-08-02	9 days	9.93 ± 4.91	14.71	37.40 ± 1.24	39	25.71 ± 0.87	27	25.31 ± 0.53	1.88 ± 0.07	1.85 ± 0.13
	1989-08-07	1989-08-10	4 days	0.12 ± 0.02	0.14	33.84 ± 1.05	35	25.52 ± 0.63	26	24.31 ± 0.77	2.02 ± 0.24	1.82 ± 0.26
	1989-08-15	1989-08-29	15 days	0.41 ± 0.43	1.23	34.41 ± 1.16	36	25.78 ± 0.62	27	24.32 ± 0.92	1.90 ± 0.32	1.88 ± 0.26
	1989-10-07	1989-10-09	3 days	0.12 ± 0.00	0.12	28.77 ± 2.04	30	24.65 ± 0.72	25	17.85 ± 1.22	2.18 ± 0.61	2.58 ± 0.58
1990	1990-07-04	1990-07-13	10 days	2.48 ± 3.45	7.59	35.25 ± 2.14	39	23.98 ± 0.90	25	23.16 ± 0.92	1.55 ± 0.18	1.75 ± 0.10
	1990-07-15	1990-07-27	13 days	9.60 ± 9.48	25.24	36.47 ± 1.86	39	25.22 ± 1.30	28	25.13 ± 1.39	2.10 ± 0.30	1.99 ± 0.20
	1990-07-31	1990-08-14	15 days	3.05 ± 3.64	10.55	35.53 ± 1.85	39	24.80 ± 0.78	26	24.58 ± 1.13	1.96 ± 0.38	2.01 ± 0.58
	1990-08-16	1990-08-23	8 days	0.10 ± 0.04	0.14	32.76 ± 1.35	35	24.31 ± 0.30	25	23.60 ± 0.42	1.62 ± 0.20	1.70 ± 0.35
	1990-08-25	1990-08-28	4 days	0.39 ± 0.18	0.48	32.77 ± 0.51	33	24.74 ± 0.37	25	23.04 ± 0.45	1.66 ± 0.11	2.22 ± 0.66
1991	1991-06-24	1991-06-27	4 days	0.35 ± 0.11	0.44	36.48 ± 0.70	37	23.17 ± 1.14	24	23.61 ± 0.73	1.73 ± 0.33	1.61 ± 0.15
	1991-07-07	1991-07-28	22 days	5.60 ± 6.76	17.11	36.47 ± 2.83	41	25.09 ± 1.78	29	24.48 ± 1.23	1.77 ± 0.23	1.83 ± 0.21
	1991-08-03	1991-08-08	6 days	7.19 ± 5.83	12.86	37.54 ± 1.28	39	25.41 ± 0.75	26	25.07 ± 1.36	1.93 ± 0.30	1.72 ± 0.16
	1991-08-11	1991-08-31	21 days	2.86 ± 2.51	7.51	35.44 ± 2.10	41	25.45 ± 1.29	27	24.51 ± 1.13	1.99 ± 0.38	1.88 ± 0.29
	1991-09-17	1991-09-19	3 days	0.06 ± 0.00	0.06	35.44 ± 0.39	36	23.90 ± 0.23	24	23.63 ± 0.05	1.59 ± 0.05	1.61 ± 0.07
1992	1992-07-15	1992-07-20	6 days	0.80 ± 0.71	1.45	34.62 ± 1.37	36	23.20 ± 1.05	25	24.15 ± 0.62	1.76 ± 0.23	1.69 ± 0.20
	1992-07-23	1992-08-08	17 days	4.87 ± 4.04	12.68	35.32 ± 1.96	38	25.10 ± 0.93	27	25.04 ± 0.98	1.89 ± 0.30	1.92 ± 0.26
	1992-08-16	1992-08-28	13 days	0.19 ± 0.07	0.28	34.54 ± 2.15	38	24.91 ± 0.75	26	23.93 ± 1.20	2.07 ± 0.21	1.86 ± 0.27

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1993	1993-07-14	1993-07-19	6 days	0.65 ± 0.41	1.07	35.53 ± 0.68	36	23.27 ± 1.02	24	23.62 ± 0.62	1.63 ± 0.07	1.65 ± 0.11
	1993-07-22	1993-07-30	9 days	0.40 ± 0.39	0.93	36.42 ± 1.53	39	23.81 ± 1.34	27	23.73 ± 1.32	1.76 ± 0.22	1.84 ± 0.34
	1993-08-02	1993-08-08	7 days	6.23 ± 5.69	12.80	36.67 ± 1.38	38	25.95 ± 1.49	28	24.76 ± 1.26	1.81 ± 0.32	1.80 ± 0.15
	1993-08-10	1993-08-13	4 days	0.21 ± 0.09	0.28	34.88 ± 1.08	36	24.21 ± 0.35	25	23.85 ± 0.53	1.58 ± 0.09	1.68 ± 0.13
	1993-08-17	1993-08-23	7 days	2.88 ± 2.70	6.14	34.30 ± 2.24	38	24.75 ± 0.67	26	24.77 ± 1.39	2.20 ± 0.26	1.91 ± 0.26
1994	1994-06-28	1994-07-31	34 days	2.97 ± 4.34	15.52	36.07 ± 2.32	43	25.32 ± 1.61	29	24.54 ± 0.90	1.88 ± 0.30	1.78 ± 0.16
	1994-08-02	1994-08-13	12 days	1.45 ± 1.67	4.51	34.94 ± 1.64	38	26.09 ± 0.99	28	24.32 ± 1.21	2.05 ± 0.29	2.03 ± 0.40
	1994-08-15	1994-08-24	10 days	1.93 ± 1.37	4.00	36.31 ± 0.97	38	26.58 ± 0.85	28	24.76 ± 0.92	1.95 ± 0.27	1.85 ± 0.21
	1994-08-26	1994-08-31	6 days	0.18 ± 0.06	0.24	34.51 ± 1.73	36	25.24 ± 0.42	26	23.92 ± 0.90	1.99 ± 0.21	1.69 ± 0.21
1995	1995-06-29	1995-07-02	4 days	0.04 ± 0.01	0.04	31.11 ± 0.38	32	22.73 ± 0.65	23	21.98 ± 0.87	1.97 ± 0.25	1.56 ± 0.10
	1995-07-11	1995-08-06	27 days	7.63 ± 11.34	33.79	36.69 ± 2.89	42	25.03 ± 1.32	28	24.79 ± 1.54	1.86 ± 0.22	1.85 ± 0.28
	1995-08-11	1995-08-17	7 days	1.07 ± 0.36	1.53	37.05 ± 1.22	39	25.39 ± 0.90	27	25.08 ± 0.47	1.78 ± 0.13	1.75 ± 0.14
	1995-08-22	1995-08-24	3 days	0.08 ± 0.00	0.08	31.52 ± 1.39	33	24.02 ± 0.51	25	21.96 ± 0.26	1.96 ± 0.24	1.76 ± 0.11
	1995-08-26	1995-08-28	3 days	0.14 ± 0.00	0.14	35.72 ± 0.32	36	23.84 ± 0.22	24	22.76 ± 0.28	1.88 ± 0.06	1.73 ± 0.23
1996	1996-06-12	1996-06-16	5 days	0.95 ± 0.53	1.33	34.23 ± 0.85	35	22.60 ± 0.51	23	23.48 ± 0.26	2.30 ± 0.21	1.77 ± 0.29
	1996-06-19	1996-06-21	3 days	0.02 ± 0.00	0.02	32.23 ± 0.86	33	22.85 ± 0.68	24	21.80 ± 1.28	1.96 ± 0.12	1.78 ± 0.30
	1996-06-28	1996-07-01	4 days	0.21 ± 0.07	0.26	35.80 ± 1.00	37	22.39 ± 0.50	23	22.75 ± 0.35	1.70 ± 0.17	1.68 ± 0.13
	1996-07-12	1996-07-26	15 days	2.79 ± 2.09	5.94	35.65 ± 1.82	38	23.99 ± 1.49	27	24.30 ± 1.17	1.92 ± 0.24	1.86 ± 0.26
	1996-07-29	1996-08-03	6 days	0.57 ± 0.35	0.97	35.47 ± 0.95	37	24.07 ± 0.25	24	23.93 ± 0.27	1.82 ± 0.29	1.64 ± 0.09
	1996-08-18	1996-08-20	3 days	0.04 ± 0.00	0.04	31.21 ± 0.66	32	24.40 ± 0.40	25	22.63 ± 0.98	1.84 ± 0.21	1.75 ± 0.33
1997	1997-06-11	1997-06-13	3 days	0.10 ± 0.00	0.10	32.78 ± 2.08	35	22.82 ± 1.05	24	21.62 ± 0.39	2.03 ± 0.11	1.65 ± 0.19
	1997-07-13	1997-07-16	4 days	0.04 ± 0.02	0.06	32.21 ± 2.02	35	23.56 ± 0.98	24	22.58 ± 0.85	2.04 ± 0.23	2.05 ± 0.72
	1997-07-26	1997-08-04	10 days	1.33 ± 1.02	2.96	35.77 ± 1.59	38	24.18 ± 0.47	25	24.61 ± 0.33	1.73 ± 0.14	1.80 ± 0.24
	1997-08-07	1997-08-10	4 days	0.06 ± 0.00	0.06	31.07 ± 1.05	32	25.05 ± 1.01	26	22.82 ± 1.09	2.11 ± 0.45	1.84 ± 0.26
	1997-08-13	1997-08-24	12 days	0.76 ± 0.72	2.05	33.67 ± 1.77	36	24.23 ± 0.42	25	24.37 ± 0.42	1.85 ± 0.23	1.84 ± 0.22
	1997-09-08	1997-09-10	3 days	0.02 ± 0.00	0.02	33.34 ± 0.15	33	24.16 ± 0.26	24	22.77 ± 0.26	1.44 ± 0.03	1.65 ± 0.13
1998	1998-06-27	1998-07-03	7 days	0.14 ± 0.03	0.16	33.55 ± 1.85	37	23.79 ± 0.75	25	22.52 ± 1.15	1.95 ± 0.25	1.83 ± 0.24
	1998-07-05	1998-07-07	3 days	0.02 ± 0.00	0.02	34.96 ± 1.71	36	23.30 ± 0.66	24	22.94 ± 0.73	1.99 ± 0.36	1.81 ± 0.47
	1998-07-10	1998-07-31	22 days	1.41 ± 1.74	4.85	36.39 ± 1.54	39	24.31 ± 0.84	26	24.29 ± 0.95	1.78 ± 0.18	1.81 ± 0.21
	1998-08-05	1998-08-17	13 days	1.57 ± 1.47	4.03	35.15 ± 2.22	38	24.57 ± 0.50	25	24.72 ± 0.82	1.89 ± 0.34	1.75 ± 0.22
	1998-08-19	1998-08-27	9 days	2.84 ± 2.90	7.33	35.87 ± 1.67	38	24.76 ± 0.74	26	24.32 ± 0.60	1.71 ± 0.24	1.84 ± 0.32
	1998-08-31	1998-09-04	5 days	0.04 ± 0.00	0.04	33.24 ± 0.95	34	24.96 ± 0.62	26	23.86 ± 0.78	1.85 ± 0.16	1.94 ± 0.30
1999	1999-06-20	1999-06-23	4 days	0.07 ± 0.02	0.08	35.38 ± 1.57	37	22.47 ± 0.22	23	22.02 ± 0.44	1.75 ± 0.25	1.80 ± 0.20
	1999-06-29	1999-07-05	7 days	2.35 ± 2.40	5.25	37.12 ± 2.71	39	24.81 ± 1.63	26	24.18 ± 1.34	1.99 ± 0.37	1.74 ± 0.23
	1999-07-07	1999-07-25	19 days	1.99 ± 2.20	6.58	36.01 ± 2.69	40	24.56 ± 0.83	26	24.12 ± 0.88	1.82 ± 0.20	1.80 ± 0.24
	1999-07-29	1999-08-02	5 days	0.18 ± 0.06	0.22	33.64 ± 0.47	34	24.43 ± 0.38	25	23.83 ± 0.26	1.54 ± 0.09	1.74 ± 0.12
	1999-08-04	1999-08-10	7 days	0.43 ± 0.27	0.72	33.67 ± 1.17	35	26.11 ± 0.71	27	23.34 ± 0.81	1.85 ± 0.15	1.79 ± 0.21
	1999-08-13	1999-08-18	6 days	0.05 ± 0.02	0.08	35.35 ± 1.72	38	25.30 ± 1.02	27	23.97 ± 0.84	1.71 ± 0.34	1.74 ± 0.40
	1999-08-20	1999-08-30	11 days	0.99 ± 0.76	1.97	35.30 ± 1.86	39	25.57 ± 1.25	28	24.63 ± 0.78	1.98 ± 0.34	2.08 ± 0.47

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2000	2000-06-14	2000-06-19	6 days	1.13 ± 0.91	2.25	34.09 ± 1.27	36	22.46 ± 0.69	23	23.09 ± 1.23	2.15 ± 0.21	1.85 ± 0.38
	2000-06-24	2000-07-03	10 days	0.27 ± 0.12	0.44	36.06 ± 1.04	38	24.86 ± 1.50	27	23.28 ± 0.72	1.84 ± 0.33	1.90 ± 0.28
	2000-07-06	2000-07-08	3 days	0.10 ± 0.00	0.10	36.41 ± 1.83	38	25.73 ± 1.79	27	23.49 ± 0.94	1.49 ± 0.06	1.77 ± 0.11
	2000-07-14	2000-07-17	4 days	0.26 ± 0.12	0.32	36.60 ± 1.63	38	23.58 ± 0.83	24	22.81 ± 0.26	1.61 ± 0.12	1.80 ± 0.37
	2000-07-20	2000-07-22	3 days	0.10 ± 0.00	0.10	36.33 ± 2.52	39	23.70 ± 0.56	24	24.39 ± 0.67	1.91 ± 0.07	1.88 ± 0.33
	2000-07-29	2000-08-03	6 days	4.73 ± 3.86	8.73	37.80 ± 1.42	40	25.47 ± 1.11	26	24.62 ± 1.10	1.76 ± 0.22	1.77 ± 0.19
	2000-08-07	2000-08-10	4 days	0.04 ± 0.01	0.04	35.81 ± 1.40	37	23.16 ± 0.23	23	23.48 ± 1.10	1.61 ± 0.18	1.64 ± 0.14
	2000-08-13	2000-08-21	9 days	0.82 ± 0.75	1.89	35.94 ± 1.88	39	25.04 ± 1.35	28	24.51 ± 1.00	1.81 ± 0.16	1.78 ± 0.22
	2000-08-24	2000-08-26	3 days	0.74 ± 0.00	0.74	33.23 ± 0.19	33	26.12 ± 0.65	27	23.26 ± 0.60	1.81 ± 0.13	1.75 ± 0.10
	2000-09-08	2000-09-10	3 days	0.12 ± 0.00	0.12	34.19 ± 1.49	36	22.94 ± 0.39	23	23.14 ± 0.12	1.64 ± 0.16	1.77 ± 0.09
2001	2001-05-28	2001-06-02	6 days	0.08 ± 0.04	0.14	34.44 ± 0.52	35	21.95 ± 0.54	23	22.68 ± 0.44	1.56 ± 0.10	1.76 ± 0.16
	2001-06-19	2001-06-26	8 days	2.53 ± 2.64	5.96	37.17 ± 1.33	40	23.82 ± 1.74	26	24.01 ± 1.33	1.93 ± 0.27	1.65 ± 0.07
	2001-06-30	2001-07-03	4 days	0.86 ± 0.20	1.03	36.13 ± 1.65	38	23.18 ± 0.51	24	24.76 ± 0.65	1.91 ± 0.08	1.79 ± 0.19
	2001-07-10	2001-07-14	5 days	0.26 ± 0.13	0.38	35.82 ± 0.88	37	24.36 ± 0.67	25	23.88 ± 0.67	1.69 ± 0.08	1.73 ± 0.14
	2001-07-22	2001-08-13	23 days	1.12 ± 2.04	6.36	35.11 ± 1.45	38	25.11 ± 1.31	29	24.31 ± 0.96	1.80 ± 0.25	1.82 ± 0.20
	2001-08-18	2001-08-30	13 days	0.91 ± 0.84	2.09	34.35 ± 1.93	38	24.92 ± 0.77	26	24.14 ± 1.14	1.97 ± 0.25	1.84 ± 0.31
	2001-09-06	2001-09-09	4 days	0.12 ± 0.00	0.12	31.86 ± 1.61	33	23.77 ± 0.26	24	21.25 ± 0.41	1.60 ± 0.09	1.87 ± 0.20
	2001-09-27	2001-09-30	4 days	0.12 ± 0.00	0.12	26.71 ± 0.25	27	23.84 ± 0.27	24	18.81 ± 0.40	1.64 ± 0.07	1.90 ± 0.22
	2001-10-05	2001-10-07	3 days	0.02 ± 0.00	0.02	27.87 ± 0.98	29	23.94 ± 0.60	25	18.94 ± 0.75	1.58 ± 0.09	2.01 ± 0.46
	2001-10-25	2001-10-27	3 days	0.10 ± 0.00	0.10	27.30 ± 0.73	28	23.65 ± 0.08	24	15.98 ± 0.42	1.77 ± 0.37	1.78 ± 0.07
2002	2002-06-14	2002-06-27	14 days	0.18 ± 0.14	0.44	35.30 ± 2.16	39	22.68 ± 1.04	24	23.29 ± 0.85	2.03 ± 0.35	1.75 ± 0.23
	2002-07-17	2002-07-30	14 days	0.93 ± 1.36	3.52	35.46 ± 1.71	38	23.74 ± 0.70	25	23.73 ± 0.94	1.73 ± 0.12	1.69 ± 0.20
	2002-08-16	2002-08-21	6 days	0.12 ± 0.00	0.12	33.51 ± 0.66	35	24.11 ± 0.61	25	23.56 ± 0.24	2.03 ± 0.20	1.60 ± 0.16
	2002-10-05	2002-10-07	3 days	0.18 ± 0.00	0.18	27.29 ± 0.77	28	24.59 ± 0.28	25	18.03 ± 0.69	2.08 ± 0.48	2.33 ± 0.44
2003	2003-06-10	2003-06-16	7 days	0.52 ± 0.40	0.95	35.61 ± 1.06	37	24.21 ± 1.41	26	24.39 ± 0.92	1.88 ± 0.21	1.77 ± 0.33
	2003-06-18	2003-07-01	14 days	0.94 ± 0.84	2.58	35.33 ± 1.55	38	24.59 ± 0.80	26	23.95 ± 1.22	1.81 ± 0.25	1.83 ± 0.23
	2003-07-06	2003-08-30	56 days	8.13 ± 10.53	31.62	36.23 ± 2.49	42	26.37 ± 0.91	28	25.01 ± 1.52	1.96 ± 0.28	1.78 ± 0.19
	2003-09-01	2003-09-03	3 days	0.26 ± 0.00	0.26	31.88 ± 1.66	34	25.01 ± 0.28	25	20.92 ± 0.49	1.84 ± 0.30	2.12 ± 0.34
	2003-09-20	2003-09-22	3 days	0.12 ± 0.00	0.12	29.21 ± 1.21	31	23.54 ± 0.13	24	21.49 ± 0.40	1.70 ± 0.08	1.70 ± 0.12
2004	2004-06-24	2004-07-05	12 days	2.75 ± 3.73	8.75	37.17 ± 2.11	40	24.09 ± 0.76	25	24.41 ± 1.04	1.72 ± 0.16	1.68 ± 0.22
	2004-07-21	2004-09-03	45 days	3.74 ± 7.08	29.62	34.71 ± 2.59	41	25.88 ± 1.31	30	23.83 ± 1.45	2.10 ± 0.53	2.22 ± 0.80
	2004-09-08	2004-09-12	5 days	0.18 ± 0.12	0.30	32.46 ± 0.57	33	25.23 ± 0.56	26	23.17 ± 0.45	1.61 ± 0.07	1.97 ± 0.27
2005	2005-06-06	2005-06-09	4 days	0.20 ± 0.08	0.24	35.68 ± 1.18	37	22.00 ± 1.04	23	22.18 ± 0.22	1.62 ± 0.07	1.73 ± 0.09
	2005-06-16	2005-07-30	45 days	1.60 ± 2.62	10.95	35.68 ± 1.86	40	24.69 ± 1.06	28	24.17 ± 1.02	1.80 ± 0.19	1.81 ± 0.23
	2005-08-03	2005-08-09	7 days	1.28 ± 1.10	2.56	37.70 ± 2.24	40	24.54 ± 1.29	26	24.59 ± 1.23	1.79 ± 0.23	1.79 ± 0.35
	2005-08-12	2005-08-18	7 days	0.37 ± 0.34	0.78	35.66 ± 2.26	39	24.73 ± 0.82	26	24.18 ± 0.54	1.76 ± 0.32	1.73 ± 0.24
	2005-08-27	2005-08-31	5 days	0.05 ± 0.02	0.06	35.41 ± 1.38	36	23.87 ± 0.66	25	23.84 ± 0.63	1.74 ± 0.26	1.71 ± 0.26
	2005-09-02	2005-09-08	7 days	1.13 ± 1.26	2.48	32.18 ± 3.91	36	25.00 ± 1.33	27	21.93 ± 2.47	2.31 ± 0.79	2.46 ± 1.08

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2006	2006-06-21	2006-06-24	4 days	0.20 ± 0.03	0.22	35.22 ± 2.32	38	23.43 ± 0.44	24	23.66 ± 0.59	2.05 ± 0.27	1.96 ± 0.24
	2006-06-26	2006-07-05	10 days	0.46 ± 0.30	0.85	33.29 ± 1.29	35	23.74 ± 0.58	25	22.95 ± 0.84	1.83 ± 0.20	1.76 ± 0.14
	2006-07-07	2006-08-12	37 days	5.62 ± 4.48	14.93	37.27 ± 1.38	40	25.56 ± 1.07	29	25.21 ± 1.02	1.84 ± 0.24	1.84 ± 0.22
	2006-08-26	2006-09-12	18 days	0.65 ± 0.80	2.39	35.78 ± 2.78	40	24.28 ± 1.03	26	23.71 ± 1.08	2.06 ± 0.61	2.01 ± 0.64
2007	2007-07-06	2007-07-15	10 days	0.12 ± 0.10	0.28	36.10 ± 0.97	37	23.15 ± 0.62	24	23.16 ± 1.12	1.66 ± 0.23	1.76 ± 0.23
	2007-07-17	2007-07-19	3 days	0.16 ± 0.00	0.16	35.13 ± 0.55	36	24.21 ± 0.14	24	22.88 ± 0.49	2.00 ± 0.16	1.95 ± 0.17
	2007-07-25	2007-08-06	13 days	1.37 ± 1.85	4.67	37.86 ± 2.55	41	24.94 ± 1.42	27	24.96 ± 0.99	2.07 ± 0.42	2.18 ± 0.76
	2007-08-26	2007-08-29	4 days	1.91 ± 1.09	2.46	35.80 ± 0.95	37	24.68 ± 0.80	26	24.64 ± 0.98	2.25 ± 0.37	1.98 ± 0.30
2008	2008-06-20	2008-07-02	13 days	0.57 ± 0.57	1.57	36.11 ± 1.59	38	23.13 ± 0.91	24	23.83 ± 0.64	1.90 ± 0.31	1.70 ± 0.21
	2008-07-09	2008-07-11	3 days	0.08 ± 0.00	0.08	35.39 ± 0.55	36	23.95 ± 0.61	25	23.55 ± 0.40	1.99 ± 0.31	1.78 ± 0.29
	2008-07-17	2008-08-08	23 days	2.03 ± 4.26	13.14	36.26 ± 1.40	39	24.67 ± 0.84	26	24.38 ± 0.91	1.84 ± 0.26	1.81 ± 0.25
	2008-08-10	2008-08-14	5 days	0.08 ± 0.05	0.14	35.44 ± 1.39	37	25.48 ± 0.69	26	23.44 ± 1.10	2.02 ± 0.71	1.60 ± 0.17
	2008-08-27	2008-08-29	3 days	0.02 ± 0.00	0.02	34.49 ± 0.79	35	23.33 ± 0.68	24	23.67 ± 0.07	1.49 ± 0.12	1.87 ± 0.13
	2008-09-02	2008-09-04	3 days	0.06 ± 0.00	0.06	32.17 ± 1.74	34	24.14 ± 0.92	25	21.86 ± 0.48	2.07 ± 0.08	1.85 ± 0.33
2009	2009-06-13	2009-06-22	10 days	0.23 ± 0.20	0.54	35.87 ± 1.49	38	24.23 ± 1.08	26	23.69 ± 0.99	1.78 ± 0.25	1.80 ± 0.13
	2009-06-28	2009-07-07	10 days	1.03 ± 0.77	2.01	35.59 ± 1.53	37	24.59 ± 1.33	27	24.14 ± 1.17	2.01 ± 0.30	1.76 ± 0.23
	2009-07-11	2009-07-16	6 days	0.04 ± 0.01	0.06	35.59 ± 0.82	37	24.89 ± 0.86	26	23.92 ± 0.60	1.92 ± 0.21	1.88 ± 0.39
	2009-07-21	2009-08-02	13 days	1.74 ± 0.75	2.58	37.23 ± 1.58	39	26.00 ± 1.20	27	24.48 ± 0.87	2.46 ± 0.47	2.35 ± 0.95
	2009-08-04	2009-08-09	6 days	0.06 ± 0.02	0.08	34.75 ± 1.81	37	24.91 ± 0.45	26	23.74 ± 1.11	2.10 ± 0.39	1.93 ± 0.37
	2009-08-11	2009-09-03	24 days	0.99 ± 1.31	4.25	35.68 ± 1.76	38	24.82 ± 0.56	26	24.50 ± 0.94	1.78 ± 0.17	1.80 ± 0.26
2010	2010-06-27	2010-07-21	25 days	2.41 ± 3.40	12.07	35.99 ± 2.02	39	24.42 ± 1.37	26	24.46 ± 1.03	1.83 ± 0.16	1.82 ± 0.17
	2010-07-24	2010-08-13	21 days	4.17 ± 4.65	11.19	36.99 ± 1.49	39	25.36 ± 1.14	28	24.24 ± 1.01	1.72 ± 0.20	1.76 ± 0.26
	2010-08-20	2010-08-31	12 days	0.87 ± 0.67	1.87	37.03 ± 1.61	40	25.44 ± 0.87	27	24.67 ± 1.20	1.97 ± 0.42	2.18 ± 0.84
	2010-09-14	2010-09-16	3 days	1.17 ± 0.00	1.17	32.26 ± 3.05	35	24.49 ± 0.61	25	22.21 ± 0.24	2.26 ± 0.54	2.22 ± 0.47
2011	2011-06-25	2011-06-30	6 days	3.84 ± 2.50	6.48	37.56 ± 0.71	39	24.16 ± 0.77	25	24.42 ± 1.36	1.69 ± 0.22	1.68 ± 0.26
	2011-07-09	2011-07-11	3 days	0.12 ± 0.00	0.12	34.86 ± 0.31	35	24.63 ± 0.52	25	23.61 ± 0.37	2.03 ± 0.24	1.79 ± 0.24
	2011-07-13	2011-07-16	4 days	0.02 ± 0.00	0.02	34.35 ± 1.39	35	24.44 ± 0.78	26	22.30 ± 1.28	1.43 ± 0.04	1.71 ± 0.16
	2011-07-25	2011-08-01	8 days	0.21 ± 0.15	0.40	35.81 ± 1.19	38	24.10 ± 0.78	25	23.51 ± 0.41	1.67 ± 0.14	1.73 ± 0.19
	2011-08-04	2011-08-26	23 days	1.04 ± 1.63	5.78	36.03 ± 1.58	39	25.26 ± 0.90	28	24.31 ± 1.11	1.96 ± 0.43	1.79 ± 0.23
	2011-08-31	2011-09-03	4 days	0.10 ± 0.04	0.12	30.82 ± 2.45	33	24.96 ± 0.76	26	21.49 ± 0.93	1.84 ± 0.14	1.70 ± 0.06
2012	2012-06-22	2012-06-30	9 days	7.58 ± 7.31	17.77	38.03 ± 1.82	41	25.04 ± 1.51	27	24.59 ± 1.89	1.79 ± 0.23	1.71 ± 0.20
	2012-07-13	2012-08-05	24 days	1.40 ± 2.46	7.63	36.62 ± 2.05	39	25.02 ± 1.15	28	24.11 ± 0.82	1.92 ± 0.28	1.78 ± 0.20
	2012-08-08	2012-08-25	18 days	10.63 ± 9.57	25.76	37.95 ± 2.18	42	26.16 ± 0.86	28	25.60 ± 1.52	2.08 ± 0.29	1.85 ± 0.22
	2012-08-27	2012-08-29	3 days	0.10 ± 0.00	0.10	34.18 ± 0.57	35	25.53 ± 0.20	26	23.72 ± 0.24	1.84 ± 0.09	2.00 ± 0.48
	2012-09-18	2012-09-20	3 days	0.30 ± 0.00	0.30	30.78 ± 0.27	31	24.20 ± 0.06	24	21.53 ± 0.46	2.02 ± 0.19	1.77 ± 0.32
	2012-09-23	2012-09-27	5 days	1.33 ± 0.47	1.65	28.67 ± 2.40	33	24.30 ± 0.37	25	18.80 ± 2.47	1.93 ± 0.14	2.01 ± 0.14

Table B.3: Summary statistics for heat wave episodes identified by temperature using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2013	2013-06-25	2013-07-01	7 days	0.07 ± 0.01	0.08	35.02 ± 1.15	36	22.15 ± 0.85	23	21.45 ± 0.85	1.60 ± 0.15	1.83 ± 0.14
	2013-07-03	2013-07-13	11 days	8.08 ± 5.90	14.81	37.47 ± 2.10	40	24.28 ± 1.14	26	24.80 ± 0.64	2.02 ± 0.22	1.79 ± 0.12
	2013-07-15	2013-08-06	23 days	0.89 ± 0.83	2.64	35.19 ± 1.53	39	24.87 ± 0.91	27	24.41 ± 0.77	1.78 ± 0.15	1.77 ± 0.19
	2013-08-08	2013-08-24	17 days	1.69 ± 1.61	5.35	36.70 ± 1.42	39	25.03 ± 1.07	27	24.37 ± 0.82	2.15 ± 0.60	2.18 ± 0.75
2014	2014-06-12	2014-06-15	4 days	0.22 ± 0.13	0.28	35.85 ± 1.58	38	23.60 ± 1.67	26	23.47 ± 1.14	1.73 ± 0.16	1.72 ± 0.22
	2014-07-04	2014-07-06	3 days	0.04 ± 0.00	0.04	32.53 ± 0.74	33	23.53 ± 0.63	24	22.11 ± 0.67	1.79 ± 0.06	1.70 ± 0.31
	2014-07-14	2014-07-20	7 days	1.88 ± 1.70	3.84	36.77 ± 2.53	40	24.83 ± 1.44	27	24.30 ± 1.42	1.94 ± 0.20	1.84 ± 0.35
	2014-07-23	2014-07-28	6 days	0.31 ± 0.20	0.50	35.90 ± 0.81	37	24.36 ± 0.88	25	24.48 ± 0.29	1.77 ± 0.17	1.63 ± 0.13
	2014-08-06	2014-08-11	6 days	0.06 ± 0.03	0.10	35.76 ± 1.06	37	25.26 ± 0.68	26	24.48 ± 0.29	1.93 ± 0.27	2.05 ± 0.41
	2014-08-26	2014-08-29	4 days	0.10 ± 0.05	0.14	36.31 ± 0.77	37	24.36 ± 0.48	25	24.47 ± 0.53	1.89 ± 0.26	1.74 ± 0.20
	2014-08-31	2014-09-03	4 days	0.17 ± 0.09	0.22	36.10 ± 0.97	37	24.21 ± 0.69	25	24.22 ± 0.40	1.71 ± 0.20	1.64 ± 0.12
	2014-09-10	2014-09-13	4 days	0.02 ± 0.00	0.02	32.76 ± 1.07	34	24.89 ± 0.89	26	22.89 ± 0.14	1.85 ± 0.16	1.70 ± 0.12
	2014-10-22	2014-10-25	4 days	1.19 ± 0.76	1.57	28.96 ± 2.01	32	24.52 ± 1.00	26	18.32 ± 0.92	2.83 ± 0.75	2.09 ± 0.66
2015	2015-06-06	2015-06-08	3 days	0.04 ± 0.00	0.04	33.74 ± 0.31	34	22.52 ± 0.69	23	22.87 ± 0.50	1.44 ± 0.05	1.65 ± 0.12
	2015-06-19	2015-06-24	6 days	0.06 ± 0.03	0.10	34.48 ± 1.61	37	22.87 ± 1.15	25	22.88 ± 0.67	1.81 ± 0.28	1.76 ± 0.28
	2015-06-26	2015-07-30	35 days	12.88 ± 7.96	29.82	38.28 ± 1.44	41	25.97 ± 1.16	29	25.98 ± 0.80	1.85 ± 0.18	1.80 ± 0.20
	2015-08-02	2015-08-14	13 days	4.59 ± 2.65	8.39	36.35 ± 1.50	38	27.26 ± 1.11	29	24.88 ± 1.22	1.89 ± 0.35	2.22 ± 0.51
	2015-08-27	2015-08-31	5 days	0.74 ± 0.45	1.13	34.76 ± 2.31	37	24.89 ± 1.21	26	24.67 ± 0.76	2.28 ± 0.41	1.88 ± 0.27
	2015-09-06	2015-09-09	4 days	0.12 ± 0.00	0.12	29.84 ± 0.80	31	24.14 ± 0.19	24	19.73 ± 0.31	1.94 ± 0.38	2.17 ± 0.16
	2015-09-11	2015-09-16	6 days	0.32 ± 0.24	0.54	29.42 ± 0.80	31	24.24 ± 0.34	25	20.25 ± 0.95	1.90 ± 0.27	2.00 ± 0.29
	2015-09-22	2015-09-25	4 days	1.45 ± 0.36	1.63	30.56 ± 2.32	34	24.73 ± 0.01	25	19.30 ± 0.67	2.18 ± 0.63	2.23 ± 0.16
	2015-10-02	2015-10-07	6 days	1.65 ± 1.02	2.46	28.84 ± 1.24	30	24.92 ± 1.22	27	18.91 ± 1.54	2.45 ± 0.75	2.37 ± 0.77
2016	2016-06-21	2016-06-23	3 days	0.06 ± 0.00	0.06	35.66 ± 0.53	36	21.78 ± 0.23	22	23.68 ± 0.42	1.62 ± 0.19	1.84 ± 0.19
	2016-06-27	2016-08-09	44 days	2.94 ± 3.31	11.73	37.00 ± 1.51	40	24.74 ± 1.28	28	24.65 ± 1.09	1.72 ± 0.22	1.77 ± 0.27
	2016-08-11	2016-08-20	10 days	0.15 ± 0.08	0.28	35.48 ± 1.19	37	24.29 ± 1.04	26	23.88 ± 0.75	1.77 ± 0.21	1.70 ± 0.11
	2016-08-22	2016-09-13	23 days	2.37 ± 3.82	11.91	35.81 ± 2.65	41	24.37 ± 0.86	26	24.39 ± 1.26	2.06 ± 0.35	1.78 ± 0.33
2017	2017-06-10	2017-06-27	18 days	12.12 ± 9.88	30.41	37.28 ± 1.61	40	25.42 ± 1.40	28	25.40 ± 1.09	1.88 ± 0.28	1.87 ± 0.16
	2017-07-04	2017-07-19	16 days	5.09 ± 6.31	16.50	36.68 ± 3.63	43	25.07 ± 1.22	28	24.79 ± 1.38	2.06 ± 0.32	2.00 ± 0.30
	2017-07-21	2017-08-09	20 days	5.08 ± 5.53	19.00	36.72 ± 2.13	41	26.34 ± 1.23	29	24.76 ± 1.52	1.86 ± 0.22	1.91 ± 0.27
	2017-08-13	2017-08-30	18 days	2.98 ± 3.34	8.19	35.69 ± 2.28	39	25.18 ± 0.76	26	24.41 ± 1.28	1.80 ± 0.17	1.76 ± 0.20
	2017-10-13	2017-10-16	4 days	1.28 ± 0.54	1.63	30.98 ± 1.55	32	25.41 ± 1.28	27	20.52 ± 0.67	2.88 ± 0.55	2.71 ± 1.02
	2017-10-26	2017-10-28	3 days	0.28 ± 0.00	0.28	28.41 ± 0.34	29	24.74 ± 1.09	26	17.75 ± 0.56	2.37 ± 0.73	2.47 ± 0.82
2018	2018-06-17	2018-07-04	18 days	0.32 ± 0.40	1.25	34.26 ± 1.85	38	23.58 ± 0.94	25	23.18 ± 0.69	1.88 ± 0.29	1.80 ± 0.29
	2018-07-07	2018-07-15	9 days	0.57 ± 0.35	1.05	34.86 ± 0.78	36	25.00 ± 0.66	26	24.19 ± 0.67	1.67 ± 0.14	1.68 ± 0.15
	2018-07-17	2018-07-20	4 days	0.17 ± 0.08	0.22	34.66 ± 1.23	36	25.27 ± 0.89	27	23.91 ± 0.39	1.66 ± 0.09	1.80 ± 0.20
	2018-07-22	2018-08-09	19 days	11.13 ± 14.04	36.63	37.01 ± 2.75	42	26.03 ± 1.53	29	25.40 ± 1.63	1.80 ± 0.24	1.78 ± 0.16
	2018-08-11	2018-08-14	4 days	0.17 ± 0.10	0.22	34.95 ± 0.86	36	26.41 ± 0.30	27	24.56 ± 0.64	1.74 ± 0.28	1.60 ± 0.10
	2018-08-18	2018-08-25	8 days	0.27 ± 0.19	0.54	34.86 ± 0.79	36	25.07 ± 0.47	26	23.84 ± 0.77	1.69 ± 0.13	1.65 ± 0.11
	2018-08-31	2018-09-02	3 days	0.12 ± 0.00	0.12	36.15 ± 0.38	36	24.78 ± 0.29	25	24.20 ± 0.41	1.69 ± 0.07	1.96 ± 0.25

Abbreviations [a] Magnitude Index

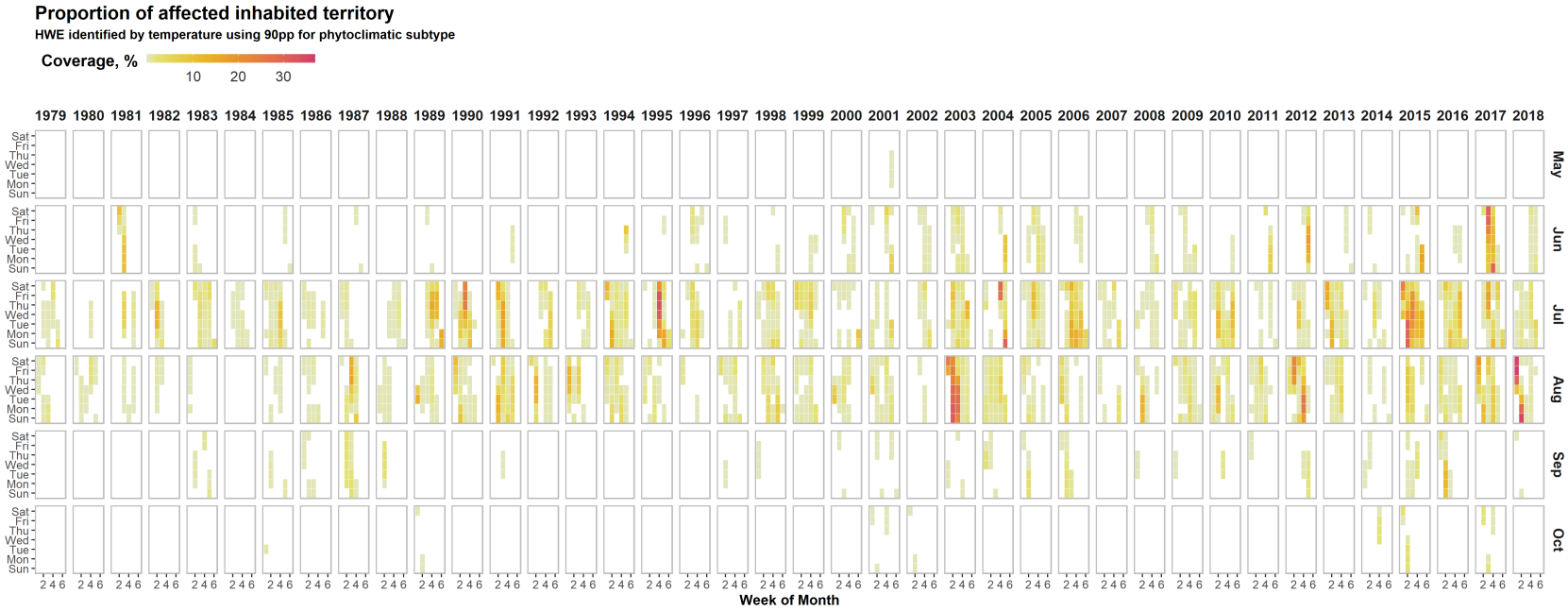


Figure B.9: Proportion of national territory affected by heatwaves identified using temperature (90pp for phytoclimatic subtype)

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1979	1979-07-16	1979-07-19	4 days	0.13 ± 0.02	0.14	35.64 ± 1.87	37	22.76 ± 0.40	23	23.61 ± 0.99	1.55 ± 0.02	1.81 ± 0.12
	1979-07-25	1979-08-09	16 days	0.52 ± 0.54	1.53	35.91 ± 1.71	39	24.12 ± 0.87	26	24.00 ± 0.94	1.62 ± 0.11	1.87 ± 0.24
	1979-08-11	1979-08-15	5 days	0.24 ± 0.16	0.40	36.61 ± 1.12	38	23.73 ± 0.67	24	23.75 ± 1.17	1.67 ± 0.05	1.67 ± 0.12
1980	1980-07-22	1980-07-25	4 days	0.16 ± 0.10	0.22	37.01 ± 1.06	39	23.42 ± 0.63	24	23.88 ± 0.77	1.78 ± 0.12	1.78 ± 0.33
	1980-08-02	1980-08-07	6 days	0.32 ± 0.13	0.50	36.19 ± 1.26	38	24.32 ± 0.83	26	24.55 ± 0.36	1.64 ± 0.10	1.96 ± 0.15
	1980-08-09	1980-08-12	4 days	0.04 ± 0.01	0.04	35.47 ± 0.76	36	23.23 ± 0.54	24	23.73 ± 0.56	1.57 ± 0.16	1.83 ± 0.26
	1980-08-20	1980-08-24	5 days	0.20 ± 0.09	0.28	36.45 ± 1.85	38	26.16 ± 1.67	28	25.01 ± 1.14	1.59 ± 0.19	2.43 ± 0.50
	1980-08-29	1980-08-31	3 days	0.02 ± 0.00	0.02	36.36 ± 0.99	37	23.67 ± 0.43	24	23.89 ± 0.74	1.62 ± 0.16	1.65 ± 0.04
1981	1981-06-10	1981-06-19	10 days	4.84 ± 4.38	9.68	38.29 ± 1.82	41	24.16 ± 2.00	28	23.55 ± 1.63	1.74 ± 0.26	1.73 ± 0.19
	1981-07-13	1981-07-17	5 days	4.23 ± 1.98	5.53	37.51 ± 0.96	38	24.67 ± 0.95	26	23.30 ± 0.41	1.80 ± 0.18	1.72 ± 0.17
	1981-07-27	1981-07-31	5 days	0.37 ± 0.26	0.62	37.44 ± 2.95	40	24.43 ± 1.89	27	24.24 ± 1.46	1.61 ± 0.20	2.19 ± 0.61
1982	1982-07-05	1982-07-14	10 days	4.82 ± 5.03	12.10	36.17 ± 2.53	40	25.23 ± 1.02	27	24.48 ± 1.81	1.68 ± 0.24	2.11 ± 0.37
	1982-07-16	1982-07-28	13 days	0.07 ± 0.06	0.16	34.26 ± 1.51	38	24.88 ± 0.68	26	23.03 ± 0.49	1.55 ± 0.15	1.90 ± 0.24
	1982-08-12	1982-08-14	3 days	0.02 ± 0.00	0.02	34.94 ± 1.07	36	23.85 ± 1.03	25	23.96 ± 0.26	1.50 ± 0.13	1.67 ± 0.15
	1982-08-17	1982-08-20	4 days	0.13 ± 0.04	0.16	36.89 ± 2.01	39	24.88 ± 1.43	27	24.28 ± 0.45	1.67 ± 0.22	2.27 ± 0.51
1983	1983-06-10	1983-06-13	4 days	0.24 ± 0.03	0.26	36.03 ± 0.48	36	23.75 ± 1.52	25	23.11 ± 0.89	1.70 ± 0.08	1.98 ± 0.31
	1983-07-08	1983-08-01	25 days	1.33 ± 0.93	3.00	34.25 ± 1.78	37	24.83 ± 1.55	28	23.86 ± 0.88	1.66 ± 0.20	1.97 ± 0.26
	1983-09-05	1983-09-08	4 days	0.54 ± 0.32	0.72	35.88 ± 1.02	37	24.25 ± 0.89	25	23.35 ± 0.38	1.48 ± 0.09	1.83 ± 0.33
	1983-09-23	1983-09-27	5 days	0.13 ± 0.09	0.22	34.11 ± 1.11	36	24.23 ± 1.39	26	23.38 ± 0.95	1.87 ± 0.25	2.17 ± 0.51
	1983-10-11	1983-10-15	5 days	0.05 ± 0.03	0.08	27.40 ± 0.62	28	24.48 ± 0.37	25	17.91 ± 1.12	1.63 ± 0.17	2.41 ± 0.41
1984	1984-07-08	1984-07-11	4 days	0.04 ± 0.00	0.04	36.05 ± 0.60	37	23.25 ± 1.25	25	23.17 ± 0.58	1.57 ± 0.17	2.01 ± 0.42
	1984-07-19	1984-07-26	8 days	0.60 ± 0.61	1.35	36.55 ± 1.46	39	23.95 ± 1.13	25	24.34 ± 0.94	1.69 ± 0.19	1.85 ± 0.27
1985	1985-07-06	1985-07-15	10 days	0.23 ± 0.25	0.62	35.90 ± 1.39	38	23.67 ± 0.46	24	24.18 ± 0.71	1.54 ± 0.15	1.85 ± 0.24
	1985-07-20	1985-07-28	9 days	3.70 ± 3.51	8.27	36.50 ± 2.42	40	23.96 ± 0.40	25	24.46 ± 1.27	1.69 ± 0.12	1.74 ± 0.17
	1985-08-03	1985-08-05	3 days	0.16 ± 0.00	0.16	37.93 ± 1.99	40	24.93 ± 1.86	27	24.66 ± 0.35	1.66 ± 0.12	2.05 ± 0.36
	1985-08-11	1985-08-14	4 days	0.04 ± 0.00	0.04	32.71 ± 0.81	34	23.48 ± 0.34	24	22.51 ± 0.61	1.61 ± 0.11	1.58 ± 0.23
	1985-08-18	1985-08-23	6 days	0.16 ± 0.09	0.22	36.15 ± 0.93	37	23.95 ± 0.59	25	24.27 ± 0.40	1.53 ± 0.08	1.89 ± 0.27
	1985-09-29	1985-10-01	3 days	0.32 ± 0.00	0.32	30.72 ± 1.18	32	24.26 ± 0.21	24	21.99 ± 0.33	1.68 ± 0.23	2.13 ± 0.14
1986	1986-06-26	1986-06-28	3 days	0.04 ± 0.00	0.04	35.02 ± 0.54	35	22.90 ± 0.51	23	23.34 ± 0.15	1.92 ± 0.25	1.52 ± 0.10
	1986-07-04	1986-07-06	3 days	0.46 ± 0.00	0.46	36.62 ± 0.25	37	23.98 ± 0.91	25	24.38 ± 0.48	1.64 ± 0.10	1.74 ± 0.16
	1986-07-16	1986-07-18	3 days	0.04 ± 0.00	0.04	37.56 ± 1.08	38	22.82 ± 0.10	23	23.44 ± 0.36	1.76 ± 0.38	1.84 ± 0.26
	1986-07-28	1986-08-04	8 days	0.25 ± 0.16	0.52	35.19 ± 1.67	38	24.27 ± 1.00	26	23.94 ± 0.96	1.61 ± 0.13	1.89 ± 0.22
	1986-08-13	1986-08-18	6 days	1.16 ± 0.97	2.13	34.42 ± 0.91	36	25.14 ± 0.78	26	23.92 ± 0.76	1.65 ± 0.10	1.86 ± 0.25
	1986-08-21	1986-08-23	3 days	0.04 ± 0.00	0.04	37.22 ± 1.48	39	25.24 ± 0.59	26	23.80 ± 0.67	1.87 ± 0.32	1.97 ± 0.36
	1986-09-06	1986-09-08	3 days	0.02 ± 0.00	0.02	31.02 ± 1.49	32	24.31 ± 0.72	25	21.99 ± 0.58	1.83 ± 0.28	2.44 ± 0.65

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1987	1987-07-08	1987-07-11	4 days	1.25 ± 0.76	1.63	35.05 ± 1.16	37	23.98 ± 0.40	25	24.14 ± 0.36	1.47 ± 0.08	1.73 ± 0.16
	1987-08-01	1987-08-04	4 days	0.06 ± 0.03	0.08	37.28 ± 1.42	38	23.66 ± 0.74	25	23.68 ± 1.25	1.76 ± 0.21	1.83 ± 0.44
	1987-08-11	1987-08-23	13 days	6.10 ± 6.13	16.50	36.52 ± 1.98	40	25.15 ± 0.62	26	25.34 ± 1.05	1.75 ± 0.23	1.93 ± 0.22
	1987-09-07	1987-09-19	13 days	1.47 ± 0.82	2.31	34.79 ± 1.71	37	25.22 ± 0.64	26	23.71 ± 0.58	2.04 ± 0.28	2.55 ± 0.55
	1987-09-21	1987-09-23	3 days	0.02 ± 0.00	0.02	30.33 ± 0.62	31	24.58 ± 0.04	25	21.58 ± 0.45	1.56 ± 0.04	1.78 ± 0.31
1988	1988-07-10	1988-07-14	5 days	0.18 ± 0.10	0.24	36.09 ± 0.58	37	23.71 ± 1.05	26	23.53 ± 0.70	1.68 ± 0.17	1.98 ± 0.24
	1988-07-21	1988-07-29	9 days	0.72 ± 0.69	1.75	36.10 ± 1.64	38	23.95 ± 0.44	25	24.25 ± 0.59	1.60 ± 0.12	1.88 ± 0.28
	1988-08-01	1988-08-04	4 days	0.36 ± 0.23	0.48	37.94 ± 2.28	40	25.28 ± 0.95	26	24.01 ± 1.79	1.60 ± 0.16	1.78 ± 0.12
	1988-08-08	1988-08-21	14 days	0.19 ± 0.12	0.36	33.99 ± 1.04	36	24.77 ± 0.68	26	23.77 ± 0.83	1.64 ± 0.11	1.79 ± 0.22
	1988-09-05	1988-09-09	5 days	2.47 ± 1.59	3.78	37.25 ± 0.68	38	24.89 ± 0.86	26	24.78 ± 0.91	1.67 ± 0.16	1.74 ± 0.25
1989	1989-07-01	1989-07-03	3 days	0.20 ± 0.00	0.20	35.68 ± 1.17	37	24.93 ± 0.21	25	23.88 ± 0.36	1.64 ± 0.22	1.90 ± 0.07
	1989-07-11	1989-08-02	23 days	6.26 ± 5.59	18.07	37.04 ± 1.62	40	25.20 ± 1.18	28	25.05 ± 1.02	1.72 ± 0.16	1.78 ± 0.22
	1989-08-08	1989-08-17	10 days	0.64 ± 0.48	1.27	34.13 ± 0.70	35	25.41 ± 0.46	26	24.29 ± 0.49	1.80 ± 0.21	1.71 ± 0.26
	1989-08-20	1989-08-29	10 days	0.53 ± 0.65	1.53	34.73 ± 1.20	36	25.99 ± 0.60	27	24.44 ± 1.07	1.55 ± 0.12	2.38 ± 0.54
	1989-10-07	1989-10-09	3 days	0.12 ± 0.00	0.12	28.77 ± 2.04	30	24.65 ± 0.72	25	17.85 ± 1.22	2.21 ± 0.65	2.45 ± 0.57
1990	1990-07-08	1990-07-12	5 days	3.50 ± 2.42	5.33	36.90 ± 1.67	39	24.45 ± 0.67	25	23.81 ± 0.42	1.67 ± 0.24	1.74 ± 0.07
	1990-07-16	1990-07-27	12 days	10.54 ± 10.53	26.61	36.76 ± 1.62	39	25.39 ± 1.21	28	25.35 ± 1.19	1.72 ± 0.15	1.80 ± 0.17
	1990-07-31	1990-08-14	15 days	2.45 ± 2.66	7.10	35.53 ± 1.85	39	24.80 ± 0.78	26	24.58 ± 1.13	1.66 ± 0.20	2.06 ± 0.61
	1990-08-19	1990-08-22	4 days	0.24 ± 0.12	0.30	32.53 ± 0.99	34	24.39 ± 0.33	25	23.82 ± 0.38	1.63 ± 0.13	1.74 ± 0.20
	1990-08-25	1990-08-28	4 days	0.35 ± 0.14	0.42	32.77 ± 0.51	33	24.74 ± 0.37	25	23.04 ± 0.45	1.67 ± 0.11	2.24 ± 0.73
1991	1991-06-24	1991-06-26	3 days	0.08 ± 0.00	0.08	36.76 ± 0.52	37	23.21 ± 1.39	24	23.92 ± 0.46	1.56 ± 0.07	1.63 ± 0.17
	1991-07-09	1991-07-26	18 days	7.91 ± 7.46	18.92	37.14 ± 2.61	41	25.50 ± 1.56	29	24.79 ± 1.00	1.79 ± 0.23	1.84 ± 0.23
	1991-08-02	1991-08-08	7 days	7.01 ± 6.66	14.47	37.45 ± 1.20	39	25.13 ± 1.00	26	24.90 ± 1.32	1.84 ± 0.25	1.73 ± 0.13
	1991-08-12	1991-08-30	19 days	3.71 ± 3.20	10.32	35.68 ± 2.06	41	25.56 ± 1.16	27	24.72 ± 0.95	1.71 ± 0.18	1.89 ± 0.26
1992	1992-07-17	1992-07-20	4 days	2.29 ± 1.45	3.02	35.38 ± 0.93	36	23.04 ± 0.45	24	24.41 ± 0.47	1.58 ± 0.07	1.76 ± 0.23
	1992-07-25	1992-08-07	14 days	5.91 ± 3.85	12.78	35.88 ± 1.53	38	25.28 ± 0.85	27	25.38 ± 0.66	1.59 ± 0.11	1.89 ± 0.18
	1992-08-17	1992-08-19	3 days	0.14 ± 0.00	0.14	35.36 ± 1.76	37	24.67 ± 1.05	26	24.98 ± 0.50	1.68 ± 0.22	1.65 ± 0.26
	1992-08-22	1992-08-28	7 days	0.35 ± 0.29	0.76	34.96 ± 2.08	38	25.34 ± 0.37	26	23.99 ± 1.15	1.70 ± 0.27	1.73 ± 0.23
1993	1993-07-14	1993-07-20	7 days	0.28 ± 0.15	0.50	35.34 ± 0.80	36	23.28 ± 0.93	24	23.28 ± 1.05	1.60 ± 0.08	1.82 ± 0.24
	1993-07-24	1993-07-30	7 days	0.50 ± 0.49	1.11	36.57 ± 1.69	39	24.04 ± 1.45	27	24.10 ± 1.21	1.76 ± 0.25	1.90 ± 0.43
	1993-08-02	1993-08-08	7 days	5.84 ± 5.39	11.81	36.67 ± 1.38	38	25.95 ± 1.49	28	24.76 ± 1.26	1.86 ± 0.27	1.80 ± 0.26
	1993-08-10	1993-08-14	5 days	0.04 ± 0.02	0.06	33.98 ± 2.22	36	23.95 ± 0.66	25	23.57 ± 0.78	1.52 ± 0.04	1.68 ± 0.19
	1993-08-17	1993-08-22	6 days	3.07 ± 2.22	5.90	34.49 ± 2.39	38	24.79 ± 0.72	26	25.10 ± 1.17	1.62 ± 0.11	1.75 ± 0.16
1994	1994-06-28	1994-07-31	34 days	2.83 ± 3.74	13.58	36.07 ± 2.32	43	25.32 ± 1.61	29	24.54 ± 0.90	1.75 ± 0.28	1.90 ± 0.21
	1994-08-02	1994-08-13	12 days	2.05 ± 1.86	4.93	34.94 ± 1.64	38	26.09 ± 0.99	28	24.32 ± 1.21	1.71 ± 0.20	2.18 ± 0.43
	1994-08-15	1994-08-29	15 days	1.31 ± 1.15	3.22	35.86 ± 1.25	38	26.20 ± 0.90	28	24.52 ± 0.96	1.74 ± 0.24	1.94 ± 0.26
1995	1995-07-13	1995-08-07	26 days	7.84 ± 11.45	34.63	36.90 ± 2.76	42	25.17 ± 1.22	28	24.87 ± 1.50	1.75 ± 0.29	1.84 ± 0.21
	1995-08-11	1995-08-18	8 days	1.51 ± 1.09	3.26	36.83 ± 1.28	39	25.45 ± 0.85	27	24.86 ± 0.76	1.59 ± 0.20	1.70 ± 0.17

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
1996	1996-06-28	1996-07-01	4 days	0.03 ± 0.01	0.04	35.80 ± 1.00	37	22.39 ± 0.50	23	22.75 ± 0.35	1.64 ± 0.18	1.57 ± 0.10
	1996-07-12	1996-07-26	15 days	2.70 ± 2.25	7.26	35.65 ± 1.82	38	23.99 ± 1.49	27	24.30 ± 1.17	1.62 ± 0.12	1.88 ± 0.26
	1996-07-29	1996-08-03	6 days	0.24 ± 0.23	0.48	35.47 ± 0.95	37	24.07 ± 0.25	24	23.93 ± 0.27	1.53 ± 0.09	1.96 ± 0.30
	1996-08-05	1996-08-07	3 days	0.04 ± 0.00	0.04	33.63 ± 0.58	34	24.66 ± 0.18	25	22.92 ± 0.25	1.46 ± 0.07	1.76 ± 0.13
	1996-08-09	1996-08-12	4 days	0.04 ± 0.01	0.04	34.32 ± 0.87	35	24.59 ± 0.46	25	23.38 ± 0.40	1.52 ± 0.14	1.70 ± 0.23
1997	1997-07-26	1997-08-04	10 days	1.01 ± 1.08	2.72	35.77 ± 1.59	38	24.18 ± 0.47	25	24.61 ± 0.33	1.54 ± 0.06	1.88 ± 0.27
	1997-08-14	1997-08-20	7 days	0.14 ± 0.05	0.18	34.44 ± 1.16	36	24.32 ± 0.38	25	24.44 ± 0.36	1.57 ± 0.11	1.91 ± 0.23
1998	1998-06-26	1998-06-29	4 days	0.08 ± 0.03	0.10	34.75 ± 1.46	37	23.27 ± 0.52	24	23.14 ± 0.76	1.65 ± 0.26	1.71 ± 0.26
	1998-07-10	1998-07-14	5 days	0.12 ± 0.08	0.20	36.62 ± 1.47	39	24.03 ± 1.49	26	23.75 ± 0.89	1.67 ± 0.20	1.84 ± 0.32
	1998-07-16	1998-08-01	17 days	1.46 ± 1.71	5.23	36.25 ± 1.72	38	24.46 ± 0.50	25	24.41 ± 1.04	1.65 ± 0.18	1.84 ± 0.14
	1998-08-05	1998-08-17	13 days	1.75 ± 2.13	5.19	35.15 ± 2.22	38	24.57 ± 0.50	25	24.72 ± 0.82	1.67 ± 0.13	1.87 ± 0.37
	1998-08-20	1998-08-27	8 days	2.02 ± 1.86	4.71	36.22 ± 1.38	38	24.66 ± 0.71	26	24.44 ± 0.52	1.61 ± 0.16	1.78 ± 0.28
1999	1999-06-29	1999-07-04	6 days	1.85 ± 1.18	3.14	37.88 ± 1.98	39	24.70 ± 1.76	26	24.45 ± 1.22	2.00 ± 0.50	1.72 ± 0.26
	1999-07-08	1999-07-11	4 days	1.26 ± 0.81	1.67	37.42 ± 2.90	40	24.33 ± 0.78	25	24.27 ± 0.62	1.83 ± 0.43	1.80 ± 0.19
	1999-07-14	1999-07-18	5 days	0.73 ± 0.60	1.21	36.18 ± 2.00	38	25.08 ± 1.02	26	24.46 ± 0.76	1.68 ± 0.21	1.98 ± 0.23
	1999-07-20	1999-07-24	5 days	3.64 ± 1.88	5.25	37.45 ± 1.33	38	24.65 ± 0.57	25	24.64 ± 0.75	1.85 ± 0.22	1.71 ± 0.11
	1999-08-03	1999-08-08	6 days	0.42 ± 0.32	0.70	34.05 ± 0.81	35	26.01 ± 0.88	27	23.68 ± 0.55	1.74 ± 0.28	2.06 ± 0.36
	1999-08-14	1999-08-18	5 days	0.49 ± 0.16	0.64	35.71 ± 1.66	38	25.34 ± 1.13	27	24.15 ± 0.80	1.66 ± 0.11	1.85 ± 0.21
	1999-08-20	1999-08-30	11 days	1.68 ± 0.63	2.17	35.30 ± 1.86	39	25.57 ± 1.25	28	24.63 ± 0.78	1.87 ± 0.39	2.17 ± 0.45
2000	2000-06-15	2000-06-17	3 days	0.02 ± 0.00	0.02	34.88 ± 1.38	36	22.80 ± 0.50	23	23.76 ± 0.79	1.50 ± 0.06	1.60 ± 0.10
	2000-06-24	2000-07-03	10 days	0.26 ± 0.19	0.46	36.06 ± 1.04	38	24.86 ± 1.50	27	23.28 ± 0.72	1.80 ± 0.30	1.89 ± 0.36
	2000-07-05	2000-07-08	4 days	0.22 ± 0.13	0.28	36.12 ± 1.61	38	25.17 ± 1.84	27	23.21 ± 0.94	1.59 ± 0.17	1.97 ± 0.26
	2000-07-14	2000-07-16	3 days	0.04 ± 0.00	0.04	37.38 ± 0.58	38	23.44 ± 0.95	24	22.90 ± 0.22	1.52 ± 0.09	1.74 ± 0.25
	2000-07-19	2000-07-22	4 days	0.21 ± 0.05	0.24	36.03 ± 2.14	39	23.48 ± 0.64	24	24.22 ± 0.65	1.60 ± 0.14	1.75 ± 0.13
	2000-07-25	2000-08-03	10 days	3.01 ± 4.26	9.36	36.53 ± 2.17	40	24.92 ± 1.13	26	23.97 ± 1.25	1.68 ± 0.22	1.91 ± 0.28
	2000-08-08	2000-08-11	4 days	0.05 ± 0.02	0.06	35.46 ± 1.99	37	23.25 ± 0.40	24	23.93 ± 0.65	1.54 ± 0.04	1.72 ± 0.28
	2000-08-13	2000-08-21	9 days	0.98 ± 0.79	2.05	35.94 ± 1.88	39	25.04 ± 1.35	28	24.51 ± 1.00	1.64 ± 0.13	1.90 ± 0.27
	2000-08-24	2000-08-26	3 days	0.64 ± 0.00	0.64	33.23 ± 0.19	33	26.12 ± 0.65	27	23.26 ± 0.60	1.63 ± 0.07	1.82 ± 0.13
2001	2001-05-29	2001-05-31	3 days	0.02 ± 0.00	0.02	34.67 ± 0.61	35	21.71 ± 0.61	22	23.01 ± 0.17	1.44 ± 0.07	1.86 ± 0.14
	2001-06-20	2001-06-26	7 days	2.74 ± 2.30	5.21	37.45 ± 1.15	40	23.88 ± 1.87	26	24.36 ± 0.94	1.91 ± 0.20	1.69 ± 0.15
	2001-06-30	2001-07-04	5 days	1.12 ± 0.69	1.79	35.75 ± 1.67	38	23.33 ± 0.57	24	24.23 ± 1.31	1.66 ± 0.17	1.92 ± 0.25
	2001-07-10	2001-07-14	5 days	0.27 ± 0.15	0.36	35.82 ± 0.88	37	24.36 ± 0.67	25	23.88 ± 0.67	1.56 ± 0.13	2.03 ± 0.16
	2001-07-22	2001-08-13	23 days	0.90 ± 1.46	4.47	35.11 ± 1.45	38	25.11 ± 1.31	29	24.31 ± 0.96	1.63 ± 0.19	2.01 ± 0.27
	2001-08-19	2001-08-30	12 days	0.66 ± 0.63	1.77	34.59 ± 1.80	38	24.99 ± 0.76	26	24.29 ± 1.06	1.68 ± 0.21	1.79 ± 0.23
	2001-09-06	2001-09-09	4 days	0.10 ± 0.00	0.10	31.86 ± 1.61	33	23.77 ± 0.26	24	21.25 ± 0.41	1.59 ± 0.10	1.75 ± 0.20
	2001-09-27	2001-09-30	4 days	0.12 ± 0.05	0.14	26.71 ± 0.25	27	23.84 ± 0.27	24	18.81 ± 0.40	1.64 ± 0.06	1.82 ± 0.15
	2001-10-05	2001-10-07	3 days	0.02 ± 0.00	0.02	27.87 ± 0.98	29	23.94 ± 0.60	25	18.94 ± 0.75	1.63 ± 0.09	2.15 ± 0.52
	2001-10-25	2001-10-27	3 days	0.06 ± 0.00	0.06	27.30 ± 0.73	28	23.65 ± 0.08	24	15.98 ± 0.42	1.78 ± 0.39	1.65 ± 0.08

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2002	2002-06-15	2002-06-18	4 days	0.16 ± 0.10	0.22	37.02 ± 0.99	38	22.32 ± 1.42	24	23.69 ± 0.58	1.63 ± 0.26	1.68 ± 0.16
	2002-06-21	2002-06-23	3 days	0.14 ± 0.00	0.14	37.08 ± 1.32	39	22.98 ± 0.65	24	24.18 ± 0.49	1.72 ± 0.16	1.73 ± 0.27
	2002-06-25	2002-06-27	3 days	0.14 ± 0.00	0.14	33.60 ± 1.46	35	23.56 ± 0.09	24	23.06 ± 0.69	1.56 ± 0.07	2.00 ± 0.16
	2002-07-11	2002-07-13	3 days	0.02 ± 0.00	0.02	33.60 ± 0.36	34	23.26 ± 0.39	24	21.90 ± 0.57	1.45 ± 0.08	1.75 ± 0.11
	2002-07-19	2002-07-30	12 days	1.01 ± 1.33	3.30	35.50 ± 1.85	38	23.91 ± 0.60	25	23.85 ± 0.95	1.64 ± 0.12	1.80 ± 0.23
	2002-08-04	2002-08-06	3 days	0.04 ± 0.00	0.04	34.43 ± 0.50	35	25.28 ± 1.08	26	22.95 ± 0.14	1.54 ± 0.03	2.14 ± 0.47
	2002-08-15	2002-08-17	3 days	0.06 ± 0.00	0.06	33.75 ± 0.97	35	23.78 ± 0.58	24	23.72 ± 0.13	1.59 ± 0.12	1.74 ± 0.19
	2002-10-04	2002-10-07	4 days	0.17 ± 0.01	0.18	27.15 ± 0.69	28	24.30 ± 0.64	25	18.24 ± 0.70	2.01 ± 0.42	2.18 ± 0.52
2003	2003-06-10	2003-06-17	8 days	0.39 ± 0.21	0.64	35.24 ± 1.44	37	24.28 ± 1.32	26	24.18 ± 1.04	1.64 ± 0.16	1.83 ± 0.28
	2003-06-19	2003-07-01	13 days	1.08 ± 0.84	2.37	35.28 ± 1.60	38	24.67 ± 0.78	26	24.00 ± 1.26	1.67 ± 0.20	2.04 ± 0.38
	2003-07-07	2003-09-03	59 days	6.82 ± 9.39	27.75	36.00 ± 2.63	42	26.32 ± 0.91	28	24.79 ± 1.76	1.83 ± 0.25	1.90 ± 0.22
	2003-09-20	2003-09-22	3 days	0.02 ± 0.00	0.02	29.21 ± 1.21	31	23.54 ± 0.13	24	21.49 ± 0.40	1.70 ± 0.11	1.84 ± 0.10
2004	2004-06-23	2004-07-02	10 days	2.35 ± 2.66	6.10	37.39 ± 2.29	40	24.18 ± 0.86	25	24.52 ± 1.12	1.76 ± 0.23	1.76 ± 0.29
	2004-07-20	2004-09-03	46 days	3.74 ± 6.98	29.20	34.71 ± 2.56	41	25.84 ± 1.31	30	23.81 ± 1.44	2.03 ± 0.52	2.22 ± 0.76
	2004-09-06	2004-09-08	3 days	0.02 ± 0.00	0.02	30.68 ± 0.82	32	26.13 ± 0.07	26	22.65 ± 0.49	1.57 ± 0.06	1.97 ± 0.19
	2004-09-10	2004-09-12	3 days	0.20 ± 0.00	0.20	32.78 ± 0.36	33	24.96 ± 0.19	25	22.95 ± 0.36	1.64 ± 0.08	1.91 ± 0.24
	2004-10-18	2004-10-20	3 days	0.02 ± 0.00	0.02	27.76 ± 1.96	30	23.79 ± 0.17	24	18.13 ± 2.60	1.71 ± 0.33	2.05 ± 0.14
2005	2005-06-06	2005-06-08	3 days	0.08 ± 0.00	0.08	36.22 ± 0.59	37	22.31 ± 1.01	23	22.29 ± 0.09	1.45 ± 0.05	1.56 ± 0.03
	2005-06-17	2005-07-05	19 days	1.31 ± 1.42	3.76	35.14 ± 1.84	38	24.67 ± 0.84	26	24.17 ± 0.91	1.62 ± 0.12	1.88 ± 0.26
	2005-07-11	2005-07-30	20 days	2.63 ± 3.10	9.92	36.24 ± 2.02	40	25.04 ± 1.14	28	24.56 ± 0.93	1.80 ± 0.23	1.78 ± 0.25
	2005-08-04	2005-08-09	6 days	1.11 ± 0.73	1.97	37.93 ± 2.36	40	24.81 ± 1.19	26	24.93 ± 0.92	1.81 ± 0.28	2.03 ± 0.51
	2005-08-12	2005-08-16	5 days	0.11 ± 0.07	0.18	36.41 ± 2.25	39	24.51 ± 0.87	25	24.35 ± 0.57	1.55 ± 0.12	1.93 ± 0.41
	2005-09-03	2005-09-08	6 days	1.31 ± 1.28	2.48	31.83 ± 4.16	36	25.17 ± 1.37	27	21.62 ± 2.55	2.41 ± 0.83	2.69 ± 1.03
2006	2006-06-21	2006-06-24	4 days	0.24 ± 0.11	0.30	35.22 ± 2.32	38	23.43 ± 0.44	24	23.66 ± 0.59	1.58 ± 0.10	2.07 ± 0.27
	2006-06-29	2006-07-06	8 days	0.52 ± 0.25	0.80	34.06 ± 0.52	35	24.03 ± 0.48	25	23.33 ± 0.57	1.63 ± 0.16	2.02 ± 0.14
	2006-07-08	2006-08-12	36 days	4.64 ± 4.35	15.76	37.29 ± 1.40	40	25.60 ± 1.06	29	25.25 ± 0.99	1.72 ± 0.17	1.86 ± 0.26
	2006-08-28	2006-09-12	16 days	0.75 ± 0.68	1.91	35.79 ± 2.95	40	24.33 ± 1.07	26	23.86 ± 1.05	2.08 ± 0.64	2.06 ± 0.73
2007	2007-06-30	2007-07-04	5 days	0.11 ± 0.02	0.12	35.27 ± 1.63	37	23.06 ± 1.31	25	22.56 ± 0.55	1.65 ± 0.29	1.78 ± 0.34
	2007-07-06	2007-07-09	4 days	0.05 ± 0.02	0.06	36.33 ± 0.46	37	23.60 ± 0.69	24	23.31 ± 0.96	1.74 ± 0.18	2.02 ± 0.36
	2007-07-11	2007-07-19	9 days	0.13 ± 0.07	0.20	35.44 ± 1.46	37	23.42 ± 0.72	24	23.16 ± 0.78	1.51 ± 0.09	1.96 ± 0.20
	2007-07-23	2007-08-06	15 days	1.14 ± 1.39	3.74	37.45 ± 2.60	41	24.90 ± 1.33	27	24.66 ± 1.22	1.85 ± 0.48	2.25 ± 0.78
	2007-08-16	2007-08-19	4 days	0.02 ± 0.00	0.02	34.92 ± 0.88	36	24.58 ± 0.70	25	22.10 ± 0.52	1.50 ± 0.13	1.93 ± 0.21
	2007-08-26	2007-08-29	4 days	1.27 ± 0.53	1.57	35.80 ± 0.95	37	24.68 ± 0.80	26	24.64 ± 0.98	1.70 ± 0.16	1.86 ± 0.39
2008	2008-06-20	2008-07-03	14 days	0.16 ± 0.07	0.26	36.02 ± 1.56	38	23.29 ± 1.06	25	23.66 ± 0.91	1.63 ± 0.10	1.95 ± 0.24
	2008-07-05	2008-07-12	8 days	0.15 ± 0.06	0.22	35.15 ± 0.52	36	24.44 ± 1.00	26	22.58 ± 1.13	1.59 ± 0.11	2.10 ± 0.32
	2008-07-17	2008-08-15	30 days	1.45 ± 3.16	10.97	36.03 ± 1.42	39	24.86 ± 0.85	26	24.08 ± 1.14	1.76 ± 0.33	1.87 ± 0.21
	2008-08-17	2008-08-20	4 days	0.04 ± 0.01	0.04	33.78 ± 0.90	35	24.04 ± 0.48	24	22.53 ± 0.37	1.48 ± 0.13	1.74 ± 0.26

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2009	2009-06-12	2009-06-15	4 days	0.24 ± 0.07	0.28	36.89 ± 1.71	39	24.38 ± 1.60	26	24.13 ± 0.54	1.66 ± 0.17	2.20 ± 0.36
	2009-06-17	2009-06-20	4 days	0.32 ± 0.19	0.42	36.52 ± 1.03	38	24.06 ± 1.05	25	24.13 ± 0.69	1.50 ± 0.02	1.79 ± 0.17
	2009-06-28	2009-07-07	10 days	1.45 ± 0.94	2.60	35.59 ± 1.53	37	24.59 ± 1.33	27	24.14 ± 1.17	1.87 ± 0.33	1.81 ± 0.20
	2009-07-11	2009-07-17	7 days	0.29 ± 0.29	0.60	35.74 ± 0.84	37	25.13 ± 1.00	27	23.72 ± 0.77	1.71 ± 0.23	1.77 ± 0.23
	2009-07-20	2009-08-02	14 days	1.86 ± 0.93	2.98	37.23 ± 1.52	39	25.84 ± 1.29	27	24.45 ± 0.84	2.31 ± 0.56	2.38 ± 0.90
	2009-08-04	2009-08-07	4 days	0.58 ± 0.30	0.76	35.81 ± 0.97	37	24.84 ± 0.35	25	24.38 ± 0.57	1.77 ± 0.06	1.66 ± 0.13
	2009-08-11	2009-08-24	14 days	1.62 ± 1.72	4.79	36.28 ± 1.25	38	24.71 ± 0.55	26	25.09 ± 0.61	1.61 ± 0.12	1.79 ± 0.15
	2009-08-26	2009-09-02	8 days	0.06 ± 0.04	0.10	35.09 ± 2.19	37	24.85 ± 0.56	26	23.82 ± 0.62	1.48 ± 0.09	2.05 ± 0.17
2010	2010-05-31	2010-06-02	3 days	0.02 ± 0.00	0.02	34.92 ± 1.12	36	22.91 ± 1.46	24	22.42 ± 0.27	1.52 ± 0.04	1.88 ± 0.37
	2010-07-04	2010-07-23	20 days	2.36 ± 3.03	10.16	36.62 ± 1.54	39	25.18 ± 0.61	26	24.72 ± 0.87	1.67 ± 0.16	2.02 ± 0.23
	2010-07-25	2010-08-13	20 days	4.20 ± 5.10	13.48	37.00 ± 1.53	39	25.36 ± 1.17	28	24.28 ± 1.02	1.65 ± 0.19	1.87 ± 0.29
	2010-08-20	2010-08-30	11 days	0.97 ± 0.77	2.19	37.32 ± 1.31	40	25.50 ± 0.89	27	24.86 ± 1.07	2.01 ± 0.37	2.25 ± 0.90
	2010-09-14	2010-09-16	3 days	1.13 ± 0.00	1.13	32.26 ± 3.05	35	24.49 ± 0.61	25	22.21 ± 0.24	2.27 ± 0.53	2.30 ± 0.48
2011	2011-06-16	2011-06-18	3 days	0.08 ± 0.00	0.08	33.89 ± 0.94	35	23.41 ± 1.24	24	21.91 ± 0.34	1.45 ± 0.04	1.91 ± 0.26
	2011-06-25	2011-06-30	6 days	2.31 ± 2.16	4.41	37.56 ± 0.71	39	24.16 ± 0.77	25	24.42 ± 1.36	1.79 ± 0.23	1.80 ± 0.22
	2011-07-05	2011-07-12	8 days	0.15 ± 0.12	0.32	35.14 ± 1.14	37	24.74 ± 0.65	26	23.21 ± 0.78	1.58 ± 0.18	1.93 ± 0.26
	2011-07-24	2011-07-31	8 days	0.64 ± 0.73	1.69	35.72 ± 1.36	38	24.08 ± 0.78	25	23.20 ± 0.86	1.58 ± 0.19	1.80 ± 0.22
	2011-08-03	2011-08-09	7 days	0.41 ± 0.30	0.74	36.07 ± 1.63	38	25.30 ± 0.66	26	23.87 ± 0.62	1.93 ± 0.53	1.95 ± 0.38
	2011-08-11	2011-08-26	16 days	1.37 ± 1.82	5.39	35.88 ± 1.69	39	25.28 ± 0.99	28	24.51 ± 1.23	1.65 ± 0.17	1.81 ± 0.20
2012	2012-06-20	2012-06-30	11 days	5.19 ± 5.93	15.03	37.30 ± 2.34	41	24.75 ± 1.50	27	24.21 ± 1.89	1.77 ± 0.25	1.85 ± 0.17
	2012-07-04	2012-07-15	12 days	0.16 ± 0.09	0.26	35.66 ± 1.73	39	24.73 ± 1.34	28	22.64 ± 0.70	1.68 ± 0.19	2.00 ± 0.33
	2012-07-17	2012-08-30	45 days	4.80 ± 7.12	22.44	36.76 ± 2.31	42	25.51 ± 1.04	28	24.62 ± 1.41	1.81 ± 0.30	1.86 ± 0.24
	2012-09-18	2012-09-21	4 days	0.24 ± 0.15	0.32	30.48 ± 0.62	31	23.98 ± 0.45	24	21.65 ± 0.45	1.89 ± 0.30	1.81 ± 0.29
	2012-09-23	2012-09-27	5 days	1.31 ± 0.50	1.67	28.67 ± 2.40	33	24.30 ± 0.37	25	18.80 ± 2.47	1.92 ± 0.13	2.02 ± 0.14
2013	2013-07-04	2013-07-12	9 days	8.09 ± 3.97	12.48	38.03 ± 1.55	40	24.55 ± 0.81	26	25.03 ± 0.41	1.79 ± 0.23	1.72 ± 0.08
	2013-07-15	2013-07-19	5 days	0.07 ± 0.04	0.10	35.16 ± 0.84	36	24.23 ± 0.38	25	24.30 ± 0.28	1.52 ± 0.04	1.65 ± 0.16
	2013-07-23	2013-07-28	6 days	1.43 ± 0.64	2.07	34.49 ± 1.12	36	25.30 ± 1.21	27	24.27 ± 1.04	1.58 ± 0.07	2.00 ± 0.21
	2013-07-30	2013-08-24	26 days	1.27 ± 1.31	4.87	36.63 ± 1.37	39	24.96 ± 1.03	27	24.45 ± 0.81	1.95 ± 0.57	2.13 ± 0.64
2014	2014-06-12	2014-06-15	4 days	0.15 ± 0.09	0.20	35.85 ± 1.58	38	23.60 ± 1.67	26	23.47 ± 1.14	1.60 ± 0.13	1.73 ± 0.14
	2014-07-12	2014-07-19	8 days	1.55 ± 1.52	3.64	36.77 ± 2.05	40	24.17 ± 1.57	27	24.04 ± 1.51	1.77 ± 0.28	1.79 ± 0.23
	2014-07-22	2014-07-29	8 days	0.31 ± 0.18	0.50	35.69 ± 1.30	37	24.43 ± 1.01	26	24.14 ± 0.77	1.56 ± 0.13	1.78 ± 0.17
	2014-08-04	2014-08-14	11 days	0.33 ± 0.24	0.76	35.13 ± 1.45	37	25.09 ± 0.77	26	23.81 ± 0.97	1.66 ± 0.15	1.80 ± 0.13
	2014-08-26	2014-08-29	4 days	0.26 ± 0.12	0.34	36.31 ± 0.77	37	24.36 ± 0.48	25	24.47 ± 0.53	1.67 ± 0.14	1.85 ± 0.23
	2014-08-31	2014-09-08	9 days	0.12 ± 0.11	0.24	34.80 ± 1.71	37	24.36 ± 0.49	25	23.52 ± 0.72	1.70 ± 0.16	1.78 ± 0.25
	2014-09-10	2014-09-14	5 days	0.07 ± 0.03	0.08	32.83 ± 0.94	34	24.80 ± 0.79	26	22.73 ± 0.37	2.03 ± 0.16	2.03 ± 0.37
	2014-10-22	2014-10-24	3 days	1.39 ± 0.00	1.39	29.61 ± 1.90	32	24.91 ± 0.77	26	18.25 ± 1.11	3.08 ± 0.55	2.40 ± 0.73

Table B.4: Summary statistics for heat wave episodes identified by temperature using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time temperature		Night-time temperature		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Temperature	Day-time MI[a]	Night-time MI[a]
2015	2015-06-22	2015-06-24	3 days	0.02 ± 0.00	0.02	33.24 ± 1.06	34	23.69 ± 0.93	25	22.82 ± 0.89	1.47 ± 0.12	1.81 ± 0.06
	2015-06-26	2015-08-14	50 days	8.22 ± 7.17	26.52	37.62 ± 1.78	41	26.31 ± 1.25	29	25.58 ± 1.16	1.92 ± 0.26	1.93 ± 0.40
	2015-08-19	2015-08-21	3 days	0.02 ± 0.00	0.02	35.25 ± 0.96	36	25.18 ± 0.42	26	24.00 ± 1.08	1.54 ± 0.16	2.20 ± 0.31
	2015-08-27	2015-09-02	7 days	0.12 ± 0.10	0.20	34.17 ± 2.22	37	24.99 ± 1.02	26	23.92 ± 1.46	1.73 ± 0.39	1.91 ± 0.22
	2015-09-06	2015-09-16	11 days	0.21 ± 0.19	0.50	29.76 ± 0.93	31	24.11 ± 0.39	25	20.11 ± 0.77	1.90 ± 0.33	1.95 ± 0.23
	2015-09-22	2015-09-25	4 days	1.44 ± 0.38	1.63	30.56 ± 2.32	34	24.73 ± 0.01	25	19.30 ± 0.67	2.20 ± 0.63	2.23 ± 0.17
	2015-10-02	2015-10-07	6 days	1.60 ± 0.98	2.46	28.84 ± 1.24	30	24.92 ± 1.22	27	18.91 ± 1.54	2.47 ± 0.76	2.38 ± 0.79
2016	2016-06-08	2016-06-14	7 days	0.09 ± 0.05	0.14	35.66 ± 1.89	38	24.03 ± 2.67	29	22.63 ± 0.97	1.73 ± 0.28	2.21 ± 0.63
	2016-06-29	2016-08-09	42 days	2.56 ± 2.89	10.24	37.07 ± 1.50	40	24.82 ± 1.24	28	24.72 ± 1.06	1.73 ± 0.20	1.87 ± 0.32
	2016-08-14	2016-09-09	27 days	1.84 ± 3.14	10.38	36.23 ± 2.09	41	24.47 ± 0.98	26	24.54 ± 0.98	1.78 ± 0.32	1.83 ± 0.31
2017	2017-06-10	2017-06-27	18 days	11.70 ± 9.44	28.68	37.28 ± 1.61	40	25.42 ± 1.40	28	25.40 ± 1.09	1.71 ± 0.17	1.92 ± 0.26
	2017-07-09	2017-08-09	32 days	5.00 ± 4.89	15.31	37.16 ± 2.54	43	26.01 ± 1.21	29	24.94 ± 1.39	1.84 ± 0.31	1.95 ± 0.24
	2017-08-13	2017-08-30	18 days	3.09 ± 3.45	9.54	35.69 ± 2.28	39	25.18 ± 0.76	26	24.41 ± 1.28	1.69 ± 0.18	1.79 ± 0.16
	2017-10-13	2017-10-16	4 days	1.42 ± 0.55	1.79	30.98 ± 1.55	32	25.41 ± 1.28	27	20.52 ± 0.67	2.84 ± 0.56	2.79 ± 1.04
	2017-10-26	2017-10-28	3 days	0.24 ± 0.00	0.24	28.41 ± 0.34	29	24.74 ± 1.09	26	17.75 ± 0.56	2.28 ± 0.70	2.30 ± 0.71
2018	2018-06-16	2018-06-18	3 days	0.02 ± 0.00	0.02	35.47 ± 1.38	37	22.23 ± 1.17	24	22.05 ± 0.35	1.43 ± 0.05	1.71 ± 0.11
	2018-06-22	2018-06-27	6 days	0.33 ± 0.23	0.54	35.20 ± 1.80	38	23.41 ± 0.28	24	23.91 ± 0.35	1.62 ± 0.17	1.75 ± 0.11
	2018-07-01	2018-07-05	5 days	0.08 ± 0.02	0.10	33.29 ± 0.55	34	24.90 ± 0.57	26	22.72 ± 0.35	1.67 ± 0.14	1.79 ± 0.04
	2018-07-07	2018-08-15	40 days	4.49 ± 9.12	31.66	35.84 ± 2.27	42	25.77 ± 1.23	29	24.66 ± 1.41	1.66 ± 0.18	1.91 ± 0.19
	2018-08-18	2018-08-29	12 days	0.18 ± 0.13	0.40	34.82 ± 1.17	36	25.05 ± 0.48	26	23.86 ± 0.77	1.55 ± 0.10	1.89 ± 0.29
	2018-08-31	2018-09-02	3 days	0.18 ± 0.00	0.18	36.15 ± 0.38	36	24.78 ± 0.29	25	24.20 ± 0.41	1.53 ± 0.04	1.89 ± 0.11

Abbreviations [a] Magnitude Index

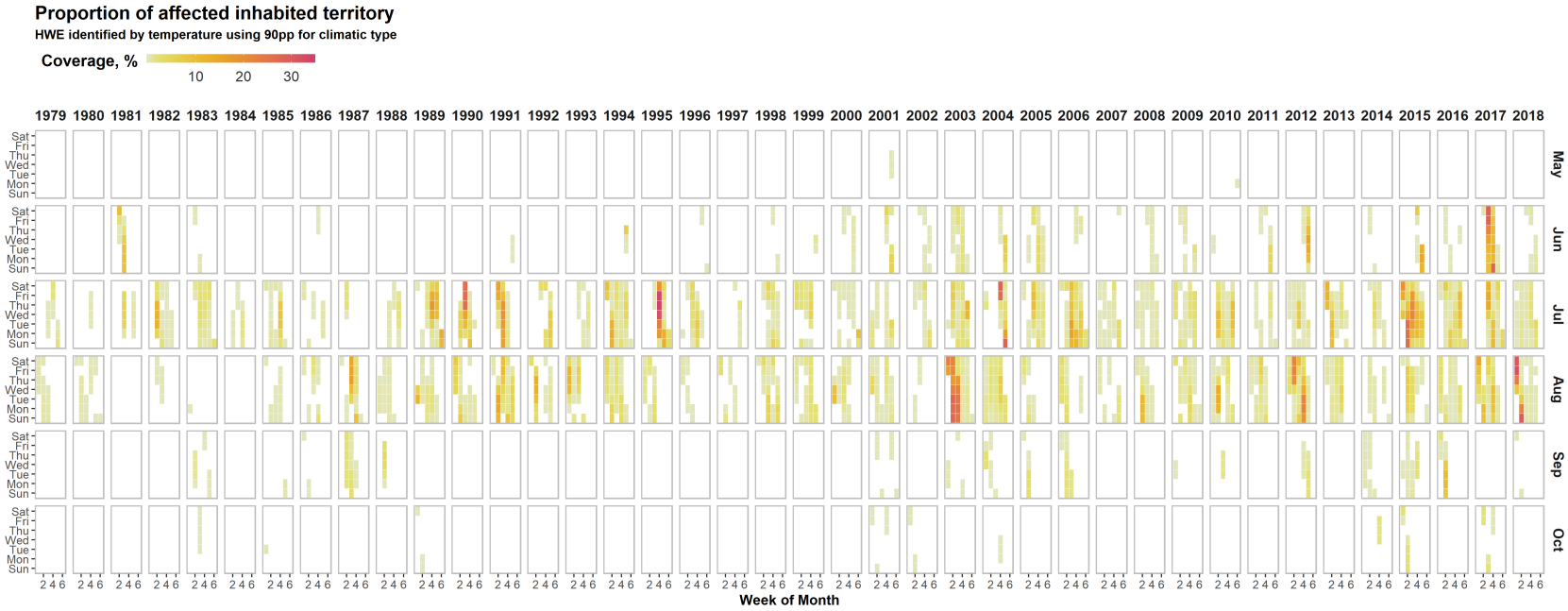


Figure B.10: Proportion of national territory affected by heatwaves identified using temperature (90pp for climatic type)

Table B.5: Summary statistics for heat wave episodes identified by heat index using 90pp for individual cell

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1979	1979-08-11	1979-08-13	3 days	0.20 ± 0.00	0.20	36.30 ± 0.18	36	24.56 ± 0.12	25	24.10 ± 0.68	1.53 ± 0.10	1.54 ± 0.05
1980	1980-08-21	1980-08-23	3 days	4.11 ± 0.00	4.11	38.60 ± 2.59	42	27.25 ± 1.84	29	26.17 ± 0.57	2.24 ± 0.44	2.46 ± 0.23
	1980-09-13	1980-09-15	3 days	0.06 ± 0.00	0.06	34.56 ± 1.50	36	24.49 ± 0.32	25	22.45 ± 0.21	2.72 ± 0.84	1.93 ± 0.10
1981	1981-06-12	1981-06-18	7 days	6.73 ± 5.18	12.09	37.68 ± 1.98	41	24.63 ± 1.52	27	23.94 ± 1.44	1.86 ± 0.23	1.83 ± 0.21
	1981-07-13	1981-07-17	5 days	1.89 ± 1.58	3.04	36.43 ± 1.18	38	24.27 ± 1.01	25	23.10 ± 0.41	1.63 ± 0.16	1.91 ± 0.11
	1981-07-28	1981-07-30	3 days	0.72 ± 0.00	0.72	36.77 ± 0.93	38	24.23 ± 2.63	27	24.85 ± 1.06	2.05 ± 0.25	1.55 ± 0.13
1982	1982-07-05	1982-07-12	8 days	9.70 ± 10.31	22.12	36.49 ± 2.03	40	25.72 ± 1.03	27	25.27 ± 1.16	1.74 ± 0.28	1.71 ± 0.33
	1982-08-09	1982-08-11	3 days	0.04 ± 0.00	0.04	34.27 ± 0.61	35	23.93 ± 0.55	25	22.94 ± 0.73	1.71 ± 0.23	1.72 ± 0.06
1983	1983-07-21	1983-08-01	12 days	1.82 ± 1.11	3.46	35.41 ± 1.38	39	27.23 ± 1.59	31	23.97 ± 0.83	1.72 ± 0.23	1.59 ± 0.17
	1983-09-23	1983-09-27	5 days	1.94 ± 1.30	3.24	32.68 ± 1.32	35	24.56 ± 1.22	26	23.21 ± 0.92	1.95 ± 0.09	2.07 ± 0.35
1984	1984-07-23	1984-07-25	3 days	0.46 ± 0.00	0.46	37.36 ± 1.28	38	25.14 ± 0.41	26	25.06 ± 1.10	2.03 ± 0.39	1.59 ± 0.10
1985	1985-07-21	1985-07-25	5 days	6.20 ± 4.10	10.28	36.50 ± 1.32	38	24.54 ± 0.57	25	25.44 ± 0.85	1.53 ± 0.07	1.54 ± 0.08
	1985-09-09	1985-09-12	4 days	0.45 ± 0.10	0.50	32.28 ± 1.73	34	24.51 ± 0.45	25	23.14 ± 0.09	2.14 ± 0.43	1.77 ± 0.45
	1985-09-29	1985-10-01	3 days	1.27 ± 0.00	1.27	30.75 ± 0.84	32	24.81 ± 0.27	25	22.02 ± 0.35	1.98 ± 0.29	2.04 ± 0.21
1986	1986-08-15	1986-08-17	3 days	0.20 ± 0.00	0.20	35.76 ± 1.51	37	25.91 ± 1.00	27	24.77 ± 0.50	1.74 ± 0.26	1.40 ± 0.04
1987	1987-07-08	1987-07-11	4 days	0.76 ± 0.44	1.01	36.45 ± 5.64	45	24.40 ± 0.57	25	24.44 ± 0.29	1.44 ± 0.12	1.69 ± 0.13
	1987-08-01	1987-08-04	4 days	1.33 ± 0.84	1.75	36.12 ± 0.90	37	23.68 ± 0.58	24	23.64 ± 1.38	1.87 ± 0.27	1.82 ± 0.26
	1987-08-11	1987-08-16	6 days	22.30 ± 13.25	34.72	38.44 ± 1.77	41	25.96 ± 0.71	27	26.39 ± 0.61	2.17 ± 0.36	1.84 ± 0.28
	1987-09-07	1987-09-20	14 days	2.38 ± 0.96	3.94	33.68 ± 1.81	37	26.11 ± 1.16	28	23.67 ± 0.58	2.63 ± 0.55	2.61 ± 0.77
1988	1988-07-26	1988-07-29	4 days	0.82 ± 0.53	1.09	38.13 ± 2.00	41	24.60 ± 0.18	25	24.72 ± 0.33	1.70 ± 0.42	1.63 ± 0.20
	1988-09-06	1988-09-09	4 days	1.20 ± 0.62	1.51	36.14 ± 0.62	37	25.14 ± 0.69	26	25.03 ± 0.80	1.63 ± 0.05	1.85 ± 0.31
1989	1989-07-11	1989-07-14	4 days	0.26 ± 0.05	0.28	35.60 ± 0.82	36	24.88 ± 0.33	25	23.77 ± 0.42	1.83 ± 0.15	1.78 ± 0.21
	1989-07-18	1989-07-22	5 days	13.10 ± 6.58	20.75	37.43 ± 2.62	41	25.93 ± 1.98	29	26.24 ± 0.74	2.04 ± 0.09	2.00 ± 0.33
	1989-07-25	1989-08-02	9 days	10.26 ± 4.90	15.72	36.73 ± 1.41	38	25.95 ± 0.59	27	25.47 ± 0.58	1.84 ± 0.12	1.92 ± 0.20
	1989-08-09	1989-08-12	4 days	1.32 ± 0.38	1.61	35.49 ± 0.62	36	26.98 ± 0.82	28	24.99 ± 0.50	1.79 ± 0.15	1.80 ± 0.42
	1989-08-19	1989-08-27	9 days	3.43 ± 2.68	6.66	36.30 ± 1.69	38	26.95 ± 0.68	28	25.22 ± 0.77	1.75 ± 0.16	1.86 ± 0.33
1990	1990-07-08	1990-07-11	4 days	3.98 ± 2.62	5.29	36.40 ± 1.55	38	24.24 ± 0.71	25	23.70 ± 0.49	1.70 ± 0.11	1.90 ± 0.16
	1990-07-16	1990-07-25	10 days	18.38 ± 14.73	38.66	36.46 ± 1.20	39	25.36 ± 1.24	28	25.90 ± 0.84	2.05 ± 0.26	2.08 ± 0.36
	1990-08-01	1990-08-09	9 days	6.05 ± 5.76	14.55	35.19 ± 1.72	37	26.03 ± 0.74	27	24.92 ± 1.45	2.02 ± 0.29	2.10 ± 0.56
	1990-08-26	1990-08-28	3 days	0.78 ± 0.00	0.78	32.47 ± 0.43	33	25.48 ± 0.50	26	23.25 ± 0.56	1.80 ± 0.09	2.39 ± 0.69
1991	1991-07-09	1991-07-21	13 days	9.27 ± 8.75	23.06	37.97 ± 3.21	44	25.50 ± 1.45	28	25.26 ± 0.71	1.75 ± 0.27	1.75 ± 0.28
	1991-08-04	1991-08-07	4 days	10.29 ± 4.19	13.66	37.63 ± 1.85	39	25.42 ± 0.40	26	25.85 ± 0.47	1.73 ± 0.10	1.56 ± 0.06
	1991-08-11	1991-08-21	11 days	3.95 ± 4.66	12.36	36.51 ± 3.28	44	25.09 ± 1.38	28	25.06 ± 1.24	1.71 ± 0.15	1.72 ± 0.24
	1991-08-25	1991-08-30	6 days	3.87 ± 2.81	6.52	35.93 ± 1.34	38	27.22 ± 0.72	28	25.12 ± 0.82	1.64 ± 0.18	1.62 ± 0.22
	1991-09-17	1991-09-20	4 days	0.13 ± 0.06	0.16	33.17 ± 2.13	35	24.53 ± 0.29	25	23.54 ± 0.40	1.77 ± 0.24	1.84 ± 0.15

Table B.5: Summary statistics for heat wave episodes identified by heat index using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1992	1992-07-26	1992-08-07	13 days	6.16 ± 2.86	10.40	36.03 ± 2.03	41	25.89 ± 0.85	27	25.82 ± 0.56	1.75 ± 0.22	1.81 ± 0.15
1993	1993-08-03	1993-08-08	6 days	9.73 ± 9.21	18.29	36.95 ± 1.92	39	26.81 ± 1.06	28	25.19 ± 1.43	1.87 ± 0.23	1.96 ± 0.46
	1993-08-17	1993-08-21	5 days	8.43 ± 6.69	13.64	34.79 ± 2.38	38	25.26 ± 0.40	26	25.52 ± 1.02	2.28 ± 0.17	1.97 ± 0.58
1994	1994-06-30	1994-07-06	7 days	4.45 ± 3.95	8.69	37.35 ± 1.87	39	26.33 ± 1.75	28	25.05 ± 0.80	1.97 ± 0.46	1.73 ± 0.24
	1994-07-18	1994-07-20	3 days	0.02 ± 0.00	0.02	36.57 ± 0.70	37	25.83 ± 0.72	27	24.55 ± 0.31	1.61 ± 0.16	1.48 ± 0.10
	1994-08-03	1994-08-11	9 days	5.75 ± 6.75	16.02	35.82 ± 1.43	39	27.54 ± 1.45	31	24.82 ± 1.71	1.71 ± 0.29	1.80 ± 0.35
	1994-08-17	1994-08-24	8 days	2.88 ± 3.04	6.62	36.66 ± 1.29	39	27.68 ± 0.61	29	25.02 ± 1.22	1.97 ± 0.31	1.81 ± 0.34
1995	1995-07-16	1995-07-25	10 days	22.02 ± 16.44	44.19	38.61 ± 2.09	42	25.82 ± 1.05	27	26.34 ± 0.97	1.91 ± 0.30	1.91 ± 0.34
	1995-08-12	1995-08-16	5 days	0.54 ± 0.27	0.81	37.61 ± 1.58	39	25.99 ± 0.85	27	25.23 ± 0.65	1.85 ± 0.15	1.63 ± 0.08
	1995-08-22	1995-08-28	7 days	0.46 ± 0.13	0.60	33.63 ± 2.05	36	24.21 ± 0.50	25	22.32 ± 0.36	1.87 ± 0.18	1.88 ± 0.28
1996	1996-06-13	1996-06-16	4 days	2.12 ± 1.05	2.64	32.14 ± 0.67	33	22.88 ± 0.21	23	23.36 ± 0.30	2.12 ± 0.37	1.83 ± 0.22
	1996-07-14	1996-07-19	6 days	2.05 ± 1.50	3.50	33.69 ± 2.10	37	23.32 ± 0.75	24	23.94 ± 1.00	1.54 ± 0.16	1.69 ± 0.15
	1996-07-22	1996-07-24	3 days	1.67 ± 0.00	1.67	35.32 ± 0.47	36	25.28 ± 0.73	26	25.34 ± 0.51	1.49 ± 0.02	1.72 ± 0.25
1997	1997-07-26	1997-07-29	4 days	0.55 ± 0.30	0.70	34.26 ± 0.98	36	23.82 ± 0.32	24	24.54 ± 0.26	1.78 ± 0.11	1.72 ± 0.25
	1997-07-31	1997-08-02	3 days	1.53 ± 0.00	1.53	36.04 ± 0.63	37	24.81 ± 0.63	25	24.72 ± 0.27	1.65 ± 0.08	1.77 ± 0.19
	1997-08-18	1997-08-24	7 days	0.82 ± 0.76	1.85	32.70 ± 1.09	34	24.92 ± 0.49	26	24.77 ± 0.48	1.82 ± 0.25	1.81 ± 0.23
1998	1998-08-05	1998-08-11	7 days	1.69 ± 0.76	2.54	35.65 ± 1.08	38	24.50 ± 0.44	25	24.84 ± 0.96	2.03 ± 0.24	1.62 ± 0.12
	1998-08-22	1998-08-25	4 days	1.54 ± 0.91	2.03	36.84 ± 0.66	38	25.43 ± 0.42	26	24.70 ± 0.42	1.56 ± 0.04	1.68 ± 0.15
1999	1999-07-21	1999-07-24	4 days	2.06 ± 1.00	2.56	36.21 ± 1.21	37	25.06 ± 0.41	26	24.56 ± 0.92	1.64 ± 0.14	1.65 ± 0.20
	1999-08-04	1999-08-08	5 days	0.71 ± 0.43	1.03	34.76 ± 0.30	35	27.54 ± 1.22	30	24.14 ± 0.82	1.67 ± 0.11	1.75 ± 0.24
	1999-08-22	1999-09-02	12 days	1.51 ± 1.03	2.80	34.59 ± 2.06	37	26.55 ± 1.65	30	24.88 ± 0.84	2.28 ± 0.78	2.28 ± 0.64
2000	2000-06-14	2000-06-18	5 days	3.75 ± 2.60	6.22	32.36 ± 1.04	34	22.14 ± 0.84	23	22.75 ± 1.20	2.14 ± 0.17	1.97 ± 0.37
	2000-07-30	2000-08-02	4 days	1.21 ± 0.65	1.55	37.56 ± 1.01	39	25.39 ± 0.83	26	25.22 ± 0.56	1.72 ± 0.20	1.71 ± 0.28
2001	2001-06-23	2001-06-25	3 days	0.46 ± 0.00	0.46	36.50 ± 2.24	39	24.57 ± 1.34	26	24.63 ± 0.32	1.61 ± 0.15	1.50 ± 0.11
	2001-07-29	2001-08-02	5 days	3.28 ± 2.21	4.95	35.11 ± 1.95	37	26.83 ± 0.80	27	25.66 ± 1.38	1.80 ± 0.37	1.66 ± 0.29
	2001-08-25	2001-08-27	3 days	0.76 ± 0.00	0.76	33.69 ± 0.31	34	26.28 ± 0.65	27	25.29 ± 0.42	1.81 ± 0.11	1.90 ± 0.26
2002	2002-10-05	2002-10-07	3 days	0.36 ± 0.00	0.36	29.80 ± 1.34	31	25.24 ± 0.29	26	17.79 ± 0.81	2.13 ± 0.49	2.31 ± 0.40
2003	2003-06-19	2003-06-22	4 days	1.12 ± 0.63	1.49	35.45 ± 0.89	37	24.23 ± 0.32	25	25.03 ± 0.60	2.02 ± 0.58	1.80 ± 0.22
	2003-06-24	2003-06-26	3 days	0.52 ± 0.00	0.52	34.02 ± 0.11	34	25.86 ± 0.75	26	24.20 ± 0.45	1.46 ± 0.03	1.40 ± 0.04
	2003-07-10	2003-07-13	4 days	0.73 ± 0.32	0.97	35.67 ± 1.57	37	26.30 ± 0.84	27	25.44 ± 0.46	1.49 ± 0.11	1.41 ± 0.07
	2003-07-19	2003-07-27	9 days	2.28 ± 2.12	5.25	36.84 ± 1.40	39	28.43 ± 1.51	31	24.73 ± 0.46	1.80 ± 0.15	1.78 ± 0.21
	2003-07-29	2003-08-28	31 days	20.52 ± 20.00	51.88	38.22 ± 2.67	48	28.59 ± 1.21	31	25.75 ± 1.43	2.06 ± 0.34	1.97 ± 0.35
	2003-09-01	2003-09-03	3 days	0.18 ± 0.00	0.18	31.46 ± 1.02	32	25.58 ± 0.38	26	20.92 ± 0.59	1.99 ± 0.46	1.94 ± 0.35

Table B.5: Summary statistics for heat wave episodes identified by heat index using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2004	2004-06-28	2004-07-01	4 days	1.66 ± 1.07	2.21	38.98 ± 3.06	42	24.57 ± 0.26	25	25.20 ± 0.77	1.81 ± 0.32	1.55 ± 0.10
	2004-07-22	2004-07-29	8 days	13.89 ± 12.95	30.43	39.45 ± 6.19	51	27.99 ± 1.30	30	25.65 ± 1.56	2.53 ± 0.42	2.60 ± 0.73
	2004-08-09	2004-08-14	6 days	1.08 ± 0.66	2.09	34.43 ± 0.57	35	27.18 ± 1.00	28	23.24 ± 0.64	1.80 ± 0.14	1.69 ± 0.09
	2004-08-16	2004-09-06	22 days	2.25 ± 1.89	6.92	34.69 ± 2.57	43	27.54 ± 1.85	31	23.02 ± 1.14	2.57 ± 1.11	2.65 ± 1.27
2005	2005-07-13	2005-07-16	4 days	2.57 ± 1.13	3.40	37.11 ± 0.46	38	25.20 ± 1.01	26	25.45 ± 0.43	1.64 ± 0.10	1.50 ± 0.05
	2005-08-04	2005-08-09	6 days	0.33 ± 0.17	0.58	36.35 ± 2.51	39	24.97 ± 1.36	27	24.53 ± 1.00	1.82 ± 0.27	1.65 ± 0.11
	2005-08-13	2005-08-15	3 days	0.74 ± 0.00	0.74	36.30 ± 0.44	37	24.50 ± 0.92	26	24.33 ± 0.17	2.39 ± 0.10	1.68 ± 0.07
	2005-09-03	2005-09-06	4 days	1.92 ± 1.09	2.46	33.74 ± 1.69	35	27.39 ± 1.97	30	22.87 ± 2.01	3.31 ± 1.37	3.48 ± 1.48
2006	2006-07-09	2006-07-28	20 days	7.92 ± 5.38	18.47	36.49 ± 1.30	39	26.71 ± 1.21	29	25.88 ± 0.66	1.81 ± 0.26	1.82 ± 0.24
	2006-07-30	2006-08-03	5 days	4.21 ± 1.57	7.02	37.36 ± 1.15	39	28.00 ± 0.80	29	25.85 ± 0.25	1.77 ± 0.12	1.82 ± 0.15
	2006-08-05	2006-08-11	7 days	0.86 ± 0.33	1.21	37.19 ± 1.42	39	24.68 ± 0.61	25	23.79 ± 0.24	1.98 ± 0.18	1.66 ± 0.09
	2006-09-03	2006-09-12	10 days	1.53 ± 0.74	2.46	34.49 ± 2.70	38	25.66 ± 1.41	28	24.09 ± 1.30	2.78 ± 0.91	2.30 ± 0.87
2007	2007-07-28	2007-07-31	4 days	1.31 ± 0.00	1.31	38.57 ± 1.19	40	26.87 ± 1.85	29	25.69 ± 0.11	2.45 ± 0.57	3.33 ± 1.45
	2007-08-26	2007-08-28	3 days	1.49 ± 0.00	1.49	35.03 ± 0.71	36	25.23 ± 1.60	27	25.23 ± 0.35	2.13 ± 0.20	1.59 ± 0.08
2008	2008-08-03	2008-08-06	4 days	5.56 ± 3.67	7.41	36.71 ± 1.55	38	25.45 ± 0.29	26	25.96 ± 0.45	1.73 ± 0.19	1.62 ± 0.20
2009	2009-07-22	2009-08-02	12 days	1.67 ± 0.74	2.46	35.73 ± 1.73	38	27.27 ± 1.54	30	24.14 ± 0.91	2.79 ± 0.50	2.54 ± 1.11
	2009-08-12	2009-08-14	3 days	0.40 ± 0.00	0.40	35.20 ± 0.54	36	24.51 ± 0.25	25	24.81 ± 0.18	1.66 ± 0.06	1.76 ± 0.10
	2009-08-19	2009-08-22	4 days	0.04 ± 0.01	0.04	35.81 ± 0.33	36	25.84 ± 1.20	28	24.90 ± 0.41	1.75 ± 0.13	1.62 ± 0.08
2010	2010-07-04	2010-07-08	5 days	4.89 ± 3.62	7.71	37.60 ± 0.56	38	25.24 ± 0.78	26	25.23 ± 0.83	1.71 ± 0.16	1.86 ± 0.20
	2010-07-26	2010-07-31	6 days	4.20 ± 3.48	7.31	36.53 ± 1.08	38	25.15 ± 0.43	26	24.58 ± 0.61	1.76 ± 0.28	1.82 ± 0.17
	2010-08-09	2010-08-12	4 days	5.68 ± 2.30	7.35	37.80 ± 1.36	39	27.72 ± 1.21	29	25.27 ± 0.56	2.00 ± 0.23	2.05 ± 0.22
	2010-08-20	2010-08-22	3 days	0.12 ± 0.00	0.12	36.03 ± 0.63	37	25.37 ± 0.07	25	25.28 ± 0.82	1.76 ± 0.07	1.81 ± 0.37
	2010-08-24	2010-08-30	7 days	1.38 ± 0.88	2.13	37.27 ± 1.42	40	27.24 ± 1.25	29	24.68 ± 1.31	2.50 ± 0.40	2.47 ± 1.32
	2010-09-14	2010-09-16	3 days	1.31 ± 0.00	1.31	32.08 ± 1.51	34	25.04 ± 0.55	25	22.06 ± 0.40	2.55 ± 0.64	2.26 ± 0.40
2011	2011-06-26	2011-06-28	3 days	0.30 ± 0.00	0.30	36.23 ± 1.52	38	24.46 ± 0.65	25	25.25 ± 0.91	1.44 ± 0.09	1.48 ± 0.03
	2011-08-06	2011-08-08	3 days	0.08 ± 0.00	0.08	36.83 ± 1.63	38	26.94 ± 1.37	28	24.02 ± 0.59	2.27 ± 0.54	1.69 ± 0.22
	2011-08-19	2011-08-21	3 days	1.35 ± 0.00	1.35	36.71 ± 1.92	38	27.95 ± 1.08	29	26.41 ± 0.69	1.66 ± 0.18	1.60 ± 0.02
2012	2012-06-25	2012-06-29	5 days	3.66 ± 1.40	5.92	37.44 ± 0.84	38	25.53 ± 1.34	27	25.55 ± 1.30	1.72 ± 0.10	1.65 ± 0.24
	2012-07-17	2012-07-19	3 days	1.53 ± 0.00	1.53	37.16 ± 0.23	37	24.41 ± 0.15	25	24.78 ± 0.34	1.65 ± 0.15	1.63 ± 0.07
	2012-08-01	2012-08-03	3 days	0.48 ± 0.00	0.48	36.19 ± 1.10	37	26.82 ± 1.48	28	24.42 ± 0.35	1.94 ± 0.28	1.67 ± 0.25
	2012-08-09	2012-08-12	4 days	11.83 ± 5.52	15.23	39.87 ± 2.03	42	27.24 ± 1.16	29	26.57 ± 1.62	2.16 ± 0.23	1.84 ± 0.12
	2012-08-18	2012-08-25	8 days	13.25 ± 8.45	25.30	37.94 ± 1.10	40	28.21 ± 0.99	30	25.97 ± 1.30	1.90 ± 0.26	1.79 ± 0.18
	2012-09-17	2012-09-20	4 days	0.77 ± 0.45	1.01	30.06 ± 0.19	30	24.64 ± 0.29	25	21.50 ± 0.32	2.15 ± 0.18	1.72 ± 0.24
	2012-09-23	2012-09-27	5 days	1.44 ± 0.48	1.79	30.49 ± 0.94	31	24.92 ± 0.37	25	18.49 ± 2.64	2.34 ± 0.31	2.06 ± 0.20

Table B.5: Summary statistics for heat wave episodes identified by heat index using 90pp for individual cell *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2013	2013-07-04	2013-07-12	9 days	7.71 ± 4.86	13.79	36.06 ± 1.87	38	24.51 ± 0.68	26	24.78 ± 0.28	1.99 ± 0.35	1.83 ± 0.19
	2013-07-20	2013-07-22	3 days	1.51 ± 0.00	1.51	33.38 ± 0.64	34	25.88 ± 0.18	26	24.54 ± 0.10	1.87 ± 0.09	1.75 ± 0.17
	2013-07-25	2013-07-28	4 days	0.36 ± 0.14	0.48	36.56 ± 1.51	38	27.21 ± 2.26	29	24.12 ± 1.21	1.64 ± 0.18	1.62 ± 0.31
	2013-08-14	2013-08-17	4 days	1.20 ± 0.41	1.41	34.60 ± 0.75	35	26.89 ± 1.62	28	24.49 ± 0.33	3.32 ± 0.46	2.77 ± 1.32
	2013-08-19	2013-08-24	6 days	1.78 ± 0.74	2.33	35.66 ± 1.53	37	26.34 ± 1.08	28	24.64 ± 0.59	2.61 ± 0.76	2.58 ± 0.93
2014	2014-08-09	2014-08-11	3 days	0.91 ± 0.00	0.91	35.54 ± 0.76	36	27.36 ± 0.15	28	24.54 ± 0.32	1.74 ± 0.15	1.66 ± 0.09
	2014-10-22	2014-10-24	3 days	1.65 ± 0.00	1.65	32.19 ± 1.48	34	25.42 ± 0.72	26	17.66 ± 1.23	3.64 ± 0.64	2.19 ± 0.62
2015	2015-06-27	2015-07-01	5 days	6.72 ± 3.19	10.75	36.97 ± 1.58	39	24.77 ± 1.08	26	25.82 ± 0.50	1.68 ± 0.23	1.65 ± 0.15
	2015-07-03	2015-08-14	43 days	13.70 ± 9.42	33.06	37.31 ± 1.57	42	27.98 ± 1.89	32	25.66 ± 1.26	1.92 ± 0.30	2.02 ± 0.45
	2015-09-11	2015-09-14	4 days	0.45 ± 0.22	0.56	30.75 ± 1.29	32	25.02 ± 0.09	25	20.40 ± 0.87	2.03 ± 0.35	1.90 ± 0.17
	2015-09-22	2015-09-25	4 days	2.13 ± 0.66	2.46	30.48 ± 1.34	32	25.34 ± 0.21	26	18.89 ± 0.69	2.77 ± 0.68	2.31 ± 0.26
	2015-10-03	2015-10-07	5 days	1.83 ± 1.03	2.46	31.43 ± 2.49	35	26.30 ± 1.87	29	19.06 ± 1.81	3.18 ± 1.35	2.62 ± 1.01
2016	2016-07-06	2016-07-12	7 days	1.98 ± 1.84	4.15	37.01 ± 2.76	42	25.48 ± 0.79	27	25.29 ± 0.94	1.57 ± 0.14	1.63 ± 0.09
	2016-07-24	2016-08-08	16 days	1.62 ± 2.73	7.04	36.29 ± 0.96	38	25.58 ± 1.33	28	25.05 ± 0.57	1.95 ± 0.30	1.86 ± 0.44
	2016-08-18	2016-08-21	4 days	0.02 ± 0.00	0.02	34.68 ± 0.96	36	26.38 ± 0.80	27	23.96 ± 0.66	1.67 ± 0.15	1.95 ± 0.31
	2016-08-26	2016-08-31	6 days	1.49 ± 1.17	2.46	34.12 ± 1.91	36	25.13 ± 1.13	27	24.12 ± 0.89	2.34 ± 0.68	2.12 ± 0.49
	2016-09-02	2016-09-07	6 days	3.52 ± 2.67	6.46	37.19 ± 1.95	40	25.39 ± 0.89	27	25.66 ± 0.65	1.87 ± 0.23	1.64 ± 0.15
2017	2017-06-11	2017-06-24	14 days	16.65 ± 14.30	39.69	36.63 ± 1.13	39	25.20 ± 1.20	27	25.63 ± 0.75	1.75 ± 0.22	1.80 ± 0.15
	2017-07-12	2017-07-16	5 days	13.30 ± 4.52	17.79	39.00 ± 2.08	41	26.39 ± 1.02	28	26.05 ± 0.58	2.12 ± 0.51	1.81 ± 0.24
	2017-07-28	2017-08-09	13 days	9.55 ± 7.29	24.19	37.30 ± 1.56	40	29.76 ± 2.71	33	25.30 ± 1.74	1.90 ± 0.31	2.01 ± 0.37
	2017-08-15	2017-08-29	15 days	1.28 ± 1.05	3.30	35.95 ± 1.25	38	26.44 ± 1.18	29	24.74 ± 0.99	1.84 ± 0.17	1.81 ± 0.35
	2017-10-13	2017-10-16	4 days	1.76 ± 0.81	2.33	31.20 ± 0.48	32	26.27 ± 1.57	28	20.21 ± 0.66	3.01 ± 0.64	2.65 ± 1.04
2018	2018-07-24	2018-08-14	22 days	13.83 ± 17.59	49.06	36.82 ± 2.70	44	27.86 ± 2.25	31	25.39 ± 1.67	1.83 ± 0.29	1.78 ± 0.25
	2018-08-20	2018-08-22	3 days	0.16 ± 0.00	0.16	33.88 ± 0.77	34	25.64 ± 0.39	26	24.29 ± 0.26	1.87 ± 0.14	1.67 ± 0.29
	2018-08-31	2018-09-02	3 days	0.16 ± 0.00	0.16	35.99 ± 0.75	37	25.31 ± 0.21	25	24.19 ± 0.41	1.85 ± 0.21	1.68 ± 0.20

Abbreviations [a] Magnitude Index

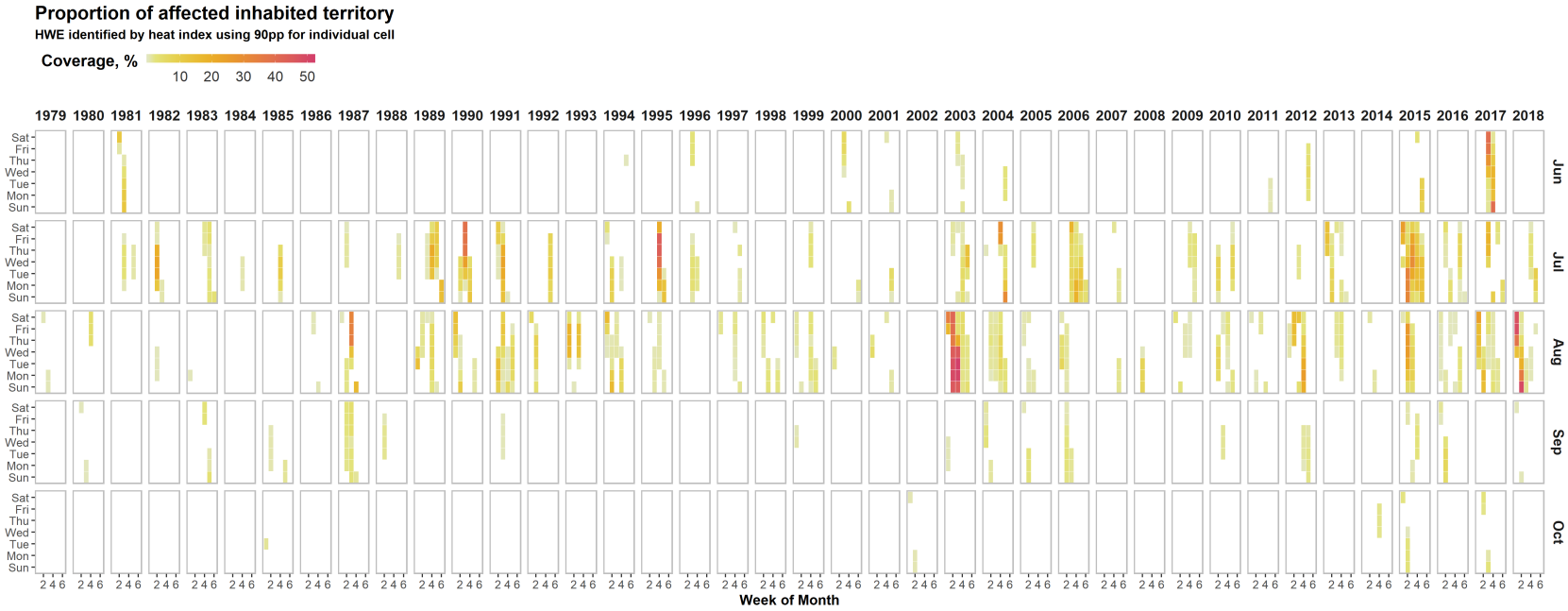


Figure B.11: Proportion of national territory affected by heatwaves identified using heat index (90pp for individual cell)

Table B.6: Summary statistics for heat wave episodes identified by heat index using 95pp for individual cell

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1980	1980-08-21	1980-08-23	3 days	1.73 ± 0.00	1.73	38.60 ± 2.59	42	27.25 ± 1.84	29	26.17 ± 0.57	2.39 ± 0.48	2.47 ± 0.25
1981	1981-06-13	1981-06-17	5 days	1.65 ± 0.94	2.37	37.89 ± 2.00	41	25.23 ± 1.32	27	24.48 ± 0.75	2.06 ± 0.18	2.05 ± 0.18
	1981-07-14	1981-07-16	3 days	0.60 ± 0.00	0.60	37.23 ± 0.53	38	24.75 ± 0.57	25	23.25 ± 0.14	1.86 ± 0.12	2.15 ± 0.24
1982	1982-07-05	1982-07-08	4 days	3.74 ± 2.04	4.85	37.66 ± 1.58	40	25.42 ± 1.12	27	26.03 ± 0.91	1.88 ± 0.21	1.99 ± 0.27
1983	1983-07-24	1983-07-31	8 days	0.30 ± 0.27	0.62	35.66 ± 1.60	39	27.52 ± 1.84	31	24.03 ± 0.98	1.83 ± 0.23	1.65 ± 0.11
1987	1987-08-02	1987-08-04	3 days	0.24 ± 0.00	0.24	36.49 ± 0.63	37	23.86 ± 0.55	24	24.15 ± 1.13	1.96 ± 0.15	2.10 ± 0.21
	1987-08-12	1987-08-16	5 days	13.82 ± 8.47	20.21	38.73 ± 1.82	41	25.98 ± 0.79	27	26.62 ± 0.30	2.52 ± 0.40	2.06 ± 0.23
	1987-09-07	1987-09-20	14 days	1.47 ± 0.64	2.21	33.68 ± 1.81	37	26.11 ± 1.16	28	23.67 ± 0.58	2.77 ± 0.48	2.73 ± 0.72
1989	1989-07-18	1989-07-22	5 days	2.83 ± 1.45	4.71	37.43 ± 2.62	41	25.93 ± 1.98	29	26.24 ± 0.74	2.24 ± 0.32	2.09 ± 0.26
	1989-07-26	1989-08-02	8 days	2.06 ± 1.41	3.74	36.97 ± 1.29	38	25.99 ± 0.62	27	25.60 ± 0.45	2.01 ± 0.09	2.18 ± 0.16
	1989-08-09	1989-08-11	3 days	0.02 ± 0.00	0.02	35.68 ± 0.61	36	27.28 ± 0.68	28	25.01 ± 0.62	2.00 ± 0.16	2.01 ± 0.52
	1989-08-21	1989-08-24	4 days	0.94 ± 0.04	0.97	37.84 ± 0.44	38	27.20 ± 0.86	28	25.89 ± 0.20	2.14 ± 0.14	2.06 ± 0.28
1990	1990-07-09	1990-07-11	3 days	1.31 ± 0.00	1.31	37.14 ± 0.56	38	24.59 ± 0.20	25	23.89 ± 0.39	1.82 ± 0.07	1.99 ± 0.03
	1990-07-17	1990-07-25	9 days	10.95 ± 9.34	22.96	36.57 ± 1.21	39	25.47 ± 1.27	28	26.12 ± 0.53	2.40 ± 0.25	2.41 ± 0.39
	1990-08-02	1990-08-05	4 days	3.53 ± 1.56	4.71	36.30 ± 1.25	37	25.86 ± 0.62	27	25.93 ± 0.22	2.05 ± 0.25	1.99 ± 0.09
1991	1991-07-12	1991-07-19	8 days	5.22 ± 2.62	7.79	39.83 ± 2.31	44	26.23 ± 1.12	28	25.65 ± 0.57	1.92 ± 0.15	2.07 ± 0.20
	1991-08-15	1991-08-17	3 days	1.17 ± 0.00	1.17	38.11 ± 2.34	41	25.41 ± 0.48	26	25.86 ± 0.46	1.92 ± 0.22	1.95 ± 0.10
	1991-08-26	1991-08-29	4 days	0.27 ± 0.06	0.30	36.41 ± 1.34	38	27.48 ± 0.19	28	25.47 ± 0.28	1.74 ± 0.06	1.79 ± 0.13
1993	1993-08-04	1993-08-07	4 days	5.74 ± 3.71	7.59	37.85 ± 1.36	39	27.11 ± 0.32	28	26.00 ± 0.82	2.08 ± 0.22	2.14 ± 0.21
	1993-08-18	1993-08-21	4 days	3.20 ± 2.04	4.27	35.22 ± 2.52	38	25.34 ± 0.40	26	25.79 ± 0.95	2.26 ± 0.34	2.32 ± 0.61
1994	1994-07-02	1994-07-06	5 days	2.56 ± 1.48	3.80	38.06 ± 1.74	39	27.21 ± 1.06	28	25.15 ± 0.96	2.40 ± 0.31	2.01 ± 0.17
	1994-08-06	1994-08-08	3 days	3.58 ± 0.00	3.58	37.33 ± 1.33	39	27.42 ± 1.19	28	26.08 ± 0.37	1.86 ± 0.05	1.78 ± 0.33
	1994-08-21	1994-08-23	3 days	1.91 ± 0.00	1.91	36.84 ± 0.58	37	27.92 ± 0.75	29	25.54 ± 0.69	2.06 ± 0.10	2.29 ± 0.47
1995	1995-07-17	1995-07-22	6 days	19.10 ± 13.25	32.48	39.02 ± 1.41	42	25.64 ± 0.67	27	26.57 ± 0.93	1.99 ± 0.27	2.03 ± 0.26
1996	1996-06-13	1996-06-15	3 days	0.72 ± 0.00	0.72	32.24 ± 0.78	33	22.95 ± 0.20	23	23.21 ± 0.07	2.23 ± 0.29	1.97 ± 0.19
1999	1999-08-27	1999-08-30	4 days	1.87 ± 0.14	1.99	34.00 ± 1.96	36	26.58 ± 0.75	27	24.47 ± 0.47	3.30 ± 0.57	2.76 ± 0.39
2000	2000-06-15	2000-06-18	4 days	1.13 ± 0.46	1.51	32.56 ± 1.09	34	22.48 ± 0.44	23	23.24 ± 0.52	2.22 ± 0.25	2.10 ± 0.33
2001	2001-07-30	2001-08-01	3 days	0.81 ± 0.00	0.81	36.28 ± 1.03	37	27.17 ± 0.31	27	26.58 ± 0.77	1.97 ± 0.12	1.84 ± 0.30
2003	2003-07-20	2003-07-24	5 days	1.12 ± 0.80	1.69	37.01 ± 1.31	39	29.19 ± 1.29	31	24.48 ± 0.35	2.03 ± 0.19	2.28 ± 0.22
	2003-07-30	2003-08-16	18 days	16.23 ± 10.12	32.18	38.99 ± 2.84	48	27.97 ± 0.83	29	26.72 ± 0.74	2.21 ± 0.26	2.08 ± 0.17
	2003-08-18	2003-08-27	10 days	1.12 ± 0.74	2.01	37.38 ± 1.77	40	29.54 ± 0.93	31	24.63 ± 0.69	2.27 ± 0.41	2.61 ± 0.35

Table B.6: Summary statistics for heat wave episodes identified by heat index using 95pp for individual cell *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2004	2004-07-23	2004-07-29	7 days	8.93 ± 6.93	17.77	40.00 ± 6.47	51	28.34 ± 0.93	30	25.69 ± 1.68	3.04 ± 0.51	3.21 ± 1.05
	2004-08-17	2004-08-20	4 days	0.04 ± 0.00	0.04	33.69 ± 1.08	35	27.61 ± 0.46	28	22.74 ± 0.98	2.27 ± 0.37	2.07 ± 0.21
	2004-08-24	2004-09-01	9 days	1.97 ± 0.99	3.28	35.32 ± 3.78	43	27.97 ± 1.51	30	23.22 ± 0.87	3.49 ± 1.16	3.64 ± 1.46
2005	2005-08-13	2005-08-15	3 days	0.02 ± 0.00	0.02	36.30 ± 0.44	37	24.50 ± 0.92	26	24.33 ± 0.17	2.52 ± 0.10	1.82 ± 0.06
	2005-09-04	2005-09-06	3 days	2.46 ± 0.00	2.46	33.42 ± 1.92	35	28.16 ± 1.51	30	22.31 ± 2.04	3.85 ± 1.04	4.10 ± 0.98
2006	2006-07-12	2006-07-28	17 days	2.13 ± 2.31	7.00	36.14 ± 1.01	38	26.90 ± 1.04	29	25.82 ± 0.66	2.05 ± 0.41	1.95 ± 0.30
	2006-07-30	2006-08-01	3 days	0.54 ± 0.00	0.54	37.91 ± 1.18	39	27.48 ± 0.49	28	26.01 ± 0.06	1.74 ± 0.10	1.83 ± 0.27
	2006-08-09	2006-08-11	3 days	0.42 ± 0.00	0.42	36.48 ± 0.67	37	24.33 ± 0.78	25	23.59 ± 0.14	2.25 ± 0.07	1.88 ± 0.09
	2006-09-03	2006-09-06	4 days	0.39 ± 0.20	0.52	36.35 ± 2.56	38	26.70 ± 1.69	28	25.05 ± 0.37	2.47 ± 0.57	2.94 ± 1.22
2007	2007-07-29	2007-07-31	3 days	0.74 ± 0.00	0.74	38.29 ± 1.28	40	27.40 ± 1.86	29	25.67 ± 0.13	3.25 ± 0.66	4.12 ± 1.56
2008	2008-08-03	2008-08-05	3 days	0.40 ± 0.00	0.40	37.45 ± 0.52	38	25.35 ± 0.26	26	26.17 ± 0.23	1.78 ± 0.19	1.74 ± 0.10
2009	2009-07-22	2009-07-24	3 days	0.16 ± 0.00	0.16	37.39 ± 0.64	38	28.11 ± 1.44	30	24.68 ± 0.74	2.13 ± 0.09	2.35 ± 0.67
	2009-07-28	2009-08-02	6 days	1.59 ± 0.95	2.46	34.57 ± 1.51	36	27.56 ± 1.45	29	23.70 ± 0.95	3.16 ± 0.47	3.21 ± 1.24
2010	2010-07-05	2010-07-07	3 days	2.88 ± 0.00	2.88	37.91 ± 0.26	38	25.79 ± 0.28	26	25.09 ± 0.53	1.84 ± 0.09	2.06 ± 0.12
	2010-07-26	2010-07-29	4 days	0.30 ± 0.11	0.36	37.12 ± 0.73	38	25.01 ± 0.11	25	24.63 ± 0.73	2.26 ± 0.30	1.97 ± 0.14
	2010-08-09	2010-08-12	4 days	1.44 ± 0.94	1.91	37.80 ± 1.36	39	27.72 ± 1.21	29	25.27 ± 0.56	2.05 ± 0.27	2.28 ± 0.19
	2010-08-26	2010-08-30	5 days	0.74 ± 0.13	0.81	37.52 ± 1.62	40	27.49 ± 1.30	29	24.65 ± 1.60	3.12 ± 0.24	2.98 ± 1.08
	2010-09-14	2010-09-16	3 days	0.81 ± 0.00	0.81	32.08 ± 1.51	34	25.04 ± 0.55	25	22.06 ± 0.40	3.48 ± 0.70	2.58 ± 0.41
2012	2012-08-09	2012-08-12	4 days	4.58 ± 2.81	6.08	39.87 ± 2.03	42	27.24 ± 1.16	29	26.57 ± 1.62	2.44 ± 0.21	1.90 ± 0.07
	2012-08-18	2012-08-25	8 days	2.70 ± 1.61	4.67	37.94 ± 1.10	40	28.21 ± 0.99	30	25.97 ± 1.30	2.35 ± 0.58	2.39 ± 0.49
	2012-09-23	2012-09-26	4 days	0.98 ± 0.58	1.27	30.72 ± 0.91	31	24.91 ± 0.43	25	19.18 ± 2.47	2.43 ± 0.08	2.13 ± 0.16
2013	2013-07-04	2013-07-09	6 days	2.93 ± 1.49	4.59	37.13 ± 0.60	38	24.63 ± 0.79	26	24.82 ± 0.33	2.30 ± 0.39	2.13 ± 0.23
	2013-08-15	2013-08-17	3 days	0.83 ± 0.00	0.83	34.66 ± 0.90	35	27.42 ± 1.50	28	24.53 ± 0.39	3.74 ± 0.98	3.84 ± 1.00
	2013-08-21	2013-08-24	4 days	1.27 ± 0.07	1.31	34.84 ± 1.10	36	26.44 ± 1.19	28	24.43 ± 0.58	2.67 ± 0.67	3.09 ± 0.73
2015	2015-06-28	2015-06-30	3 days	0.64 ± 0.00	0.64	37.26 ± 1.43	39	24.85 ± 0.73	25	26.15 ± 0.29	1.94 ± 0.24	1.81 ± 0.10
	2015-07-03	2015-07-09	7 days	10.41 ± 7.31	17.91	37.58 ± 0.83	38	26.61 ± 0.73	28	26.21 ± 0.73	1.83 ± 0.13	1.81 ± 0.14
	2015-07-13	2015-07-30	18 days	4.85 ± 2.92	9.46	37.69 ± 1.51	42	28.05 ± 1.94	32	26.17 ± 0.87	2.05 ± 0.35	2.06 ± 0.46
	2015-08-02	2015-08-14	13 days	5.53 ± 4.54	12.94	37.43 ± 1.70	41	29.23 ± 1.45	32	25.15 ± 1.46	2.29 ± 0.29	2.49 ± 0.51
	2015-09-11	2015-09-13	3 days	0.18 ± 0.00	0.18	31.14 ± 1.25	32	25.00 ± 0.11	25	20.77 ± 0.58	2.18 ± 0.28	2.03 ± 0.05
	2015-09-22	2015-09-25	4 days	0.86 ± 0.38	1.05	30.48 ± 1.34	32	25.34 ± 0.21	26	18.89 ± 0.69	3.08 ± 0.83	2.28 ± 0.21
	2015-10-03	2015-10-06	4 days	2.04 ± 0.49	2.46	32.25 ± 1.97	35	26.73 ± 1.84	29	19.59 ± 1.57	3.62 ± 1.12	2.90 ± 0.93
2016	2016-07-27	2016-08-03	8 days	0.05 ± 0.04	0.10	35.81 ± 0.71	37	26.00 ± 1.19	28	25.25 ± 0.55	1.94 ± 0.30	2.06 ± 0.57
	2016-08-28	2016-08-31	4 days	0.70 ± 0.43	0.93	33.67 ± 2.08	36	25.65 ± 0.98	27	23.94 ± 1.00	2.47 ± 0.38	2.53 ± 0.32
	2016-09-04	2016-09-07	4 days	0.60 ± 0.27	0.80	38.28 ± 1.26	40	25.78 ± 0.81	27	26.02 ± 0.26	2.20 ± 0.27	1.91 ± 0.11

Table B.6: Summary statistics for heat wave episodes identified by heat index using 95pp for individual cell *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2017	2017-06-14	2017-06-23	10 days	6.14 ± 7.06	16.80	36.79 ± 1.20	39	25.61 ± 1.03	27	26.00 ± 0.47	1.92 ± 0.19	1.87 ± 0.16
	2017-07-12	2017-07-16	5 days	5.12 ± 2.85	7.65	39.00 ± 2.08	41	26.39 ± 1.02	28	26.05 ± 0.58	2.27 ± 0.51	1.95 ± 0.26
	2017-07-31	2017-08-08	9 days	6.49 ± 4.68	12.60	38.00 ± 1.14	40	31.25 ± 1.58	33	25.57 ± 1.42	2.18 ± 0.16	2.46 ± 0.29
	2017-08-19	2017-08-21	3 days	0.06 ± 0.00	0.06	37.15 ± 0.61	38	26.23 ± 1.04	27	25.08 ± 0.30	2.29 ± 0.11	2.03 ± 0.18
	2017-10-13	2017-10-15	3 days	0.99 ± 0.00	0.99	31.44 ± 0.14	32	26.83 ± 1.36	28	20.34 ± 0.75	3.21 ± 0.11	3.24 ± 1.00
2018	2018-07-29	2018-08-14	17 days	9.80 ± 11.53	31.58	37.50 ± 2.70	44	28.63 ± 1.97	31	25.66 ± 1.81	2.07 ± 0.29	2.06 ± 0.35

Abbreviations [a] Magnitude Index

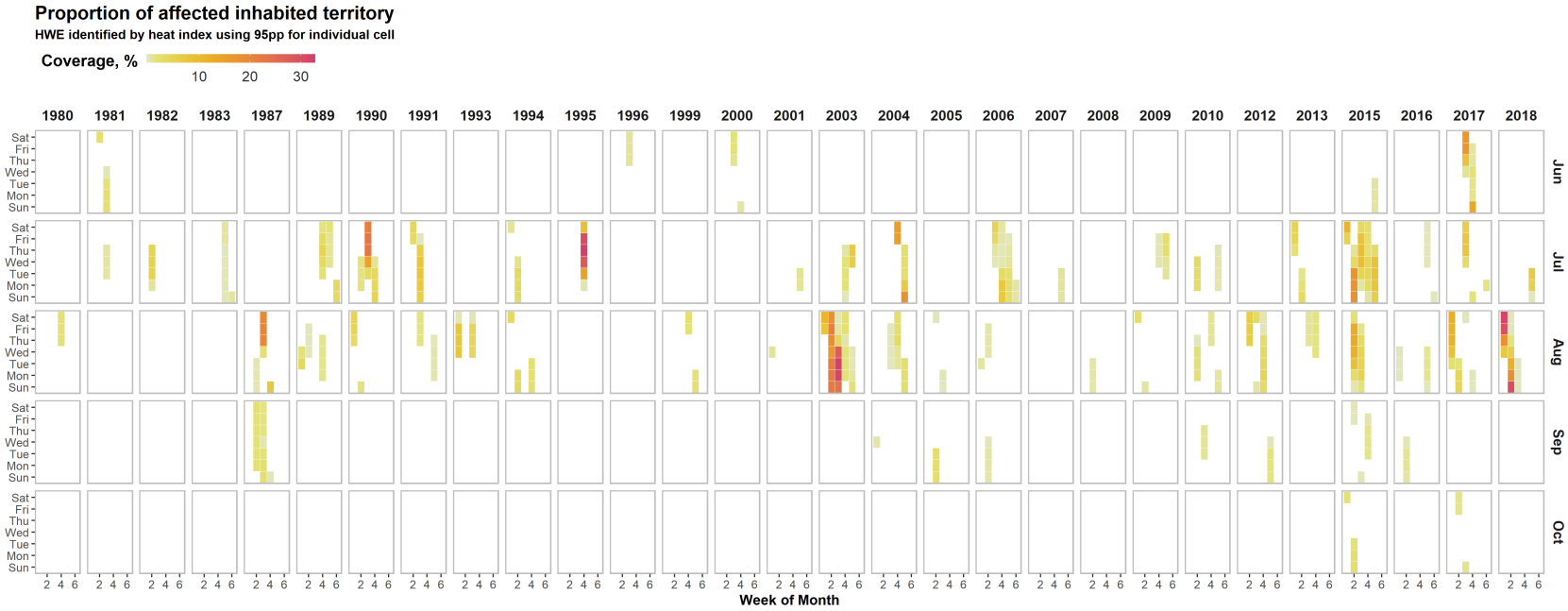


Figure B.12: Proportion of national territory affected by heatwaves identified using heat index (95pp for individual cell)

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1979	1979-07-09	1979-07-12	4 days	0.06 ± 0.03	0.08	32.80 ± 3.46	36	24.05 ± 1.21	25	23.11 ± 1.71	2.07 ± 0.38	1.75 ± 0.40
	1979-07-14	1979-07-19	6 days	0.08 ± 0.03	0.14	33.97 ± 0.91	35	23.09 ± 0.47	24	23.01 ± 1.02	1.82 ± 0.32	1.80 ± 0.29
	1979-07-24	1979-08-07	15 days	1.00 ± 0.70	2.41	35.06 ± 2.23	41	24.24 ± 0.77	26	24.04 ± 0.99	1.66 ± 0.12	1.83 ± 0.10
	1979-08-10	1979-08-15	6 days	0.78 ± 0.72	1.49	35.74 ± 1.09	36	24.40 ± 0.57	25	23.66 ± 1.05	1.66 ± 0.18	1.63 ± 0.06
	1979-09-10	1979-09-12	3 days	0.02 ± 0.00	0.02	32.49 ± 0.86	33	23.40 ± 0.31	24	22.03 ± 0.63	1.40 ± 0.06	1.86 ± 0.16
1980	1980-07-22	1980-07-24	3 days	0.24 ± 0.00	0.24	35.41 ± 1.25	37	23.09 ± 0.38	23	23.89 ± 0.98	1.78 ± 0.13	1.87 ± 0.29
	1980-08-01	1980-08-07	7 days	1.02 ± 0.42	1.33	35.64 ± 1.36	38	24.71 ± 0.64	26	24.48 ± 0.69	1.74 ± 0.14	1.78 ± 0.18
	1980-08-09	1980-08-15	7 days	0.10 ± 0.10	0.22	33.51 ± 0.84	35	23.98 ± 0.55	25	23.42 ± 1.01	1.50 ± 0.11	1.90 ± 0.20
	1980-08-20	1980-08-24	5 days	2.00 ± 1.62	3.20	37.16 ± 2.74	42	26.50 ± 1.68	29	25.33 ± 1.22	2.08 ± 0.49	2.17 ± 0.28
	1980-08-28	1980-08-31	4 days	0.02 ± 0.00	0.02	38.27 ± 2.39	41	24.07 ± 0.38	25	23.78 ± 0.83	2.11 ± 0.27	1.88 ± 0.26
	1980-09-12	1980-09-15	4 days	0.02 ± 0.00	0.02	34.59 ± 1.23	36	24.18 ± 0.68	25	22.55 ± 0.27	1.70 ± 0.18	2.08 ± 0.20
1981	1981-06-11	1981-06-20	10 days	4.16 ± 3.58	8.05	36.95 ± 2.33	41	23.97 ± 1.69	27	23.19 ± 1.84	1.85 ± 0.39	1.72 ± 0.20
	1981-07-13	1981-07-17	5 days	3.81 ± 1.96	5.21	36.43 ± 1.18	38	24.27 ± 1.01	25	23.10 ± 0.41	1.77 ± 0.24	1.77 ± 0.17
	1981-07-27	1981-07-31	5 days	0.46 ± 0.24	0.74	35.21 ± 2.33	38	24.08 ± 2.00	27	24.05 ± 1.51	2.27 ± 0.77	1.95 ± 0.47
	1981-08-11	1981-08-16	6 days	0.08 ± 0.00	0.08	33.67 ± 1.86	37	23.15 ± 0.55	24	23.15 ± 0.51	1.54 ± 0.14	1.76 ± 0.19
	1981-08-26	1981-08-28	3 days	0.04 ± 0.00	0.04	32.58 ± 0.52	33	23.74 ± 1.04	24	22.31 ± 0.06	1.51 ± 0.10	1.69 ± 0.17
1982	1982-07-01	1982-07-23	23 days	2.29 ± 3.66	11.11	34.05 ± 2.55	40	25.71 ± 0.94	28	23.56 ± 1.70	1.73 ± 0.36	1.99 ± 0.40
	1982-08-09	1982-08-20	12 days	0.20 ± 0.14	0.36	34.83 ± 2.62	41	24.75 ± 1.20	28	23.72 ± 0.72	1.59 ± 0.25	1.98 ± 0.48
1983	1983-06-05	1983-06-07	3 days	0.16 ± 0.00	0.16	30.36 ± 0.93	31	20.75 ± 0.28	21	21.42 ± 0.11	2.09 ± 0.34	1.64 ± 0.28
	1983-06-12	1983-06-14	3 days	0.02 ± 0.00	0.02	34.35 ± 0.80	35	24.45 ± 0.85	25	21.80 ± 1.17	1.74 ± 0.25	2.01 ± 0.28
	1983-07-08	1983-08-04	28 days	2.82 ± 1.81	6.14	34.18 ± 1.64	39	25.76 ± 1.99	31	23.81 ± 0.89	1.82 ± 0.29	1.81 ± 0.16
	1983-09-05	1983-09-08	4 days	0.24 ± 0.12	0.30	35.40 ± 1.51	37	24.95 ± 0.91	26	23.36 ± 0.38	1.49 ± 0.05	1.83 ± 0.25
	1983-09-23	1983-09-27	5 days	0.50 ± 0.22	0.83	32.68 ± 1.32	35	24.56 ± 1.22	26	23.21 ± 0.92	2.03 ± 0.04	2.07 ± 0.43
	1983-10-11	1983-10-15	5 days	0.12 ± 0.06	0.20	28.34 ± 0.30	29	25.14 ± 0.46	26	17.59 ± 1.25	1.75 ± 0.14	2.30 ± 0.39
1984	1984-07-15	1984-07-25	11 days	0.39 ± 0.42	1.05	34.98 ± 2.07	38	23.60 ± 1.23	26	23.71 ± 1.21	1.64 ± 0.17	1.71 ± 0.17
	1984-07-27	1984-07-29	3 days	0.02 ± 0.00	0.02	35.77 ± 1.39	37	23.88 ± 0.19	24	23.95 ± 0.20	1.75 ± 0.15	1.83 ± 0.20
	1984-08-06	1984-08-08	3 days	0.02 ± 0.00	0.02	33.94 ± 0.46	34	23.80 ± 0.22	24	21.62 ± 0.59	1.50 ± 0.12	1.94 ± 0.26
1985	1985-06-26	1985-07-02	7 days	0.06 ± 0.03	0.10	32.98 ± 0.64	34	22.36 ± 0.47	23	22.44 ± 0.69	1.54 ± 0.15	1.76 ± 0.14
	1985-07-05	1985-07-29	25 days	1.83 ± 3.14	9.78	34.51 ± 1.63	38	24.29 ± 0.84	27	24.13 ± 1.07	1.72 ± 0.18	1.75 ± 0.19
	1985-08-02	1985-08-05	4 days	0.24 ± 0.11	0.30	38.22 ± 4.66	45	24.84 ± 1.35	27	24.15 ± 1.30	1.78 ± 0.25	1.86 ± 0.37
	1985-08-14	1985-08-16	3 days	0.06 ± 0.00	0.06	33.01 ± 0.35	33	24.27 ± 0.15	24	22.95 ± 0.26	1.99 ± 0.19	1.59 ± 0.18
	1985-08-18	1985-08-24	7 days	0.61 ± 0.41	0.99	35.67 ± 1.52	38	24.63 ± 0.51	25	24.19 ± 0.74	1.71 ± 0.25	1.80 ± 0.19
	1985-09-09	1985-09-11	3 days	0.04 ± 0.00	0.04	33.01 ± 1.14	34	24.54 ± 0.55	25	23.13 ± 0.11	2.11 ± 0.20	1.57 ± 0.18
	1985-09-14	1985-09-16	3 days	0.02 ± 0.00	0.02	33.43 ± 0.98	35	24.01 ± 0.38	24	21.35 ± 1.15	1.51 ± 0.11	1.95 ± 0.17
	1985-09-29	1985-10-01	3 days	1.31 ± 0.00	1.31	30.75 ± 0.84	32	24.81 ± 0.27	25	22.02 ± 0.35	1.97 ± 0.25	2.04 ± 0.22

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1986	1986-07-02	1986-07-06	5 days	0.28 ± 0.22	0.44	34.69 ± 1.31	36	23.46 ± 0.56	24	23.76 ± 0.78	1.65 ± 0.12	1.68 ± 0.21
	1986-07-08	1986-07-11	4 days	0.04 ± 0.01	0.04	34.05 ± 0.67	35	23.77 ± 0.41	24	23.65 ± 0.23	1.82 ± 0.10	1.62 ± 0.14
	1986-07-15	1986-07-18	4 days	0.14 ± 0.07	0.18	35.33 ± 1.92	37	22.67 ± 0.19	23	22.79 ± 0.78	1.68 ± 0.31	1.81 ± 0.20
	1986-07-28	1986-08-04	8 days	0.55 ± 0.17	0.74	34.69 ± 1.45	37	24.74 ± 0.81	26	23.97 ± 1.07	1.70 ± 0.18	1.76 ± 0.14
	1986-08-06	1986-08-11	6 days	0.10 ± 0.05	0.14	33.33 ± 0.76	35	25.12 ± 1.26	27	23.15 ± 0.41	1.88 ± 0.31	1.74 ± 0.22
	1986-08-14	1986-08-23	10 days	1.01 ± 1.11	2.66	34.89 ± 1.55	37	26.20 ± 1.13	28	23.79 ± 0.89	1.61 ± 0.19	1.82 ± 0.17
	1986-09-06	1986-09-08	3 days	0.12 ± 0.00	0.12	29.63 ± 0.83	30	24.85 ± 0.80	26	21.98 ± 0.52	2.04 ± 0.34	2.27 ± 0.57
1987	1987-06-26	1987-06-29	4 days	0.28 ± 0.13	0.34	33.99 ± 1.34	36	22.28 ± 0.55	23	23.06 ± 0.78	1.58 ± 0.18	1.77 ± 0.32
	1987-07-01	1987-07-12	12 days	0.61 ± 0.28	0.89	34.18 ± 3.52	45	24.03 ± 0.87	25	24.01 ± 0.49	1.52 ± 0.11	1.82 ± 0.18
	1987-08-01	1987-08-05	5 days	0.51 ± 0.43	0.83	35.95 ± 0.87	37	23.89 ± 0.70	25	23.80 ± 1.25	1.87 ± 0.39	1.84 ± 0.24
	1987-08-10	1987-08-23	14 days	6.72 ± 7.15	20.23	36.13 ± 2.64	41	25.66 ± 0.63	27	25.51 ± 1.32	1.94 ± 0.56	1.86 ± 0.21
	1987-09-07	1987-09-21	15 days	1.54 ± 0.81	2.44	33.64 ± 1.76	37	26.06 ± 1.14	28	23.59 ± 0.64	2.41 ± 0.46	2.50 ± 0.74
1988	1988-07-10	1988-08-03	25 days	0.36 ± 0.53	1.81	36.25 ± 2.33	41	24.37 ± 0.81	27	23.86 ± 1.14	1.85 ± 0.31	1.88 ± 0.28
	1988-08-07	1988-08-20	14 days	0.64 ± 0.32	0.97	33.77 ± 0.98	35	25.34 ± 0.85	27	24.05 ± 0.52	1.65 ± 0.10	1.71 ± 0.12
	1988-08-23	1988-08-28	6 days	0.02 ± 0.00	0.02	35.07 ± 1.86	38	24.89 ± 0.37	25	22.57 ± 1.35	1.74 ± 0.14	1.99 ± 0.25
	1988-09-05	1988-09-09	5 days	1.38 ± 0.92	2.09	36.36 ± 0.72	37	25.07 ± 0.62	26	24.78 ± 0.89	1.76 ± 0.14	1.71 ± 0.21
1989	1989-06-21	1989-06-23	3 days	0.04 ± 0.00	0.04	32.24 ± 1.27	33	22.42 ± 0.40	23	22.67 ± 0.31	1.83 ± 0.04	1.67 ± 0.22
	1989-07-10	1989-08-03	25 days	6.20 ± 6.28	16.18	36.33 ± 1.86	41	25.45 ± 1.16	29	24.99 ± 1.08	1.85 ± 0.32	1.87 ± 0.27
	1989-08-06	1989-08-27	22 days	1.81 ± 1.90	6.48	35.25 ± 1.63	38	26.60 ± 0.88	28	24.73 ± 0.85	1.70 ± 0.15	1.94 ± 0.27
	1989-10-07	1989-10-09	3 days	0.12 ± 0.00	0.12	29.97 ± 1.39	31	25.27 ± 0.78	26	17.31 ± 1.45	2.61 ± 0.70	2.56 ± 0.56
1990	1990-07-03	1990-07-13	11 days	2.43 ± 3.53	8.03	34.63 ± 1.71	38	24.05 ± 0.66	25	22.94 ± 0.98	1.60 ± 0.21	1.82 ± 0.12
	1990-07-15	1990-07-28	14 days	11.46 ± 10.58	28.42	35.41 ± 2.09	39	25.38 ± 1.28	28	25.01 ± 1.68	1.94 ± 0.24	1.91 ± 0.14
	1990-07-31	1990-08-22	23 days	1.95 ± 2.57	8.27	34.37 ± 1.53	37	25.39 ± 0.85	27	24.39 ± 1.07	1.78 ± 0.32	2.00 ± 0.51
	1990-08-24	1990-08-29	6 days	0.35 ± 0.27	0.60	32.16 ± 0.67	33	25.28 ± 0.39	26	23.39 ± 0.52	1.82 ± 0.19	2.17 ± 0.52
	1990-09-03	1990-09-05	3 days	0.02 ± 0.00	0.02	32.58 ± 0.96	33	24.55 ± 0.11	25	22.93 ± 0.15	1.46 ± 0.08	2.03 ± 0.13
1991	1991-06-24	1991-06-27	4 days	0.20 ± 0.09	0.26	35.94 ± 1.64	38	22.64 ± 0.93	23	23.37 ± 0.71	1.88 ± 0.25	1.61 ± 0.12
	1991-07-09	1991-07-28	20 days	7.25 ± 7.61	20.85	36.96 ± 3.02	44	25.41 ± 1.18	28	24.82 ± 1.07	1.75 ± 0.24	1.85 ± 0.16
	1991-08-02	1991-08-09	8 days	5.39 ± 5.86	12.76	36.21 ± 2.34	39	25.07 ± 0.66	26	24.29 ± 2.21	1.67 ± 0.23	1.76 ± 0.25
	1991-08-11	1991-08-31	21 days	4.98 ± 4.21	13.22	35.82 ± 2.63	44	26.09 ± 1.57	29	24.77 ± 1.19	1.80 ± 0.29	1.80 ± 0.21
	1991-09-17	1991-09-19	3 days	0.06 ± 0.00	0.06	34.23 ± 0.27	35	24.45 ± 0.30	25	23.74 ± 0.06	1.54 ± 0.07	1.64 ± 0.04
1992	1992-07-15	1992-07-21	7 days	0.66 ± 0.68	1.39	33.97 ± 1.92	37	23.49 ± 0.96	25	23.96 ± 0.73	1.81 ± 0.27	1.72 ± 0.21
	1992-07-23	1992-08-08	17 days	6.37 ± 5.23	17.09	35.27 ± 2.29	41	25.65 ± 1.01	27	25.33 ± 1.03	1.96 ± 0.34	1.87 ± 0.19
	1992-08-16	1992-08-28	13 days	0.76 ± 0.41	1.27	34.03 ± 1.78	37	25.45 ± 0.87	27	24.08 ± 1.24	1.62 ± 0.08	1.76 ± 0.15
	1992-09-14	1992-09-16	3 days	0.02 ± 0.00	0.02	33.96 ± 0.90	35	23.89 ± 0.58	24	22.30 ± 0.62	1.58 ± 0.08	1.91 ± 0.21
1993	1993-07-14	1993-07-19	6 days	0.37 ± 0.26	0.64	34.28 ± 0.82	36	23.34 ± 1.27	24	23.46 ± 0.68	1.58 ± 0.10	1.60 ± 0.11
	1993-07-22	1993-07-30	9 days	0.27 ± 0.33	0.72	35.22 ± 1.65	39	24.07 ± 1.31	26	23.62 ± 1.48	1.69 ± 0.24	1.75 ± 0.32
	1993-08-02	1993-08-08	7 days	10.24 ± 10.24	21.59	36.44 ± 2.20	39	26.42 ± 1.42	28	24.96 ± 1.44	1.71 ± 0.23	1.75 ± 0.14
	1993-08-10	1993-08-14	5 days	0.11 ± 0.06	0.18	33.06 ± 1.50	35	24.41 ± 0.53	25	23.70 ± 0.81	1.69 ± 0.31	1.91 ± 0.23
	1993-08-17	1993-08-23	7 days	2.63 ± 2.55	5.61	34.31 ± 2.14	38	25.14 ± 0.39	26	24.92 ± 1.34	2.20 ± 0.24	1.80 ± 0.24

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1994	1994-06-28	1994-07-06	9 days	5.40 ± 3.89	10.75	36.63 ± 2.21	39	25.22 ± 2.69	28	24.55 ± 1.23	1.86 ± 0.26	1.74 ± 0.20
	1994-07-08	1994-08-13	37 days	2.18 ± 3.53	13.91	34.40 ± 1.63	39	26.09 ± 1.37	31	24.47 ± 1.09	1.72 ± 0.24	1.85 ± 0.20
	1994-08-15	1994-08-24	10 days	3.90 ± 3.59	9.40	36.44 ± 1.25	39	27.77 ± 0.66	29	25.03 ± 1.09	1.78 ± 0.21	1.76 ± 0.20
	1994-08-26	1994-09-01	7 days	0.51 ± 0.42	1.01	34.98 ± 0.96	36	26.10 ± 0.87	28	23.76 ± 1.37	1.63 ± 0.18	2.08 ± 0.47
1995	1995-06-29	1995-07-02	4 days	0.02 ± 0.00	0.02	30.30 ± 0.26	31	22.93 ± 0.83	24	22.04 ± 0.95	1.99 ± 0.13	1.55 ± 0.12
	1995-07-12	1995-08-06	26 days	8.22 ± 11.58	35.02	35.73 ± 3.10	42	25.34 ± 1.01	27	24.93 ± 1.54	1.81 ± 0.23	1.82 ± 0.16
	1995-08-09	1995-08-17	9 days	2.12 ± 1.83	4.79	36.55 ± 2.12	39	26.28 ± 1.27	28	25.11 ± 0.62	1.62 ± 0.15	1.79 ± 0.17
	1995-08-24	1995-08-28	5 days	0.04 ± 0.02	0.06	34.68 ± 1.16	36	23.97 ± 0.26	24	22.42 ± 0.34	1.77 ± 0.29	1.69 ± 0.21
1996	1996-06-12	1996-06-16	5 days	0.69 ± 0.51	1.07	32.32 ± 0.70	33	22.63 ± 0.59	23	23.25 ± 0.35	2.25 ± 0.21	1.70 ± 0.25
	1996-06-19	1996-06-21	3 days	0.02 ± 0.00	0.02	30.65 ± 1.08	31	23.26 ± 0.73	24	21.67 ± 1.43	1.91 ± 0.14	1.66 ± 0.25
	1996-06-29	1996-07-01	3 days	0.12 ± 0.00	0.12	34.14 ± 1.48	35	22.13 ± 0.27	22	22.57 ± 0.28	1.70 ± 0.19	1.88 ± 0.16
	1996-07-14	1996-07-26	13 days	3.03 ± 1.84	6.04	34.56 ± 2.28	39	24.39 ± 1.32	27	24.42 ± 1.13	1.95 ± 0.21	1.79 ± 0.28
	1996-07-28	1996-08-06	10 days	0.17 ± 0.17	0.44	33.33 ± 1.26	36	24.79 ± 0.36	25	23.66 ± 0.53	1.73 ± 0.25	1.75 ± 0.20
	1996-08-18	1996-08-20	3 days	0.02 ± 0.00	0.02	32.45 ± 0.95	34	24.93 ± 0.48	25	22.90 ± 1.01	1.96 ± 0.15	1.76 ± 0.34
1997	1997-06-11	1997-06-13	3 days	0.08 ± 0.00	0.08	32.24 ± 2.35	35	23.09 ± 0.78	24	21.58 ± 0.43	2.07 ± 0.03	1.62 ± 0.19
	1997-07-13	1997-07-15	3 days	0.02 ± 0.00	0.02	31.28 ± 1.56	33	23.70 ± 1.23	25	22.97 ± 0.36	2.16 ± 0.16	1.78 ± 0.61
	1997-07-26	1997-08-04	10 days	1.46 ± 1.00	3.10	34.55 ± 1.34	37	24.41 ± 0.71	26	24.66 ± 0.32	1.73 ± 0.12	1.79 ± 0.20
	1997-08-07	1997-08-10	4 days	0.20 ± 0.05	0.22	32.69 ± 1.93	35	26.21 ± 1.62	28	23.17 ± 1.26	1.87 ± 0.20	1.76 ± 0.16
	1997-08-13	1997-08-24	12 days	1.23 ± 0.90	2.80	33.01 ± 1.36	35	24.80 ± 0.44	26	24.64 ± 0.48	2.04 ± 0.42	1.92 ± 0.21
1998	1998-06-21	1998-06-23	3 days	0.02 ± 0.00	0.02	33.93 ± 0.70	35	22.29 ± 0.52	23	22.84 ± 0.15	1.46 ± 0.12	1.69 ± 0.13
	1998-06-27	1998-07-03	7 days	0.13 ± 0.05	0.16	32.81 ± 2.02	35	24.23 ± 0.77	25	22.52 ± 1.27	1.93 ± 0.15	1.75 ± 0.21
	1998-07-10	1998-07-31	22 days	1.24 ± 1.50	3.78	35.75 ± 1.95	39	24.61 ± 0.77	26	24.25 ± 1.04	1.73 ± 0.17	1.77 ± 0.18
	1998-08-05	1998-08-27	23 days	2.03 ± 1.95	6.86	35.11 ± 1.71	38	25.19 ± 0.92	28	24.57 ± 0.70	1.76 ± 0.33	1.78 ± 0.23
	1998-08-31	1998-09-04	5 days	0.10 ± 0.06	0.16	34.26 ± 1.47	36	25.94 ± 1.05	28	24.24 ± 0.84	1.64 ± 0.23	1.94 ± 0.18
1999	1999-06-21	1999-06-23	3 days	0.06 ± 0.00	0.06	33.45 ± 1.39	35	22.40 ± 0.42	23	21.52 ± 0.53	1.64 ± 0.20	1.79 ± 0.18
	1999-06-30	1999-07-25	26 days	1.34 ± 1.72	5.74	34.74 ± 2.52	39	24.81 ± 0.90	27	24.03 ± 0.99	1.78 ± 0.22	1.73 ± 0.19
	1999-07-29	1999-08-01	4 days	0.10 ± 0.01	0.10	32.53 ± 0.33	33	25.00 ± 0.53	26	23.85 ± 0.25	1.43 ± 0.09	1.68 ± 0.09
	1999-08-04	1999-08-10	7 days	1.03 ± 0.77	1.93	34.39 ± 0.69	35	27.50 ± 1.01	30	23.63 ± 1.09	1.92 ± 0.36	1.93 ± 0.26
	1999-08-13	1999-08-18	6 days	0.19 ± 0.10	0.30	35.42 ± 3.06	41	25.76 ± 0.91	27	24.01 ± 0.94	1.54 ± 0.19	1.98 ± 0.15
	1999-08-20	1999-09-02	14 days	1.91 ± 1.49	3.92	34.48 ± 1.92	37	26.51 ± 1.58	30	24.73 ± 0.87	1.97 ± 0.69	2.20 ± 0.47

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2000	2000-06-15	2000-06-17	3 days	0.97 ± 0.00	0.97	32.93 ± 0.98	34	22.57 ± 0.49	23	23.25 ± 0.63	1.96 ± 0.02	1.85 ± 0.01
	2000-06-24	2000-07-03	10 days	0.29 ± 0.27	0.68	34.35 ± 1.11	36	24.58 ± 1.39	27	23.15 ± 0.74	1.77 ± 0.22	1.70 ± 0.26
	2000-07-06	2000-07-08	3 days	0.04 ± 0.00	0.04	34.53 ± 1.97	37	26.03 ± 1.51	27	23.19 ± 1.02	1.60 ± 0.07	1.75 ± 0.14
	2000-07-14	2000-07-17	4 days	0.11 ± 0.02	0.12	35.48 ± 1.43	37	23.36 ± 1.00	24	22.51 ± 0.18	1.71 ± 0.08	1.90 ± 0.27
	2000-07-19	2000-07-22	4 days	0.07 ± 0.03	0.10	34.16 ± 2.07	36	23.80 ± 0.51	24	24.11 ± 0.67	1.62 ± 0.13	1.69 ± 0.24
	2000-07-29	2000-08-04	7 days	4.08 ± 3.99	8.77	36.14 ± 2.37	39	25.44 ± 0.88	27	23.99 ± 1.89	1.70 ± 0.24	1.77 ± 0.17
	2000-08-08	2000-08-10	3 days	0.02 ± 0.00	0.02	34.36 ± 0.81	35	23.15 ± 0.08	23	23.59 ± 0.85	1.48 ± 0.11	1.80 ± 0.08
	2000-08-13	2000-08-22	10 days	0.82 ± 0.70	1.81	35.78 ± 3.70	45	25.42 ± 1.15	28	24.13 ± 1.51	1.70 ± 0.19	1.80 ± 0.18
	2000-08-24	2000-08-26	3 days	0.46 ± 0.00	0.46	34.39 ± 2.07	37	27.71 ± 0.95	29	23.27 ± 0.73	1.78 ± 0.14	1.88 ± 0.18
	2000-08-28	2000-08-30	3 days	0.02 ± 0.00	0.02	33.13 ± 0.51	34	24.92 ± 0.54	26	22.71 ± 0.43	1.49 ± 0.19	2.21 ± 0.23
	2000-09-08	2000-09-10	3 days	0.10 ± 0.00	0.10	33.28 ± 0.35	34	23.18 ± 0.56	24	22.93 ± 0.15	1.53 ± 0.12	1.65 ± 0.11
2001	2001-05-28	2001-06-01	5 days	0.06 ± 0.03	0.08	33.07 ± 0.62	34	21.83 ± 0.62	23	22.39 ± 0.27	1.41 ± 0.07	1.73 ± 0.14
	2001-06-20	2001-06-26	7 days	1.24 ± 1.19	2.54	35.35 ± 1.75	39	23.35 ± 1.77	26	23.83 ± 0.98	1.69 ± 0.10	1.64 ± 0.08
	2001-06-30	2001-07-03	4 days	0.98 ± 0.20	1.13	34.78 ± 1.12	36	23.42 ± 0.64	24	24.48 ± 0.60	1.59 ± 0.06	1.74 ± 0.19
	2001-07-10	2001-07-14	5 days	0.15 ± 0.08	0.24	35.05 ± 1.74	37	24.42 ± 0.43	25	23.81 ± 0.67	1.58 ± 0.16	1.81 ± 0.18
	2001-07-24	2001-08-14	22 days	1.28 ± 2.29	6.92	34.86 ± 2.81	45	25.58 ± 1.20	27	24.40 ± 1.07	1.75 ± 0.30	1.90 ± 0.24
	2001-08-18	2001-08-30	13 days	1.52 ± 1.31	3.36	33.73 ± 1.30	36	25.73 ± 1.10	29	24.22 ± 1.20	1.90 ± 0.36	1.96 ± 0.47
	2001-09-02	2001-09-04	3 days	0.02 ± 0.00	0.02	32.85 ± 0.79	34	24.15 ± 0.08	24	22.38 ± 0.90	1.43 ± 0.06	2.20 ± 0.27
	2001-09-27	2001-09-30	4 days	0.12 ± 0.00	0.12	28.44 ± 0.18	29	24.38 ± 0.23	25	18.74 ± 0.52	1.81 ± 0.13	1.90 ± 0.18
	2001-10-25	2001-10-27	3 days	0.12 ± 0.00	0.12	30.17 ± 1.48	32	24.34 ± 0.11	24	15.70 ± 0.53	2.22 ± 0.37	1.89 ± 0.09
2002	2002-06-15	2002-06-27	13 days	0.15 ± 0.14	0.40	33.73 ± 2.23	38	22.90 ± 0.96	24	23.04 ± 0.80	2.03 ± 0.40	1.72 ± 0.23
	2002-07-19	2002-07-23	5 days	0.18 ± 0.06	0.28	33.21 ± 1.78	36	24.11 ± 0.84	25	23.24 ± 0.91	1.85 ± 0.32	1.71 ± 0.27
	2002-07-25	2002-07-30	6 days	1.26 ± 0.86	2.19	35.27 ± 1.57	37	24.31 ± 0.56	25	24.33 ± 0.67	1.65 ± 0.11	1.68 ± 0.13
	2002-08-03	2002-08-06	4 days	0.04 ± 0.01	0.04	33.44 ± 0.38	34	25.61 ± 1.72	28	22.70 ± 0.31	1.42 ± 0.08	1.92 ± 0.11
	2002-08-14	2002-08-21	8 days	0.26 ± 0.13	0.42	32.61 ± 0.90	34	24.43 ± 0.74	26	23.63 ± 0.22	1.68 ± 0.20	1.58 ± 0.12
	2002-10-05	2002-10-07	3 days	0.54 ± 0.00	0.54	29.80 ± 1.34	31	25.24 ± 0.29	26	17.79 ± 0.81	2.36 ± 0.55	2.29 ± 0.39
2003	2003-06-09	2003-06-27	19 days	1.23 ± 1.09	3.24	34.52 ± 1.00	37	24.51 ± 1.23	26	24.17 ± 0.95	1.72 ± 0.24	1.74 ± 0.17
	2003-06-29	2003-07-01	3 days	0.10 ± 0.00	0.10	33.30 ± 1.28	35	25.91 ± 1.61	28	22.15 ± 0.67	2.38 ± 0.49	2.20 ± 0.35
	2003-07-06	2003-09-03	60 days	8.84 ± 10.90	32.72	36.61 ± 2.91	48	27.88 ± 1.68	31	24.78 ± 1.79	1.94 ± 0.28	1.94 ± 0.28
	2003-09-20	2003-09-22	3 days	0.08 ± 0.00	0.08	29.57 ± 1.45	31	24.12 ± 0.19	24	21.54 ± 0.33	1.89 ± 0.14	1.74 ± 0.15
2004	2004-06-24	2004-07-06	13 days	2.51 ± 3.63	8.69	37.57 ± 3.66	45	24.31 ± 0.58	25	24.22 ± 1.10	1.77 ± 0.21	1.82 ± 0.35
	2004-07-13	2004-07-15	3 days	0.02 ± 0.00	0.02	34.07 ± 0.28	34	22.45 ± 0.24	23	21.93 ± 1.10	1.45 ± 0.10	1.93 ± 0.14
	2004-07-21	2004-08-03	14 days	9.00 ± 12.28	31.31	37.34 ± 5.26	51	26.75 ± 1.78	30	25.41 ± 1.30	2.24 ± 0.57	2.29 ± 0.91
	2004-08-06	2004-09-06	32 days	1.72 ± 1.42	5.65	34.69 ± 2.16	43	27.24 ± 1.69	31	23.28 ± 1.15	2.19 ± 0.84	2.43 ± 1.05
	2004-09-09	2004-09-12	4 days	0.02 ± 0.00	0.02	33.16 ± 1.03	34	25.62 ± 0.21	26	23.45 ± 0.62	1.57 ± 0.17	2.14 ± 0.13
	2004-10-18	2004-10-20	3 days	0.02 ± 0.00	0.02	28.57 ± 0.60	29	24.39 ± 0.23	25	18.01 ± 2.92	1.86 ± 0.35	1.96 ± 0.17

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2005	2005-06-06	2005-06-09	4 days	0.12 ± 0.05	0.14	33.75 ± 1.11	35	21.73 ± 0.77	23	21.67 ± 0.27	1.50 ± 0.05	1.63 ± 0.09
	2005-06-16	2005-07-18	33 days	2.48 ± 2.95	9.98	35.00 ± 1.59	38	24.93 ± 1.38	28	23.97 ± 1.10	1.68 ± 0.16	1.76 ± 0.18
	2005-07-20	2005-07-29	10 days	1.25 ± 0.54	1.99	34.52 ± 2.09	38	25.19 ± 0.58	26	24.46 ± 0.74	1.60 ± 0.06	1.88 ± 0.16
	2005-08-03	2005-08-08	6 days	0.48 ± 0.34	0.85	36.93 ± 1.65	39	24.32 ± 1.02	26	24.21 ± 1.40	1.96 ± 0.24	1.92 ± 0.41
	2005-08-13	2005-08-18	6 days	0.25 ± 0.20	0.44	34.92 ± 1.56	37	25.25 ± 1.10	27	24.16 ± 0.28	1.77 ± 0.40	1.81 ± 0.32
	2005-08-28	2005-08-31	4 days	0.03 ± 0.01	0.04	34.75 ± 1.31	36	24.38 ± 0.76	25	24.15 ± 0.44	1.64 ± 0.18	1.80 ± 0.33
	2005-09-02	2005-09-08	7 days	1.16 ± 1.23	2.48	32.21 ± 2.81	35	26.11 ± 2.12	30	21.87 ± 2.55	2.51 ± 1.10	2.65 ± 1.34
2006	2006-06-21	2006-06-24	4 days	0.20 ± 0.03	0.22	34.76 ± 2.28	38	23.61 ± 0.17	24	23.62 ± 0.51	2.04 ± 0.24	1.94 ± 0.22
	2006-06-26	2006-07-05	10 days	0.54 ± 0.38	1.05	31.71 ± 1.15	33	24.07 ± 0.52	25	22.79 ± 0.79	1.77 ± 0.17	1.82 ± 0.19
	2006-07-07	2006-08-13	38 days	6.60 ± 5.29	17.87	36.53 ± 1.47	39	26.30 ± 1.47	29	25.10 ± 1.30	1.85 ± 0.25	1.85 ± 0.21
	2006-08-26	2006-09-12	18 days	0.73 ± 0.90	2.54	35.62 ± 2.81	42	24.89 ± 1.38	28	23.70 ± 1.13	2.40 ± 0.82	2.03 ± 0.70
	2006-10-02	2006-10-04	3 days	0.04 ± 0.00	0.04	30.16 ± 1.23	32	24.55 ± 0.77	25	18.98 ± 2.44	1.79 ± 0.13	1.95 ± 0.39
2007	2007-07-04	2007-07-15	12 days	0.06 ± 0.04	0.10	34.98 ± 1.02	36	23.45 ± 0.64	24	22.75 ± 1.14	1.67 ± 0.10	1.81 ± 0.14
	2007-07-17	2007-07-19	3 days	0.16 ± 0.00	0.16	32.91 ± 0.58	34	24.67 ± 0.16	25	22.72 ± 0.55	2.07 ± 0.13	1.88 ± 0.17
	2007-07-25	2007-08-05	12 days	1.09 ± 1.08	2.66	37.13 ± 1.85	40	25.52 ± 1.59	29	24.96 ± 0.91	1.98 ± 0.46	2.28 ± 0.91
	2007-08-26	2007-08-29	4 days	2.00 ± 1.12	2.58	35.07 ± 0.58	36	25.19 ± 1.31	27	24.74 ± 1.02	2.32 ± 0.49	1.82 ± 0.11
2008	2008-06-20	2008-06-22	3 days	0.12 ± 0.00	0.12	33.97 ± 0.94	35	21.85 ± 0.95	23	23.31 ± 0.51	2.21 ± 0.16	1.64 ± 0.24
	2008-06-26	2008-07-02	7 days	0.85 ± 0.50	1.47	35.32 ± 1.67	37	23.87 ± 0.46	25	23.97 ± 0.65	1.69 ± 0.11	1.70 ± 0.20
	2008-07-09	2008-07-11	3 days	0.04 ± 0.00	0.04	33.61 ± 0.20	34	24.27 ± 0.36	25	23.40 ± 0.38	1.51 ± 0.08	1.65 ± 0.08
	2008-07-17	2008-08-08	23 days	2.22 ± 4.26	13.34	35.07 ± 1.57	38	25.10 ± 0.97	27	24.26 ± 0.99	1.63 ± 0.16	1.86 ± 0.18
	2008-08-10	2008-08-14	5 days	0.49 ± 0.35	0.76	34.40 ± 0.69	35	26.63 ± 1.42	28	23.30 ± 1.29	1.51 ± 0.13	2.09 ± 0.14
	2008-08-26	2008-08-29	4 days	0.02 ± 0.00	0.02	33.25 ± 1.18	35	24.19 ± 0.83	25	23.62 ± 0.22	1.49 ± 0.14	2.06 ± 0.12
	2008-09-02	2008-09-04	3 days	0.06 ± 0.00	0.06	31.46 ± 0.94	32	24.70 ± 0.85	25	21.77 ± 0.50	2.08 ± 0.03	1.80 ± 0.33
2009	2009-06-13	2009-06-23	11 days	0.24 ± 0.24	0.66	34.44 ± 1.33	36	23.99 ± 1.10	26	23.37 ± 1.07	1.65 ± 0.22	1.76 ± 0.13
	2009-06-28	2009-07-06	9 days	1.15 ± 0.77	1.97	33.90 ± 1.64	35	24.75 ± 1.31	27	24.17 ± 1.10	1.72 ± 0.23	1.94 ± 0.43
	2009-07-12	2009-07-16	5 days	0.33 ± 0.06	0.38	34.21 ± 0.63	35	26.04 ± 1.08	28	23.84 ± 0.65	1.58 ± 0.03	1.97 ± 0.07
	2009-07-20	2009-08-02	14 days	1.71 ± 1.39	3.50	35.80 ± 1.63	38	26.82 ± 1.82	30	24.20 ± 0.88	2.25 ± 0.53	2.36 ± 0.96
	2009-08-04	2009-08-08	5 days	0.38 ± 0.24	0.60	33.80 ± 1.15	35	25.75 ± 0.68	27	24.05 ± 0.97	1.60 ± 0.23	1.85 ± 0.24
	2009-08-11	2009-09-04	25 days	1.07 ± 1.21	4.00	34.78 ± 1.12	36	25.43 ± 0.85	28	24.31 ± 0.94	1.68 ± 0.25	1.82 ± 0.16
	2009-09-06	2009-09-08	3 days	0.02 ± 0.00	0.02	33.67 ± 1.26	35	24.56 ± 0.43	25	23.09 ± 0.45	1.47 ± 0.10	2.37 ± 0.12
2010	2010-06-28	2010-08-15	49 days	2.95 ± 3.89	12.16	35.56 ± 1.77	39	25.36 ± 1.34	29	24.16 ± 1.22	1.72 ± 0.19	1.87 ± 0.25
	2010-08-19	2010-09-05	18 days	0.97 ± 0.92	2.56	35.33 ± 2.23	40	25.74 ± 1.58	29	23.98 ± 1.44	1.80 ± 0.45	2.11 ± 0.82
	2010-09-14	2010-09-16	3 days	1.31 ± 0.00	1.31	32.08 ± 1.51	34	25.04 ± 0.55	25	22.06 ± 0.40	2.59 ± 0.65	2.20 ± 0.39
2011	2011-06-21	2011-07-02	12 days	1.54 ± 2.16	5.37	35.41 ± 1.38	38	24.37 ± 0.60	25	23.67 ± 1.32	1.70 ± 0.24	1.80 ± 0.23
	2011-07-09	2011-07-12	4 days	0.06 ± 0.01	0.06	33.09 ± 0.44	34	25.46 ± 0.50	26	23.44 ± 0.31	1.98 ± 0.18	1.86 ± 0.24
	2011-07-14	2011-07-16	3 days	0.02 ± 0.00	0.02	33.49 ± 0.95	34	24.41 ± 0.33	25	22.34 ± 1.49	1.60 ± 0.11	1.82 ± 0.26
	2011-07-25	2011-07-31	7 days	0.16 ± 0.10	0.28	34.79 ± 1.38	37	24.49 ± 0.78	25	23.33 ± 0.51	1.63 ± 0.16	1.68 ± 0.19
	2011-08-03	2011-08-26	24 days	1.79 ± 1.92	7.26	35.39 ± 1.54	38	26.07 ± 1.28	29	24.28 ± 1.17	1.70 ± 0.25	1.84 ± 0.15
	2011-08-29	2011-09-03	6 days	0.10 ± 0.06	0.16	32.77 ± 2.26	35	25.40 ± 1.21	28	21.90 ± 0.92	1.66 ± 0.23	1.72 ± 0.13
	2011-09-09	2011-09-11	3 days	0.12 ± 0.00	0.12	33.03 ± 0.62	34	24.08 ± 0.78	25	22.93 ± 0.50	1.51 ± 0.01	1.46 ± 0.03

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2012	2012-06-22	2012-06-30	9 days	5.14 ± 4.93	12.48	36.74 ± 2.31	41	24.96 ± 1.43	27	24.23 ± 1.95	1.70 ± 0.14	1.70 ± 0.20
	2012-07-13	2012-07-28	16 days	0.96 ± 1.76	4.51	34.83 ± 1.86	37	25.16 ± 1.22	28	23.69 ± 0.78	1.70 ± 0.26	1.72 ± 0.16
	2012-07-30	2012-08-06	8 days	0.98 ± 0.73	1.89	35.25 ± 1.70	38	26.28 ± 1.26	28	23.78 ± 1.13	1.66 ± 0.11	2.07 ± 0.52
	2012-08-08	2012-08-30	23 days	8.21 ± 8.43	25.52	36.78 ± 2.49	42	27.18 ± 1.23	30	25.02 ± 1.70	1.84 ± 0.26	1.87 ± 0.23
	2012-09-17	2012-09-20	4 days	0.53 ± 0.22	0.64	30.06 ± 0.19	30	24.64 ± 0.29	25	21.50 ± 0.32	2.27 ± 0.17	1.80 ± 0.23
	2012-09-23	2012-09-27	5 days	1.40 ± 0.46	1.71	30.49 ± 0.94	31	24.92 ± 0.37	25	18.49 ± 2.64	2.32 ± 0.23	2.04 ± 0.13
2013	2013-07-03	2013-08-07	36 days	3.29 ± 3.36	12.30	34.90 ± 1.85	38	25.27 ± 1.57	29	24.36 ± 0.74	1.87 ± 0.30	1.90 ± 0.41
	2013-08-09	2013-08-25	17 days	1.59 ± 1.42	4.71	35.68 ± 3.15	47	25.73 ± 1.50	28	24.32 ± 0.85	2.16 ± 0.74	2.24 ± 0.85
2014	2014-06-12	2014-06-15	4 days	0.22 ± 0.13	0.28	34.14 ± 1.42	36	23.65 ± 1.35	26	23.06 ± 1.18	1.72 ± 0.22	1.75 ± 0.17
	2014-07-09	2014-07-12	4 days	0.02 ± 0.00	0.02	32.94 ± 0.75	34	22.91 ± 0.75	23	21.06 ± 0.47	1.40 ± 0.04	1.64 ± 0.11
	2014-07-14	2014-07-19	6 days	2.21 ± 1.67	3.92	35.33 ± 1.79	37	25.10 ± 1.71	28	24.52 ± 1.25	1.83 ± 0.31	1.72 ± 0.22
	2014-07-24	2014-07-28	5 days	0.42 ± 0.24	0.62	33.72 ± 0.95	35	25.26 ± 0.54	26	24.46 ± 0.35	1.53 ± 0.11	1.72 ± 0.18
	2014-08-06	2014-08-13	8 days	0.80 ± 0.43	1.35	34.85 ± 1.21	37	26.45 ± 1.05	28	24.25 ± 0.67	1.66 ± 0.13	2.06 ± 0.24
	2014-08-16	2014-08-18	3 days	0.02 ± 0.00	0.02	33.16 ± 1.24	34	24.32 ± 0.56	25	22.31 ± 0.91	1.54 ± 0.13	2.06 ± 0.52
	2014-08-25	2014-09-13	20 days	0.23 ± 0.23	0.78	34.46 ± 1.14	36	25.18 ± 0.86	27	23.66 ± 0.69	1.52 ± 0.15	1.88 ± 0.30
	2014-09-16	2014-09-18	3 days	0.02 ± 0.00	0.02	32.24 ± 1.59	34	25.47 ± 0.13	26	21.39 ± 0.27	1.45 ± 0.16	2.73 ± 0.20
	2014-10-22	2014-10-24	3 days	1.19 ± 0.00	1.19	32.19 ± 1.48	34	25.42 ± 0.72	26	17.66 ± 1.23	3.41 ± 0.55	2.22 ± 0.63
2015	2015-06-19	2015-06-21	3 days	0.06 ± 0.00	0.06	33.44 ± 0.98	34	21.88 ± 0.28	22	22.45 ± 0.58	1.49 ± 0.10	1.65 ± 0.13
	2015-06-26	2015-08-14	50 days	11.90 ± 7.11	27.21	37.17 ± 1.61	42	27.54 ± 2.16	32	25.62 ± 1.21	1.88 ± 0.26	1.94 ± 0.28
	2015-08-19	2015-08-23	5 days	0.16 ± 0.08	0.20	34.36 ± 0.96	36	26.15 ± 0.77	27	23.69 ± 1.31	1.43 ± 0.07	2.14 ± 0.15
	2015-08-26	2015-09-01	7 days	1.17 ± 0.84	2.42	34.51 ± 2.07	37	25.88 ± 1.64	28	24.47 ± 1.14	1.88 ± 0.43	1.84 ± 0.25
	2015-09-06	2015-09-09	4 days	0.16 ± 0.00	0.16	29.33 ± 0.63	30	24.63 ± 0.19	25	19.54 ± 0.32	2.07 ± 0.33	2.05 ± 0.15
	2015-09-11	2015-09-15	5 days	0.38 ± 0.22	0.54	30.36 ± 1.42	32	24.82 ± 0.44	25	20.01 ± 1.16	2.12 ± 0.33	2.06 ± 0.23
	2015-09-22	2015-09-25	4 days	1.87 ± 0.48	2.11	30.48 ± 1.34	32	25.34 ± 0.21	26	18.89 ± 0.69	2.51 ± 0.69	2.20 ± 0.24
	2015-10-02	2015-10-07	6 days	1.60 ± 1.12	2.46	31.10 ± 2.37	35	25.92 ± 1.91	29	18.73 ± 1.80	2.84 ± 1.09	2.43 ± 0.89
2016	2016-06-27	2016-08-09	44 days	2.73 ± 3.27	11.25	35.83 ± 1.75	42	24.95 ± 1.35	28	24.46 ± 1.19	1.68 ± 0.18	1.81 ± 0.28
	2016-08-12	2016-08-20	9 days	0.46 ± 0.44	1.05	34.13 ± 1.06	36	24.69 ± 1.32	27	23.94 ± 0.60	1.64 ± 0.19	1.76 ± 0.19
	2016-08-22	2016-09-10	20 days	2.36 ± 3.28	9.72	35.09 ± 2.29	40	24.90 ± 0.96	27	24.47 ± 1.14	1.91 ± 0.38	1.88 ± 0.35
2017	2017-06-10	2017-06-27	18 days	11.10 ± 9.75	28.98	36.03 ± 1.60	39	25.18 ± 1.45	27	25.23 ± 1.10	1.81 ± 0.29	1.86 ± 0.18
	2017-07-04	2017-07-07	4 days	0.47 ± 0.30	0.62	33.40 ± 1.26	34	24.36 ± 1.26	26	23.64 ± 0.69	2.19 ± 0.27	1.82 ± 0.40
	2017-07-09	2017-08-09	32 days	6.47 ± 6.34	21.39	36.18 ± 2.42	41	27.61 ± 2.59	33	24.87 ± 1.50	1.79 ± 0.31	2.00 ± 0.23
	2017-08-11	2017-08-30	20 days	3.62 ± 3.26	8.47	35.31 ± 1.60	38	25.98 ± 1.36	29	24.13 ± 1.54	1.72 ± 0.16	1.87 ± 0.22
	2017-09-01	2017-09-03	3 days	0.02 ± 0.00	0.02	33.25 ± 0.32	34	24.75 ± 0.54	25	21.05 ± 0.62	1.53 ± 0.08	1.95 ± 0.27
	2017-09-06	2017-09-08	3 days	0.02 ± 0.00	0.02	33.21 ± 0.97	34	23.89 ± 0.59	25	21.81 ± 1.18	1.53 ± 0.10	1.75 ± 0.12
	2017-10-13	2017-10-16	4 days	1.44 ± 0.62	1.85	31.20 ± 0.48	32	26.27 ± 1.57	28	20.21 ± 0.66	2.90 ± 0.53	2.74 ± 1.03

Table B.7: Summary statistics for heat wave episodes identified by heat index using 90pp for phytoclimatic subtype *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2018	2018-06-17	2018-07-04	18 days	0.47 ± 0.42	1.41	33.38 ± 1.25	36	23.82 ± 1.16	25	23.13 ± 0.72	1.66 ± 0.24	1.77 ± 0.21
	2018-07-07	2018-07-15	9 days	1.20 ± 0.37	1.69	34.10 ± 0.83	36	25.67 ± 1.03	28	24.21 ± 0.68	1.61 ± 0.08	1.85 ± 0.13
	2018-07-17	2018-07-20	4 days	0.60 ± 0.27	0.74	33.18 ± 0.60	34	25.61 ± 0.54	26	23.73 ± 0.41	1.59 ± 0.11	1.91 ± 0.14
	2018-07-23	2018-08-15	24 days	10.76 ± 12.97	38.08	36.57 ± 2.73	44	27.72 ± 2.26	31	25.27 ± 1.65	1.86 ± 0.28	1.92 ± 0.20
	2018-08-18	2018-08-29	12 days	0.34 ± 0.22	0.64	34.30 ± 0.83	36	25.57 ± 0.61	27	23.80 ± 0.88	1.51 ± 0.07	1.78 ± 0.23
	2018-08-31	2018-09-05	6 days	0.12 ± 0.07	0.22	34.73 ± 1.47	37	25.55 ± 0.40	26	23.56 ± 0.98	1.61 ± 0.20	1.95 ± 0.49
	2018-09-11	2018-09-13	3 days	0.02 ± 0.00	0.02	32.60 ± 1.49	34	25.64 ± 1.31	27	22.93 ± 0.34	1.50 ± 0.23	2.04 ± 0.09
	2018-09-17	2018-09-24	8 days	0.02 ± 0.01	0.04	33.05 ± 1.11	35	24.07 ± 0.41	25	22.94 ± 0.43	1.42 ± 0.06	1.75 ± 0.19

Abbreviations [a] Magnitude Index

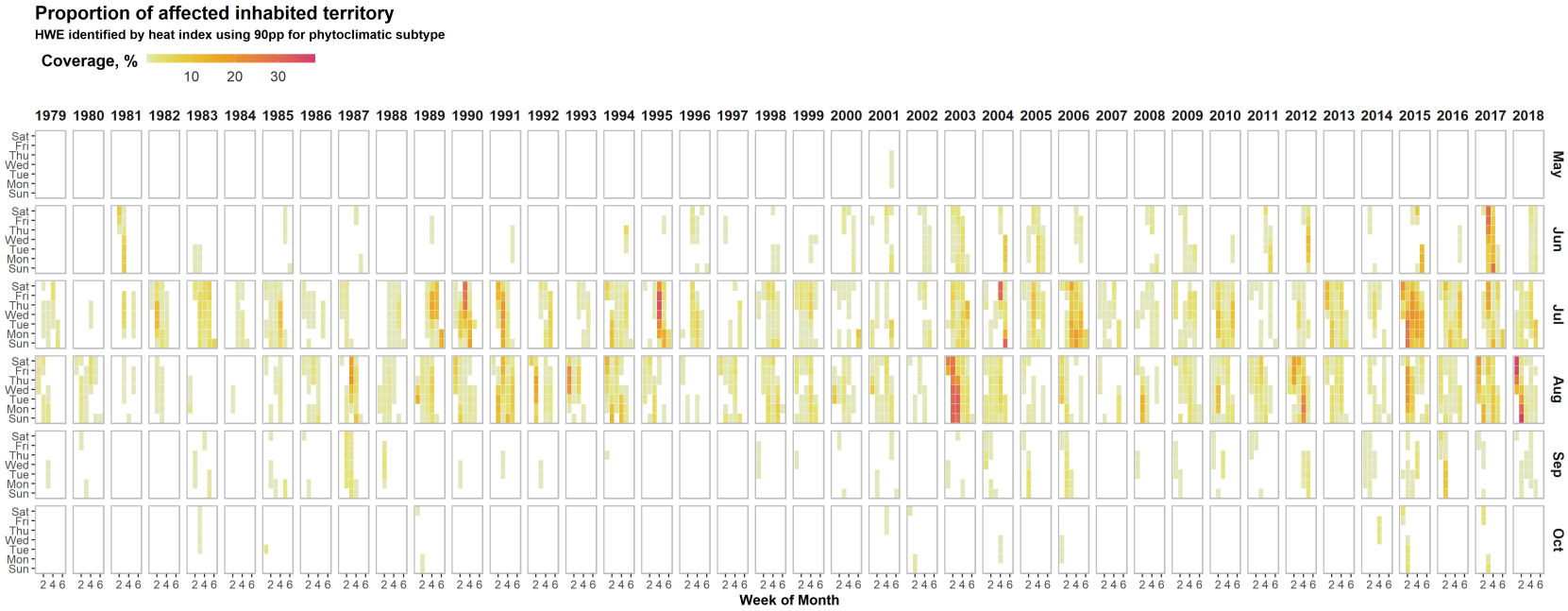


Figure B.13: Proportion of national territory affected by heatwaves identified using heat index (90pp for phytoclimatic subtype)

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1979	1979-07-16	1979-07-18	3 days	0.02 ± 0.00	0.02	34.37 ± 0.62	35	22.80 ± 0.12	23	23.90 ± 0.35	1.44 ± 0.14	1.72 ± 0.11
	1979-07-25	1979-08-15	22 days	0.59 ± 0.65	2.03	35.11 ± 2.03	41	24.39 ± 0.68	26	23.88 ± 1.00	1.52 ± 0.12	1.88 ± 0.22
	1979-08-24	1979-08-26	3 days	0.02 ± 0.00	0.02	31.43 ± 0.48	32	22.97 ± 0.59	24	20.61 ± 0.53	1.39 ± 0.05	1.77 ± 0.30
1980	1980-07-22	1980-07-25	4 days	0.09 ± 0.03	0.12	35.06 ± 1.23	37	23.26 ± 0.46	24	23.75 ± 0.84	1.55 ± 0.17	1.67 ± 0.19
	1980-08-01	1980-08-14	14 days	0.38 ± 0.29	0.85	34.64 ± 1.51	38	24.38 ± 0.72	26	24.07 ± 0.73	1.57 ± 0.13	1.91 ± 0.17
	1980-08-20	1980-08-25	6 days	1.78 ± 1.68	3.34	36.36 ± 3.13	42	26.30 ± 1.58	29	24.93 ± 1.47	1.64 ± 0.30	2.21 ± 0.28
	1980-08-28	1980-08-31	4 days	0.14 ± 0.05	0.16	38.27 ± 2.39	41	24.07 ± 0.38	25	23.78 ± 0.83	1.54 ± 0.13	2.23 ± 0.15
	1980-09-12	1980-09-15	4 days	0.04 ± 0.00	0.04	34.59 ± 1.23	36	24.18 ± 0.68	25	22.55 ± 0.27	1.66 ± 0.34	2.60 ± 0.29
1981	1981-06-10	1981-06-18	9 days	3.87 ± 3.45	7.57	37.51 ± 1.86	41	23.99 ± 1.84	27	23.62 ± 1.45	1.70 ± 0.19	1.70 ± 0.14
	1981-07-14	1981-07-17	4 days	4.05 ± 0.61	4.49	36.79 ± 0.99	38	24.68 ± 0.48	25	23.27 ± 0.12	1.99 ± 0.21	1.69 ± 0.07
	1981-07-27	1981-07-31	5 days	0.11 ± 0.06	0.18	35.21 ± 2.33	38	24.08 ± 2.00	27	24.05 ± 1.51	1.53 ± 0.20	2.12 ± 0.63
	1981-08-10	1981-08-13	4 days	0.04 ± 0.01	0.04	33.98 ± 2.01	37	23.71 ± 0.17	24	22.65 ± 0.24	1.39 ± 0.04	1.78 ± 0.19
1982	1982-06-20	1982-06-22	3 days	0.02 ± 0.00	0.02	31.92 ± 0.98	33	22.84 ± 0.77	24	21.91 ± 0.71	1.45 ± 0.13	1.81 ± 0.29
	1982-07-05	1982-07-21	17 days	3.01 ± 4.56	12.38	34.65 ± 2.38	40	25.95 ± 0.95	28	23.87 ± 1.66	1.58 ± 0.24	2.10 ± 0.27
	1982-07-24	1982-07-28	5 days	0.06 ± 0.01	0.06	33.51 ± 1.17	36	24.68 ± 0.63	26	23.00 ± 0.61	1.59 ± 0.19	1.90 ± 0.29
	1982-08-13	1982-08-15	3 days	0.06 ± 0.00	0.06	33.18 ± 0.70	34	24.66 ± 0.89	25	23.71 ± 0.44	1.57 ± 0.32	1.68 ± 0.08
	1982-08-17	1982-08-20	4 days	0.28 ± 0.15	0.36	37.32 ± 3.28	41	25.60 ± 1.39	28	24.31 ± 0.50	1.77 ± 0.16	2.24 ± 0.48
1983	1983-06-10	1983-06-13	4 days	0.20 ± 0.05	0.22	34.64 ± 0.66	35	23.57 ± 1.50	25	22.88 ± 1.08	1.63 ± 0.09	1.96 ± 0.36
	1983-07-08	1983-08-03	27 days	2.10 ± 1.30	4.37	34.21 ± 1.67	39	25.81 ± 2.00	31	23.85 ± 0.89	1.59 ± 0.19	2.00 ± 0.27
	1983-09-06	1983-09-08	3 days	0.32 ± 0.00	0.32	35.21 ± 1.79	37	25.32 ± 0.64	26	23.55 ± 0.09	1.40 ± 0.08	1.84 ± 0.27
	1983-09-25	1983-09-27	3 days	0.54 ± 0.00	0.54	33.35 ± 1.10	35	25.37 ± 0.58	26	23.22 ± 1.31	1.85 ± 0.12	2.19 ± 0.35
	1983-10-11	1983-10-15	5 days	0.10 ± 0.07	0.16	28.34 ± 0.30	29	25.14 ± 0.46	26	17.59 ± 1.25	2.24 ± 0.23	2.39 ± 0.45
1984	1984-07-08	1984-07-11	4 days	0.03 ± 0.01	0.04	34.16 ± 0.43	35	23.34 ± 1.23	25	22.94 ± 0.57	1.55 ± 0.22	1.89 ± 0.48
	1984-07-19	1984-07-29	11 days	0.49 ± 0.61	1.49	35.63 ± 1.86	38	24.21 ± 1.02	26	24.10 ± 0.89	1.62 ± 0.21	1.84 ± 0.12
1985	1985-07-06	1985-07-29	24 days	1.38 ± 2.47	7.49	34.46 ± 1.65	38	24.37 ± 0.77	27	24.17 ± 1.08	1.50 ± 0.13	1.86 ± 0.25
	1985-08-02	1985-08-05	4 days	0.29 ± 0.17	0.38	38.22 ± 4.66	45	24.84 ± 1.35	27	24.15 ± 1.30	1.63 ± 0.24	1.96 ± 0.33
	1985-08-14	1985-08-16	3 days	0.02 ± 0.00	0.02	33.01 ± 0.35	33	24.27 ± 0.15	24	22.95 ± 0.26	1.47 ± 0.08	1.65 ± 0.15
	1985-08-18	1985-08-24	7 days	0.54 ± 0.33	0.87	35.67 ± 1.52	38	24.63 ± 0.51	25	24.19 ± 0.74	1.54 ± 0.09	1.82 ± 0.21
	1985-09-14	1985-09-16	3 days	0.02 ± 0.00	0.02	33.43 ± 0.98	35	24.01 ± 0.38	24	21.35 ± 1.15	1.47 ± 0.03	1.90 ± 0.19
	1985-09-29	1985-10-01	3 days	1.09 ± 0.00	1.09	30.75 ± 0.84	32	24.81 ± 0.27	25	22.02 ± 0.35	2.39 ± 0.30	2.09 ± 0.23
1986	1986-07-04	1986-07-12	9 days	0.11 ± 0.08	0.24	34.46 ± 1.28	36	23.91 ± 0.42	24	23.62 ± 0.75	1.52 ± 0.12	1.87 ± 0.28
	1986-07-28	1986-08-04	8 days	0.50 ± 0.20	0.72	34.69 ± 1.45	37	24.74 ± 0.81	26	23.97 ± 1.07	1.51 ± 0.11	1.82 ± 0.15
	1986-08-06	1986-08-11	6 days	0.10 ± 0.05	0.14	33.33 ± 0.76	35	25.12 ± 1.26	27	23.15 ± 0.41	1.48 ± 0.10	2.03 ± 0.18
	1986-08-13	1986-08-18	6 days	1.81 ± 1.27	2.98	34.85 ± 1.58	37	26.13 ± 1.36	28	24.11 ± 0.89	1.58 ± 0.24	1.92 ± 0.27
	1986-08-21	1986-08-23	3 days	0.06 ± 0.00	0.06	35.60 ± 1.41	37	26.30 ± 1.15	28	23.59 ± 0.64	1.56 ± 0.27	2.28 ± 0.39
	1986-09-06	1986-09-08	3 days	0.12 ± 0.00	0.12	29.63 ± 0.83	30	24.85 ± 0.80	26	21.98 ± 0.52	1.92 ± 0.33	2.13 ± 0.55

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1987	1987-06-26	1987-06-29	4 days	0.14 ± 0.06	0.18	33.99 ± 1.34	36	22.28 ± 0.55	23	23.06 ± 0.78	1.52 ± 0.16	1.62 ± 0.13
	1987-07-02	1987-07-14	13 days	0.68 ± 0.71	1.89	33.98 ± 3.45	45	24.30 ± 0.70	25	23.96 ± 0.49	1.44 ± 0.07	1.82 ± 0.23
	1987-08-02	1987-08-05	4 days	0.14 ± 0.07	0.18	36.19 ± 0.79	37	24.09 ± 0.63	25	24.22 ± 0.94	1.46 ± 0.08	1.91 ± 0.31
	1987-08-11	1987-08-23	13 days	6.96 ± 7.17	18.37	36.36 ± 2.60	41	25.69 ± 0.65	27	25.68 ± 1.20	1.80 ± 0.36	1.91 ± 0.25
	1987-09-05	1987-09-19	15 days	1.53 ± 0.86	2.50	33.82 ± 1.85	37	25.99 ± 1.22	28	23.53 ± 0.71	2.70 ± 0.60	2.45 ± 0.77
	1987-09-21	1987-09-26	6 days	0.04 ± 0.00	0.04	31.46 ± 1.27	33	25.47 ± 0.77	27	21.50 ± 0.53	2.06 ± 0.68	1.78 ± 0.23
1988	1988-07-10	1988-07-18	9 days	0.15 ± 0.14	0.32	36.06 ± 1.74	39	23.82 ± 0.58	25	23.20 ± 1.22	1.54 ± 0.15	2.09 ± 0.34
	1988-07-20	1988-08-05	17 days	0.66 ± 0.77	2.35	36.22 ± 2.63	41	24.82 ± 0.75	27	24.01 ± 1.17	1.61 ± 0.32	1.93 ± 0.27
	1988-08-07	1988-08-21	15 days	0.37 ± 0.15	0.60	33.74 ± 0.96	35	25.49 ± 1.00	28	23.86 ± 0.90	1.51 ± 0.13	1.83 ± 0.22
	1988-08-23	1988-08-29	7 days	0.10 ± 0.09	0.20	34.84 ± 1.80	38	25.30 ± 1.15	28	22.41 ± 1.30	1.64 ± 0.19	2.33 ± 0.25
	1988-09-05	1988-09-09	5 days	0.95 ± 0.56	1.45	36.36 ± 0.72	37	25.07 ± 0.62	26	24.78 ± 0.89	1.69 ± 0.19	1.96 ± 0.42
1989	1989-07-01	1989-07-03	3 days	0.24 ± 0.00	0.24	34.00 ± 0.33	34	24.94 ± 0.36	25	23.71 ± 0.53	1.60 ± 0.11	1.83 ± 0.10
	1989-07-10	1989-08-03	25 days	6.17 ± 5.81	18.23	36.33 ± 1.86	41	25.45 ± 1.16	29	24.99 ± 1.08	1.71 ± 0.23	1.85 ± 0.25
	1989-08-07	1989-08-29	23 days	2.15 ± 2.38	7.89	35.17 ± 1.63	38	26.72 ± 0.80	28	24.64 ± 0.94	1.68 ± 0.18	1.99 ± 0.35
	1989-10-07	1989-10-09	3 days	0.14 ± 0.00	0.14	29.97 ± 1.39	31	25.27 ± 0.78	26	17.31 ± 1.45	2.49 ± 0.69	2.40 ± 0.54
1990	1990-06-30	1990-07-06	7 days	0.05 ± 0.03	0.08	33.18 ± 0.94	34	24.28 ± 0.72	25	22.10 ± 0.75	1.56 ± 0.18	2.10 ± 0.14
	1990-07-08	1990-07-12	5 days	2.52 ± 1.43	3.78	35.98 ± 1.64	38	24.21 ± 0.62	25	23.64 ± 0.44	1.84 ± 0.31	1.67 ± 0.18
	1990-07-16	1990-07-27	12 days	11.57 ± 10.28	28.17	36.03 ± 1.48	39	25.56 ± 1.27	28	25.50 ± 1.21	1.65 ± 0.16	1.82 ± 0.15
	1990-07-31	1990-08-22	23 days	1.56 ± 2.11	5.80	34.37 ± 1.53	37	25.39 ± 0.85	27	24.39 ± 1.07	1.63 ± 0.31	2.06 ± 0.53
	1990-08-24	1990-08-29	6 days	0.50 ± 0.47	0.93	32.16 ± 0.67	33	25.28 ± 0.39	26	23.39 ± 0.52	2.09 ± 0.49	2.35 ± 0.48
	1990-09-03	1990-09-05	3 days	0.04 ± 0.00	0.04	32.58 ± 0.96	33	24.55 ± 0.11	25	22.93 ± 0.15	1.34 ± 0.01	2.65 ± 0.10
1991	1991-06-24	1991-06-26	3 days	0.06 ± 0.00	0.06	36.32 ± 1.78	38	22.68 ± 1.13	23	23.67 ± 0.45	1.51 ± 0.04	1.60 ± 0.16
	1991-07-09	1991-07-28	20 days	6.90 ± 7.44	19.98	36.96 ± 3.02	44	25.41 ± 1.18	28	24.82 ± 1.07	1.79 ± 0.37	1.89 ± 0.32
	1991-08-02	1991-08-09	8 days	5.28 ± 5.80	12.72	36.21 ± 2.34	39	25.07 ± 0.66	26	24.29 ± 2.21	1.61 ± 0.21	1.89 ± 0.36
	1991-08-12	1991-09-03	23 days	3.72 ± 3.59	10.85	35.55 ± 2.69	44	26.17 ± 1.34	29	24.64 ± 1.21	1.62 ± 0.18	1.90 ± 0.32
	1991-09-17	1991-09-19	3 days	0.04 ± 0.00	0.04	34.23 ± 0.27	35	24.45 ± 0.30	25	23.74 ± 0.06	1.42 ± 0.09	2.55 ± 0.04
1992	1992-07-17	1992-08-08	23 days	5.42 ± 4.70	15.72	35.02 ± 2.19	41	25.11 ± 1.30	27	24.97 ± 1.15	1.58 ± 0.19	1.84 ± 0.20
	1992-08-17	1992-08-28	12 days	0.67 ± 0.37	1.17	34.05 ± 1.86	37	25.54 ± 0.84	27	24.12 ± 1.29	1.51 ± 0.10	1.86 ± 0.24
	1992-09-14	1992-09-16	3 days	0.02 ± 0.00	0.02	33.96 ± 0.90	35	23.89 ± 0.58	24	22.30 ± 0.62	1.44 ± 0.09	1.98 ± 0.23
1993	1993-07-16	1993-07-20	5 days	0.27 ± 0.09	0.36	34.22 ± 1.06	36	24.00 ± 0.48	24	23.23 ± 1.29	1.62 ± 0.09	1.76 ± 0.17
	1993-07-24	1993-07-31	8 days	0.42 ± 0.36	0.87	35.02 ± 1.94	39	24.46 ± 1.28	26	23.84 ± 1.39	1.59 ± 0.18	2.05 ± 0.39
	1993-08-02	1993-08-13	12 days	4.83 ± 7.32	16.99	35.11 ± 2.43	39	25.76 ± 1.37	28	24.43 ± 1.34	1.62 ± 0.27	1.96 ± 0.24
	1993-08-16	1993-08-23	8 days	2.29 ± 2.57	5.86	34.11 ± 2.06	38	25.09 ± 0.38	26	24.75 ± 1.34	1.45 ± 0.09	1.80 ± 0.24
1994	1994-06-28	1994-07-31	34 days	2.00 ± 2.60	9.82	34.67 ± 2.04	39	25.40 ± 1.50	28	24.43 ± 0.94	1.59 ± 0.24	1.89 ± 0.18
	1994-08-02	1994-08-31	30 days	2.94 ± 3.53	11.27	35.48 ± 1.60	39	27.23 ± 1.26	31	24.55 ± 1.31	1.65 ± 0.22	1.97 ± 0.33
1995	1995-07-15	1995-08-18	35 days	6.16 ± 9.79	34.45	36.01 ± 2.77	42	25.73 ± 1.00	28	24.99 ± 1.35	1.68 ± 0.29	1.88 ± 0.26
	1995-08-25	1995-08-28	4 days	0.04 ± 0.01	0.04	35.03 ± 0.98	36	23.98 ± 0.30	24	22.48 ± 0.35	1.40 ± 0.05	2.41 ± 0.50

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
1996	1996-07-12	1996-07-25	14 days	1.74 ± 1.59	5.23	34.70 ± 2.03	39	23.92 ± 1.56	27	24.31 ± 1.17	1.53 ± 0.12	1.81 ± 0.22
	1996-07-28	1996-08-04	8 days	0.23 ± 0.15	0.42	33.41 ± 1.40	36	24.68 ± 0.30	25	23.80 ± 0.49	1.40 ± 0.09	1.76 ± 0.12
	1996-08-08	1996-08-11	4 days	0.04 ± 0.02	0.06	33.28 ± 1.09	34	25.16 ± 0.42	26	23.41 ± 0.38	1.44 ± 0.09	2.01 ± 0.26
1997	1997-06-12	1997-06-14	3 days	0.02 ± 0.00	0.02	32.94 ± 1.62	35	23.63 ± 1.04	24	21.81 ± 0.44	1.45 ± 0.08	1.91 ± 0.27
	1997-07-26	1997-08-04	10 days	1.24 ± 1.33	3.28	34.55 ± 1.34	37	24.41 ± 0.71	26	24.66 ± 0.32	1.46 ± 0.09	1.96 ± 0.24
	1997-08-08	1997-08-10	3 days	0.08 ± 0.00	0.08	33.47 ± 1.41	35	26.88 ± 1.13	28	23.66 ± 0.97	1.53 ± 0.15	2.14 ± 0.13
	1997-08-13	1997-08-18	6 days	0.22 ± 0.08	0.30	33.42 ± 1.53	35	24.73 ± 0.39	25	24.44 ± 0.43	1.49 ± 0.14	2.00 ± 0.16
	1997-08-22	1997-08-24	3 days	1.69 ± 0.00	1.69	31.89 ± 1.11	33	24.92 ± 0.63	26	24.78 ± 0.74	1.56 ± 0.19	1.91 ± 0.22
1998	1998-06-27	1998-06-30	4 days	0.02 ± 0.00	0.02	34.13 ± 1.25	35	23.97 ± 0.96	25	23.51 ± 0.42	1.38 ± 0.04	1.74 ± 0.25
	1998-07-11	1998-07-20	10 days	1.21 ± 1.54	3.76	35.79 ± 2.05	39	24.43 ± 0.79	26	24.10 ± 1.17	1.60 ± 0.19	2.01 ± 0.38
	1998-07-22	1998-07-31	10 days	0.72 ± 0.48	1.43	35.83 ± 1.49	38	24.97 ± 0.35	26	24.65 ± 0.76	1.62 ± 0.11	1.90 ± 0.19
	1998-08-05	1998-08-27	23 days	1.27 ± 1.28	3.98	35.11 ± 1.71	38	25.19 ± 0.92	28	24.57 ± 0.70	1.57 ± 0.16	1.83 ± 0.24
	1998-09-01	1998-09-04	4 days	0.05 ± 0.02	0.06	34.54 ± 1.53	36	26.07 ± 1.15	28	24.19 ± 0.96	1.45 ± 0.07	1.99 ± 0.43
1999	1999-06-30	1999-07-04	5 days	0.68 ± 0.13	0.87	36.06 ± 0.98	37	25.00 ± 1.68	27	24.46 ± 1.09	1.66 ± 0.20	1.87 ± 0.24
	1999-07-06	1999-07-10	5 days	0.73 ± 0.63	1.19	36.17 ± 2.49	39	24.29 ± 0.69	25	23.75 ± 0.88	1.87 ± 0.50	1.81 ± 0.33
	1999-07-14	1999-07-18	5 days	0.57 ± 0.31	0.80	35.00 ± 2.40	37	25.09 ± 0.65	26	24.46 ± 0.85	1.56 ± 0.19	2.01 ± 0.33
	1999-07-20	1999-07-25	6 days	1.97 ± 1.28	3.34	35.24 ± 1.83	37	24.84 ± 0.50	26	24.46 ± 0.76	1.74 ± 0.30	1.76 ± 0.22
	1999-07-29	1999-07-31	3 days	0.02 ± 0.00	0.02	32.41 ± 0.28	33	24.95 ± 0.64	26	23.78 ± 0.26	1.42 ± 0.14	1.81 ± 0.27
	1999-08-02	1999-08-08	7 days	1.09 ± 0.78	1.97	34.13 ± 1.16	35	26.94 ± 1.44	30	24.13 ± 0.68	1.61 ± 0.17	1.96 ± 0.21
	1999-08-13	1999-08-31	19 days	1.37 ± 1.11	3.12	34.80 ± 2.36	41	26.47 ± 1.54	30	24.45 ± 1.01	1.89 ± 0.82	2.24 ± 0.44
2000	2000-06-27	2000-07-02	6 days	0.31 ± 0.03	0.36	34.23 ± 0.73	35	24.93 ± 1.25	27	23.53 ± 0.44	1.60 ± 0.12	2.02 ± 0.13
	2000-07-05	2000-07-08	4 days	0.24 ± 0.15	0.32	34.21 ± 1.73	37	25.48 ± 1.65	27	22.89 ± 1.03	1.48 ± 0.13	2.16 ± 0.43
	2000-07-14	2000-07-16	3 days	0.02 ± 0.00	0.02	36.12 ± 0.80	37	23.18 ± 1.15	24	22.53 ± 0.22	1.81 ± 0.14	1.84 ± 0.30
	2000-07-19	2000-07-22	4 days	0.31 ± 0.05	0.34	34.16 ± 2.07	36	23.80 ± 0.51	24	24.11 ± 0.67	1.47 ± 0.08	1.73 ± 0.06
	2000-07-25	2000-08-04	11 days	2.08 ± 3.02	7.02	35.14 ± 2.57	39	25.17 ± 0.81	27	23.58 ± 1.61	1.68 ± 0.30	1.83 ± 0.28
	2000-08-09	2000-08-11	3 days	0.06 ± 0.00	0.06	33.80 ± 1.77	35	23.31 ± 0.34	24	24.01 ± 0.36	1.39 ± 0.01	1.72 ± 0.25
	2000-08-13	2000-08-21	9 days	0.86 ± 0.77	1.93	36.11 ± 3.77	45	25.41 ± 1.22	28	24.50 ± 1.02	1.54 ± 0.16	1.95 ± 0.41
	2000-08-24	2000-08-26	3 days	0.40 ± 0.00	0.40	34.39 ± 2.07	37	27.71 ± 0.95	29	23.27 ± 0.73	1.55 ± 0.13	1.85 ± 0.22
	2000-08-30	2000-09-02	4 days	0.12 ± 0.00	0.12	32.74 ± 0.93	34	25.37 ± 0.90	27	22.33 ± 0.44	1.46 ± 0.07	2.28 ± 0.17
2001	2001-05-28	2001-05-31	4 days	0.02 ± 0.00	0.02	33.11 ± 0.71	34	21.63 ± 0.51	22	22.49 ± 0.19	1.40 ± 0.05	1.77 ± 0.20
	2001-06-21	2001-06-26	6 days	1.50 ± 1.13	2.58	35.64 ± 1.72	39	23.72 ± 1.61	26	24.10 ± 0.74	1.66 ± 0.09	1.65 ± 0.14
	2001-06-30	2001-07-04	5 days	0.54 ± 0.36	0.85	34.46 ± 1.20	36	23.56 ± 0.64	24	24.00 ± 1.19	1.45 ± 0.07	1.87 ± 0.25
	2001-07-10	2001-07-14	5 days	0.32 ± 0.20	0.46	35.05 ± 1.74	37	24.42 ± 0.43	25	23.81 ± 0.67	1.52 ± 0.08	2.03 ± 0.14
	2001-07-22	2001-08-16	26 days	0.87 ± 1.39	4.63	34.77 ± 2.61	45	25.48 ± 1.19	27	24.26 ± 1.04	1.57 ± 0.17	2.11 ± 0.28
	2001-08-19	2001-08-29	11 days	1.09 ± 0.83	2.37	33.96 ± 1.18	36	25.55 ± 0.69	27	24.48 ± 1.11	1.52 ± 0.12	1.78 ± 0.23
	2001-09-02	2001-09-04	3 days	0.02 ± 0.00	0.02	32.85 ± 0.79	34	24.15 ± 0.08	24	22.38 ± 0.90	1.41 ± 0.06	2.29 ± 0.17
	2001-09-06	2001-09-08	3 days	0.02 ± 0.00	0.02	31.18 ± 0.97	32	24.34 ± 0.30	25	20.96 ± 0.47	2.22 ± 0.09	1.99 ± 0.26
	2001-09-27	2001-09-30	4 days	0.12 ± 0.00	0.12	28.44 ± 0.18	29	24.38 ± 0.23	25	18.74 ± 0.52	1.69 ± 0.13	1.77 ± 0.17
	2001-10-25	2001-10-27	3 days	0.12 ± 0.00	0.12	30.17 ± 1.48	32	24.34 ± 0.11	24	15.70 ± 0.53	2.09 ± 0.36	1.76 ± 0.08

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2002	2002-06-16	2002-06-18	3 days	0.02 ± 0.00	0.02	34.85 ± 0.98	36	22.33 ± 1.15	23	23.45 ± 0.41	1.59 ± 0.23	1.65 ± 0.15
	2002-06-21	2002-06-27	7 days	0.06 ± 0.03	0.10	33.68 ± 2.71	38	23.46 ± 0.49	24	23.12 ± 0.97	1.53 ± 0.17	1.82 ± 0.24
	2002-07-04	2002-07-06	3 days	0.02 ± 0.00	0.02	33.17 ± 0.75	34	22.82 ± 0.60	23	21.85 ± 0.27	1.65 ± 0.13	1.67 ± 0.14
	2002-07-09	2002-07-14	6 days	0.08 ± 0.06	0.14	32.35 ± 0.47	33	23.56 ± 0.60	24	21.32 ± 1.11	1.42 ± 0.08	1.77 ± 0.27
	2002-07-19	2002-07-31	13 days	0.67 ± 0.86	2.27	34.16 ± 1.95	37	24.26 ± 0.63	25	23.56 ± 1.10	1.50 ± 0.12	1.88 ± 0.24
	2002-08-03	2002-08-06	4 days	0.04 ± 0.00	0.04	33.44 ± 0.38	34	25.61 ± 1.72	28	22.70 ± 0.31	1.47 ± 0.11	2.07 ± 0.36
	2002-08-11	2002-08-13	3 days	0.02 ± 0.00	0.02	34.65 ± 2.70	37	24.00 ± 0.65	25	21.45 ± 1.62	1.59 ± 0.11	1.67 ± 0.16
	2002-08-15	2002-08-21	7 days	0.11 ± 0.05	0.18	32.66 ± 0.96	34	24.51 ± 0.77	26	23.61 ± 0.24	1.44 ± 0.07	1.81 ± 0.18
	2002-10-04	2002-10-07	4 days	0.42 ± 0.19	0.52	29.57 ± 1.19	31	24.87 ± 0.77	26	18.05 ± 0.84	2.84 ± 0.55	2.15 ± 0.49
2003	2003-06-09	2003-06-29	21 days	0.86 ± 0.80	2.39	34.30 ± 1.21	37	24.52 ± 1.17	26	24.07 ± 0.96	1.51 ± 0.15	1.82 ± 0.23
	2003-07-07	2003-08-28	53 days	8.73 ± 10.07	30.69	37.14 ± 2.64	48	28.05 ± 1.62	31	25.19 ± 1.45	1.85 ± 0.31	2.00 ± 0.24
	2003-09-01	2003-09-03	3 days	0.42 ± 0.00	0.42	31.46 ± 1.02	32	25.58 ± 0.38	26	20.92 ± 0.59	1.98 ± 0.44	2.00 ± 0.32
	2003-09-20	2003-09-22	3 days	0.02 ± 0.00	0.02	29.57 ± 1.45	31	24.12 ± 0.19	24	21.54 ± 0.33	2.55 ± 0.21	1.87 ± 0.14
	2003-09-26	2003-09-28	3 days	0.02 ± 0.00	0.02	29.50 ± 0.09	30	24.32 ± 0.51	25	20.78 ± 0.20	2.38 ± 0.43	2.02 ± 0.39
2004	2004-06-23	2004-07-06	14 days	1.44 ± 2.04	5.25	37.23 ± 3.74	45	24.19 ± 0.72	25	24.14 ± 1.11	1.71 ± 0.33	1.99 ± 0.40
	2004-07-17	2004-09-06	52 days	3.54 ± 7.06	30.57	35.17 ± 3.49	51	26.87 ± 1.82	31	23.85 ± 1.47	2.25 ± 0.90	2.34 ± 0.89
	2004-09-09	2004-09-12	4 days	0.14 ± 0.08	0.18	33.16 ± 1.03	34	25.62 ± 0.21	26	23.45 ± 0.62	1.46 ± 0.14	2.34 ± 0.15
	2004-10-18	2004-10-20	3 days	0.02 ± 0.00	0.02	28.57 ± 0.60	29	24.39 ± 0.23	25	18.01 ± 2.92	2.50 ± 0.46	2.07 ± 0.18
2005	2005-06-04	2005-06-06	3 days	0.02 ± 0.00	0.02	34.28 ± 1.31	35	21.29 ± 0.38	22	21.51 ± 0.39	1.41 ± 0.05	1.56 ± 0.06
	2005-06-17	2005-06-29	13 days	2.50 ± 2.28	6.34	34.28 ± 1.80	37	25.04 ± 1.57	28	24.27 ± 0.74	1.57 ± 0.17	1.82 ± 0.19
	2005-07-01	2005-07-30	30 days	1.62 ± 2.05	7.39	35.20 ± 1.65	38	25.13 ± 1.04	28	24.02 ± 1.16	1.59 ± 0.19	1.86 ± 0.25
	2005-08-02	2005-08-09	8 days	0.28 ± 0.23	0.68	35.98 ± 2.29	39	24.73 ± 1.30	27	23.79 ± 1.65	1.55 ± 0.22	2.22 ± 0.36
	2005-08-12	2005-08-18	7 days	0.05 ± 0.02	0.08	34.71 ± 1.54	37	25.28 ± 1.01	27	24.01 ± 0.47	1.45 ± 0.14	1.99 ± 0.36
	2005-08-27	2005-08-31	5 days	0.10 ± 0.07	0.16	34.48 ± 1.28	36	24.36 ± 0.66	25	23.87 ± 0.74	1.47 ± 0.08	1.99 ± 0.34
	2005-09-02	2005-09-08	7 days	1.21 ± 1.24	2.58	32.21 ± 2.81	35	26.11 ± 2.12	30	21.87 ± 2.55	2.94 ± 1.25	2.73 ± 1.27
2006	2006-06-20	2006-06-24	5 days	0.23 ± 0.12	0.36	34.07 ± 2.51	38	23.71 ± 0.28	24	23.35 ± 0.74	1.41 ± 0.06	1.95 ± 0.23
	2006-06-29	2006-08-13	46 days	4.24 ± 4.58	15.72	35.81 ± 2.07	39	25.96 ± 1.55	29	24.75 ± 1.42	1.68 ± 0.20	2.01 ± 0.30
	2006-08-21	2006-09-12	23 days	0.60 ± 0.70	2.03	35.31 ± 2.58	42	24.64 ± 1.32	28	23.53 ± 1.06	2.29 ± 1.14	2.15 ± 0.61
2007	2007-06-30	2007-07-05	6 days	0.06 ± 0.04	0.10	33.95 ± 2.09	36	23.17 ± 1.00	24	22.16 ± 0.60	1.54 ± 0.28	1.78 ± 0.36
	2007-07-07	2007-07-19	13 days	0.12 ± 0.08	0.24	34.05 ± 1.24	36	23.69 ± 0.82	25	22.76 ± 1.06	1.45 ± 0.08	1.86 ± 0.17
	2007-07-23	2007-08-05	14 days	1.01 ± 0.98	2.62	36.52 ± 2.31	40	25.47 ± 1.48	29	24.59 ± 1.26	1.99 ± 0.74	2.35 ± 0.90
	2007-08-16	2007-08-21	6 days	0.06 ± 0.03	0.08	33.45 ± 1.45	36	24.66 ± 0.96	26	21.32 ± 0.97	1.44 ± 0.14	1.93 ± 0.17
	2007-08-26	2007-08-29	4 days	1.47 ± 0.70	1.83	35.07 ± 0.58	36	25.19 ± 1.31	27	24.74 ± 1.02	1.58 ± 0.13	1.85 ± 0.32
2008	2008-06-20	2008-07-12	23 days	0.17 ± 0.10	0.34	33.88 ± 1.58	37	23.93 ± 1.03	25	23.01 ± 1.18	1.47 ± 0.09	1.96 ± 0.27
	2008-07-17	2008-08-15	30 days	1.31 ± 2.68	9.40	34.80 ± 1.56	38	25.39 ± 1.15	28	23.92 ± 1.29	1.53 ± 0.16	1.88 ± 0.26
	2008-08-17	2008-08-19	3 days	0.04 ± 0.00	0.04	32.21 ± 0.51	33	24.36 ± 0.60	25	22.38 ± 0.50	1.41 ± 0.09	1.77 ± 0.26
	2008-08-25	2008-08-28	4 days	0.04 ± 0.01	0.04	33.74 ± 0.63	35	24.62 ± 0.56	25	23.40 ± 0.52	1.44 ± 0.08	2.32 ± 0.36

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2009	2009-06-12	2009-06-23	12 days	0.20 ± 0.16	0.46	34.58 ± 1.35	36	23.82 ± 1.20	26	23.35 ± 1.02	1.46 ± 0.09	2.03 ± 0.19
	2009-06-28	2009-07-07	10 days	1.18 ± 0.95	2.54	33.78 ± 1.59	35	24.79 ± 1.24	27	23.94 ± 1.26	1.49 ± 0.10	1.82 ± 0.17
	2009-07-11	2009-07-17	7 days	0.25 ± 0.19	0.46	34.03 ± 0.94	35	26.18 ± 1.67	29	23.48 ± 0.86	1.49 ± 0.12	1.82 ± 0.16
	2009-07-20	2009-08-07	19 days	1.72 ± 1.39	4.19	35.30 ± 1.68	38	26.48 ± 1.66	30	24.17 ± 0.86	2.37 ± 0.84	2.26 ± 0.87
	2009-08-11	2009-09-06	27 days	1.03 ± 1.50	5.03	34.70 ± 1.12	36	25.48 ± 0.88	28	24.13 ± 1.13	1.52 ± 0.12	2.00 ± 0.35
2010	2010-06-28	2010-07-02	5 days	0.11 ± 0.05	0.14	34.03 ± 1.28	36	22.85 ± 0.62	23	23.55 ± 0.69	1.42 ± 0.06	1.97 ± 0.12
	2010-07-04	2010-08-15	43 days	2.77 ± 3.72	12.76	35.80 ± 1.70	39	25.67 ± 1.07	29	24.25 ± 1.25	1.65 ± 0.22	2.02 ± 0.34
	2010-08-19	2010-09-04	17 days	0.96 ± 0.98	2.78	35.44 ± 2.26	40	25.85 ± 1.55	29	24.02 ± 1.47	1.83 ± 0.64	2.24 ± 0.86
	2010-09-14	2010-09-16	3 days	1.23 ± 0.00	1.23	32.08 ± 1.51	34	25.04 ± 0.55	25	22.06 ± 0.40	3.23 ± 0.80	2.27 ± 0.39
2011	2011-06-15	2011-06-18	4 days	0.06 ± 0.03	0.08	32.27 ± 0.56	33	22.84 ± 1.18	24	21.78 ± 0.48	1.39 ± 0.06	1.79 ± 0.19
	2011-06-21	2011-07-03	13 days	0.75 ± 1.09	2.76	35.18 ± 1.55	38	24.50 ± 0.74	26	23.64 ± 1.27	1.83 ± 0.46	2.02 ± 0.38
	2011-07-05	2011-07-07	3 days	0.06 ± 0.00	0.06	34.48 ± 0.96	35	24.90 ± 0.63	25	22.84 ± 1.04	1.58 ± 0.25	1.97 ± 0.28
	2011-07-09	2011-07-12	4 days	0.22 ± 0.11	0.28	33.09 ± 0.44	34	25.46 ± 0.50	26	23.44 ± 0.31	1.42 ± 0.07	2.06 ± 0.25
	2011-07-15	2011-07-17	3 days	0.02 ± 0.00	0.02	34.38 ± 0.69	35	24.57 ± 0.60	25	22.98 ± 0.72	1.48 ± 0.11	2.05 ± 0.07
	2011-07-25	2011-07-31	7 days	0.33 ± 0.22	0.64	34.79 ± 1.38	37	24.49 ± 0.78	25	23.33 ± 0.51	1.60 ± 0.20	1.89 ± 0.25
	2011-08-03	2011-08-27	25 days	1.20 ± 1.44	5.23	35.24 ± 1.70	38	26.12 ± 1.28	29	24.11 ± 1.44	1.61 ± 0.22	1.93 ± 0.33
	2011-08-31	2011-09-02	3 days	0.02 ± 0.00	0.02	33.85 ± 1.31	35	26.25 ± 1.15	28	22.04 ± 0.80	1.41 ± 0.06	2.08 ± 0.07
	2011-09-09	2011-09-11	3 days	0.02 ± 0.00	0.02	33.03 ± 0.62	34	24.08 ± 0.78	25	22.93 ± 0.50	1.41 ± 0.02	1.76 ± 0.04
2012	2012-06-20	2012-06-30	11 days	3.24 ± 3.66	9.54	35.95 ± 2.74	41	24.79 ± 1.35	27	23.86 ± 1.93	1.68 ± 0.23	1.78 ± 0.16
	2012-07-07	2012-07-23	17 days	0.63 ± 0.98	2.68	34.94 ± 1.61	37	25.04 ± 0.77	28	23.15 ± 1.00	1.64 ± 0.20	1.90 ± 0.34
	2012-07-25	2012-08-05	12 days	0.62 ± 0.65	1.61	34.29 ± 1.95	38	25.96 ± 1.23	28	23.95 ± 0.67	1.48 ± 0.14	1.89 ± 0.25
	2012-08-07	2012-08-30	24 days	7.52 ± 8.42	24.93	36.70 ± 2.46	42	27.19 ± 1.20	30	24.94 ± 1.70	1.82 ± 0.38	1.96 ± 0.23
	2012-09-17	2012-09-21	5 days	0.32 ± 0.25	0.50	30.03 ± 0.18	30	24.47 ± 0.46	25	21.63 ± 0.41	2.66 ± 0.37	1.78 ± 0.25
	2012-09-23	2012-09-27	5 days	1.45 ± 0.44	1.75	30.49 ± 0.94	31	24.92 ± 0.37	25	18.49 ± 2.64	2.65 ± 0.30	2.03 ± 0.12
2013	2013-07-04	2013-07-28	25 days	2.74 ± 2.81	9.26	34.69 ± 2.10	38	25.20 ± 1.35	29	24.47 ± 0.58	1.61 ± 0.25	1.90 ± 0.33
	2013-07-30	2013-08-25	27 days	1.47 ± 1.19	4.11	35.57 ± 2.55	47	25.66 ± 1.50	29	24.26 ± 0.94	2.16 ± 0.94	2.26 ± 0.71
2014	2014-06-12	2014-06-15	4 days	0.06 ± 0.03	0.08	34.14 ± 1.42	36	23.65 ± 1.35	26	23.06 ± 1.18	1.58 ± 0.16	1.84 ± 0.12
	2014-07-11	2014-07-20	10 days	0.96 ± 1.15	2.78	34.09 ± 2.09	37	24.62 ± 1.97	28	23.44 ± 1.72	1.48 ± 0.13	1.84 ± 0.32
	2014-07-22	2014-07-31	10 days	0.23 ± 0.15	0.40	33.50 ± 0.92	35	24.60 ± 1.08	26	23.80 ± 0.92	1.53 ± 0.10	1.78 ± 0.18
	2014-08-04	2014-08-19	16 days	0.46 ± 0.44	1.25	33.84 ± 1.46	37	25.50 ± 1.27	28	23.31 ± 1.25	1.51 ± 0.17	1.94 ± 0.22
	2014-08-25	2014-09-08	15 days	0.21 ± 0.15	0.50	34.64 ± 1.20	36	24.95 ± 0.68	26	23.87 ± 0.67	1.76 ± 0.43	1.77 ± 0.19
	2014-09-10	2014-09-14	5 days	0.14 ± 0.07	0.18	33.55 ± 0.99	34	25.48 ± 0.93	27	22.83 ± 0.44	2.94 ± 0.24	1.99 ± 0.34
	2014-10-22	2014-10-24	3 days	1.23 ± 0.00	1.23	32.19 ± 1.48	34	25.42 ± 0.72	26	17.66 ± 1.23	4.08 ± 0.65	2.25 ± 0.64
2015	2015-06-26	2015-08-14	50 days	9.17 ± 6.12	23.95	37.17 ± 1.61	42	27.54 ± 2.16	32	25.62 ± 1.21	1.91 ± 0.29	1.95 ± 0.31
	2015-08-17	2015-08-23	7 days	0.18 ± 0.08	0.26	33.87 ± 1.20	36	26.17 ± 0.86	27	23.34 ± 1.25	1.44 ± 0.11	2.04 ± 0.17
	2015-08-26	2015-09-01	7 days	0.83 ± 0.55	1.41	34.51 ± 2.07	37	25.88 ± 1.64	28	24.47 ± 1.14	1.57 ± 0.23	2.00 ± 0.25
	2015-09-06	2015-09-09	4 days	0.12 ± 0.00	0.12	29.33 ± 0.63	30	24.63 ± 0.19	25	19.54 ± 0.32	1.97 ± 0.32	1.97 ± 0.14
	2015-09-11	2015-09-16	6 days	0.32 ± 0.25	0.54	30.23 ± 1.31	32	24.79 ± 0.40	25	20.13 ± 1.08	2.02 ± 0.28	1.87 ± 0.23
	2015-09-22	2015-09-25	4 days	1.90 ± 0.49	2.15	30.48 ± 1.34	32	25.34 ± 0.21	26	18.89 ± 0.69	2.77 ± 0.82	2.17 ± 0.23
	2015-10-02	2015-10-07	6 days	1.56 ± 1.09	2.46	31.10 ± 2.37	35	25.92 ± 1.91	29	18.73 ± 1.80	3.21 ± 1.22	2.44 ± 0.89

Table B.8: Summary statistics for heat wave episodes identified by heat index using 90pp for climatic type *(continued)*

	Dates			Coverage		Day-time heat index		Night-time heat index		Average daily		
Year	Start	End	Duration	Mean	Max	Mean	Max	Mean	Max	Heat Index	Day-time MI[a]	Night-time MI[a]
2016	2016-06-08	2016-06-10	3 days	0.04 ± 0.00	0.04	34.46 ± 0.82	35	22.99 ± 2.12	25	23.02 ± 0.74	1.66 ± 0.30	1.95 ± 0.51
	2016-06-12	2016-06-14	3 days	0.02 ± 0.00	0.02	33.99 ± 2.00	36	24.25 ± 3.23	28	22.04 ± 1.01	1.78 ± 0.39	2.40 ± 1.00
	2016-06-27	2016-07-15	19 days	1.21 ± 1.58	4.83	35.50 ± 2.40	42	24.58 ± 1.15	27	23.96 ± 1.44	1.51 ± 0.20	1.96 ± 0.33
	2016-07-17	2016-08-09	24 days	2.01 ± 2.42	7.61	36.09 ± 1.04	38	25.29 ± 1.44	28	24.90 ± 0.73	1.78 ± 0.22	1.82 ± 0.34
	2016-08-15	2016-09-09	26 days	1.52 ± 2.09	6.86	34.98 ± 2.01	40	25.07 ± 1.07	27	24.45 ± 0.95	1.80 ± 0.51	2.08 ± 0.39
	2016-09-11	2016-09-13	3 days	0.02 ± 0.00	0.02	31.88 ± 0.42	32	24.77 ± 0.28	25	23.10 ± 0.99	1.45 ± 0.07	1.76 ± 0.25
2017	2017-06-10	2017-06-26	17 days	10.92 ± 9.36	27.71	36.25 ± 1.33	39	25.14 ± 1.48	27	25.38 ± 0.93	1.68 ± 0.19	1.91 ± 0.26
	2017-07-09	2017-07-20	12 days	5.75 ± 5.14	13.85	36.34 ± 2.84	41	25.99 ± 0.94	28	25.18 ± 1.13	1.74 ± 0.41	1.87 ± 0.27
	2017-07-22	2017-08-09	19 days	5.59 ± 5.34	17.59	36.29 ± 2.07	40	28.62 ± 2.86	33	24.79 ± 1.67	1.80 ± 0.29	2.11 ± 0.30
	2017-08-11	2017-08-30	20 days	2.37 ± 2.12	7.02	35.31 ± 1.60	38	25.98 ± 1.36	29	24.13 ± 1.54	1.80 ± 0.34	2.00 ± 0.27
	2017-09-01	2017-09-03	3 days	0.04 ± 0.00	0.04	33.25 ± 0.32	34	24.75 ± 0.54	25	21.05 ± 0.62	1.46 ± 0.13	2.63 ± 0.14
	2017-09-06	2017-09-08	3 days	0.04 ± 0.00	0.04	33.21 ± 0.97	34	23.89 ± 0.59	25	21.81 ± 1.18	1.43 ± 0.01	2.32 ± 0.05
	2017-10-13	2017-10-16	4 days	1.58 ± 0.57	2.01	31.20 ± 0.48	32	26.27 ± 1.57	28	20.21 ± 0.66	3.67 ± 0.42	2.78 ± 1.06
2018	2018-06-20	2018-07-04	15 days	0.32 ± 0.34	0.97	33.17 ± 1.24	36	24.14 ± 0.95	25	23.33 ± 0.56	1.49 ± 0.12	1.81 ± 0.24
	2018-07-07	2018-07-15	9 days	0.73 ± 0.23	1.05	34.10 ± 0.83	36	25.67 ± 1.03	28	24.21 ± 0.68	1.47 ± 0.06	1.89 ± 0.18
	2018-07-17	2018-08-15	30 days	7.53 ± 11.33	35.30	35.86 ± 2.84	44	27.31 ± 2.18	31	24.89 ± 1.67	1.69 ± 0.22	1.92 ± 0.17
	2018-08-18	2018-08-29	12 days	0.28 ± 0.12	0.40	34.30 ± 0.83	36	25.57 ± 0.61	27	23.80 ± 0.88	1.52 ± 0.08	2.06 ± 0.34
	2018-08-31	2018-09-04	5 days	0.16 ± 0.11	0.26	35.04 ± 1.41	37	25.60 ± 0.42	26	23.88 ± 0.68	1.62 ± 0.22	1.99 ± 0.33
	2018-09-17	2018-09-26	10 days	0.03 ± 0.01	0.04	33.00 ± 1.03	35	24.23 ± 0.49	25	22.52 ± 1.01	1.44 ± 0.10	2.32 ± 0.18

Abbreviations [a] Magnitude Index

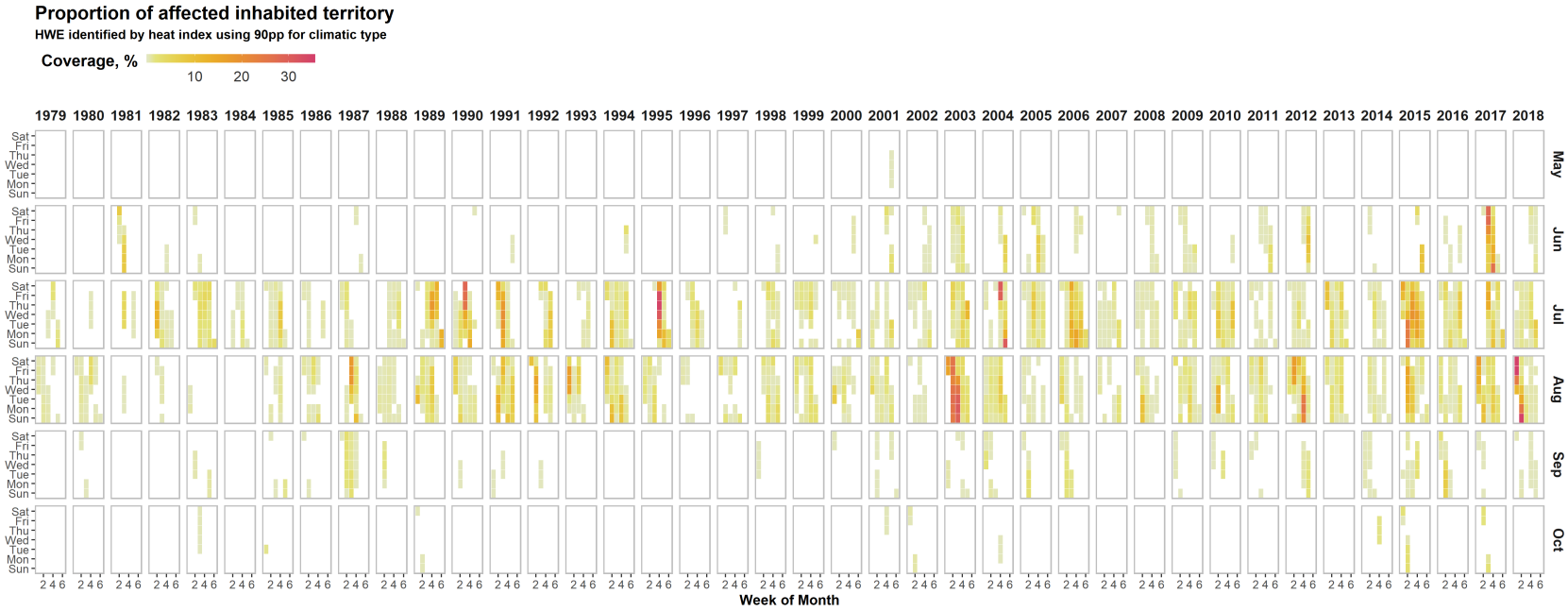


Figure B.14: Proportion of national territory affected by heatwaves identified using heat index (90pp for climatic type)

C

Appendix for Chapter 5

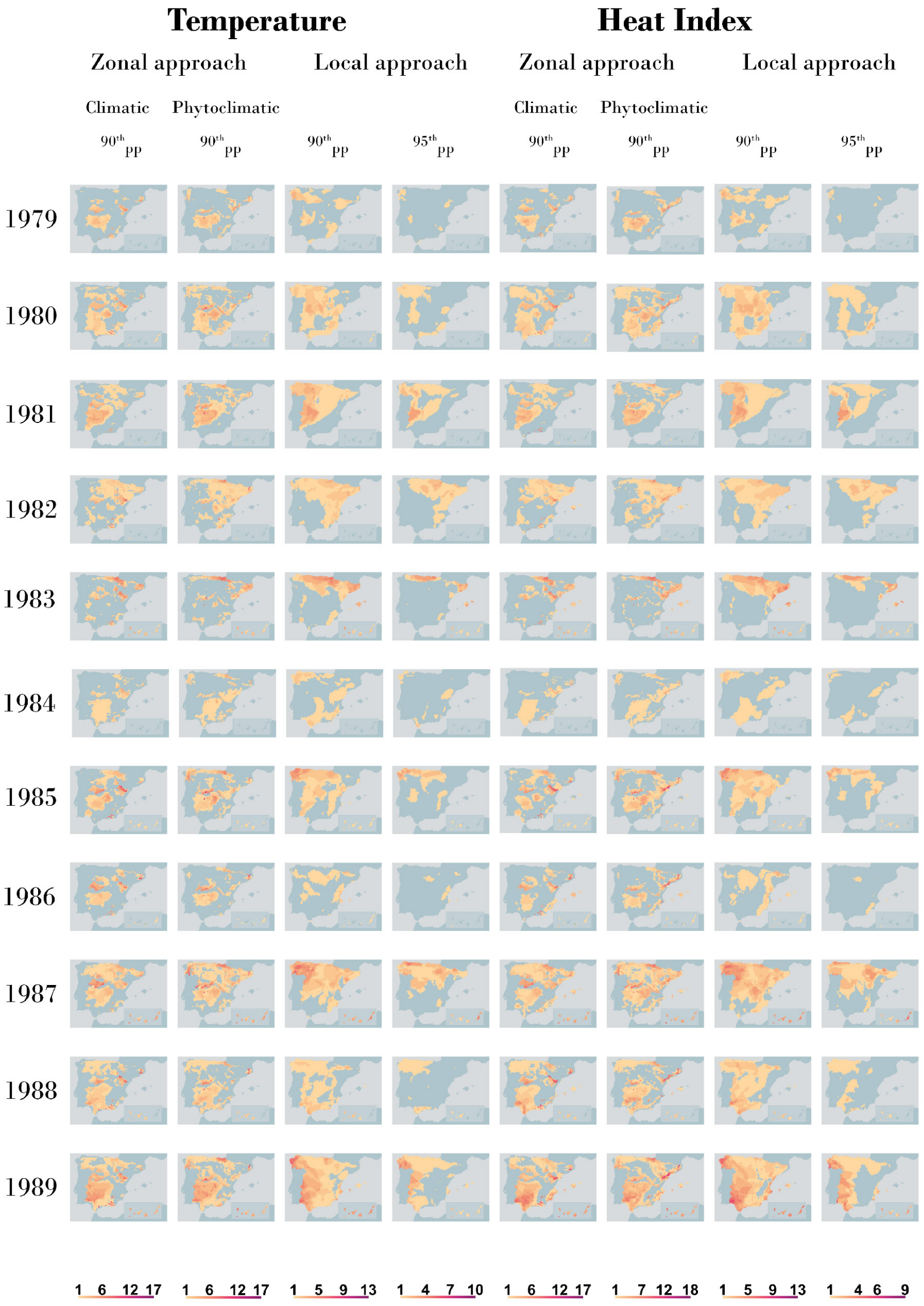


Figure C.1: Accumulated incidence of heat wave episodes in Spain (1979-1989)

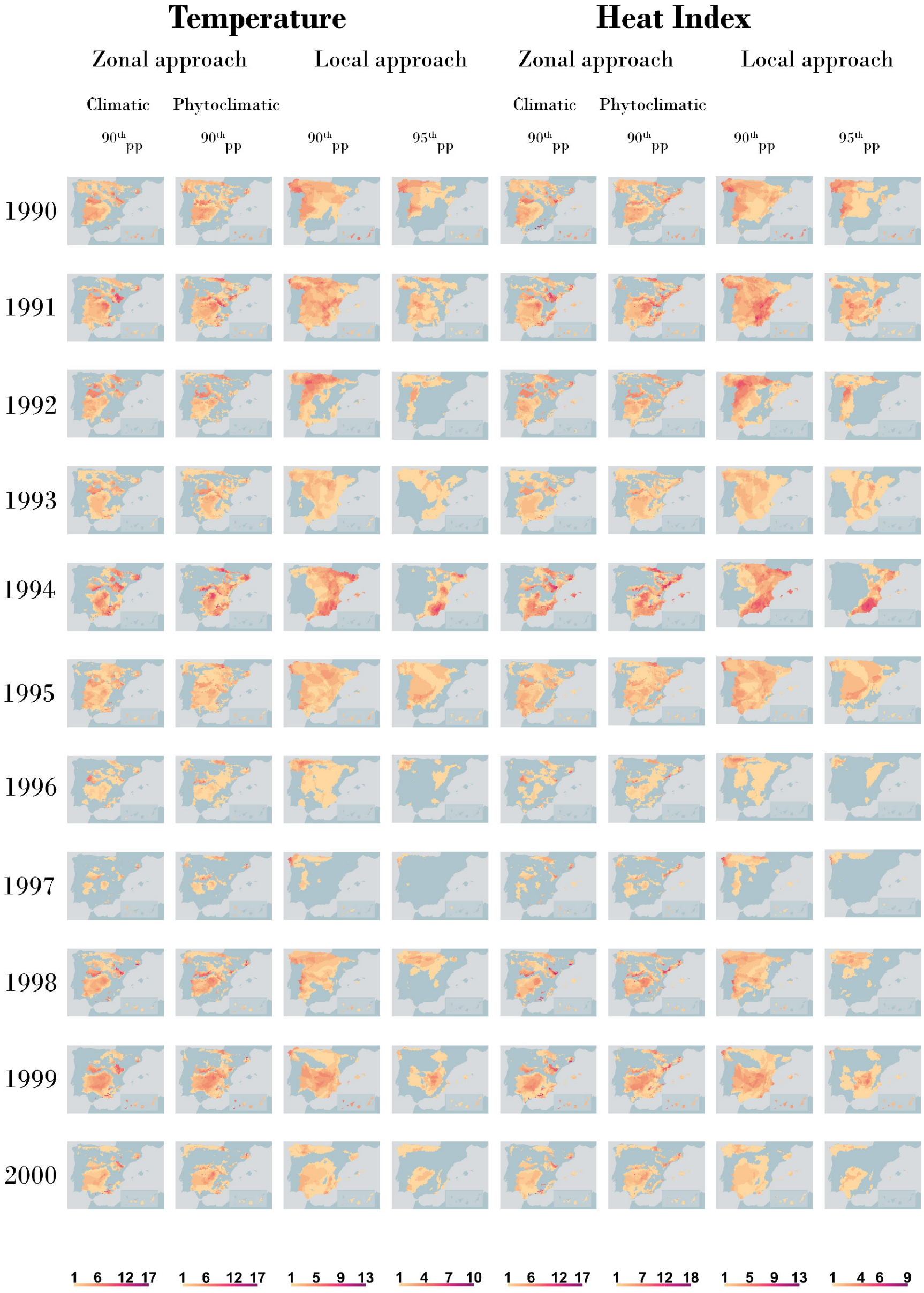


Figure C.2: Accumulated incidence of heat wave episodes in Spain (1990-2000)

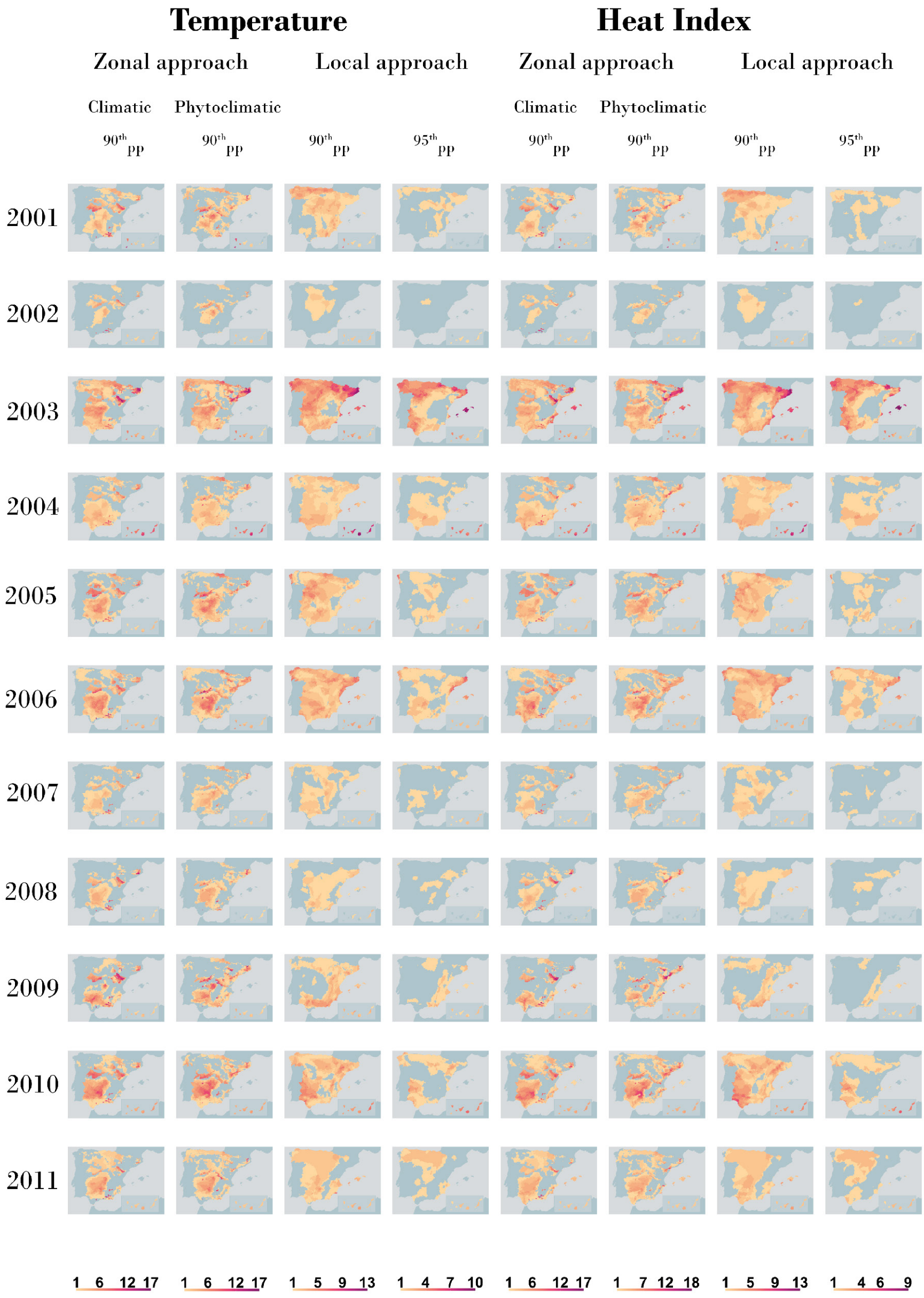


Figure C.3: Accumulated incidence of heat wave episodes in Spain (2001-2011)

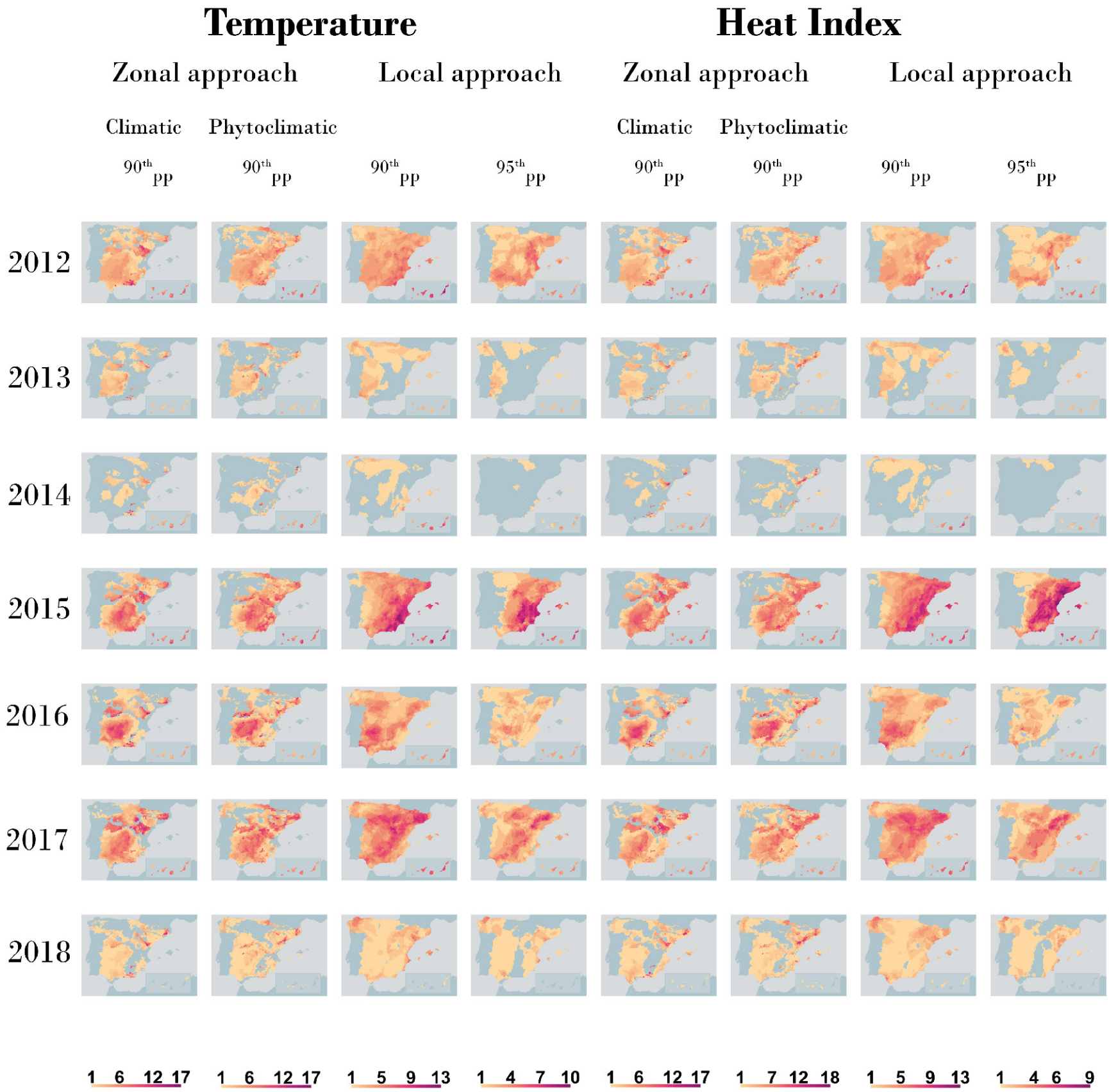


Figure C.4: Accumulated incidence of heat wave episodes in Spain (2012-2018)

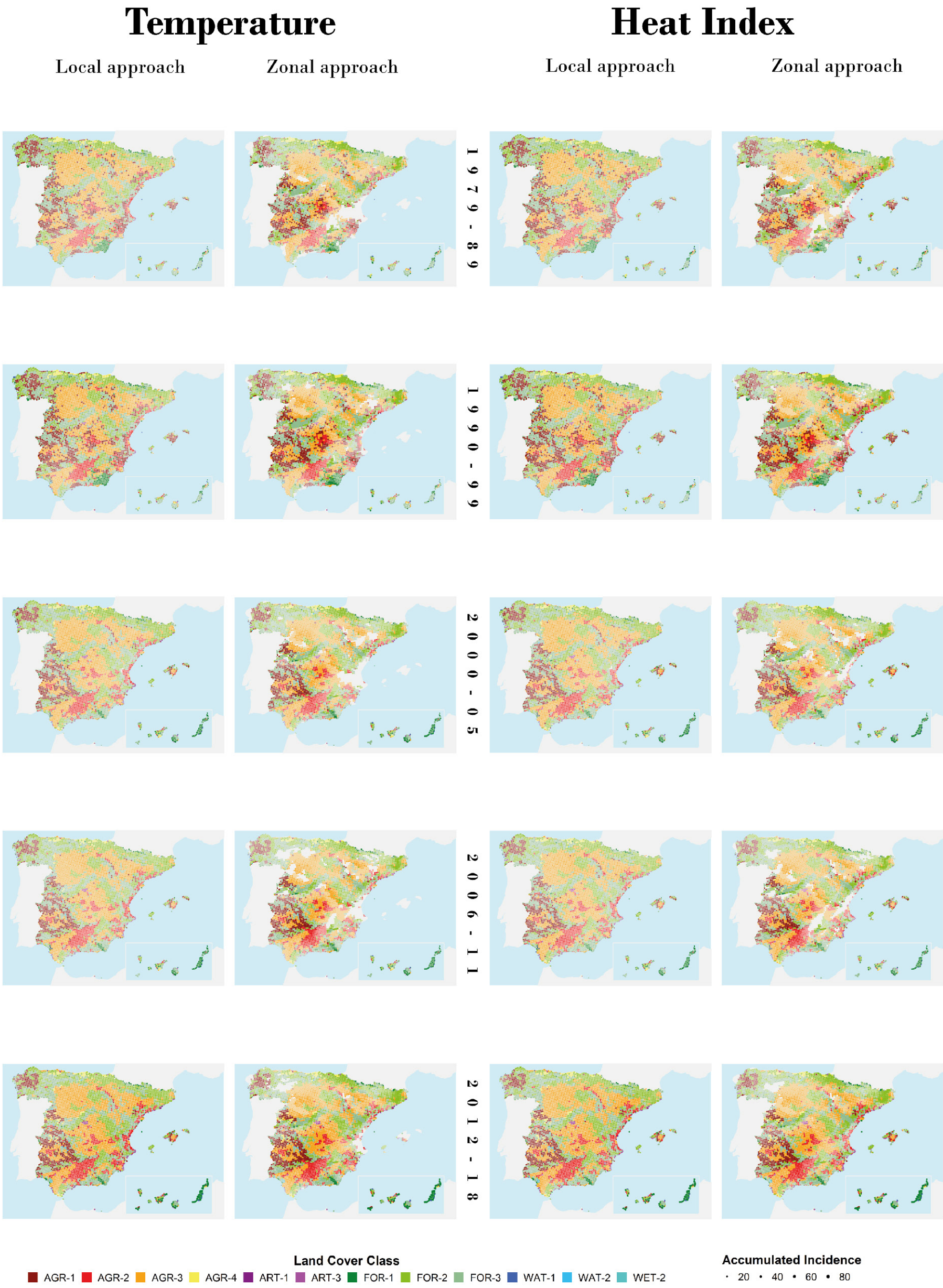


Figure C.5: Land cover transitions and heat wave incidence rates in 1990-2018

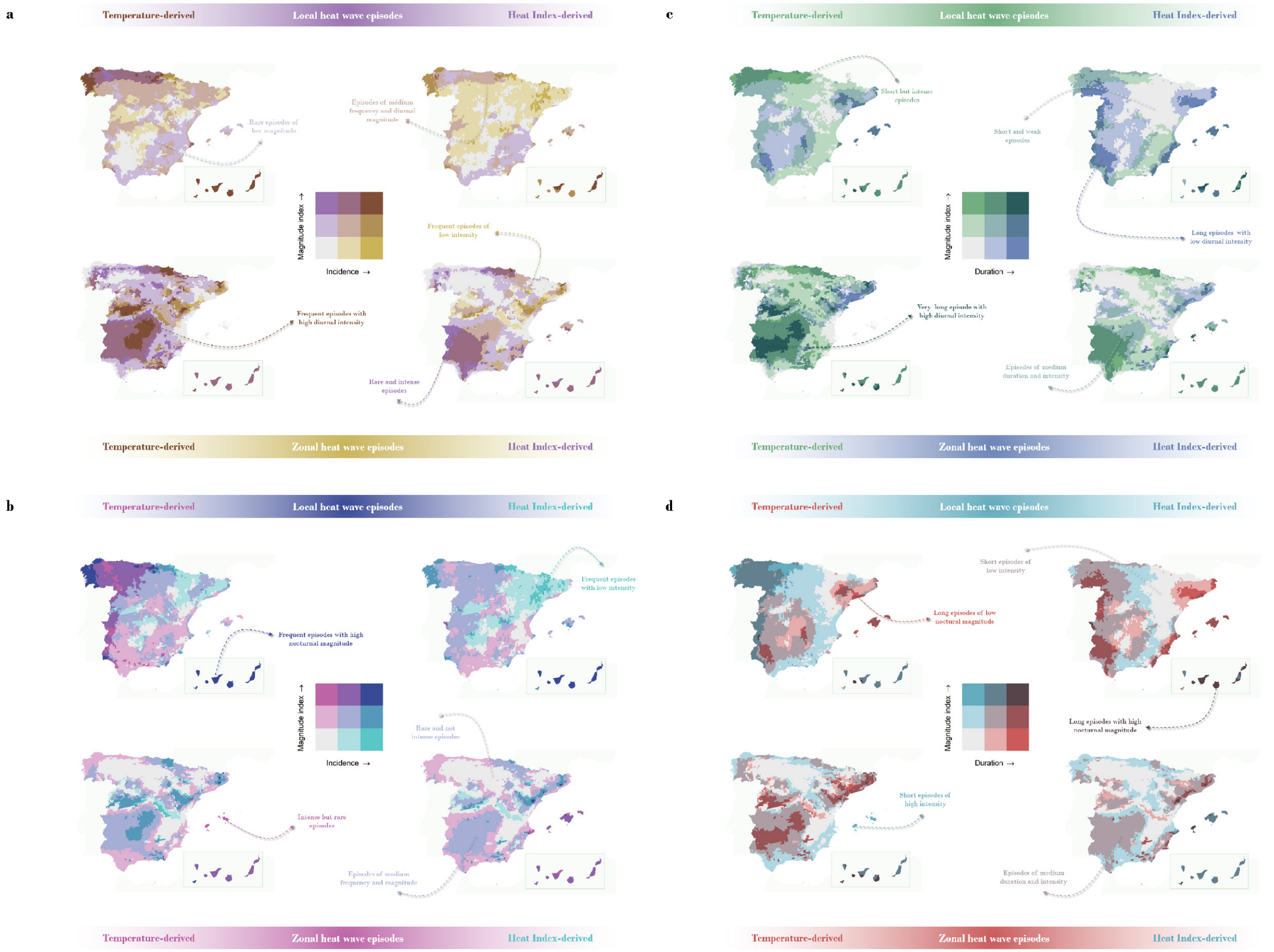


Figure C.6: Bivariate maps app

D

Appendix for Chapter 6

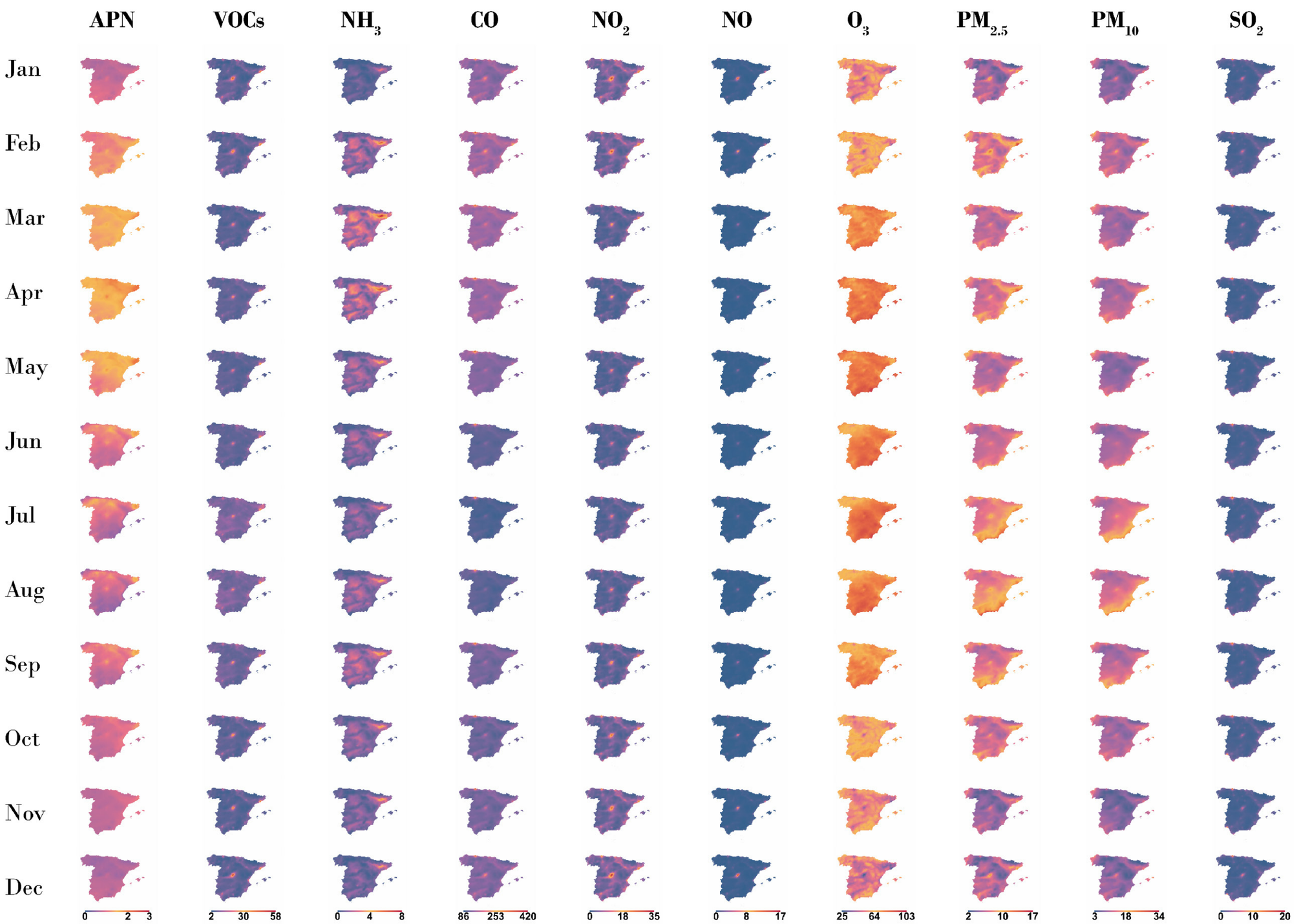


Figure D.1: Spatial distribution of main air pollutants across Spain by month

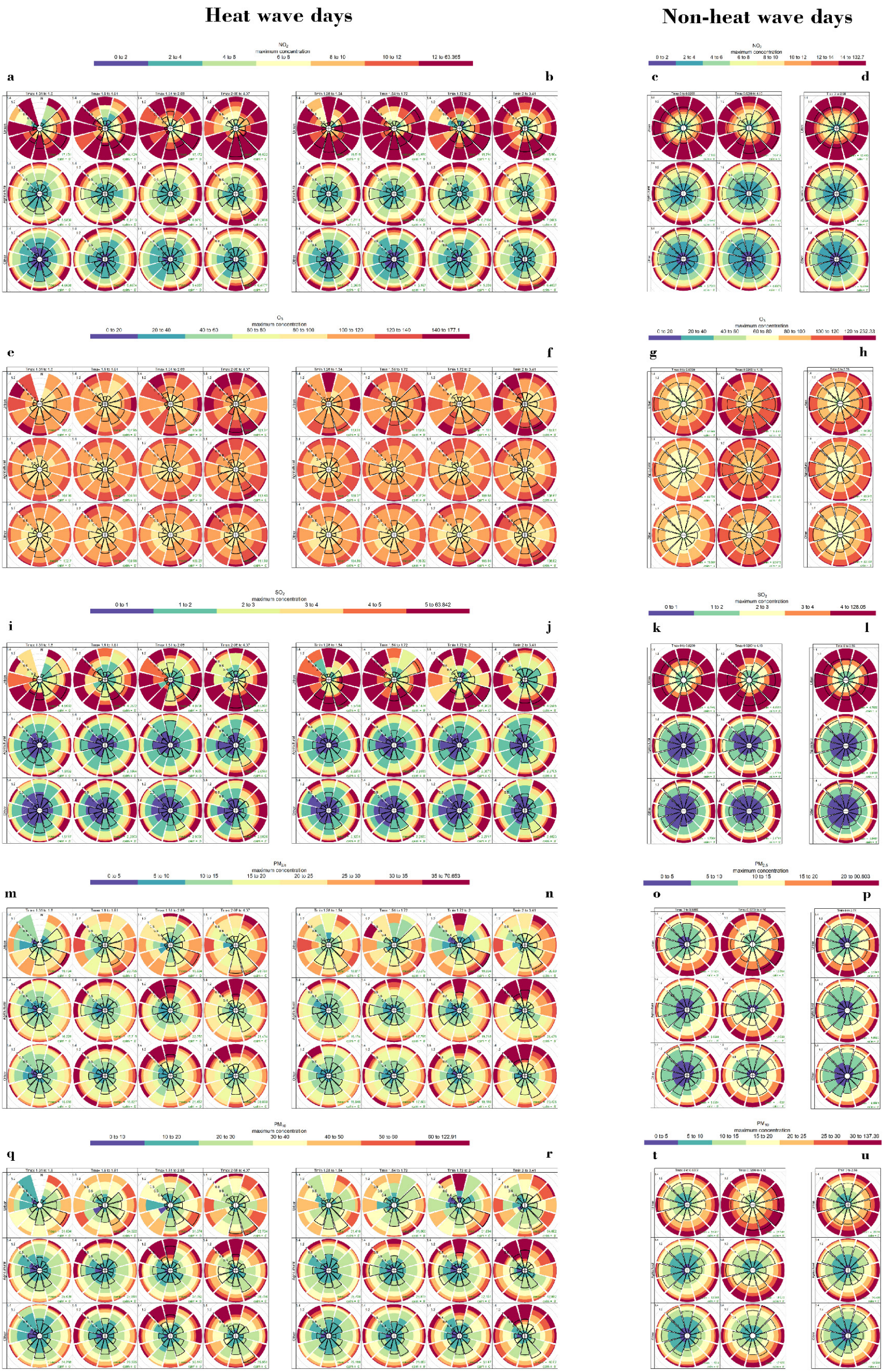


Figure D.2: Peak concentrations of O3, NO2, SO2, PM2.5 and PM10 by heat intensity and land cover class in 2017-2018

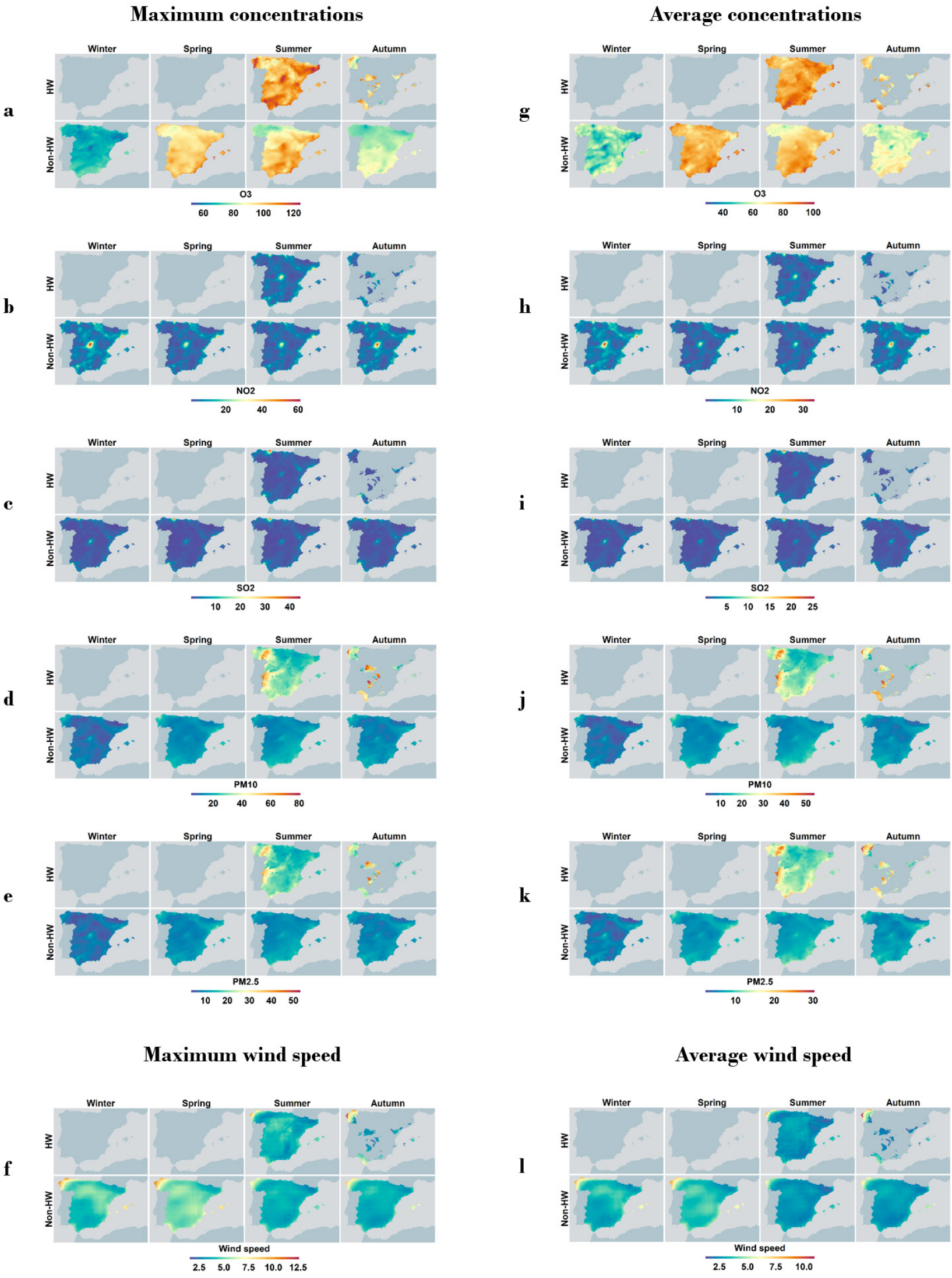


Figure D.3: Spatial variations of O3, NO2, SO2, PM2.5 and PM10 concentrations on heat wave and non-heat wave days in 2017-2018

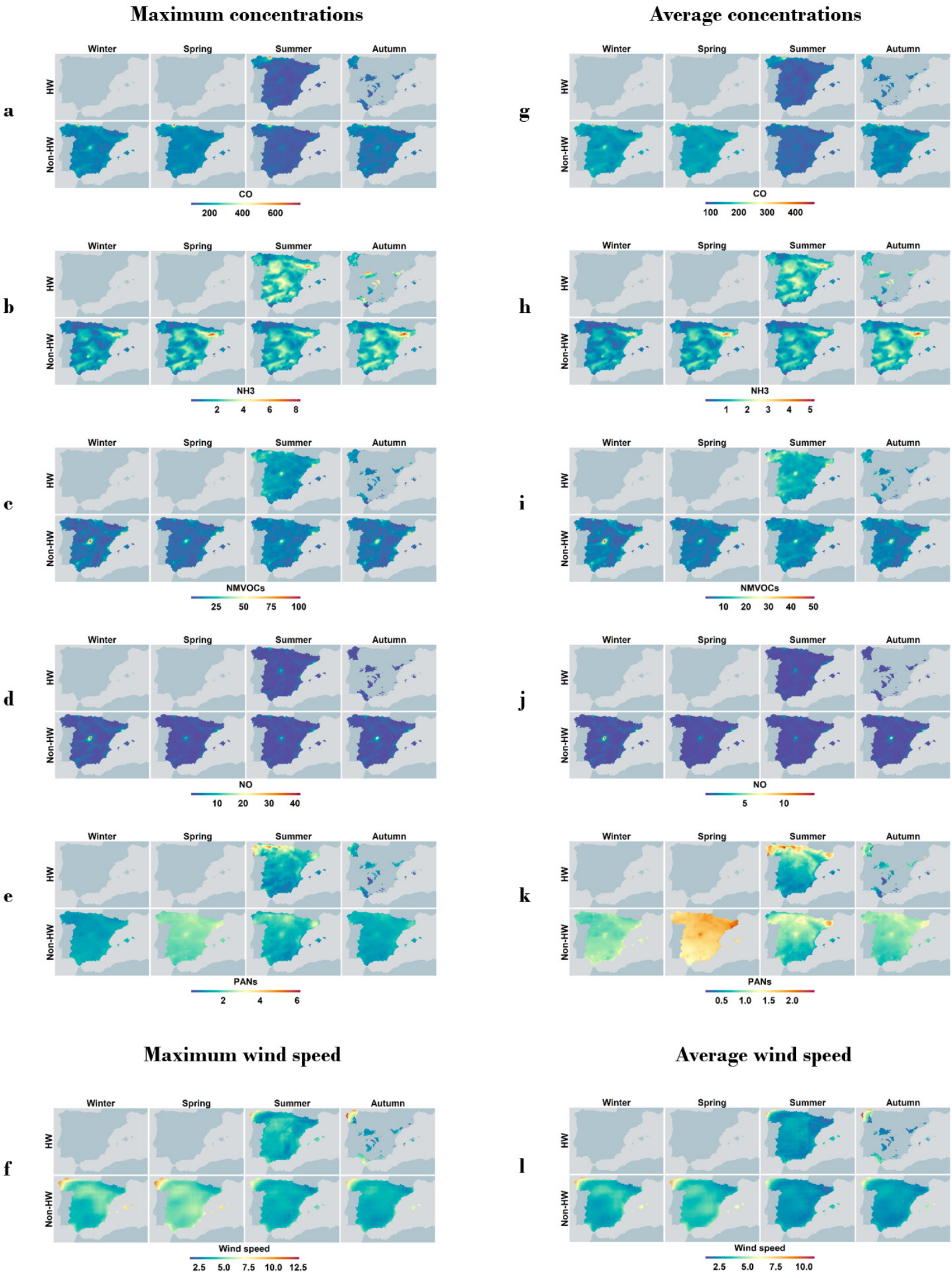


Figure D.4: Spatial variations of CO, NH3, NMVOCs, NO and PANs on heat wave and non-heat wave days in 2017-2018

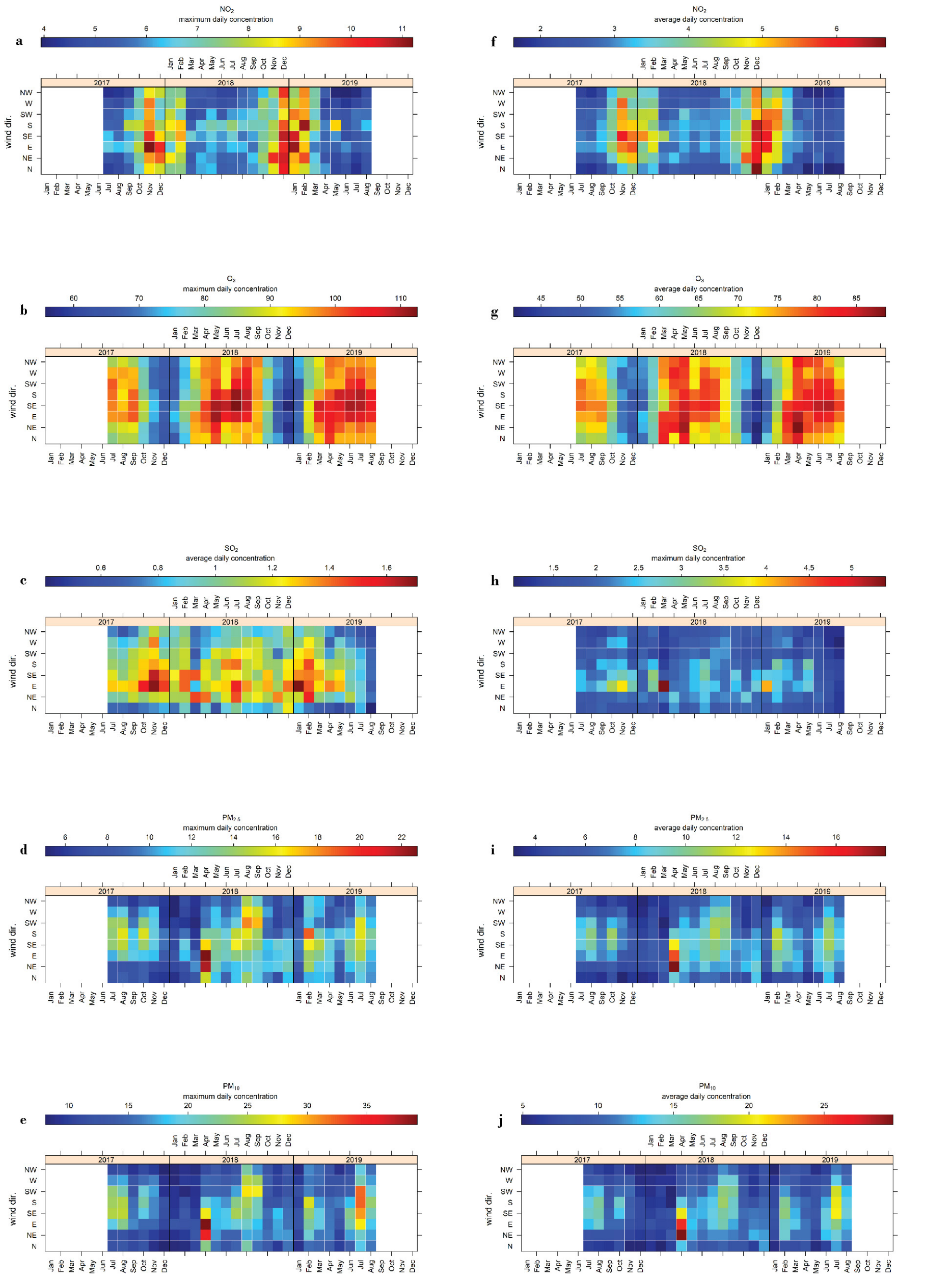


Figure D.5: Seasonal variations of average, maximum and minimum concentrations (µg/m3) of NO2, O3, SO2, PM2.5 and PM10

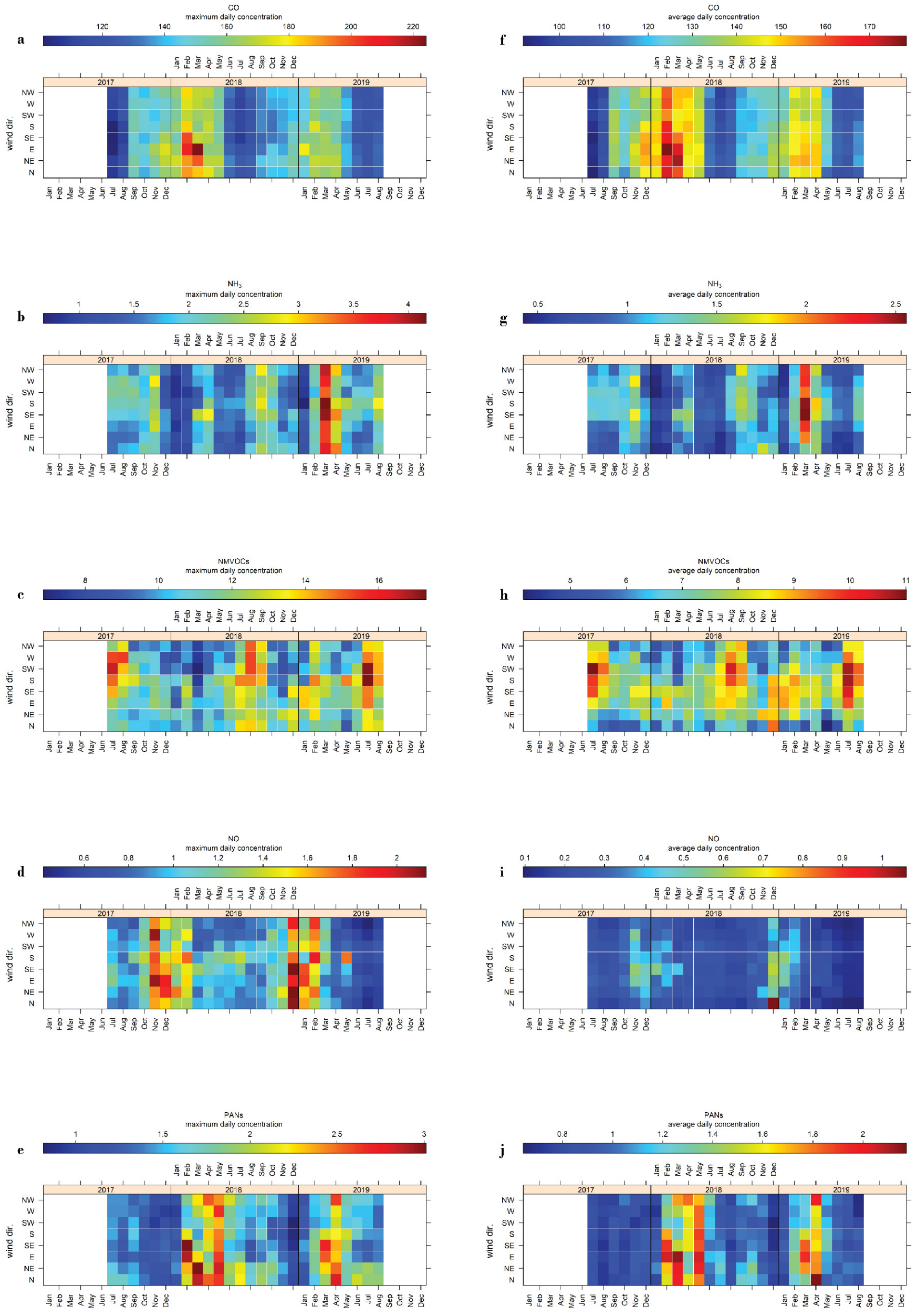


Figure D.6: Seasonal variations of average, maximum and minimum concentrations (µg/m3) of CO, NH3, NMVOCs, NO and PANs

E

Appendix for Chapter 8

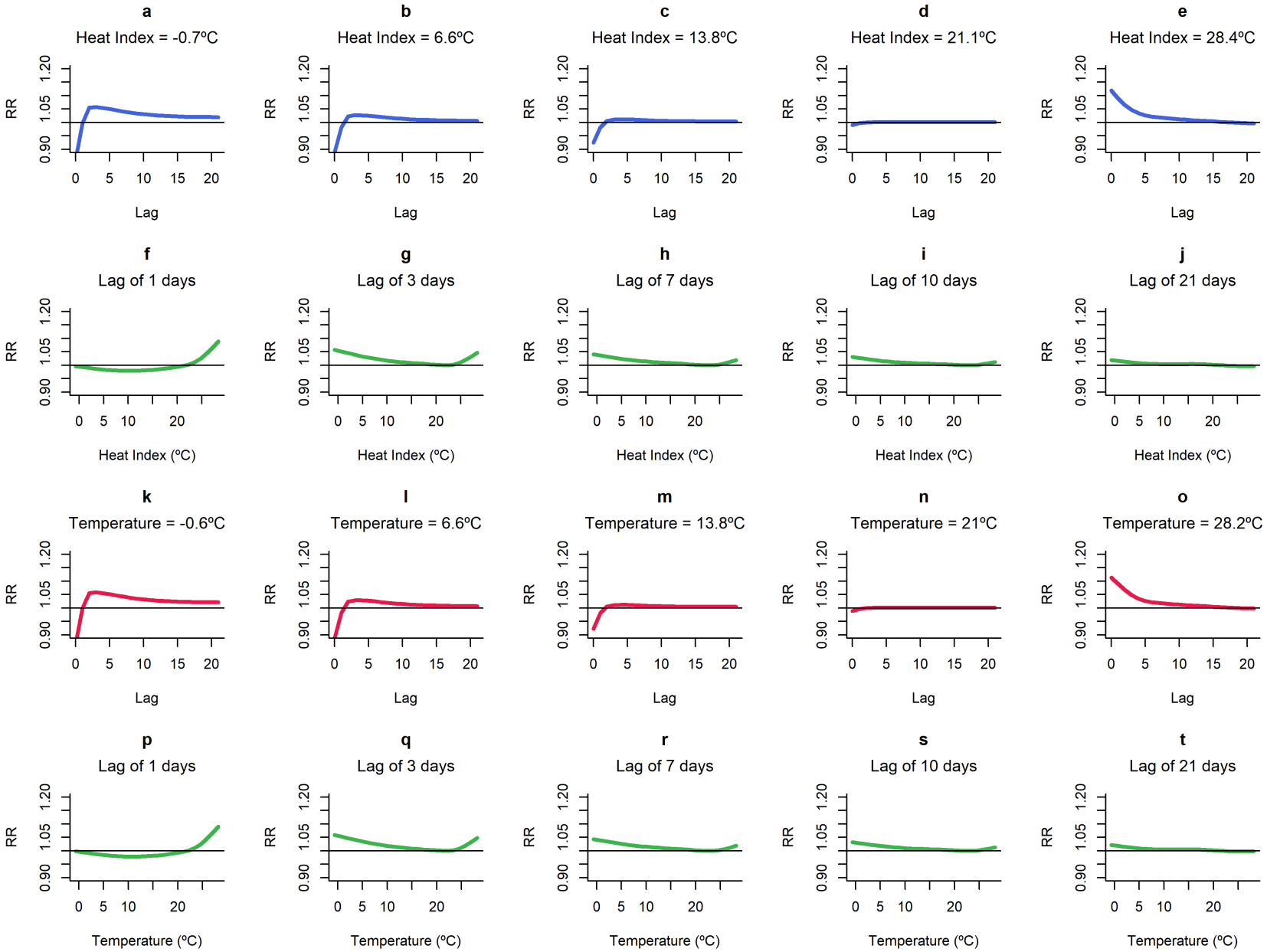


Figure E.1: Dose-response and lag-response relationship for average temperatures and heat index at national level

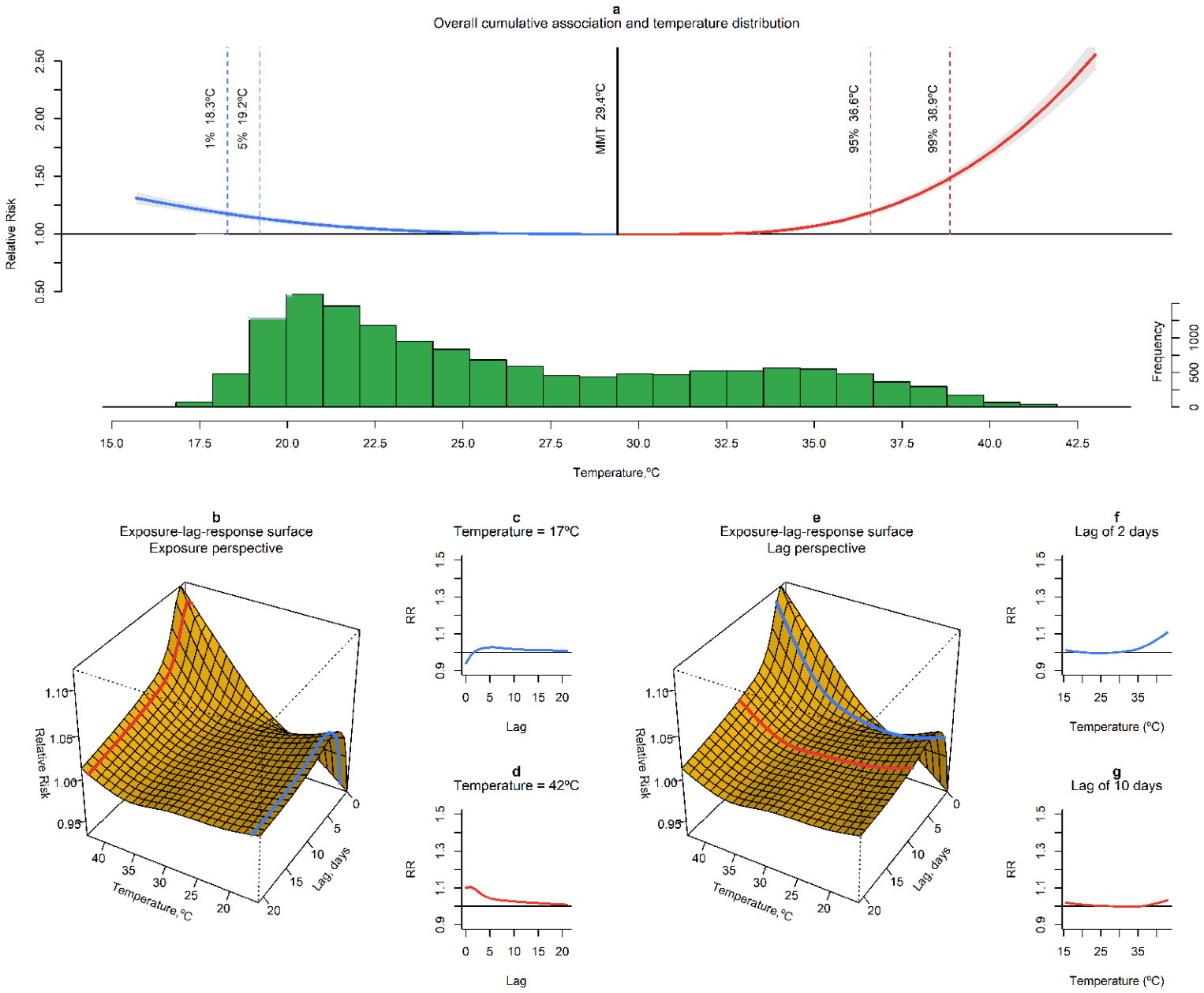


Figure E.2: Exposure-lag-response associations between daily mortality in elderly (65+) females and maximum temperature at national level

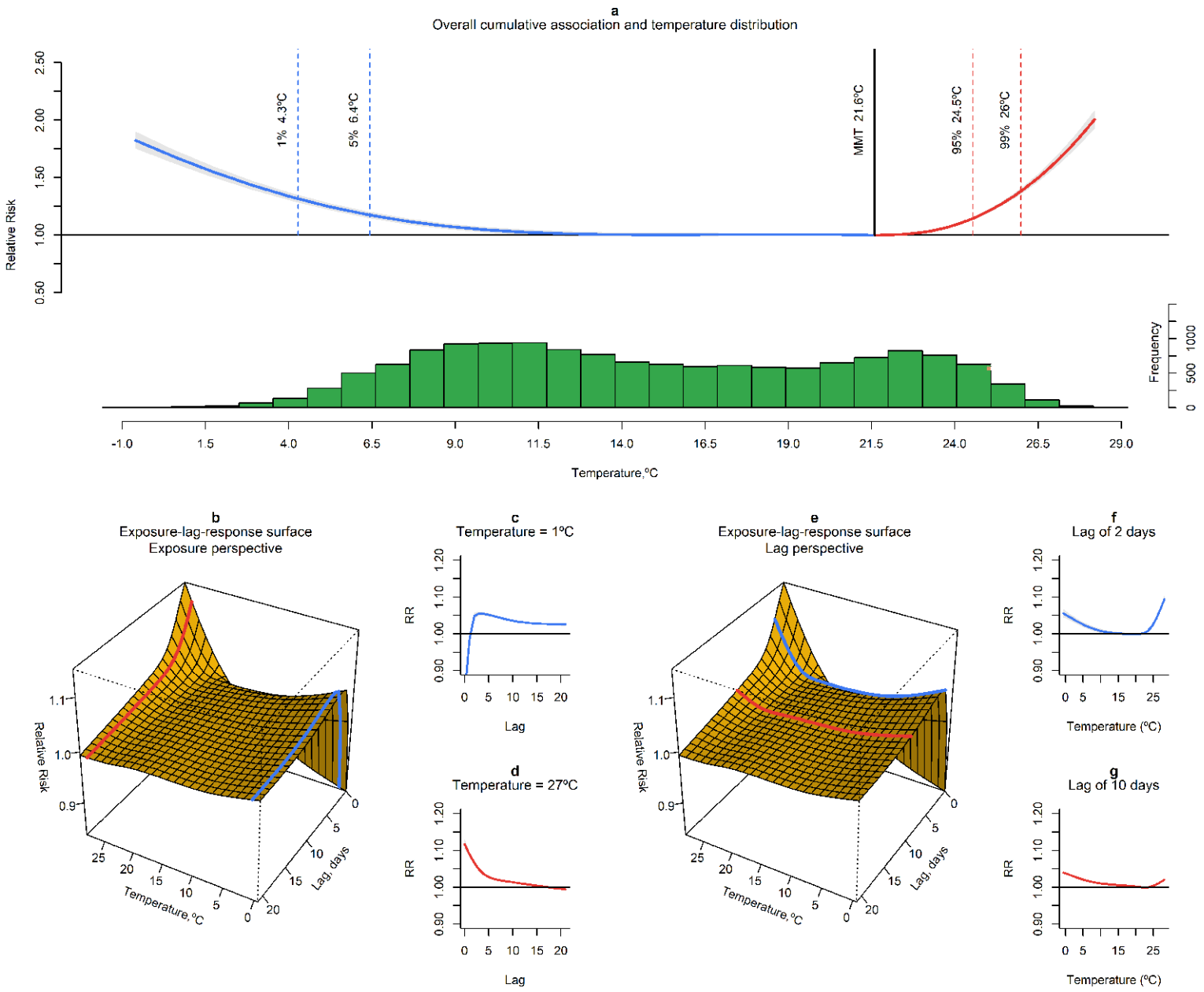


Figure E.3: Exposure-lag-response associations between daily mortality in elderly (65+) females and mean temperature at national level

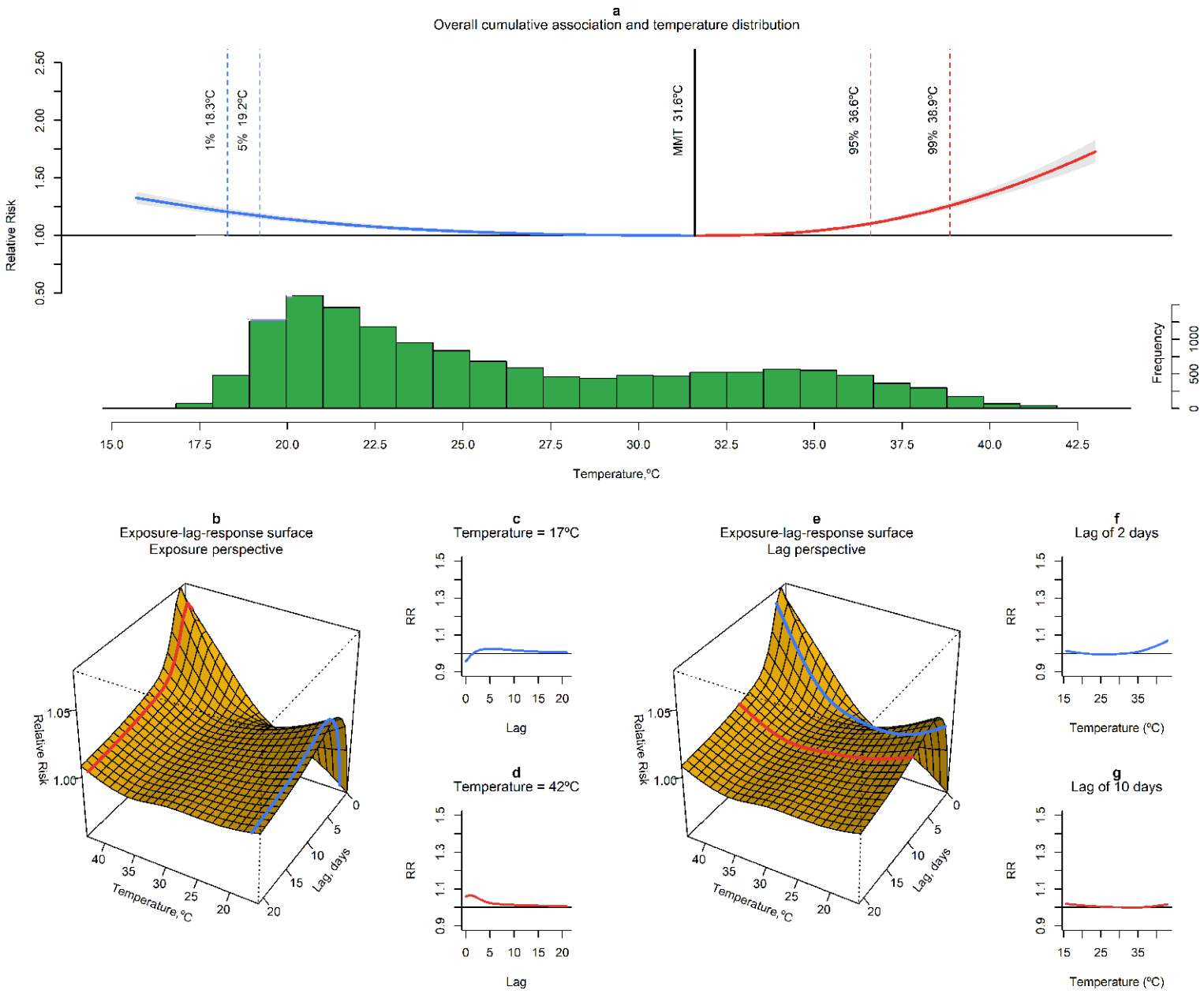


Figure E.4: Exposure-lag-response associations between daily mortality in elderly (65+) males and maximum temperature at national level

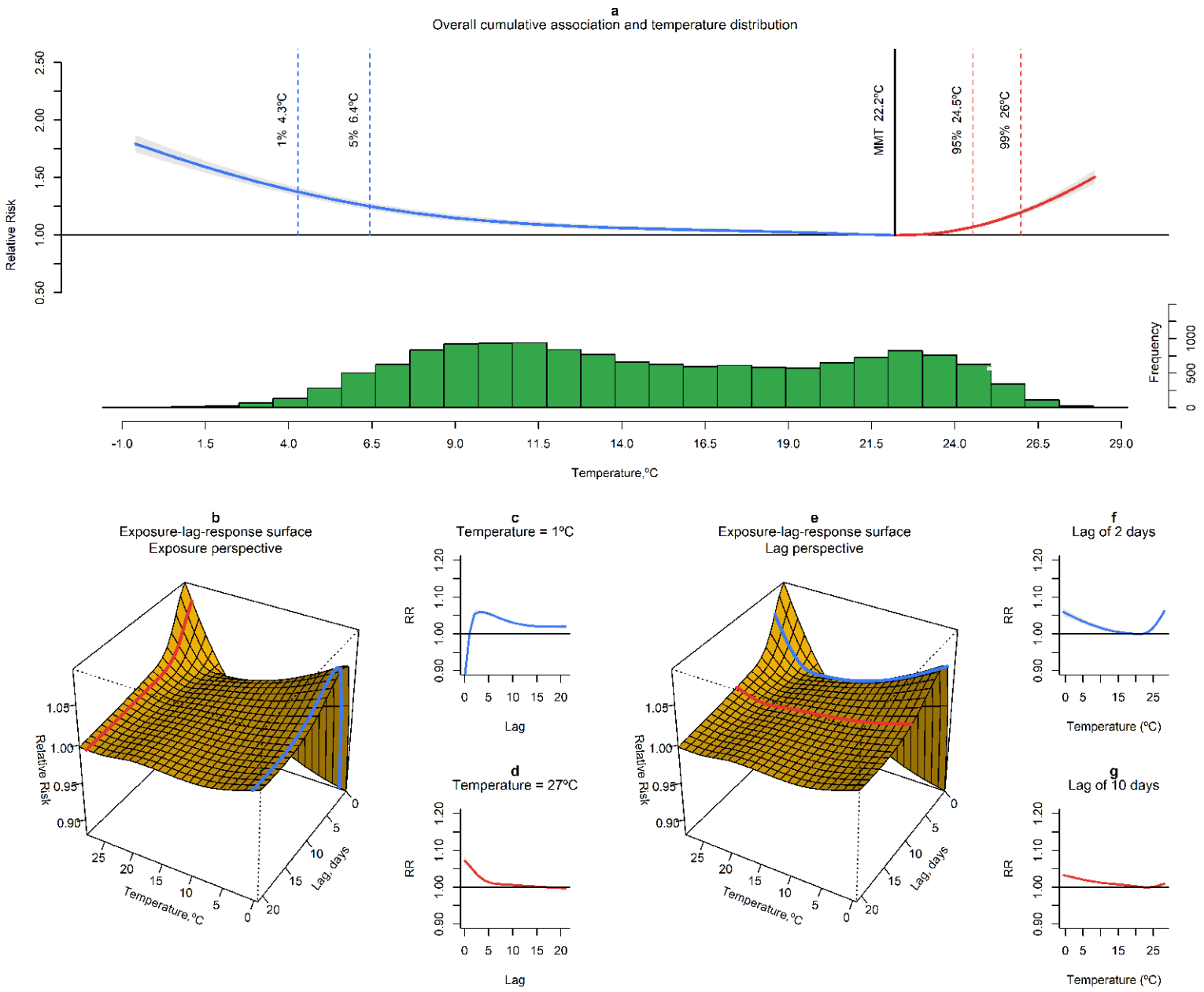


Figure E.5: Exposure-lag-response associations between daily mortality in elderly (65+) males and mean temperature at national level

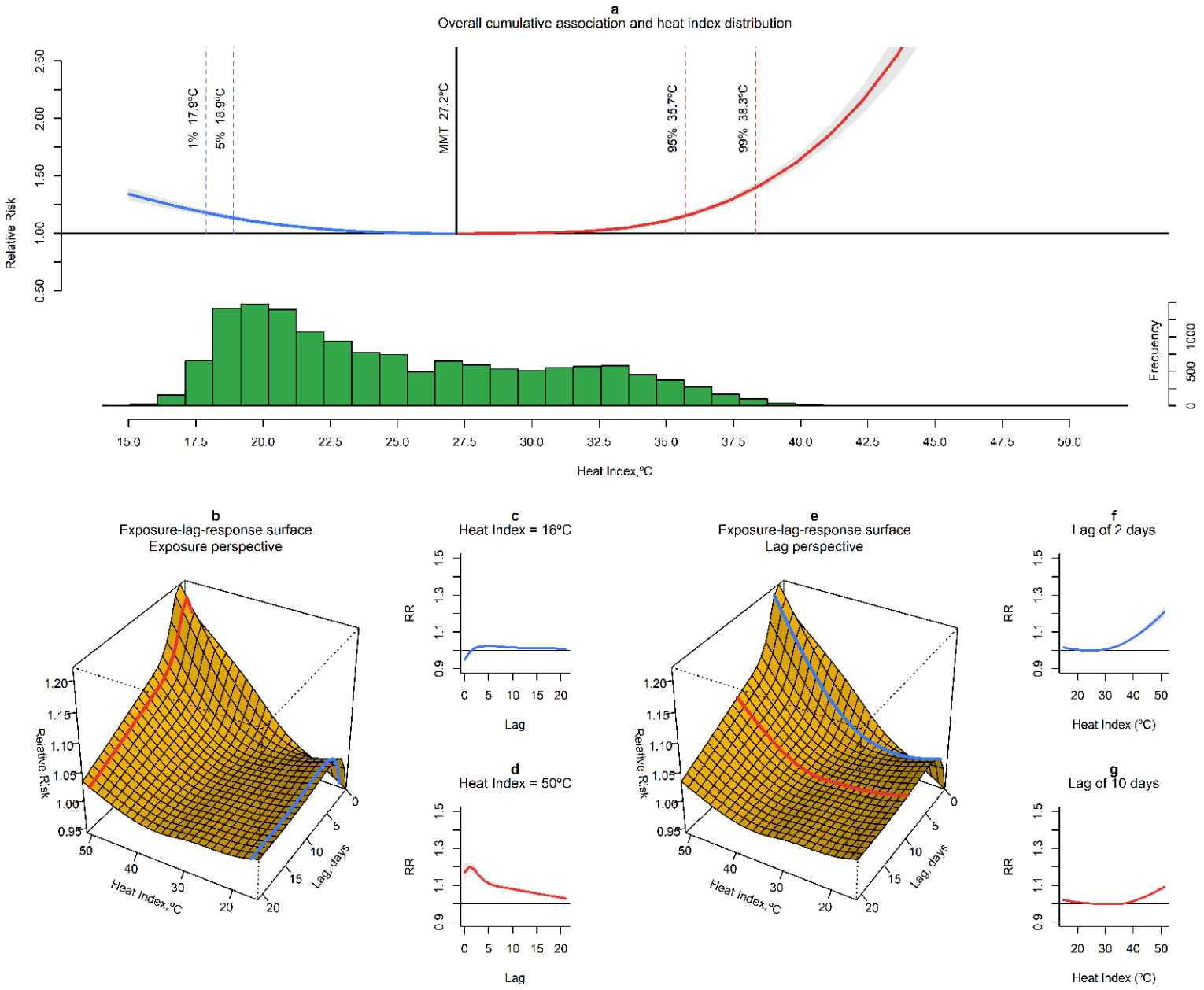


Figure E.6: Exposure-lag-response associations between daily mortality in elderly (65+) females and maximum heat index at national level

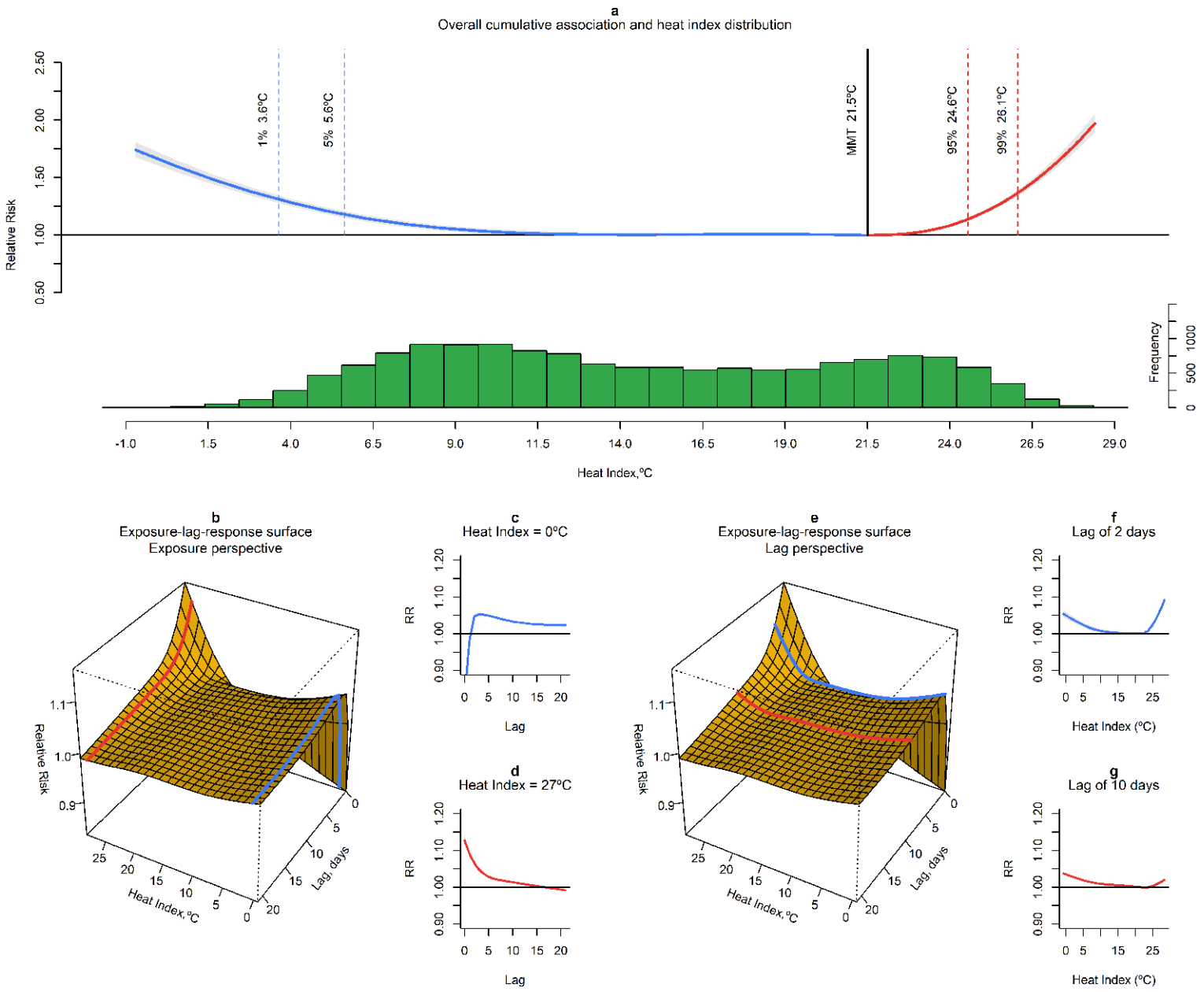


Figure E.7: Exposure-lag-response associations between daily mortality in elderly (65+) females and mean heat index at national level

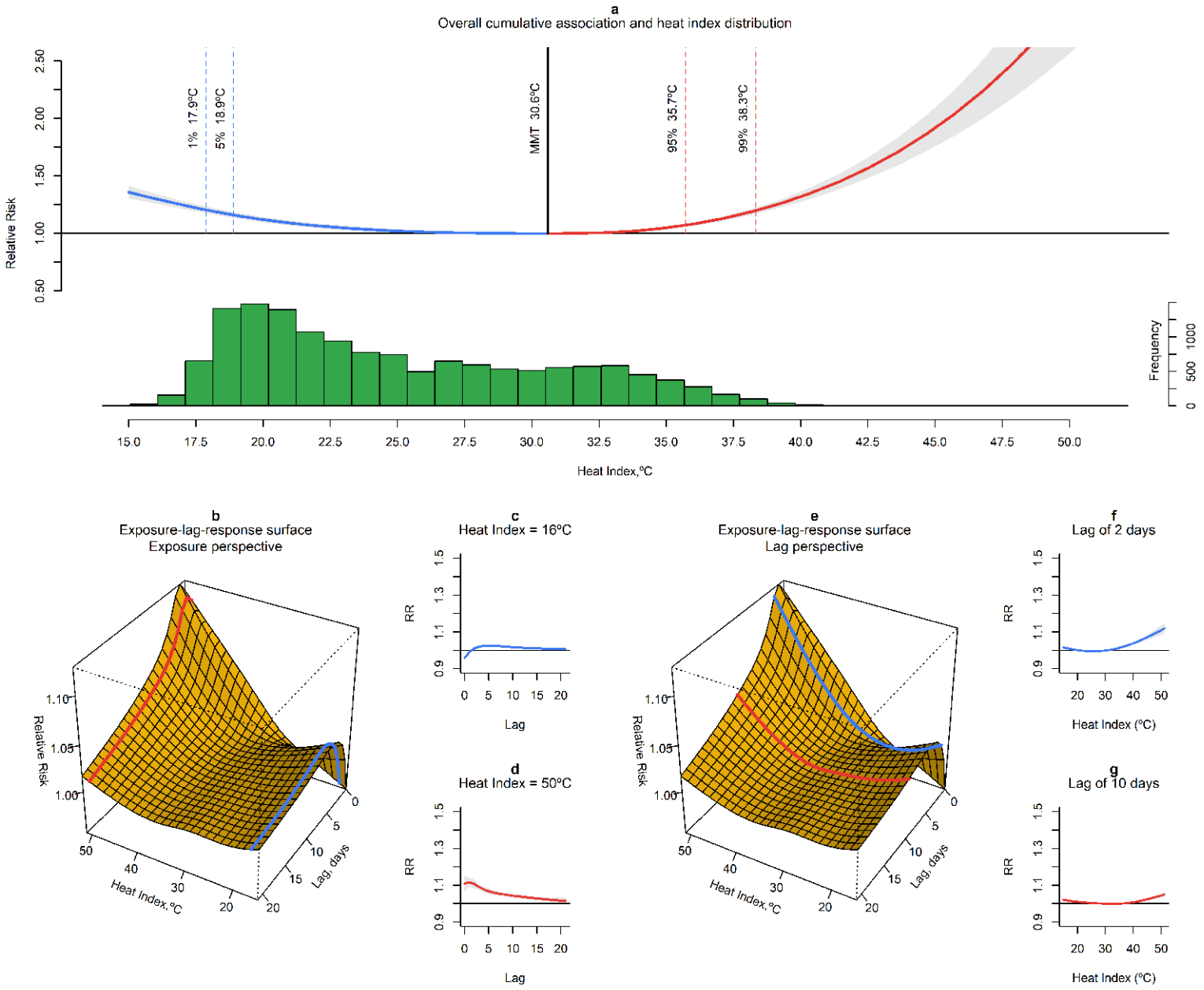


Figure E.8: Exposure-lag-response associations between daily mortality in elderly (65+) males and maximum heat index at national level

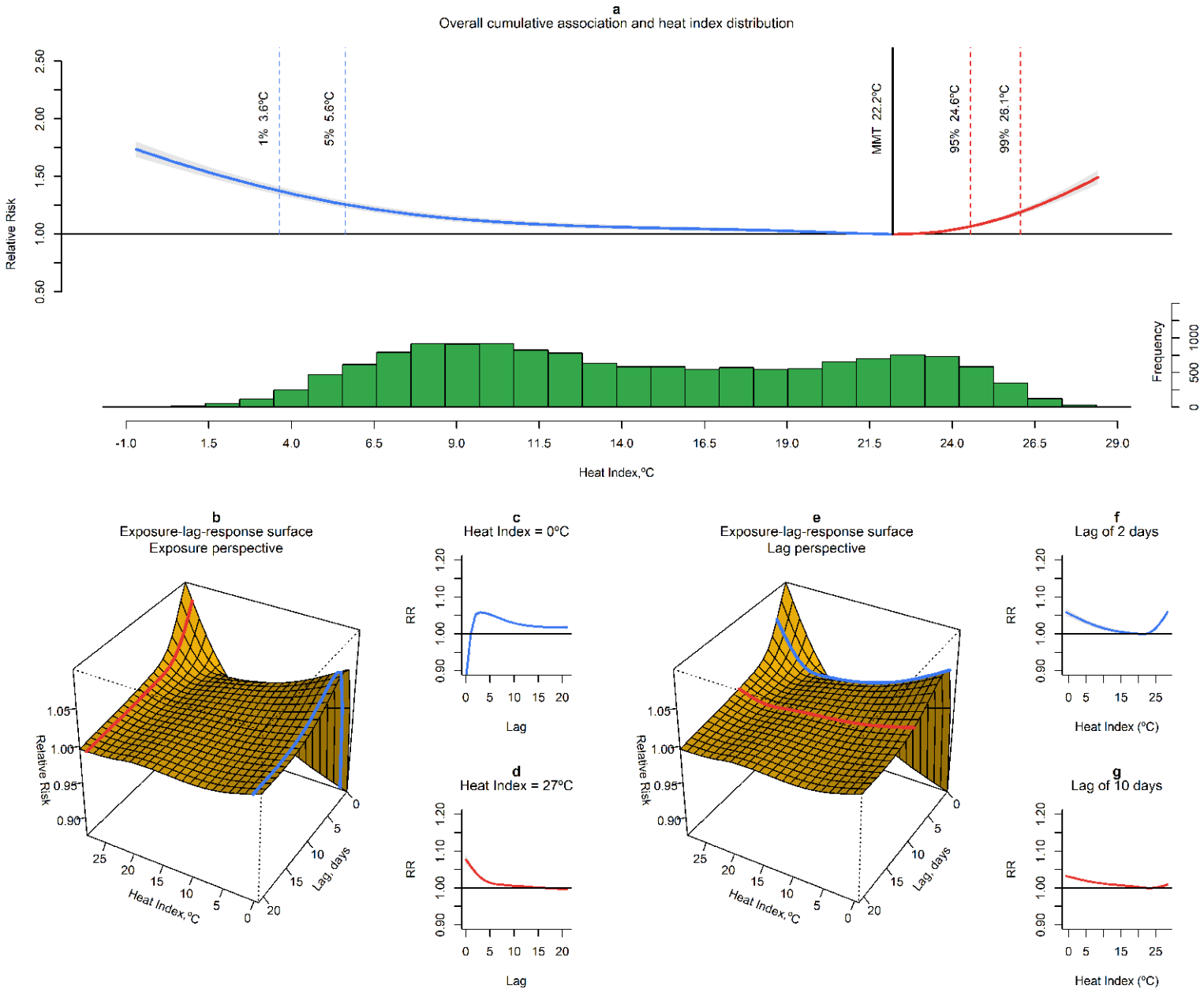


Figure E.9: Exposure-lag-response associations between daily mortality in elderly (65+) males and mean heat index at national level

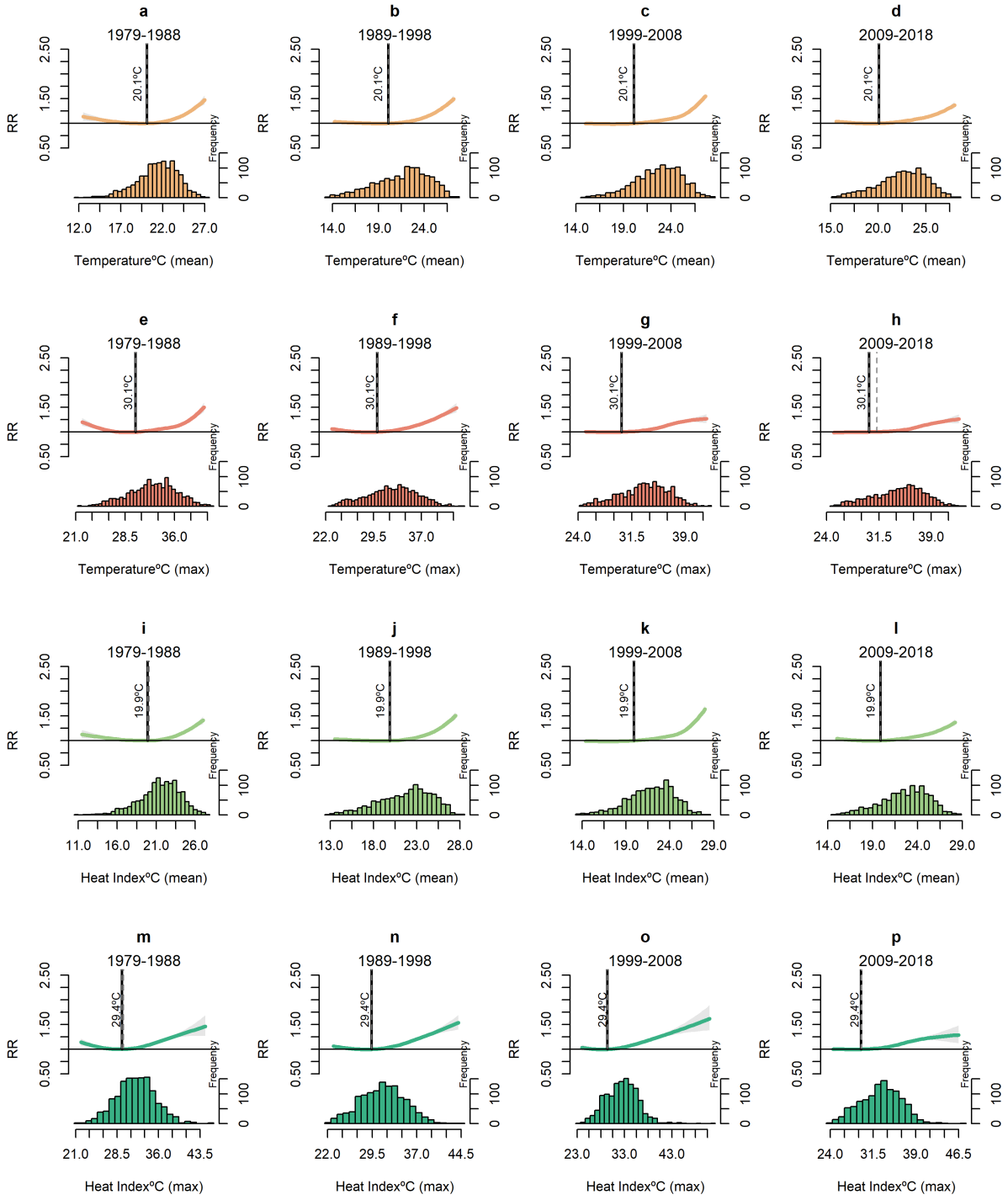
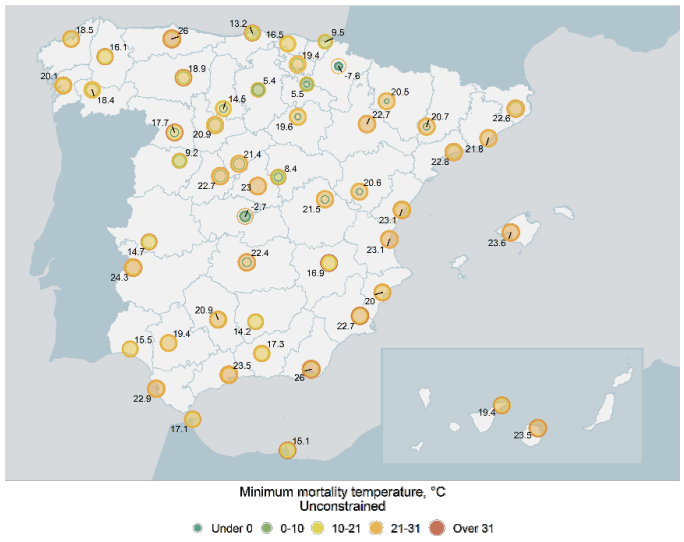


Figure E.10: Change in minimum mortality temperature (constrained to 1-99 centile range) by decade at national level for maximum and average summer temperature and heat index

a



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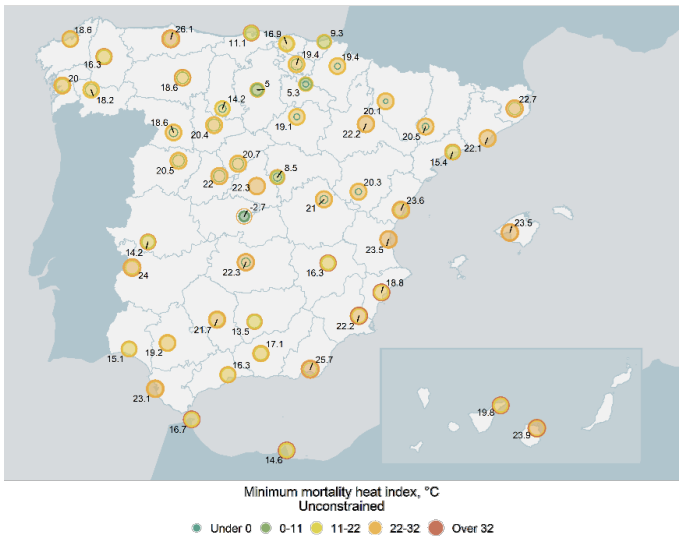

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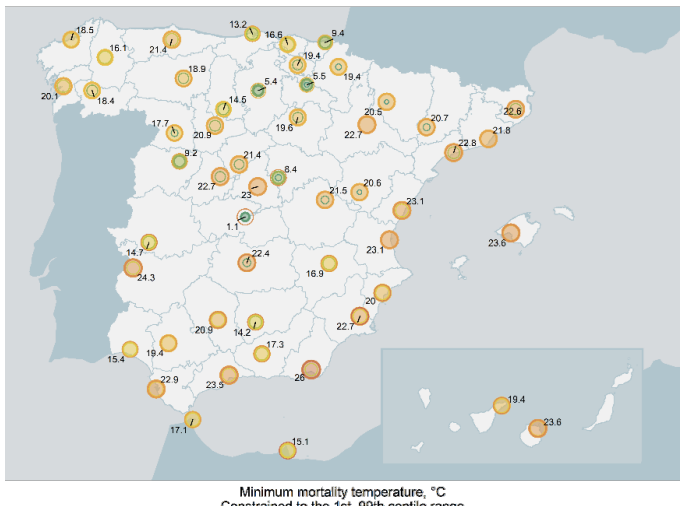

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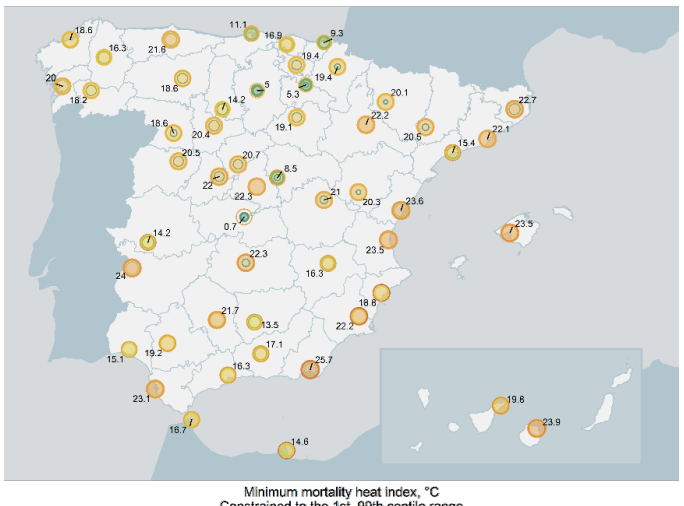

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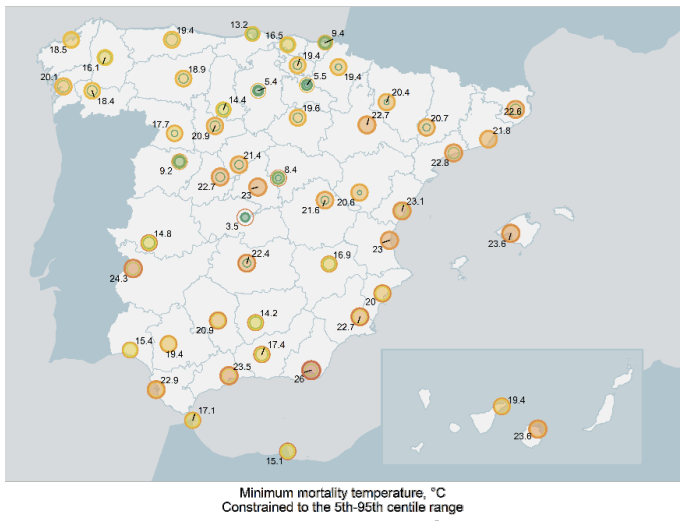

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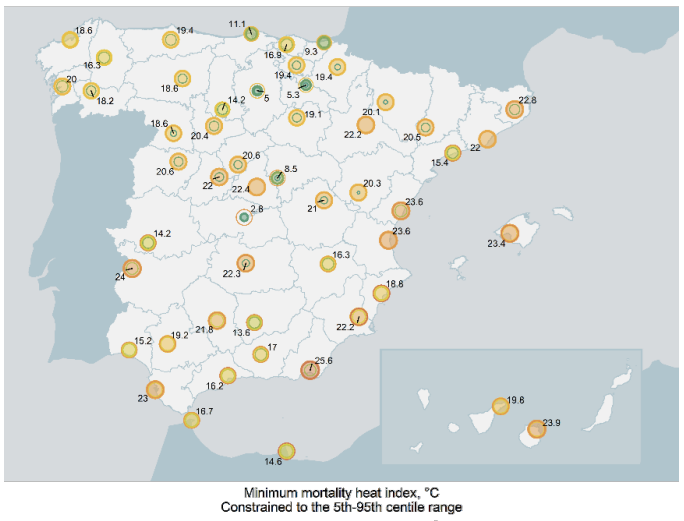

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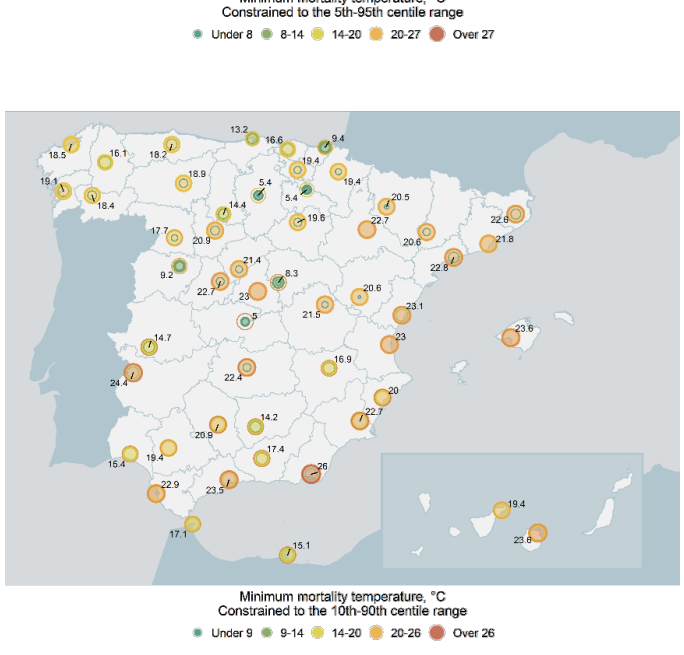

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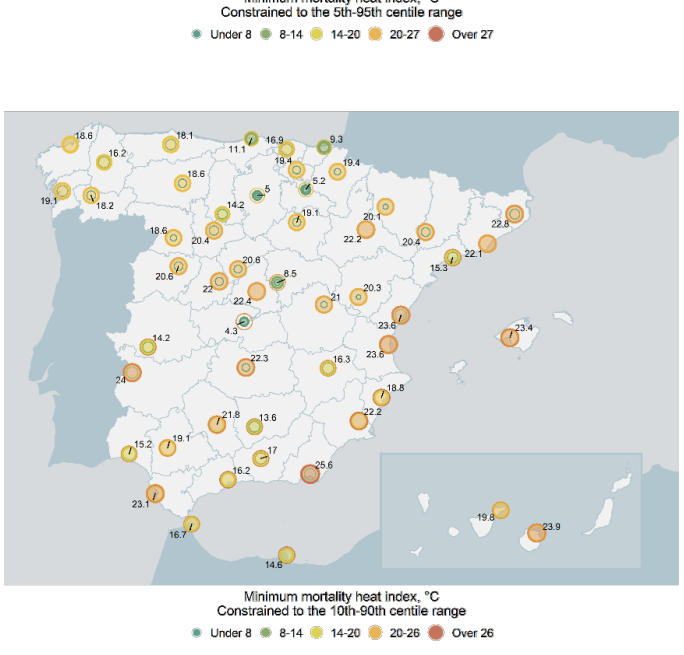
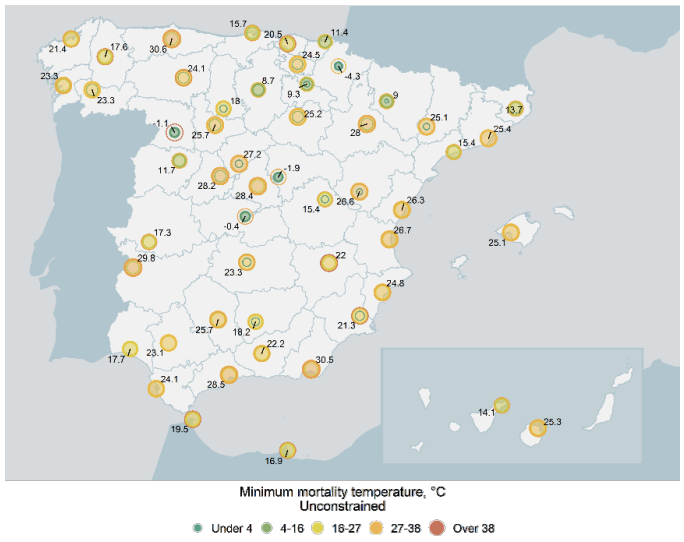


Figure E.11: MMT for all seasons estimated for municipalities of provincial capitals in Spain using average daily temperatures in 1979-2018

a



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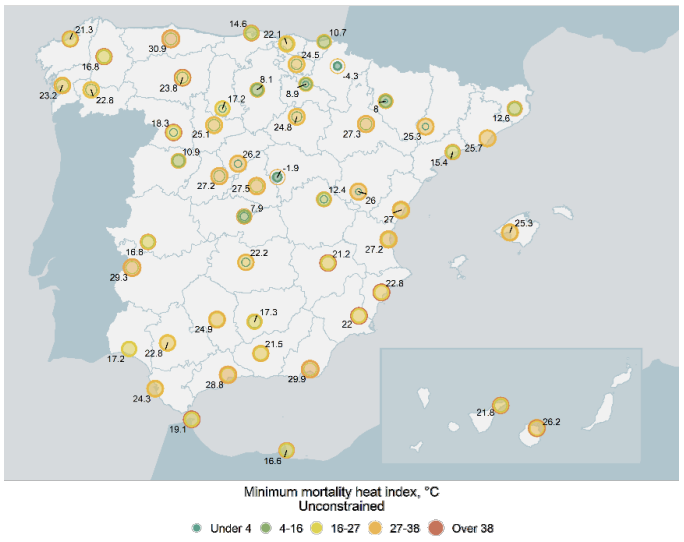

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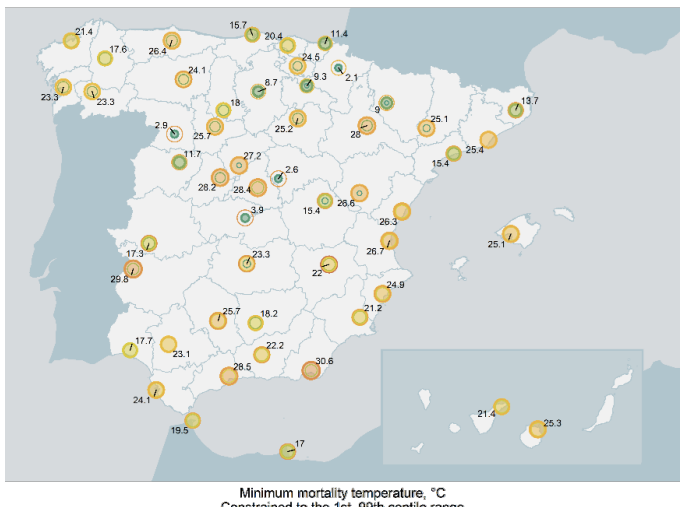

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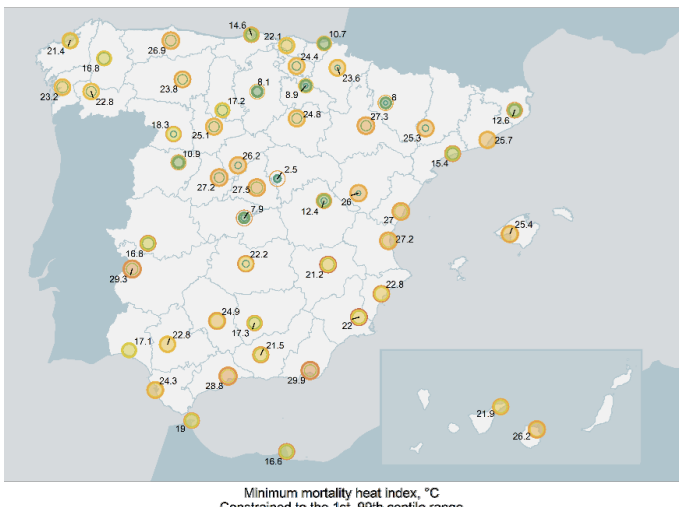

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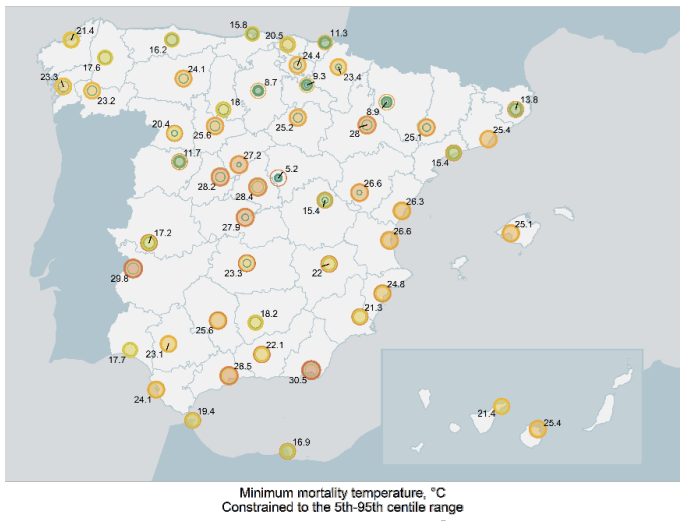

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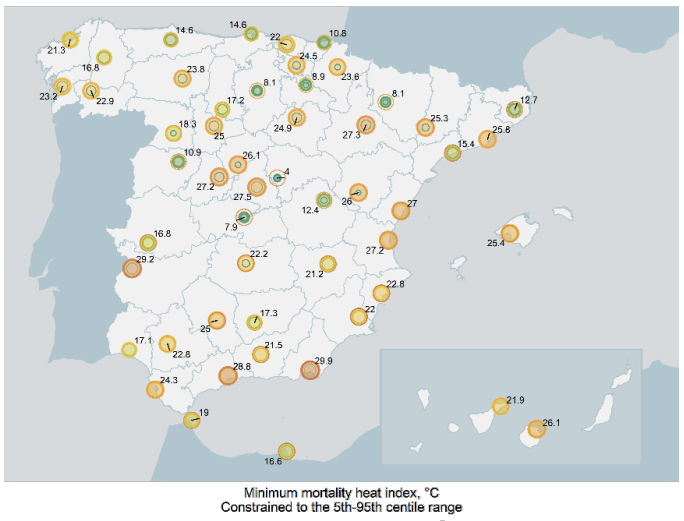

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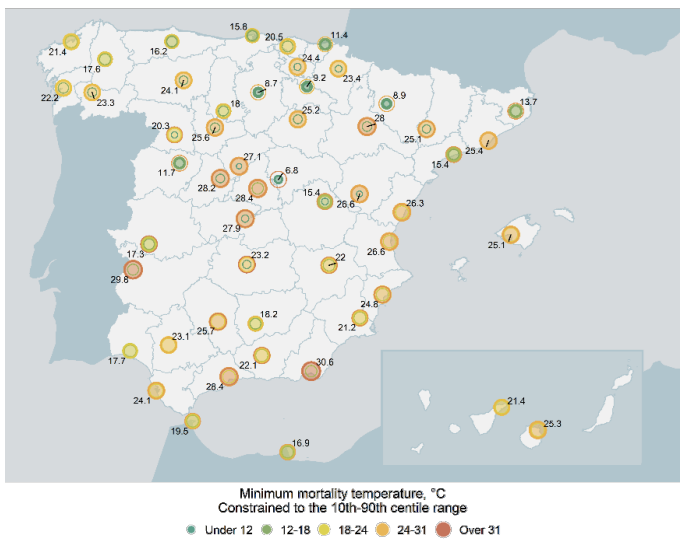

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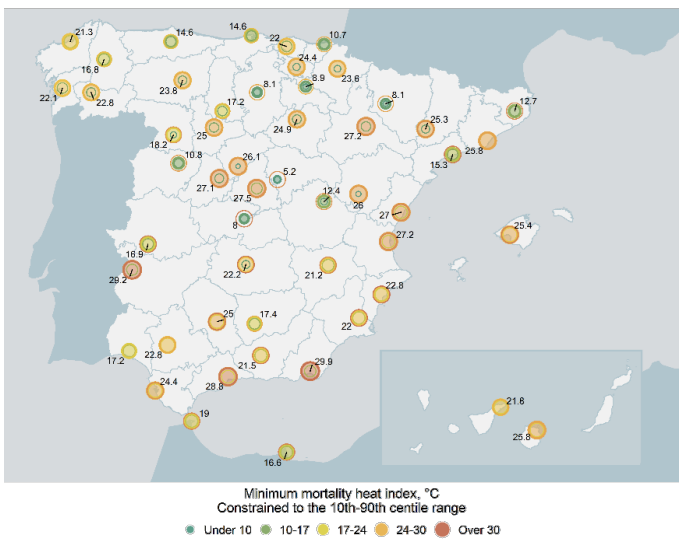
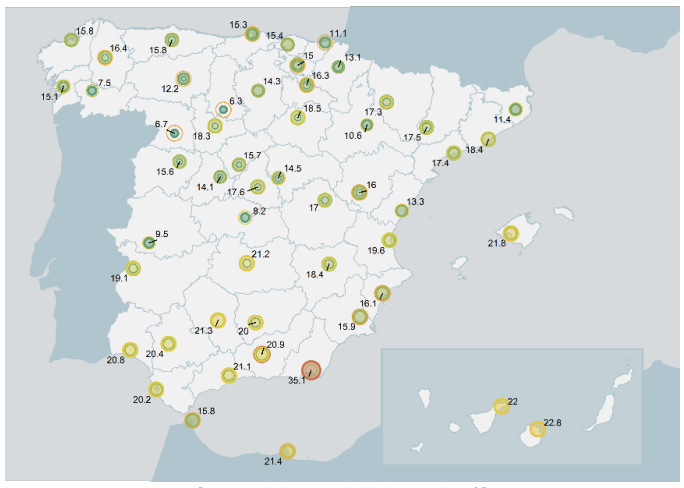


Figure E.12: Minimum mortality temperature for all seasons estimated for municipalities of provincial capitals in Spain using maxium daily temperatures in 1979-2018

a



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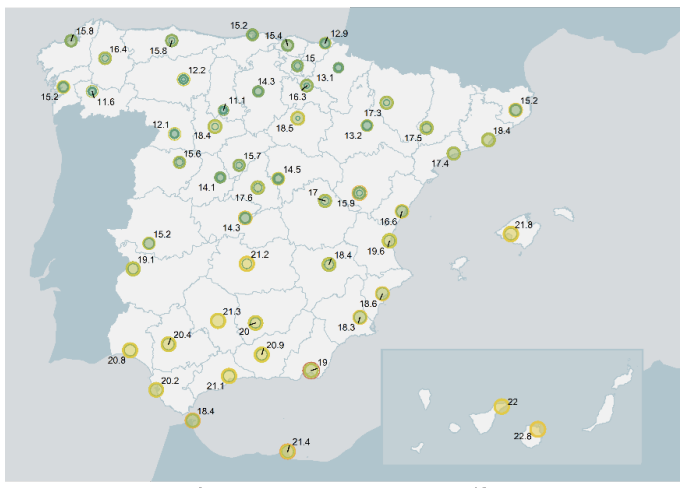

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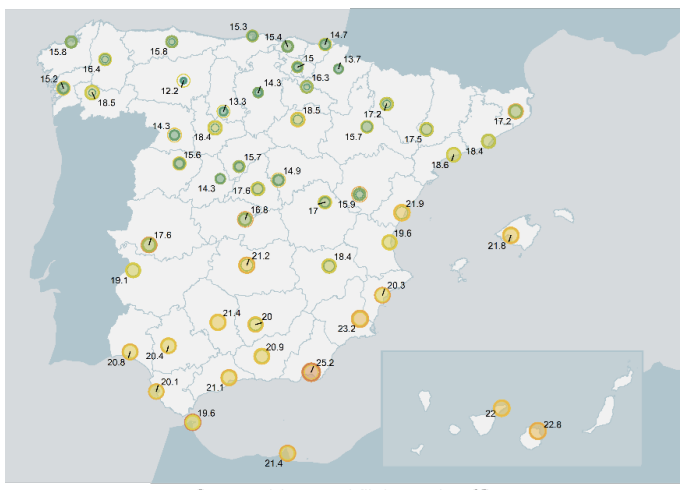

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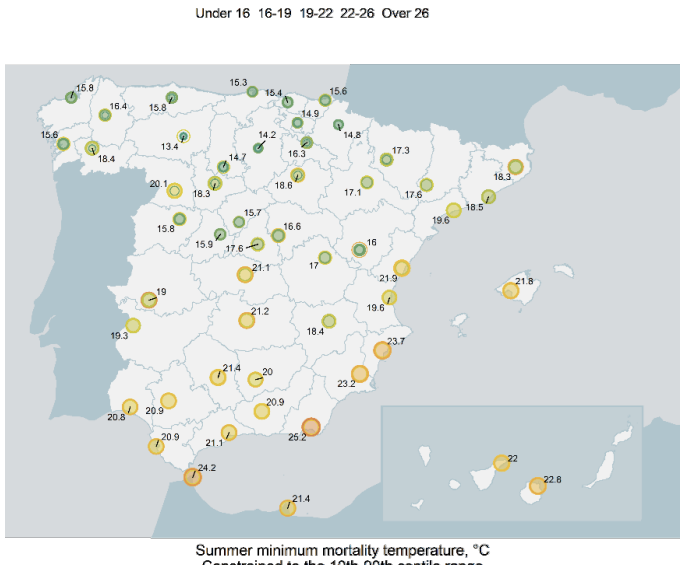

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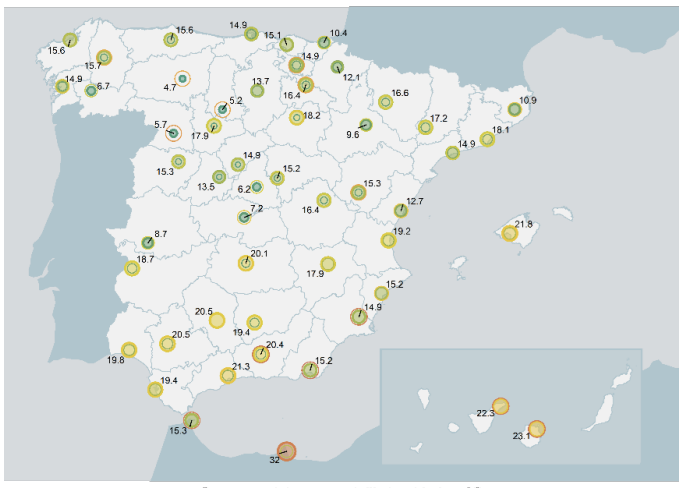

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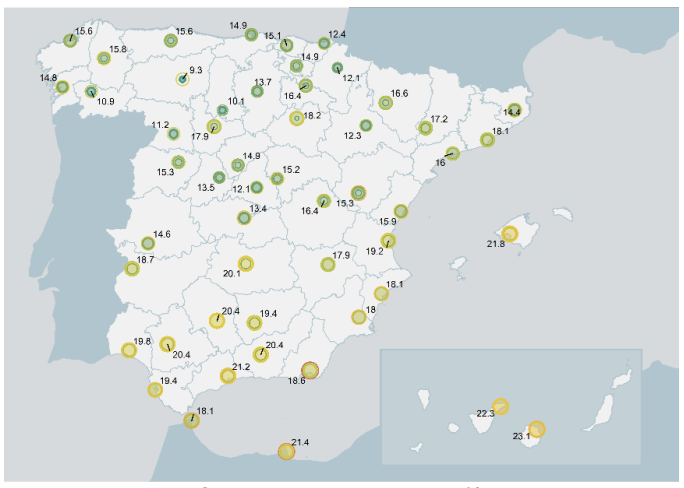

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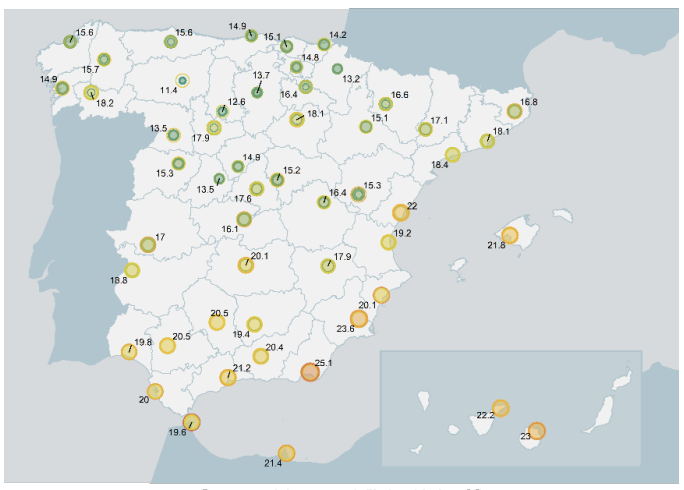

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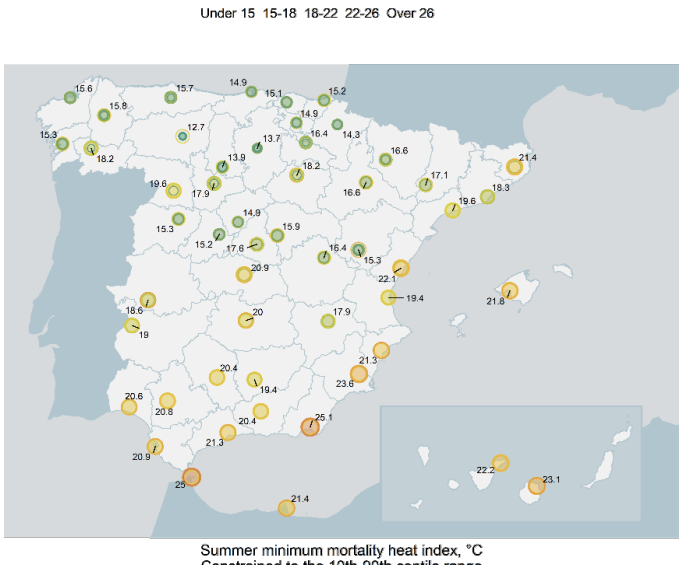
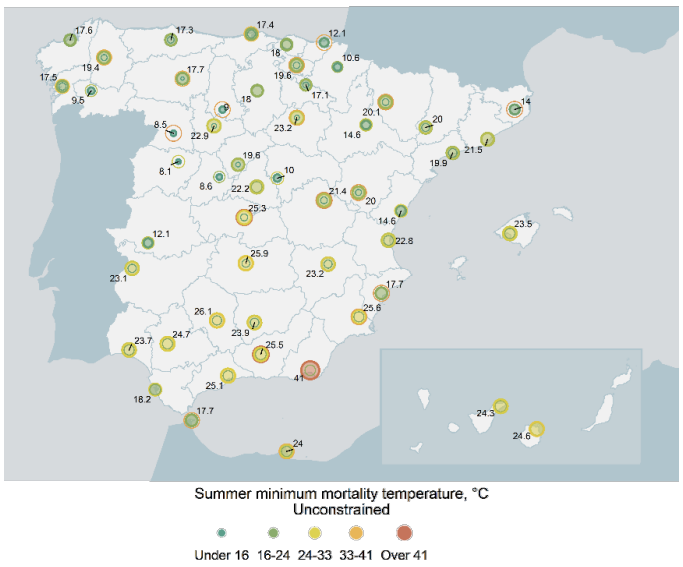


Figure E.13: Summer MMT estimated for municipalities of provincial capitals in Spain using average daily temperatures in 1979-2018

a



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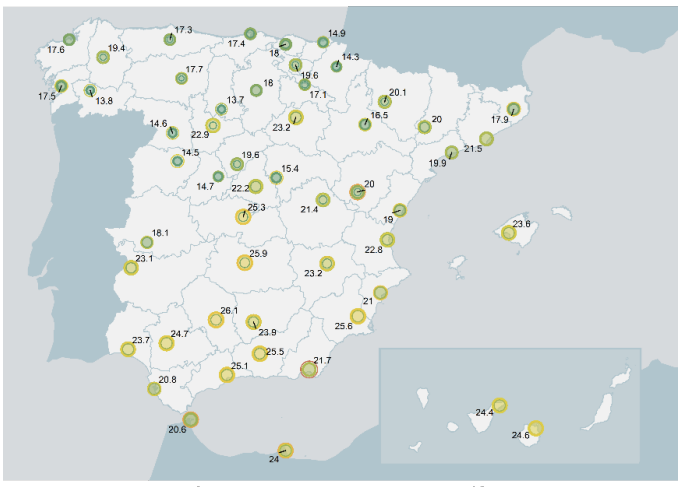

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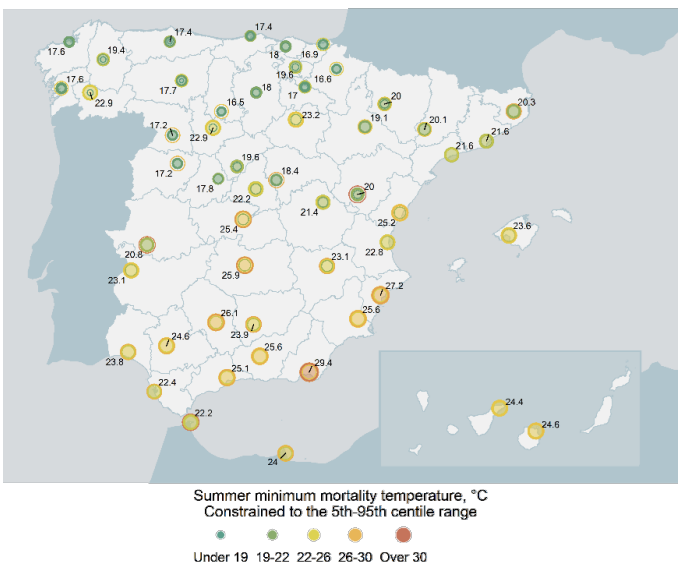

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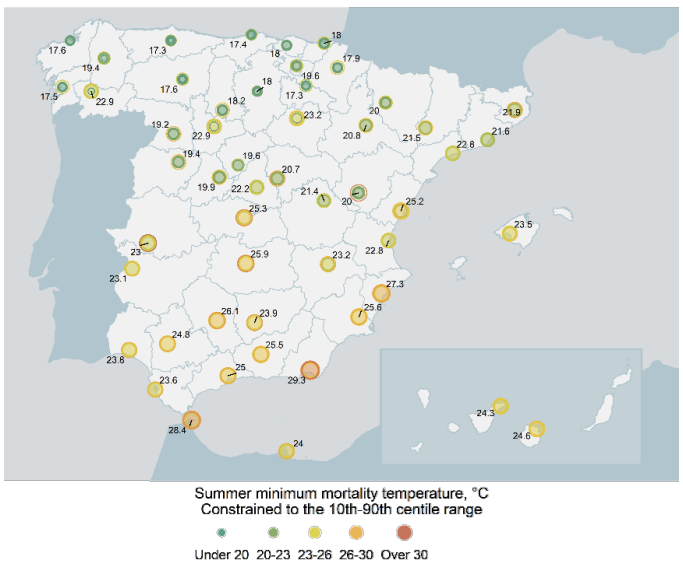

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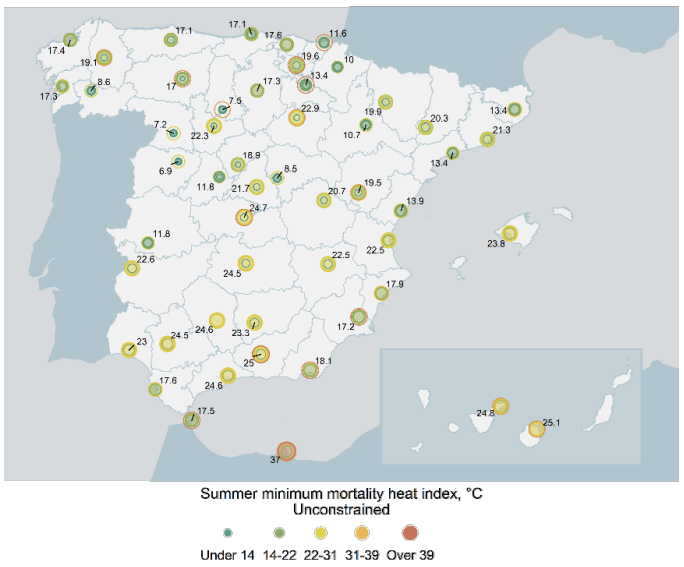

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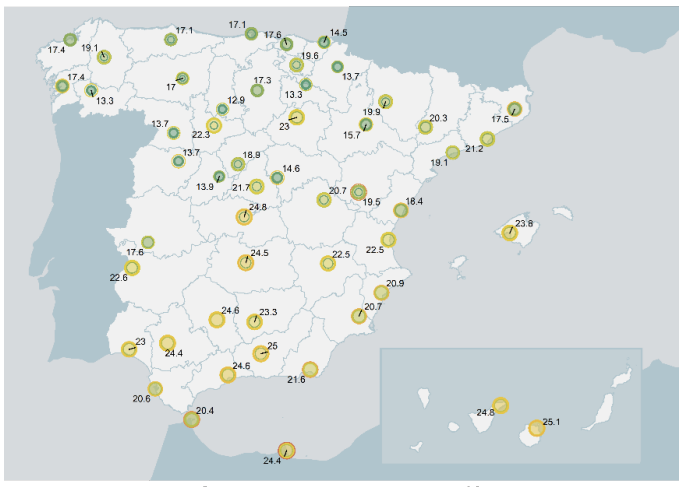

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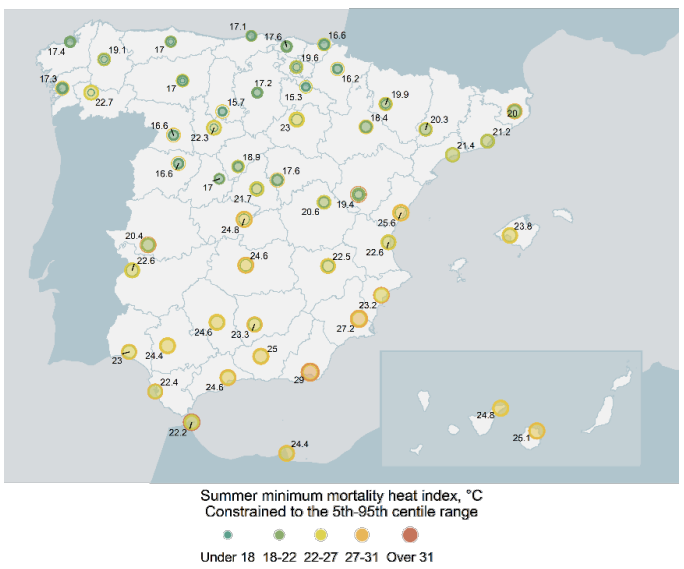

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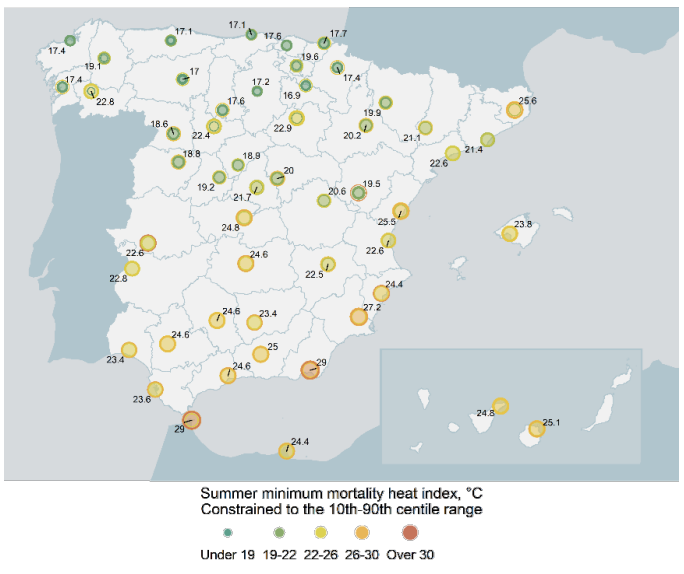

Figure E.14: Summer minimum mortality temperature estimated for municipalities of provincial capitals in Spain using maximum daily temperatures in 1979-2018

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Oviedo	Heat Index	Percentile	Maximum	100 [38.1-100]	99 [37.6-99]	54.6 [36.3-94.9]	54.6 [35.8-89.8]
			Mean	100 [53.2-100]	99 [47.3-99]	94.9 [43.3-94.9]	89.6 [41.6-89.6]
		Value	Maximum	30.9 [11.4-30.9]	26.9 [11.3-26.9]	14.6 [11.1-23.5]	14.6 [11-21.9]
			Mean	26.1 [11.6-26.1]	21.6 [10.5-21.6]	19.4 [9.8-19.4]	18.1 [9.5-18.1]
	Temperature	Percentile	Maximum	100 [45.2-100]	98.9 [41.7-98.9]	59.6 [40.1-95]	59.9 [39.1-89.9]
			Mean	100 [57-100]	98.9 [48.9-98.9]	94.8 [45.6-94.8]	89.5 [42.8-89.5]
		Value	Maximum	30.6 [13.4-30.6]	26.4 [12.8-26.4]	16.2 [12.5-23.6]	16.2 [12.3-22]
			Mean	26 [12.9-26]	21.4 [11.5-21.4]	19.4 [10.9-19.4]	18.2 [10.5-18.2]
Santander	Heat Index	Percentile	Maximum	49 [24.2-100]	49 [24.8-99]	48.8 [24.5-91.8]	48.8 [25-89.8]
			Mean	43.6 [23.6-100]	43.4 [23.2-99]	43.4 [23.9-94.9]	43.6 [23.6-89.9]
		Value	Maximum	14.6 [10.3-31.9]	14.6 [10.4-27.5]	14.6 [10.3-23]	14.6 [10.4-22.6]
			Mean	11.1 [8-27.5]	11.1 [8-22.6]	11.1 [8.1-20.4]	11.1 [8-19.3]
	Temperature	Percentile	Maximum	51.8 [22.6-100]	51.8 [25.5-99]	52 [25.3-91.7]	52 [26.5-89.5]
			Mean	52 [21.9-100]	52 [21.3-99]	52 [22.5-94.8]	52 [22.5-89.7]
		Value	Maximum	15.7 [10.9-31.4]	15.7 [11.4-26.6]	15.8 [11.3-23]	15.8 [11.6-22.4]
			Mean	13.2 [8.7-27.1]	13.2 [8.6-22.2]	13.2 [8.8-20.2]	13.2 [8.8-19.2]
Coruña	Heat Index	Percentile	Maximum	87 [56.8-100]	87.3 [54.4-98.9]	87 [55.3-95]	87 [55.3-89.9]
			Mean	87.7 [60.9-100]	87.2 [62-99]	87.7 [58.9-94.7]	87.7 [59.5-89.7]
		Value	Maximum	21.3 [16.4-33.1]	21.4 [15.9-26]	21.3 [16.1-23.3]	21.3 [16.1-21.9]
			Mean	18.6 [14.8-26.6]	18.6 [14.9-21.9]	18.6 [14.5-19.9]	18.6 [14.6-18.9]
	Temperature	Percentile	Maximum	87.4 [54.3-100]	87.4 [53.7-98.9]	87.8 [55.2-94.9]	87.4 [54.3-90]
			Mean	87 [60-100]	87 [60.9-99]	87 [60.9-94.8]	87 [60-89.4]
		Value	Maximum	21.4 [16.3-31.7]	21.4 [16.2-25.8]	21.4 [16.4-23.2]	21.4 [16.3-21.9]
			Mean	18.5 [15-26.2]	18.5 [15.1-21.6]	18.5 [15.1-19.8]	18.5 [15-18.8]
Lugo	Heat Index	Percentile	Maximum	61.8 [43-100]	61.8 [43.5-89.7]	61.5 [43.2-88.8]	61.8 [44-89]
			Mean	76.9 [45.1-100]	76.9 [44.5-91.8]	76.9 [44.5-91.2]	76.6 [44.8-89.7]
		Value	Maximum	16.8 [12.8-34.9]	16.8 [12.9-23.1]	16.8 [12.8-22.9]	16.8 [13-22.9]
			Mean	16.3 [10.5-27]	16.3 [10.4-19.1]	16.3 [10.4-19]	16.2 [10.4-18.6]
	Temperature	Percentile	Maximum	63.3 [47.4-100]	63.3 [47.4-88.3]	63.1 [47.2-87]	63.1 [46.7-87]
			Mean	74.2 [48-100]	74.2 [49.2-91.4]	74.2 [49.2-90.9]	74.2 [49.7-89.4]
		Value	Maximum	17.6 [14.3-33.8]	17.6 [14.3-22.9]	17.6 [14.2-22.6]	17.6 [14.2-22.6]
			Mean	16.1 [11.6-27]	16.1 [11.8-19.1]	16.1 [11.8-19]	16.1 [11.9-18.7]
Ourense	Heat Index	Percentile	Maximum	84.7 [20.3-91]	84.7 [22.8-90.7]	84.8 [23.8-90.6]	84.7 [23.4-89.9]
			Mean	84.1 [22-90.4]	84.1 [22-90.8]	84.1 [23.2-90.4]	84.1 [22.6-90]
		Value	Maximum	22.8 [9.1-24.8]	22.8 [9.5-24.7]	22.9 [9.7-24.6]	22.8 [9.6-24.4]
			Mean	18.2 [6.8-19.6]	18.2 [6.8-19.7]	18.2 [7-19.6]	18.2 [6.9-19.5]
	Temperature	Percentile	Maximum	85.6 [19.8-91.5]	85.6 [22.7-90.9]	85.4 [23-90.7]	85.6 [23.4-89.7]
			Mean	84.2 [20.6-90.7]	84.2 [21.9-90.7]	84.2 [21.1-90.7]	84.2 [21.1-89.9]
		Value	Maximum	23.3 [9.9-25.1]	23.3 [10.3-24.9]	23.2 [10.3-24.9]	23.3 [10.4-24.5]
			Mean	18.4 [7.4-19.8]	18.4 [7.6-19.8]	18.4 [7.5-19.8]	18.4 [7.5-19.6]
Pontevedra	Heat Index	Percentile	Maximum	93.9 [30.1-100]	93.9 [30.1-99]	93.9 [29.3-94.7]	89.7 [27.1-89.7]
			Mean	94.2 [30.6-100]	94.2 [29.9-98.9]	94.2 [29.9-94.9]	89.6 [26.2-89.6]
		Value	Maximum	23.2 [12.5-30.5]	23.2 [12.5-26.2]	23.2 [12.4-23.5]	22.1 [12.2-22.1]
			Mean	20 [10.7-25.2]	20 [10.6-22.2]	20 [10.6-20.2]	19.1 [10.2-19.1]
	Temperature	Percentile	Maximum	94.1 [31.2-100]	94.1 [31.2-98.9]	94.1 [30.3-94.8]	89.8 [27.8-89.8]
			Mean	94.7 [31.1-100]	94.7 [31.2-99]	94.7 [26.8-94.7]	89.8 [24.5-89.8]
		Value	Maximum	23.3 [13.2-30]	23.3 [13.2-25.8]	23.3 [13.1-23.5]	22.2 [12.8-22.2]
			Mean	20.1 [11.4-25]	20.1 [11.4-22.1]	20.1 [10.9-20.1]	19.1 [10.7-19.1]
Huesca	Heat Index	Percentile	Maximum	22.1 [0-87.2]	22.1 [1-87.2]	22.4 [5.1-87.2]	22.4 [10.2-87.2]
			Mean	84.3 [0-88.2]	84.3 [1-88.2]	84.5 [5-88]	84.5 [10.1-88.3]
		Value	Maximum	8 [-6.7-26.1]	8 [1.4-26.1]	8.1 [3.9-26.1]	8.1 [5.2-26.1]
			Mean	20.1 [-9.3-21.2]	20.1 [-1.6-21.2]	20.1 [1.2-21.1]	20.1 [2.9-21.2]
	Temperature	Percentile	Maximum	21.3 [0-88.3]	21.3 [1-88.3]	21 [5.1-88.2]	21 [10.1-88.4]
			Mean	84.9 [0-88.4]	84.9 [1-88.4]	84.7 [5-88.3]	84.9 [10-88.4]
		Value	Maximum	9 [-6.7-26.6]	9 [1.4-26.6]	8.9 [4.8-26.6]	8.9 [6.6-26.6]
			Mean	20.5 [-9.3-21.5]	20.5 [-1.6-21.5]	20.4 [1.6-21.4]	20.5 [3.4-21.5]
	Heat Index	Percentile	Maximum	86.2 [0-91.2]	86.2 [1.1-90.7]	86.4 [5.2-91.5]	86.4 [10.1-90]
			Mean	85.2 [0-91.4]	85.2 [1.1-92.1]	85.2 [5.2-91]	85.2 [10.1-90]
		Value	Maximum	26 [-4.5-27.4]	26 [1.8-27.3]	26 [3.8-27.4]	26 [4.8-27.1]
			Mean	20.3 [-7.2-21.9]	20.3 [-1.4-22.1]	20.3 [1-21.8]	20.3 [2.4-21.5]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Teruel	Temperature	Percentile	Maximum	87.3 [0-92.9]	87.3 [1.1-92.9]	87.2 [5.1-92.5]	87.2 [10.1-89.8]
			Mean	85.4 [0-92]	85.4 [1-92]	85.4 [5-91.7]	85.4 [10.1-89.7]
		Value	Maximum	26.6 [-4.5-28.3]	26.6 [1.8-28.3]	26.6 [4.8-28.1]	26.6 [6.3-27.4]
			Mean	20.6 [-7.2-22.3]	20.6 [-1.4-22.3]	20.6 [1.3-22.2]	20.6 [3-21.7]
Zaragoza	Heat Index	Percentile	Maximum	84.1 [23.6-86.3]	84.1 [24.5-86.3]	84.1 [23.6-86.3]	83.9 [24.3-86.5]
			Mean	83.7 [75.4-86.1]	83.7 [76.5-86.1]	83.8 [77-86.3]	83.8 [75.9-86.3]
		Value	Maximum	27.3 [10-27.9]	27.3 [10.2-27.9]	27.3 [10-27.9]	27.2 [10.2-28]
			Mean	22.2 [19.8-22.9]	22.2 [20.1-22.9]	22.2 [20.2-23]	22.2 [20-23]
	Temperature	Percentile	Maximum	85 [22.8-87]	85 [23.3-87]	85 [24.4-87]	85.2 [24.1-87.1]
			Mean	84.4 [78.5-86.8]	84.4 [78.5-86.8]	84.4 [77.8-86.8]	84.4 [78.8-86.8]
		Value	Maximum	28 [11-28.7]	28 [11.1-28.7]	28 [11.3-28.7]	28 [11.2-28.8]
			Mean	22.7 [21-23.4]	22.7 [21-23.4]	22.7 [20.8-23.4]	22.7 [21.1-23.4]
Pamplona/Iruña	Heat Index	Percentile	Maximum	0 [0-90]	83.9 [1-90.1]	83.8 [5.2-90.2]	83.9 [10.2-89.8]
			Mean	85.5 [0-90.4]	85.5 [1-90.4]	85.5 [5.1-90.4]	85.5 [10-89.6]
		Value	Maximum	-4.3 [-4.3-25.5]	23.6 [2-25.6]	23.6 [4.3-25.6]	23.6 [6.2-25.4]
			Mean	19.4 [-7.6-20.6]	19.4 [-0.4-20.6]	19.4 [2.2-20.6]	19.4 [3.8-20.4]
	Temperature	Percentile	Maximum	0 [0-89.7]	1.1 [1.1-89.7]	82.5 [5.1-89.7]	82.5 [10-89.7]
			Mean	0 [0-90]	85.3 [1-90.2]	85.3 [5.1-90.5]	85.3 [10.1-89.7]
		Value	Maximum	-4.3 [-4.3-25.4]	2.1 [2.1-25.4]	23.4 [5.5-25.4]	23.4 [7.3-25.4]
			Mean	-7.6 [-7.6-20.4]	19.4 [-0.3-20.4]	19.4 [2.6-20.6]	19.4 [4.4-20.4]
Bilbao	Heat Index	Percentile	Maximum	82.2 [34.1-91.4]	82.2 [34.6-90.8]	82 [34.9-91]	82 [34.3-89.9]
			Mean	73.3 [41.7-90.5]	73.3 [41.7-90]	73 [42.1-89.8]	73 [41.4-89.8]
		Value	Maximum	22.1 [12.3-24.4]	22.1 [12.4-24.2]	22 [12.4-24.2]	22 [12.3-24]
			Mean	16.9 [10.8-20]	16.9 [10.8-19.9]	16.9 [10.8-19.9]	16.9 [10.8-19.9]
	Temperature	Percentile	Maximum	73.4 [35.2-100]	73.2 [36-90.7]	73.4 [36.2-90.6]	73.4 [35.2-89.9]
			Mean	69.2 [41.4-92.3]	69.5 [42.3-90.3]	69.2 [40.2-89.9]	69.5 [41.8-89.7]
		Value	Maximum	20.5 [13.3-34.9]	20.4 [13.4-24.1]	20.5 [13.5-24.1]	20.5 [13.3-23.9]
			Mean	16.5 [11.5-20.3]	16.6 [11.7-19.9]	16.5 [11.3-19.8]	16.6 [11.6-19.8]
Donostia/San Sebastián	Heat Index	Percentile	Maximum	25.4 [15.7-90.3]	25.4 [15.7-89.9]	25.6 [15.5-90.1]	25.4 [16.2-89.9]
			Mean	32.3 [18.8-89.6]	32.3 [18.2-89.6]	32.3 [19.3-89.6]	32.5 [19-89.3]
		Value	Maximum	10.7 [8.7-24.6]	10.7 [8.7-24.5]	10.8 [8.7-24.6]	10.7 [8.8-24.5]
			Mean	9.3 [7-20.4]	9.3 [6.9-20.4]	9.3 [7.1-20.4]	9.3 [7-20.4]
	Temperature	Percentile	Maximum	24.5 [14.5-89.1]	24.5 [14-89.4]	24.1 [14.2-89.3]	24.5 [14.5-89.1]
			Mean	28.1 [15.8-89.5]	27.8 [15.6-89.3]	27.8 [16.1-89.3]	27.8 [15.6-89.3]
		Value	Maximum	11.4 [9.4-24.2]	11.4 [9.3-24.3]	11.3 [9.3-24.2]	11.4 [9.4-24.2]
			Mean	9.5 [7.4-20.3]	9.4 [7.3-20.2]	9.4 [7.4-20.2]	9.4 [7.3-20.2]
Vitoria-Gasteiz	Heat Index	Percentile	Maximum	89.3 [10.2-92.2]	89.1 [11.7-92]	89.3 [12.2-92.2]	89.1 [12.8-89.8]
			Mean	88.6 [16.2-91.4]	88.4 [16.5-91.5]	88.4 [17-91.2]	88.4 [17-89.6]
		Value	Maximum	24.5 [6.1-25.5]	24.4 [6.4-25.4]	24.5 [6.6-25.5]	24.4 [6.8-24.6]
			Mean	19.4 [5.1-20.1]	19.4 [5.2-20.1]	19.4 [5.2-20]	19.4 [5.2-19.6]
	Temperature	Percentile	Maximum	89.1 [9.9-91.7]	89.1 [11-91.7]	89 [11.3-91.6]	89 [11.3-90]
			Mean	88.5 [14.3-91.2]	88.3 [14.2-91.4]	88.5 [14.3-91.2]	88.5 [14-89.8]
		Value	Maximum	24.5 [7.2-25.3]	24.5 [7.5-25.3]	24.4 [7.6-25.2]	24.4 [7.6-24.8]
			Mean	19.4 [5.5-20]	19.4 [5.4-20]	19.4 [5.5-20]	19.4 [5.4-19.7]
Logroño	Heat Index	Percentile	Maximum	26 [0-84.5]	26.3 [1-84.4]	26.3 [5.2-84.7]	26.3 [10.2-84.7]
			Mean	22.4 [0-87.4]	22.4 [1-87.4]	22.4 [5.1-87.4]	22.1 [10.2-87.6]
		Value	Maximum	8.9 [-4.7-23.5]	8.9 [1.4-23.4]	8.9 [4-23.6]	8.9 [5.2-23.6]
			Mean	5.3 [-7.9-19.1]	5.3 [-1.3-19.1]	5.3 [1.4-19.1]	5.2 [3-19.1]
	Temperature	Percentile	Maximum	22.8 [0-84.1]	22.8 [1.1-84.8]	22.8 [5-85.1]	22.6 [10.1-84.6]
			Mean	19.4 [0-87.5]	19.4 [1-87.5]	19.4 [5-87.5]	19.1 [10.1-87.2]
		Value	Maximum	9.3 [-4.7-23.5]	9.3 [1.5-23.7]	9.3 [4.7-23.8]	9.2 [6.4-23.6]
			Mean	5.5 [-7.9-19.2]	5.5 [-1.2-19.2]	5.5 [1.7-19.2]	5.4 [3.5-19.1]
Madrid	Heat Index	Percentile	Maximum	81.9 [40.9-83.5]	81.9 [40.9-83.5]	81.9 [40.9-83.5]	81.9 [40.9-83.5]
			Mean	82.4 [80.1-83.9]	82.4 [80.1-83.9]	82.6 [80.3-83.7]	82.6 [80.3-83.7]
		Value	Maximum	27.5 [13.1-27.9]	27.5 [13.1-27.9]	27.5 [13.1-27.9]	27.5 [13.1-27.9]
			Mean	22.3 [21.7-22.7]	22.3 [21.7-22.7]	22.4 [21.8-22.6]	22.4 [21.8-22.6]
	Temperature	Percentile	Maximum	81.3 [42.9-83]	81.3 [43.2-83]	81.3 [42.9-83]	81.2 [43-82.8]
			Mean	82.1 [77-83.9]	82.1 [79.1-83.9]	82.1 [79.1-83.9]	82.1 [79.4-83.9]
		Value	Maximum	28.4 [14.7-29]	28.4 [14.8-29]	28.4 [14.7-29]	28.4 [14.8-29]
			Mean	23 [21.4-23.5]	23 [22.1-23.5]	23 [22.1-23.5]	23 [22.2-23.5]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Burgos	Heat Index	Percentile	Maximum	27 [18.3-89.6]	27 [18.3-89.6]	26.8 [18.5-89.8]	26.8 [18.5-89.5]
			Mean	24.1 [10-92.3]	24.1 [10.9-91.7]	24.1 [11.4-91.7]	23.8 [10.7-89.9]
		Value	Maximum	8.1 [6.2-25.2]	8.1 [6.2-25.2]	8.1 [6.2-25.2]	8.1 [6.2-25.1]
			Mean	5 [2.3-20.2]	5 [2.5-20]	5 [2.6-20]	5 [2.5-19.4]
	Temperature	Percentile	Maximum	24.2 [14.1-90.1]	24.2 [14.6-90.1]	24.2 [14.1-90.1]	24.2 [15.1-89.9]
			Mean	22.2 [11.5-92.1]	22.2 [11.9-91.6]	22.2 [11.9-91.6]	22.4 [11.2-89.8]
		Value	Maximum	8.7 [6.6-25.6]	8.7 [6.7-25.6]	8.7 [6.6-25.6]	8.7 [6.8-25.5]
			Mean	5.4 [3.1-20.3]	5.4 [3.2-20.2]	5.4 [3.2-20.2]	5.4 [3-19.6]
León	Heat Index	Percentile	Maximum	87.3 [29.1-100]	87.3 [32-99]	87.3 [31.9-94.9]	87.3 [32-89.7]
			Mean	88.1 [29.5-100]	88.1 [31.4-99]	87.9 [32.4-94.8]	88.1 [29.5-89.9]
		Value	Maximum	23.8 [8.2-36.5]	23.8 [8.8-29.2]	23.8 [8.8-26.9]	23.8 [8.8-24.6]
			Mean	18.6 [5.8-27.5]	18.6 [6.1-23]	18.6 [6.2-20.6]	18.6 [5.8-19.1]
	Temperature	Percentile	Maximum	87.2 [28-100]	87.2 [31.4-99]	87.2 [32.4-94.8]	87.2 [31.4-89.8]
			Mean	88 [28.6-100]	88 [29.2-99]	87.8 [30.7-95]	88 [30.4-89.6]
		Value	Maximum	24.1 [9.1-33.9]	24.1 [9.7-30.2]	24.1 [9.9-27]	24.1 [9.7-24.9]
			Mean	18.9 [6.5-28.4]	18.9 [6.6-23.5]	18.9 [6.8-21]	18.9 [6.8-19.3]
Palencia	Heat Index	Percentile	Maximum	60.8 [0-81.3]	60.8 [33.8-80.4]	60.9 [35.6-80.5]	60.9 [35.6-80.8]
			Mean	64.5 [0-83.4]	64.5 [36-83.4]	64.5 [38-83.8]	64.5 [37.1-83.4]
		Value	Maximum	17.2 [-2.5-24.1]	17.2 [9.8-23.8]	17.2 [10.2-23.9]	17.2 [10.2-24]
			Mean	14.2 [-5.3-19.3]	14.2 [7.6-19.3]	14.2 [8-19.4]	14.2 [7.8-19.3]
	Temperature	Percentile	Maximum	60.7 [0-80.5]	60.7 [31.6-79.5]	60.5 [35.3-80]	60.5 [37.2-80]
			Mean	62.9 [0-83.1]	62.9 [33.6-82.8]	62.8 [35.4-83]	62.8 [36.9-83]
		Value	Maximum	18 [-2.5-24.3]	18 [10.4-24]	18 [11.2-24.1]	18 [11.6-24.1]
			Mean	14.5 [-5.3-19.7]	14.5 [8.1-19.6]	14.4 [8.4-19.6]	14.4 [8.8-19.6]
Salamanca	Heat Index	Percentile	Maximum	35.6 [26-84.5]	35.6 [25.5-84.5]	35.6 [25.5-84.5]	35.4 [25.8-84.8]
			Mean	82.4 [23.8-86.2]	82.4 [24.4-86.2]	82.6 [24.1-86]	82.6 [24.8-86]
		Value	Maximum	10.9 [8.9-26.7]	10.9 [8.8-26.7]	10.9 [8.8-26.7]	10.8 [8.8-26.8]
			Mean	20.5 [6.2-21.5]	20.5 [6.3-21.5]	20.6 [6.2-21.4]	20.6 [6.3-21.4]
	Temperature	Percentile	Maximum	35 [23-86]	35 [23.5-86]	35 [23.5-86]	35 [23.5-86]
			Mean	35.3 [20.5-86.2]	35.3 [19.9-86.2]	35.1 [20.2-86.4]	35.1 [20.2-86.4]
		Value	Maximum	11.7 [9.4-27.8]	11.7 [9.5-27.8]	11.7 [9.5-27.8]	11.7 [9.5-27.8]
			Mean	9.2 [6.6-22.1]	9.2 [6.5-22.1]	9.2 [6.6-22.1]	9.2 [6.6-22.1]
Segovia	Heat Index	Percentile	Maximum	82.6 [0-87.8]	82.6 [4.3-87.4]	82.5 [9-87.6]	82.5 [10.1-87.6]
			Mean	83.8 [19.9-88.4]	83.8 [22.2-88.4]	83.6 [22.6-88.7]	83.6 [24.4-88.7]
		Value	Maximum	26.2 [-2.2-27.4]	26.2 [3.6-27.3]	26.1 [4.3-27.4]	26.1 [4.4-27.4]
			Mean	20.7 [4.6-21.9]	20.7 [5-21.9]	20.6 [5-22]	20.6 [5.3-22]
	Temperature	Percentile	Maximum	84.5 [0-87.9]	84.5 [1-87.9]	84.5 [5.1-87.9]	84.3 [10.1-88]
			Mean	84.2 [16-88.6]	84.2 [17.9-88.6]	84.4 [19.6-88.7]	84.2 [19.8-88.6]
		Value	Maximum	27.2 [-2.2-28.4]	27.2 [1.8-28.4]	27.2 [4.4-28.4]	27.1 [6-28.4]
			Mean	21.4 [4.6-22.6]	21.4 [5-22.6]	21.4 [5.3-22.6]	21.4 [5.4-22.6]
Soria	Heat Index	Percentile	Maximum	86.7 [14.7-90.3]	86.7 [32.5-90.2]	86.8 [34.2-90.3]	86.8 [31.8-89.8]
			Mean	85.9 [0-90.4]	85.9 [27.6-90.9]	85.9 [29.3-90.7]	86.1 [29.1-89.9]
		Value	Maximum	24.8 [5.4-26.2]	24.8 [9.2-26.1]	24.9 [9.6-26.1]	24.9 [9.1-26]
			Mean	19.1 [-7.9-20.4]	19.1 [5.5-20.6]	19.1 [5.8-20.5]	19.1 [5.8-20.2]
	Temperature	Percentile	Maximum	87.1 [23.6-90.9]	87.1 [34-90.9]	87.1 [28.2-90.9]	87.1 [31.4-89.9]
			Mean	86.9 [0-90.7]	86.9 [26.2-91]	86.7 [27.8-90.8]	86.9 [29.3-89.7]
		Value	Maximum	25.2 [8.6-26.5]	25.2 [10.6-26.5]	25.2 [9.5-26.5]	25.2 [10.1-26.1]
			Mean	19.6 [-7.9-20.7]	19.6 [6.1-20.8]	19.6 [6.4-20.8]	19.6 [6.7-20.4]
Valladolid	Heat Index	Percentile	Maximum	81.1 [33.1-83.8]	81.1 [33.1-83.8]	81 [33.8-83.9]	81 [33.3-83.9]
			Mean	83.9 [32.7-86.5]	83.9 [32.7-86.5]	83.7 [32-86.7]	83.9 [33.2-86.5]
		Value	Maximum	25.1 [10-26.1]	25.1 [10-26.1]	25 [10.1-26.1]	25 [10.1-26.1]
			Mean	20.4 [7.4-21.1]	20.4 [7.4-21.1]	20.4 [7.2-21.1]	20.4 [7.5-21.1]
	Temperature	Percentile	Maximum	81.5 [31.8-85.2]	81.5 [31.8-85.2]	81.3 [32.2-85.4]	81.3 [32.2-85.4]
			Mean	83.9 [29.4-86.8]	83.9 [28.2-86.8]	83.7 [29.1-87]	83.7 [29.1-87]
		Value	Maximum	25.7 [10.8-27]	25.7 [10.8-27]	25.6 [10.8-27]	25.6 [10.8-27]
			Mean	20.9 [7.8-21.7]	20.9 [7.6-21.7]	20.9 [7.8-21.8]	20.9 [7.8-21.8]
	Heat Index	Percentile	Maximum	61.2 [0-100]	61.2 [1-89.6]	61.2 [5.1-88.3]	61 [10.1-87.4]
			Mean	75.8 [0-90.8]	75.8 [1.1-89.4]	75.8 [5.1-89.2]	75.8 [10.1-88.8]
		Value	Maximum	18.3 [-1.1-35.3]	18.3 [2.8-27.8]	18.3 [4.2-27.5]	18.2 [5.6-27.3]
			Mean	18.6 [-3.1-22.7]	18.6 [0.7-22.3]	18.6 [2.5-22.2]	18.6 [3.8-22.1]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Zamora	Temperature	Percentile	Maximum	0 [0-100]	1 [1-91.7]	64.9 [5.1-88.7]	64.8 [10.1-88.5]
			Mean	70.7 [0-100]	70.7 [1-89.9]	70.7 [5-89.4]	70.7 [10-89.4]
		Value	Maximum	-1.1 [-1.1-37.3]	2.9 [2.9-29.8]	20.4 [5.3-28.6]	20.3 [6.9-28.6]
			Mean	17.7 [-3.1-30.5]	17.7 [0.7-23.1]	17.7 [3-22.9]	17.7 [4.5-22.9]
Ávila	Heat Index	Percentile	Maximum	85.4 [28.4-89.9]	85.4 [28.8-89.9]	85.4 [28.8-89.9]	85.2 [28.7-89.7]
			Mean	87.1 [24.8-90.6]	87.1 [24.8-90.6]	87.1 [25.3-90.6]	87.1 [24.8-89.9]
		Value	Maximum	27.2 [9-28.3]	27.2 [9.1-28.3]	27.2 [9.1-28.3]	27.1 [9.1-28.2]
			Mean	22 [5.7-22.9]	22 [5.7-22.9]	22 [5.8-22.9]	22 [5.7-22.7]
	Temperature	Percentile	Maximum	85.6 [27.2-89.4]	85.6 [27.6-89.4]	85.6 [27.6-89.7]	85.6 [27.6-89.4]
			Mean	87.1 [23.3-90.2]	87.1 [22.8-90.2]	87.1 [22.1-90.2]	87.1 [22.8-89.9]
		Value	Maximum	28.2 [9.8-29.5]	28.2 [9.9-29.5]	28.2 [9.9-29.6]	28.2 [9.9-29.5]
			Mean	22.7 [6.3-23.6]	22.7 [6.2-23.6]	22.7 [6.1-23.6]	22.7 [6.2-23.5]
Albacete	Heat Index	Percentile	Maximum	62.2 [39.5-100]	62.2 [41.2-99]	62.2 [40.1-87.9]	62.2 [40.9-86.6]
			Mean	62.3 [41.5-100]	62.3 [41.5-89.7]	62.3 [41.5-85.3]	62.3 [41.5-86.1]
		Value	Maximum	21.2 [14.2-36.5]	21.2 [14.7-33.1]	21.2 [14.4-29]	21.2 [14.6-28.7]
			Mean	16.3 [10.7-29.9]	16.3 [10.7-24]	16.3 [10.7-23]	16.3 [10.7-23.2]
	Temperature	Percentile	Maximum	63.1 [35.5-100]	63.1 [40.1-99]	63.1 [40.5-87.7]	63.1 [40.5-87.3]
			Mean	62.6 [40.2-100]	62.6 [39.7-88.2]	62.4 [40.9-85.2]	62.4 [41.9-85.6]
		Value	Maximum	22 [14.2-38.9]	22 [15.3-34.3]	22 [15.4-29.7]	22 [15.4-29.6]
			Mean	16.9 [11.3-31.4]	16.9 [11.2-24.1]	16.9 [11.4-23.4]	16.9 [11.7-23.4]
Ciudad Real	Heat Index	Percentile	Maximum	61.4 [0-85]	61.4 [1.1-85]	61.4 [5.1-85]	61.4 [10.2-85.4]
			Mean	75.6 [0-85.9]	75.6 [1-86.3]	75.6 [5.1-86.3]	75.6 [10.1-86.3]
		Value	Maximum	22.2 [-0.1-30]	22.2 [4-30]	22.2 [6.3-30]	22.2 [7.9-30.1]
			Mean	22.3 [-2.2-25]	22.3 [1.5-25.1]	22.3 [3.8-25.1]	22.3 [5.3-25.1]
	Temperature	Percentile	Maximum	62.7 [0-83.6]	62.7 [1-83.6]	62.7 [5.1-83.3]	62.5 [10.1-83.5]
			Mean	74 [0-85.3]	74 [1-84.9]	74 [5-84.9]	73.8 [10.1-85.1]
		Value	Maximum	23.3 [-0.1-31.1]	23.3 [5.1-31.1]	23.3 [7.7-31]	23.2 [9.2-31]
			Mean	22.4 [-2.2-25.8]	22.4 [2.1-25.7]	22.4 [4.5-25.7]	22.4 [6.2-25.8]
Cuenca	Heat Index	Percentile	Maximum	39.5 [0-84.5]	39.5 [1.1-84.5]	39.5 [8-84.5]	39.7 [13.4-84.7]
			Mean	81 [0-85.7]	81 [6.4-85.7]	81 [11.8-85.7]	81 [11.8-85.7]
		Value	Maximum	12.4 [-2.2-27.4]	12.4 [2.8-27.4]	12.4 [5-27.4]	12.4 [6.4-27.4]
			Mean	21 [-4.6-22.2]	21 [2.3-22.2]	21 [3.7-22.2]	21 [3.7-22.2]
	Temperature	Percentile	Maximum	46.7 [0-84.9]	46.7 [1-85.3]	46.7 [5.1-85.3]	46.9 [10.2-85.1]
			Mean	81 [0-86.1]	81 [3.5-86.1]	81.2 [11.8-86.3]	81 [12.9-86.1]
		Value	Maximum	15.4 [-2.2-28.3]	15.4 [2.9-28.4]	15.4 [5.6-28.4]	15.4 [7.2-28.4]
			Mean	21.5 [-4.6-22.9]	21.5 [1.8-22.9]	21.6 [4.4-23]	21.5 [4.7-22.9]
Guadalajara	Heat Index	Percentile	Maximum	0 [0-87.7]	1 [1-87.3]	5.2 [5.2-86.7]	10 [10-87]
			Mean	37.6 [0-90.2]	37.6 [1.1-89]	37.6 [5.1-88.7]	37.6 [10.2-88.7]
		Value	Maximum	-1.9 [-1.9-28.2]	2.5 [2.5-28.1]	4 [4-28]	5.2 [5.2-28]
			Mean	8.5 [-3.9-23.5]	8.5 [-0.1-23.2]	8.5 [1.8-23.1]	8.5 [3.2-23.1]
	Temperature	Percentile	Maximum	0 [0-88.5]	1 [1-87.9]	5.1 [5.1-87.9]	10.1 [10.1-87.7]
			Mean	32.6 [0-91.1]	32.6 [1.1-89.5]	32.6 [5-88.9]	32.3 [10.1-89.1]
		Value	Maximum	-1.9 [-1.9-29.8]	2.6 [2.6-29.6]	5.2 [5.2-29.6]	6.8 [6.8-29.6]
			Mean	8.4 [-3.9-24.7]	8.4 [0-24.2]	8.4 [2.3-24]	8.3 [3.9-24]
Toledo	Heat Index	Percentile	Maximum	14.8 [0-84.6]	14.8 [1-84.6]	14.8 [5.1-84.6]	15 [10.1-84.8]
			Mean	0 [0-84.6]	1 [1-84.6]	5.1 [5.1-85.1]	10.1 [10.1-85.1]
		Value	Maximum	7.9 [-0.4-29.2]	7.9 [3.4-29.2]	7.9 [5-29.2]	8 [6.7-29.2]
			Mean	-2.7 [-2.7-24]	0.7 [0.7-24]	2.8 [2.8-24.1]	4.3 [4.3-24.1]
	Temperature	Percentile	Maximum	0 [0-83.4]	1 [1-83.4]	76.7 [5.1-83.4]	76.5 [10.1-83.6]
			Mean	0 [0-84.1]	1.1 [1.1-84.5]	5.1 [5.1-84.5]	10.1 [10.1-84.7]
		Value	Maximum	-0.4 [-0.4-30.4]	3.9 [3.9-30.4]	27.9 [6.5-30.4]	27.9 [8-30.4]
			Mean	-2.7 [-2.7-24.8]	1.1 [1.1-24.9]	3.5 [3.5-24.9]	5 [5-25]
Badajoz	Heat Index	Percentile	Maximum	85.4 [25.8-88.1]	85.4 [26.9-88.1]	85.2 [26.1-88.3]	85.2 [27.2-88.3]
			Mean	85.6 [32.8-88.3]	85.6 [32.5-88.3]	85.6 [33.3-88.3]	85.4 [32.2-88.4]
		Value	Maximum	29.3 [13.1-30.1]	29.3 [13.3-30.1]	29.2 [13.2-30.1]	29.2 [13.3-30.1]
			Mean	24 [11.7-24.7]	24 [11.6-24.7]	24 [11.8-24.7]	24 [11.5-24.8]
	Temperature	Percentile	Maximum	83.7 [21.8-87.1]	83.7 [24.9-87.1]	83.6 [25.2-87]	83.6 [25.9-87]
			Mean	84.9 [31.1-87.7]	84.9 [31.8-87.7]	84.9 [31.1-87.7]	85 [32.1-87.9]
		Value	Maximum	29.8 [13.2-30.9]	29.8 [13.7-30.9]	29.8 [13.8-30.9]	29.8 [13.8-30.9]
			Mean	24.3 [12.1-25.1]	24.3 [12.2-25.1]	24.3 [12.1-25.1]	24.4 [12.2-25.1]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Cáceres	Heat Index	Percentile	Maximum	45.3 [25.1-87.6]	45.3 [26.7-86.6]	45.3 [26.7-86.2]	45.4 [26.4-85.7]
			Mean	48.3 [23.3-94.1]	48.3 [25.9-89.3]	48.6 [26.3-88.1]	48.6 [25.6-87.7]
		Value	Maximum	16.8 [12.1-30]	16.8 [12.4-29.7]	16.8 [12.4-29.6]	16.9 [12.3-29.4]
			Mean	14.2 [9.1-26.6]	14.2 [9.6-25.1]	14.2 [9.7-24.8]	14.2 [9.6-24.6]
	Temperature	Percentile	Maximum	44.7 [25.4-85.6]	44.7 [27-85]	44.5 [25.7-84.8]	44.7 [26.1-84.7]
			Mean	47.6 [22.5-91.7]	47.6 [24.1-87.8]	47.9 [23.8-87.6]	47.6 [25.5-87.4]
		Value	Maximum	17.3 [13-30.7]	17.3 [13.3-30.5]	17.2 [13.1-30.4]	17.3 [13.1-30.4]
			Mean	14.7 [9.9-26.6]	14.7 [10.2-25.4]	14.8 [10.2-25.4]	14.7 [10.4-25.3]
Palma	Heat Index	Percentile	Maximum	76 [56.2-89.2]	76.2 [56.4-88.7]	76.2 [55.9-88.3]	76.2 [56.7-88.3]
			Mean	77.5 [60.8-89.2]	77.5 [59.7-88.8]	77.3 [60.7-89]	77.3 [60.7-88.6]
		Value	Maximum	25.3 [20.6-29.2]	25.4 [20.6-29]	25.4 [20.6-29]	25.4 [20.8-29]
			Mean	23.5 [19.7-26.1]	23.5 [19.4-26]	23.4 [19.6-26]	23.4 [19.6-26]
	Temperature	Percentile	Maximum	76.6 [57.4-88.8]	76.9 [57.1-88.5]	76.9 [56.7-87.8]	76.9 [56.7-87.8]
			Mean	80.1 [62.1-89.3]	80.1 [63-89.3]	80.1 [62.1-88.7]	80.3 [62.3-88.5]
		Value	Maximum	25.1 [20.9-27.2]	25.1 [20.9-27.1]	25.1 [20.8-27]	25.1 [20.8-27]
			Mean	23.6 [20-25.1]	23.6 [20.2-25.1]	23.6 [20-25]	23.6 [20-25]
Barcelona	Heat Index	Percentile	Maximum	82 [76.5-83.8]	82 [72.9-83.8]	82.3 [75.2-83.6]	82.3 [73.5-83.6]
			Mean	82 [77-84.1]	82 [77.5-84.1]	81.8 [77.3-83.9]	82 [77.5-84.1]
		Value	Maximum	25.7 [24.3-26.4]	25.7 [23.4-26.4]	25.8 [24-26.4]	25.8 [23.6-26.4]
			Mean	22.1 [20.9-22.6]	22.1 [21-22.6]	22 [21-22.6]	22.1 [21-22.6]
	Temperature	Percentile	Maximum	81.2 [76.9-83.4]	81.2 [76.9-83.4]	81.4 [76.7-83.6]	81.2 [76.9-83.4]
			Mean	81.7 [77.3-83.5]	81.7 [77.8-83.5]	81.7 [77.3-83.5]	81.5 [77-83.8]
		Value	Maximum	25.4 [24.4-25.9]	25.4 [24.4-25.9]	25.4 [24.4-26]	25.4 [24.4-25.9]
			Mean	21.8 [20.9-22.2]	21.8 [21-22.2]	21.8 [20.9-22.2]	21.8 [20.9-22.2]
Girona	Heat Index	Percentile	Maximum	26.4 [17.5-90.8]	26.4 [17-90.8]	26.6 [17.2-90.9]	26.6 [17.2-89.8]
			Mean	85.1 [23.6-90.4]	85.1 [23.6-90.4]	85.2 [23.9-90.2]	85.2 [23.9-89.8]
		Value	Maximum	12.6 [10.8-28.6]	12.6 [10.7-28.6]	12.7 [10.8-28.6]	12.7 [10.8-28.4]
			Mean	22.7 [8.3-24.1]	22.7 [8.3-24.1]	22.8 [8.3-24]	22.8 [8.3-24]
	Temperature	Percentile	Maximum	26.9 [16.8-91.3]	26.9 [16.8-91.1]	27.2 [16.6-90.9]	26.9 [16.8-89.8]
			Mean	85 [22-90.3]	85 [21.4-90.3]	84.8 [21.1-90.1]	85 [22-89.8]
		Value	Maximum	13.7 [11.8-28.5]	13.7 [11.8-28.4]	13.8 [11.8-28.4]	13.7 [11.8-28.1]
			Mean	22.6 [9.1-23.8]	22.6 [9-23.8]	22.6 [8.9-23.8]	22.6 [9.1-23.7]
Lleida	Heat Index	Percentile	Maximum	77.8 [0-88.3]	77.8 [1.1-88.3]	77.8 [5-87.9]	77.8 [10.1-87.9]
			Mean	77.7 [0-89.5]	77.7 [1-88.8]	77.7 [14.5-88.8]	77.6 [18.1-88.6]
		Value	Maximum	25.3 [-3.8-28.3]	25.3 [3.4-28.3]	25.3 [6-28.2]	25.3 [7.8-28.2]
			Mean	20.5 [-6.8-23.6]	20.5 [0.4-23.4]	20.5 [5.7-23.4]	20.4 [6.3-23.4]
	Temperature	Percentile	Maximum	76.4 [0-89.7]	76.6 [1-89.4]	76.6 [5-89.4]	76.4 [10.2-88.9]
			Mean	77.9 [0-89.6]	77.9 [1-89.1]	77.9 [5.1-89.1]	77.7 [10-88.9]
		Value	Maximum	25.1 [-3.8-28.5]	25.1 [4.2-28.4]	25.1 [7.6-28.4]	25.1 [9.2-28.3]
			Mean	20.7 [-6.8-23.5]	20.7 [0.7-23.4]	20.7 [3.8-23.4]	20.6 [5.6-23.4]
Tarragona	Heat Index	Percentile	Maximum	35.7 [17.7-89.4]	35.7 [17.1-89.4]	35.7 [17.7-89.4]	35.5 [17.5-89.6]
			Mean	51.3 [19.7-88.7]	51.3 [20.7-88.7]	51.3 [21.3-88.7]	51.1 [21.6-88.6]
		Value	Maximum	15.4 [11.9-29.4]	15.4 [11.8-29.4]	15.4 [11.9-29.4]	15.3 [11.8-29.4]
			Mean	15.4 [9.2-25]	15.4 [9.4-25]	15.4 [9.5-25]	15.3 [9.6-25]
	Temperature	Percentile	Maximum	31.5 [14.9-89.2]	31.8 [15.8-89]	31.5 [15.5-88.7]	31.5 [15.5-88.7]
			Mean	81.1 [17.9-87.9]	80.8 [18.1-88.1]	80.8 [18.1-88.1]	81.1 [17.9-87.9]
		Value	Maximum	15.4 [12.4-28.2]	15.4 [12.6-28.1]	15.4 [12.5-28.1]	15.4 [12.5-28.1]
			Mean	22.8 [9.9-24.1]	22.8 [9.9-24.1]	22.8 [9.9-24.1]	22.8 [9.9-24.1]
Alicante/Alacant	Heat Index	Percentile	Maximum	59.9 [36.3-100]	59.9 [35.8-91.8]	59.7 [36.1-89.1]	59.7 [35.5-90]
			Mean	58.4 [38-100]	58.4 [38-98.9]	58.2 [37.1-93.1]	58.2 [37.1-89.4]
		Value	Maximum	22.8 [17.3-38.1]	22.8 [17.2-30.9]	22.8 [17.2-30.2]	22.8 [17.1-30.4]
			Mean	18.8 [14.1-32.1]	18.8 [14.1-28.8]	18.8 [13.9-27]	18.8 [13.9-26.2]
	Temperature	Percentile	Maximum	67.2 [32-90.1]	67.4 [32.2-88.9]	67.2 [32.5-88.6]	67.2 [32.5-89.1]
			Mean	62.2 [36.9-92.3]	62.2 [37.4-89.2]	62.2 [36.9-89.2]	62.4 [37.1-88.9]
		Value	Maximum	24.8 [17.2-29.5]	24.9 [17.2-29.2]	24.8 [17.3-29.2]	24.8 [17.3-29.3]
			Mean	20 [14.6-26]	20 [14.7-25.5]	20 [14.6-25.5]	20 [14.7-25.4]
	Heat Index	Percentile	Maximum	84.1 [41.3-90.7]	84.1 [41.8-90.4]	84.4 [42.1-90.5]	84.1 [41.8-89.9]
			Mean	85.8 [33.6-91.5]	85.8 [34.1-91.5]	86 [33.9-91.2]	86 [33.9-89.8]
		Value	Maximum	27 [16.2-28.6]	27 [16.3-28.5]	27 [16.4-28.6]	27 [16.3-28.4]
			Mean	23.6 [11.6-24.8]	23.6 [11.7-24.8]	23.6 [11.7-24.8]	23.6 [11.7-24.4]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Castelló de la Plana	Temperature	Percentile	Maximum	85.3 [50.3-91.3]	85.3 [48.5-91.3]	85.3 [49.4-90.9]	85.3 [49.1-89.9]
			Mean	85.9 [34.7-92.1]	85.9 [37.1-92.1]	85.9 [36.6-92.6]	85.9 [36.1-89.5]
		Value	Maximum	26.3 [18.7-27.5]	26.3 [18.3-27.5]	26.3 [18.5-27.4]	26.3 [18.4-27.2]
			Mean	23.1 [12.6-24.1]	23.1 [13-24.1]	23.1 [12.9-24.2]	23.1 [12.8-23.7]
València	Heat Index	Percentile	Maximum	82.8 [41.4-87.1]	82.8 [41.4-86.7]	82.8 [42.4-87.1]	83.1 [42.2-86.9]
			Mean	83.9 [74.3-86.9]	83.9 [76.6-86.9]	84.1 [76.4-87.2]	84.1 [72.9-87.2]
		Value	Maximum	27.2 [16.6-28.2]	27.2 [16.6-28.1]	27.2 [16.8-28.2]	27.2 [16.8-28.1]
			Mean	23.5 [21.2-24.2]	23.5 [21.8-24.2]	23.6 [21.8-24.2]	23.6 [20.9-24.2]
	Temperature	Percentile	Maximum	84.4 [49.2-86.9]	84.4 [49.7-86.9]	84.1 [46.4-86.6]	84.1 [44.9-86.6]
			Mean	84.1 [79.9-86.9]	84.1 [79.3-86.9]	83.8 [79.6-86.6]	83.8 [79.6-86.6]
		Value	Maximum	26.7 [18.8-27.2]	26.7 [18.9-27.2]	26.6 [18.2-27.1]	26.6 [18-27.1]
			Mean	23.1 [22.3-23.6]	23.1 [22.2-23.6]	23 [22.2-23.6]	23 [22.2-23.6]
Almería	Heat Index	Percentile	Maximum	85.9 [18.9-90.5]	85.9 [19.4-90.5]	85.7 [19.1-90.2]	85.7 [19.1-89.8]
			Mean	83.8 [21-88.6]	83.8 [21.6-88.6]	83.5 [21.3-88.9]	83.5 [21.3-88.9]
		Value	Maximum	29.9 [14.1-31]	29.9 [14.2-31]	29.9 [14.2-31]	29.9 [14.2-30.9]
			Mean	25.7 [11-26.7]	25.7 [11.1-26.7]	25.6 [11.1-26.8]	25.6 [11.1-26.8]
	Temperature	Percentile	Maximum	86.8 [18.9-91]	87.1 [18.5-90.7]	86.8 [18.9-91]	87.1 [19.1-89.9]
			Mean	85 [20-90]	85 [20-89.5]	85 [20-90]	84.7 [20.3-89.7]
		Value	Maximum	30.5 [15-31.5]	30.6 [14.9-31.4]	30.5 [15-31.5]	30.6 [15.1-31.2]
			Mean	26 [11.7-27]	26 [11.7-26.9]	26 [11.7-27]	26 [11.8-27]
Cádiz	Heat Index	Percentile	Maximum	67.6 [46.4-83.4]	67.6 [45.9-82.8]	67.6 [46.4-82.8]	67.9 [45.7-83.1]
			Mean	77 [46.8-84.8]	77 [46.2-84.8]	76.7 [47-85.1]	77 [46.8-84.8]
		Value	Maximum	24.3 [19.6-28]	24.3 [19.5-27.9]	24.3 [19.6-27.9]	24.4 [19.4-28]
			Mean	23.1 [17-24.5]	23.1 [16.9-24.5]	23 [17-24.6]	23.1 [17-24.5]
	Temperature	Percentile	Maximum	66.7 [45.7-83.9]	66.7 [45.1-83.9]	66.7 [45.7-84.5]	66.7 [45.7-84.5]
			Mean	77.2 [45.9-84.8]	76.9 [46.2-85.1]	76.9 [44.9-85.1]	77.2 [46.5-84.8]
		Value	Maximum	24.1 [19.7-27.4]	24.1 [19.6-27.4]	24.1 [19.7-27.5]	24.1 [19.7-27.5]
			Mean	22.9 [17.1-24.1]	22.9 [17.1-24.1]	22.9 [17-24.1]	22.9 [17.2-24.1]
Córdoba	Heat Index	Percentile	Maximum	65.4 [46.4-81.5]	65.4 [48.1-81.5]	65.5 [48.6-81.7]	65.5 [48.6-81.7]
			Mean	70.9 [44.2-83.1]	70.9 [45.5-83.1]	71.1 [45.3-83.4]	71.1 [45.7-82.9]
		Value	Maximum	24.9 [18.4-29.6]	24.9 [18.9-29.6]	25 [19-29.6]	25 [19-29.6]
			Mean	21.7 [13.8-24.8]	21.7 [14.1-24.8]	21.8 [14.1-24.9]	21.8 [14.2-24.8]
	Temperature	Percentile	Maximum	66.6 [41.4-80.2]	66.6 [51.6-80.2]	66.4 [51.8-80]	66.6 [52.3-80.2]
			Mean	67.2 [44.9-81.8]	67.2 [45.7-82.1]	67.2 [46.3-81.8]	67.2 [46.7-82.1]
		Value	Maximum	25.7 [17.6-30.3]	25.7 [20.5-30.3]	25.6 [20.6-30.2]	25.7 [20.7-30.3]
			Mean	20.9 [14.6-25.1]	20.9 [14.8-25.2]	20.9 [14.9-25.1]	20.9 [15-25.2]
Granada	Heat Index	Percentile	Maximum	57.2 [36.2-83.8]	57.2 [36.2-83.8]	57.2 [36.6-83.8]	57.2 [36.2-83.8]
			Mean	58.5 [33.8-83.5]	58.5 [33.3-83.9]	58.3 [34.5-83.7]	58.3 [34.1-83.7]
		Value	Maximum	21.5 [15.5-29.4]	21.5 [15.5-29.4]	21.5 [15.6-29.4]	21.5 [15.5-29.4]
			Mean	17.1 [10.8-24.3]	17.1 [10.7-24.4]	17 [10.9-24.4]	17 [10.8-24.4]
	Temperature	Percentile	Maximum	57.7 [37.5-81.8]	57.7 [38.3-82.2]	57.5 [38.5-82]	57.5 [37.7-81.6]
			Mean	57.4 [33.6-82.5]	57.4 [34.1-82.5]	57.6 [34.4-82.7]	57.6 [34.4-82.7]
		Value	Maximum	22.2 [16.6-29.8]	22.2 [16.8-29.9]	22.1 [16.9-29.9]	22.1 [16.6-29.8]
			Mean	17.3 [11.6-24.6]	17.3 [11.7-24.6]	17.4 [11.8-24.6]	17.4 [11.8-24.6]
Huelva	Heat Index	Percentile	Maximum	36.3 [26.2-50]	36.1 [25.9-49.8]	36.1 [26.6-49.7]	36.3 [26.2-49.4]
			Mean	38.3 [27.3-80.9]	38.3 [26.6-82.6]	38.5 [26.9-82.3]	38.5 [26.2-80.6]
		Value	Maximum	17.2 [15.6-20]	17.1 [15.6-20]	17.1 [15.7-20]	17.2 [15.6-19.9]
			Mean	15.1 [13.4-23.8]	15.1 [13.3-24.1]	15.2 [13.3-24]	15.2 [13.2-23.8]
	Temperature	Percentile	Maximum	36.6 [27.5-48.9]	36.6 [27.4-48.9]	36.6 [27.5-49.4]	36.6 [27.5-49.4]
			Mean	38.1 [27.4-80.9]	37.8 [27-80.7]	37.8 [27-77.8]	37.8 [27-81.8]
		Value	Maximum	17.7 [16.3-20.1]	17.7 [16.3-20.1]	17.7 [16.3-20.2]	17.7 [16.3-20.2]
			Mean	15.5 [14-23.7]	15.4 [13.9-23.6]	15.4 [13.9-23.2]	15.4 [13.9-23.9]
Jaén	Heat Index	Percentile	Maximum	45.9 [26-69.1]	45.9 [27-76.8]	45.9 [28-68.9]	46.1 [27.8-67.8]
			Mean	47.6 [31.5-83.9]	47.6 [31.5-83.5]	47.8 [31.8-83.7]	47.8 [31.2-84.2]
		Value	Maximum	17.3 [12.3-25.5]	17.3 [12.5-27.7]	17.3 [12.7-25.4]	17.4 [12.7-25]
			Mean	13.5 [9.9-24.3]	13.5 [9.9-24.2]	13.6 [9.9-24.2]	13.6 [9.8-24.4]
	Temperature	Percentile	Maximum	46.5 [0-64.9]	46.5 [25.6-66.9]	46.5 [26-64.6]	46.7 [27.2-65.6]
			Mean	47.4 [30.5-80.4]	47.4 [30.5-81.6]	47.4 [30-79.6]	47.4 [31.1-80.4]
		Value	Maximum	18.2 [-0.2-24.3]	18.2 [13.1-25]	18.2 [13.2-24.2]	18.2 [13.4-24.6]
			Mean	14.2 [10.6-24.1]	14.2 [10.6-24.4]	14.2 [10.5-23.9]	14.2 [10.7-24.1]

Table E.1: Minimum mortality temperature and heat index and its corresponding percentiles estimated at meso level *(continued)*

				Constrains			
				None	1-99 centile	5-95 centile	10-90 centile
Málaga	Heat Index	Percentile	Maximum	84 [39.8-90.1]	84 [39.8-90.1]	84 [39.8-90.1]	84 [39.8-89.8]
			Mean	52.2 [37.2-90.8]	52.2 [37.2-89.8]	52 [36.9-90]	52 [36.9-90]
		Value	Maximum	28.8 [17.3-30.1]	28.8 [17.3-30.1]	28.8 [17.3-30.1]	28.8 [17.3-30]
			Mean	16.3 [13.2-25.5]	16.3 [13.2-25.3]	16.2 [13.2-25.4]	16.2 [13.2-25.4]
	Temperature	Percentile	Maximum	82.8 [41.2-88.6]	82.8 [40.7-88.6]	82.8 [41.2-88.6]	82.6 [41-88.5]
			Mean	80.5 [38.4-87.9]	80.5 [37.7-87.9]	80.5 [37.7-87.9]	80.5 [38.4-87.9]
		Value	Maximum	28.5 [18.1-29.8]	28.5 [18-29.8]	28.5 [18.1-29.8]	28.4 [18-29.8]
			Mean	23.5 [14-24.9]	23.5 [13.9-24.9]	23.5 [13.9-24.9]	23.5 [14-24.9]
Sevilla	Heat Index	Percentile	Maximum	58.2 [48.2-66.9]	58.2 [48.2-66.9]	58.1 [48.3-66.8]	58.1 [48.7-66.8]
			Mean	60.7 [47.3-79.5]	60.7 [47.8-79.9]	60.7 [47.8-79.9]	60.4 [48-79.6]
		Value	Maximum	22.8 [20-25.6]	22.8 [20-25.6]	22.8 [20-25.6]	22.8 [20.1-25.6]
			Mean	19.2 [15.9-24]	19.2 [16-24.1]	19.2 [16-24.1]	19.1 [16-24]
	Temperature	Percentile	Maximum	58.3 [48.5-67.4]	58.3 [48.5-67]	58.4 [48.7-66.9]	58.3 [48.5-67.4]
			Mean	60.5 [49.1-76.8]	60.5 [49.1-76.8]	60.5 [49.6-77.2]	60.5 [48.6-76.3]
		Value	Maximum	23.1 [20.5-25.9]	23.1 [20.5-25.8]	23.1 [20.6-25.8]	23.1 [20.5-25.9]
			Mean	19.4 [16.7-23.6]	19.4 [16.7-23.6]	19.4 [16.8-23.7]	19.4 [16.6-23.5]
Ceuta	Heat Index	Percentile	Maximum	45.7 [15.4-100]	45.4 [21.3-89.3]	45.4 [22.1-89.3]	45.4 [23-88.9]
			Mean	47.7 [21.2-100]	47.7 [23.8-85.4]	47.7 [23.8-85.4]	47.7 [23.8-84.9]
		Value	Maximum	19.1 [14.8-37.7]	19 [15.6-28.4]	19 [15.7-28.4]	19 [15.8-28.4]
			Mean	16.7 [13.2-31.8]	16.7 [13.5-23.9]	16.7 [13.5-23.9]	16.7 [13.5-23.8]
	Temperature	Percentile	Maximum	46.8 [15.3-100]	46.8 [22.3-93.5]	46.5 [23.6-92]	46.8 [22.3-89.7]
			Mean	48.8 [20.6-98]	49.1 [26-85.3]	49.1 [25-84.6]	49.1 [25-85.3]
		Value	Maximum	19.5 [15.3-35.8]	19.5 [16.1-28.2]	19.4 [16.2-27.9]	19.5 [16.1-27.4]
			Mean	17.1 [13.6-25.8]	17.1 [14.2-23.4]	17.1 [14.1-23.2]	17.1 [14.1-23.4]
Melilla	Heat Index	Percentile	Maximum	28 [13-97.1]	28 [13-95.8]	28 [13.7-94.5]	27.6 [13.4-89.6]
			Mean	31.7 [15-100]	31.7 [15-97.9]	31.7 [15.7-95]	31.2 [16.1-89.7]
		Value	Maximum	16.6 [14.5-31]	16.6 [14.5-30.3]	16.6 [14.6-29.9]	16.6 [14.6-28.6]
			Mean	14.6 [12.6-32]	14.6 [12.6-27.6]	14.6 [12.7-26.5]	14.6 [12.8-25.4]
	Temperature	Percentile	Maximum	26.5 [13.4-100]	26.9 [13.8-98.9]	26.5 [13.4-95]	26.5 [13.4-89.4]
			Mean	32.1 [16.3-100]	31.7 [16.6-98.8]	31.7 [15.9-94.6]	31.7 [16.6-89.7]
		Value	Maximum	16.9 [15.2-33.9]	17 [15.2-30]	16.9 [15.2-28.3]	16.9 [15.2-27.2]
			Mean	15.1 [13.4-29.7]	15.1 [13.4-26.8]	15.1 [13.3-25.4]	15.1 [13.4-24.6]
Murcia	Heat Index	Percentile	Maximum	57.4 [27.7-100]	57.4 [30.8-98.9]	57.4 [30.3-94.8]	57.6 [30.1-89.7]
			Mean	72.2 [40.7-100]	72.2 [40.7-98.9]	72.2 [41.3-95]	72.2 [41.8-89.7]
		Value	Maximum	22 [15.4-37.7]	22 [16-33.7]	22 [15.9-31.6]	22 [15.8-30.2]
			Mean	22.2 [14.4-32.2]	22.2 [14.4-28.6]	22.2 [14.5-27.2]	22.2 [14.6-26.1]
	Temperature	Percentile	Maximum	53.3 [0-100]	53 [26.9-87.5]	53.3 [27.7-86.3]	53 [27.4-85.5]
			Mean	74.7 [37.8-100]	74.7 [37.2-99]	74.7 [37.8-94.6]	74.7 [39.4-89.6]
		Value	Maximum	21.3 [2.5-36.5]	21.2 [16-29]	21.3 [16.2-28.8]	21.2 [16.1-28.7]
			Mean	22.7 [14.5-30.5]	22.7 [14.4-27.8]	22.7 [14.5-26.4]	22.7 [14.8-25.5]
Palmas de Gran Canaria	Heat Index	Percentile	Maximum	92.3 [12-100]	92.3 [15.5-99]	92.3 [14.9-94.9]	89.3 [15.9-89.3]
			Mean	87.5 [13.9-100]	87.5 [22.4-98.9]	87 [23.1-94.6]	87.5 [20.9-89.4]
		Value	Maximum	26.2 [18.9-36]	26.2 [19.2-29.1]	26.1 [19.1-27.2]	25.8 [19.2-25.8]
			Mean	23.9 [17.7-32.7]	23.9 [18.3-26.4]	23.9 [18.4-24.9]	23.9 [18.2-24.1]
	Temperature	Percentile	Maximum	89.5 [12.7-100]	89.5 [16.4-99]	90 [15.9-94.9]	89.5 [15.2-89.5]
			Mean	87.8 [20.7-100]	88.4 [23.1-99]	88.4 [23.1-94.4]	88.4 [21.5-89.4]
		Value	Maximum	25.3 [19.2-30]	25.3 [19.5-27]	25.4 [19.4-26]	25.3 [19.4-25.3]
			Mean	23.5 [18.4-28.8]	23.6 [18.6-25.4]	23.6 [18.6-24.1]	23.6 [18.4-23.6]
Santa Cruz de Tenerife	Heat Index	Percentile	Maximum	49.8 [0-100]	50.2 [1.1-98.9]	50.2 [5.2-94.8]	49.8 [10.4-89.6]
			Mean	46.6 [0-100]	46.6 [1.1-99]	46.6 [5.3-94.5]	46.6 [10.1-89.2]
		Value	Maximum	21.8 [13.5-35.3]	21.9 [16.6-28.6]	21.9 [17.6-26.9]	21.8 [18.3-25.5]
			Mean	19.8 [12.7-32.1]	19.8 [15.4-26]	19.8 [16.4-24.4]	19.8 [16.9-23.7]
	Temperature	Percentile	Maximum	0 [0-100]	45.6 [1.1-98.9]	45.6 [5.2-94.7]	46.3 [10.3-90]
			Mean	41.3 [0-100]	40.7 [1.1-98.9]	41.3 [5.1-94.9]	41.3 [10.6-89.2]
		Value	Maximum	14.1 [14.1-29.9]	21.4 [17-26.8]	21.4 [18-25.6]	21.4 [18.6-25.1]
			Mean	19.4 [13.4-28.5]	19.4 [15.9-25]	19.4 [16.8-23.9]	19.4 [17.3-23.3]

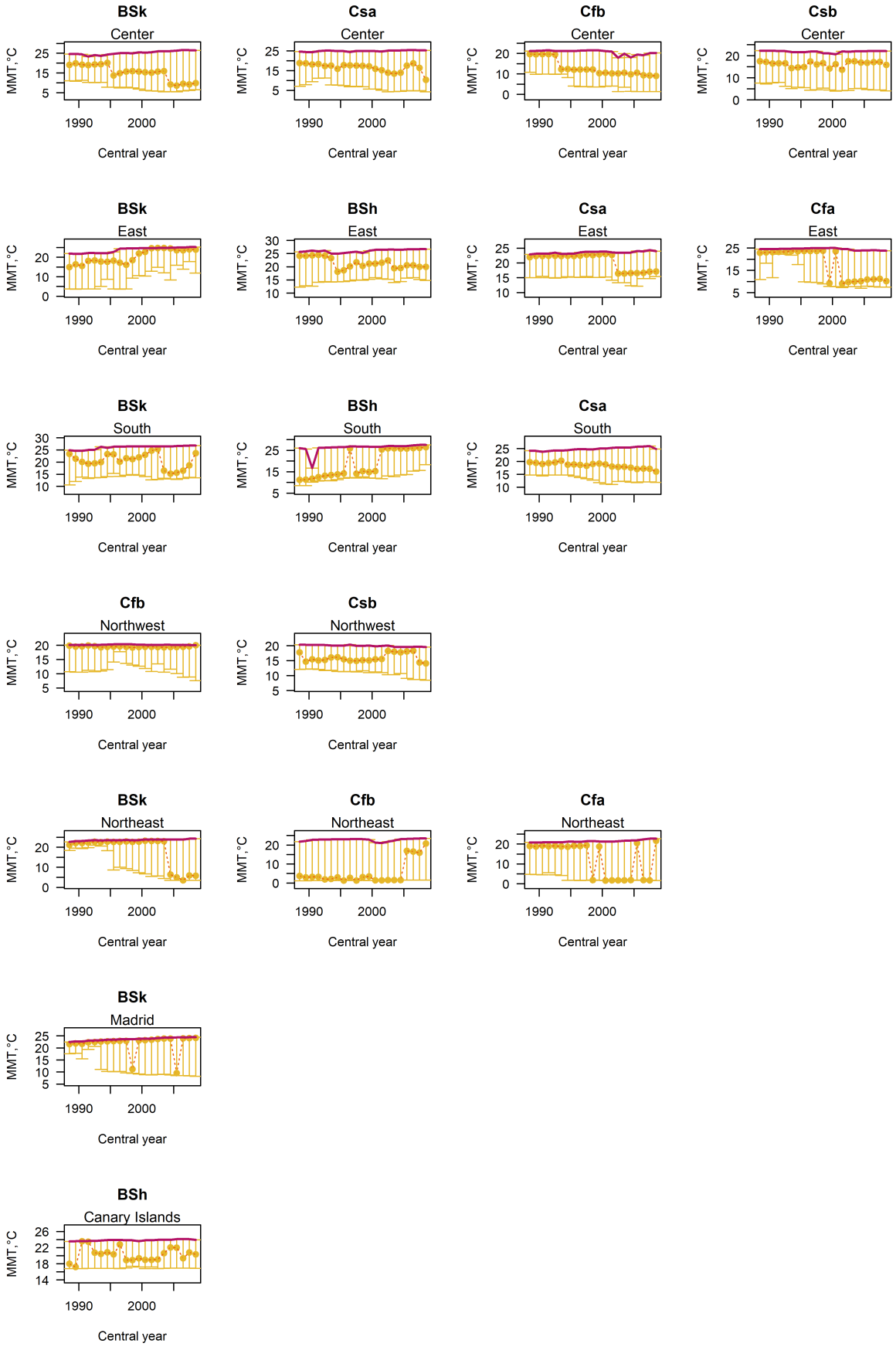

Figure E.15: Changes in MMT (constrained to 5-95th centile range) in provincial capitals of Spain from 1979 to 2018 grouped by climatic regimen (moving average windows of 20 years)

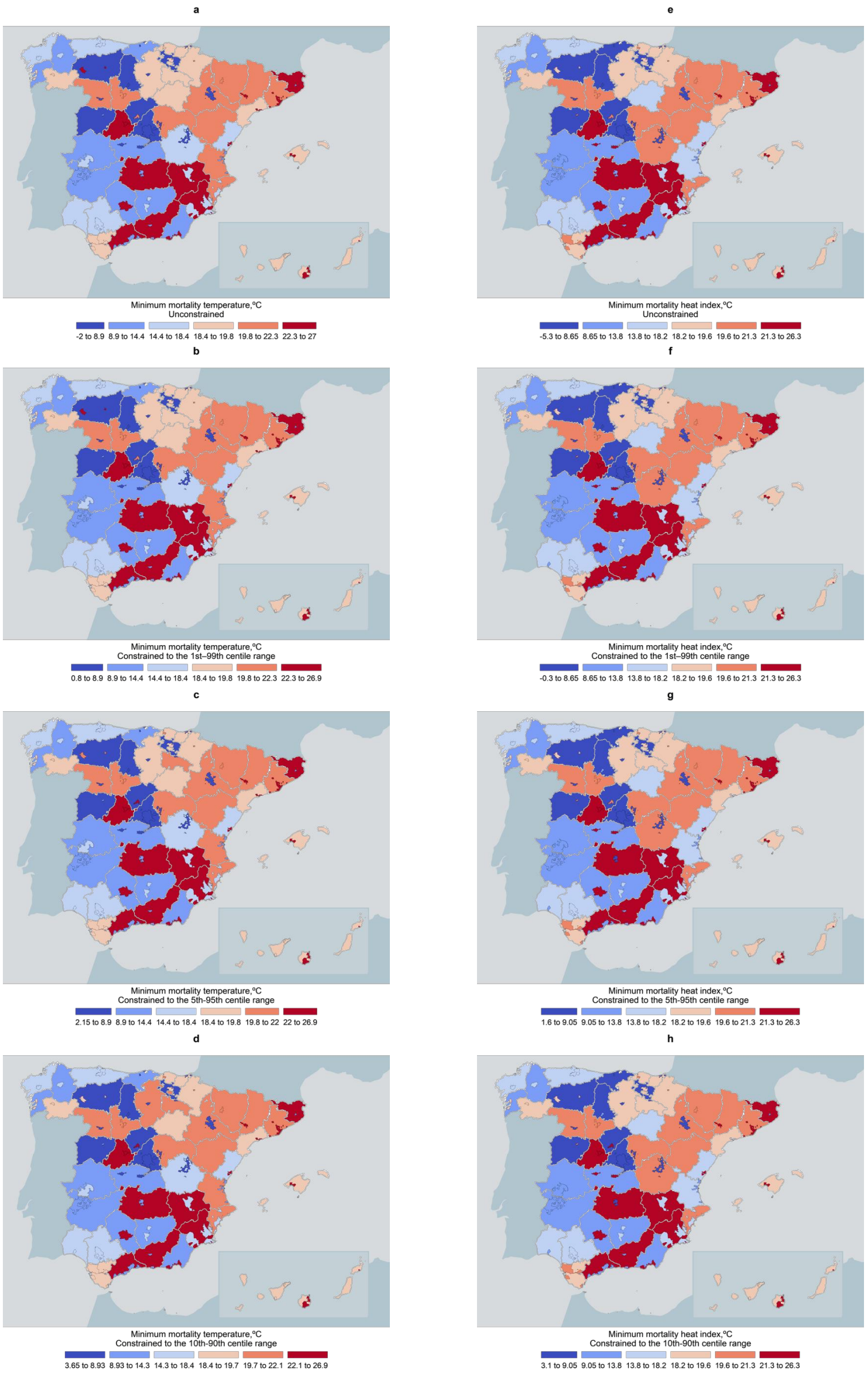

Figure E.16: MMT and MMHI for all seasons estimated for urban and rural municipalities using average daily temperatures in 1998-2018

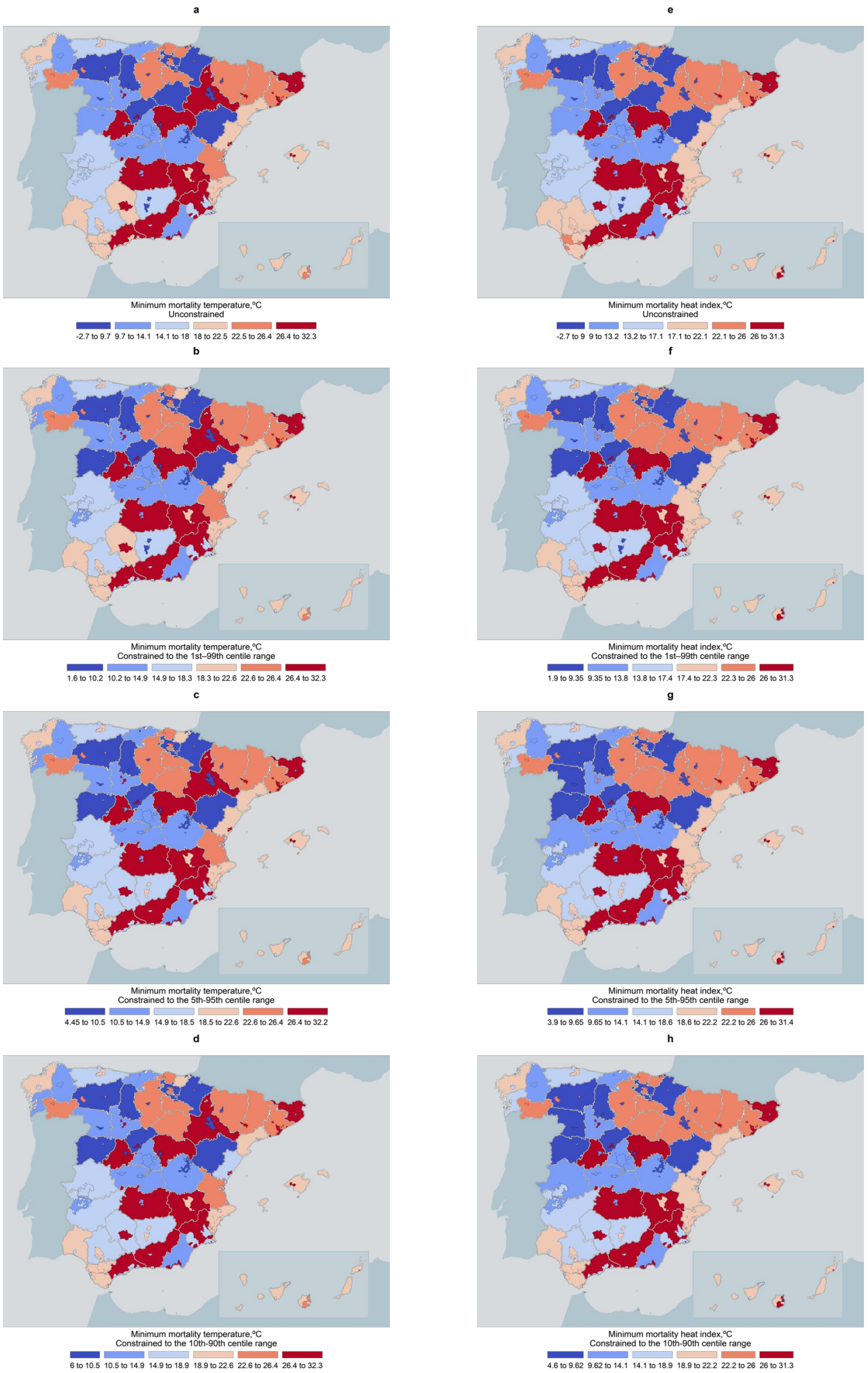

Figure E.17: MMT and MMHI for all seasons estimated for urban and rural municipalities using maximum daily temperatures in 1998-2018

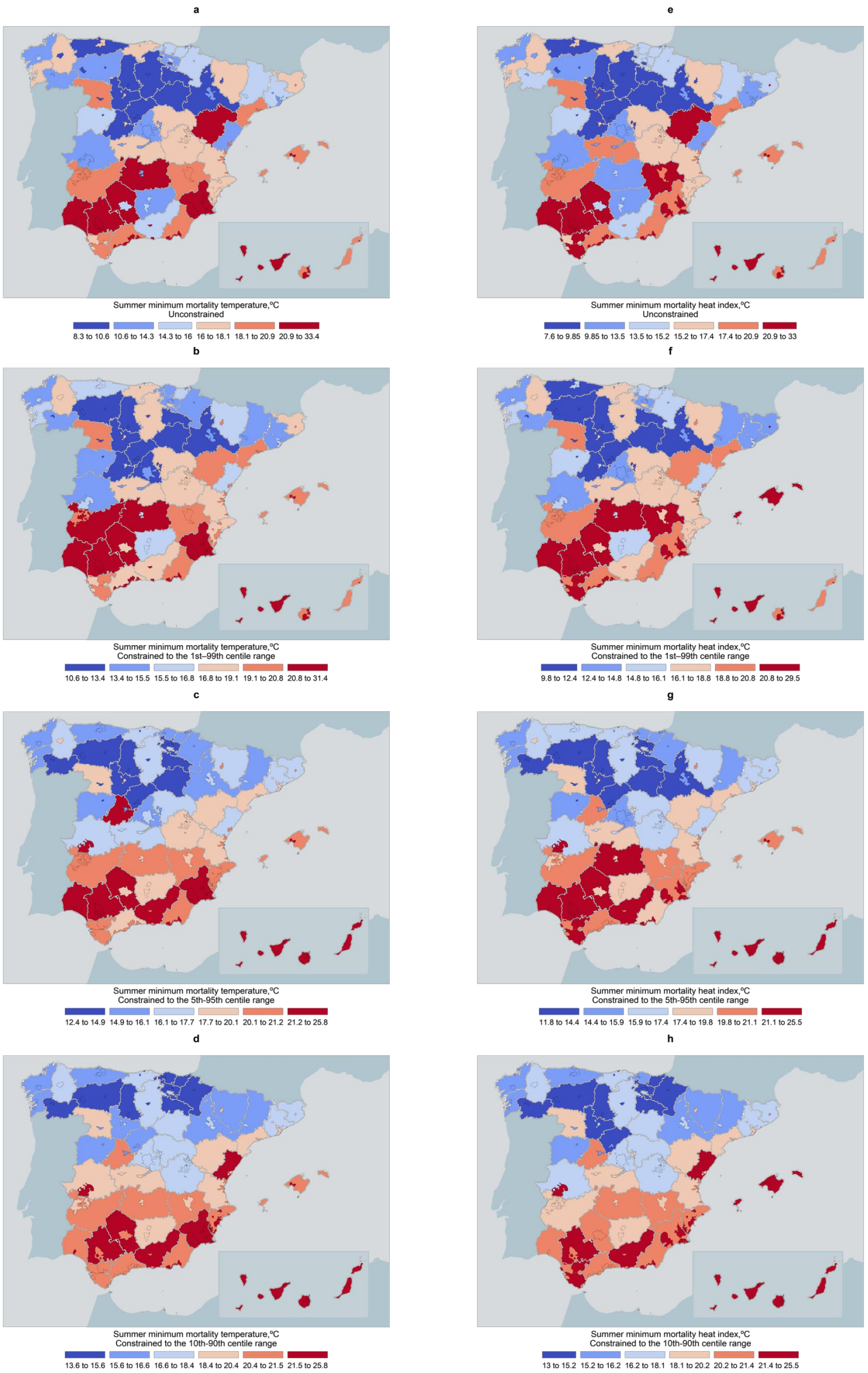

Figure E.18: MMT and MMHI for summer season estimated for urban and rural municipalities using average daily temperatures in 1998-2018

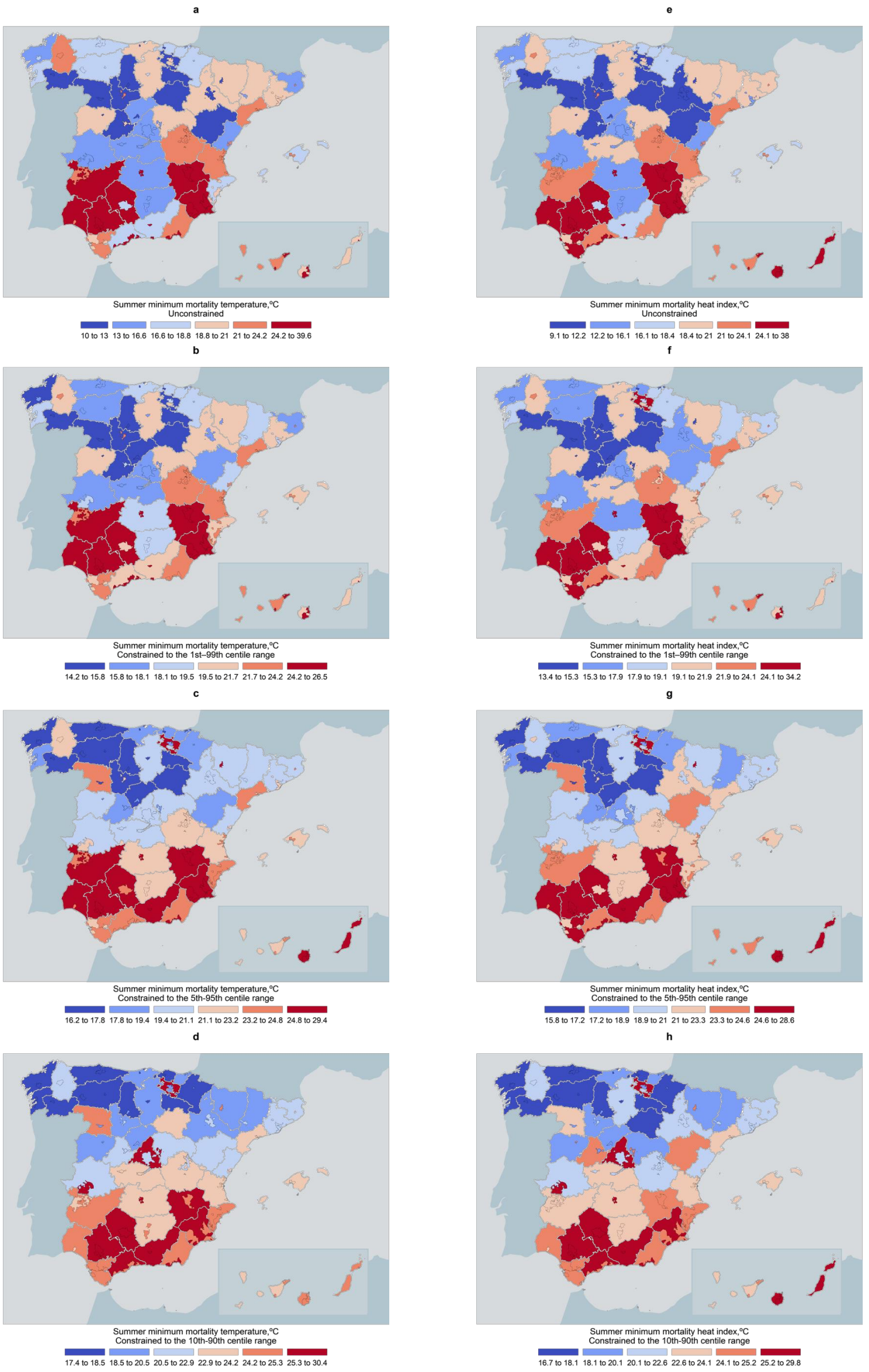

Figure E.19: MMT and MMHI for summer season estimated for urban and rural municipalities using maximum daily temperatures in 1998-2018

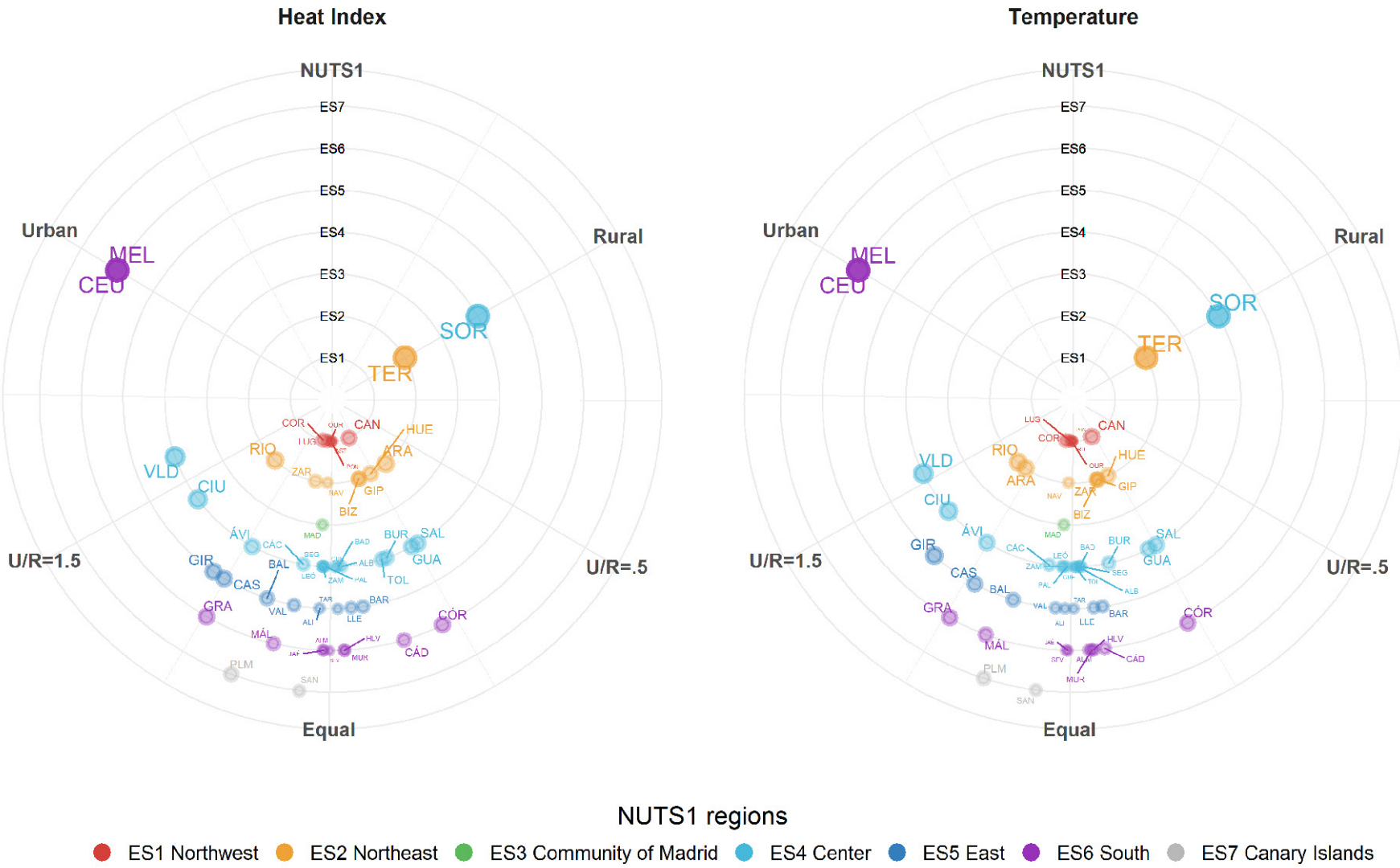

Figure E.20: Regional variations in urbanicity as protective factor for summer mortality due to heat (maximum temperatures and heat index)

F

List of publications, conference presentations and awards

F.1 Publications

- Voigt, M, Ordanovich, D, Viciana Fernández, F, Cilek, LA, Canovas Balboá, R, Ramiro Fariñas, D. *Urban environment and mortality differentials in Spain.* Popul Space Place. 2019; 25:e2239. https://doi.org/10.1002/psp.2239

F.2 Public presentations

F.2.1 International conferences

- Voigt, M., Ordanovich, D., Viciana, F. J., Cilek, L. A., & Ramiro-Fariñas, D. (2018, April). *Urban Environment and Mortality Differentials in Southern Spain.* In Population Association of America 2018 Annual Meeting. PAA.

- Ordanovich, D., Viciana, F., Ramiro-Fariñas, D. (2018, June). *Spatial Variations in Mortality Due to Heat Waves in Southern Spain.* In European Population Conference 2018. EAPS. https://eaps.confex.com/eaps/2018/meetingapp.cgi/Paper/2243

- Voigt, M., Ordanovich, D., Viciana, F., Ramiro-Fariñas, D., & Canovas, R. (2018, June). *Urban Environment and Mortality Differentials in Southern Spain.* In European Population Conference 2018. EAPS. https://eaps.confex.com/eaps/2018/meetingapp.cgi/Pap

- Ordanovich, D., Viciana, F., Ramiro-Fariñas, D. (2018, September). *Spatial Variations in Mortality Due to Heat Waves in Southern Spain.* In British Society

for Population Studies 2018 Conference. BSPS.

- Casado Ruiz, Y., Ordanovich, D., Ramiro-Fariñas, D. (2018, November). *Exploring Spatio-temporal Patterns of Mortality in the Early Twentieth Century in Madrid, Spain.* In Social Science History Association 2018 Meeting. SSHA.

- Ordanovich, D., Ramiro-Fariñas, D., Billari, F., Tugores, A., Viciana, F., Ramasco, JJ. (2019, April). *What Were You Thinking Nine Month Ago? Using Twitter for Fertility Nowcasting Over Time and Space.* In Population Association of America 2019 Annual Meeting. PAA.

- Ordanovich, D., Ramiro-Fariñas, D. (2019, December). *Spatial variations in mortality due to heat waves in Andalusia, Southern Spain.* United Nations Conference against the climate change (COP25). http://cchs.csic.es/es/article/investigadores-ipp-iegd-suman-cop25

F.2.2 Research meetings and seminars

- Ramiro-Fariñas, D., Voigt, M., Ordanovich, D., Viciana, F. *How does the effect of sociodemographic characteristics on health outcomes vary by levels of urbanicity in Spain.* IUSSP Seminar: Urban Health Transformations. Organised by the IUSSP Historical Demography Panel & The Cambridge Group for the History of Population and Social Structure. Homerton College, Cambridge, UK, 11-12 July 2017.

- Ordanovich, D. *Spatial analysis of the heat wave effects on population health in Southern Spain.* Summer School on Complex Socio-Technical Systems, IFISC, Palma de Mallorca, Spain, 4-8 September 2017.

- Ordanovich, D. *Spatial analysis of heat waves on population health in Andalusia.* Brown Bag Seminar Series of the Population and Health Research Group of the School of Geography and Sustainable Development at the University of St Andrews, UK, 17 August 2017.

- Ordanovich, D., Ramiro-Fariñas, D. *Twitter, geocoded data and demography.* DisCont and APC Workshops 2018. Nuffield College, University of Oxford, UK, 30-31 August 2018.

- Ordanovich, D., Ramiro-Fariñas, D., Billari, F., Tugores, A., Viciana, F., Ramasco, JJ. *What Were You Thinking Nine Months Ago? Using Twitter for Fertility Nowcasting Over Time and Space.* IUSSP Research Workshop on Digital Demography in the Era of Big Data, Seville, Spain, 6-7 June 2019.

F.2.3 Teaching activities and other interventions

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During the period from 09/2016 to 09/2019 Dariya Ordanovich with NIE Y4852076X was employed by **Esri Spain** as a **Senior Technical Specialist** at the **Training department.** All the activities performed over this period formed part of her **Early Stage Researcher Maria Skłodowska-Curie** development program within the framework of the H2020 **LongPop ITN project** on the *Methodologies and Data mining techniques for the analysis of Big Data based on Longitudinal Population and Epidemiological Registers.*

The official duties at Dariya's position included:

- Development of the **Web Portal for Health and Population in Spain** (http://longpop-itn.eu/esr9/).
- Elaboration of the program and contents for the pilot course entitled **Introduction to R and R-ArcGIS Bridge** taught internally and externally.
- Performing analytical and technical tasks on request.

Apart from aforementioned tasks Dariya carried out the following activities:

Public Conferences

Esri Spain national conference 2017	25/10/17
Speaker at the plenary session.	
Text mining using R-ArcGIS Bridge	
Esri Spain national conference 2018	25/10/18
Speaker at the technical session.	
Spatial analysis in ArcGIS: geostatistics and R-ArcGIS Bridge	

Teaching activities

Universitat Jaume I	1 hr	21/02/17
External training. R-ArcGIS Bridge		
Esri Spain. Development expert program	6 hr	23/02/18
Internal training. R-ArcGIS Bridge		
Esri Spain. Master GIS program	6 hr	06/03/18
Internal training. R-ArcGIS Bridge		
Esri Spain. ArcGIS: Development	12 hr	08-09/03/18
Internal training. R-ArcGIS Bridge		
Esri Spain. Master GIS program	6 hr	20/11/18
Internal training. R-ArcGIS Bridge		
Esri Spain. Development expert program	6 hr	22/02/19
Internal training. R-ArcGIS Bridge		
National Institute of Statistics of Spain	6 hr	27/02/19
External training. Spatial analysis in R & ArcGIS Bridge		
TELNET Redes Inteligentes	12 hr	12-13/03/19

Esri España Soluciones Geoespaciales, S.L.
Emilio Muñoz, 35
28037 Madrid, España
C.I.F.: B-86900057

T +34 91 559 43 75
F +34 91 010 86 65
informacion@esri.es

esri.es

Inscrita en el Registro Mercantil de la Provincia de Madrid Hoja nº M-573.864, Folio 25, Tomo 31.887 Madrid

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External training. Introduction to R, RMarkdown and Shiny.
Complutense University of Madrid 4 hr 25/06/19
External training. R-ArcGIS Bridge

Received training

ArcGIS Server Administration	15 hr	14-16/12/16
Sharing GIS content online	10 hr	12-13/12/16
ArcGIS: Introduction	15 hr	09-13/01/17
ArcGIS: Architecture	25 hr	26/02/18-02/03/18
ArcGIS: Development	25 hr	05-09/03/18

DATE: Madrid, 29/07/2019

esri España

Signature

Antonio Remirez Remirez
Service Manager Educación y Formación
ESRI España
Emilio muñoz 35 4ªPlanta
28037 Madrid España
+34915594375 Ext 3912

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 676060

CENTRO DE CIENCIAS HUMANAS Y SOCIALES
Instituto de Economía, Geografía y Demografía

Methodologies and Data mining techniques for the analysis of Big Data based on Longitudinal Population and Epidemiological Registers

LONGPOP

CERTIFICADO

A quien corresponda:

Yo, Diego Ramiro Fariñas, Coordinador del proyecto LONGPOP y Director del Instituto de Economía, Geografía y Demografía (IEGD),

CERTIFICO

Que Dariya Ordanovich, con número de pasaporte 752968889, ha participado en la preparación e implementación de las siguientes actividades de divulgación científica:

1. ***Exposición virtual para el seminario internacional de IUSSP**: "Pandemics: Reflections on the Centennial of the 1918 Spanish Influenza Virus"*, celebrado en Madrid (España) del 27 al 29 de noviembre de 2017 (https://aulaesri.maps.arcgis.com/apps/Cascade/index.html?appid=c85a0f713e934a7abb83bad0d932e377).
2. ***Décima Noche Europea de los Investigadores e Investigadoras***, del 14 de mayo al 27 de septiembre de 2019, en Madrid.

Que la participación en dichas actividades se realizó como parte del contrato de Dariya Ordanovich como investigadora en formación del proyecto LONGPOP (http://longpop-itn.eu/). Este proyecto ha recibido financiación del programa de investigación e innovación Horizonte 2020 de la Unión Europea en el marco de las redes de formación innovadoras Marie Sklodowska-Curie (acuerdo de subvención número 676060).

Y como prueba de ello, expido este certificado en Madrid, a 2 de septiembre de 2019.

Diego Ramiro Fariñas.

Coordinador de LONGPOP, Investigador Científico y Director
Instituto de Economía, Geografía y Demografía
Consejo Superior de Investigaciones Científicas (CSIC)
C/ Albasanz, 26-28, 3ª planta, módulo F, despacho 3F12 28037. Madrid, España.

C/ ALBASANZ 26-28
28037 MADRID. ESPAÑA
TEL.: 916 022 300
FAX: 916 022 971
http://www.cchs.csic.es

F.3 Awards

- Ordanovich, D., Viciana, F., Ramiro-Fariñas, D. (2018, September). *Spatial Variations in Mortality Due to Heat Waves in Southern Spain.* In British Society for Population Studies 2018 Conference. BSPS. https://www.lse.ac.uk/social-policy/Assets/Documents/bsps/Abstracts-book.pdf. Best poster award.

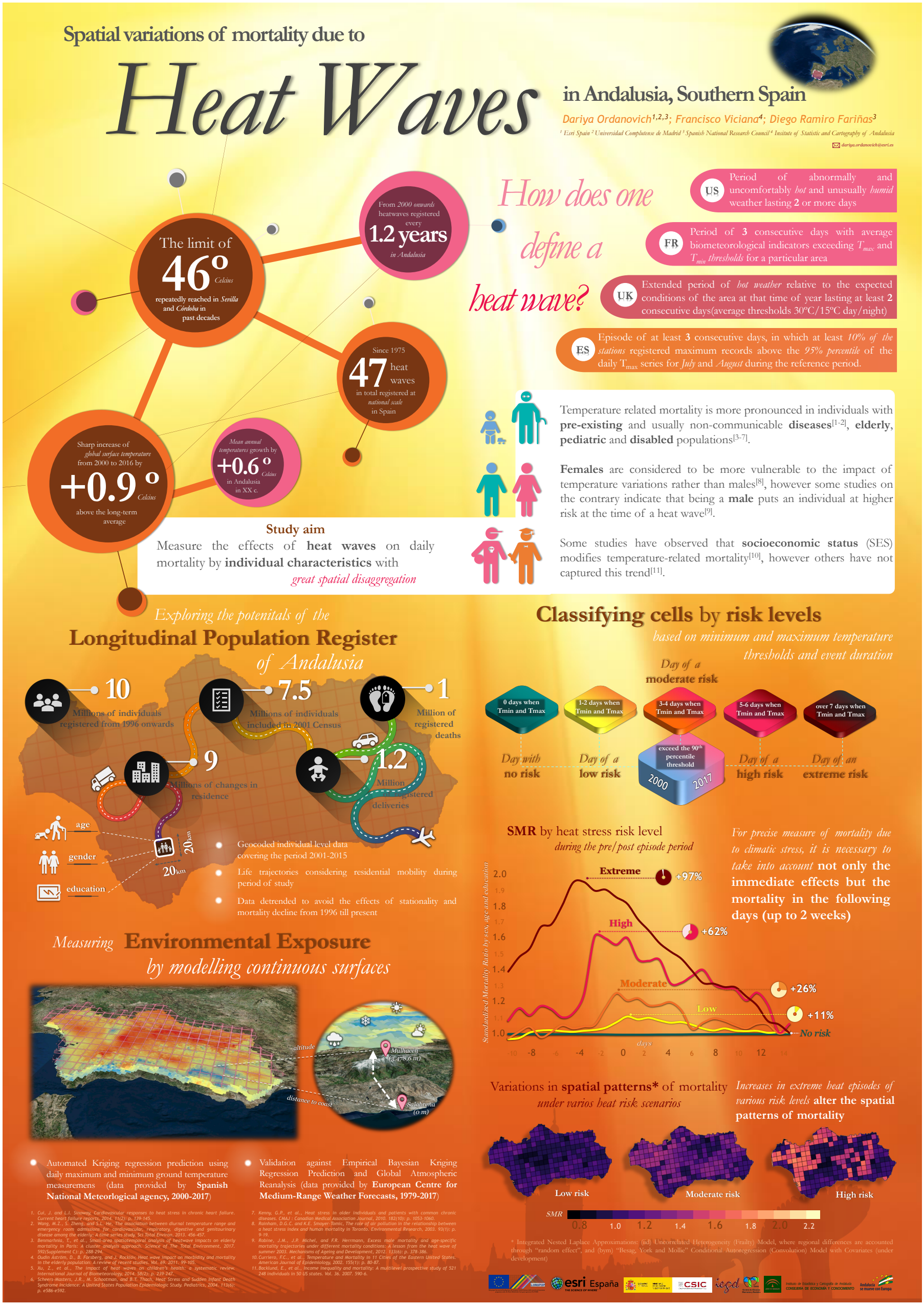

Figure F.1: Poster work. Spatial variations of mortality due to heat waves in Andalusia

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