UNIVERSITAT ROVIRA I VIRGILI

CHANGING HORIZON OF CLIMATE SCIENCE: FROM SCIENTIFIC KNOWLEDGE TOWARDS DEMAND BASED, INTEGRATED CLIMATE SERVICES

Annamária Lehoczky

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Annamária Lehoczky
Doctoral Thesis

Changing horizon of Climate Science: from scientific knowledge
towards demand based, integrated Climate Services

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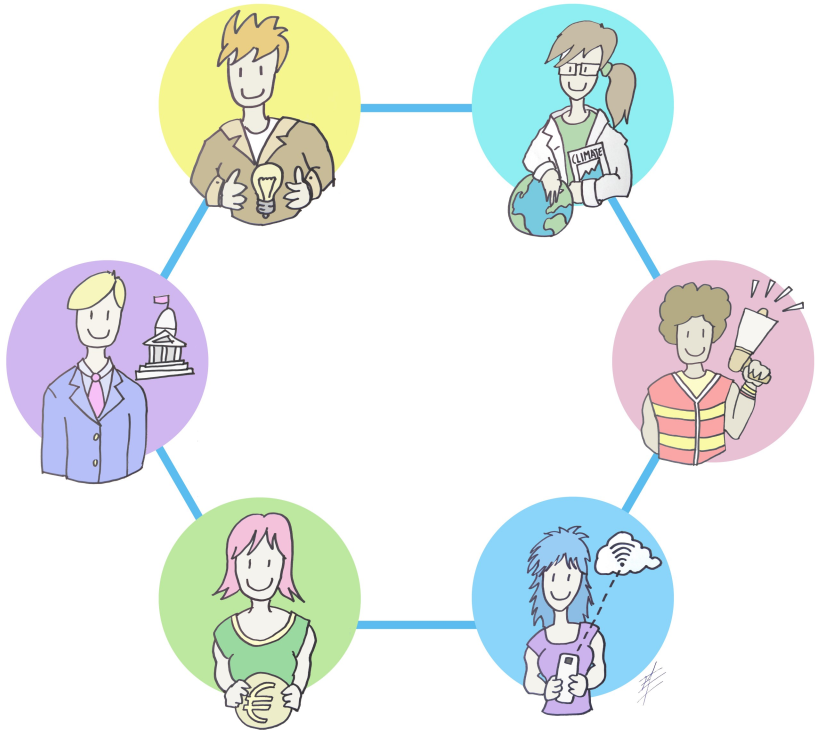

Doctoral Thesis

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Changing horizon of Climate Science: from scientific knowledge towards demand based, integrated Climate Services

Annamária Lehoczky

Doctoral thesis

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We STATE that the present study, entitled "*Changing horizon of Climate Science: from scientific knowledge towards demand based, integrated Climate Services*", presented by Annamária Lehoczky for the degree of Doctor of Philosophy with international distinction, has been carried under my supervision at the Centre for Climate Change (C3), Department of Geography, Universitat Rovira i Virgili and at the Global Change Unit, Image Processing Laboratory, Universitat de Valencia.

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I have one more reason for optimism: climate change.

–Christiana Figueres, Former Executive Secretary of UNFCCC

Abstract

Climate Services (CS) assign an additional role to Climate Science, aiming to provide different kinds of users with usable and actionable information on climate variability, climate change impacts and its related risks, opportunities and uncertainties. Thus, to bridge the gap between reliable data and their usability, CS research is highly important.

This interdisciplinary research thesis addresses the climate information distillation challenge. Its overall aim is to pave the way for the integration of regional and local climate information into CS that support climate adaptation planning and policy-making. The novelty of this thesis is that it reflects on the user-oriented approach of CS, i.e., as well as quantitative climatological analysis, it also uses qualitative social data to better understand the needs of practitioners and academics engaged in climate-related knowledge co-production.

The thesis uses various datasets, including remotely sensed land surface temperature data, ground-measured meteorological data and temperature simulations obtained from a high resolution (12.5 km) regional climate model. The recommendations are supported by practical experience.

The local scale case study offers valuable new insights into the urban heat hazard in the city of Valencia (Spain), revealing the considerable nighttime urban heat island effect along with unfavourable thermal comfort in the densely built-up urban areas. This underlines the need for climate-resilient urban planning, especially in light of the projected gradual warming trend over the entire Iberian Peninsula towards the end of the 21st century.

To explore the factors that influence the efficiency of transdisciplinary collaborations working on urban climate adaptation and planning, in-depth interviews were conducted with academics and practitioners. This thesis demonstrated that integrating different disciplines and perspectives is vital for efficient CS. An improved understanding of the needs and motives of stakeholders from science and practice communities greatly contributes to the development of CS.

Resum

Els Serveis Climàtics (SC) tenen un rol addicional en la ciència del clima, amb l'objectiu de proporcionals als diferents tipus d'usuaris informació útil y processada sobre variabilitat climàtica, els impactes i riscos del canvi climàtic, així com les oportunitats i incerteses. Per tant, per reduir la distancia entre dades fiables i la seva usabilitat, la investigació de SC és de gran importància.

Aquesta tesis d'investigació interdisciplinària aborda el desafiament de sintetitzar la informació climàtica. El seu objectiu general és facilitar la integració d'informació climàtica a escala regional dels SC per donar justificació a la planificació i formulació de polítiques d'adaptació al canvi climàtic. La novetat és què reflecteix l'enfoc orientat als usuaris dels SC, és a dir, a més de l'anàlisi climatològic quantitatiu, també utilitza dades socials qualitatives per entendre millor les necessitats dels professionals i acadèmics involucrats en la co-producció del coneixement relacionat amb el clima.

Aquesta tesis utilitza diversos conjunts de dades, incloent dades remotes de la temperatura de la superfície terrestre, dades meteorològiques mesurades en superfície i simulacions de temperatura obtingudes d'un model climàtic regional d'alta resolució (12.5km). Les recomanacions se suporten en l'experiència pràctica.

L'estudi de cas a escala local afavoreix nous resultats sobre el risc del calor urbà a la ciutat de València. Revelant un considerable efecte d'illa de calor urbana nocturna juntament amb un confort tèrmic desfavorable a les zones densament urbanitzades. Això subratlla la necessitat d'una planificació urbana resilient amb el canvi climàtic, especialment considerant la tendència d'escalfament gradual projectada per a finals del segle XXI a tota la Península Ibèrica.

Per explorar els factors que influeixen en l'eficiència de les col•laboracions transdisciplinaries en els estudis de planificació i adaptació al clima urbà, es realitzaren entrevistes amb acadèmics i professionals. Concloent que la integració de diferents disciplines i perspectives es vital per a l'eficiència dels SC. Una major compressió de les necessitats i motivacions dels actors de les comunitats científiques i professionals contribueix a millorar les prestacions dels SC.

Resumen

Los Servicios Climáticos (SC) desempeñan un rol adicional en la ciencia del clima, con el objetivo de proporcionar a los diferentes tipos de usuarios información útil sobre variabilidad climática, los impactos del cambio climático y sus riesgos, así como las oportunidades e incertidumbres. Por lo tanto, para salvar la brecha entre los datos fiables y su usabilidad, la investigación SC es de gran importancia.

El objetivo general de esta tesis de investigación interdisciplinaria es facilitar la integración de información climática a escala regional y local de los SC que apoye la planificación y formulación de políticas de adaptación al cambio climático. La novedad es que refleja el enfoque orientado al usuario del SC, es decir, además del análisis climatológico cuantitativo, también utiliza datos sociales cualitativos para entender mejor las necesidades de los profesionales y académicos involucrados en la co-producción del conocimiento relacionado con el clima.

Esta tesis utiliza varios conjuntos de datos, incluyendo datos remotos de la temperatura de la superficie terrestre, datos meteorológicos medidos en superficie y simulaciones de temperatura obtenidas de un modelo climático regional de alta resolución (12,5 km). Las recomendaciones se apoyan en la experiencia práctica.

El estudio de caso a escala local ofrece nuevos resultados sobre el riesgo del calor urbano en la ciudad de Valencia. Revelando un considerable efecto de la isla de calor urbana nocturna junto con un confort térmico desfavorable en las zonas densamente urbanizadas. Esto subraya la necesidad de una planificación urbana resiliente al cambio climático, especialmente considerando la tendencia de calentamiento gradual proyecta para finales del siglo XXI en toda la Península Ibérica.

Para explorar los factores que influyen la eficiencia de las colaboraciones transdisciplinarias en los estudios de planificación y adaptación al clima urbano, se realizaron entrevistas con académicos y profesionales. Concluyendo que la integración de diferentes disciplinas y perspectivas es vital para la eficiencia de los SC. Una mejor comprensión de las necesidades y motivaciones de los actores de las comunidades científicas y profesionales contribuye a mejorar las prestaciones de los SC.

Associated publications

Lehoczky A., Sobrino J.A., Skoković D., Aguilar E. (2017): The Urban Heat Island Effect in the City of Valencia: A Case Study for Hot Summer Days. *Urban Science* 1(1), p. 9. DOI:10.3390/urbansci1010009

Sánchez A., Amendola L., Depool T., **Lehoczky A.** (2017): Estrategia de Adaptación al Cambio Climático a Través del Desarrollo de la Ciudad Inteligente y Sostenible. XIX Congreso Internacional de Mantenimiento y Gestión de Activos, Bogotá, Colombia, 16–18 August 2017. Full article in the conference issue, 8 p.

Dominguez M.C., **Lehoczky A.**, López Á.P., Tomás V.R. (2016): BIKE GENERATION: How to improve the sustainable mobility in the city of Valencia? In Proceedings of the Innovation Festival, Frankfurt, Germany, 7–9 November 2016.

Lehoczky A., Boroneant C. (2015): Validation of a high-resolution version of the regional climate model RCA4 from the EURO-CORDEX ensemble over the Iberian Peninsula. Climate-ES 2015 International Symposium, 11–13 March 2015, Tortosa, Spain. Session 5, poster.

Other publications during the doctoral research period:

Templ B., Templ M., Filzmoser P., **Lehoczky A.**, Bakšienė E., Fleck S., Gregow, H., Hodzic S., Kalvane G., Kubin E., Palm. V., Romanovskaja D., Vucetic. V., Zust, A., Czucz B. (2017): Phenological patterns of flowering across biogeographical regions of Europe. *International Journal of Biometeorology*. 61(7), pp. 1347–1358. DOI:10.1007/s00484-017-1312-6.

Lehoczky A., Szabó B., Pongrácz R., Szentkirályi F. (2016): Testing plant phenophase as proxy: sensitivity analysis of first flowering data from the 19th century. *Applied Ecology and Environmental Research* 14(2), pp. 213–233. DOI: 10.15666/aeer/1402_213233.

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Acronyms

Acronym	Description
AEMet	Agencia Estatal de Meteorología
AMS	American Meteorological Society
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AT	Air temperature
CNRM	Full acronym: CNRM-CERFACS-CNRM-CM5. Generic Circulation Model, see description in Table 3.1
CRU	Climatic Research Unit (University of East Anglia) gridded observational dataset
CS	Climate Services
CSDI	Cold Spell Duration Indicator
DI	Discomfort Index
DJF	December-January-February (Winter)
E-OBS	European gridded observational dataset developed by EU-FP6 project ENSEMBLES, provided by the ECA&D project
EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA-Interim	Global atmospheric reanalysis dataset provided by European Centre for Medium-Range Weather Forecasts
ETCCDI	Expert Team on Climate Change Detection and Indices
EU	European Union
GCM	Generic/Global Circulation Model
GFCS	Global Framework for Climate Services
GHG	Greenhouse Gas
HadGEM2	Full acronym: MOHC-HadGEM2-ES. Generic Circulation Model, see description in Table 3.1
ICHEC	Full acronym: ICHEC-EC-EARTH. Generic Circulation Model, see description in Table 3.1
ID	Interdisciplinary
IP	Iberian Peninsula
IPCC	Intergovernmental Panel on Climate Change

Acronym	**Description**
IPSL	Full acronym: IPSL-IPSL-CM5A-MR. Generic Circulation Model, see description in Table 3.1
JJA	June-July-August (Summer)
JPI Climate	Joint Programming Initiative Connecting Climate Change Knowledge for Europe
LST	Land Surface Temperature
MAM	March-April-May (Spring)
MODIS	Moderate-resolution Imaging Spectroradiometer
MPI	Full acronym: MPI-MPI-ESM-LR. Generic Circulation Model, see description in Table 3.1
NDVI	Normalized Difference Vegetation Index
RCA4	Rossby Centre regional atmospheric model
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
SMHI	Swedish Meteorological and Hydrological Institute
SON	September-October-November (Autumn)
sUHI	Surface Urban Heat Island
TD	Transdisciplinary
Tmax	Maximum temperature
Tmin	Minimum temperature
TN10p	Cool nights
TN90p	Warm nights
TR20	Tropical nights
TX10p	Cool days
TX90p	Warm days
UHI	Urban Heat Island
UN DESA	United Nations Department of Economic and Social Affairs
UN HABITAT	United Nations Human Settlements Programme
UN SDGs	United Nations Sustainable Development Goals
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation
WSDI	Warm Spell Duration Indicator

Chapter 1

Introduction

1.1 The global challenge

More than half of the world’s population live in urban areas and rapid urban growth is predicted to continue; by 2030, 60 percent of the global population will live in cities (UN DESA, 2014). This widespread urbanisation has many consequences. Cities are key contributors to many environmental problems, such as air and water pollution, and more than 70 percent of global greenhouse gas emissions (GHG) can be traced back to cities (UN HABITAT, 2011), as can around 80 percent of the world's energy production (KPMG, 2014).

At the same time, cities are highly vulnerable to climate change impacts, due to the fact that many urbanized settlements are located in highly exposed coastal areas and riverbanks, which are prone to sea level rise, storm surges, tropical cyclones, flash floods and landslides (UNDP, 2016). Reports on climate change-related disaster impacts (e.g., IFRC, 2010; UNISDR, 2013) point out that a high proportion of the people and economic activity affected by extreme weather events is concentrated in urban areas.

According to the latest Intergovernmental Panel on Climate Change (IPCC) report, global mean temperatures are expected to increase by as much as 5.5 °C by the end of this century (IPCC, 2013b), which is, in turn, expected to increase heat risk imposed on human and natural systems around the world (IPCC, 2014b). The impacts of higher temperatures include intensification of droughts, diminished crop yields, increased evapotranspiration, increased energy consumption, direct effects on human health and increased economic losses related to all of the aforementioned (Basu, 2009; Dell, Jones and Olken, 2014; Mazdiyasni and AghaKouchak, 2015; Park, 2016). As cities can substantially increase local temperatures (IPCC, 2012), additional risk is posed on the rapidly growing urban population, having a real impact on human society.

The Paris Agreement (UNFCCC, 2015) is a major step forward in setting tangible goals to minimize anthropogenic climate change, aiming to keep the increase in average global temperature to well below 2 °C and requiring substantial reductions in global GHG emissions. Besides the GHG mitigation effort, climate adaptation action is required to prevent and minimise the impacts of climate change. The Cancun Adaptation Framework, adopted in 2010 under the UN Framework Convention on Climate Change (UNFCCC), establishes that climate change adaptation has the same level of priority as mitigation of GHG emissions (UNFCCC, 2010). The EU climate change adaptation strategy adopted in 2013 encourages countries to develop their own adaptation strategies, promotes local action towards climate-resilient cities, mainstreams adaptation in EU policies, facilitates research and information-sharing, and provides funding (European Commission, 2013).

1.2 How to make climate information actionable?

To limit climate-related economic, social and ecological impacts and damages, there is an increasing demand for easily accessible, timely, and decision-relevant scientific information (JPI Climate, 2011). According to the Climate Services Roadmap by the European Commission, Climate Services (CS) refer to the "*transformation of climate-related data—together with other relevant information—into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large*", and include "*data, information and knowledge that support adaptation, mitigation and disaster risk management*" (European Commission, 2015, p10).

Other definitions of Climate Services (AMS, 2012; Hewitt, Mason and Walland, 2012; WMO GFCS, 2014) emphasize the collaboration and engagement with users to respond to their exact needs, but they do not identify a set of priority areas and sectors (Lourenço *et al.*, 2015). In turn, Lourenço *et al.* (2015) suggest that to lead CS to flourish, "climate services need to move from science-driven and user-informed to demand-driven and science-informed practices". This means that providers need to adopt the preferred terminologies of their clients and gain a proper understanding of the regulatory and cultural systems of their users (Kirchhoff, Lemos and Kalafatis, 2015; Lourenço *et al.*, 2015). Thus, more intensive forms of knowledge exchange and collaboration across traditionally divided scientific-practice-policy communities is essential to ensure that scientific information can be used for meaningful action (Lemos and Morehouse, 2005; Vogel *et al.*, 2007; Hering *et al.*, 2014).

However, the gap between science, practice and policy-making in relation to environmental issues has been hindering climate action for a long time (Dramstad and Fjellstad, 2011; Lemos, Kirchhoff and Ramprasad, 2012; Kirchhoff, Lemos and Dessai, 2013; Faragó, 2016). Policy-makers and environmental managers often complain that they do not receive the information they need, while scientists are frustrated when their information is not being used or is misinterpreted (Vogel *et al.*, 2007). Thus, finding the way to make climate information useable and actionable, i.e. creating climatic products that have practical value so that decision-makers are able to take legal action is crucial.

Moving beyond the traditional climatological products, Goosen *et al.* (2013) pointed out that not only should primary impacts of climate change be produced, e.g., the disclosure of precipitation and temperature data trends, but also the consequences of climate change in terms of vulnerability and potential risk. These products should meet the specific needs and perceptions of municipal or provincial level spatial planners as they play a critical role in promoting robust adaptation to climatic changes (Wilson, 2006; Ford, Berrang-Ford and Paterson, 2011). Therefore, the term of Climate Adaptation Services is defined as an integrated approach supporting decision-making and spatial planning, that not only provide information for vulnerability and risk assessment, but also support the identification, evaluation and implementation of adaptation options in a multi-stakeholder setting (Goosen *et al.*, 2013).

The complexity that accompanies climate change adaptation planning and policy-making translates into a need for inter- and transdisciplinary approaches, to achieve an integrated and comprehensive vision of the issues (Blanchard and Vanderlinden, 2010). Furthermore, applied science addressing complex problems should account for different types of knowledge (beyond technical/scientific frames) to co-develop solutions in the scientific-practice-policy communities (Vogel *et al.*, 2007; Regeer and Bunders, 2009; Bruno Soares, Alexander and Dessai, 2017). Therefore, climate change adaptation planning and decisions are made within a complex web that includes local, regional, and national government, elected officials, technical and strategic consultants, sectoral agencies and associations, business people, members of the public and scientists.

1.3 Transdisciplinary collaborations for urban climate change adaptation

To address socially relevant, complex problems, such as climate change adaptation and mitigation, crossing disciplinary borders is necessary. Pursuing the demand-based and solution-oriented approaches in Climate Services requires more intensive communication and collaboration between service providers and users (Lourenço *et al.*, 2015). These collaborations should promote and facilitate opportunities for co-production of knowledge (Kirchhoff, Lemos and Dessai, 2013) that enables users to be active participants in knowledge creation with valid expertise of the particularities of their decision-making context (Vaughan and Dessai, 2014).

The integration of different types of knowledge, e.g., scientific and practical expertise via co-production is delivered by transdisciplinary (TD) approaches (Regeer and Bunders, 2009). The principles of TD methodologies include joint problem definition; creating connections between areas of specialization; searching for solutions to complex problems; knowledge integration and collaboration; participation and mutual learning; and connections between ‘science’ and its application to the ‘real world’ (Wiesmann *et al.*, 2008; Lelea *et al.*, 2014). Thus, the outcomes of TD collaborations include not only new knowledge, but also practical activities or products that help improve the problematic situation the TD project focuses on (Hirsch Hadorn *et al.*, 2008; Lelea *et al.*, 2014).

Since climate adaptation and planning requires a high level of integration between academic and practical knowledge, TD collaborations are essential to address the related complex urban issues (Hansson and Polk, 2016; Mistra Urban Futures, 2016; May and

Perry, 2017). However, TD efforts require mastery of specific competences from the collaborators (Stokols *et al.*, 2008; Larson, Landers and Begg, 2011). There are various contextual factors that influence the effectiveness of TD collaborations, they can flourish or struggle depending on the competence and attitude of team members, as well as the availability of organizational, political and financial incentives and support (NAS/NAE/IM, 2004; Stokols *et al.*, 2008; Larson, Landers and Begg, 2011; Nancarrow *et al.*, 2013). Furthermore, engaging in activities that aim towards societal problem solving and transformations, calls scientists to challenge their conventional researcher roles (Wittmayer and Schäpke, 2014).

1.4 Aims and objectives of this thesis

The research design and development of this thesis was motivated by questions such as: How does climate change affect the heat conditions of the Iberian Peninsula? How can we provide reliable, understandable and useful information to decision-makers? What does heat risk mean in a local context? How can the heat risk be reduced? How can researchers and practitioners successfully collaborate in solving climate-related urban issues? What is the role of climate science in climate action? How can this role be addressed through Climate Services?

The research project is developed with an interdisciplinary approach based on a broad literature review including climate and sustainability science, environmental management and team science. The overall aim is to pave the way for the integration of regional and local scale climate information into CS that supports climate adaptation planning and policy-making. The interdisciplinary research thesis addresses the climate information distillation challenge, i.e. how to provide the users with understandable and useful climate information. The novelty of the thesis is that it reflects on the user-oriented approach of Climate Services, i.e. besides quantitative climatological analysis it uses qualitative social data too, to better understand the needs of academics and practitioners engaged in climate-related knowledge co-production.

Regional scale information on future temperature changes over the Iberian Peninsula is produced by using climate simulations from a high-resolution regional climate model after evaluating the performance of the model. To explore the local scale heat hazard in the Spanish city of Valencia, the urban heat island effect and thermal comfort is quantified using remotely sensed data and in-situ meteorological measurements. To understand better the factors that influence TD collaborations focusing on climate-related problems, in-depth interviews are conducted with academics and practitioners involved in urban climate adaptation projects. Practical experience is also incorporated in the implications to aid the development of CS.

The hypothesis can be defined as:
Through the development and use of Climate Services along with transdisciplinary approaches urban climate adaptation and planning can be improved.

The research is split into four specific objectives:

1) Assess climate projections over the Iberian Peninsula via a high-resolution regional climate model ensemble and evaluate model performance to provide scientifically solid and easily understandable illustrations of future temperature change and its uncertainties.
2) Evaluate the intensity and spatial pattern of the urban heat island and thermal comfort over the city of Valencia to create solid foundations for urban climate change adaptation planning. Analyse the locally observed temperature extremes.
3) Analyse the factors that influence and foster transdisciplinary collaborations in urban climate adaptation projects and map the voices of stakeholders in regard to their motivations, challenges and needs.
4) Provide practical insights to facilitate the development of actionable climate information based on user-focused Climate Services research and practical experience.

Exploring the diverse needs of CS users involved in projects using climate information is identified by the Climate Services agenda (EC CS Roadmap, JPI Climate) as a research gap needing to be addressed. The objectives of thesis are in line with the activities defined as “Competences for provision of climate services” determined by the World Meteorological Organization Global Framework for Climate Services (WMO GFCS) (WMO, 2015) and with the Joint Programming Initiative “Connecting Climate Knowledge for Europe” (JPI Climate) – Strategic Research Agenda (JPI Climate, 2011).

1.5 Structure of thesis

The structure of the thesis is illustrated in Figure 1.1. This introductory chapter has outlined the motives and some key concepts for the thesis, including the general background of research (section 1.1), defining Climate Services (section 1.2), connecting transdisciplinary collaborations and Climate Services (section 1.3), as well as outlining the general research method and aims (section 1.4) that will be followed by detailed methodologies and objectives in each main chapter.

The background to research areas relevant to the thesis and conceptual frameworks are introduced in Chapter 2. After presenting Climate Services in more detail (section 2.2), literature reviews are provided on the three main topics addressed in the thesis: regional climate model projections (Section 2.3.) relevant for Chapter 3; urban heat island, thermal comfort, temperature extremes and climate adaptation (Section 2.4.) relevant for Chapter 4 and Chapter 6; and the transdisciplinary approach (Section 2.5.) relevant for Chapter 5.

There are three main analysis components in this thesis, presented in Chapters 3, 4 and 5, that constitute the core of this work. In the first component (Chapter 3) I evaluate the performance of a high spatial resolution (12.5 km) regional climate model ensemble based on simulations with the Rossby Centre model of RCA4. I describe the future changes in seasonal mean features of near surface temperature over the Iberian Peninsula and assess the uncertainties.

To analyse the impact of excessive heat on a local scale, in the second component (Chapter 4), I analyse the urban heat island effect and human comfort in the city of Valencia (Spain), during summer hot days, combining thermal remote sensing techniques and in-situ meteorological observations. Daily mean temperature, as well as warm and cold extremes are also examined from a long-term climatological perspective.

The third analysis component (Chapter 5) offers a qualitative social research based on fieldwork in Lisbon and Cascais (Portugal). This highly urbanized coastal region was chosen for this research because of the long tradition of adaptation efforts, and stakeholders' considerable expertise and experience in cross-sectoral climate adaptation and planning projects. Informant interviews were conducted to map the voices of various stakeholders and draw the key determinants that has influenced the TD collaboration focused on urban climate adaptation and planning in Portugal.

Chapter 6 is a brief summary of projects that I have participated in during the thesis development. These works provided insights into the practical use of climate information that enrich the research and help to formulate recommendations. The three related projects are market research to design a living lab (section 6.2), multi-expert team work on sustainable urban mobility and green design (section 6.3) and addressing climate risk and adaptation through the asset management of the city (section 6.4).

The thesis finishes (Chapter 7) with a summary and critical reflection alongside ideas for further work.

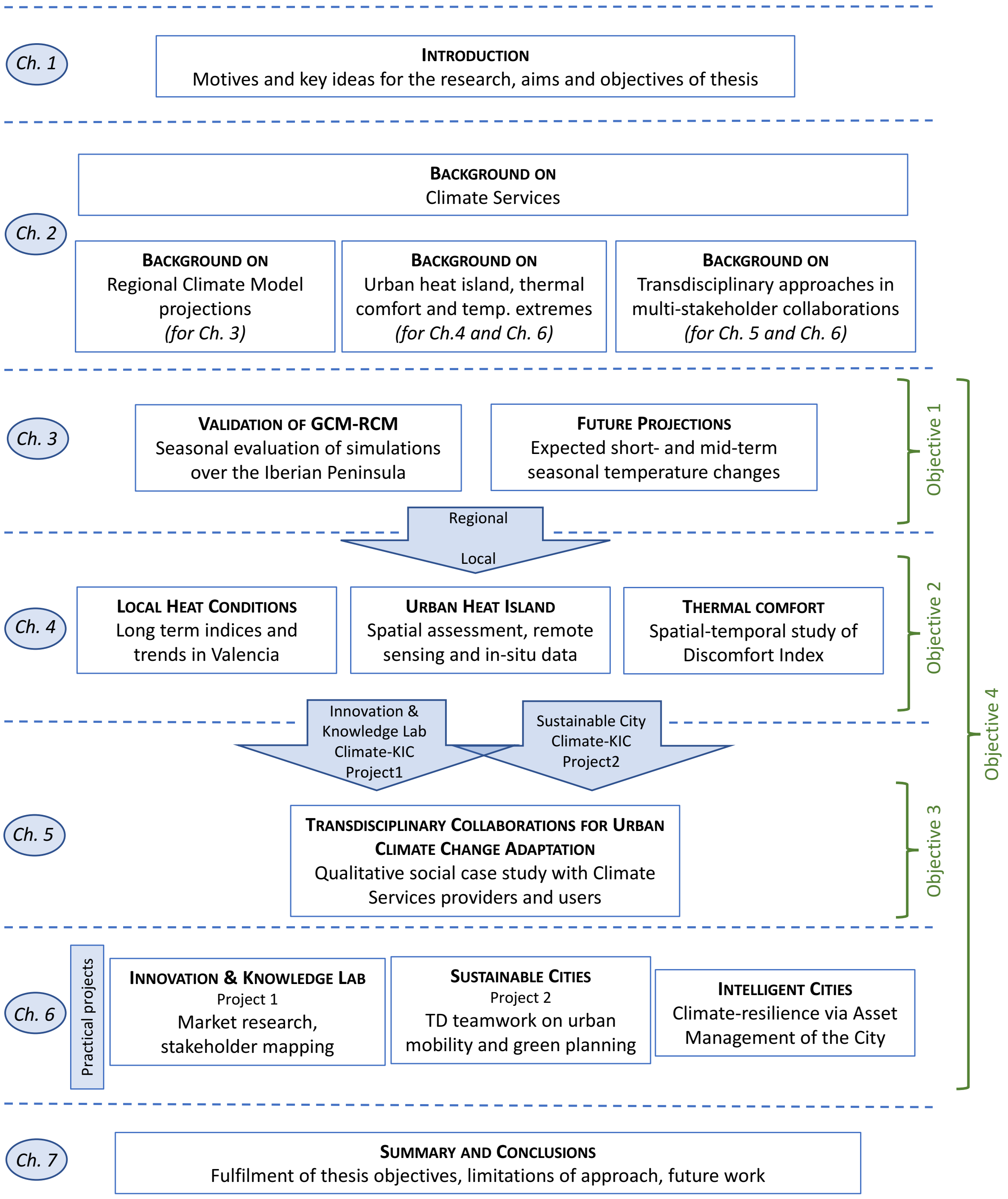


Figure 1. 1 Structure of thesis

Chapter 2

Background and conceptual frameworks

2.1 Overview

The Introduction (Chapter 1) presented the motives and objectives of thesis as well as introduced some key ideas and concepts that the thesis focuses on. Chapter 2 aims to give a detailed background to the research topics addressed in the thesis, and to connect these topics with the objectives of the CS research agenda (JPI Climate, 2011; European Commission, 2015).

Section 2.2 places CS Research into context (2.2.1) and explains how CS can support decision-making (2.2.2).

Section 2.3 presents climate models as tools to obtain climate information for the future. The subsections provide background to climate modelling in general (2.3.1), to evaluate regional climate model outputs (2.3.2), to assess uncertainty in simulations (2.3.3) and to communicate future climate model projections (2.3.4).

Section 2.4 provides background to Chapter 4 and it is formulated around the topic of excessive heat in urban areas. Section 2.4.1. describes temperature extremes, section 2.4.2 introduces the phenomenon of urban heat island and describes thermal comfort. In section

2.4.3 some concepts are clarified in relation to climate adaptation and climate risk management that lead us to the topic of Chapter 5 and provides theoretical background to the practical projects introduced in Chapter 6.

The final section in this chapter defines the conceptual framework for the social case study in Chapter 5 and explains the significance of transdisciplinary (TD) approaches in climate adaptation projects. Section 2.5.1 describes the connection between climate science and TD research, section 2.5.2 defines multi- inter- and transdisciplinary approaches, section 2.5.3 reveals the various market actors in Climate Services and section 2.5.4 describes the different researcher roles in TD collaborations. Section 2.5.5 introduces the conceptual framework of factors influencing the effectiveness of TD collaborations that forms the spine of the social study.

2.2 Climate Services

2.2.1 The need for Climate Services Research

Climate Services (CS) assign an additional role to climate science, aiming to develop, translate and customize climate information to the various user needs, including knowledge for understanding the climate, climate change and its impacts, as well as guidance in its use to researchers and to decision-makers in policy and business (European Commission, 2015). The demand-driven and solution-oriented Climate Services provide the stakeholders with usable and actionable information on climate change related risks, opportunities and uncertainties as well. These stakeholders include academics, practitioners—e.g. NGOs, decision-makers in enterprises and administrative bodies, policy makers from various levels (transnational, national, regional and local)—as well as citizens (JPI Climate, 2011; European Commission, 2015).

Depending on the target sector the climate information requirements may differ significantly. For this reason, user oriented market research is indispensable in order to identify the different user needs as well as investigation is needed to explore good practices and shortcomings of academic information distillation. As Street (2016) suggests we need to understand better the existing and potential demand (i.e. market potential), but also need to discover why the market is relatively unknown and fragmented at present.

Using different perspectives and disciplines CS research addresses research gaps that exist between the diverse needs of user communities and climate system science (European Commission, 2015). Based on the solution-oriented approach of CS strategies users should contribute to the development of climate products via collaborations, co-development and feedback loops. The use of transdisciplinary approaches such as knowledge co-production (see section 2.5.1) is critical when delivering CS research and innovation (Kirchhoff, Lemos and Dessai, 2013; Street, 2016).

Figure 2.1 illustrates Climate Services described as the bridge between data and users by the EC Roadmap. The "user community" of Climate Services represent a wide range of organisations (public, private and civil society) and actors (e.g. end-users, intermediary organisations) that functions with very different institutional settings and information requirements to support their activities (Bruno Soares, Alexander and Dessai, 2017). The provision of CS can be pursued by various actors such as National Meteorological and Hydrological Services, private consultancies, research institutes, and even in-house development within organisations (European Commission, 2015). The chain of information supply can include intermediary organisation (or purveyors) that link information producers and end-users or other purveyors (Vaughan and Dessai, 2014; Kirchhoff, Lemos and Kalafatis, 2015).

There are a couple of reports that aims to map the Climate Services provider landscape, and the climate information and tools that they produced. For example Máñez, Zölch and Cortekar (2014) provides a German case study by the Climate Service Centre combining theoretical and empirical results. Banos de Guisasola (2014) reports about the Italian case study of CS providers and Göransson and Rummukainen (2014) summarizes results from the Netherlands and Sweden.

The main European initiatives that foster the development of CS are for example the Horizon2020 SC5 Actions, the Joint Programming Initiative (JPI) on Connecting Climate Knowledge for Europe (JPI Climate), the European Copernicus Climate Change Service, the European Research Area for Climate Services (ERA4CS), the European Institute of Innovation and Technology – Knowledge and Innovation Communities (EIT/Climate-KIC), and at a global level the World Meteorological Organisation's Global Framework for Climate Services (WMO GFCS).

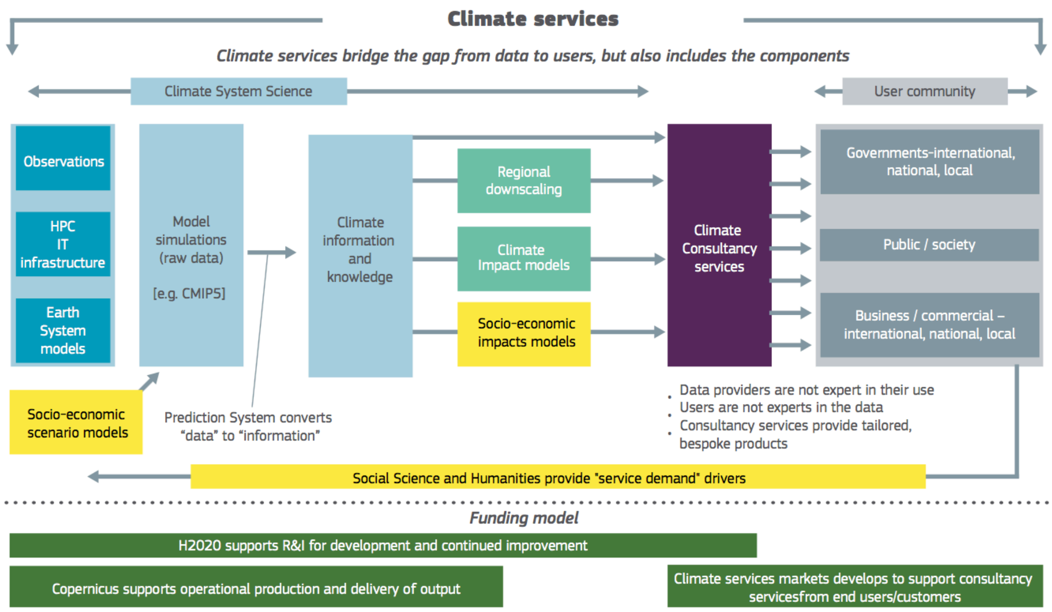


Figure 2. 1 The essence of Climate Services adopted from EC Roadmap for Climate Services (European Commission, 2015).

The JPI is a European Joint Programming Initiative of EU Climate aiming to develop and coordinate a pan-European research programming platform to provide useful Climate Services for transnational and national climate strategies as well as contributions to the UNFCCC and the UN Sustainable Development Goals (UN SDGs, 2015). This thesis places Climate Services Research into context through the JPI Climate Strategic Research Agenda (JPI Climate, 2011).

There are only few studies on the specific climate information needs of users, e.g. Turnpenny *et al.* (2004) addressed the needs of UK organisations regarding information from integrated assessments of climate change and Dessai and Bruno Soares (2015) summarised the sector specific user needs regarding seasonal to decadal climate predictions across Europe in the framework of the EUPORIAS project. A recent study by Bruno Soares, Alexander and Dessai (2017) provide a synoptic overview of the sectoral use of climate information in Europe based on a comprehensive online survey and interviews with (potential) users from sectors including agriculture, forestry, energy, water, tourism, insurance, health, emergency services and transport sectors.

According to their study (Bruno Soares, Alexander and Dessai, 2017), 37 % and 23 % of the sampled organisations stated that current weather and climate information is either not useful or fails to suit their needs. This suggests that questions need to be addressed urgently on how to tailor this information to the user requirements. Furthermore, 26 % cited a lack of in-house expertise suggesting that either there should be some form of organisational/institutional capacity building to ensure appropriate resources are in place, or information needs to be provided in a way that is compatible with in-house systems (Bruno Soares, Alexander and Dessai, 2017). Another interesting insight from this study is that 67 % of survey respondents needed information to be presented in a way that helps inform dichotomous (yes/no) decision-making.

2.2.2 Climate Services as decision-support

Besides improving the scientific expertise on climate variability, risks and adaptation options, CS aims to provide relevant knowledge to decision-making on safety and major investments in climate-vulnerable sectors. According to the JPI Climate Strategic Research Agenda (JPI Climate, 2011), in order support decision-making CS research should focus on (i) the development and deployment of CS (including data accessibility and commercial versus non-commercial approaches) (ii) communication of climate knowledge to users (including understanding users' needs, developing proper tools and communicating uncertainty), and (iii) improving the interface between climate research and its application (i.e., improving science-society interfaces and knowledge exchange) (Fig. 2.2).

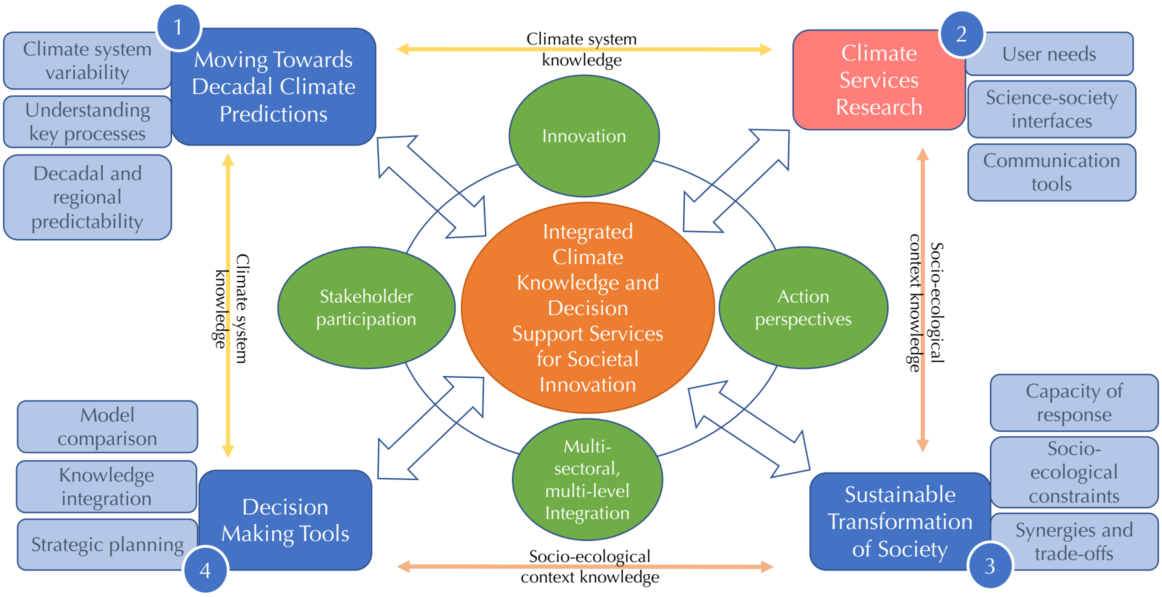


Figure 2. 2 The JPI Climate Strategic Research Agenda. The thesis delivers Climate Services Research (module 2) that connects climate system knowledge and socio-ecological context knowledge. (Adapted from: http://www.jpi-climate.eu/)

These science-society interfaces (or science-practice-policy interfaces) are defined as a "complex terrain that it is best described as a multi-level system of governance and knowledge production among a range of actors engaged in understanding and managing environment–society interactions" (Vogel *et al.*, 2007, p351). They play an important role in connecting scientific insights with the demands of policy makers and other stakeholders from local to international levels, leading to more effective policies (Cash *et al.*, 2003).

A climate adaptation decision support tool was developed by Goosen *et al.* (2013) aiming at bridging the gap between the sources of primary climate information (e.g., the disclosure of precipitation and temperature data) and the local spatial planning level. They introduced the term Climate Adaptation Services (CAS) that not only support vulnerability assessments but include the design and appraisal of adaptation options (Goosen *et al.*, 2013; Masselink *et al.*, 2017).

The CAS approach is a stepwise elaboration of climate maps through assessing primary, secondary and tertiary impacts of climate change. The approach by Goosen *et al.* (2013) operationalises the different steps within the vulnerability assessment framework by Füssel and Klein (2006) to produce policy-relevant indicators that support the design of adaptation strategies. In Figure 2.3 the CAS approach is presented that I combined with the climate risk concept by Carter *et al.* (2015), explained in detail in section 2.4.3.

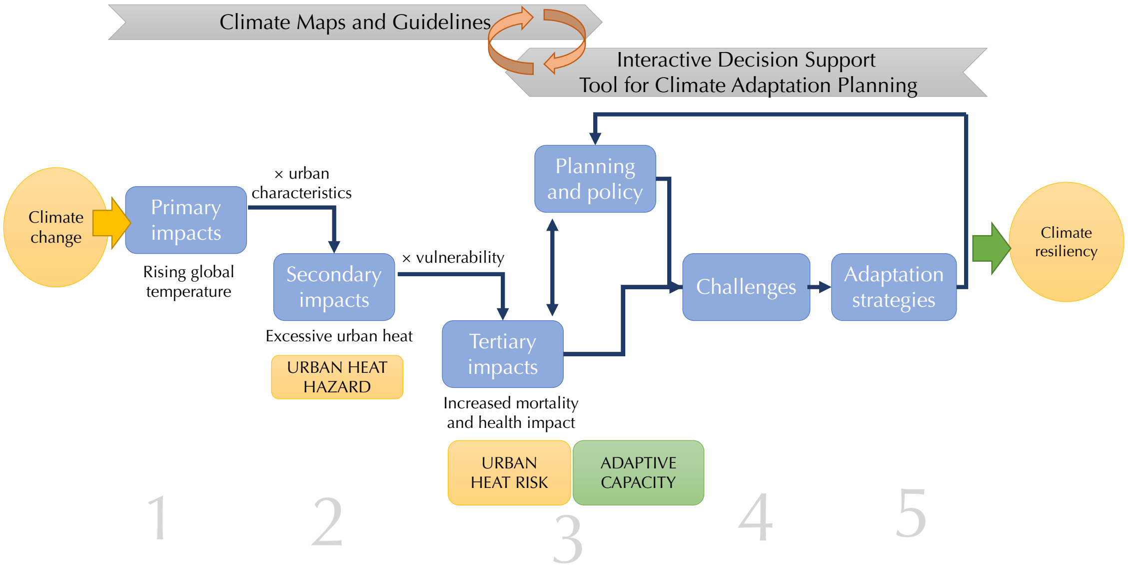


Figure 2. 3 Urban Climate Adaptation Services addressing heat related risk based on the operational stepwise elaboration of the vulnerability assessment framework by Goosen et al., (2013), Füssel and Klein (2006) and the climate risk concept by Carter et al. (2015).

Step 1 assesses and discloses the primary impacts of climate change through downscaling of climate scenarios that can cover for example mean temperature or temperature extremes. Step 2 performs impact modelling (and/or further calculations) to determine secondary impacts such as excessive urban heat or strong nighttime urban heat island. Step 3 identifies and visualise climate change vulnerabilities linked to socio-economic (tertiary) impacts according to the needs of spatial planners. For example, health impacts or thermal discomfort can be presented. Step 4 is the assessment of challenges that happens through interactive design workshops with spatial planners, policy makers and researchers to evaluate vulnerability, adaptive capacity and identify policy challenges. Step 5 includes the identification and integration of adaptation strategies.

The steps followed in the thesis chapter by chapter is in synchrony with the CAS approach. In Chapter 3, I provide maps of "primary impacts" (temperature projections and uncertainties) (Step 1) and in Chapter 4, I disclose information of "secondary and tertiary impacts" by mapping the urban heat island (Step 2) and thermal discomfort (Step 3) in the city of Valencia. Finally, in Chapter 5, I discuss some aspects of the challenges of adaptation planning and policy making (Step 4) by highlighting the different perspectives of stakeholders involved in such projects. Further insights to the concepts of vulnerability, adaptive capacity, climate risk and climate resiliency can be found in section 2.4.3.

2.3 Regional climate model projections

As explained in Chapter 1 and in section 2.2, there is an increasing demand for practical information about climate change and its impact on different sectors in different geographical regions. The users, including policy-making communities, have long sought reliable regional- and local-scale projections to provide a solid basis for guiding response options (Giorgi, Jones and Asrar, 2009). Traditionally, most of the general knowledge on climate and weather impacts was based on earlier experienced events, weather observations, forecasts and reanalyses of historical data, nonetheless, in the last decades future climate projections have become increasingly important to all sectors dealing with the impacts of climate change (Persson *et al.*, 2007). The exploitation of the vast amount of data derived from the climate models should be focused to transform them into Climate Services, meaning by this to make these data relevant for a wide range of users.

Communicating the expected climatic changes and the uncertainties of projections is a challenging task. In the following subsections, after giving a general overview on climate modelling (section 2.3.1) and model performance (section 2.3.2), I address the different sources of uncertainty in climate simulations (section 2.3.3) and discuss the interpretation of future projections and the related uncertainties (section 2.3.4).

2.3.1 Climate modelling

Since the beginning of climate modelling in the 1960s a range of varying complexity of models have been developed, from simple energy-balance models to 3-dimensional coupled global models (Edwards, 2011). On a global scale GCMs (general circulation models or global climate models) are used to describe the atmosphere, land surface, sea, lakes and ice, as well as the atmosphere-ocean interactions and some aspects of the biosphere. To achieve a higher spatial resolution over a specific region regional climate models (RCMs) are applied to downscale the results from the GCMs. As the calculation of meteorological and hydrological parameters over a global grid requires a lot of computing capacity, the GCMs operate on a relatively coarse horizontal resolution (100–300 km), while RCMs run on a finer grid placed over a smaller area (e.g., Europe), forced by the GCM that provides boundary conditions for the regional scale simulation. The RCM's finer resolution (10–50 km) allows for a better description of local topography, land-sea distribution or vegetation, and a simulation of regional-scale features in the atmosphere (Strandberg *et al*., 2014).

RCM simulations are essential for various impact studies, such as hydrological (Hay and Clark, 2003; Andréasson *et al.*, 2004; Wood *et al.*, 2004; Beldring *et al.*, 2008), ecological (on ecosystem productivity: Morales *et al.* (2007)) and health—e.g., on malaria transmission: Paaijmans *et al.* (2014), on mortality and heat waves: Lowe *et al.* (2015)—research. Moreover, they provide a reliable base for climate vulnerability assessments (e.g., Sekulić *et al.*, 2012; Kane *et al.,* 2013), climate risk management (e.g., Andersson-Sköld *et al.*, 2015), and adaptation strategies, e.g. sustainable way of urban planning based on RCM projections (e.g., Andersson-Sköld *et al.*, 2014).

The connection between climate models and Climate Services can be illustrated with the Swedish example (Persson *et al.*, 2007; Kjellström *et al.*, 2016). In some sectors there is a high awareness that specific weather conditions may play a major role in the present climate, but they have a rather limited knowledge regarding possible impacts of future climate change (Rummukainen *et al.*, 2005 via Persson *et al.*, 2007). Thus, co-operation was facilitated with a wide range of authorities, regional governments and communities as well as with representatives from trade and industry, scientific institutions and organisations across the Swedish society to discuss what information was needed by the stakeholder groups and how this could be provided (Persson *et al.*, 2007).

As a result of this long experience of collaborating with a wide range of users, the Swedish Meteorological and Hydrological Institute (SMHI) provides a useful example of building Climate Services centred on regional climate model results, presented by Kjellström *et al.* (2016). They confirmed that involving the users in the development of the climate service products has been effective as the service is widely used and is an important source of information for work on climate adaptation in Sweden. Thus, learning from the good practice they shared, I applied their methodology in illustrating and presenting the climate projection results, described in detail in section 2.3.3.

2.3.2 Evaluating the climate models

Evaluating the ability of a climate model to simulate the mean climate, and the slow, externally forced change in that mean state has been a key topic of climate research for decades (IPCC, 2013b). A model's ability to simulate climate variability is central to achieving skill in climate prediction, hence, in-depth comparisons of simulations against observations is indispensable. According to the Fifth Assessment Report (AR5) improvements in climate models since the IPCC Fourth Assessment Report (AR4) are evident in simulations of various components and phenomena of the climate system, e.g., continental-scale surface temperature patterns, large-scale precipitation, atmospheric chemistry and aerosols, the El Niño-Southern Oscillation. Climate models reproduce—to a reasonable extent—the observed multi-decadal temperature trends, including the cooling immediately following large volcanic eruptions and the more rapid warming since the mid-20th century (IPCC, 2013b).

To obtain climate variability and climate change information on a finer scale nested high-resolution regional climate models (Giorgi and Mearns, 1999) are commonly used. There are numerous studies of regional model performance over Europe (e.g., Sanchez *et al.*, 2009; Lorenz and Jacob, 2010; Vautard *et al.*, 2013; Jacob *et al.*, 2014) and over the Mediterranean region (e.g., Díez *et al.*, 2005, 2011; Dasari *et al.*, 2014). Evaluations of individual regional climate models, e.g. Jones *et al.* (2004), Bergant, Belda and Halenka (2007), Samuelsson *et al.* (2011), Torma *et al.* (2011) focus on the model performance over a chosen domain to represent the regional scale climate features.

A joint evaluation of RCMs at European scale was carried out by Kotlarski *et al.* (2014), in which the RCA4 model (Rossby Centre regional climate model, subject to present study) was also assessed. They compared the skills of 7 different RCMs based on performance metrics calculated from spatial mean values over 8 subdomains of the European continent —one of them was the Iberian Peninsula (IP). The RCA4 had good results in comparison to other RCMs over the IP, however, no detailed spatial evaluation of the fine-resolution version (12.5 km) of RCA4 was addressed. Thus, in order to gain a comprehensive view on the uncertainties in RCA4 temperature simulations over the IP an in-depth comparison of temperature simulations against observations is performed (Chapter 3).

2.3.3 Uncertainty

There are three main sources of uncertainty in future climate projections: a) the natural variability of climate; b) uncertainties in climate model parameters and structure; and c) uncertainties in the projections of future greenhouse gas emissions (IPCC, 2012). Each specific uncertainty is handled similarly by performing several simulations in targeted experiments. Projections have historically been conditioned upon ‘‘scenarios’’ of greenhouse gas emissions, each associated with a particular ‘‘storyline’’ of global economic and societal development during the twenty-first century (Nakicenovic and Swart, 2000; Northrop and Chandler, 2014), although recently these scenarios have been replaced by a set of representative concentration pathways (RCPs) (Moss *et al.*, 2010).

The RCPs or radiation scenarios are based on assumptions about how the greenhouse effect will increase in the future, depending on the course of greenhouse gas emissions throughout this century (Moss *et al.*, 2010). They are identified by their approximate total radiative forcing (W/m^2) in year 2100 relative to 1750: 2.6 W/m^2 for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0, and 8.5 W/m^2 for RCP8.5 (IPCC, 2013b). The RCPs can thus represent a range of 21st century climate policies, in contrast to the no-climate policy of the Special Report on Emissions Scenarios (SRES) used in the Third and the Fourth Assessment Report (IPCC, 2001, 2007). In case of the RCP2.6 (mitigation scenario) the radiative forcing peaks and declines before 2100, for RCP4.5 it stabilizes by the end of century, while for RCP6.0 and RCP8.5 radiative forcing does not peak by year 2100 (Moss *et al.*, 2010). In present study, two different RCP scenarios are used, one stabilization scenario (RCP4.5) and the high-end scenario (RCP8.5).

For the next 2–3 decades, regional temperature projections for differing scenarios do not strongly diverge, but uncertainty in the sign of change is relatively large over this time frame because climate change signals are expected to be relatively small compared to natural climate variability (IPCC, 2012). Towards the end of century, the uncertainty originating from the differing scenarios is growing while the fraction related with climate variability is decreasing. In Figure 2.4 green regions represent scenario uncertainty, blue regions correspond to model uncertainty, and orange regions to the internal variability component. As Hawkins and Sutton (2009) explained, with the reduction of the size of region, the relative importance of internal variability in the uncertainty increases, and scenario uncertainty only becomes important at multi-decadal lead times.

Earlier studies have shown that a large fraction of the uncertainties in regional climate change simulations is connected to the GCM that is used for driving the regional climate model (e.g., Christensen *et al.*, 2007; Hawkins and Sutton, 2009). Indeed, this uncertainty depends both on model formulation and internal variability since different RCMs can respond differently to the forcing boundary conditions by the GCM and the course of unforced internal variability in specific model simulations differs (Kjellström *et al.*, 2011). These uncertainties can be characterized by using multiple models, forcing scenarios and runs. The different sources of uncertainties and their relative role in different temporal and spatial contexts are discussed in detail by Hawkins and Sutton (2009).

An ensemble is a collection of estimates of the future climate (combination of a radiation scenario, a global climate model, a regional climate model and the modelled time period) where the individual estimates (i.e., members) are different from each other. An ensemble can be used to illustrate uncertainties on the regional scale or to derive probabilistic climate change information in a region (Kjellström *et al.*, 2011). An ensemble gives a good overview of the spread of the difference between the members, and highlights some of the uncertainties associated with simulating the future climate, thus it is frequently used as a tool to indicate the robustness of the results (e.g., *SMHI website*). If many different climate runs give similar results, then the results are relatively more robust than if they pointed in different directions. Depending on the type of ensemble, the significance of the choice of climate models (multi-model ensembles) and the dependence on initial conditions (perturbed physical ensembles) can be studied (Knutti, 2010).

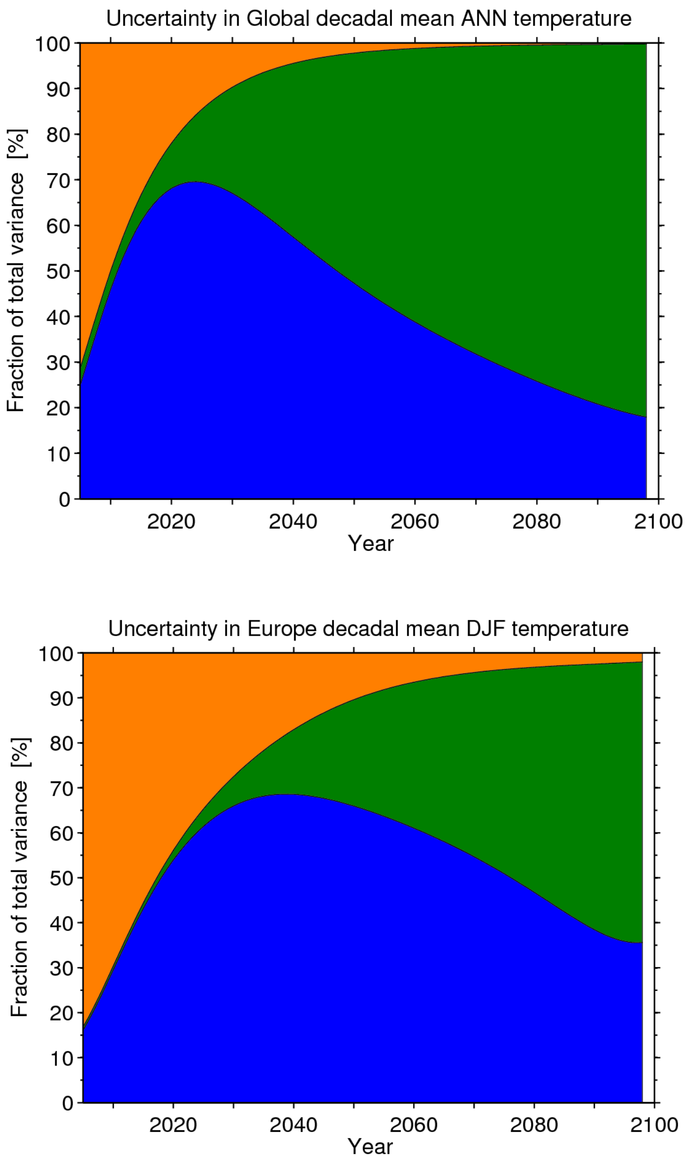


Figure 2. 4 Sources of uncertainty in global decadal mean annual (top) and European decadal mean winter (bottom) temperature projections, expressed as a fraction of the total variance. Source: Climate Lab Book (https://www.climate-lab-book.ac.uk/2013/sources-of-uncertainty/) Credit: Ed Hawkins (accessed 6 September 2017)

In different applications, the use of an ensemble has been shown to provide better estimations than those coming from a single model (e.g., Doblas-Reyes, Pavan and Stephenson, 2003; Thomson *et al.*, 2006). Using a 16-member ensemble of RCM simulations with the previous version of the Rossby Centre model (RCA3) over Europe, Kjellström *et al.* (2011) found that the ensemble mean for temperature is generally better than the individual simulations conforming it. These evidences suggest that even adding a model below the state-of-the-art can improve a future projection if the individual models tend to be overconfident (Weigel, Liniger and Appenzeller, 2008). However, Knutti (2010) warns, that ensemble means should be assessed carefully, because usually the models are not completely independent (as several institutions have contributed to a set of two or three models by sharing expertise, parts of the code and datasets), that is, parts of model biases are similar in some or all models (Tebaldi and Knutti, 2007; Knutti *et al.*, 2010). Furthermore, averaging models leads to unwanted effects like smoothing of spatially heterogeneous patterns (Knutti *et al.*, 2010).

To further reduce uncertainties some studies proposed to down-weight or eliminate some “bad” climate models, recalibrate projections or estimate uncertainties based on metrics of model skill (e.g., Giorgi and Mearns, 2003; Tebaldi *et al.*, 2005; Perkins, Pitman and Sisson, 2009). Nevertheless, climate projections are inherently uncertain, and part of uncertainty in relation to variability is irreducible (Hawkins and Sutton, 2009), and could, in fact, further increase due to added complexity of models (Knutti, 2010). Thus, there is a need for decisions and decision-support tools that are robust against alternative future outcomes (Dessai *et al.*, 2009; Knutti, 2010).

In order to help policy making, the IPCC established a specific language to communicate uncertainty. Here I clarify those terms because I will use them later to present the state-of-art on observed climatic changes and future climate projections as a background to the thesis research. The following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence. Furthermore, the following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99–100 % probability, very likely 90–100 %, likely 66–100 %, about as likely as not 33–66 %, unlikely 0–33 %, very unlikely 0–10 %, exceptionally unlikely 0–1 %. Additional terms (extremely likely: 95–100 %, more likely than not > 50–100 %, and extremely unlikely 0–5 %) may also be used when appropriate (IPCC, 2013a)

2.3.4 Assessing future projections

The time periods used for analysing climatological changes differ much throughout the literature. Traditionally, current climate (better said recent past climate) is defined based on the reference period 1961–1990, and observations are compared to the mean value of this reference period to measure how they differ. WMO defined this period as the Standard Reference Period for Climate Change studies, for the sake of comparability. But it is necessary to point out that since the climate has been changing rapidly in the last decades, the period 1961–1990 is not fully representative for what we consider to be the current climate (*SMHI website*). Hence, more recent reference periods have started to be used, and many projects are now working with the years 1971–2000—especially in terms of climate projections (*SMHI website*).

I followed the routine that is the most commonly used in the specific fields of the research questions addressed in the thesis in order to obtain comparable results to the literature. Thus, the mid-term (2041–2070) and long-term (2071–2100) climate projections are compared to the 1971–2000 reference period (Chapter 3) and the temperature indices of observations in Valencia are calculated based on the 1961–1990 reference period (Chapter 4).

All climate models produce some systematic errors (biases) that affect both mean climate and climate variability (Persson *et al.*, 2007). By calculating the difference between the mean climatologies of the future period and the current period there is no need for bias correction, since by subtracting the reference run from the future run the structural error of models is eliminated (Szépszó *et al.*, 2014). In this case we assume that the model bias is stationary in time. This approach is widely used when assessing future changes of climate variables on a monthly, seasonal or yearly scale (e.g., Krüzselyi *et al.*, 2011; Önol *et al.*, 2014). However, when one deals with daily data and/or indices associated with threshold values, bias correction is recommended as the frequency distribution of daily observations and model outputs might be very different (Dosio, 2016).

When assessing future projections, rather than speaking generally about ‘‘uncertainty”, it is more useful for communication with the wider community outside of climate sciences to discuss ‘‘spread” and ‘‘robustness” of climate projections under a given scenario (Kjellström *et al.*, 2016). Moreover, presenting the calculated change in the mean of a given climate variable (e.g., temperature) between its future and current state, provides the user with the direct information of expected changes. The representation of climatic changes in the nearest decades (2011–2040), in the middle of the century (2041–2070) and at the end of the century (2071–2100) all reflecting different time horizons with different interest to different users depending on their respective planning horizon (Kjellström *et al.*, 2016).

The choice of maps that are the most informative to be displayed in the Swedish web application has been decided upon dialogue with the users as described by Kjellström *et al.* (2016). In the service site of SMHI, data are presented both as ensemble means and in terms of spread and robustness. The spread is given as the standard deviation calculated from the different runs, as well as, maps disclose how many of the ensemble members show changes in the same direction (defined as "robustness criterion"). Assessing all this information together, the main direction and amplitude of climate change as well as the spread around the central value can be seen, and an indication of the robustness of the results is also provided (Kjellström *et al.*, 2016). Furthermore, by displaying results separately for each scenario, users of climate information can compare between what ‘‘business-as-usual", ‘‘some reduction in emissions" or ‘‘stronger reduction in emissions" would imply for the regional climate change signal (Kjellström *et al.*, 2016).

2.4 Excessive urban heat as hazard

This chapter provides background to Chapter 4. In section 2.4.1 temperature extremes are described in terms of defining indicators, observations and projections. Section 2.4.2 introduces the phenomenon of UHI, and describes different measures to characterize thermal comfort. In section 2.4.3 some concepts are clarified in relation to climate adaptation and climate risk management.

In heat risk assessments, the excessive urban heat is identified as hazard (i.e., a factor that may cause risk) to the vulnerable segments of the urban population (e.g., Tomlinson *et al.*, 2011; Buscail, Upegui and Viel, 2012; Dong *et al.*, 2014). Excessive heat negatively influences not only human health (Patz *et al.*, 2005)—including increasing mortality rates due to heat stress (Zanobetti and Schwartz, 2008; Nastos and Matzarakis, 2012; Chung *et al.*, 2015; Mazdiyasni *et al.*, 2017), more frequent insomnia events during hot nights (Vineis, 2010)—but it has an impact on the labour productivity (Pérez-Alonso *et al.*, 2011; Mazon, 2014; Zander *et al.*, 2015) and the urban metabolism (Kennedy, Pincetl and

Bunje, 2011; van Timmeren, 2014) and built environment (Wilby, 2007) as well.

In terms of impacts on health the projections by Fischer and Schär (2010) indicate that the harmful effects of excessive heat (e.g., heat waves) are much more severe for low-altitude river basins in Southern Europe and for the Mediterranean coasts, and the frequency of dangerous heat conditions also increases significantly faster and more strongly in these regions—affecting many densely populated urban areas. As evidence suggests (Kenney, DeGroot and Alexander Holowatz, 2004; Lin *et al.*, 2015), there are upper limits to human adaptation to temperature. It is, therefore, important to measure the consequences of increased temperature, and provide precise information to urban planners to reduce heat risk in the city (Blumberg, 2014; Andersson-Sköld *et al.*, 2015; EEA, 2017).

As urban heat islands (UHI) pose an additional risk to urban inhabitants (IPCC, 2012), quantifying the extent and intensity of UHI as well as describing the spatial pattern of thermal discomfort in the city is important. According to the Climate Adaptation Services approach introduced in section 2.2.2 (Fig. 2.3), producing “secondary and tertiary impacts” maps, such as the UHI and thermal discomfort in the city, can support the design of adaptation strategies. In light of increasing global temperatures, in Chapter 4 I investigate the local scale observed changes in mean and extreme temperatures that provides context to the spatial studies of urban heat hazard.

2.4.1 Discussing temperature extremes through indices, observations and projections

An extreme (weather or climate) event is defined as “the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable” in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) by IPCC (IPCC, 2012). To enable global analysis of extremes a set of climate indices has been developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) in the framework of WMO WCRP project CLIVAR (Peterson *et al.*, 2001; Peterson, 2005).

The ETCCDI climate indices of temperature are based on daily values, and they are used worldwide by research groups to detect and attribute of changes in climate extremes

(ETCCDI; Peterson and Manton, 2008). Some of them are based on fixed thresholds that are of relevance to particular applications, e.g. health impact studies—in these cases the thresholds are same for any station. Other indices are based on thresholds that vary from location to location, typically defined as a percentile of the relevant data series (Peterson, 2005). The advantage of using these indices is that the results for different regions are comparable across the globe (ETCCDI; Karl, Nicholls and Ghazi, 1999), especially for those indices that use percentiles as thresholds instead of absolute values.

Regarding heat waves/warm spells there is a variety of indices in the literature, differing from each other in terms of which aspect of the extreme event it measures (e.g., frequency, persistence, intensity). Orlowsky and Seneviratne (2012) showed that the magnitude of changes in heat wave length were highly dependent on the choice of index used for the assessment of heat wave and warm spell duration. This dependence is due to the large geographical variations in the variability of daily temperature (Alexander *et al.*, 2006). Perkins and Alexander (2013) also highlighted the ambiguity and inconsistency of heat wave definitions and measurements by comparing an extensive set of indices employed in the literature. Based on their results, they advocate the use of percentile-based calculations, so long as the percentile is not set too low or too high (Perkins and Alexander, 2013).

Based on the evidences gathered by the SREX (IPCC, 2012), it is *very likely* that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights, at the global scale, and it is *likely* that these changes have also occurred at European scale (Kiktev *et al.*, 2003; Klein Tank and Können, 2003; Alexander *et al.*, 2006). The IPCC states with *high confidence* that there has been (*likely)* increase in warm days and warm nights and (*likely)* decrease in cold days and cold nights in most of Southern Europe and the Mediterranean region (Bartolini *et al.*, 2008; Kuglitsch *et al.*, 2010; Hirschi *et al.*, 2011). The *likely* strongest and most significant trends were detected in southern France and the Iberian Peninsula (Alexander *et al.*, 2006; Brunet *et al.*, 2007; Della-Marta *et al.*, 2007a, b; Rodríguez-Puebla *et al.*, 2010).

Furthermore, there is *medium confidence* that the length or number of warm spells or heat waves has increased globally since the middle of the 20th century (IPCC, 2012). An overall consistent positive trend of Warm Spell Duration Index was detected across

Europe (Alexander *et al.*, 2006). The IPCC states with *high confidence*, that there has been *likely* overall increase in heat waves in summer (JJA) in Southern Europe and the Mediterranean region. Della-Marta *et al.* (2007a) detected significant increase in heat wave indices in West-Central Europe and the Iberian Peninsula.

One of the most comprehensive analysis focusing on the Iberian Peninsula was conducted by Brunet *et al.* (2007), using daily maximum (Tmax), minimum (Tmin) and mean (Tmean) temperatures from the 22 longest and most reliable Spanish records over the period 1850–2005. According to their results, the overall warming trend is associated with higher rates of change for Tmax (0.11 °C/decade) than Tmin (0.08 °C/decade), and with reductions in cold extremes, as opposed to increases in warm extremes (Brunet *et al.*, 2007). Taking a closer look at the Mediterranean coastal region of the Iberian Peninsula, Miró, Estrela and Millán (2006) examined the daily summer temperatures (July and August) over the Valencia Region, taking into account time series of 8 sites, but excluding urban centres as Valencia and Elche. They found increasing frequency of days with tropical characteristics over the period 1958–2003 (Miró, Estrela and Millán, 2006).

Climate models project substantial warming in temperature extremes by the end of the 21st century (IPCC, 2012, 2013b) at global scale. The IPCC states with *high confidence* that there will be *very likely* increase in frequency and intensity of warm days and warm nights (Fischer and Schär, 2009, 2010; Giannakopoulos *et al.*, 2009) and *very likely* decrease in cold days and cold nights (Goubanova and Li, 2007; Kjellström *et al.*, 2007; Sillmann and Roeckner, 2008) in Southern Europe and the Mediterranean region. Furthermore, the number of days with combined hot summer days (Tmax > 35 °C) and tropical nights (Tmin > 20 °C) is *very likely* to increase (Sillmann and Roeckner, 2008; Fischer and Schär, 2010).

It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase, with *likely* largest increases in southernmost Europe (Beniston *et al.*, 2007; Diffenbaugh *et al.*, 2007; Koffi and Koffi, 2008; Giannakopoulos *et al.*, 2009; Clark, Murphy and Brown, 2010). According to Fischer and Schär (2010) the frequency of heatwave days is projected to increase from an average of about two days per summer for the period 1961–1990 to around 13 days for mid-century and 40 days for the end of century, over the Iberian Peninsula and the Mediterranean region. The affected areas by the most severe heat waves are some of the most densely populated European regions, such as the urban areas of Athens, Marseille or Rome, where, indeed, the impact of extreme heat might be even stronger, due to the urban heat island effect (Fischer and Schär, 2010).

2.4.2 The urban heat island effect and thermal comfort

The well-documented phenomenon of the **urban heat island (UHI) effect** refers to cities being warmer than their rural surroundings because of the built environment absorbing, retaining, and/or producing more heat than the natural landscape it replaces (Oke, 1982). The UHI intensity is greatest at night, and it may disappear by day or the city may be cooler than the rural environments (Arnfield, 2003). The effect has been mainly described in large cities and towns with high concentration of populations, nevertheless, even rural-villages—small built-up urban areas—can have considerably higher temperatures than their surroundings as a recent study showed (Lindén, Grimmond and Esper, 2015).

The UHI is traditionally defined as the difference between the air temperature (AT) within the city and the AT of its surroundings, measured in the urban canopy layer, i.e. at standard screen height 2 m above ground and below the city's mean roof height (Stewart and Oke, 2012) (Fig. 2.5). The phenomenon can also be studied via land surface temperatures (LST) with the increased spatial coverage offered by satellite remote sensing techniques in comparison to weather station data (Mendelsohn *et al.*, 2007)—however to the cost of a larger uncertainty. When the urban heat island effect is estimated from LST measurements it is called surface UHI (sUHI), and usually has a different magnitude than the UHI. Remote sensing data are especially useful when there is no sufficient amount of in-situ measurements over the heterogeneous urban area and its surroundings, or when the few stations are not ideally located, so that, their representativeness is limited.

This human-induced modification of the local climate is principally caused by alterations to the energy balance influenced by variations of landuse, surface properties (e.g., surface roughness, albedo, emissivity) and geometry of the urban area (Oke, 1982; Tomlinson *et al.*, 2011). The heating-cooling systems of buildings, as well as the vehicles in traffic also promote warmer thermal environment in cities (Taha, 1997). The cumulative effect of these factors can result in a maximum air UHI of significant magnitude as large as 7 °C in London (Watkins *et al.*, 2002) or 8 °C in New York (Gedzelman *et al.*, 2003). UHI research was carried out in more than 17 cities over the Iberian Peninsula in the 1990s (Cuadrat and Martín Vide, 2007) finding a maximum intensity of 8–9 °C in Madrid (López Gómez *et al.*, 1993), 8 °C in Barcelona (Moreno-Garcia, 1994), and 5 °C in Zaragoza (Cuadrat, 2004).

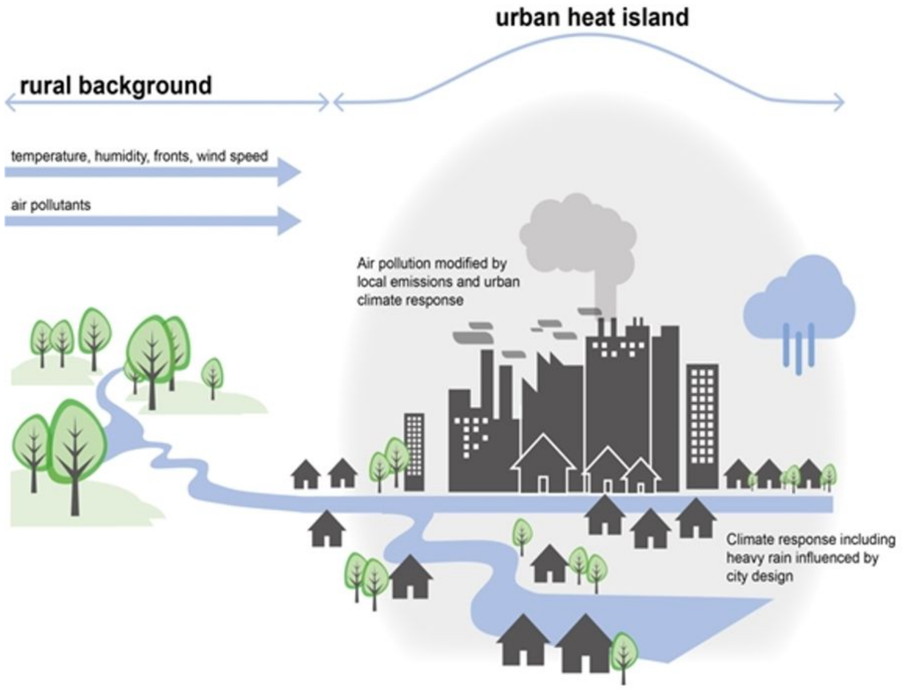


Figure 2. 5 The urban heat island profile. Source: Urban Sectoral Information System by Copernicus and Climate Change Service (http://climate.copernicus.eu/urbansis, accessed 5 September 2017)

There are many attempts to quantify the changes of UHI under climate change scenarios, however, research on the topic is still in an early state. A modelling study on the UHI of Paris during the severe heat wave of 2003 summer showed that the UHI intensity increases during heat wave days, and that for the cooler parts of the urban fabric (e.g., parks), the UHI intensification is around half of that of the dense urban fabric (De Ridder *et al.*, 2017). In contrast, a study on the UHI of Brussels employing very high spatial resolution (250 m) modelling experiments (Lauwaet *et al.*, 2016) found that the magnitude of the UHI is expected to decrease slightly due to global warming. Furthermore, they showed that presence of the UHI has a significant impact on the frequency of extreme temperatures in the urban area, i.e. heat wave days in the city increases twice as fast as in the surroundings (Lauwaet *et al.*, 2016). A comprehensive study on 8 cities from different continents found that urban and rural air temperatures increase strongly by the end of century, however, the UHI intensity in most cases increases only slightly, often even below the range of uncertainty (Lauwaet *et al.*, 2015).

In case of the study region of this thesis, an early study on the heat island effect of Valencia (Pérez Cueva, 2001) examined the phenomenon in relation to human comfort in the city in the late 1980s, to express the need for more environmentally-conscious urban planning. A measurement campaign carried out in the same year found significantly higher temperatures in the inner city—based on AT transect measurements by car (+3 °C) and LST values from NOAA satellite thermal images (+4.5 °C)—during two winter nights (Caselles *et al.*, 1991).

Many indicators have been developed to estimate **thermal comfort**, including simple ones such as predicted mean vote (PMV, e.g., Ye *et al.*, 2003; Mazon, 2014), standard effective temperature (SET*, e.g., Mazon, 2014), humidex (H, e.g., Rainham and Smoyer-Tomic, 2003; Callejon-Ferre *et al.*, 2011; Giannopoulou *et al.*, 2014) or Discomfort Index (DI or THI, e.g., Toy, Yilmaz and Yilmaz, 2007) that are based on relative humidity, air temperature and/or equivalent temperature measurements, and more complex ones such as physiologically equivalent temperature (PET, e.g., Cohen, Potchter and Matzarakis, 2013; Mazon, 2014) or Universal Thermal Climate Index (UTCI, e.g., Mazon, 2014) that are based on air temperature, relative humidity, wind speed and mean radiant temperature. The PET developed by Mayer and Höppe (1987) is based on a heat-balance model of the human body, and has been employed in several studies (e.g., Gómez *et al.*, 2013) characterizing indoor and outdoor human thermal comfort.

Thom's Discomfort Index (DI, Thom, 1959) estimates effective temperature and describes the degree of discomfort at various combinations of temperature and relative humidity. It is a commonly used bioclimatic index in urban climate studies (Clarke and Bach, 1971; Unger, 1999; Poupkou *et al.*, 2011; Papanastasiou, Melas and Kambezidis, 2015) and to assess heat stress in relation to animal welfare (Bouraoui *et al.*, 2002; García-Ispierto *et al.*, 2007). For example, Toy, Yilmaz and Yilmaz (2007) compared the human bioclimatic conditions in rural, urban and urban forest areas in the city of Erzurum (Turkey), applying the DI on hourly in-situ temperature and relative humidity data over a 10-month period. Sobrino *et al.* (2013) calculated the DI from nighttime land surface data obtained by remote sensing, to evaluate the general bioclimatic comfort conditions over the metropolitan area of Madrid (Spain). In present work, I also use the DI as it deemed to be simple but adequate tool to estimate urban bioclimatic comfort.

It is worth mentioning the Tourism Climatic Index (TCI, Mieczkowski, 1985) that is developed especially for the tourism sector based on climatic aspects relevant for tourists, such as daytime comfort, average (or daily) comfort, sunshine, precipitation and wind (Perch-Nielsen, Amelung and Knutti, 2010). It is used to evaluate climatic conditions of cities/regions in light of tourism attractiveness and appropriateness (Ramazanipour and Behzadmoghaddam, 2013; Kovács and Unger, 2014), and to explore the impact of projected climate change on the tourism climate resources (Amelung and Viner, 2006; Perch-Nielsen, Amelung and Knutti, 2010; Scott *et al.*, 2016). Another specific index is the Wet Bulb Globe Temperature (WBGT, National Weather Service), that is a specific measure of heat stress in direct sunlight, taking into consideration: temperature, humidity, wind speed, sun angle and cloud cover (solar radiation). It is commonly applied to manage workload in direct sunlight (e.g., study on greenhouse-construction industry in SE Spain by Pérez-Alonso *et al.* (2011)). The heat index is a similar indicator calculated for shady areas, which takes into account temperature and humidity.

Quantifying the additional hazard that the UHI poses on the urban population and illustrating the intra-urban variability of the thermal environment and discomfort (Hart and Sailor, 2009) is among the first steps towards designing climate adaptation strategies. As Eliasson (2000) pointed out, urban climate knowledge is much needed all along the urban planning process, and climatologists should meet the planners' needs by providing them with good arguments, suitable methods and tools. In section 2.4.3 the concept of urban climate adaptation and climate risk management are further discussed.

2.4.3 Urban climate adaptation and climate risk management

According to the definition of the IPCC **climate adaptation** is "the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects" (IPCC, 2014a). This definition highlights that adaptation is not solely future-oriented, that it is not purely anthropocentric, and that there are potential benefits associated with adaptation efforts.

Another term that is strongly associated with climate adaptation is **climate resilience**. "Resilience means the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of the hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.", as the United Nations Office for Disaster Risk Reduction (UNISDR) defines it. The IPCC provides similar description of resilience, adding "maintaining the capacity for adaptation, learning and transformation" as further components (IPCC, 2014a). Note, that climate adaptation refers to the *process* of adjusting to changes, while climate resilience describes the subject's *ability* to adjust.

In recent years, climate adaptation is increasingly conceived as the management of **climate risk** (Carter *et al.*, 2015). According to Crichton's risk triangle (Crichton, 1999) risk is a function of hazard, exposure and vulnerability. This concept is used for various risk assessments, including natural hazards disaster management and the insurance industry, as well as the IPCC and the UNISDR also adopted this. Here I introduce a slightly modified version by Carter *et al.* (2015) that emphasises adaptive capacity and integrates exposure in vulnerability (Fig. 2.6). As Carter *et al.* (2015) argues, it is important to separate out adaptive capacity from vulnerability when trying to formulate targeted policies or assessing barriers to implementing adaptation responses in urban context.

In Figure 2.6 *hazard* is the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life or other health impacts, as well as damage and loss to property, service provision and environmental resources (IPCC, 2014a). Hence, weather and climate events that a city experiences, for instance floods, heat waves or urban heat island are assessed as hazards in this framework. Carter *et al.*, (2015) sees the *vulnerability* of city residents, the infrastructure and the built and natural environment as a state, irrespective of whether they experience a hazard that could cause harm. Vulnerability constraints of physical and socio-economic factors, which influence the sensitivity and exposure of elements to climate change hazards (Alcamo and Olesen, 2012; EEA, 2012). *Adaptive capacity* then refers to "the ability of city governors, businesses and residents, and associated structures and systems to prepare for and moderate potential harm from climate change hazards and exploit any emerging opportunities" (Carter *et al.*, 2015).

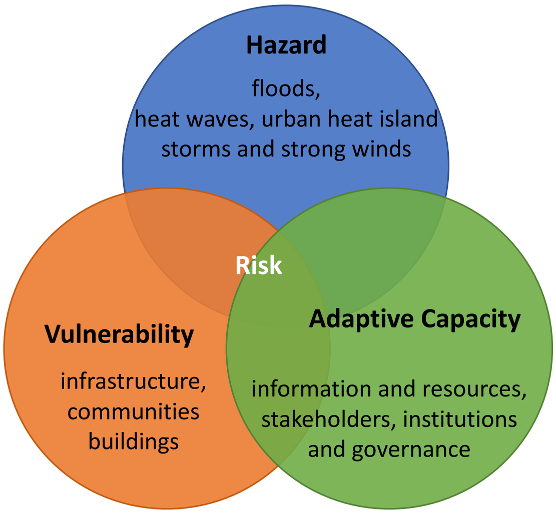


Figure 2. 6 The concept of climate risk, adapted from Carter et al. (2015).

The risk assessment conceptual framework of Carter *et al.* (2015) is based on the framework by Rosenzweig *et al.* (2011), and has been applied in a range of cities worldwide, and is underpinned by World Bank research (Mehrotra *et al.*, 2009). In general, risk-based management approaches to climate adaptation includes the assessment of impacts, vulnerabilities, the potential threats, and their causes (Kettle *et al.*, 2014).

To enhance risk assessment and climate adaptation the integration of scientific and local knowledge is essential (Grêt-Regamey *et al.*, 2013; Kettle *et al.*, 2014). Local knowledge on the complex details of community characteristics, such as infrastructure design and performance, governance structures, and vulnerable populations need to be incorporated in the assessments of local risks and potential impacts, and at the same time, local managers need to be assisted with information of climate change impacts and projections for their regions (Amundsen, Berglund and Westskog, 2010; Kettle, 2012; Picketts, Curry and Rapaport, 2012; Kettle *et al.*, 2014). This implies, that the co-production of knowledge (see section 2.5.2) is key in climate risk assessment and designing adaptation strategies (Moser and Dilling, 2007; Kettle *et al.*, 2014). In the next section I describe the role of transdisciplinary approaches such as knowledge co-production in climate adaptation planning.

2.5 Urban climate adaptation and transdisciplinary collaboration

The inherent complexity of contemporary challenges of health, migration, climate change, poverty, equality, new technologies or sustainable development, and the realization that an integration of multiple disciplinary perspectives is required to better understand and solve these problems prompted increasing commitment to TD collaboration in science and training (Klein, 1996; Stokols *et al.*, 2008).

This chapter provides background to the social study presented in Chapter 5. In section 2.5.1 I explain the connection between climate science and transdisciplinary approaches, section 2.5.2 defines multi- inter- and transdisciplinary approaches, section 2.5.3 aims to clarify the different actors relevant to the studied TD collaborations, section 2.5.4 describes the different researcher roles in TD collaborations and section 2.5.5 introduces the conceptual framework of factors influencing the effectiveness of TD collaborations.

2.5.1 Facing complex global challenges, towards societal problem solving

The role of science as serving society has gained new ground in relation to sustainability transitions (*Future Earth website*; Lang *et al.*, 2012; Miller, 2013; Wittmayer and Schäpke, 2014). Inter- and transdisciplinarity, as well as social relevance are key elements of a science that aims to ameliorate pressing global issues, and support sustainability transitions (Loorbach, 2010; Wiek *et al.*, 2012; Wittmayer, Roorda and Steenbergen, 2014; van der Hel, 2016). In recent years, an innovative collaboration form, knowledge co-production, has emerged as a rewarding approach for addressing the complex problems of sustainable urban development (Hansson and Polk, 2016; Mistra Urban Futures, 2016). As the "Mistra Urban Futures" project defined it, knowledge co-production refers to collaboratively based processes where different actors and interest groups come together with researchers to share and create knowledge that contributes to creating viable solutions for today's problems, and increase the research capacity for societal problem-solving in the future (Mistra Urban Futures, 2016). "Co-" stands for collaborative, or working together cooperatively.

Diverse—climate and non-climate related—global challenges generated a need to integrate different types of knowledge from different disciplines (Klein, 1996; NAS/NAE/IM, 2004;

Miller, Muñoz-Erickson and Redman, 2011; Scholz, 2011), and a great need for closer collaboration at different decision-making levels and across organisational borders that historically were cut off from one another institutionally and administratively (Weart, 2012, 2013). Especially in health research the importance of teamwork including various disciplines has been realised long ago, based on the evidences that in terms of scientific, training, policy, and health outcomes these collaborations are more efficient, especially relative to smaller-scale, discipline-based research projects (Stokols *et al.*, 2003, 2008; Klein, 2008).

The connections between climate science and policy makers were limited during the last decades of the 20th century and started gaining momentum with the appearance of the IPCC's First Assessment Report (IPCC, 1990). In its early ages, it focused mainly on regional statistical studies and providing local and regional information on rainfall rates, flood recurrence, and seasonal temperatures to farmers, planners and engineers (Weart, 2013). This shows, that in its nascence, much of climatology was a service for industry, and intrinsically interdisciplinary (Shaman *et al.*, 2013). However, as the field expanded thanks to post-war funding of meteorology and geophysics, individual researchers grew more specialized and the field became fragmented (Shaman *et al.*, 2013; Weart, 2013).

The diverse disciplines that had something to say about climate started to contact each other in the 1960s and 1970s, due to the increasing worries about climate change and the growing impact of humans on the Earth system (Mooney, Duraiappah and Larigauderie, 2013; Shaman *et al.*, 2013). In the 1990s and 2000s the integration of climate related disciplines had been advancing, but none of the cooperation could solve entirely the problem of fragmentation. To address this problem in an international policy level, the Intergovernmental Panel on Climate Change (IPCC) was established around the turn of the 21st century that finally institutionalized an unprecedented process of exchanges, and became a centre of integrated interdisciplinary cooperation in climate (Weart, 2013).

2.5.2 Terminology: Multi-, Inter- and transdisciplinary

A wide range of terms—such as interdisciplinary, transdisciplinary, multidisciplinary, or multi-expert—are used to describe collaborative working arrangements between different professionals (Thylefors, Persson and Hellstrom, 2005; Aboelela *et al.*, 2007; Nancarrow *et al.*, 2013). Although these terms are often used interchangeably, there are some distinctions determined in the literature. A common consideration is that the prefixes multi-, inter- and trans- refer to the intensities of integration of various disciplines (Klein, 1996; NAS/NAE/IM, 2004; Blanchard and Vanderlinden, 2010), however the use of terms are not always consistent through the literature of various fields. (Throughout the thesis when referring to the literature, I kept the original terms (TD, ID) used by the authors.)

The Fig. 2.7 adapted from Blanchard and Vanderlinden (2010) illustrates the four level of cross-disciplinary interaction as four points on a scale. Still, according to the Network for Transdisciplinary Research – Swiss Academies of Arts and Sciences (*td-net website*), the boundaries between interdisciplinarity and transdisciplinarity are fuzzy, thus a broader definition might be more helpful when studying such collaborations.

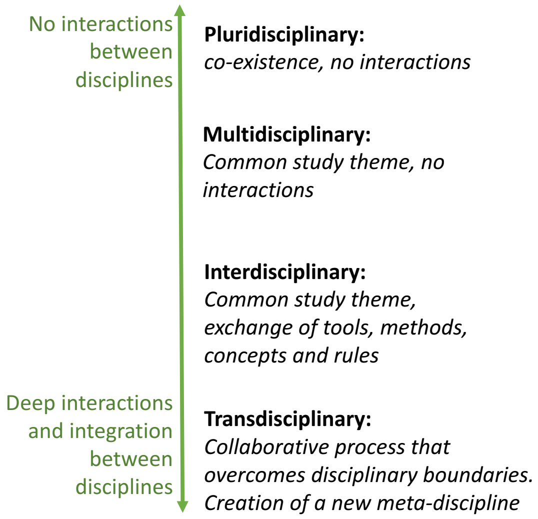


Figure 2. 7 Four levels of cross-disciplinary interaction. Adapted from Blanchard and Vanderlinden (2010), inspired by Klein (1996) and Jakobsen, Hels and McLaughlin (2004).

The US National Academy of Sciences proposed a definition that considers interdisciplinary research as the umbrella of transdisciplinary research: “Interdisciplinary (ID) research is a mode of research by teams or individuals that integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialized knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or area of research practice” (NAS/NAE/IM, 2004, p188). This broad definition has two main concept that is worth to point out. It emphasizes that such ID/TD research approach integrate knowledge not only from different scientific disciplines, but also from other bodies of specialised or expert knowledge, furthermore, it assigns two main purpose: advancing fundamental understanding and solving problems (*td-net website*; Pohl and Hirsch Hadorn, 2007; Regeer and Bunders, 2009; Klein, 2010).

Based on the concepts summarised by the Network for Transdisciplinary Research, TD research integrates two processes in the **co-production of knowledge**: a scientific process of answering research questions and a societal process of addressing challenges according (Fig. 2.8) (*td-net website*; Pohl and Hirsch Hadorn, 2007; Regeer and Bunders, 2009). As none of the mentioned processes are seldom capable to solve complex and diverse challenges of today, it is essential that researchers from different disciplines collaborate with actors from civil society and the private and public sector to jointly produce knowledge that leads to adequate solutions (*td-net website*). According to Lemos and Morehouse (2005), highly interactive models of research fosters higher levels of innovation and social impact.

There is a growing amount of studies that consider Climate Services within the conceptual framework of transdisciplinarity (e.g., Lemos and Morehouse, 2005; Kirchhoff, Lemos and Dessai, 2013; Bruno Soares, Alexander and Dessai, 2017). In regard to seasonal climate forecasts Dilling and Lemos (2011) found that nearly all of the examined cases of successful use of climate information involved some kind of iteration between knowledge producers and users.

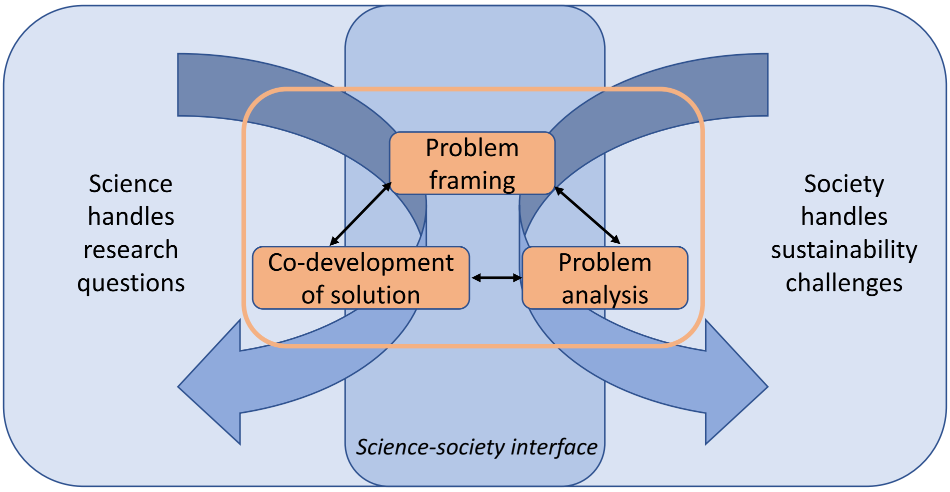


Figure 2. 8 Linking societal problem solving with scientific knowledge production in a process of co-producing knowledge in TD research. The process encompasses three tasks: problem framing (identifying and structuring a problem), problem analysis, and co-development of solution. (Adapted from td-net website with slight modifications.)

2.5.3 Science-practice-policy interface: who is who?

There is a growing consensus that knowledge exchange and user engagement is essential to build effective Climate Services for all sectors and contexts (AMS, 2012; Lemos, Kirchhoff and Ramprasad, 2012; Bruno Soares, Alexander and Dessai, 2017). Lourenço *et al.* (2015) pointed out, potential—climate and non-climate—impacts, risks, ways to reduce them, and opportunities that the adaption options create are often more important for decision-makers than the raw or even transformed climate data. Nevertheless, decision-makers are not a coherent entity, but a collection of individuals, each of whom uses different information to address different goals in a unique context (Morss *et al.*, 2005). To satisfy the diverse needs of users/decision-makers, opportunities for interaction and co-production of knowledge should be promoted and facilitated by building science-practice-policy interfaces (Kirchhoff, Lemos and Dessai, 2013).

In the next paragraphs, I clarify some terms used in the cross-sectoral case study, and connect them to the Climate Services market. The term ‘actor’ refers to a category of person who performs a certain function within a system or process (Long, 1990) while ‘stakeholder’ is a term commonly used to identify those actors who have a stake or an interest in a particular issue (Grimble and Wellard, 1997). This interest belongs to those affected or who can affect a particular decision or actions (Lelea *et al.*, 2014).

Another term to clarify is the ‘practitioner’. In the case study of climate adaptation planning, I use the term practitioners to those stakeholders that have relevant professional expertise in relation to the issue and they work outside of the academy, e.g., technical/strategic consultants, municipality representatives. They are classified as primary stakeholders, because they are directly involved with the issue at hand (Lelea *et al.*, 2014).

‘Policy maker’ is a person with power to influence or determine policies and practices at an international, national, regional, or local level. They are classified as secondary stakeholders, as they are indirectly affecting (by setting rules) or being affected by the issue at hand (Lelea *et al.*, 2014).

The term ‘decision-makers’ is used inconsistently in the literature, depending on the sector and discipline. For instance, some studies refer only to policy-makers as decision-makers, while others use the term equivalent to stakeholders. To avoid confusion between the use of various terms, in this work I refer to all participants as stakeholders, and make a clear distinction between academics, practitioners and policy makers.

Nevertheless, in real life cases one might discover that there are individuals who fit in multiple categories. Tools to graphically assess and represent stakeholders of different categories can be found e.g., Zimmermannn and Maennling (2007). Considering the above classification of market actors, the providers of Climate Services (detailed in section 2.2.1) correspond to the academic stakeholders, and the users are the practitioners.

2.5.4 Roles of researchers

Wittmayer and Schäpke (2014) established an in-depth understanding of the activities and roles of researchers in sustainability transitions based on action research and transition management approaches. In light of the emerging complex global challenges, the understanding of what a researcher does and is supposed to do is changing, as researchers more and more often face the demand to "recognise and accept their social responsibility" (Cornell *et al.*, 2013, p67). Thus, researchers tend to engage in process and action-oriented activities, e.g. they guide collective learning processes, put sustainability into practice or commit themselves to knowledge co-production serving various stakeholders with scientific information (Pohl *et al.*, 2010; Loorbach, Frantzeskaki and Thissen, 2011). These are emerging activities for researchers that could lead to confusion of roles and responsibilities, or tension due to the need to adjust for the new requirements, or inefficient collaborative work (Stokols *et al.*, 2008; Pohl *et al.*, 2010).

Five ideal-type roles of researchers are identified by Wittmayer and Schäpke (2014) in the scientific arena of sustainability transitions, which are: *reflective scientist*, *process facilitator*, *knowledge broker*, *change agent* and *self-reflexive scientist*. The role of *reflective scientist* is the closest to what is conventionally understood as 'research'. They systematically collect, analyse, interpret and report data from an observer point of view (Wittmayer and Schäpke, 2014).

The role designation of *process facilitator* refers to the activity of initiation and facilitation of processes and concrete short-term actions (Pohl *et al.*, 2010). The *knowledge broker* is a scientist that wants to hold an active role in (sustainability) transitions, thus mediates between different perspectives and pursues relevant and tangible outcomes (Loorbach, Frantzeskaki and Thissen, 2011; Miller *et al.*, 2013). The *change agent*'s role also includes the explicit participation of the researcher in processes aiming to address real-world problems; the researcher seeks to motivate and empower partners, and networks with stakeholders to address local environmental/sustainability challenges (Miller *et al.*, 2013; Wittmayer and Schäpke, 2014). The role of *self-reflexive scientist* refers to being reflexive about one's positionality and normativity, and to seeing oneself as part of the dynamic that one seeks to change (Wittmayer and Schäpke, 2014).

In case of Climate Services there is a higher need for additional researcher roles besides *reflective scientist,* as engaging with stakeholders is demanding in terms of time and requires extra learning (Stokols *et al.*, 2008; Bennett, Gadlin and Levine-Finley, 2010; Wittmayer and Schäpke, 2014).

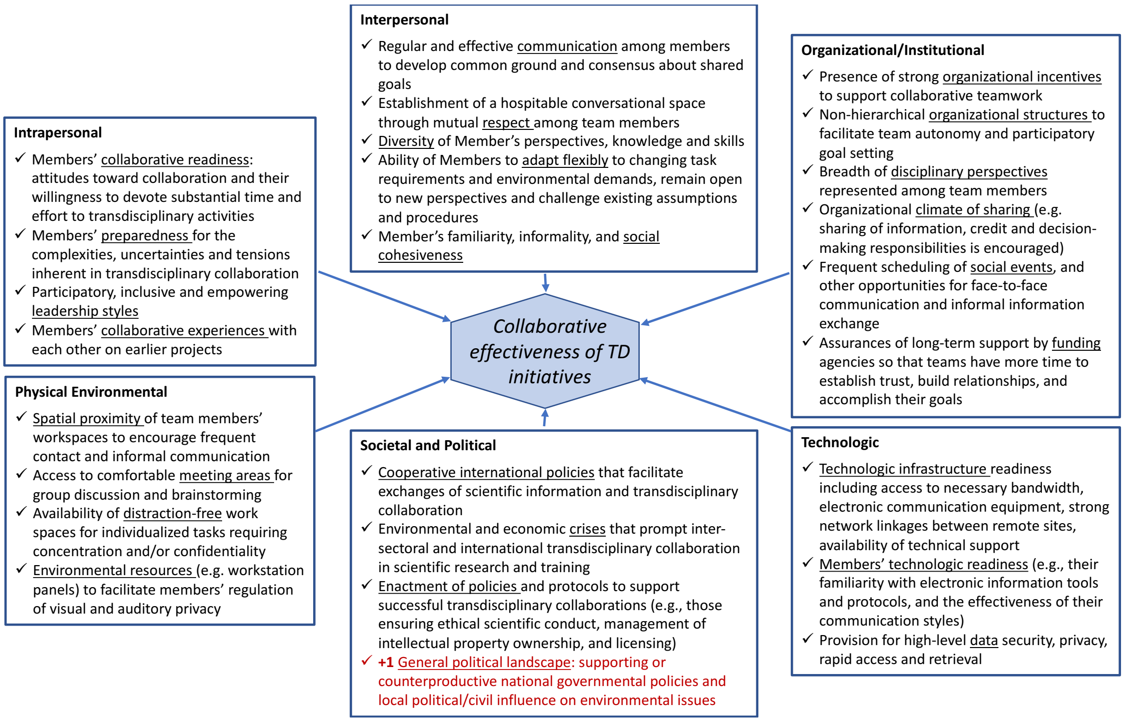
2.5.5 Key determinants of effective TD collaborations

Stokols *et al.* (2008) provided basic guidelines on how to establish a strategic basis for designing, managing and evaluating team science initiatives, by reviewing the literature of transdisciplinary collaborations with a special focus on the health care sector. By the analysis of the ecology of team science, they established six categories of contextual factors that influence the effectiveness of TD collaborations in research, training, and cross-sectoral settings. The typology of these a) intrapersonal, b) interpersonal, c) organizational, d) physical environmental, e) technologic and f) other political and societal factors with slightly modified descriptions is drawn in Figure 2.9. The complex web of contextual determinants defined by Stokols *et al.* (2008) is based on the comprehensive review of four distinct areas of research on team performance and collaboration. These areas cover studies of cyber-infrastructures designed to support TD collaborations across remote sites, research on community-based coalitions for health promotion, investigations about practices of TD research centres and training programs as well as social psychology and management studies.

A framework of competencies for effective interdisciplinary team work by Nancarrow *et al.* (2013) was also deemed to be useful for present study. They identified ten principles for good interdisciplinary team work based on a systematic review of literature on interdisciplinary collaborations and the perceptions of over 200 staff from health care teams in the UK. They found that the characteristics underpinning effective interdisciplinary team work are (1) positive leadership and management attributes; (2) communication strategies and structures; (3) personal rewards, training and development;

(4) appropriate resources and procedures; (5) appropriate skill mix; (6) supportive team climate; (7) individual characteristics that support interdisciplinary team work; (8) clarity of vision; (9) quality and outcomes of care; and (10) respecting and understanding roles.

The framework on contextual factors that influence TD collaborations (Stokols *et al.*, 2008) and the framework of competences that support effective interdisciplinary team work (Nancarrow *et al.*, 2013) have several common points and similarities, however the former provides a broader view by including different social and political levels of analysis (individual, team, institutional, national, global), meanwhile the latter mainly focuses on the level of individual acting in a team. Thus, both frameworks are taken into consideration in the present study, but the former one provides the backbone for the analysis. A brief description of the different contextual factors and the corresponding principles is given below.



Interpersonal
- ✓ Regular and effective communication among members to develop common ground and consensus about shared goals
- ✓ Establishment of a hospitable conversational space through mutual respect among team members
- ✓ Diversity of Member's perspectives, knowledge and skills
- ✓ Ability of Members to adapt flexibly to changing task requirements and environmental demands, remain open to new perspectives and challenge existing assumptions and procedures
- ✓ Member's familiarity, informality, and social cohesiveness

Intrapersonal
- ✓ Members' collaborative readiness: attitudes toward collaboration and their willingness to devote substantial time and effort to transdisciplinary activities
- ✓ Members' preparedness for the complexities, uncertainties and tensions inherent in transdisciplinary collaboration
- ✓ Participatory, inclusive and empowering leadership styles
- ✓ Members' collaborative experiences with each other on earlier projects

Organizational/Institutional
- ✓ Presence of strong organizational incentives to support collaborative teamwork
- ✓ Non-hierarchical organizational structures to facilitate team autonomy and participatory goal setting
- ✓ Breadth of disciplinary perspectives represented among team members
- ✓ Organizational climate of sharing (e.g. sharing of information, credit and decision-making responsibilities is encouraged)
- ✓ Frequent scheduling of social events, and other opportunities for face-to-face communication and informal information exchange
- ✓ Assurances of long-term support by funding agencies so that teams have more time to establish trust, build relationships, and accomplish their goals

Physical Environmental
- ✓ Spatial proximity of team members' workspaces to encourage frequent contact and informal communication
- ✓ Access to comfortable meeting areas for group discussion and brainstorming
- ✓ Availability of distraction-free work spaces for individualized tasks requiring concentration and/or confidentiality
- ✓ Environmental resources (e.g. workstation panels) to facilitate members' regulation of visual and auditory privacy

Societal and Political
- ✓ Cooperative international policies that facilitate exchanges of scientific information and transdisciplinary collaboration
- ✓ Environmental and economic crises that prompt inter-sectoral and international transdisciplinary collaboration in scientific research and training
- ✓ Enactment of policies and protocols to support successful transdisciplinary collaborations (e.g., those ensuring ethical scientific conduct, management of intellectual property ownership, and licensing)
- ✓ **+1** General political landscape: supporting or counterproductive national governmental policies and local political/civil influence on environmental issues

Technologic
- ✓ Technologic infrastructure readiness including access to necessary bandwidth, electronic communication equipment, strong network linkages between remote sites, availability of technical support
- ✓ Members' technologic readiness (e.g., their familiarity with electronic information tools and protocols, and the effectiveness of their communication styles)
- ✓ Provision for high-level data security, privacy, rapid access and retrieval

Figure 2. 9 Typology of contextual factors influencing TD collaboration. The figure is adapted from Stokols et al. (2008). The text in red is added as another important factor by the author of this thesis (discussed in detail in Chapter 5).

2.5.5.1 Intrapersonal Factors

Members' collaborative readiness depends on several factors, and can be measured in terms of their preparedness for the uncertainties, tensions and complexities of TD teamwork, their openness to other disciplinary perspectives and world views, their methodologic flexibility and their willingness to devote substantial amounts of time both to learn about other's expertise and to develop intellectual and personal relationships (*td-net website*; Israel *et al.*, 1998; Stokols, 2006; Stokols *et al.*, 2008). TD success is further enhanced when members support a culture of sharing (responsibility, common goals), and embrace TD ethical conduct and egalitarian values (Wray, 2002; Stokols *et al.*, 2003). Furthermore, the extent of previous collaborative experience as well as empowering, inclusive and transformational leadership style appears to be crucial to effective TD collaborations (Bennis, 1997; Lantz *et al.*, 2001; Hall, Stokols and Moser, 2008).

Eight from the ten principles of effective interdisciplinary team work described by Nancarrow *et al.* (2013) have common implications with the Intrapersonal Factors (Table 2.1). The principle of Individual characteristics (7) includes necessary knowledge, experience, listening skills, reflexive practice and desire to work on the same goals. It is necessary to have a clear leader of the team with clear direction and management, democratic, shared power, support and supervision, leader who acts and listens—also correspond to the Intrapersonal Factors.

2.5.5.2 Interpersonal Factors

Earlier studies on teamwork found that interpersonal communication is a critical determinant of collaborative effectiveness (e.g., Molyneux, 2001; Aboelela *et al.*, 2007; Xyrichis and Lowton, 2008; Bennett, Gadlin and Levine-Finley, 2010). Regular and effective intellectual and social communications are necessary so members can build trusted partnership, set common goals, learn about their colleagues and understand their perspectives, clarify roles, and eventually transcend disciplinary boundaries to develop novel conceptual frameworks to solve complex problems (NAS/NAE/IM, 2004; Xyrichis and Ream, 2008).

The most important determinant that contribute to good interdisciplinary team work via Interpersonal Factors is the principle of Communication (2) (Nancarrow *et al.*, 2013). Individuals with communication skills, as well as appropriate systems to promote interaction within the team are essential (Xyrichis and Lowton, 2008; Nancarrow *et al.*, 2012). In general, most of those principles identified by Nancarrow *et al.* (2013) that belong to the Intrapersonal Factors, also relate to the Interpersonal Factors (see table 2.1).

2.5.5.3 Organizational Factors

A prerequisite for sustaining motivation among participants in TD collaborations is the presence of strong organizational incentives (Aboelela *et al.*, 2007; Xyrichis and Lowton, 2008; Wittmayer and Schäpke, 2014). As team projects require substantial time expenditure for group meetings, workshops, brainstorming sessions, organizations need to recognize participating in TD projects and reward members for engaging in collaborative activities by providing organizational, environmental, and technologic support and incentive structures (Olson and Olson, 2000; NAS/NAE/IM, 2004; Rhoten and Parker, 2004; Stokols, 2006).

Considering the framework of principles by Nancarrow *et al.* (2013), the principal of Appropriate resources and procedures (4) include structures such as team meetings, organizational competences, and team members' workspaces, that should be ensured by the institution. The principal (3) of Personal rewards, training and development also belong to the Organizational Factors. This principle correspond to the learning, training and career development opportunities, incorporates individual rewards (e.g. merit and promotion procedures in academic settings) and opportunity, morale and motivation (Nancarrow *et al.*, 2012, 2013) (Table 2.1). Nonetheless, the latter mentioned principal (3) is also related to the Intrapersonal Factors.

2.5.5.4 Physical Environmental Factors

One effective strategy for fostering communication and encouraging the integration of intellectual ideas is to maximize spatial proximity among members' offices (Steele, 1986; Stokols, 2006). If this arrangement is not feasible, scheduling regular face-to-face meetings, social gatherings and opportunities to interact personally become more important. Studies of team environments (e.g., Sundstrom, DeMeuse and Futrell, 1990; Brill and Weidemann, 2001) highlighted that proper environmental support is necessary to improve performance. For instance, access to distraction-free work spaces and comfortable meeting areas are indispensable to facilitate members' participation in both individualized tasks requiring high levels of concentration or confidentiality and collective activities involving group discussion or ideation (Stokols *et al.*, 2008).

As mentioned in section 2.5.5.3, the principle (4) Appropriate resources and procedures include working environmental factors such as team members working from the same location or via remote connections (Nancarrow *et al.*, 2013) (Table 2.1). It also refers to the appropriate communication systems, which are related to the Technological Factors.

2.5.5.5 Political and Societal Factors

Easing of political barriers through cooperative international policies can encourage the initiation and long-term success of TD collaborations (Sonnenwald, 2007; Andonova, Betsill and Bulkeley, 2009; Börner *et al.*, 2010). As the global environmental changes impose more pressure on the socio-economic systems, the need for transformative environmental policies towards global sustainability become more evident (van der Hel, 2016). Thus, new forms of cross-border and cross-sector collaborations are emerging, such as large-scale international research/practice co-operations (*Future Earth website*, *td-net website*, *Climate-ADAPT website*), transnational environmental political organizations (Andonova, Betsill and Bulkeley, 2009), public-private partnerships (Link, 1999) and cooperative research centres between science and industry (Adams, Chiang and Starkey, 2001; Boardman and Gray, 2010).

The socio-political factors are not taken into account in the framework of principals by Nancarrow *et al.* (2013), as the principal competences studied by them are focused on the individual and team level of analysis, and not looking at external influences on the collaboration.

2.5.5.6 Technologic Factors

An organization's technologic infrastructure and members' technologic readiness strongly influence remote as well as place-based collaborations (Olson & Olson, 2000). Linkages between sites, electronic networking capabilities, access to necessary bandwidth, data security and technical support provided by an organization are essential to improve a team's prospects to achieve its goals (Lipnack and Stamps, 1997; Xyrichis and Lowton, 2008). Members' technologic readiness, including their familiarity with various electronic information and communication tools, protocols, and codes of conduct has been found to enhance teamwork (Sonnenwald, 2007; Stokols *et al.*, 2008).

In the framework by Nancarrow *et al.* (2013) the Technologic Factors are marginally incorporated as the principles of Appropriate resources and procedures (4) and Communications (2), that both refer to the proper communication systems and technical facilities that foster cooperation between team members. The Technologic Factors were not measured directly in this study. The technologic readiness is partly described in relation to the Physical Environmental Factors, however, evaluating the full spectrum of technologic preparedness (both the organization's and the member's) requires deeper investigation with different methods, that is beyond the scope of this analysis.

Table 2. 1 Common points of the framework on contextual factors that influence TD collaborations (Stokols et al., 2008) and the framework of competences that support effective interdisciplinary team work (Nancarrow et al., 2013).

Principles	**Corresponding Contextual factors**
1. Leadership and management	Inter- and Intrapersonal
2. Communication	Interpersonal
3. Personal rewards, training and development	Intrapersonal, Organizational
4. Appropriate resources and procedures	Organizational/Physical Environmental, Technologic
5. Appropriate skill mix	Inter- and Intrapersonal
6. Climate	Inter- and Intrapersonal, Organizational
7. Individual Characteristics	Intrapersonal
8. Clarity of vision	Inter- and Intrapersonal, Organizational
9. Quality and outcomes of care *» Beneficiary Stakeholder relations**	Inter- and Intrapersonal, Organizational
10. Respecting and understanding roles	Intra-and interpersonal
–	Societal and Political

*The beneficiary stakeholders in present case study are the municipalities and their citizens.

Chapter 3

Evaluating the performance of the RCA4 regional climate model and analysing the temperature projections over the Iberian Peninsula

3.1 Introduction

The Mediterranean region has been identified as one of the Earth's most sensitive regions to global warming (Giorgi, 2006) as it is pronounced in the high number of evidences, such as intensification of heat stress (Diffenbaugh *et al.*, 2007), longer summer heat waves (Paul M. Della-Marta *et al.*, 2007a), growing number of temperature extremes (Brunet *et al.*, 2007; Huhne and Slingo, 2011) and marked decrease in river discharges (López-Moreno *et al.*, 2011). The region is particularly responsive to the climate system's changes due to increased GHG forcing, that is manifested in large decrease in precipitation, increase in inter-annual warm season variability and pronounced mean warming (Giorgi, 2006).

The Iberian Peninsula (IP) is situated in the western Mediterranean region, between subtropical and mid-latitude. It is characterized by a complex topography and its climate is mainly influenced by the Atlantic Ocean, the Mediterranean Sea and air masses from the Sahara Desert (Dasari *et al.*, 2014). These results in complex interactions and feedbacks involving ocean atmosphere-land processes, which play a prominent role in climate and, in turn, heavily impact on human activities (*MED-CORDEX website*). Since most global coupled climate models are still run at coarse (one to a few hundred kilometres) horizontal resolutions, they are not able to accurately describe these smaller scale regional differences (e.g. the Pyrenees or the river basins).

EURO-CORDEX *(EURO-CORDEX website*) is the European branch of the CORDEX (COordinated Regional climate Downscaling Experiment) initiative aiming at producing ensemble climate simulations based on multiple dynamical and empirical-statistical downscaling models forced by multiple general climate models from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Jacob *et al.*, 2014). As the Mediterranean region is a good case study for climate regionalization and was naturally chosen as a CORDEX sub-domain (MED), the Med-CORDEX framework endorsed by Med-CLIVAR and HyMeX was established (Herrmann *et al.*, 2011; Ruti *et al.*, 2016). Thanks to this there is an emerging number of downscaling and RCM based impact studies for the whole Mediterranean basin (e.g., Flaounas, Drobinski and Bastin, 2013; Tramblay *et al.*, 2013).

The present study focuses on dynamically downscaled regional climate simulations by an RCM ensemble over the Iberian Peninsula. To describe future changes in seasonal mean temperature (section 3.4), in the first part of the study, I evaluate the performance of a GCM-RCM ensemble to reproduce the general features of near surface temperature over the domain (section 3.3). The high resolution (0.11°, ca. 12.5 km) version of the Regional Climate Model RCA4 developed by the Rossby Center (SMHI, Sweden) is chosen for this analysis provided by the EURO-DORDEX experiments. Given the model-user perspective, I pursue an application-driven evaluation of the generic aspects of the model in terms of capturing the mean climatology over the Iberian Peninsula, and do not delve into in-depth analysis of the representation of physical processes. Data and methods are described in section 3.2.

As a first step of evaluation, the performance of the RCA4 is examined by given "perfect boundary conditions" from reanalysis data. As studies (Hawkins and Sutton, 2009) have shown that a significant fraction of the uncertainties in regional climate simulations is connected to the GCM that is used for deriving the regional climate information, as a second step, I quantify the contribution of GCMs to the overall bias structure. Third, the ensemble of RCA4 simulations driven by five GCMs is compared to the observations. Evaluation metrics that integrate information over the domain as well as maps are used to reveal geographical details in the bias pattern.

In the second part of the study (section 3.4), the seasonal mean temperature change projected for the mid- and long-term future is analysed in an ensemble of RCA4 simulations taking boundary conditions from the five GCMs under two emission scenarios. The uncertainties in future climate change related to the different boundary conditions and emissions are assessed through characterizing the robustness and spread between projections. It is clear that there is a growing demand for future climate information from different sectors, thus, the development of easily understandable and useful climate products is urgent. The study aims to facilitate the integration of regional climate model outputs into Climate Services by highlighting a good practice of illustrating future climatic changes.

The objectives of study are as follows:

(i) evaluate the performance of RCA4 driven by "perfect boundary conditions" in terms of reproducing mean seasonal temperature features over the IP, in comparison to different observational datasets;
(ii) evaluate the overall bias in the ensemble of five GCM-driven RCA4 temperature simulations compared to observations;
(iii) evaluate the contribution of driving GCMs to the overall bias structure in the RCA4 temperature simulations;
(iv) assess seasonal mean temperature projections and uncertainties from different driving GCMs and emission scenarios on mid- and long-term timescales;
(v) provide easily understandable illustration of future temperature change and its uncertainties over the Iberian Peninsula to improve the communication of climate knowledge to users.

3.2 Data and Methods

According to the objective of present study, analysis of future temperature projections for the IP is carried out after a thorough evaluation of the performance of the climate models. In the "Data and Methods" section first the study area (3.2.1), afterwards the simulations from the RCM (3.2.2.1), the driving GCMs (3.2.2.2), and the observational data (3.2.2.3) is presented, furthermore, the regridding method of model output data (3.2.3.1) and the metrics used for model evaluation (3.2.3.2) are described.

The monthly near-surface (2 m) temperature data were analysed over the 25-year period of 1981-2005 (evaluation period). The evaluation period was chosen based on the availability of historical climate model simulations and observations. The mid-term (2041-2070) and long-term (2071-2100) future projections are compared to current climate that is represented by the 1971-2000 reference period. Even though the latest IPCC report (IPCC, 2013b) started to use 20-year periods, I selected 30-year periods based on the common practice recorded in the literature, so that the results of this study are comparable to previous works. For more details on reference periods see section 2.3.4 in Chapter 2.

3.2.1 Study area

The IP is the westernmost Southern European peninsula with an area of approximately 582 000 km^2, bordered on the southeast and east by the Mediterranean Sea, and on the north, west, and southwest by the Atlantic Ocean. The Pyrenees mountains are situated along the northeast edge of the peninsula, forming a natural border from the rest of Europe. The peninsula is divided between Spain and Portugal, but it also includes the mini state of Andorra and smaller territories of France (on the NE) and United Kingdom (Gibraltar). The advection of Atlantic air masses dominates the precipitation regime in winter, while in summer it is determined by convective processes which depend on land surface conditions (Font-Tullot, 2000). There is a marked climate gradient of increased diurnal and seasonal thermal variation from the coastal areas to the centre of the peninsula (Dasari *et al.*, 2014).

The IP is a largely mountainous terrain (Fig. 3.1). A major part of the peninsula consists of the Meseta, a highland plateau rimmed and dissected by mountain ranges, such as the Central System in the heart of the Meseta, Sierra Morena on the south, the Cantabrian Mountains on the north, and the Iberian System in the central/eastern region. The vast plateau ranges from 610 to 760 m in altitude, staggered slightly to the east and tilted slightly toward the west (Font-Tullot, 2000). The major lowland regions are the Andalusian Plain in the southwest (the river valley of Río Guadalquivir), the Ebro Basin in the northeast (the river valley of Río Ebro), the Tejo Valley on the west and the coastal plains.

Figure 3. 1 The topography of the Iberian Peninsula. (Base of map: Google Earth)

The northern parts of the peninsula have temperate climate while southward the climate gradually becomes subtropical. The north-western region (Galicia and North Portugal) can be characterized with temperate oceanic climate (*Cfb* in Köppen–Geiger climate classification system, Kottek *et al.*, 2006), while the Pyrenees (2000–3000 m high) has alpine climate classified as "tundra type" (group *E* by Köppen–Geiger). The inner parts and the "southern half" of the peninsula are characterised by hot-summer Mediterranean climate (*Csa* by Köppen–Geiger), with smaller regions (e.g. around Zaragoza) characterised by cold semi-arid climate (*BSk*, by Köppen–Geiger). Andalucía region (on the south of peninsula) represents the warmest part of the domain, as the winters are mild (mean T = 8–12 °C) and the summers are hot (mean T = 24–26 °C) across the region. The subtropical conditions turn into arid, i.e. cold desert climate (*BWk* by Köppen–Geiger) in the foreground of Baetic Mountains and Sierra Nevada, on the SE coast.

Considering all the seasons, the warmest regions of the domain are the SW region—especially the basin of Guadalquivir—, the Mediterranean coast and the Ebro Basin in the foreground of Pyrenees. Relatively colder regions correspond to higher orographic features, such as the Cantabrian Mountains on the NW, the Pyrenees on the NE border, the Iberian System and Central System in the inner part of the peninsula and the Baetic Mountains along with Sierra Nevada on the SE.

3.2.2 Climate Model Simulations

3.2.2.1 The RCM

The simulations of the regional climate model RCA4 (Rossby Centre Atmosphere version 4) are available from the EURO-CORDEX framework (*EURO-CORDEX website*). The RCM is based on the numerical weather prediction model HIRLAM (Undén *et al.*, 2002) and this version, RCA4, was built on its predecessor RCA3, described by Samuelsson *et al.* (2011). During the development of RCA4 various criteria were addressed to improve the model and its usability. A criterion was that it should be easily transferable and applicable for any domain worldwide without retuning it (Kjellström *et al.*, 2016).

Furthermore, RCA has been improved both in physical and technical characteristics (Kupiainen *et al.*, 2011). The global physiography data read by RCA include Gtopo30 orography, ECOCLIMAP land-use and soil information, soil carbon and lake depth which make possible that RCA4 can be applied globally. Among other updates and improvements of its globally applicable routing scheme (Berg, P., Döscher, R., Koenigk, 2013), some parameterization schemes have been modified, mainly the land and hydrological processes. The Kain-Fritsch convective scheme (Kain and Fritsch, 1990) has been updated to the Bechtold Kain-Fritsch scheme (Bechtold *et al.*, 2001) which separates the shallow and deep convective processes. The technical modifications in going from RCA3 to RCA4 and the model performance in hindcast experiments are documented by Strandberg *et al.* (2014).

The choice of RCA4 is supported by the good validation results of the RCA3 (Samuelsson *et al.*, 2011) and RCA4 (Kotlarski *et al.*, 2014; Strandberg *et al.*, 2014). In the high-resolution experiment design carried out in the EURO-CORDEX framework, RCA4 was setup on a rotated latitude-longitude grid over Europe with a horizontal resolution of 0.11°, corresponding to approx. 12.5 km. The integration domain includes all Europe, and I extracted the Iberian Peninsula (9.8°W– 3.8°E, 35.7°S – 43.8°N) as study region.

For the evaluation run, the RCA4 model was driven by "perfect boundary conditions" provided by the ERA-Interim reanalysis (Dee *et al.*, 2011) covering the period 1981-2005. Reanalysis means the analyses of temperature, wind, and other meteorological and oceanographic quantities, created by processing observational data using fixed state-of-the-art weather forecasting models and data assimilation techniques (IPCC, 2014b). Thus, a reanalysis yields complete, global gridded data that are as temporally homogeneous as possible to serve e.g. as input data ("perfect boundary conditions") to climate models. In present case, for the evaluation run of the RCA4, the ERA-Interim provided the required atmospheric lateral boundary conditions, sea surface temperature and sea ice cover over ocean surfaces.

The ERA-Interim is considered to be of very high quality (Dee *et al.*, 2011), particularly in the Northern Hemisphere extratropical area where reanalysis uncertainty is considered to be negligible (Brands *et al.*, 2013). To evaluate the RCM performance over the IP, the RCA4 driven by ERA-Interim was compared to observations and to the ERA-Interim reanalysis itself.

3.2.2.2 Boundary data from GCMs and emission scenarios

As a next step of evaluation, the RCA4 has been given boundary conditions from five different GCMs: CNRM-CM5, EC-EARTH, HadGEM2-ES, IPSL-CM5A-MR, MPI-ESM-LR. All of them are fully coupled atmosphere–ocean General Circulation Models forced by different emission scenarios. The list of the GCMs and the RCM with references can be found in Table 3.1. Throughout this study, the individual RCM simulations driven by GCMs will be identified by a shorter version of the GCM acronym used by EURO-CORDEX (referring to the institution that took part in the development of the model). The simulations have been performed by SMHI for i) 1961–2005 with historical forcing and ii) for 2006–2100 under different Representative Concentration Pathway (RCP) scenarios (Moss *et al.*, 2010).

GCMs may simulate quite different responses to the same forcing, simply because of the way certain processes and feedbacks are modelled. For this reason, it is important to evaluate the performance of different GCMs under historical forcing. In these simulations (historical runs) time-varying external forcing—such as GHG and aerosol concentrations, solar input—is applied based on historic records from a given year up to the present. As these forcing elements change over time, the GCM simulates the evolution of the climate over this period in these historical runs.

Table 3. 1 Overview on the models used in this study. All simulations were performed by SMHI and model outputs are provided by the EURO-CORDEX framework (EURO-CORDEX website).

Climate model	**Acronym in EURO-CORDEX**	**Institute (country)**	**Acronym in this study**	**Reference**	**Website**
RCM	RCA4	Swedish Meteorological and Hydrological Institute (Sweden)	RCA4	Samuelsson *et al.* (2014), Strandberg *et al.* (2014)	www.smhi.se
Driving GCM	CNRM-CERFACS-CNRM-CM5	Météo-France and Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)	CNRM	Voldoire *et al.* (2013)	www.cnrm-game.fr
	ICHEC-EC-EARTH	Irish Centre for High-End Computing and EC-Earth consortium of weather services and universities in Europe (EU)	ICHEC	Hazeleger *et al.* (2010)	www.ec-earth.org
	MOHC-HadGEM2-ES	Met Office Hadley Centre (UK)	HADGEM2	Collins *et al.* (2011)	www.metoffice.gov.uk
	IPSL-IPSL-CM5A-MR	Institut Pierre Simon Laplace (France)	IPSL	Dufresne *et al.* (2013)	www. icmc.ipsl.fr
	MPI-MPI-ESM-LR	Max-Planck-Institut für Meteorologie (Germany)	MPI	Giorgetta *et al.* (2013) and Popke, Stevens and Voigt (2013)	www.mpimet.mpg.de

For the future (scenario runs) the external forcing is set to vary according to one of the future scenarios, e.g. the Representative Concentration Pathways (RCP) applied in the latest IPCC report (AR5). The RCP scenarios are expressed as changes in equivalent carbon dioxide concentrations as interpolated from one year to the next (Kotlarski *et al.*, 2014). Here two different pathways are used, the RCP4.5 and the RCP8.5, in order to represent a stabilization and a high-end scenario. The RCP4.5 assumes GHG peak by 2040 and the RCP8.5 is the “business-as-usual” pathway (that is the closest to reality at the moment), their detailed description is given in section 2.3.3 in Chapter 2.

To quantify the bias introduced by the GCMs, the RCA4 historical runs driven by different GCMs were compared to the RCA4 runs driven by ERA-Interim and to the observational datasets for the evaluation period 1981–2005. For the future projections two 30-year periods, the middle (2041–2070) and the end of the century (2071–2100), were used for both scenarios (RCP4.5 and RCP8.5.), and a 30-year reference period (1971–2000) was selected from the historical runs.

3.2.2.3 Observations

The RCM simulations (driven by the ERA-Interim and by GCMs with historical forcing) are compared to three datasets listed in Table 3.2. For the evaluation of seasonal and spatial patterns of the simulated near-surface temperature, the driving ERA-Interim reanalysis dataset (*ERA-Interim website*; Dee *et al.*, 2011) itself was used as one of the reference datasets, so that the analysis reveals to what extend the model distort the large-scale flow imposed by the boundary conditions (Kotlarski *et al.*, 2014).

Table 3. 2 Reference datasets for the evaluation of the model simulations.

Dataset	Description	Resolution: time	Resolution: space	Reference
ERA-Interim	European Centre for Medium range Weather Forecasts (ECMWF) reanalysis	daily	0.75°	Dee *et al.* (2011)
E-OBS	European, gridded from observations (version 10.0)	daily	0.25°	Haylock *et al.* (2008)
CRU	Climate Research Unit, gridded from observations (version CRU TS3.21)	monthly	0.50°	Harris *et al.* (2014)

The RCM run was also evaluated against the gridded observational dataset E-OBS (*E-OBS website*; Haylock *et al.*, 2008) which was produced as part of the ENSEMBLES project and provided by the European Climate Assessment & Dataset (ECA&D) project. This dataset covers the entire European land surface and it is based upon an extensive station network. It is available at daily scale and four different resolutions; I used the regular 0.25° version (highest resolution). The 0.25° grid corresponds to a horizontal resolution of about 25 km. Several previous studies have questioned the quality of E-OBS in regions of sparse station density (e.g., Hofstra *et al.*, 2009; Hofstra, New and McSweeney, 2010; Kyselý and Plavcová, 2010), as the gridding procedure tends to smooth the spatial variability. This is especially undesirable when analysing daily extremes (Rajczak, Pall and Schär, 2013). However, as in this work monthly mean temperature values are examined, the potential effect of inaccuracies is considered to be low over most of the domain.

The Climatic Research Unit (CRU) TS 3.21 dataset (*CRU website*; Harris *et al.*, 2014) provided by the University of East Anglia was also considered for RCA4 validation. CRU is a land-only dataset with a 0.50° regular grid and monthly temporal resolution. Both the E-OBS and the CRU datasets utilise partly the same underlying station data, which makes them, and consequently our comparisons, not fully independent (Lorenz and Jacob, 2010).

3.2.3 Methods and metrics of comparing datasets

To quantify the bias originating from different sources, the validation was carried out in three phases for the common period 1981–2005: 1) RCM driven by reanalysis ("perfect boundary conditions") vs. observations, 2) RCM driven by GCMs vs. RCM forced by reanalysis and 3) ensemble mean of five GCM-driven RCA4 vs. observations. Figure 3.2 illustrates the process and the different sources of uncertainty. Phase 1 estimates the bias of RCM, i.e. to what extend the RCA4 distort the large-scale flow imposed by the "perfect boundary conditions". In Phase 2, I evaluate the additional contribution of GCMs to the overall bias structure and in Phase 3, the overall bias of the ensemble mean of five GCM-driven RCA4 simulations is quantified compared to the observations. Through the RCM experiments assessed here we cannot separately quantify the uncertainty originating from different sources like the imperfection of reanalysis data or the internal climate variability inherent in model simulations, thus present results on the model biases are interpreted and discussed accordingly.

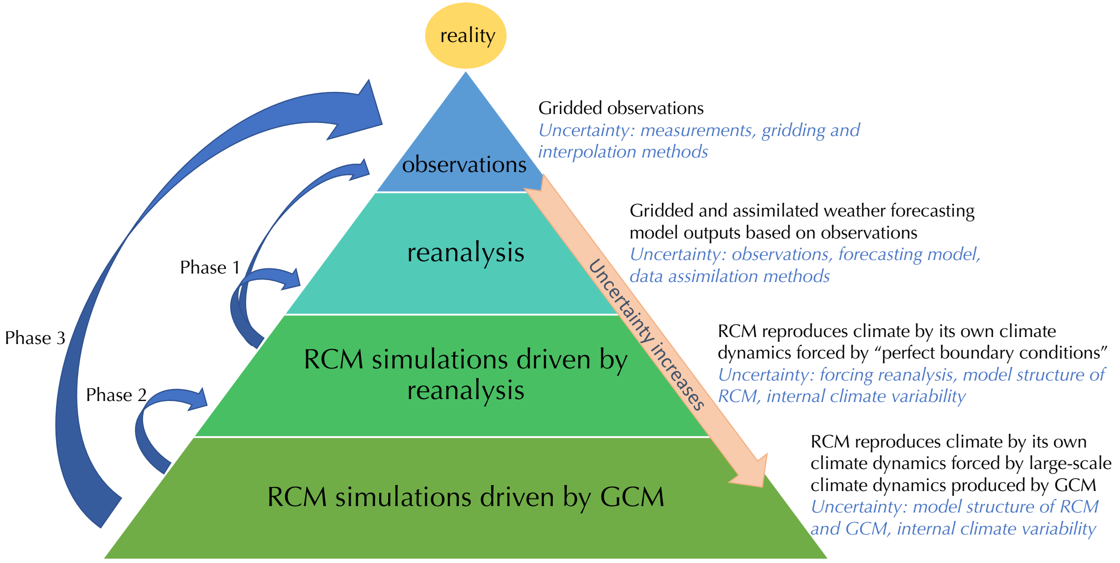


Figure 3. 2 The uncertainty cascade from observations to climate model simulations. In the three phases of model evaluation the bias is attributed to different sources. Figure developed by the author.

3.2.3.1 Regridding

Before starting the analysis, the gridded datasets and model outputs were transformed from their native grids to a common regular grid of 0.25° (the E-OBS grid) using first-order conservative (Jones, 1999) and bilinear interpolation (Nikulin *et al.*, 2012). I chose the 0.25° grid as a compromise between the coarser resolution observational datasets (ERA-Interim: 0.75°, CRU: 0.50°) and the finer resolution RCM outputs (0.11°), as Kalognomou *et al.* (2013) suggests. The remapping was carried out with special attention according to the recommendations of the EURO-CORDEX community, Haylock *et al.* (2008) and McGinnis et al (2010). Conservative projection in the context means that the value of target grid cell is calculated by an area-weighted average of all overlapping grid cells of the original grid, conserving area mean values. Bilinear interpolation (McGinnis, Mearns and McDaniel, 2010) is a simple linear interpolation in two directions.

When going from finer to coarser grid, the conservative interpolation is recommended, while in the opposite case the bilinear (*NCAR-UCAR website*; Nikulin *et al.*, 2012; Kalognomou *et al.*, 2013). Nevertheless, in case of monthly-scale mean temperature there were no or negligible difference between the resulted regridded maps—as I tested both methods. In case of CRU and ERA-Interim, data on a coarser grid was interpolated onto the 0.25° regular grid, however we need to keep in mind that the climatic information did not improve with the higher resolution grid.

In order to study the annual cycle and spatial patterns in the temperature simulations compared to reference datasets, monthly and seasonal mean values were calculated in every grid point. For each season, I derived climatologies of air temperature for the evaluation period 1981-2005 and the spatial variability of systematic error (bias) between simulated and reference fields was analysed.

3.2.3.2 Evaluation metrics, spatial bias assessment and ensemble characteristics

To assess the quality of regional climate simulations various evaluation metrics were applied to monthly and seasonal (winter: DJF, spring: MAM, summer: JJA, autumn: SON) mean values of temperature. The chosen metrics are commonly used distance measures to compare model outputs against gridded observational data (i.e., reference). These are the *BIAS*, *BIASSD*, *MAE* and *95%-P* which are defined below following Kotlarski *et al.* (2014):

a) *BIAS:* the difference (model – reference) of spatially averaged climatological seasonal mean values for the domain;
b) *BIASSD*: the spatial standard deviation of the bias field. The bias field is calculated as the difference between the climatological seasonal mean fields (model – reference);
c) *MAE*: the mean absolute error (model – reference) of spatially averaged climatological seasonal mean values for the domain;
d) *95%-P*: the 95th percentile of all absolute grid cell differences (model – reference) across the domain based on climatological seasonal mean values.

To describe the evaluation metrics with exact mathematical formulas, the following definitions should be clarified first:

Let M_{nki} and R_{nki} be the seasonal mean value of temperature of the model simulation (M) and the reference data (R) of year i at grid point n with $n = 1, \ldots, N$; N is the number of grid points of the domain D. $k = 1, \ldots, K$; K is the number of analysed periods per year: $K = 4$ for seasonal. $i = 1, \ldots, I$; I is the number of years (25 in present case).

The simulated spatial mean of period k and year i across the domain is defined as

$$\widehat{M}_{ki} = \frac{1}{N}\sum_{n\in D} M_{nki}. \tag{Eq. 3.1}$$

The climatological mean of period k at grid point n is defined as

$$\overline{M}_{nk} = \frac{1}{I}\sum_{i=1}^{I} M_{nki}. \tag{Eq. 3.2}$$

The climatological mean of period k averaged across the domain D is then computed as

$$\widehat{\overline{M}}_{k} = \frac{1}{N}\sum_{n\in D} \overline{M}_{nk} = \frac{1}{I}\sum_{i=1}^{I} \widehat{M}_{ki} = \overline{\widehat{M}}_{k}. \tag{Eq. 3.3}$$

The corresponding means for the reference data R are defined accordingly. Seasonal means of year i are calculated as an average of three consecutive monthly means beginning with December of year $i-1$ for the winter season (DJF). Using these definitions by Kotlarski *et al.* (2014), for climatological seasonal ($k = 1, \ldots, 4$) mean values averaged across the domain the evaluation metrics are as follows:

a) Mean bias (*BIAS*)

$$BIAS_k = \widehat{\overline{M}}_k - \widehat{\overline{R}}_k = \frac{1}{N}\sum_{n\in D} BIAS_{nk} \tag{Eq. 3.4}$$

with the bias field: $BIAS_{nk} = \bar{M}_{nk} - \bar{R}_{nk}$. *(Eq. 3.5)*

b) Spatial standard deviation of bias (*BIASSD*)

$$BIASSD_k = \sqrt{\frac{1}{N}\sum_{n\in D}(BIAS_{nk} - BIAS_k)^2}\ . \qquad \text{(Eq. 3.6)}$$

c) Mean absolute error (*MAE*)

$$MAE_k = \frac{1}{N}\sum_{n\in D}|BIAS_{nk}|. \qquad \text{(Eq. 3.7)}$$

d) 95 % percentile of the absolute value of grid point differences (*95%-P*)

$$95\% - P_k = \max_{n\in X}|\bar{M}_{nk} - \bar{R}_{nk}| \qquad \text{(Eq. 3.8)}$$

$$X = \{n \in D|Rank|\bar{M}_{nk} - \bar{R}_{nk}| \leq 0.95N\}.$$

Spatial average analysis was carried out considering the same grid points over land only in each dataset.

The interpretation of metrics is as follows. The average model bias is measured by the *BIAS* (also known as Mean Bias Error, MBE) that is calculated as the difference (error) between model simulations and the reference, without removing the signs of the error. It conveys useful information about the main direction of error over the domain, however, it should be interpreted cautiously because positive and negative errors will cancel out. *BIASSD* gives additional information on the spatial variability of the model bias (*BIAS*). *MAE* measures the absolute difference between model simulations and the reference, i.e. the average magnitude of errors in the simulations, without considering their direction. In *MAE* all individual differences have equal weight in contrast to other model-evaluation metrics such as RMSE (Root Mean Squared Error) that gives a relatively high weight to large errors. *95%-P* provide information on the high-end of *MAE* without considering the extreme large values and outliers.

Besides the metrics that provide a single value to measure the model skills, the seasonal mean biases at grid-point scale were also analysed in case of the RCM forced by ERA-Interim. The spatial variability of mean bias is presented in form of seasonal maps. Furthermore, the temporal correlation of each grid point of the two seasonal fields (model vs. observations) was visualised for spatial assessment. To obtain the mean seasonal correlation field, the following formula was applied (Schulzweida, Kornblueh and Quast, 2012):

$$TIMCOR_{nk} = \frac{\sum_{i\in S(n)} M_{nki}\cdot R_{nki} - n\cdot \bar{M}_{nki}\cdot \bar{R}_{nki}}{\sqrt{\left[\sum_{i\in S(n)} M_{nki}{}^{2} - n\cdot \bar{M}_{nki}{}^{2}\right]\cdot\left[\sum_{i\in S(n)} R_{nki}{}^{2} - n\cdot \bar{R}_{nki}{}^{2}\right]}} \quad \textit{(Eq. 3.9)}$$

$S(n) = \{i, M_{nki} \neq NA \cup R_{nki} \neq NA\}$, where *S(n)* represents the time series at *n* grid point, *NA* = missing value, i.e., for every grid point *n* only those time steps *i* (years) belong to the sample, which have value (not missing value).

For the evaluation of RCM driven by GCM the temporal correlation was not calculated. Since climate models develop their own climatology, a specific month should not necessarily relate exactly to the corresponding measured point in time from observations. When the RCM is driven by reanalysis data for the evaluation run, the regional climate model has a lower degree of freedom to alter the conditions imposed by the boundary forcing, consequently the temporal correlation between model simulations and observations should be high if the model is good. When the RCM is driven by GCM, the degree of freedom is higher, hence the year-to-year variability of simulations not necessarily correspond to the year-to-year variability of observations. Thus, in case of evaluating the RCM driven by GCM, instead of measuring temporal variability, the mean climatological statistics are comparable among datasets (Landgren, Haugen and Førland, 2014).

In present case of RCM runs driven by 5 GCMs, after evaluating the mean seasonal biases of each GCM-driven run, seasonal ensemble means and the standard deviation of the ensemble (indicating the spread of ensemble members around the mean) were calculated in order to describe the robustness and spread of the GCM-driven simulations. The following formulas were applied (Schulzweida, Kornblueh and Quast, 2012):

A. Ensemble mean (*ENSMEAN*)

   $ENSMEAN_{nk} = \boldsymbol{mean}\{GCM1_{nk}, GCM2_{nk}, \dots, GCM5_{nk}\}$, *(Eq. 3.10)*

   where $GCM1_{nk}$, … , $GCM5_{nk}$ are the 30-year mean value of temperature projections by the RCM driven by 5 GCMs for each *k* season and at each grid point *n*. The ***mean****{…}* is the statistical function of computing the average of the sample without weighting, and it is not calculated in case of missing values.

B. Ensemble standard deviation (*ENSSD*)

   $ENSSD_{nk} = \boldsymbol{SD}\{GCM1_{nk}, GCM2_{nk}, \dots, GCM5_{nk}\}$, *(Eq. 3.11)*

   where the variables are same as in A. The ***SD****{…}* is the statistical function of calculating the standard deviation of a sample without weighting, and it is not calculated in case of missing values.

The goal of this study is not to produce an overall skill score but to document different aspects of model performance. As I assess the models from the point of users, I do not aim to look into model dynamics and parametrizations for detailed explanation. I pursue a general evaluation of the RCM and GCMs to gain a good estimate of the uncertainties (originating from the models and the different future scenarios) in the RCA4 simulations.

I keep to the idea of "model democracy"—discussed by Weigel, Liniger and Appenzeller (2008), Knutti (2010) and section 2.3.3—, not giving a preference to any GCM when evaluating future projections, though, there are studies that propose that future GCM simulations should be weighted based on the model skills (e.g., Giorgi and Mearns, 2003; Tebaldi *et al.*, 2005; Perkins, Pitman and Sisson, 2009). To enhance the robustness of the results I use an ensemble of maximum available number of GCM-driven runs for projections, bearing in mind the different model uncertainties. For this reason, I quantify the spread of model ensemble and also comment the robustness of results based on the sign of the projected temperature change by each GCM-driven run. To visualise the future projections and uncertainties I follow the methods recommended by SMHI for Climate Services (Kjellström *et al.*, 2016).

For calculating and visualising the results different climate data visualising and statistical computing tools were applied: Grid Analysis and Display System (*GrADS website*) and Climate Data Operators, version 1.5.9. (*CDO website*; Schulzweida, Kornblueh and Quast, 2012).

3.3 Evaluating the models (1981–2005)

In this section, the evaluation results of the GCM-RCM are presented to gain an overview of the model bias in climate model simulations. To quantify the climate model contributions to the overall bias structure, the evaluation was carried out in three phases illustrated in Fig. 3.2. The evaluation period (1981–2005) was chosen as the common period of simulations. The results of model evaluation are presented according to the three phases: 1) RCM driven by reanalysis vs. observations (section 3.3.1), 2) RCM driven by GCMs vs. RCM forced by reanalysis (section 3.3.2) and 3) RCM driven by GCM ensemble vs. observations (section 3.3.3).

3.3.1 Evaluation of RCM: reanalysis-driven simulation

First, the evaluation was carried out on the RCM simulation driven by the ERA-Interim reanalysis data (so-called evaluation run) against the observational datasets, using the 0.25° regular grid of E-OBS for the comparisons. This analysis reveals to what extend the model distort the large-scale flow imposed by the boundary conditions (Kotlarski *et al.*, 2014).

3.3.1.1 Mean annual cycle

As a first step of evaluation, the annual cycle of simulated mean temperature averaged over the Iberian Peninsula (IP) are compared to the E-OBS and CRU observations, as well as to the ERA-Interim reanalysis data which were used to drive the RCM. The spatially averaged values of mean monthly temperature over the IP and over the evaluation period 1981-2005 are shown in Fig. 3.3. Compared to the observations, the RCA4 model tends to systematically underestimate the temperature in each month, with a well-pronounced cold bias in the cold half of the year. The largest biases occur in February and March (-2.1 and -1.8 °C, respectively), depending on the reference dataset. During summer (JJA) the RCM reproduces reasonably well the observed temperature, giving the smallest bias (< 0.1 °C) against the E-OBS in July and August.

There are also slight differences between the two observational and the reanalysis datasets. Even though the E-OBS and the CRU are built on almost the same station network, the E-OBS tends to be slightly cooler (with approx. 0.2 °C, SD = 0.1 °C) than the CRU. This discrepancy might be due to the regridding process because of the different resolution of datasets—the 0.5° CRU and the 0.75° ERA-Interim were interpolated onto 0.25° E-OBS grid—, the interpolation methods applied when constructing the datasets (Kotlarski *et al.*, 2012) and the different number of stations included in the datasets (Haylock *et al.*, 2008).

The CRU and the ERA-Interim have similar monthly mean values throughout the year, the difference between their annual cycle is negligible (±0.03 °C, SD = 0.1 °C). As the E-OBS have the lowest monthly mean temperatures among the observational datasets, the RCA4 simulations tend to be closest to the E-OBS observations (yearly mean bias = -1.1 °C, SD = 0.7 °C). When comparing to ERA-Interim—the reanalysis dataset that provided the boundary conditions for the RCA4 run—the yearly mean bias is -1.2 °C (SD = 0.6

°C). This general bias characteristic reveals to what extent the individual RCA4 alternate the large-scale flow imposed by the ERA-Interim driving database. When comparing to the CRU the same annual mean bias value is obtained, i.e. -1.2 °C (SD = 0.6 °C).

Since there is negligible difference between the observational and reanalysis datasets, for the next phase of the evaluation study (evaluation of GCM-RCM, section 3.3.2–3) only the E-OBS dataset is used with the specific reasons of a) the E-OBS data can be used on its native grid (no need of regridding), b) it has a reasonably good resolution (0.25° against the 0.50° of CRU and the 0.75° of ERA-Interim) and c) it provides gridded and assimilated observations unlike ERA-Interim that is a reanalysis dataset, i.e. product of weather forecasting models based on observations.

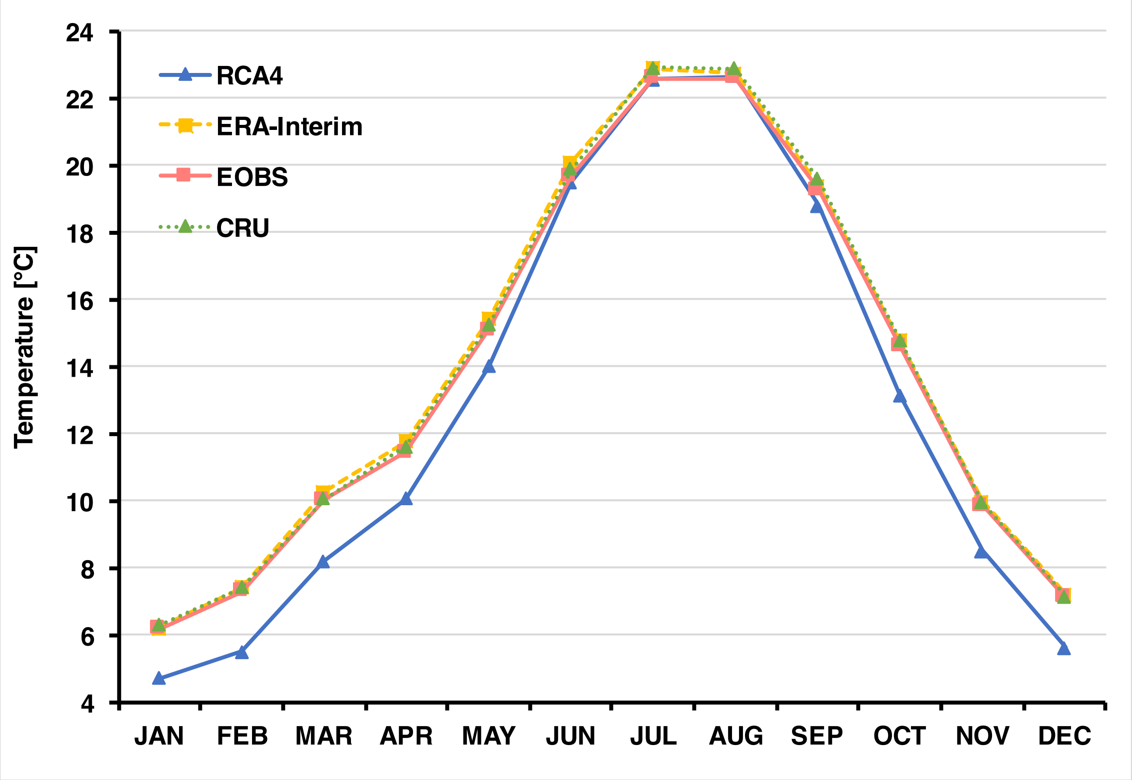


Figure 3. 3 The mean monthly temperature averaged over the Iberian Peninsula for the period 1981-2005. The details of the datasets can be found in Table 3.2.

3.3.1.2. Spatial patterns of seasonal temperature variability

In this section, the patterns of seasonal temperature means are analysed over the Iberian Peninsula, based on monthly gridded data averaged over the evaluation period 1981–2005. The main focus of this study is to assess the ability of the regional model to simulate the surface climate in response to large-scale forcing imposed by the ERA-Interim reanalysis and by local topographical features. I evaluate the regional scale spatial distribution and temporal correlation of bias between the RCA4 simulations and reference datasets (ERA-Interim reanalysis, E-OBS and CRU observations). A special focus is placed on the cold and warm season of the year (summer and winter), nevertheless, the transition seasons are also evaluated—but less extensively. To quantify the average bias over the whole domain, evaluation metrics (*BIAS*, *BIASSD*, *MAE*, *95%-P*) are calculated.

The climatic conditions of the Iberian Peninsula are determined by various factors, such as the Atlantic Ocean influence from the west, the Mediterranean Sea from the east, and various topographical features, for instance the high mountainous region of Pyrenees on the northeast border. Based on the E-OBS observational dataset, the seasonal temperature means for the evaluation period 1981–2005 are 6.9 °C in winter, 12.2 °C in spring, 21.6 °C in summer and 14.6 °C in autumn, respectively. The spatial differences of mean temperature are illustrated in Figure 3.4.

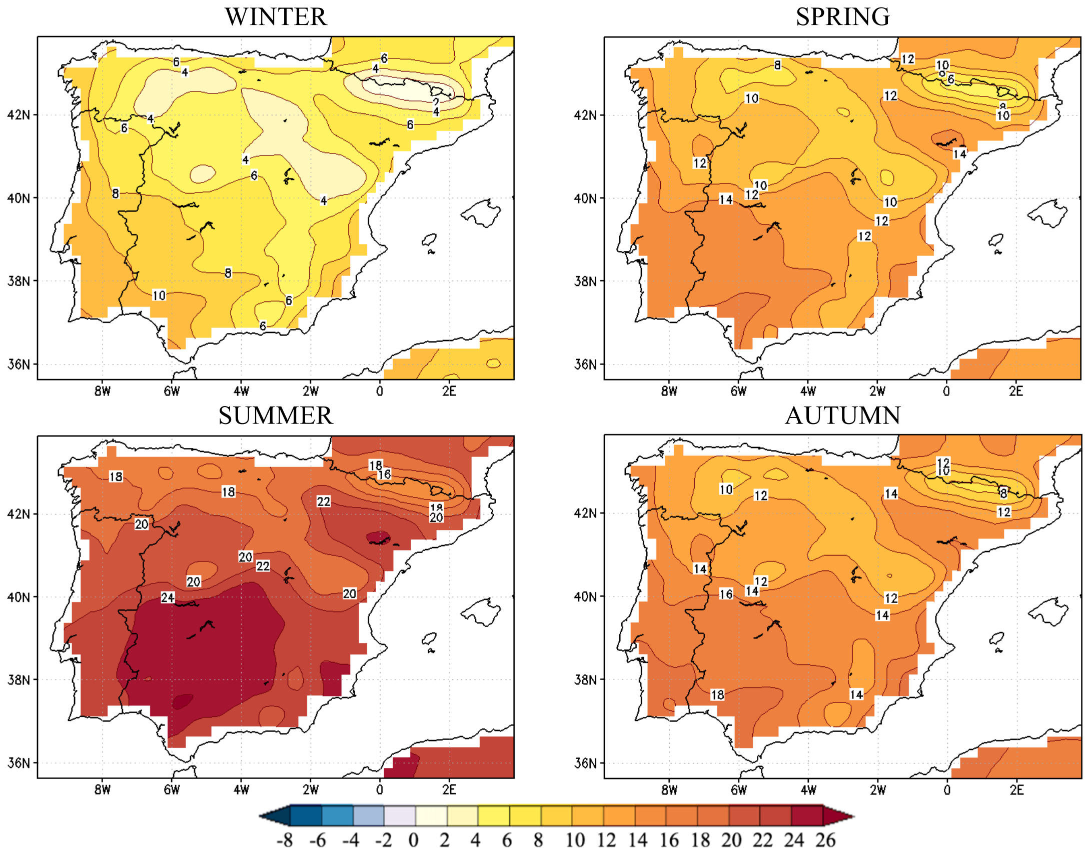


Figure 3. 4 The climatology of seasonal near surface temperature over the Iberian Peninsula for the evaluation period 1981–2005 based on the E-OBS dataset. Unit: °C

The Figures 3.5–3.8 show the seasonal mean temperature bias and the temporal correlation of seasonal temperature over the Iberian Peninsula. The seasonal mean temperature bias is calculated as the difference between the seasonal mean temperature from RCA4 driven by ERA-Interim and the seasonal mean temperature from ERA-Interim/E-OBS/CRU datasets (left column). The temporal correlation of seasonal temperature is calculated between seasonal temperature time series from RCA4 driven by ERA-Interim and the seasonal temperature time series from ERA-Interim/E-OBS/CRU datasets (right column). At first sight on the Figures 3.5–3.8 we can observe that summer is the only season, when warm and cold biases are almost equally represented over the peninsula. In the rest of the seasons, the cold bias is prevalent all over the domain.

Figure 3.5 shows the spatial distribution of mean temperature bias and the temporal correlation of temperature for **winter**. Generally, the RCM underestimates the mean temperature over most of the domain, specifically, the cold bias against the E-OBS and the CRU is typically between -3 °C and 0 °C. Compared to the ERA-Interim the model gives slightly bigger negative biases, with a maximum cold bias over the Pyrenees (-8 °C). In every map, there are slightly higher cold bias values on the S–SW part of the peninsula. The correlation coefficient (r) is lower than in summer, but typically higher than 0.8 over the entire domain. The amplified cold bias over high mountainous areas (e.g., Pyrenees) (r = 0.6–0.8), is probably due to the relative lack of high-elevation observing stations and the scarcity of fine-scale modelling over complex terrain. Also, the imperfect reanalysis representation of orographic features and the different resolutions in the datasets might contribute to the higher absolute bias, as Torma *et al.* (2011) pointed out in the case of Alps in a similar study for the Carpathian Basin.

In **summer** (Fig. 3.7), the RCM temperature bias against E-OBS observations is typically between -1 °C and 1 °C across most of the domain, with more warm bias around the central areas and towards the south. Comparing the RCM simulations to ERA-Interim and CRU, the bias is typically between -2 °C and 1 °C, with more heterogeneous pattern. On the northern edge of the peninsula along the coast the cold bias reaches -3 °C and, on the contrary, on the SW part of the domain there are some spots with warm bias reaching 2 °C. These are generally related to topographic features, such as the Pyrenees on the northeast (cold bias), the Ebro basin in the foreground of Pyrenees (warm bias), or the basin of Guadalquivir (warm bias) in between the Sierra Morena and Baetic Mountains on the south. Comparing the RCM simulations to ERA-Interim, noticeably high deviations (> -6 °C) occur over the mountainous areas of Pyrenees and near to the high mountains of Sierra Nevada on the SE. The correlation coefficient between the seasonal temperature from RCM simulations and from the observational datasets is the highest on the SW part of the IP (r > 0.9), that slightly weakens towards NE.

The transition seasons, **spring** and **autumn** (Fig. 3.6, 3.8), have very similar bias patterns and correlation values. The difference maps with E-OBS show a more homogenous pattern of bias, with a prevalent cold bias of typically -2–0 °C for both seasons. The comparison with CRU resulted in similar values. Comparing the simulations to ERA-Interim, slightly larger bias values are present, with maximum cold bias over the Pyrenees (> -5 °C) and warm bias in the basin of Ebro and Guadalquivir (typically 1–2 °C) in both seasons. The temporal correlation of seasonal temperature is higher than 0.9 over most of the domain for both transition seasons suggesting a very good performance of the RCM in reproducing the year to year variability in these seasons.

The evaluation metrics support the previous findings that the RCM has highest spatial mean bias values (*BIAS*) as well as spatial variability of bias (*BIASSD*) against the ERA-Interim as reference, in each season. The highest spatial mean bias occurs in spring (*BIAS* = -1.7 °C, *MAE* = 1.8 °C) with a spatial variability of *BIASSD* = 1.5 °C and highest absolute value of grid-point difference (*95%-P* = 4.1 °C). The 95% percentile indicates the highest absolute bias values without considering the 5 % of extremities that in present case mainly occur in the mountainous regions.

The lowest values of evaluation metrics are found when comparing the RCM simulations to E-OBS. The lowest spatial mean bias occurred in summer (*BIAS* = -0.1 °C), however, the bias pattern had a high variability (*BIASSD* = 1.1 °C, *95%-P* = 2.4 °C). As the higher mean absolute error (*MAE* = 0.8 °C) shows, the fairly equal amount of ±signs over the domain cancelled out resulting in a smaller *BIAS*. The second lowest value of spatial mean bias is -1.1 °C, with 0.4 °C of spatial variability (*BIASSD*), and 1.8 °C of 95 % percentile (*95%-P)* in autumn. It is worthwhile mentioning that the *BIAS* and *MAE* indicated fairly the same magnitude of bias regarding each reference and each season except summer, when *MAE* was considerably higher than the *BIAS*. The seasonal values of evaluation metrics are summarised in Table 3.3 at the end of section 3.3, as on overview of the evaluation results.

To sum up, the RCA4 driven by “perfect boundary conditions” reproduced well the seasonal mean temperature climatology over the Iberian Peninsula, however considerable deficiencies are also revealed by this analysis. A predominant cold bias occurs in most of the seasons all over the domain, except summer, when warm and cold biases are present in a fairly equal amount over the peninsula. The seasonal absolute bias value is typically 1–2 °C, with larger bias values (up to 5–8 °C) over high mountainous regions, e.g. the Pyrenees. Based on the evaluation metrics, in general, the simulations show larger bias against the ERA-Interim reanalysis than the CRU and E-OBS observational data.

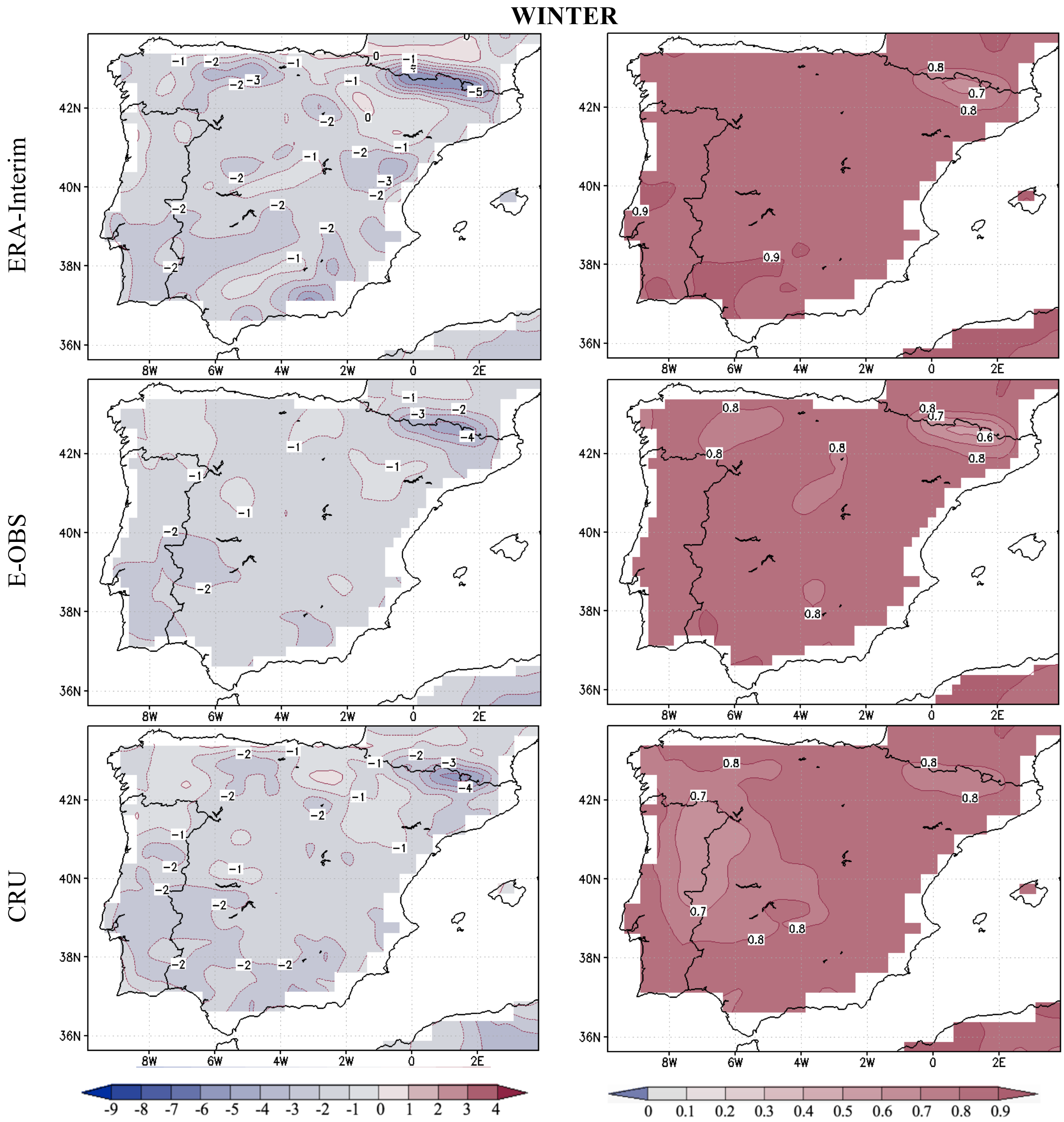


Figure 3. 5 The winter mean temperature bias and the temporal correlation of winter temperature over the Iberian Peninsula for the evaluation period 1981–2005. The winter mean temperature bias is calculated as the difference between the winter temperature mean from RCA4 forced by ERA-Interim and the winter temperature mean from ERA-Interim/E-OBS/CRU datasets (left column, unit: °C). The temporal correlation of winter temperature is calculated between the winter temperature from RCA4 forced by ERA-Interim and the winter temperature from ERA-Interim/E-OBS/CRU datasets (right column).

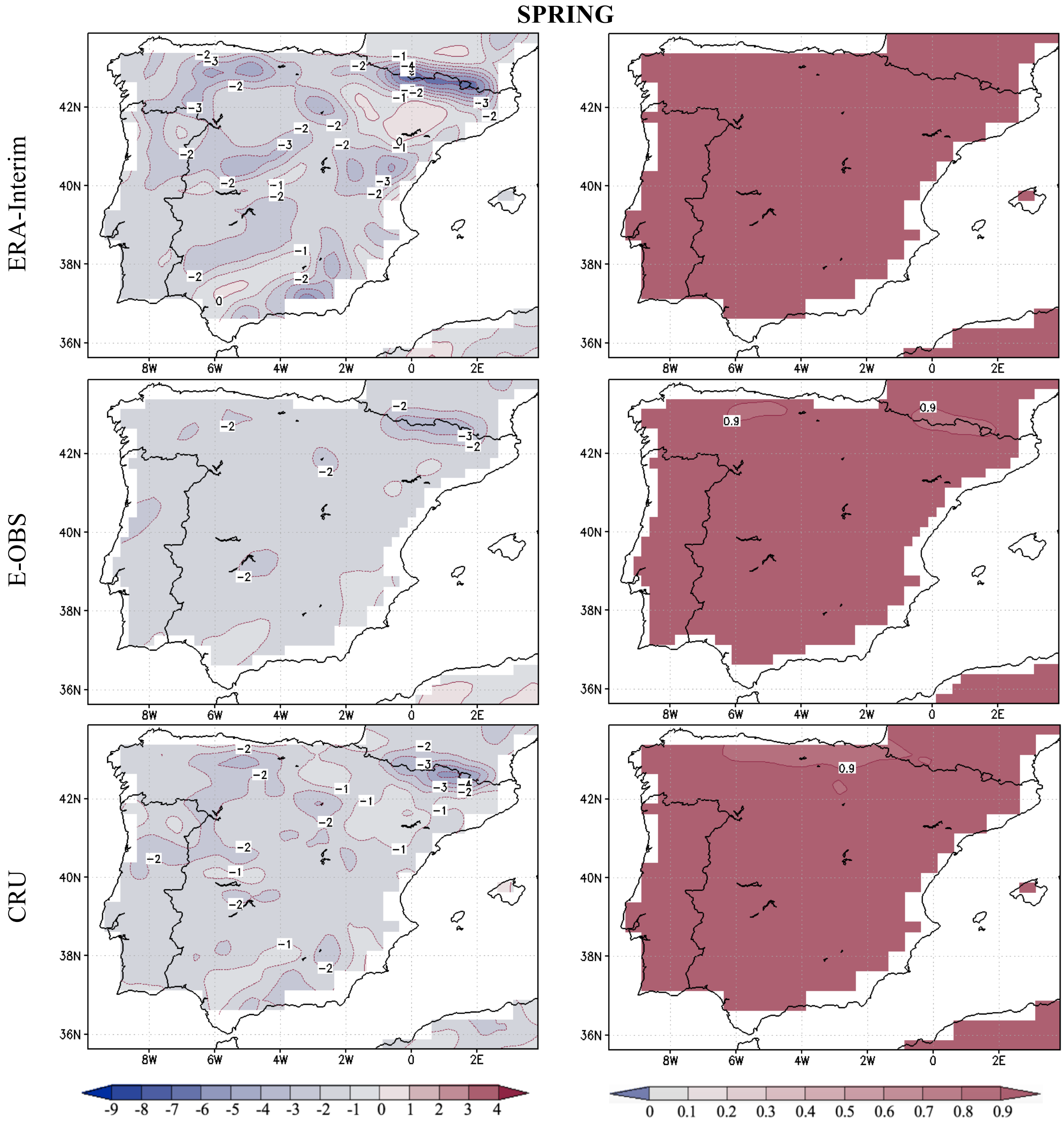


Figure 3. 6 The same as Figure 3.5 but for spring.

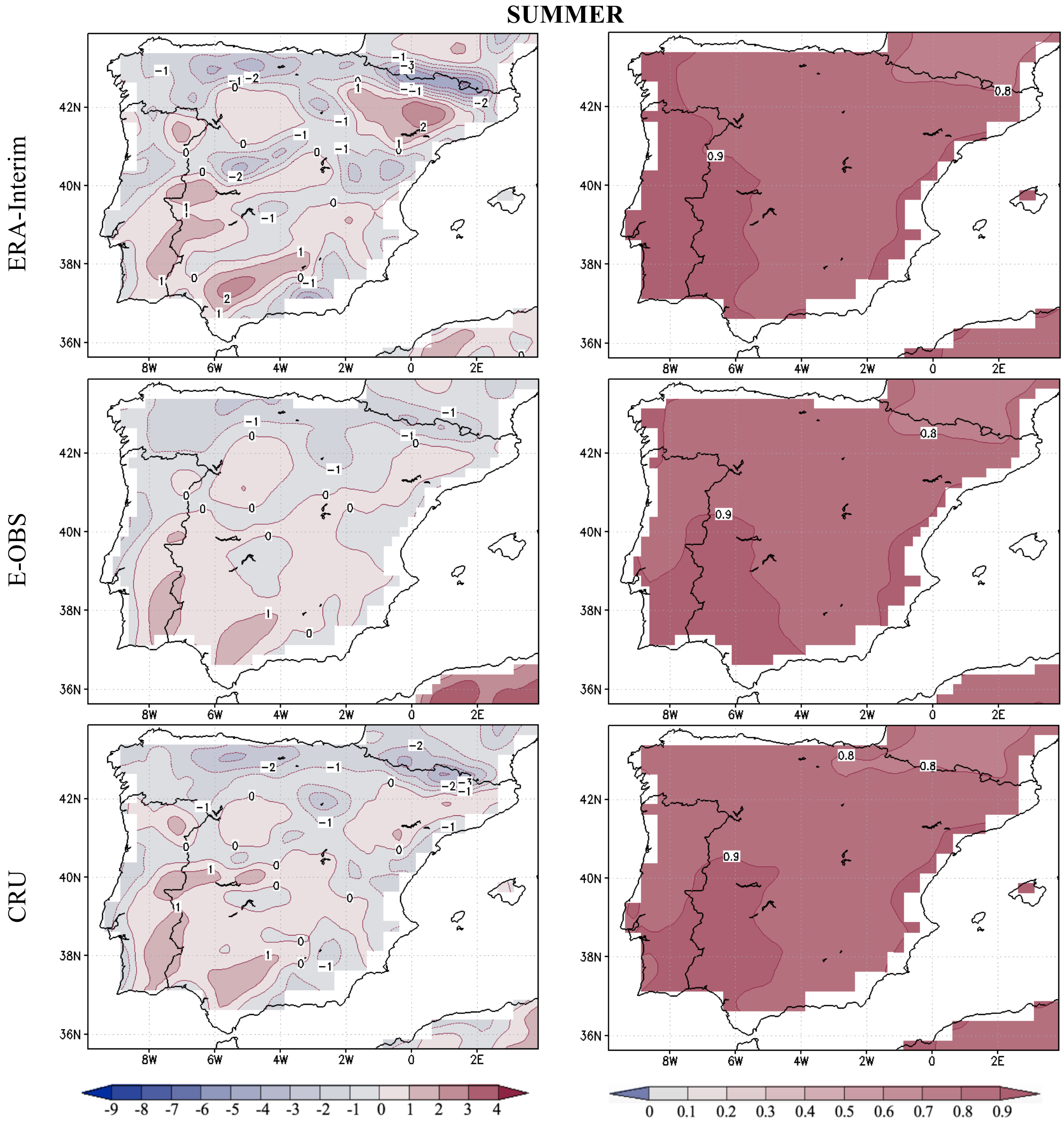


Figure 3. 7 The same as Figure 3.5 but for summer.

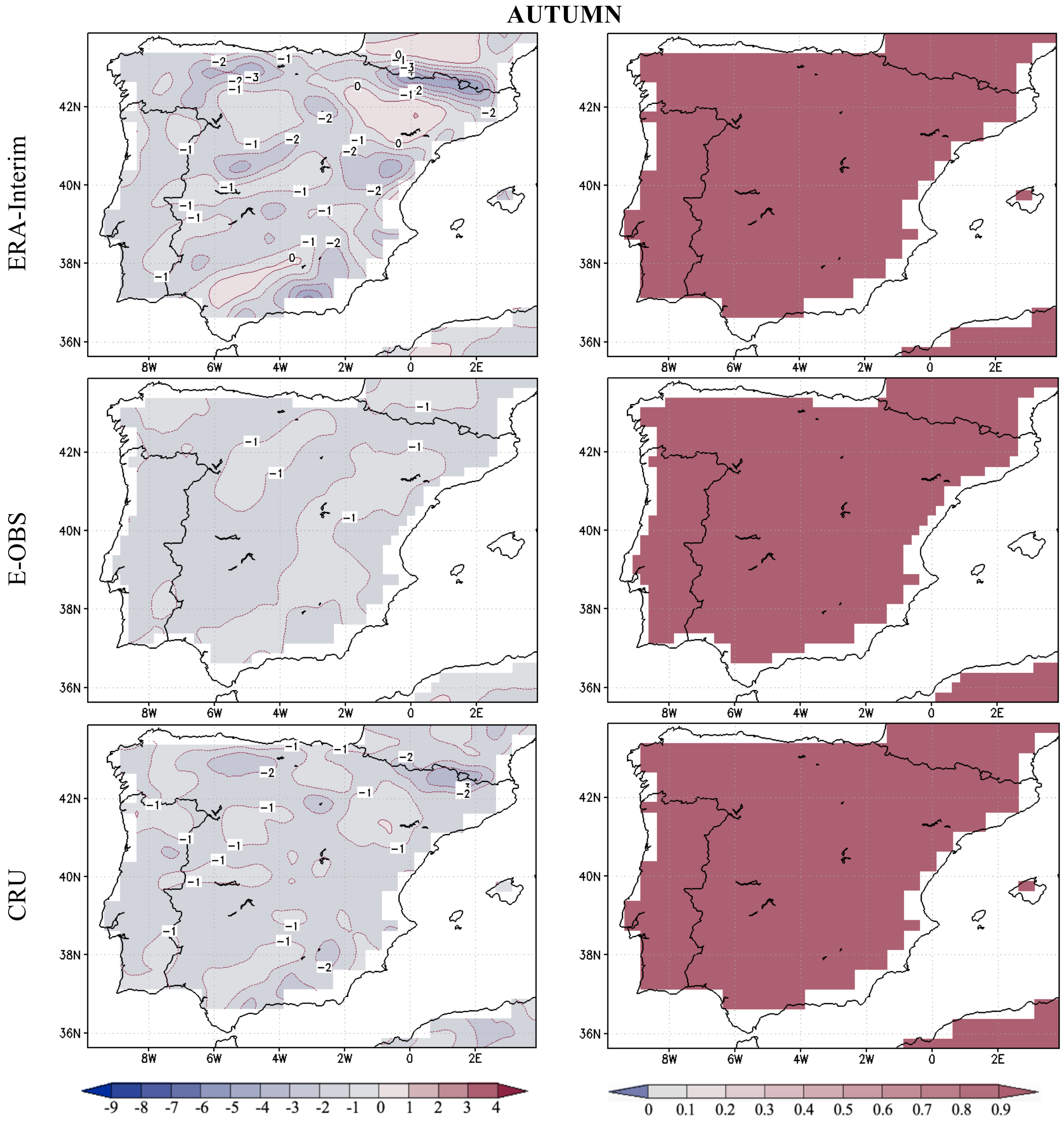


Figure 3. 8. The same as Figure 3.5 but for autumn.

3.3.2 Evaluation of GCM-RCM: GCM-driven RCM simulations vs. evaluation run

In this section (evaluation Phase 2), to evaluate the performance of RCM under different driving GCMs, five individual GCM-driven RCM simulations and the ensemble mean of these GCM-driven simulations are analysed. For this, historical runs (RCA4 simulations driven by GCMs with historical forcing, see description in section 3.2.2.2) are compared to the evaluation run (reanalysis-driven RCA4 simulations) over the evaluation period 1981–2005. In this way, the bias introduced by the GCM in the RCM model output can be estimated. First, the annual cycle is analysed, in order to gain an overview on the model bias averaged over the IP for each month. Second, the seasonal spatial pattern of mean temperature bias (GCM-RCM historical runs vs. RCM evaluation run) is described in form of difference maps. The comparison was carried out on the native high-resolution grid (0.125°) of the RCA4 model simulations. For the sake of comparability between evaluation phases, the seasonal mean temperature bias maps are drawn with the same colour scale as in the previous and forthcoming sections.

3.3.2.1 Mean annual cycle

To analyse the mean annual cycle of the GCM-driven RCM simulations, I calculated the spatial averages of monthly mean temperatures over the Iberian Peninsula for the evaluation period 1981–2005. In Figure 3.9 the five historical runs and the ensemble mean (Eq. 3.10) of these historical runs are compared to the RCM evaluation run. As Fig. 3.9 shows, each of the five GCM-driven simulations systematically underestimates the monthly mean temperature, with a strong cold bias in the warm part of the year. The flattening of the annual cycle can be observed as the winter temperatures are only slightly underestimated (and in some cases even overestimated) in contrast to the strongly underestimated summer temperatures.

Figure 3.10 presents the mean bias introduced to the simulations by the GCMs, calculated as the difference of the five GCM historical runs versus the RCM evaluation run. By subtracting the RCM simulation forced by “perfect boundary conditions” from the GCM-driven RCM simulations the magnitude of error attributed to the GCMs can be evaluated. CNRM and ICHEC tend to be at the high end of the bias range in each month, while HADGEM2, IPSL and MPI give moderated biases.

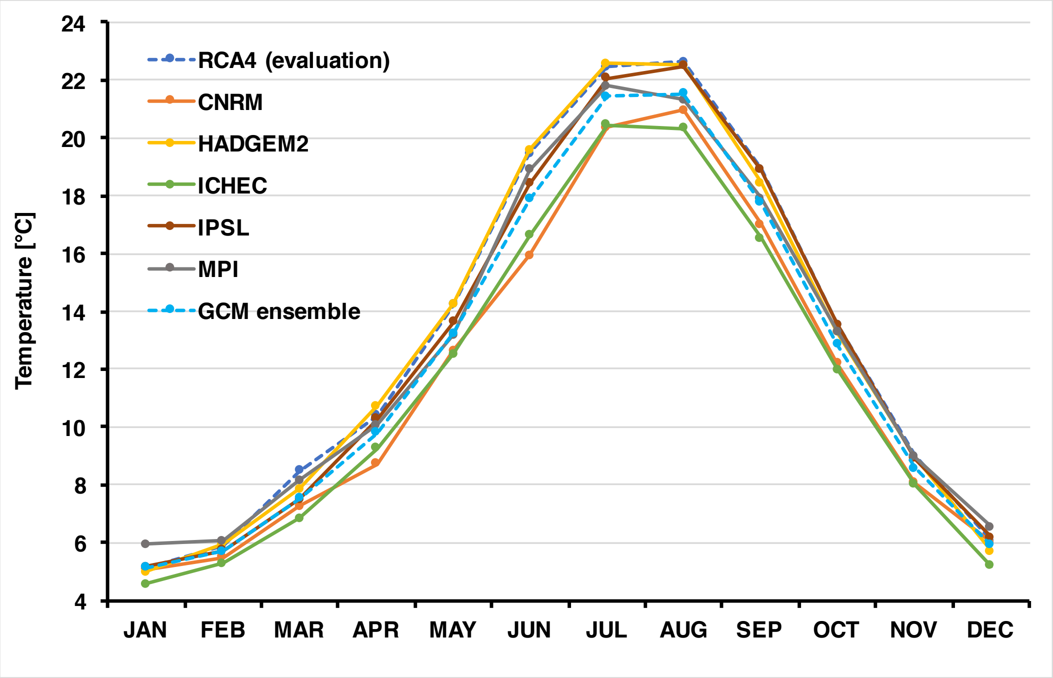


Figure 3. 9 Spatial averages of monthly mean temperatures over the Iberian Peninsula for the evaluation period 1981–2005. The evaluation run, the five GCM-driven historical runs and the ensemble mean of the five historical runs are compared here. The details of the models can be found in Table 3.1.

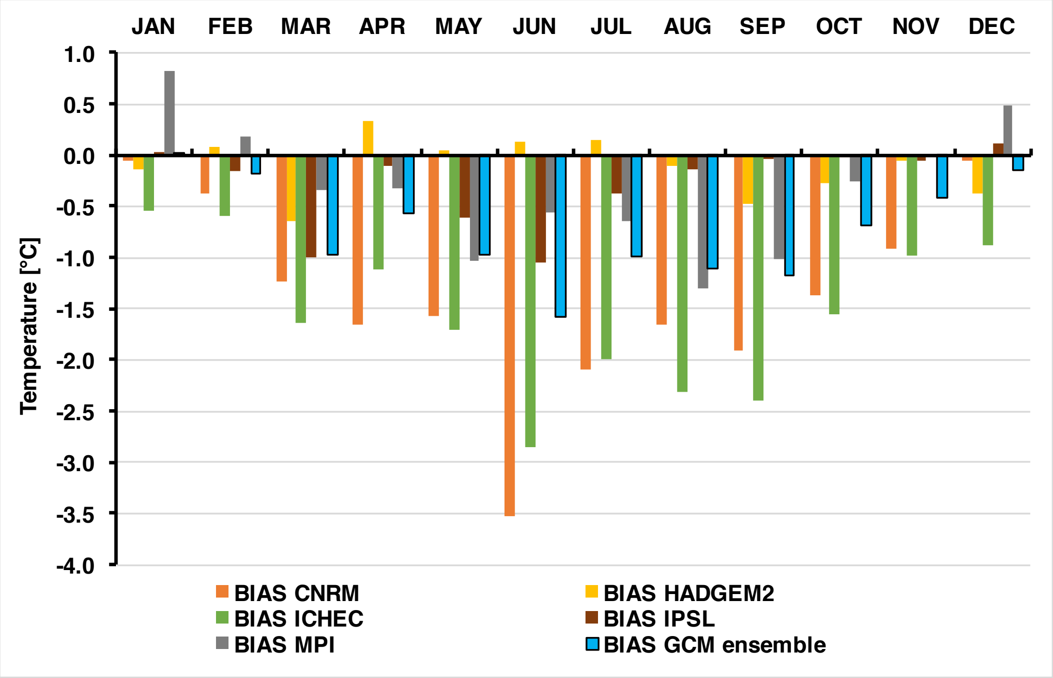


Figure 3. 10 The mean bias introduced to the simulations by the GCMs, calculated as the difference of the five GCM historical runs versus the RCM evaluation run. The estimated bias of the ensemble mean is also added. The details of the models can be found in Table 3.1.

In most of the cases, the GCM-driven RCM simulations are biased in the same direction (underestimation), however they have a wide spread in the amount of bias. For this reason, the ensemble mean of the five GCM-driven runs is also added to the graphs to evaluate the joint performance of the five historical runs. Based on the ensemble, the estimated mean bias attributed to the GCMs is -0.7 °C (SD = 0.5 °C) during the year, with the highest value in June (-1.6 °C) and the lowest in January (0 °C).

3.3.2.2 Spatial patterns of simulated seasonal temperature variability

To examine the bias pattern over the IP attributed to the GCMs that provided boundary conditions to the simulations, the seasonal mean temperature bias maps are drawn similar to the previous section 3.3.1.2. The seasonal mean temperature of each GCM-driven historical run was calculated, and the seasonal mean of the evaluation run was subtracted. The ensemble mean of the five historical runs was also added to the analysis to see the level of agreement between the GCM-RCM simulations.

The bias maps (Figures 3.11 to 3.14) show the seasonal mean temperature bias for the five historical runs and for the ensemble of these runs. In each season, all the GCM-driven runs have a prevailing cold bias of different magnitudes over the domain. The only exception is the MPI in winter, which can be associated with a warm bias of typically about 0–1 °C over the peninsula. In **winter** (Fig. 3.11), most of the GCM-driven runs have a cold bias around -1–0 °C, and over the Pyrenees an absolute bias of 1–2 °C magnitude with a positive sign in IPSL and MPI, and negative sign in CNRM and ICHEC. The ensemble mean shows warm bias (typically 0–1 °C) over the Ebro basin and the northern coast. In **summer** (Fig. 3.13), an extensive cold bias (typically -4– -3 °C) can be seen in case of CNRM over the whole domain, while HADGEM2 has a warm bias of around 0–2 °C on the northern part of the peninsula. The ensemble mean shows a cold bias around -2–0 °C in general, with a rather small peak of negative values indicating the Pyrenees.

The **transition seasons** have similar patterns, shown in Fig. 3.12 and Fig. 3.14. CNRM, ICHEC and MPI have a homogenous cold bias over the peninsula typically between -2–0 °C. HADGEM2 and IPSL can be attributed with warm bias of around 0–1 °C on the northern and eastern parts of the peninsula, respectively. The Pyrenees appears as a relatively cold spot (up to -2 °C) in the ensemble mean of spring, but not autumn.

The evaluation metrics for the ensemble mean give the spatial mean bias for winter -0.1 °C (*BIASSD* = 0.3 °C), for spring -0.9 °C (*BIASSD* = 0.2 °C), for summer -1.3 °C

(*BIASSD* = 0.4 °C) and for autumn -0.8 °C (*BIASSD* = 0.3 °C). The low absolute value of *BIAS* in winter is probably mainly related to the MPI, that alone had a high positive value against the relatively smaller negative biases of other GCM-driven runs. The *MAE* gives slightly bigger value for winter (*MAE* = 0.3 °C), but for the other seasons it is equal to the absolute value of *BIAS*. The highest mean absolute bias appears in summer (*MAE* = 1.3 °C), that is not surprising looking at the extremely high cold bias in case of CNRM alone (Fig. 3.13). The 95 % percentile of mean absolute bias in the ensemble is the highest in summer too, *95%-P* = 1.8 °C. An overview of the evaluation metrics can be found in Table 3.3, at the end of section 3.3.

To sum up, in general, the ensemble of GCMs introduced more cold bias to the RCA4 simulations, especially in the warm half of the year. The spatial pattern and amplitude of bias differ among historical simulations, indicating the differences in structure and representation of climate mechanisms in the GCMs. Although with the averaging among simulations some geographical features disappeared from the bias map, the ensemble mean fairly illustrates the main direction of GCM biases. Hence, the ensemble mean is a robust tool for future projections, balancing between the capabilities and drawbacks of different GCMs. Nevertheless, when using the ensemble for future projections, the spread between simulations need to be assessed to indicate the level of agreement among the future GCM-RCM runs.

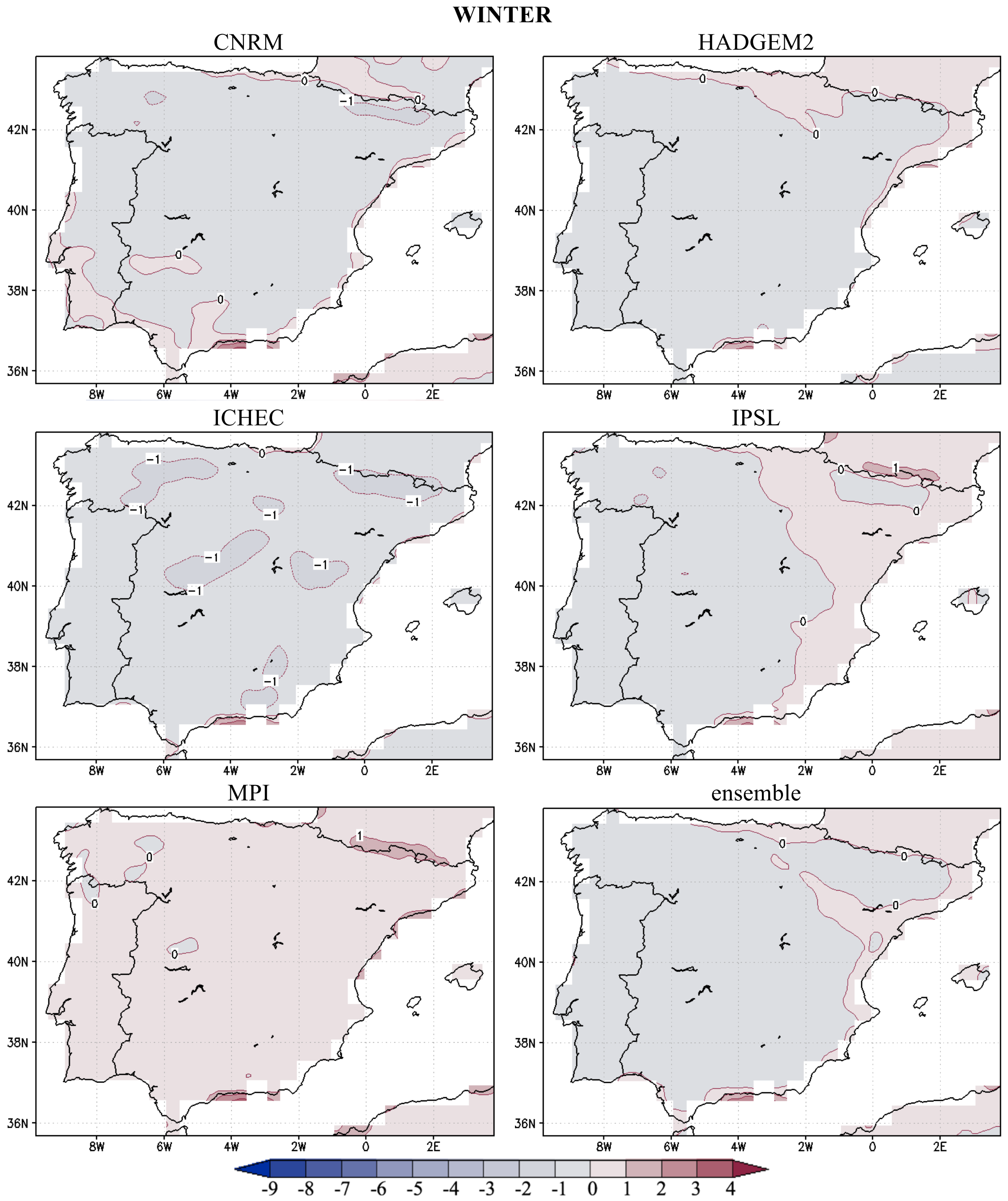


Figure 3. 11 Winter mean temperature bias of the five GCM-driven historical runs versus the evaluation run. The winter mean temperature bias is calculated as the difference between the winter temperature mean from RCA4 forced by the five GCMs and the winter temperature mean from RCA4 forced by ERA-Interim. The bias map of the ensemble mean is also added. Unit: °C.

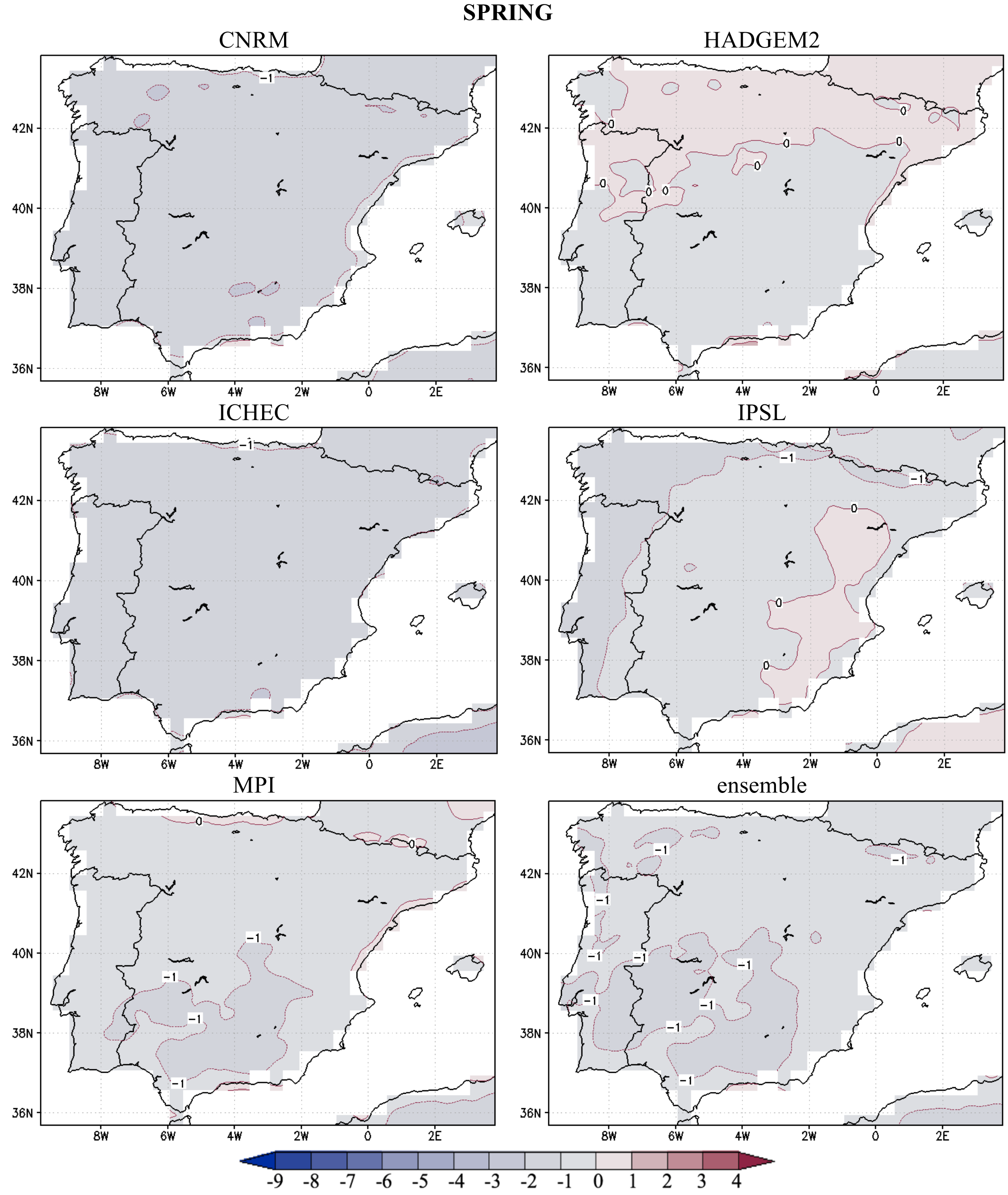


Figure 3. 12 The same as Figure 3.11 but for spring.

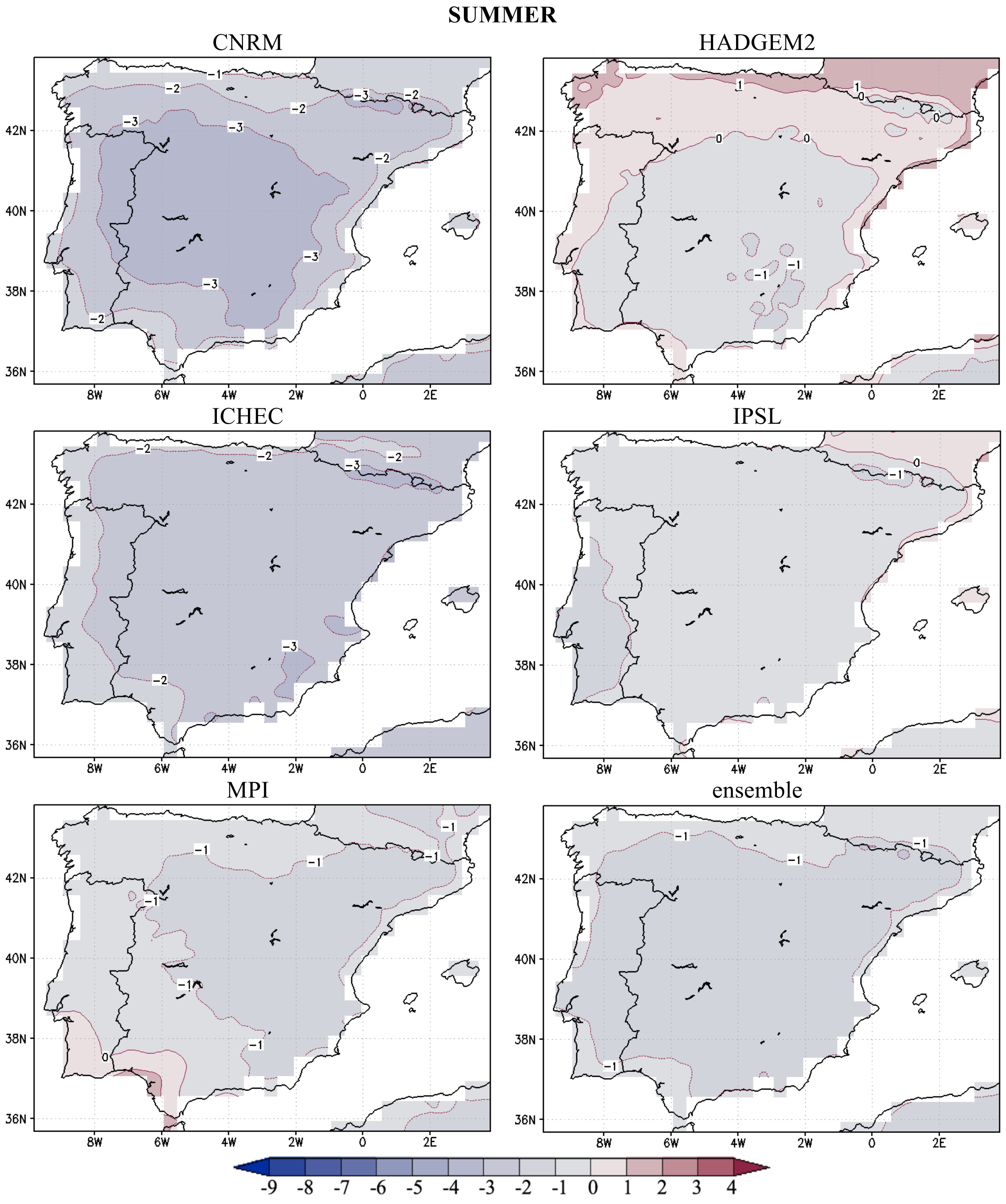


Figure 3. 13 The same as Figure 3.11 but for summer.

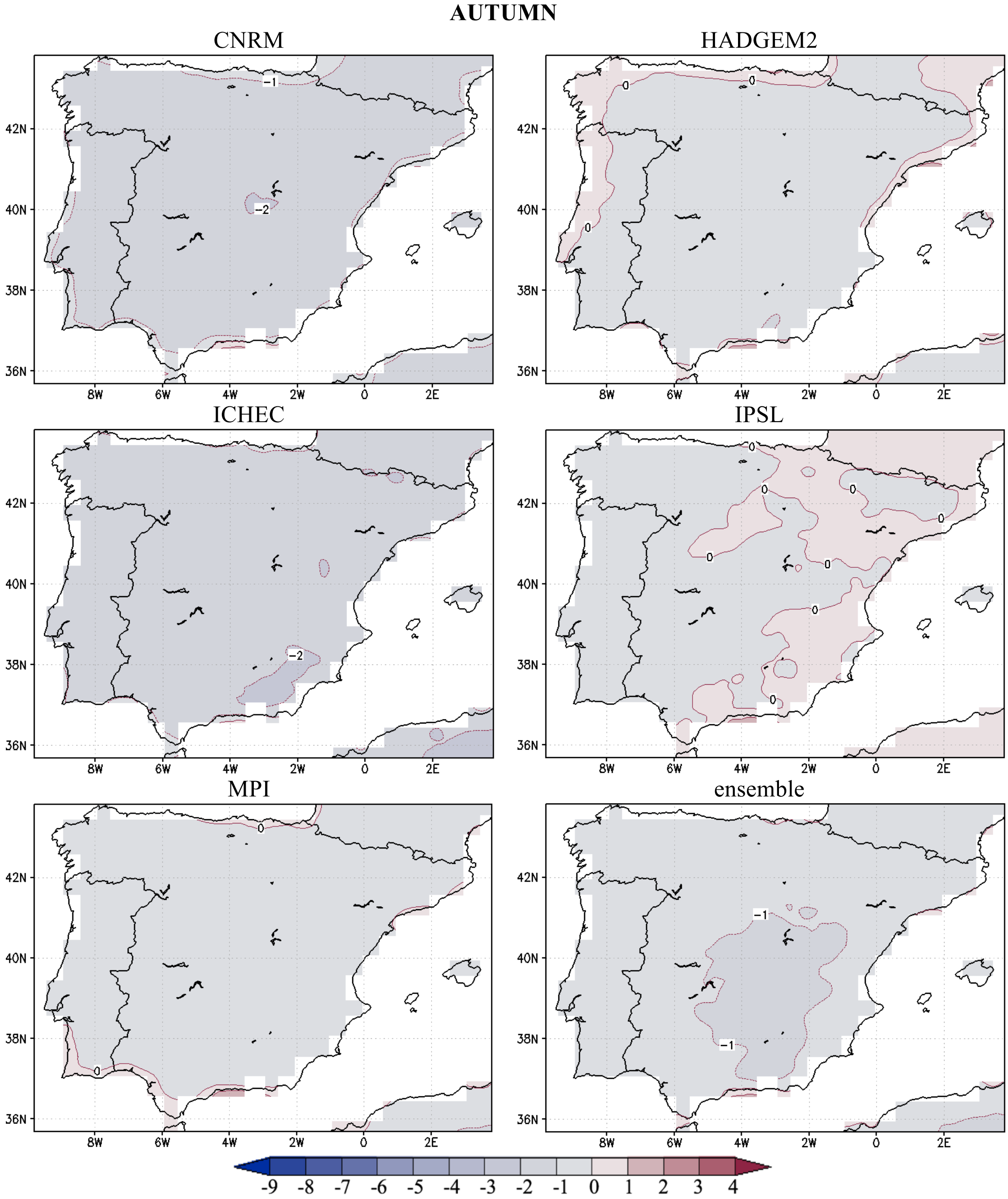


Figure 3. 14 The same as Figure 3.11 but for autumn.

3.3.3 Evaluation of ensemble mean of five GCM-driven RCM simulations vs. observations

In the last phase of the evaluation, to give an estimate of the overall bias of the GCM-driven RCA4 simulations, the ensemble mean of historical runs (ensemble of five GCM-driven RCA4 simulations, Eq. 3.10) is compared to the observations. Based on the comparison of the observational and reanalysis datasets in the section 3.3.1, the E-OBS database is used as a reference. First, the annual cycle of the ensemble mean of five historical runs is compared to the observations. Second, the seasonal mean temperature bias maps illustrate the overall bias pattern over the IP. The analysis was carried out on the 0.25° grid of E-OBS. For the sake of comparability between validation phases, the seasonal bias maps are drawn with the same colour scale as the previous bias maps.

3.3.3.1 Mean annual cycle

In Figure 3.15 the annual cycles of the RCA4 evaluation run, the ensemble mean of the five GCM-driven historical runs and the E-OBS observations are drawn. It is clear, that the RCM simulations—either forced by “perfect boundary conditions” or by GCMs—underestimate the mean temperature over most of the domain, however, the magnitude of the bias attributed to the RCM and GCMs is different. As Fig. 3.9 shows, the individual GCM-driven simulations have their strongest cold bias in the warm half of the year. For the evaluation run, the case is the opposite, RCA4 has its strongest cold bias in the cold part of the year, as Fig. 3.3 and Fig. 3.15 show. Consequently, the ensemble mean of the five GCM-forced RCA4 simulations against the observations (including the bias from both models) have an evenly distributed overall bias over the seasons.

The ensemble mean of the five GCM-forced RCA4 simulations systematically underestimates the mean temperature throughout the year, with an average of -1.8 °C (SD = 0.5 °C), compared to E-OBS. For the sake of comparison, the mean bias attributed to the RCA4 compared to E-OBS in section 3.3.1 was -1.1 °C (SD = 0.7 °C) and the mean bias attributed to the driving GCMs in section 3.3.2 was -0.7 °C (SD = 0.5 °C). Nevertheless, the exact bias values given here should not be “over-interpreted” since to some degree they could originate from internal random variability (Kotlarski *et al.*, 2014) not assessed here.

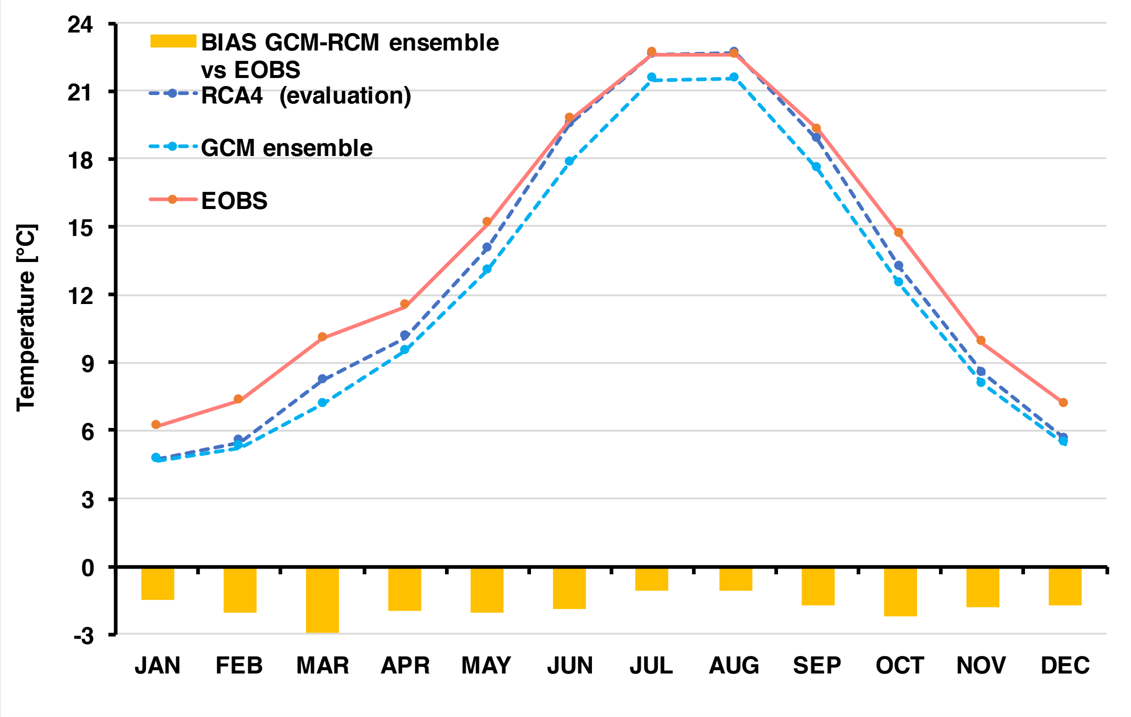


Figure 3. 15 The annual cycles of the RCA4 evaluation run, the ensemble of GCM-driven historical runs and the E-OBS observations (line chart). The overall mean bias of the ensemble of GCM-forced RCA4 simulations versus observations (E-OBS) is presented as column chart.

3.3.3.2 Spatial patterns of simulated seasonal temperature variability

Figure 3.16 presents the seasonal mean temperature bias maps calculated from the ensemble of GCM-driven simulations versus E-OBS (Fig. 3.16 left panel) and the same bias maps for the reanalysis-driven RCA4 versus E-OBS (Fig. 3.16 right panel). Comparing the left and right panel, we can see to what extent the GCM ensemble enhanced the RCM bias when compared to the same observational reference. In general, the GCMs introduced more cold bias to the simulations, increasing the absolute bias values of RCM with about 0.5–1.0 °C, especially in the cold half of the year. In the RCM evaluation run in summer the cold and warm biased areas covered almost equal parts of the domain, but with the GCM-forcing the warm bias weakened—in some cases even turned into negative values—, and the cold bias became stronger and widespread over the domain. Overall, the bias pattern did not change substantially due to the boundary conditions introduced by the GCMs, for example, the topography related biases such as the cold spot over the Pyrenees are still clearly recognizable, if not intensified.

Looking further into the overall bias of the ensemble of GCM-forced RCA4 simulations, we shall take a closer look at the left panel of Fig. 3.16. The systematic error is a general cold bias, typically between -1 °C and -3 °C. According to the evaluation metrics, the overall spatial mean bias of GCM-RCM is slightly lower in summer (*BIAS* = -1.4 °C, *BIASSD* = 1.1 °C) and winter (*BIAS* = -1.8 °C, *BIASSD* = 0.7 °C), and higher in the transition seasons, spring (*BIAS* = -2.3 °C, *BIASSD* = 0.7 °C) and autumn (*BIAS* = -1.9 °C, *BIASSD* = 0.5 °C). In each case the *MAE* is equal to the absolute value of *BIAS* except summer, when it is slightly higher (*MAE* = 1.6 °C) than the *BIAS* (as it is expected due to the sign cancellation explained in section 3.3.1.2). The 95 % percentile of absolute bias is the highest in spring, 3.2 °C. An overview of evaluation metrics is presented in Table 3.3, summarizing the model biases in the RCM simulations in response to different forcing data.

To sum up, the ensemble of GCM-driven RCA4 simulations systematically underestimate the temperature over the Iberian Peninsula, with an absolute bias typically between 1 °C and 3 °C. The spatial pattern of bias depends on the season—except the cold spot of the high mountainous region of Pyrenees that can be identified in each season. Because of the predominant cold bias, the direct values of future climate projection cannot be used without correcting for this systematic error. When examining changes in the mean climatologies—the difference between the mean temperatures of the future period and the current period—there is no need for bias correction, since by calculating the difference between the two periods (i.e. subtracting the 30-year seasonal temperature mean of current climate (1971–2000) from the 30-year seasonal temperature mean of the future climate) the structural error of models is eliminated (Szépszó *et al.*, 2014). Through this method it is assumed that the model biases are stationary in time (discussed in section 3.5.3). The so-called delta-approach is used widely when assessing future changes of climate variables on a monthly, seasonal or yearly scale (Krüzselyi *et al.*, 2011; Önol *et al.*, 2014; Szépszó *et al.*, 2014).

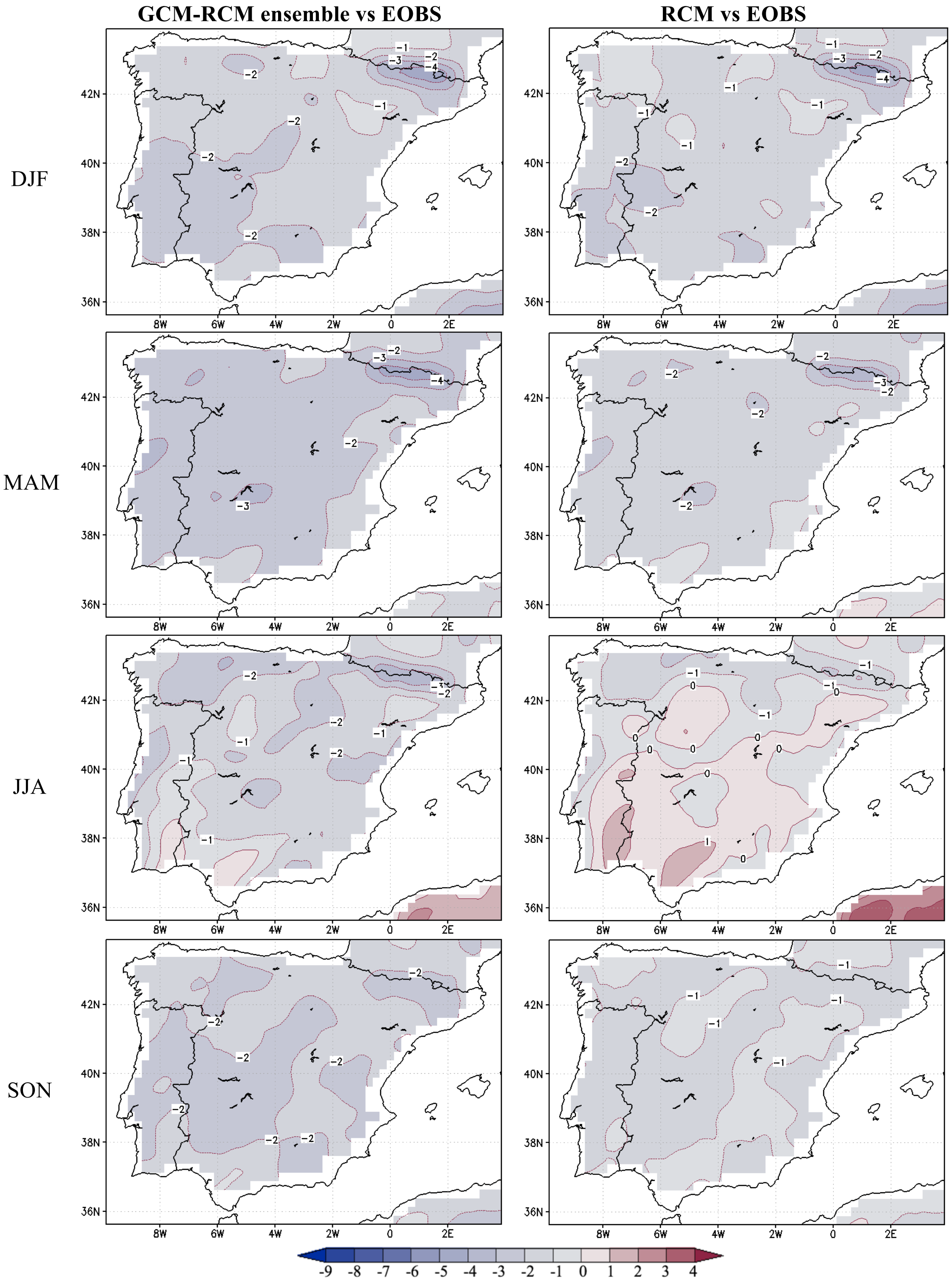


Figure 3. 16 The seasonal mean temperature bias maps calculated from the ensemble of GCM-driven simulations versus E-OBS (left panel) and the same bias maps for the reanalysis-driven RCA4 versus E-OBS (right panel). Unit: °C.

Table 3. 3 Summary of evaluation metrics by seasons and by phases of the evaluation. The second column contains the model or dataset that provided boundary conditions for the RCM simulation and the third column further specifies this by the name of dataset/model in brackets. The evaluation metrics are defined in section 3.2.3.2.

Seas.	Eval.	Driving Model	Simulation	Eval. grid	Reference	*BIAS*	*BIASSD*	*MAE*	*95%-P*
WINTER	Phase1	“perfect boundary cond.”	RCA4(ERA-Int.)	0.25	ERA-Interim	-1.7	1.3	1.7	3.7
					EOBS	-1.6	0.7	1.6	2.7
					CRU	-1.7	1.1	1.8	3.4
	Phase 2	GCM	RCA4(CNRM)	0.125	RCA4(ERA-Int.)	-0.2	0.4	0.3	0.9
			RCA4(HADGEM2)			-0.2	0.3	0.3	0.5
			RCA4(ICHEC)			-0.7	0.4	0.8	1.2
			RCA4(IPSL)			-0.1	0.5	0.4	0.9
			RCA4(MPI)			0.5	0.3	0.5	0.9
			ensemble			-0.2	0.3	0.3	0.6
	Phase 3	GCM	ensemble	0.25	EOBS	-1.8	0.7	1.8	2.8
SPRING	Phase 1	“perfect boundary cond.”	RCA4(ERA-Int.)	0.25	ERA-Interim	-1.7	1.5	1.8	4.1
					EOBS	-1.4	0.6	1.5	2.3
					CRU	-1.5	1.1	1.6	3.3
	Phase 2	GCM	RCA4(CNRM)	0.125	RCA4(ERA-Int.)	-1.5	0.4	1.5	1.9
			RCA4(HADGEM2)			-0.1	0.3	0.2	0.6
			RCA4(ICHEC)			-1.5	0.3	1.5	1.9
			RCA4(IPSL)			-0.6	0.5	0.7	1.5
			RCA4(MPI)			-0.6	0.4	0.6	1.2
			ensemble			-0.9	0.2	0.9	1.1
	Phase 3	GCM	ensemble	0.25	EOBS	-2.3	0.7	2.3	3.2
SUMMER	Phase 1	“perfect boundary cond.”	RCA4(ERA-Int.)	0.25	ERA-Interim	-0.3	1.6	1.2	3.1
					EOBS	-0.1	1.1	0.8	2.4
					CRU	-0.3	1.4	1.1	2.9
	Phase 2	GCM	RCA4(CNRM)	0.125	RCA4(ERA-Int.)	-2.5	0.8	2.5	3.5
			RCA4(HADGEM2)			0	0.7	0.6	1.4
			RCA4(ICHEC)			-2.4	0.4	2.4	3
			RCA4(IPSL)			-0.5	0.4	0.6	1.2
			RCA4(MPI)			-0.8	0.5	0.9	1.5
			ensemble			-1.3	0.4	1.3	1.8
	Phase 3	GCM	ensemble	0.25	EOBS	-1.4	1.1	1.6	2.9
AUTUMN	Phase 1	“perfect boundary cond.”	RCA4(ERA-Int.)	0.25	ERA-Interim	-1.2	1.3	1.4	3.4
					EOBS	-1.1	0.4	1.1	1.8
					CRU	-1.3	1	1.4	2.9
	Phase 2	GCM	RCA4(CNRM)	0.125	RCA4(ERA-Int.)	-1.5	0.4	1.5	1.9
			RCA4(HADGEM2)			-0.3	0.4	0.4	0.8
			RCA4(ICHEC)			-1.7	0.3	1.7	2
			RCA4(IPSL)			-0.1	0.3	0.2	0.5
			RCA4(MPI)			-0.5	0.3	0.5	0.8
			ensemble			-0.8	0.3	0.8	1.1
	Phase 3	GCM	ensemble	0.25	EOBS	-1.9	0.5	1.9	2.6

3.4 Future projections

Since the ensemble mean of GCM-driven RCM simulations can provide robustness to the results, the projected change in temperature is analysed by using the ensemble of five GCM-driven RCA4 simulations for the mid-term (2041-2070) and long-term (2070-2100) future. As the evaluation results indicated a significant cold bias throughout the year, I calculated the change between the future and current climatologies using delta-approach, to rule out the systematic error of models, assuming that the bias is stationary in time (discussed in section 3.3.2). Thus, the future projections are quantified in form of seasonal change values and the calculated difference between the mean temperature fields are illustrated as change maps. The RCA4 took boundary conditions from five GCMs under two emission scenarios (RCP4.5, RCP8.5) from which the ensemble mean (Eq. 3.10) and spread (Eq. 3.11) of models was calculated. The ensemble is used to (a) assess future climate change over the Iberian Peninsula and (b) illustrate uncertainties in future climate change related to boundary conditions and emissions.

3.4.1 Analysis of spatially averaged mid- and long-term temperature change

In general, gradual increase in temperature is widely evident during the twenty-first century for each GCM and scenario simulation. A spider chart diagram (Fig. 3.17) was produced to show monthly climatologies of temperature change for the mid-term (2041-2070) and long-term (2070-2100) periods in respect to the current climate (1971-2000). Furthermore, the ensemble mean of spatially averaged monthly and seasonal temperature change was also calculated, to evaluate the robustness and spread of model results (Fig. 3.18, Table 3.4).

The future simulations in case of both scenarios indicate rising temperatures in all seasons, with a significant contrast between winter and summer. In general, the projected changes are 1–2 °C higher in summer months than those in winter months. More specifically, the warming signal is strongest in June-July-August-September-October and weakest in February and March. The RCA4 simulations driven by HADGEM2 and IPSL in general showed higher increase than the ensemble mean of the five GCM-driven RCM simulations, while the lowest values of temperature change was projected by the CNRM-driven simulation.

The monthly ensemble means under the RCP4.5 scenario indicate temperature rise of 1.1–2.5 °C for the mid-century and 1.6–3.1 °C for the end of the century. The change values under RCP8.5 scenario are 1.8–3.3 °C and 3.1–5.5 °C, respectively. The strongest increase in temperature is expected for September (5.5 °C by the end of century, RCP8.5), however this month has the highest spread of model simulations too (SD = 0.7–1.1 °C), as Fig. 3.17 and 3.18 show.

Looking at the seasonal scale, in general, the strongest warming is expected for summer that is followed by autumn, spring and winter, respectively, summarised in Table 3.4. The warming expected for summer under RCP4.5 is 2.2 °C and 2.7 °C for the mid- and long-term future, respectively, while under RCP8.5 it is 3.0 °C and 5.2 °C, respectively. The expansion of summer season warming effect is quite revealing since the autumn season has a stronger warming signal than winter and spring for both periods. Towards the end of century, the spread of the projected changes among the five members of ensemble increases in case of RCP8.5 in all seasons. In case of RCP4.5 the spread also increases in two seasons and in the other two seasons it does not change.

It is worth mentioning that the 2 °C global warming threshold marked in the Paris Agreement—aiming to limit global GHG emissions to keep global temperature rise well under this threshold (UNFCCC, 2015)—is expected to be exceeded in three seasons under RCP8.5 (in two seasons under RCP4.5) until mid-century. By the end of century following the RCP8.5 trajectory the target will be overrun in every season—in summer and autumn expecting more than doubled amount of temperature increase than the threshold. Even though he RCP4.5 stabilization scenario projects more moderated warming effect, the temperature rise is expected to reach the threshold in winter and spring, and even exceed the 2 °C in summer and autumn.

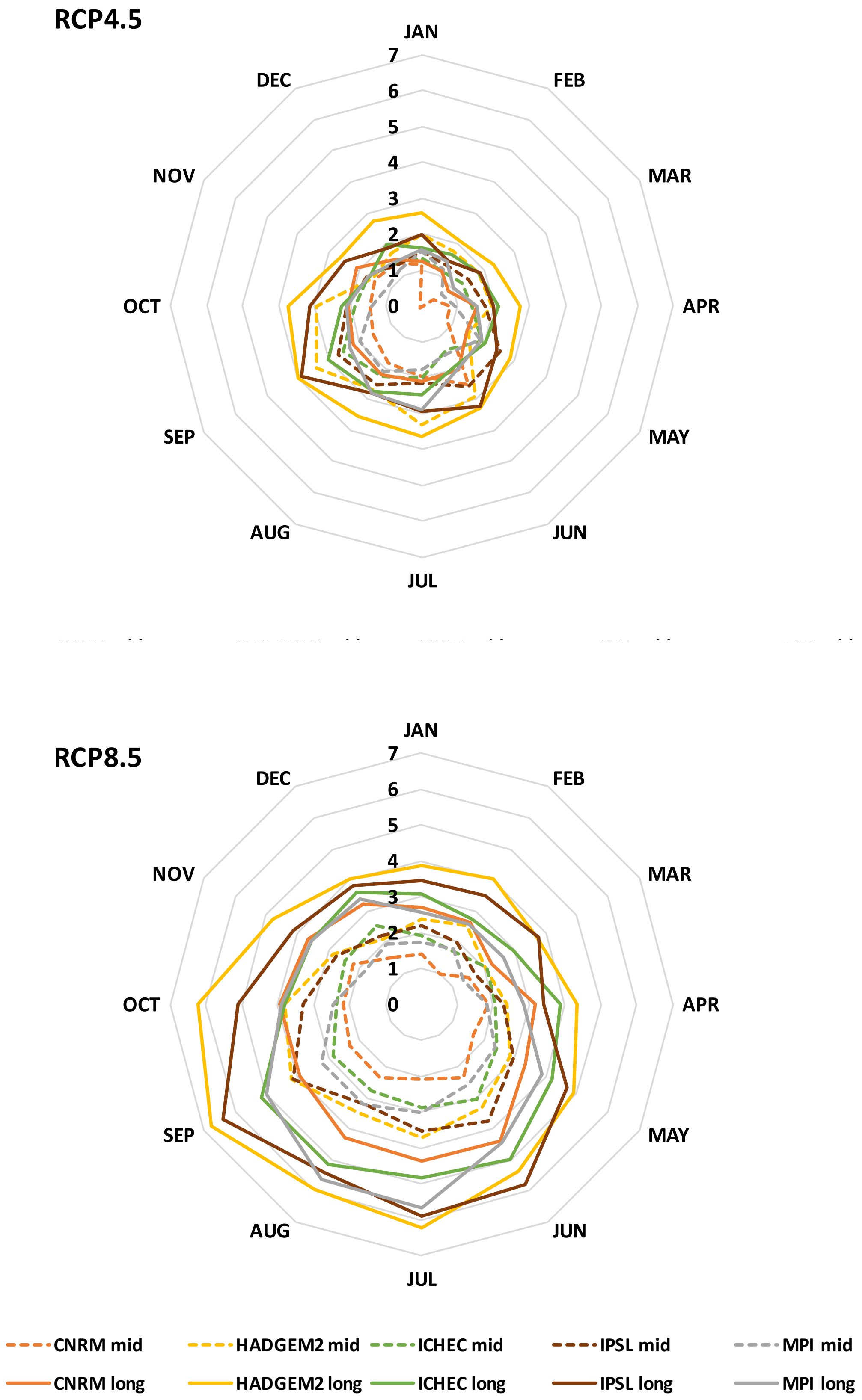


Figure 3. 17 Spatially averaged monthly temperature change [°C] for the mid-term and long-term 30-year periods under RCP4.5 and RCP8.5 climate scenarios over the Iberian Peninsula. The GCMs driving RCA4 are described in Table 3.1.

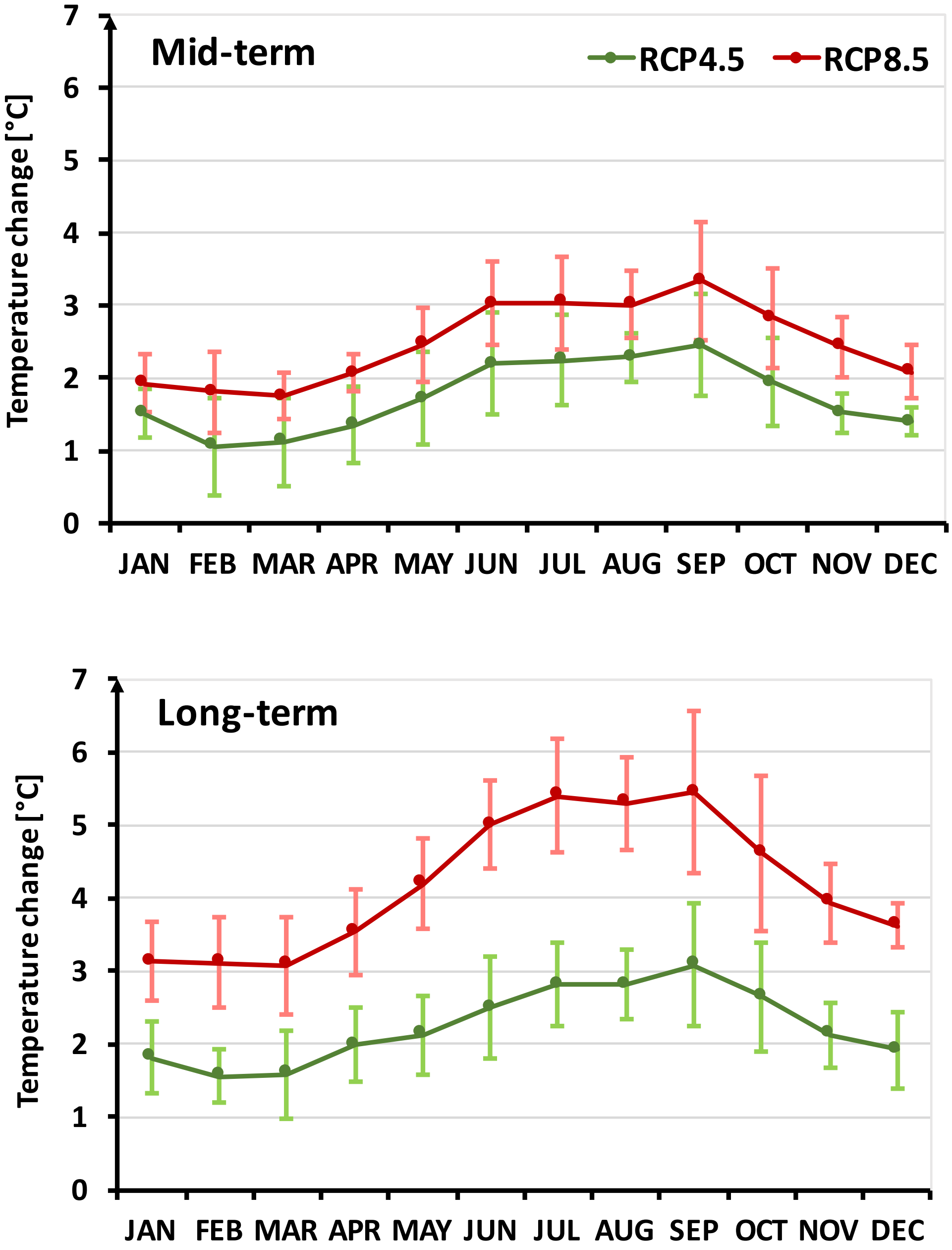


Figure 3. 18 Ensemble mean of spatially averaged monthly temperature change [°C] for the mid-term and long-term 30-year periods under RCP4.5 and RCP8.5 climate scenarios. The standard deviation bars represent the spread of the projected changes among the five members of ensemble.

Table 3. 4 The ensemble mean (ENSMEAN) and standard deviation (ENSSD) of spatially averaged seasonal mean temperature change [°C] based on five GCM-driven RCA4 simulations for the mid-term (2041–2070) and long-term (2071–2100) future in respect to current climate (1971–2000). The definition of ENSMEAN and ENSSD is given in section 3.2.3.2.

Scenario	**Season**	**Mid-term (2041–2070)**		**Long-term (2071–2100)**	
		ENSMEAN	***ENSSD***	***ENSMEAN***	***ENSSD***
RCP4.5	**DJF**	1.3	0.4	1.8	0.5
	MAM	1.4	0.5	1.9	0.5
	JJA	2.2	0.5	2.7	0.5
	SON	2.0	0.5	2.6	0.7
RCP8.5	**DJF**	1.9	0.4	3.3	0.5
	MAM	2.1	0.3	3.6	0.6
	JJA	3.0	0.5	5.2	0.6
	SON	2.9	0.6	4.7	0.9

3.4.2 Spatial pattern of seasonal temperature changes

Regarding the illustration of climate projections, I followed the recommendations of SMHI on presenting climate information in an easily understandable form to Climate Services users (*SMHI website*; Kjellström *et al.*, 2016). The ensemble mean (*ENSMEAN*) and the standard deviation of the ensemble (*ENSSD,* indicating the spread of ensemble members around the mean) are visualised in separate maps to provide information on the spread and robustness of climate projections in a simple way. An important indicator of robustness is the sign of change that can be presented through the proportion of models that point to the same direction (Kjellström *et al.*, 2016). Since in this case all the model projections pointed to the same direction regardless of the driving GCM or emission scenario (Fig. 3.19–3.22), here I do not dedicate a separate figure to this aspect.

Under the RCP4.5 scenario for the 2041–2070 period a quite homogeneous warming pattern is projected for the Iberian Peninsula, with an increase of about 1 °C in winter (Fig. 3.19) and spring (Fig. 3.20) and about 2 °C in summer (Fig. 3.21) and autumn (Fig. 3.22). By the end of century, general increase of temperature is expected to occur, with the highest value of around 3 °C in summer in the central part of the peninsula and in the high mountainous region of Pyrenees (Fig. 3.21). The standard deviation of the ensemble simulations has more heterogeneous pattern, with highest values (0.6–0.8) in the eastern and central part of the peninsula, as well as over the Pyrenees, in all seasons. Although significant modification in the pattern of SD cannot be seen, a slight increase in the amplitude of spread across model simulations occurs in winter and autumn towards the end of the century.

Under the RCP8.5 scenario, a well-pronounced contrast can be noticed between the mid-term and long-term periods. Similar to the RCP4.5, for the 2041–2070 period winter and spring have modest values of temperature change over the peninsula (about 2 °C), with the highest values in the central and southeast parts, while in summer and autumn the temperature rise reaches approx. 3 °C over most of the IP. For the period 2071–2100, the projected changes exceed 6 °C in summer and 5 °C in autumn in the central part of the peninsula. These regions with the strongest warming signal correspond to the central mountainous terrain of the peninsula (*Meseta*), the Baetic Mountains and Sierra Nevada on the SE as well as the Pyrenees on the NE (Fig. 3.1).

Similar to RCP4.5, the lowest spread across GCM-driven simulations is in winter, the SD value remains under 0.4 over most of the domain. Again, summer and especially autumn have the highest spread, with more than 0.8 and 1.0 SD values in the central-eastern mountainous part of the peninsula, respectively. The SD pattern is similar in all seasons, showing larger spread in the central-eastern part. In addition, the SD clearly increases towards the end of the century.

According to the reference maps (top panel in Fig. 3.19–3.22), under current climate conditions, the Andalusian Plain (valley of Río Guadalquivir) on the south is the warmest part of the peninsula, with 8–10 °C and 24–26 °C mean temperature of winter and summer, respectively. Based on the projections of this study, not only the current sub-tropical regions, such as the Andalusian Plain, but the major part of the peninsula—especially the central and south-eastern parts—will be dominated by hot conditions in general.

To sum up, the warming signal is strongest in the central and south-eastern part of the peninsula according to most of the simulations, but there are some differences between seasons, scenarios and time scales. These parts partly overlap with the areas marked by high SD too. The strongest warming is expected to occur in the central mountainous terrain of *Meseta* and its mountain ranges of Central System and Iberian System, in the Baetic Mountains and Sierra Nevada on the southeast and in the Pyrenees on the northeast that can be identified in almost all maps. Under both scenarios, summer and autumn seasons are projected to experience the most warming, but also the highest spread of simulations is found here.

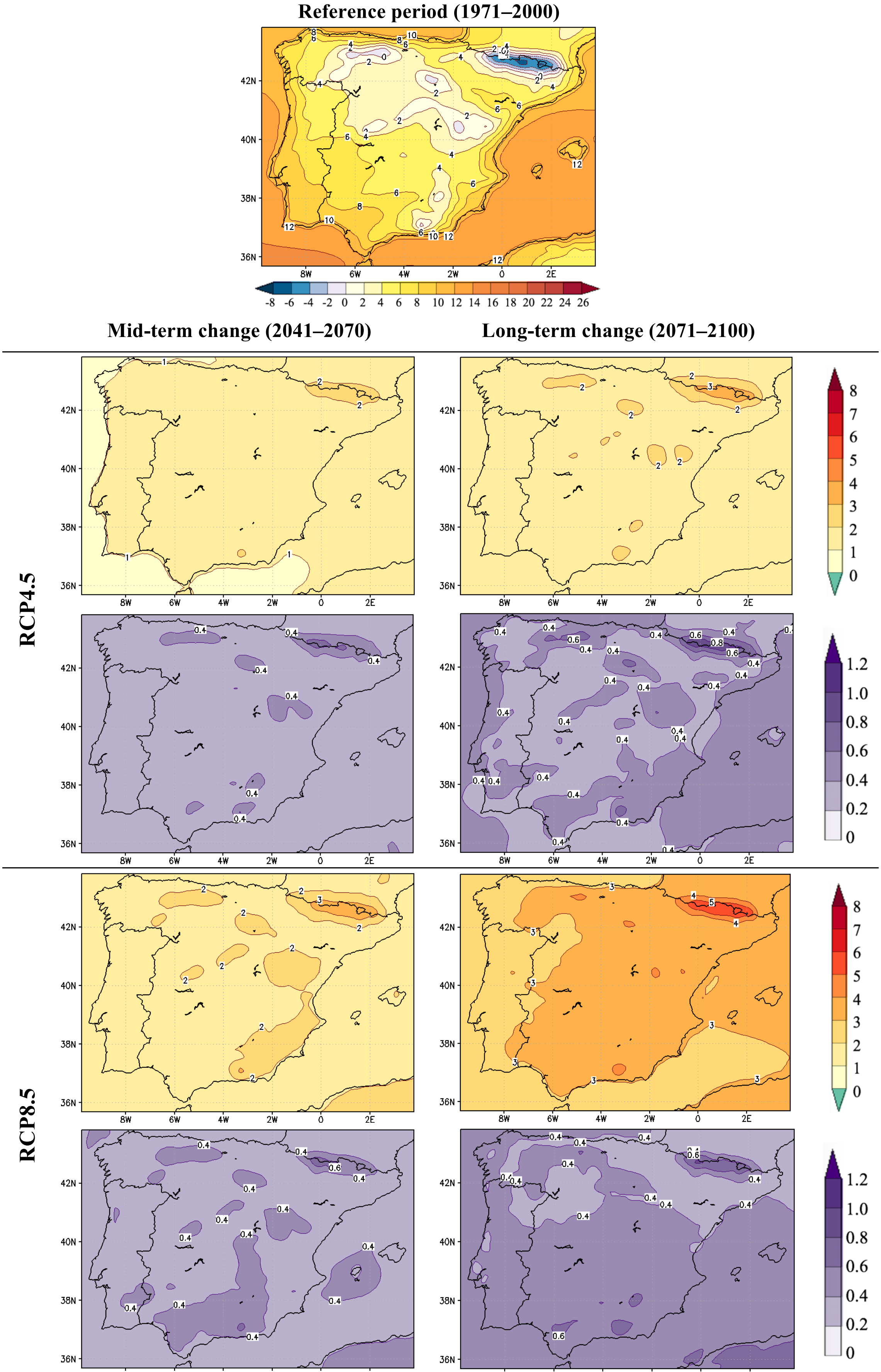
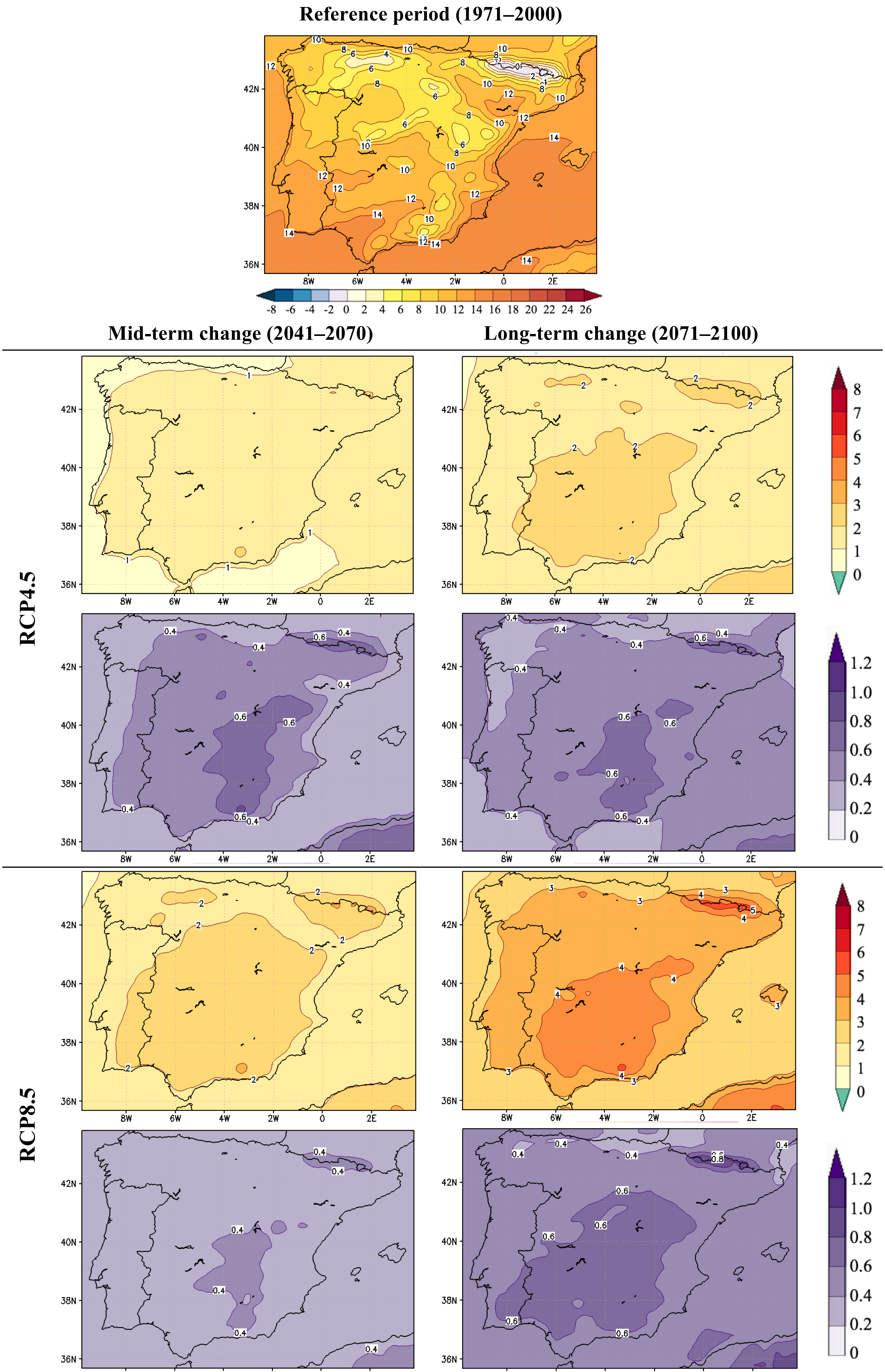


Figure 3. 19 The projected temperature change for winter over the IP based on the ensemble of five GCM-driven RCA4 simulations for the mid-term (2041-2070) and long-term (2070-2100)

future under RCP4.5 and RCP8.5 scenarios. Top panel: the simulation of current climate for reference period 1971–2000. First row after top panel: the projected mid-term temperature change (left panel) and long-term temperature change (right panel) calculated as the ensemble mean under RCP4.5 scenario, unit: °C. Second row after top panel: the spread across the ensemble members measured as standard deviation of the ensemble of five GCM-driven RCA4 projections corresponding to the temperature change maps above them. The third and fourth row present the same maps as the first and second rows, but under scenario RCP8.5.



Reference period (1971–2000)

Mid-term change (2041–2070)

Long-term change (2071–2100)

Figure 3. 20 The same as Fig. 3.19, but for spring.

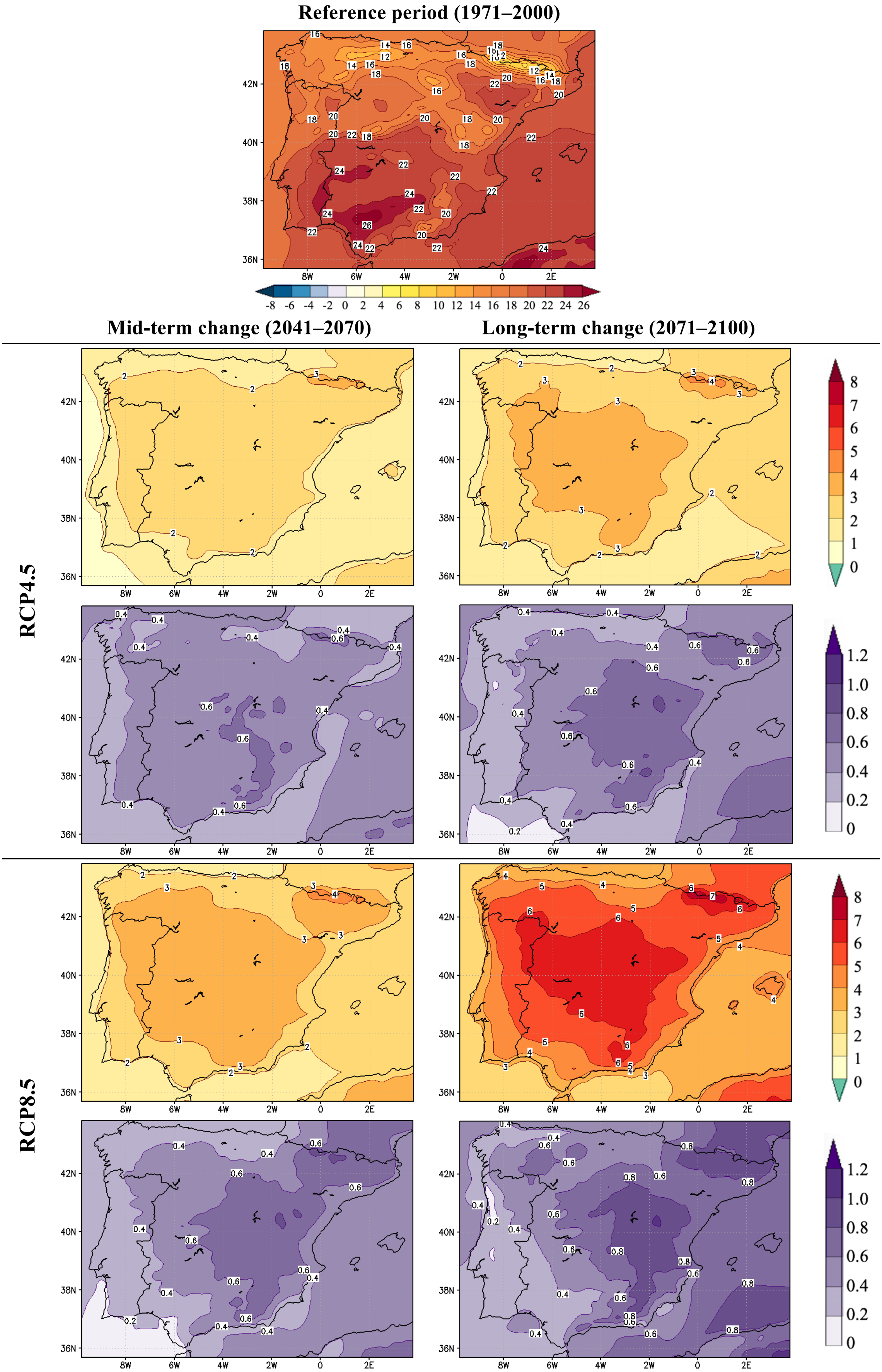
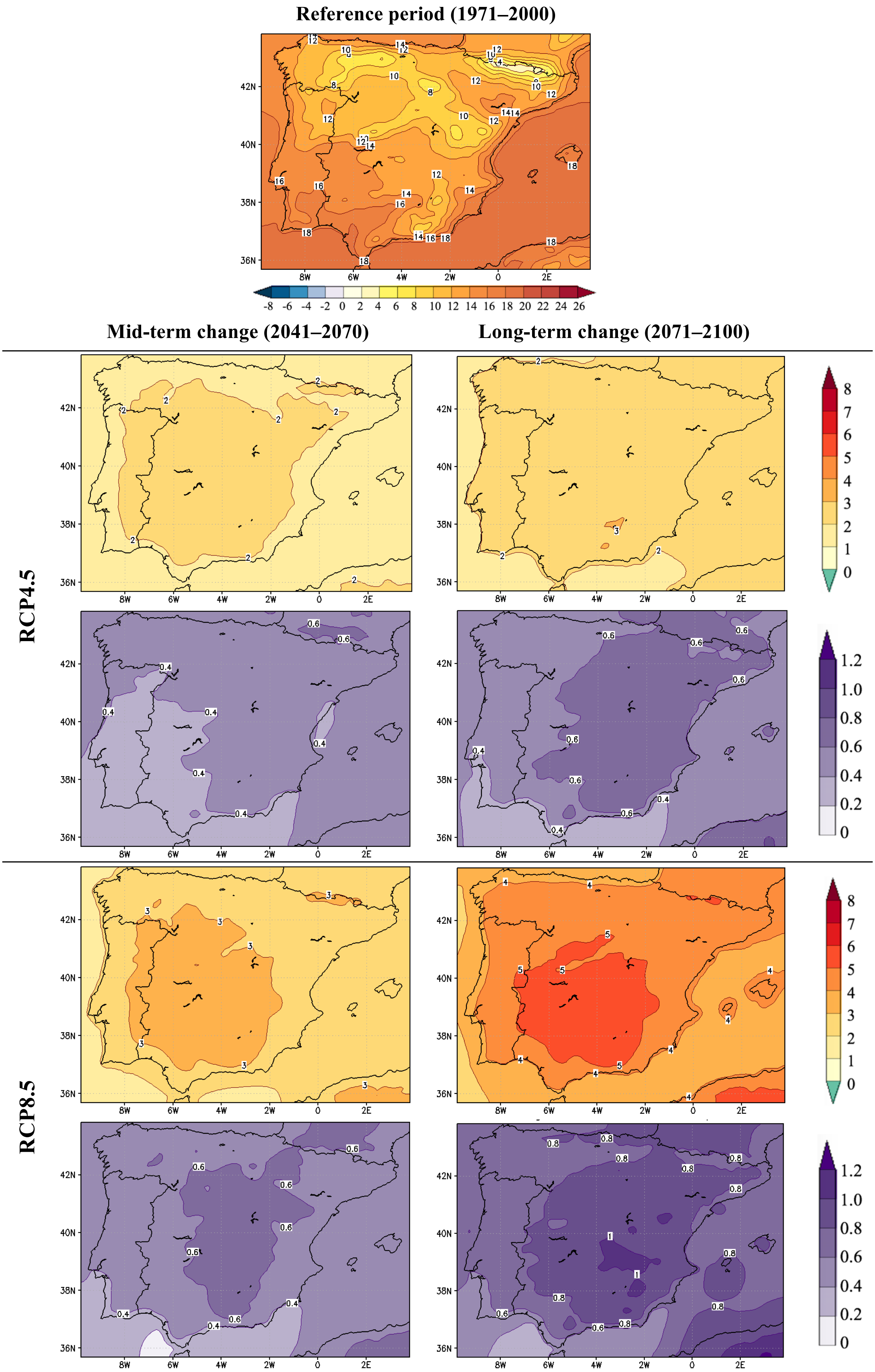


Figure 3. 21 The same as Fig. 3.19, but for summer.



Reference period (1971–2000)

Mid-term change (2041–2070)

Long-term change (2071–2100)

RCP4.5

RCP8.5

Figure 3. 22 The same as Fig. 3.19, but for autumn.

3.5 Discussion

3.5.1 On the RCA4 skill to reproduce IP near-surface temperature

The RCA4 reproduces the basic features of observed near surface air temperature over the Iberian Peninsula quite well, however, systematic biases do still exist. According to the comparison of 16 RCM experiments over Europe by Kotlarski *et al.* (2014) the RCA4 was not the best, neither the worst performing RCM over the IP subdomain concerning seasonal mean temperature simulations. The predominant cold bias over most parts of Europe is a common model bias found in majority of experiments with 6 different RCMs included in the EURO-CORDEX project. In correspondence to earlier RCA model versions, the RCA4 has equally good, or better skills in simulating mean temperature, as Strandberg *et al.* (2014) showed for the entire European domain including the IP.

The most prominent deficiencies revealed by this RCA4 evaluation over the Iberian Peninsula is the predominant cold bias (typically 1–2 °C) in most seasons—with higher absolute values in the cold part of the year—in line with the findings by Kotlarski *et al.* (2014). The bias can be larger in individual cases, for example over complex topographic terrain. For regions with higher elevation and the high-mountain areas such as the Pyrenees, this cold bias might be related to the pronounced topography, associated with large elevation differences between the RCM and the E-OBS reference at grid point level—as several studies noted this (López-Moreno, JI, Goyette and Beniston, 2008; Minder, 2010; Torma *et al.*, 2011; Kotlarski *et al.*, 2012).

An exception to the general picture of a predominant cold bias is summer, when underestimations and overestimations of temperature occur almost equally, typically between -2 and 2 °C. These results are consistent with previous findings for the RCA4 and the previous model version RCA3 (Samuelsson *et al.*, 2011; Kotlarski *et al.*, 2014; Strandberg *et al.*, 2014) over the Iberian Peninsula. Indeed, according to Kotlarski *et al.* (2014), one of the improvements of the EURO-CORDEX simulations with respect to the previous framework of ENSEMBLES is the reduced overestimation of southern European summer temperatures. Nevertheless, it is worth noting that even though summer seems to have the smallest absolute bias based on the evaluation metrics (Table 3.3), the analysis of spatial patterns of bias reveals that the low absolute error is caused by the fact that biases of opposite signs in the models tend to cancel each other when added (Kjellström *et al.*, 2011).

The causes for the winter-spring-autumn cold bias over the Mediterranean region is still not clear. An overestimate in the intensity and/or frequency of winter anti-cyclonic conditions might contribute to the problem, since wintertime anti-cyclonic circulation is generally associated with dry, clear-sky conditions, and hence relatively strong surface cooling in form of long-wave radiation (Samuelsson *et al.*, 2011). Some of the systematic biases in temperature simulations have been linked to problems in representing cloud and radiation processes in RCA3, that have been mitigated somewhat in the latest version of RCA4 (Barrett, Hogan and O ’Connor, 2009; Samuelsson *et al.*, 2011).

Concerning the spatial variability of the bias, the alterations do likely not only reveal true model biases but also deficiencies of the reference observational datasets related to the spatial smoothing and an effective resolution lower than the nominal grid resolution in regions of a low network density (Hofstra, New and McSweeney, 2010; Kyselý and Plavcová, 2010; Kotlarski *et al.*, 2014). As the regridding process from coarser to finer grid in case of CRU and ERA-Interim also enhanced the undesirable smoothing effect, E-OBS on its native 0.25° grid was used for most of the comparisons. Nevertheless, for further detailed examinations of small-scale climatological features and the added value of the 0.125° fine scale model simulations, high-resolution regional observations, such as the Spain02 gridded dataset (Herrera *et al.*, 2012) should be applied in future studies. (At the time of this study the dataset was not fully available.)

The analysis of the temporal variability by the correlation between the simulated and observed seasonal mean values over the 25-year evaluation period found weaker correlation in summer and winter (mostly between 0.7–0.9) than in the transition seasons (mostly larger than 0.9). The most heterogeneous pattern occurs in winter, with lower correlation values in the western-central part of the peninsula and in the high-mountainous region of Pyrenees. In general, the lower correlation in summer can be explained by the fact that the European summer climate is strongly controlled by local- to regional-scale processes than by large-scale atmospheric drivers, giving the RCM a higher degree of freedom to alter the conditions imposed by the boundary forcing (Déqué *et al.*, 2005).

3.5.2 The overall picture

The comparison of GCM-driven simulations to the reanalysis-driven run (evaluation Phase

2) revealed that the relative ranking of GCMs with respect to seasonal mean temperature bias is relatively stable, i.e. mostly independent of the season. The historical simulations driven by CNRM and ICHEC systematically underestimate temperatures as opposed to the systematic overestimations by the RCA4 forced by HADGEM2, IPSL and MPI. Each GCM introduced further cold bias to the simulations—except MPI in winter—, with higher absolute value of bias in the warm part of the year. The two coldest GCMs, CNRM and ICHEC are responsible for the largest fraction of the seasonal bias range in the ensemble mean of the five GCM-driven RCA4 simulations. The bias attributed to the GCMs might be related to errors in the representation of the large-scale circulation in the GCMs and to biases in SSTs and sea-ice cover in them, discussed in studies e.g., Van Ulden and Van Oldenborgh, (2005), Kjellström *et al.* (2011), Bozkurt *et al.* (2012) and Önol *et al.* (2014).

When comparing the ensemble of GCM-forced simulations to the E-OBS observations (evaluation Phase 3), the overall bias of the GCM-RCM combination is quantified, thus the capability of the ensemble to reproduce current climate could be assessed. Seasonal biases are larger (typically between -1 and -3 °C) when RCA4 was forced by the ensemble of GCMs compared to when it was forced by reanalysis data, in line with the findings of a similar study of 16-member ensemble with the RCA3 (Kjellström *et al.*, 2011). In case of GCM-forced simulations against EOBS the summer warm biases became weaker or turned into weak cold biases, and in the rest of the seasons the cold biases strengthened compared to the biases of the reanalysis-driven simulations against EOBS. This often occurs during downscaling, i.e. the opposite signs weaken each other, that can be revealed by the detailed attribution of bias (Hawkins and Sutton, 2009).

It is important to note, that besides the description of systematic errors originating from the model structures and uncertain future scenarios, there are further sources of uncertainty that have not been quantified in the present study, such as a) internal climate variability, b) uncertainties in the observational reference data, c) deficiencies of the driving reanalysis. The internal variability of the climate models can influence the simulated mean climatology even in multi-decadal RCM experiments that are subject to an identical boundary forcing (Deser *et al.*, 2012). As only one experiment was considered (the only available in the EUR-11 setup), this effect of internal random variability could not be quantified. Thus, as Kotlarski *et al.* (2014) suggests, slight nuances of bias characteristics should not be "over-interpreted" since to some degree they could originate from internal climate variability. The uncertainties of the E-OBS observational reference should be handled in a similar way.

Furthermore, the model evaluation run carried out in a perfect boundary context assumes a bias-free representation of the lateral atmospheric boundary conditions and sea surface temperatures. Since the driving data was the ERA-Interim reanalysis in the studied experiment, a certain influence of a biased boundary forcing on the evaluation results should be accounted, even though studies documented negligible reanalysis uncertainty (Brands *et al.*, 2013).

Despite the described shortcomings in the representation of specific climate features over the IP domain, the model evaluation indicates a considerable skill of the studied GCM-driven RCA4 ensemble to reproduce regional scale horizontal variability of seasonal mean temperature values. Also, the shape and amplitude of regionally averaged mean annual cycles are reproduced to a large extent by both the evaluation run of RCM and by the GCM-driven runs.

3.5.3 Climate change sign and uncertainty of projections

Different sources of uncertainty (described in detail in section 2.3.3 in Chapter 2) is a frequently discussed topic in the modelling literature (e.g., Walker, Lempert and Kwakkel, 2008; Hawkins and Sutton, 2009), as the uncertainty in simulations limits the ability to give precise answers about the course of future climate at both global and regional scale. In future scenarios, uncertainty is addressed related to the choice of GCM driving the RCA4 simulations by using an ensemble of five GCMs. The uncertainty related to future emissions of GHGs was assessed by using a stabilization (RCP4.5) and a high-end (RCP8.5) scenario. The ensemble is a powerful tool as it indicates the strength of the evidences for a certain climate change signal, thus, they are appropriate for Climate Services purposes (Kjellström *et al.*, 2016).

To assess the expected future changes in temperature, the delta-approach was applied, assuming that the identified model biases are stationary in time. It is a widely used practice when only working with monthly and seasonal mean values of climate variables (e.g., Jacob *et al.*, 2014; Szépszó *et al.*, 2014), however, the question of whether model biases are temporally stable is a research frontier. For example, Boberg and Christensen (2012) showed that most RCMs tend to have temperature-dependent biases. On the other hand, Bellprat *et al.* (2013) pointed out, that even bias corrected RCM simulations are object to the non-stationary nature of bias.

The future simulations in case of both scenarios indicated gradual rising temperatures in all seasons throughout the 21st century. By the end of century stronger warming is expected in summer than in winter, under RCP4.5 and RCP8.5 JJA: 2.7 °C (*ENSSD* = 0.5 °C) and 5.2 °C (*ENSSD* = 0.6 °C), and DJF: 1.8 °C (*ENSSD* = 0.5 °C) and 3.3 °C (*ENSSD* = 0.5 °C), respectively (Table 3.4). (The *ENSSD* is the standard deviation across ensemble members, i.e., the spread of projections.) It can be explained by the changes in large-scale circulation over Europe and lower cyclonic activity in the Mediterranean discussed by Pinto *et al.* (2007) and Kjellström *et al.* (2011). Warming of similar amplitude over the IP by the end of century was shown by Kjellström *et al.* (2011) based on a 16-member ensemble of RCA3 simulations on coarser horizontal resolution grid (0.44°).

Under both scenarios, summer and autumn seasons are projected to experience the most warming, but also the highest spread of simulations. Robustness and spread are often referred to as various aspects of the uncertainty in climate scenarios, and are used to illustrate reliability of model projections (Kjellström *et al.*, 2016). Since in this study all the simulations pointed to the same direction, the climate change signal can be considered highly robust based on the robustness criterion applied by SMHI. (The robustness criterion is simply calculated by adding the number of models indicating an increase in the index in question.) However, the spread of simulations increased towards the end of century in case of both scenarios, that is mainly associated with the uncertainty of emission scenarios.

As Hawkins and Sutton (2009) explained, the relative contribution from internal variability is largest in the nearest few decades and in a regional perspective, while forcing conditions by the GCMs and emission scenarios as well as the climate system response have a dominant role on longer time scales in the overall uncertainty. Thus, the main direction and amplitude of climate change as well as the spread around the ensemble mean need to be assessed by taken together the information of robustness and spread. Kjellström *et al.* (2016) also recommends that for communication with the Climate Services users it is more useful to discuss “spread” and “robustness” of climate projections rather than referring only to “uncertainty”.

As Morss *et al.* (2005) also pointed out, the perception of "uncertainty" can be very different in the user communities of different sectors, thus, better explanation and illustration of the terms in use by various disciplines is essential. They also add that the discussion of uncertainty from a scientific perspective sometimes confused the practitioners involved in flood risk management projects, as the two communities see uncertainty in a different way. Academics tend to look at uncertainty as something that can be conceptualized, calculated, and addressed, and to do so, they generally seek for additional data and carry out more sophisticated analysis (Morss *et al*., 2005). On the other hand, the practitioners interviewed for the same study, view uncertainty as an unavoidable factor in their everyday decision-making process in a complex, continuously changing social, institutional, and political environment. Hence, the term "uncertainty" and its interpretation can act as a linguistic barrier that limits knowledge exchange between academic researchers and practitioners (Fothergill, 2000).

As briefly explained above, the quantification and proper communication of uncertainty of climate change projections is important to help practitioners to make right decisions under high level of uncertainty (robust decision-making). As uncertainty about climate risks (e.g., floods, heat waves) often must be translated into dichotomous decisions (e.g., where construction should be restricted or regulated and where it should not), scientific information should be provided in an easily understandable, decision-relevant form, such as the robustness and spread of future projections presented above. In Chapter 5 this topic is addressed in more detail in relation to the challenges that academics and practitioners face when collaborating on urban climate adaptation projects.

In order to fully explore the uncertainty ranges a larger ensemble containing more RCMs, forcing GCMs, emission scenarios and ensemble members initiated with slightly different conditions and/or modified physical parameters (to sample the internal climate variability) is needed. However, it must be noted that a broader ensemble (e.g., by adding all available high-resolution RCMs from the EURO-CORDEX framework) would not necessarily improve the projections, but would increase the uncertainty range. Here I demonstrated that such a small ensemble of climate simulations may be useful to illustrate uncertainties from various sources and to provide insights to the future climate of IP using an RCM with the highest spatial resolution available now.

3.6 Summary and Conclusions

In this study, I evaluated the performance of a GCM-RCM ensemble and described future changes in seasonal mean features of near surface temperature over the Iberian Peninsula based on a 5-member ensemble of RCM simulations with the Rossby Centre model RCA4. In the first part, the simulated climate for the period 1981–2005 is I analysed both when forced by reanalysis data and when forced by boundary data from GCMs. The uncertainty in simulations originating from the RCM and the driving GCMs is quantified, and the additional contribution of GCM to the overall bias structure is separated from the intrinsic RCA4 contribution. Evaluation metrics (integrated information over the domain) and maps are used to reveal the geographical details in the bias pattern.

Based on the first part of the study the findings are as follows:

- Given the “perfect boundary conditions” from ERA-Interim the RCA4 tends to systematically underestimate the mean temperature over most of the IP, except during summer, when warm and cold biases are equally present. The seasonal absolute bias value is typically 1–2 °C, with larger bias values (up to 5–8 °C) over complex terrain, e.g. the Pyrenees.
- In general, the GCMs introduced more cold bias to the RCA4 simulations, increasing the absolute bias values of RCM with about 0.5–1.0 °C, especially in the warm half of the year. The summer warm biases of RCM are turned into cold biases over most of the domain.
- The ensemble of five GCM-driven RCA4 simulations have a well-pronounced cold bias over most of the IP throughout the year, compared to the E-OBS observations. The seasonal overall absolute bias value is typically 1–3 °C.

Taken together, the ensemble of GCM-driven RCA4 simulated the seasonal mean features of the temperature patterns over the IP reasonably close to the observations, however, the systematic underestimation should be kept in mind when using the model for future projections. Thus, to assess the future changes in seasonal mean temperature based on the ensemble of RCA4 simulations, the difference between future and current climatologies was calculated (delta-approach).

In the second part of the study, I gave an overview of the climate change signal in the ensemble of future simulations by presenting the change in the seasonal means of temperature, including the illustration of the spread of ensemble. The scenario uncertainty is addressed by using two different Representative Concentration Pathways, the stabilization scenario of RCP4.5 and the high-end scenario of RCP8.5.

From this part of work the findings and conclusions are:

- In general, each projection shows a gradual warming trend over the whole IP in every season throughout the 21st century. Under both scenarios, summer and autumn seasons are projected to experience the highest temperature rise (up to 3–6 °C by the end of century), but also the highest spread of simulations (SD = 0.5–0.9 °C) is projected in these seasons. Warming more than 2 °C (threshold signed in Paris Agreement) is expected to occur over the IP in these seasons already by mid-century.
- The warming signal is strongest in the central and south-eastern mountainous part of the peninsula and in the Pyrenees according to most of the simulations, but there are some differences in the amplitude and pattern across seasons, scenarios and time scales. Areas with high spread of simulations are the central and eastern regions, partly overlapping with the regions with the strongest warming signal.
- Taken together, the projected temperature changes imply that summers are becoming longer and warmer while winters are becoming shorter and milder over the IP. Spring and autumn shift in time with the spring season occurring earlier and autumn later.

Identifying possible reasons for model-specific bias characteristics is beyond the scope of this study, as it would require a deeper and dedicated analysis, as well as additional metrics, and explicitly taking into account uncertainties in the observational reference and the internal climate variability. These tasks need to be accomplished with specific expertise in model-developing and also would require running more experiments.

Here I gave an example of a simple evaluation of model skills before future scenarios are included in Climate Services products. The future changes along with the robustness and spread of projections are presented in an easily understandable way, based on the good practice applied in Climate Services by SMHI. The user-focused development of climate change maps for the Iberian Peninsula has started only recently, in spite of the growing demand for future climate information from different sectors. Further work should consider sector-specific variables and indicators (e.g., indices of vegetation period or heat waves) on different time-scales, in order to tailor the climate products to the exact needs of users.

3.7 Practical Implications

The study presented here is based on climate information derived from an ensemble of simulations with the Rossby Centre regional climate model (RCA4). Inspired by the SMHI climate scenario web pages (*SMHI website*) I presented traditional climate change information in form of maps that not only show the ensemble means, but the spread between the different simulations too, for different time-scales and under different scenarios.

The spread is calculated as the standard deviation of the five different GCM-driven runs, indicating to what extend the ensemble members deviate from the ensemble mean. The direction of projections is also an important information on the robustness of the results, indicating how many of the ensemble members point to the same direction of change. (In present case it is not shown in a separate map as all the projections showed an increase in the mean temperature over the entire domain.) Taken together this information one can get an indication of the robustness of the results by assessing the main direction and amplitude of climate change as well as the spread of projections around the mean value of change.

Next to the temperature change maps the simulated current climate is also presented, that helps to get a consistent information about how the regional and local climate change signal compares to the climate that we experience today. The observations for the same period can be shown here too, to get a picture on the inter-annual and/or spatial variability of the variable in relation to the future variability as projected by the climate model.

As the *SMHI website* exemplifies, the climate change maps and diagrams can be completed with detailed information on site and guiding documents on how the results could be interpreted and further used. The website also displays materials along several dimensions such as area (different levels of administrative units), season, scenario or climate variable/index. For this study, I used two from the latest generation of RCPs (Representative Concentration Pathways) that were used in the most recent IPCC assessment reports (IPCC, 2013b, 2014).

Mean temperature change maps were produced for the four seasons to highlight the usefulness of producing such illustrations explained above. Further sector-specific variables and indices should be chosen based on the interest of the users (e.g., impact studies, risk assessment). Another criterion is that the basic variable or index should represent features for which the RCM performance has been evaluated against the observations. To ensure that the climate products are tailored to the specific needs frequent interaction between service providers and users as well as co-development of products are essential.

Chapter 4

Urban heat island, thermal comfort and temperature extremes – the case of the city of Valencia

4.1 Introduction

Besides the general warming trends in the Mediterranean region (e.g., Giorgi, 2006; Brunet *et al.*, 2007), an increase in warm extremes and decrease in cold extremes were detected since 1950 (Alexander *et al.*, 2006; Paul M. Della-Marta *et al.*, 2007a). These trends are expected to continue throughout the 21st century (e.g., Fischer and Schär, 2010), as I explained in detail in Chapter 2. Since the Valencian summer is characterized by humid heat that makes hot weather less comfortable, it is important to understand the evolution of Urban Heat Island (UHI) effect that imposes even higher heat stress on the urban environment. Realising the growing demand on urban climate and spatial thermal comfort information for climate change adaptation planning, the aim of this study is to analyse the intensity, spatial extent and evolution of the UHI during hot summer days.

The present work combines two methods, thermal remote sensing techniques and in-situ meteorological observations, to measure the UHI over the city of Valencia. As the positive temperature contrast between the city and its surroundings tend to be the largest after sunset, and strong UHI nights impose more severe heat stress on the human body (e.g., Vineis, 2010; Stevens, Thomas and Grommen, 2015), the main focus of the present study is the nighttime UHI and thermal comfort. To facilitate the involvement of UHI in urban adaptation strategies the more favourable and less pleasant parts of the city are identified using the Discomfort Index (Thom, 1959). Additionally, a year-round calendar is prepared to describe the general thermal comfort of an average day, month by month. In order to evaluate the urban climatological context, long-term historical data are also analysed. Besides the mean temperature, the warm and cold extremes are examined during the period 1906-2014. Finally, the study aims at providing recommendations to advance climate-resilient urban planning.

The specific objectives of this study:

(i) Analysing the long-term temperature conditions in Valencia in terms of mean temperature, as well as warm and cold extremes;
(ii) Examining the evolution, intensity and spatial extent of UHI effect during summer hot days via remote sensing and in-situ meteorological data;
(iii) Describing the general thermal comfort in the city and assessing the spatial pattern of Discomfort Index during summer hot nights;
(iv) Practical implications to enhance Climate Services contribution to climate adaptation planning and decision-making.

4.2 Data and Methods

4.2.1 Study area

The metropolitan area of Valencia is the third largest conurbation in Spain. The city of Valencia has 787 266 inhabitants, distributed over an area of 137.5 km^2, with a population density of around 7 966 inhabitants/km^2 (Figure 4.1) (*Statistical Analysis of Census 2011, Stat. Of. website*). The city is located on the Spanish Mediterranean coast on a small alluvial plain formed during the Quaternary by the carriage of the Turia River. The flat relief has a maximum E-W increase in height of 40 m from the sea to the beginning of alluvial fan (Caselles *et al.*, 1991). The geographical area of the city can be characterized by sub-arid Mediterranean climate with “hot dry-summers” (*Csa* according to the updated Köppen-Geiger climate classification, Kottek *et al.*, 2006). The dominant local wind flows perpendicular to the shoreline (E-W) and shows a typical daily periodicity of a sea-breeze. Sunshine duration is 2 660 h per year, with an average above 10 h per day in July (*AEMet website*).

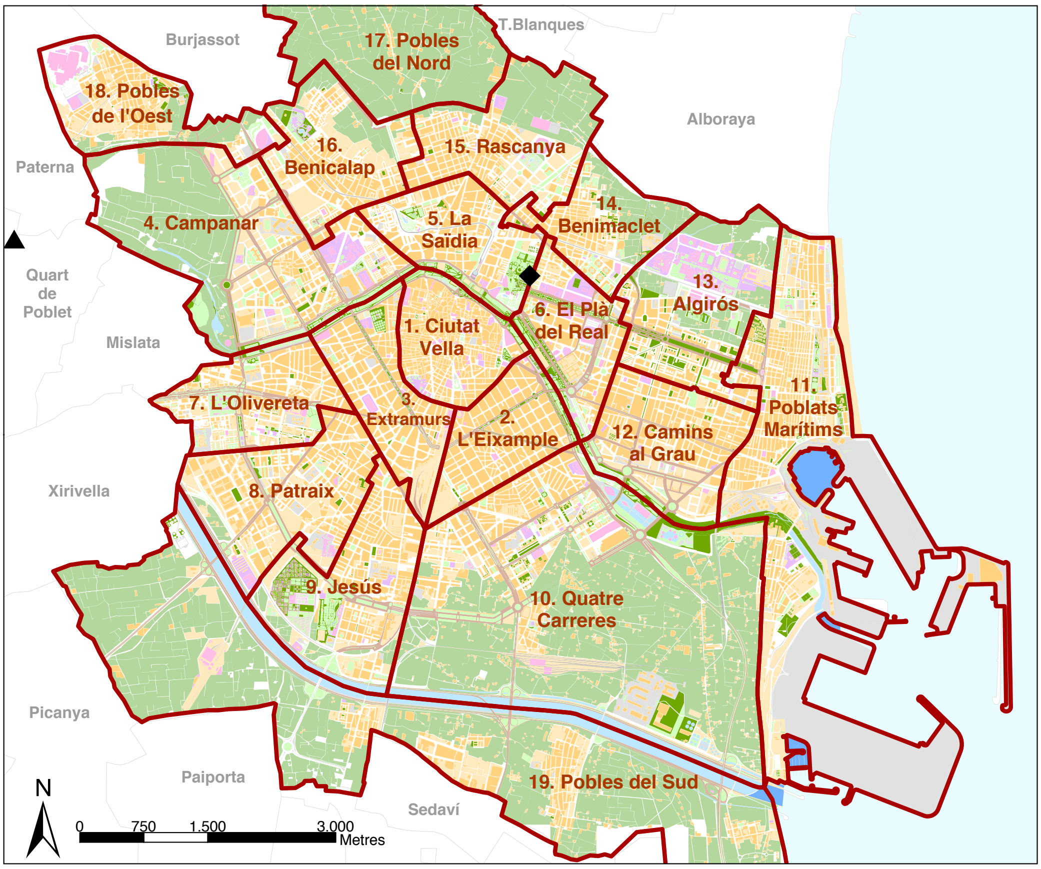


Figure 4. 1 The map of Valencia city (Statistical analysis of Census 2011, Stat. Of. website) (diamond: Viveros meteorological station, triangle: Airport meteorological station).

The city is distributed into 19 districts with very different characteristics regarding both the building density and height, as well as green areas. The continuous urban surface extends over 36.3 km^2, while green surfaces cover more than 4.5 km^2, to which gardens contribute with 2.5 km^2, urban parks with 0.6 km^2 and the Turia riverbed with 1.2 km^2 (Lozano Esteban, 2010). Valencia went through a star-shaped growth in the last few decades as it has spread over the surrounding farmland and has absorbed several small towns and villages nearby (e.g., Campanar—District 4). Thus, the type of urban area greatly varies throughout the city, from the ancient central nucleus (Ciutat Vella—District 1) which is densely urbanized (only small urban parks can be found here), to the outskirts of the city where a few farmland areas still remain within the city borders (Caselles *et al.*, 1991). This unique farmland called “Huerta” is a socio-cultural heritage that organically connects the traditional agriculture to the urban metabolism. During the urban expansion in the second part of the 20th century the “Huerta” was reduced to a belt around the city consisting of small farms and vegetable gardens with dispersed habitat dedicated to crops, mainly green vegetables (Caselles *et al.*, 1991; Lozano Esteban, 2010).

4.2.2 Climatological data

The study area of Valencia has only one long-term weather station (Viveros, AEMet ref. 8416, N 39°28′50″ W 0°21′59″; 11 m) within the city limits despite its size, and another one in the suburbs (Airport, AEMet ref. 8414A, N 39°29′06″ W 0°28′29″; 56 m) that could provide reliable and sufficiently long data for the study. For the Viveros station the data were obtained from the SDATS homogenized dataset, provided by the Centre for Climate Change (Brunet *et al.*, 2006), and for the Airport station the data were retrieved from the Agencia Estatal de Meteorología (*AEMet website*). The Viveros station is located ca. 1 km from the old city centre, at the side of a green park and next to a main road and high built residences. The airport is ca. 10 km away from downtown, in the outskirts of Valencia, at the edge of a small town which is a medium dense built-up area.

The instruments are placed in the open field over bare soil, with few asphalt surfaces nearby (ca. 200 m). The Airport station is significantly further away from the sea than the urban station, which can lead to higher temperatures especially in the mornings and early afternoon, as the sea breeze front only reaches a few km inland. Air temperature measurements at both stations are taken at 2 m in standard Stevenson shelter. Daily maximum and minimum temperature (Tmax, Tmin) data series of Viveros cover more than a century (1906–2014), while the Airport extends between 1966 and 2014. As the latter station is not included in the SDATS dataset, thorough quality control and homogenisation procedures were carried out using best practice software RClimDex-extraQC (Aguilar and Prohom, 2011) and HOMER (HOMogEnization software in R) (Mestre *et al.*, 2013) before analysing the time series. Furthermore, in order to evaluate the meteorological conditions during the studied 3-day period in August 2014, hourly temperature (AT), relative humidity (RH) as well as wind speed and wind direction data were involved into analyses from both stations, provided by the AEMet. The general thermal comfort in the city was described based on hourly AT and RH time series of a 4-year period (March 2012 – December 2015) made available by AEMet too.

4.2.3 Climate indices

To gain general overview on the long-term climatic conditions in the Valencian region, the yearly mean temperature was calculated from the daily Tmin and Tmax time series over the 1906-2014 period. To detect temporal changes linear trend was fit by using the least squares method and tested for statistical significance at the 0.01, 0.05 and 0.1 level. For the long-term evaluation of changes in climate extremes, the ETCCDI (Expert Team on Climate Change Detection and Indices, ETCCDI) were applied (see description in Chapter 2, section 2.4.1). Seven indices were chosen, most of them percentile based, and thus suitable for interregional comparisons. The indices are defined as follows (Peterson *et al.*, 2001):

a) *Cool days (TX10p)*, Percentage of days when *Tmax* < 10th percentile:
Let $Tmax_{ij}$ be the daily maximum temperature on day *i* in period (year or month) *j* and let $Tmax_{in}10$ be the calendar day 10th percentile centred on a 5-day window for the base period 1961–1990. The percentage of time for the base period is determined where: $Tmax_{ij} < Tmax_{in}10$

b) *Cool nights (TN10p)*, Percentage of days when *Tmin* < 10th percentile:
Calculated in the same way as for *Tmax*, see section a).

c) *Warm days (TX90p)*, Percentage of days when *Tmax* > 90th percentile:
Let $Tmax_{ij}$ be the daily maximum temperature on day *i* in period *j* and let $Tmax_{in}90$ be the calendar day 90th percentile centred on a 5-day window for the base period 1961–1990. The percentage of time for the base period is determined where: $Tmax_{ij} > Tmax_{in}90$

d) *Warm nights (TN90p)*, Percentage of days when *Tmin* > 90th percentile:
Calculated in the same way as for *Tmax*, see section c).

e) *Warm spell duration indicator (WSDI)*: Annual count of days with at least 6 consecutive days when *Tmax* > 90th percentile
Let $Tmax_{ij}$ be the daily maximum temperature on day *i* in period *j* and let $Tmax_{in}90$ be the calendar day 90th percentile centred on a 5-day window for the base period 1961–1990. Then the number of days per period is summed where, in intervals of at least 6 consecutive days: $Tmax_{ij} > Tmax_{in}90$

f) *Cold spell duration indicator (CSDI)*: Annual count of days with at least 6 consecutive days when *Tmin* < 10th percentile
Let $Tmin_{ij}$ be the daily maximum temperature on day *i* in period *j* and let $Tmin_{in}10$

be the calendar day 10th percentile centred on a 5-day window for the base period 1961–1990. Then the number of days per period is summed where, in intervals of at least 6 consecutive days: $TN_{ij} < TN_{in}10$

g) *Tropical nights (TR20)*: Annual count of days when Tmin > 20 °C.
Let $Tmin_{ij}$ be daily minimum temperature on day *i* in year *j*. Count the number of days where: $Tmin_{ij} > 20$ °C.

For computing the indices the RClimDex statistical package in R (Aguilar and Prohom, 2011) was used.

4.2.4 Remote-sensing data

The MODerate resolution Imaging Spectroradiometer (MODIS) sensor was deemed to be the most suitable for this study for different reasons. The MODIS sensor is carried on both NASA’s Aqua and Terra satellites that have near polar orbits resulting in three images per satellite per day. Image acquisition on Aqua is two per night and one per day and on Terra is vice versa. This is a high temporal resolution, meanwhile the spatial resolution is only ca. 1 km that is considered coarse compared to other alternatives such as the Advanced Thermal Emission and Reflection Radiometer (ASTER), the Landsat series as Enhanced Thematic Mapper Plus (ETM+) or the Thermal Infra-Red Sensor (TIRS), all of which have spatial resolutions below 100 m. However, the number of images available from ASTER or Landsat is significantly less than MODIS, and in this case there were hardly any images suitable. A strength of the MODIS sensor is the compromise between regular image acquisition and reasonable spatial resolution, in comparison to other sensors that offer higher spatial resolution but lower temporal resolution (e.g., Landsat), or higher temporal resolution but lower spatial resolution (e.g., SEVIRI) (Tomlinson *et al.*, 2012). In spite of the coarse resolution of the MODIS LST product, the high temporal resolution of MODIS makes it reasonable for UHI studies (Tomlinson *et al.*, 2012; Sobrino *et al.*, 2013).

The MODIS data are available from the EOSDIS Reverb ECHO—NASA (*NASA website*) and useful land surface temperature (LST) products include MYD11 (Aqua) and MOD11 (Terra) at 1 km resolution. As MODIS data have a limited number of useful images (clear sky conditions and not too high zenith angle of the observing sensor are needed), detailed study of the development of UHI can be carried out in a limited number of consecutive days. Potential cases have been selected by analysing the nighttime heat conditions of the summer semester (May, June, July, August, September), by highlighting the days when the Tmin exceeded the 90th percentile of the MJJAS daily data calculated on the base of 109 years. Accordingly, a 3-day period of August 2014—with a record hot day in the middle of the period—was chosen based on the climatological criteria and the availability of MODIS images. Eleven MODIS products (two MODIS images from both satellites for day and night) were eligible for the study as these products provided LST data with moderate bias due to the image acquisition angle. The thermal products were obtained directly from the NASA, then they were georeferenced and multiplied by the MOD11 scaling factor of 0.02. Depending on the angle of image acquisition, the error was between 1.5–2 °C, as Wang, Liang and Meyers (2008), Sobrino and Skoković (2016) described it.

To evaluate more precisely the spatial structure of the UHI and DI, a high resolution (90 m) nighttime image of ASTER was retrieved for a summer day (28 June 2014, 22:06 GMT). This was the only appropriate image that could be used as an example for further studies, because of the limited number of available high-resolution images: ASTER collects nighttime data only on request and the couple of available LANDSAT images did not have sufficient quality. Although the ASTER image covers only the ca. 80 % of the studied region, fortunately the MODIS and ASTER data are gathered at the same time—both sensors are carried on the same platform (Terra) —, that enabled us to pursue a comparison.

4.2.5 NDVI

Three regions (Urban, Semi-Urban and Rural) were determined to calculate the surface UHI (sUHI) across Valencia. The areas with human constructions and areas covered with vegetation were distinguished according to the NDVI (Normalized Difference Vegetation Index) (Figure 4.2). The index was calculated using the infrared and red bands of the Terra satellite thermal image on 26th of August 2014. The Urban area (U) (NDVI ≤ 0.20) is a relatively homogenous built up area considering the resolution of MODIS image, where the average NDVI value was 0.18 (SD = 0.02). The western zone shows a Semi-Urban (SU) inhomogeneous area around the airport, with a mixture of rural and urban surfaces (NDVI ≈ 0.26; SD = 0.06). The relatively homogenous Rural area (R) north from the city (NDVI > 0.27) had the highest NDVI, an average of 0.34 (SD = 0.04). The three regions were chosen to have equal areas of 34 020 km^2 (including 40 pixels).

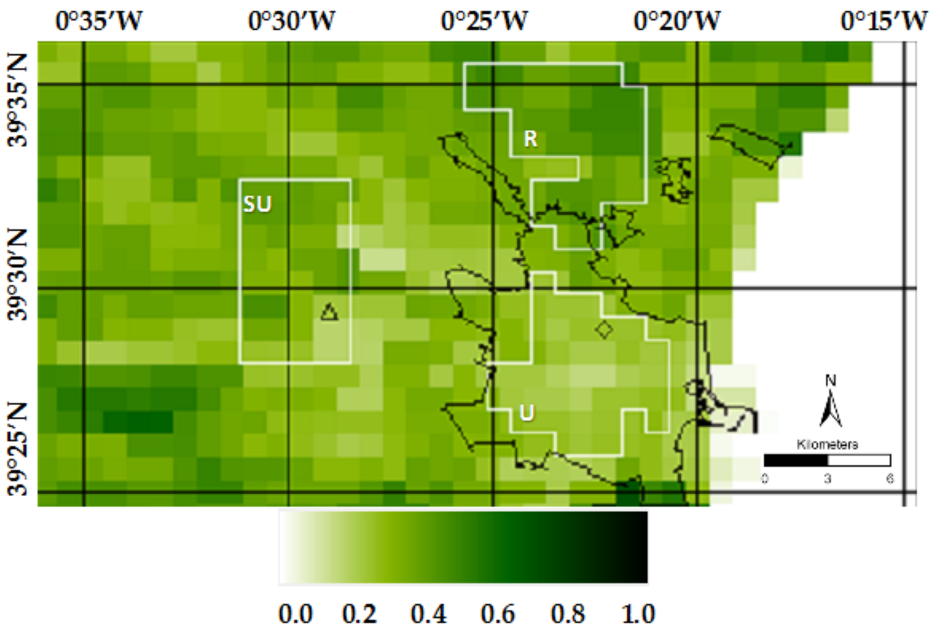


Figure 4. 2 The different regions determined according to the calculated NDVI on 26th of August. (U: Urban, SU: Semi-Urban, R: Rural region; diamond: Viveros meteorological station, triangle: Airport meteorological station, black border: administrative border of Valencia).

4.2.6 Discomfort Index

Although there are many complex and multi-variant based methods for determining bioclimatic comfort, one of the best indices for estimating the effective temperature is the DI index (Toy, Yilmaz and Yilmaz, 2007), also known as Thom’s discomfort index (THI) (Thom, 1959). This index is based on the effective temperature and humidity conditions and describes the degree of discomfort by categories covering the whole spectrum from cold to tropical climates. DI is defined as

$$DI = AT - (0.55 - 0.0055\, RH)\,(AT - 14.5) \qquad \text{(Eq. 4.1)}$$

where AT is air temperature expressed in °C and RH stands for relative humidity in percentage.

To evaluate the average annual and daily cycle of DI in Valencia, 4-year (March 2012 – December 2015) hourly AT and RH data were analysed both at the Airport and Viveros stations. A color-coded calendar was prepared to illustrate the thermal comfort throughout the year, during daytime-nighttime.

4.3 Long-term temperature in Valencia

4.3.1 Observed mean temperature

To detect the long-term changes in climatic conditions in Valencia I analysed the 109-year (1906–2014) homogenised temperature time series registered at Viveros. A significant increasing trend was found in the annual average of daily mean air temperature, with a rate of 0.2 °C per decade ($p < 0.05$) (Figure 4.3). Around the mid-century (from late 1940s until late 1960s) a warm period interrupted the positive trend of temperature. This warm period can be found in most Spanish and Northern Hemisphere stations (see Brunet *et al.*, 2007). In the last 2 decades, the yearly mean temperatures had the highest values considering the whole 11 decades, even though the pace of warming decreased in this period. 2014 was a record warm year with +2 °C anomaly compared to the reference period (1961–1990).

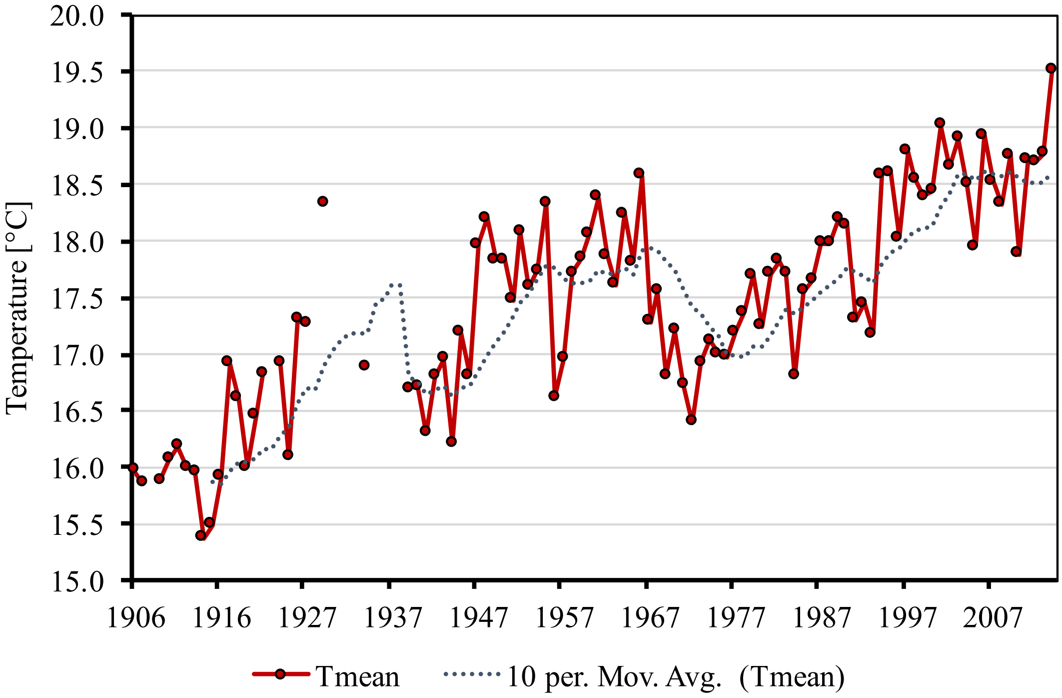


Figure 4. 3 The mean temperature in Valencia over the period 1906–2014.

4.3.2 Temperature extremes

To evaluate the frequency of temperature extremes during the studied period, different climate indices were analysed based on Tmin and Tmax times series. Figure 4.4 shows the extreme climate indicators describing the frequency of *warm days* (TX90P, panel *a*), *warm nights* (TN90P, panel *b*), *cool days* (TX10P, panel *c*), *cool nights* (TN10P, panel *d*) and a simple index to monitor heat and cold waves, based on the persistence of warm days (WSDI, panel *e*) and cool days (CSDI, panel *f*).

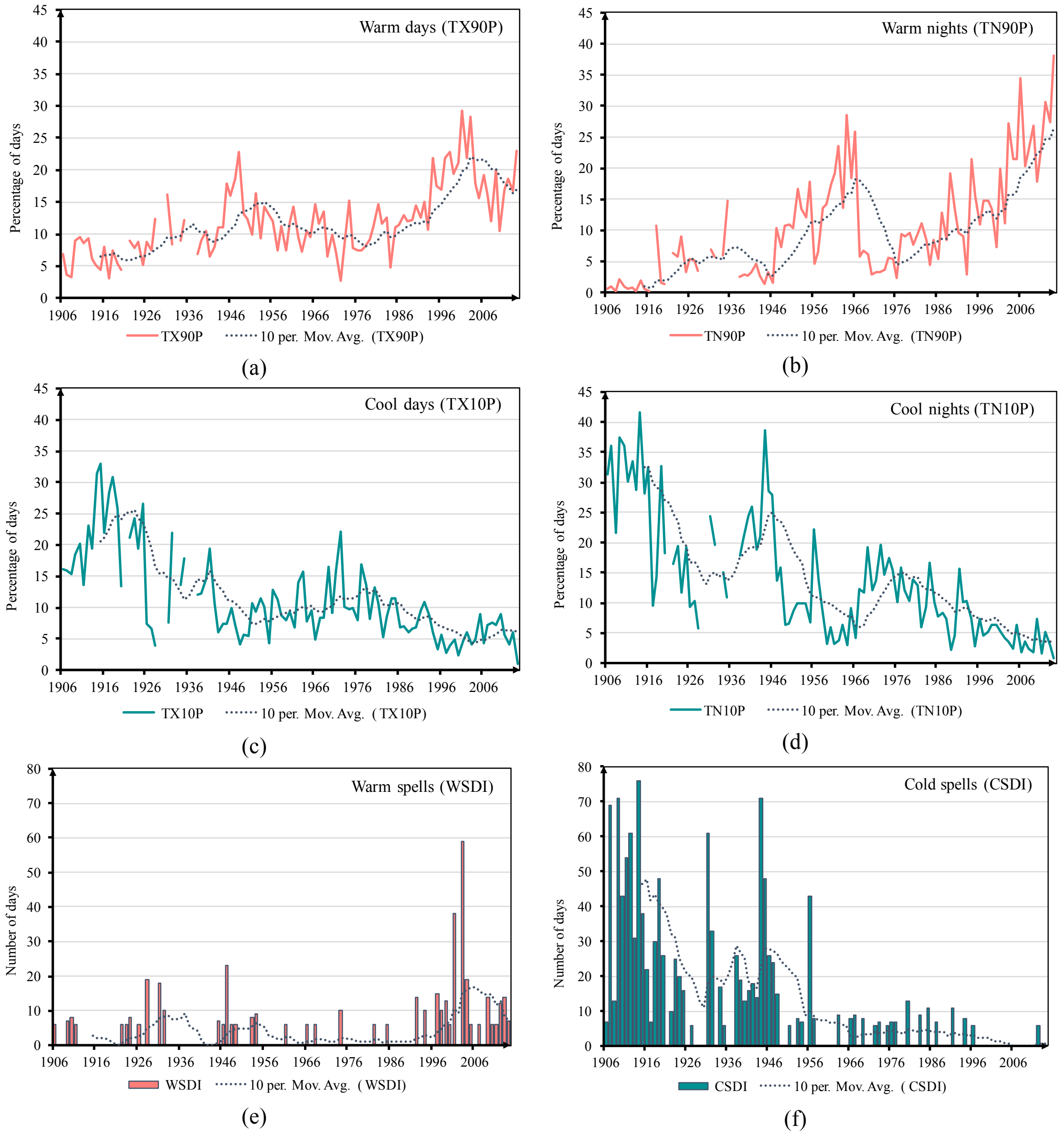
First, we look at the indices based on Tmax, which characterise the *warm days* (the percentage of days when Tmax > 90th percentile, panel *a*) and the *cool days* (the percentage of days when Tmax < 10th percentile, panel *c*) (see section 4.2.3 for a detailed description). The cold extremes significantly decreased with -0.15 % average annual rate ($p < 0.01$) in the last 11 decades, and warm extremes significantly increased with an average annual rate of +0.11 % ($p < 0.01$) (Table 4.1). Consequently, *cool days* have become less frequent and *warm days* more frequent during 1906–2014. The TX90P (*warm days*) and TX10P (*cool days*) showed simultaneous opposite behaviour, i.e. the constant increasing (decreasing) trend of *warm days* (*cool days*) was interrupted with a period (from late 1940s until late 1960s) of slight decrease (increase) as it was the case with the mean temperature too.

Second, the indices based on Tmin are evaluated to characterize the nighttime conditions, i.e. *warm nights* (the percentage of days when Tmax > 90th percentile, panel *b*) and the *cool nights* (the percentage of days when Tmax < 10th percentile, panel *d*) (see formula in section 4.2.3). Similarly to Tmax, a long-term decreasing trend with an average annual rate of -0.23 % ($p < 0.01$) in the cold extremes (TN10P) and an increasing trend with a rate of +0.18 % ($p < 0.01$) in the warm extremes (TN90P) was found (Table 4.1). As a consequence, *cool nights* have become less and *warm nights* more frequent in the examined period. As we saw in case of *warm days–cool days*, the course of *warm nights* follows a “mirrored” tendency compared to *cool nights* throughout the examined period.

In the bottom panels of Fig. 4.4 the Warm Spell Duration Index (WSDI) and Cold Spell Duration Index (CSDI) are presented to attribute the persistence of warm and cool days during the period 1906–2014. WSDI is defined as the annual count of days with at least 6 consecutive days when Tmax > 90th percentile (see formula in section 4.2.3). CSDI is calculated in a similar way as WSDI, but with the threshold Tmin < 10th percentile.

The WSDI (panel *e*) showed low frequency of warm spells throughout the last century, with a couple of outstanding years in the mid-century (e.g. 1928, 1947). However, after 1997 warm spells become more frequent at an inter-annual level. The spike in WSDI in

2003 indicates the extreme long and intense heat wave that occurred across Europe. As the number of warm spell days in a year did not increase significantly but the inter-annual frequency, the fit linear trend (slope = +0.06 day per year, $p < 0.06$) is less powerful and dominated by the outstanding value of 2003 (Table 4.1).



(a) (b)

(c) (d)

(e) (f)

Figure 4. 4 Warm and cool temperature extremes in Valencia over the period 1906–2014. The "percentage of days" refers to monthly values that are averaged for every year.

According to the duration index of cold spells (panel *f*), persisting cold days were more common at the first half of the century. After 1956 cold spells gradually became less frequent, and in the last 2 decades—except 2012—there was no period with at least 6 consecutive days when Tmin < 10th. During 1906–2014 there was a significant decrease in CSDI with a rate of -0.37 day per year ($p < 0.01$) (Table 4.1). In addition, it is remarkable to see how the sequence of years without a cold spell increases and how the number of years with warm spells decreases.

*Table 4. 1 Summary of trends detected in the extreme indices. * Indicates significance at 1 % confidence level, ** indicates 10 % confidence level.*

Extreme index	Indicator name	Trend slope	Confidence level
TX90P	warm days	0.11	*
TX10P	cool days	-0.15	*
TN90P	warm nights	0.18	*
TN10P	cool nights	-0.23	*
WSDI	Warm Spell Duration Index	0.06	**
CSDI	Cold Spell Duration Index	-0.38	*

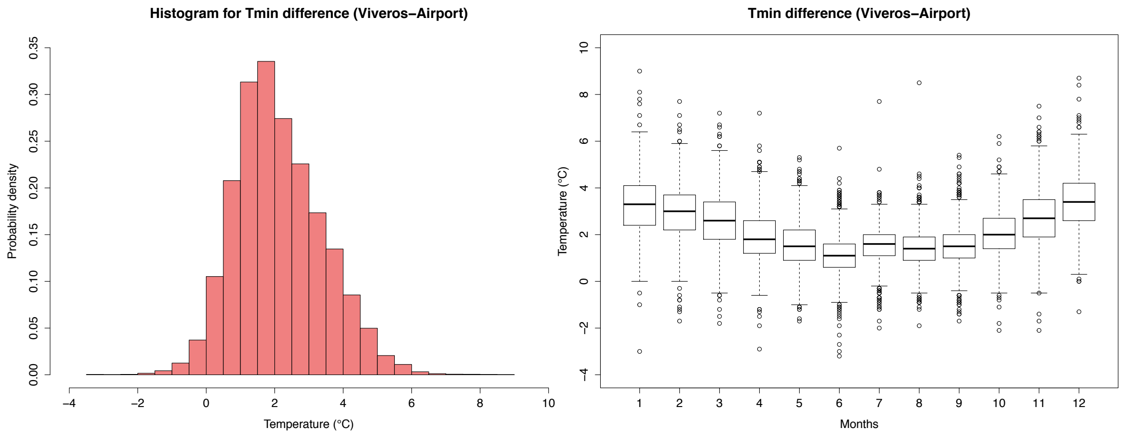
To sum up, based on the studied indices warm extremes have become more frequent and the occurrence of cold extremes decreased during the examined period. The point estimates of trends suggest a larger change in cold extremes indices (TN10p, TX10p, CSDI) compared to their warm extremes counterparts (TN90p, TX90p, WSDI) and a larger change in nighttime indices (TN10p, TN90p, CSDI) compared to their daytime counterparts (TX10p, TX90, WSDI).

4.4 The urban heat island effect

4.4.1 The long-term estimation of nighttime UHI and Tropical Nights

To describe the nighttime temperature conditions in the city centre and surroundings of Valencia five decades (1966–2014) of daily minimum temperature (Tmin) records were analysed. (Here I use this period of five decades because data is available at the airport station only from 1966.) As the positive AT contrast between the urban and rural areas tends to be the largest in the late night–early morning hours, the daily Tmin can be used as an indicator of the general heat conditions of the night. Thus, a rough estimate can be given for the nighttime UHI by calculating the difference of Tmin time series at the two meteorological stations.

As shown in Figure 4.5a, the intensity of the estimated nighttime UHI was most frequently between +1.5 and +2.0 °C, with an extreme value of +9.0 °C on the 26th of January 1978 (quality controlled). Furthermore, the most intense positive contrast between the city centre and the airport usually occurred in the cold half of the year, especially in December and January (Figure 4.5b). During summer (MJJAS) the average value was +1.4 °C (SD = 3.0 °C), however negative values also occurred. The two "extreme" outlier values in the summer (8.5 °C, 7.7 °C) were recorded in the early morning on days with summer storms with precipitation of 26.5 mm and 123 mm, respectively. The annual number of tropical nights (Tmin > 20.0 °C, ETCCDI) significantly increased at both stations, at the Airport from 10 to 76 between 1966 and 2014 (slope of linear trend: 1.12 per year), at Viveros from 64 to 88 between 1906 and 2014 (slope of linear trend for 11 decades: 0.48, for the last 5 decades: 1.10 per year) (Figure 4.6).



(a) (b)

*Figure 4. 5 The frequency distribution of the temperature contrast between the Viveros and the Airport station calculated from daily in-situ measurements of Tmin (1966-2014): (**a**) The probability density; (**b**) Monthly statistics.*

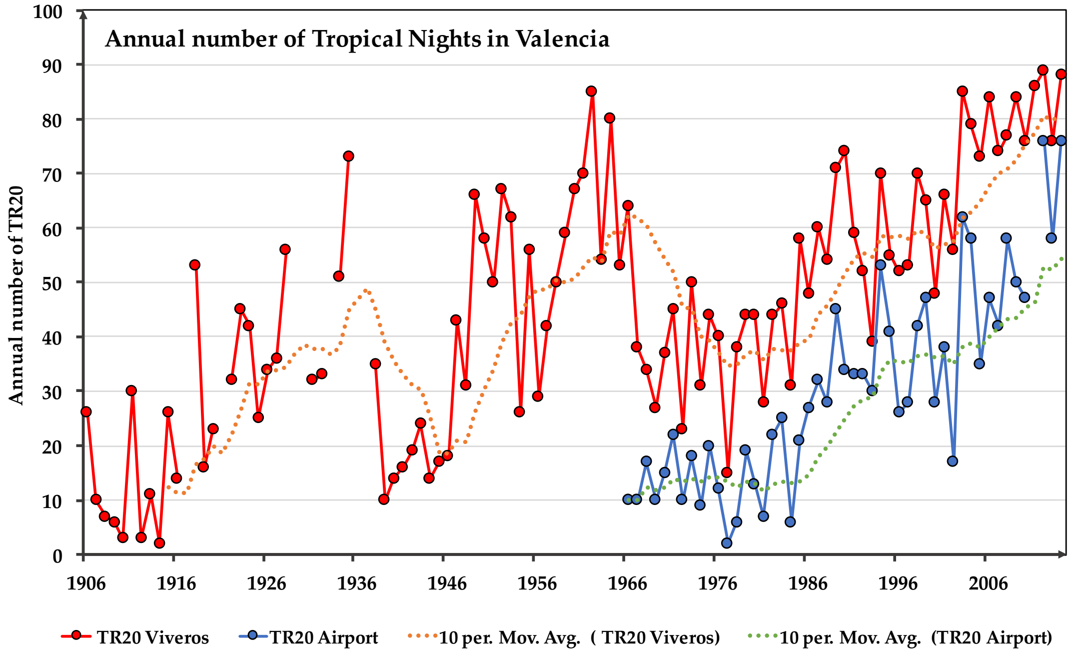


Figure 4. 6 The annual number of tropical nights (Tmin > 20.0 °C) at the airport and at the city centre (Viveros).

4.4.2 Case study of the evolution of sUHI

In August of 2014 the region of Valencia experienced its 5th largest daily maximum air temperature on record (26th of August, 42.2 °C measured at Airport) that was accompanied by tropical nights throughout the month and followed by extreme hot nights with Tmin > 22.0 °C (i.e., exceeding the 90th percentile of Tmin data as described in section 4.2.3). The LST images (Figure 4.7) present the evolution of the surface urban heat island over the city of Valencia during 3 consecutive days around the hot record (25–27 of August).

The daytime images (Figure 4.7a,b,e,f,j,k) taken in the early and middle afternoon show the so-called negative sUHI in the city. During the day the surrounding fields—characterized mostly by bare soil and low level vegetation—warmed up faster due to the direct insolation, meanwhile the urban areas stayed relatively cooler thanks to the shadows provided by the buildings, the higher specific heat capacity of the urbanized soil and the breeze coming from the direction of the sea (Table 4.2). The right column images (Figure 4.7c,d,g,h,l) presenting the nighttime conditions were taken around midnight and early morning. This well-pronounced positive temperature anomaly of the urban surface temperature is the phenomenon that is conventionally defined as sUHI.

Table 4. 2 The weather conditions during 25–27 August 2014 at the Airport and temperature at Viveros. (AT_v: AT measured at Viveros, AT_a: AT measured at Airport, v.a.: veering around, lower index a: measured at the Airport).

Date	**AT_v (°C) min/max**	**AT_a (°C) min/max**	**RH_a (%) min/max**	**Solar Time (GMT)**	**Wind $Direction_a$**	**Wind $Speed_a$ (km h^{-1})**	**Description**
25 August	22.7/30.2	21.1/32.4	32/88	0–5 6–8 9–16 17–20 21–24	NW-W Calm SE–E NE-E variable	2–5 0 4–19 15–21 0–5	light air calm gentle breeze mild/gentle breeze calm/light air
26 August	22.2/41.6	20.5/42.2	8/90	0–10 11–16 17–20 21–24	v.a. W SW NE-E variable	2–6 21–33 8–20 0–8	light air mild breeze gentle breeze calm/light breeze
27 August	23.1/30.5	22.6/32.4	41/87	0–4 5–8 9–18 19–24	E variable E SE	6–9 3–9 8–22 2–6	light breeze light air mild/gentle breeze light air

The previous day of the record heat (25th) was a common, cloudless August day, with a gentle breeze from the sea cooling the city during the day, and having light air flow after sunset. In the afternoon the highest negative value of sUHI occurred near Viveros (Figure 4.7a, black rectangle) and in the eastern part of the city (−2 °C), meanwhile SW-NE gradient can be noticed over the city (SW: 37 °C, NE: 34 °C). 1.5 h later the differences between the urban and rural areas became negligible, hence the “island of city” cannot be clearly distinguished in the Figure 4.7b. The nighttime images taken approximately 4 and 6 h after sunset (Figure 4.7c) show a generally warmer city (+2 °C). Around midnight the western and eastern residential areas of the city were the warmest, while 2 h later the warmest spots were the densely built old city centre in the vicinity of Viveros and the harbour (Figure 4.7d). The pixels with outstanding low/high values near the beach should not be considered as they might be influenced by the sea (Baghdadi and Zribi, 2016).

On the 26th wind was blowing from west all the morning indicating the arrival of the so-called “Poniente” (meaning “westerly wind”) that usually brings hot air from the inner plateau which warms more, by adiabatic compression, when descending into the coast. The Poniente prevailed all the afternoon as a mild breeze from SW—with the maximum velocity of 33 km h^{-1} at early afternoon (11 GMT)—resulting in a warm air advection to the city. The MODIS image in the early afternoon (Figure 4.7e) also captures this phenomenon as the LST was generally higher (42–46 °C) than the previous day at similar time (Figure 4.7a). The image 1.5 h later has a similar pattern and presents the rapidly warming surroundings, however there is less precision due to the high angle of the measuring sensor (Figure 4.7f). By twilight the wind had turned 180° and the NE-E gentle breeze from the sea started to refresh the city. The early night image (Figure 4.7g) presents an extended sUHI effect (2.5 °C) with the highest LST values in the inner city (25.5–26.5 °C). Later on in the night (Figure 4.7h) the city started to cool down, however still keeping its contrast with the surroundings (+1.5 °C). Furthermore, thanks to the northerly winds over open land the northern agricultural area of the city—the “Huerta”—stayed significantly cooler than the rest of the city.

The afternoon images for the next day (27th) are similar to those from the 25th, with strong negative sUHI in the early afternoon that became weaker as the city warmed up and the breeze fostered the heat transport from the surface to the air (Figure 4.7j,k). The early night image of 27/28 (Figure 4.7l) shows a similar sUHI pattern than the late night the day before (Figure 4.7h), with an average +2 °C. Later the night became cloudy, resulting in extreme high Tmin (24.5 °C) by early morning.

As the Figure 4.7 maps show, even though the Airport weather station is set up over bare soil and away from buildings, its surrounding is affected by artifical surfaces that influence the thermal radiance data. Hence, in order to evaluate the sUHI quantitatively, the differences between the average LST of the Urban and Rural, as well as the Urban and Semi-Urban (i.e., the surrounding of the airport) regions were calculated (Table 4.3). As the defined Rural region is a good representative of the agricultural belt around the city, using it as a reference resulted in the most precise estimation of the sUHI of Valencia. Further qualitative evaluation is provided in form of "difference maps" where the average LST value of the Rural region is subtracted from all the pixels (Figure 4.8a-l). These maps also support the findings that during daytime the urban area was generally cooler than the rural area (−0.6–−3.3 °C), and during nighttime the city area was a relatively homogenous warm spot (+1.7–2.6 °C). It should be noted that the western suburbs (including the airport) were also warmer during night, but showed more heterogenous pattern than the city.

Table 4. 3 The average LST over the three regions and the sUHI with Semi-Urban (SU) and Rural (R) references. (The best estimation of sUHI [Urban vs. Rural] is marked in bold. Letters in brackets correspond to the images of Figure 4.7a–l.)

Image Acquisition Time (GMT)	View Zenith Angle (°) [1]	Pixel Size (km)	Urban (°C)	Semi-Urban (°C)	Rural (°C)	sUHI Ref.: SU (°C)	sUHI Ref.: R (°C)
25 August 2014. 11:35 (a)	54	2.7	35.8	37.9	36.3	−2.2	**−0.6**
25 August 2014. 13:15 (b)	14	1.0	41.7	42.6	41.8	−0.9	**−0.1**
25 August 2014. 22:40 (c)	53	2.7	23.9	22.2	21.9	1.7	**2.0**
26 August 2014. 01:15 (d)	61	3.6	22.0	21.0	20.9	0.9	**2.0**
26 August 2014. 10:40 (e)	28	1.2	43.8	44.9	45.5	−1.1	**−1.7**
26 August 2014. 12:20 (f)	61	3.6	42.0	45.4	45.2	−3.3	**−3.1**
26 August 2014. 21:45 (g)	30	1.3	26.1	24.3	23.5	1.8	**2.6**
27 August 2014. 02:00 (h)	7	1.0	24.6	23.1	22.9	1.6	**1.7**
27 August 2014. 11:25 (j)	42	1.7	37.4	39.6	38.5	−2.2	**−1.1**
27 August 2014. 13:05 (k)	12	1.0	41.5	42.1	41.9	−0.6	**−0.4**
27 August 2014. 22:30 (l)	41	1.7	24.7	23.6	22.7	1.2	**2.0**

[1] Pixel size is estimated from the view zenith angle based on the calculations of (Wolfe et al., 1998).

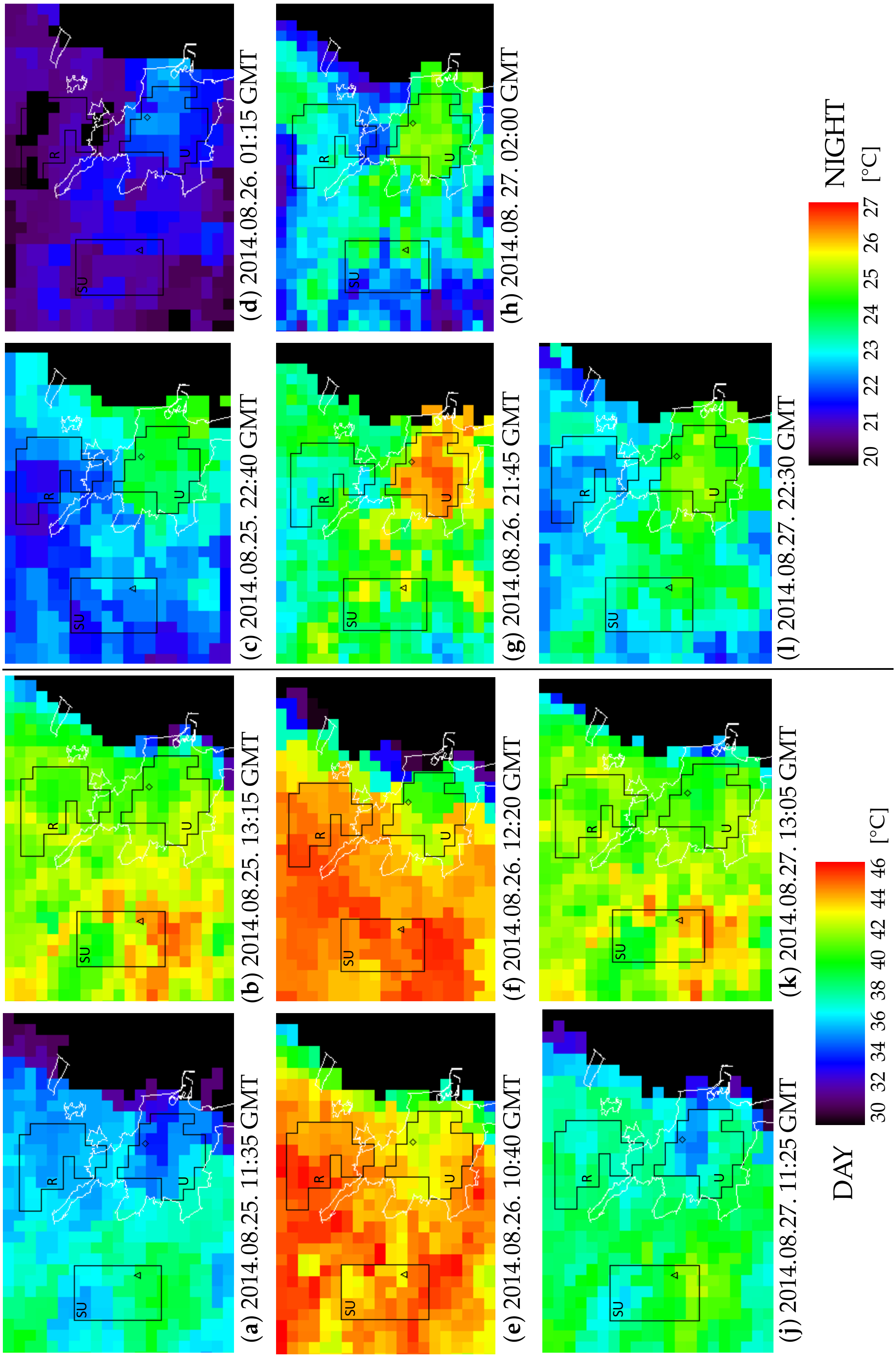


*Figure 4. 7 The evolution of sUHI during three hot summer days (25–27 August 2014). (U: Urban, SU: Semi-Urban, R: Rural region; diamond: Viveros meteorological station, triangle: Airport meteorological station, white border: administrative border of Valencia, black pixels: missing value/sea). **(a–l)**: MODIS LST images, see the corresponding data in Table 4.3.*

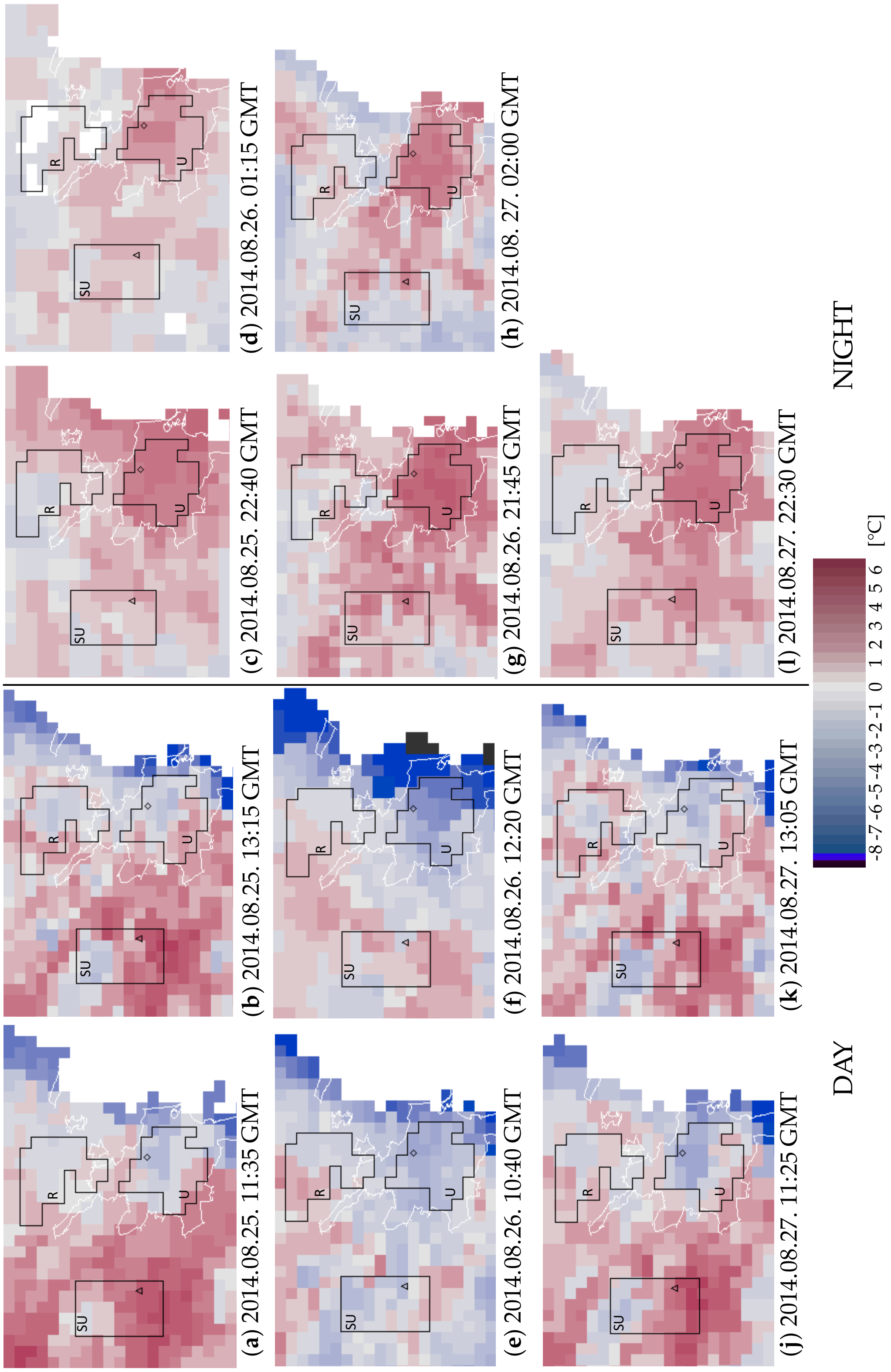


*Figure 4. 8 The evolution of sUHI during three hot summer days (25–27 August 2014) presented in form of "difference maps": the average LST value of the Rural region is subtracted from all the pixels in order to have a general view on the urbanized landscape in the region of Valencia. (U: Urban, SU: Semi-Urban, R: Rural region; diamond: Viveros meteorological station; triangle: Airport meteorological station; white border: administrative border of Valencia, white pixels: missing value/sea, dark blue-black pixels: values significantly influenced by the sea). **(a–l)**: MODIS LST difference images, see the corresponding data in Table 4.3.*

4.4.3 Comparison of AT and LST

In order to evaluate the differences between the urban heat island effect in terms of surface and air temperature observations during the studied 3-day period, LST data (point values retrieved from pixel as well as regional averages) and AT time series from the two weather stations were analysed (Figure 4.9). The point LST values were obtained from the nearest pixel to the stations to compare them directly with the air temperature measurements. During daytime the differences between AT and LST at the Airport reached more than 10 °C, however during the night the difference was not greater than 2.5 °C. This discrepancy was due to the different physical nature of AT and LST as it has been studied in several settings (Boudhar *et al.*, 2011; Gallo *et al.*, 2011; Tomlinson *et al.*, 2012).

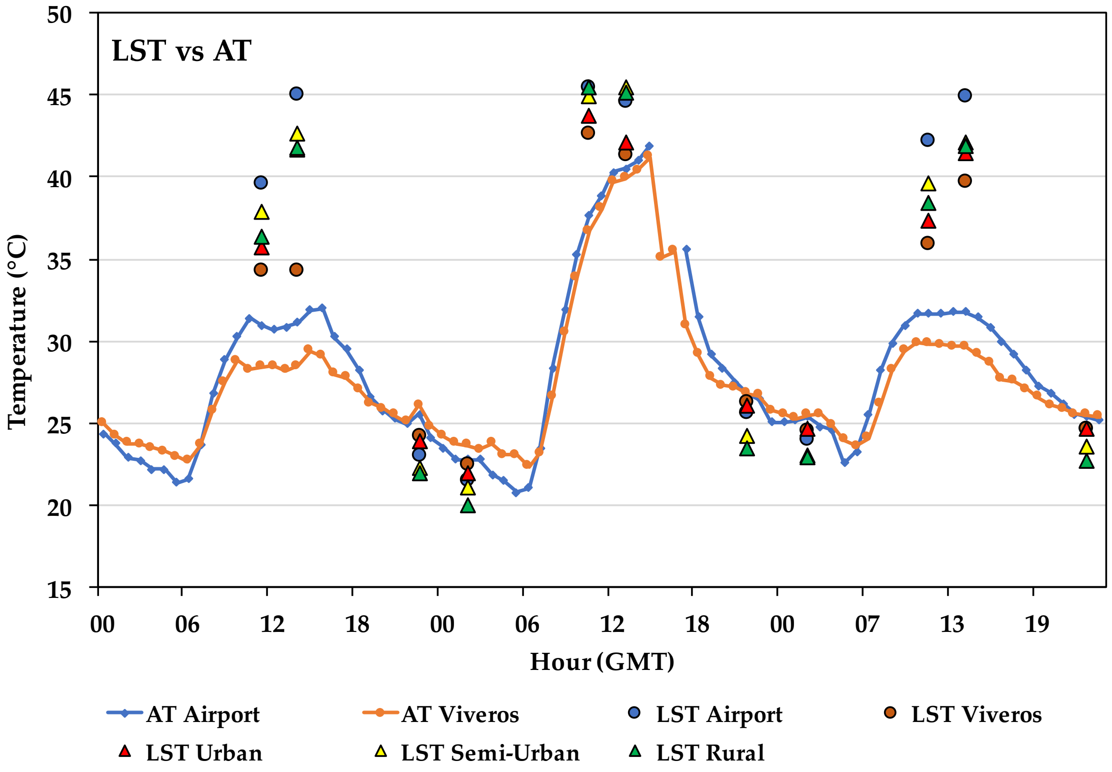


Figure 4. 9 Comparison of the LST and AT values during 25–27 August 2014. (AT Airport: air temperature from the in-situ measurements at the Airport; AT Viveros: air temperature from the in-situ measurements at Viveros; LST Airport: LST of one pixel nearest to the Airport; LST Viveros: LST of one pixel nearest to Viveros; LST Urban: average of LST over the Urban region; LST Semi-Urban: average of LST over the Semi-Urban region; LST Rural: average of LST over the northern Rural region).

At Viveros the difference between AT and LST was more moderated, during daylight less than 6 °C, and during nighttime less than 2 °C. This is a consequence of the altered surface-atmosphere interaction resulting in the urban canopy layer (UCL, the lower atmosphere from the surface until the mean building height) and the urban boundary layer (UBL, the lower atmosphere above UCL) that function as "buffer" layers over the surface of the city (Stewart and Oke, 2012).

The regional LST averages characterizing the 3 regions defined by the NDVI (Figure 4.2) provide a further description of the surface heat conditions over the different (Urban, Semi-Urban, Rural) regions. Similar to the point LST values during the day the regional LST values were much higher than the corresponding AT, showing the lowest difference in the city (LST Urban - AT Viveros). There were smaller differences between the regional values than between the point values during night, and the point LST values were the closest to the AT values. Additionally, in most of the cases the point LST value at Viveros fit well to the Urban regional average, meanwhile the point LST at the Airport had larger discrepancies compared to the Semi-Urban regional average.

The evolution of the urban heat island effect estimated from LST and AT measurements is presented in the Figure 4.10. The "biphasic" day-to day rhythm of the urban heat island effect is clearly seen in the air temperature measurements, showing a maximum difference between the Viveros and Airport station right before sunrise (5 GMT) with values of 1.6, 2.3 and 1.4 °C on the 3 consecutive days. On the other hand, the LST measurements suggest that the differences between the Urban and Semi-Urban region (Figure 4.10, blue triangles), as well as the Urban and Rural region (Figure 4.10, green triangles) were generally larger than the contrast in AT, showing the highest value (Urban - Rural: 2.6 °C) after sunset on the record hot day. Interestingly, on the 26th, a higher value of sUHI was found right after sunset (ca. 22 GMT) than at 2 GMT, probably due to the intense heat transport from the surface to the atmosphere.

The sUHI estimations from the regional LST values were in accordance with the sUHI estimations from point LST values, however during the day the point values suggest extreme sUHI values that is not representative for the region. Another relevant point to highlight is that in the afternoon the estimated UHI and sUHI had maximum discrepancies, while at night reasonable agreement was found between both effects (< 0.6 °C in case of point LST). Thus, during nighttime land surface data may indicate not only the sUHI pattern but the UHI pattern as well.

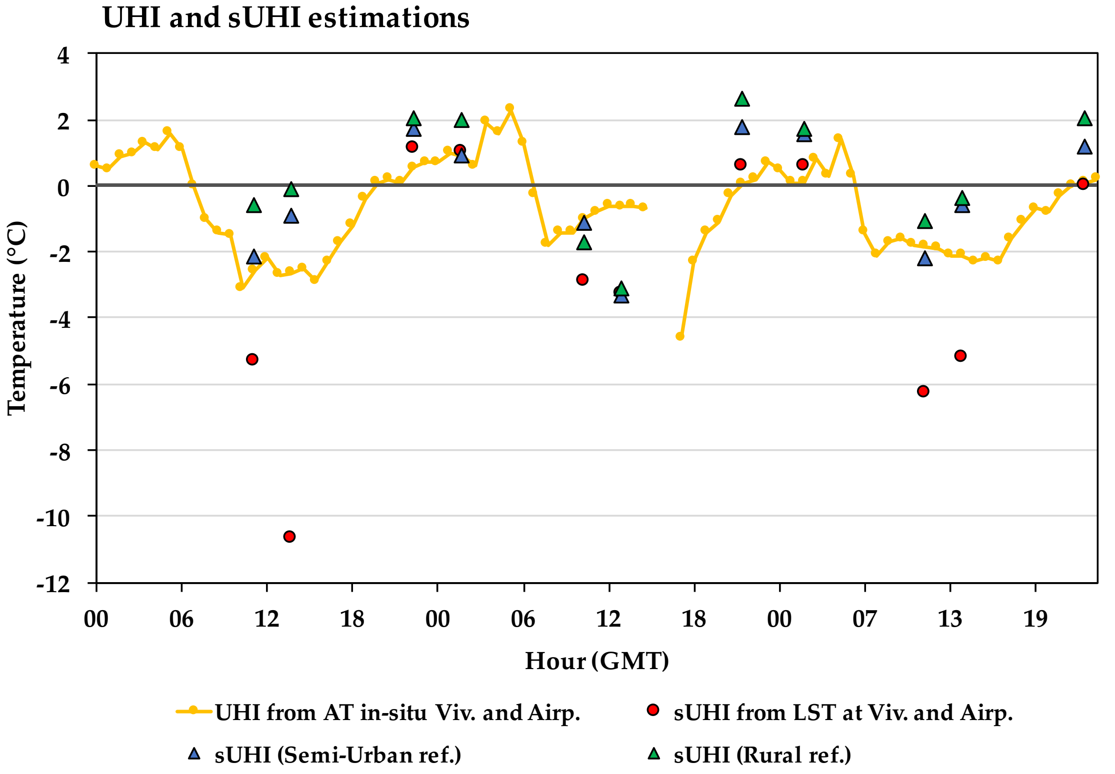


Figure 4. 10 Comparison of the estimated UHI and sUHI. (UHI from AT in-situ Viv. and Airp.: the difference between the in-situ measurements of AT recorded at Viveros and AT recorded at Airport; sUHI from LST at Viv. and Airp.: the difference between the LST obtained from one pixel nearest to the meteorological stations at Viveros and the Airport; sUHI (Semi-Urban ref.): the difference between the LST averages over the Urban region and the Semi-Urban region; sUHI (Rural ref.): the difference between the LST averages over the Urban region and the Rural region).

4.5 Human Comfort in the city

4.5.1 Annual characteristics

Based on the 4-year hourly temperature and relative humidity data, the annual cycle and daily cycle of DI were calculated at both the Airport and Viveros stations. According to the Equation 4.1 of DI, the optimum comfort occurs between 15 °C and 20 °C (Table 4.4).

As the annual cycle shows (Figure 4.11), Viveros station has more temperate winters than the rural/sub-urban areas represented by the Airport station. The annual mean DI index is slightly higher in the city (DI = 17.6 °C, SD = 4.2 °C) than at the airport (DI = 17.2 °C, SD = 4.7 °C). The standard deviation of hourly mean data in every month is higher at the airport than in the city, indicating more extensive daily range of DI—following the daily cycle of temperature (Figure 4.11).

Table 4. 4 The DI categories based on Toy, Yilmaz and Yilmaz (2007).

DI Category	DI temperature (°C)
Hyperglacial	<-40
Glacial	−39.9 to −20
Extremely cold	−19.9 to −10
Very cold	−9.9 to −1.8
Cold	−1.7 to 12.9
Cool	13–14.9
Comfortable	15–19.9
Hot	20–26.4
Very hot	26.5–29.9
Torrid	>30

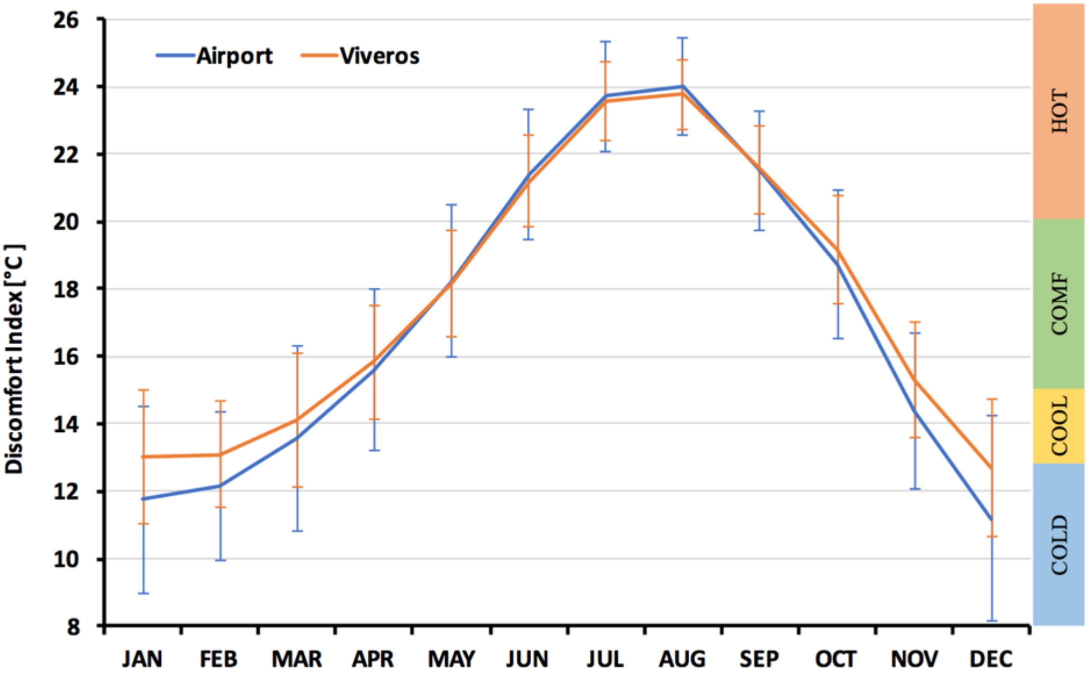


Figure 4. 11 The annual cycle of daily mean Discomfort Index at Viveros and Airport station in Valencia. The error bars indicate the standard deviation of hourly DI in the average day of each month.

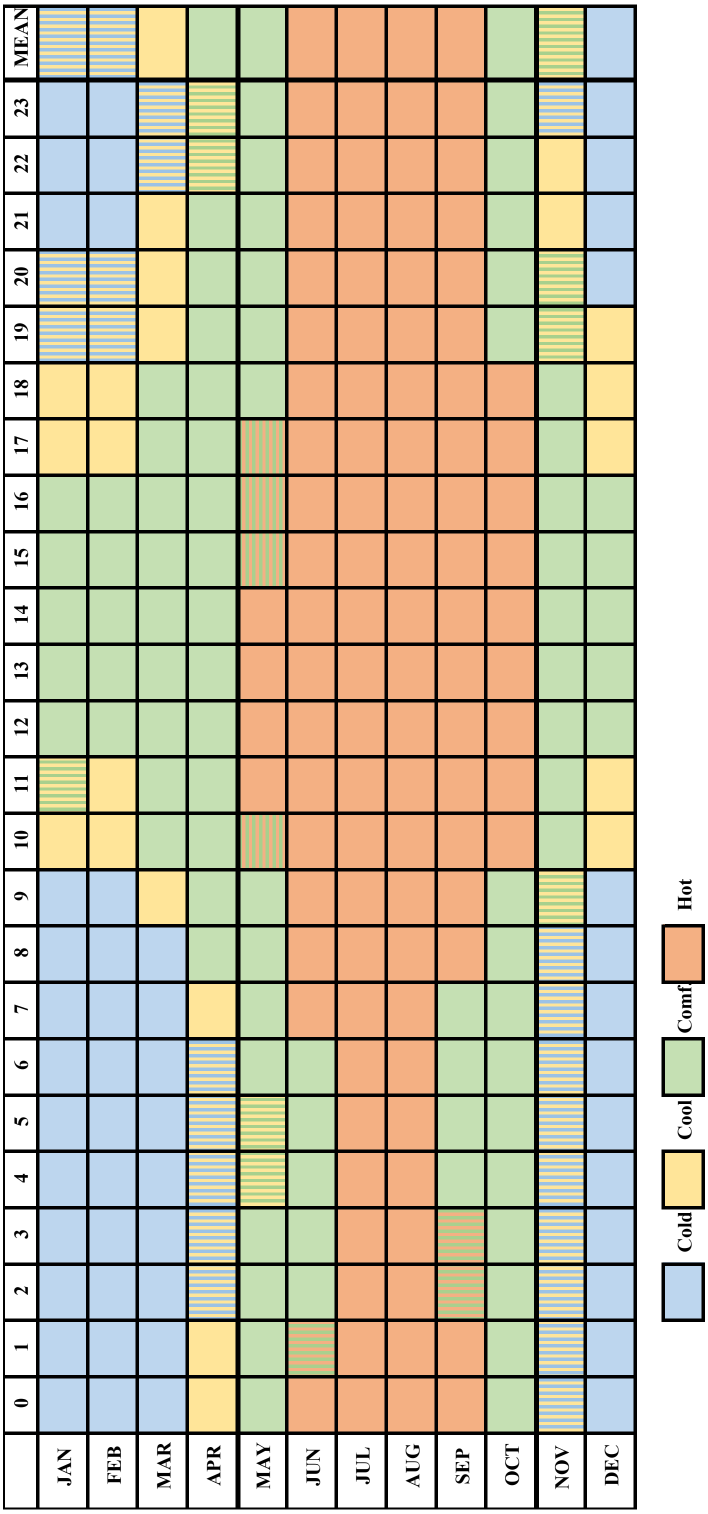
At each station five DI categories were detected throughout the year: *cold*, *cool*, *comfortable*, *hot* and *very hot* (defined in Table 4.4). In general, the majority of *cold* and *cool* hourly values were found in the cold part of the year (NOV-DEC-JAN-FEB-MAR-APR) and the majority of *comfortable*, *hot* and *very hot* values in the warm half (MAY-JUN-JUL-AUG-SEP-OCT). The Airport station has more values in the *cold* and *very hot* categories (the low and high end of the range) than the Viveros station, indicating that the suburban station has a larger daily and annual range of temperature (Table 4.5). The more frequent occurrence of *cool* and *comfortable* categories at Viveros are due to the milder wind in the city. *Very hot* hours were detected slightly (about 1 %) more often at the airport—in contrast, *hot hours* slightly (about 1 %) more often in the city—that is due to the negative urban heat island effect, i.e. in the hottest part of the day the rural areas warm up more, than the built-up areas (see section 4.4).

Table 4. 5 Percentage of days falling in the different DI categories at Viveros and Airport station.

DI	**Viveros**	**Airport**
COLD	16.3	21.2
COOL	12.2	10.7
COMFORTABLE	33.8	30.4
HOT	37.1	36.1
VERY HOT	0.6	1.7

In Table 4.6 the colour-coded average daily cycles can be seen for each month. As there were not many differences between the urban and sub-urban stations, only one table is shown here, marking those data that alter between the two stations. According to the monthly mean value of daily average cycle (Table 4.6, last column), in the city 4 month belong to the *comfortable* category (APR, MAY, OCT, NOV), 4 months to the *hot* (JUN, JUL, AUG, SEP), 3 months to the *cool* (JAN, FEB, MAR) and 1 month to the *cold* (DEC). The airport has similar category map over the year, however, the slightly colder wintertime can be noticed: JAN and FEB belong to the *cold* category instead of the *cool*, and NOV to the *cool* instead of the *comfortable*. In Table 4.6 the colours marked with vertical stripes belong to higher category (warmer) in the city than in the airport, while the ones marked with horizontal stripes refer to colder hours in the city compared to the airport.

Table 4. 6 A year-round calendar of the average daily thermal comfort based on the Discomfort Index calculated at Viveros and at the Airport in Valencia. The colors with vertical stripes indicate when Viveros has a higher DI category (i.e. warmer) than the Airport. The colors with horizontal stripes indicate the opposite case. The hours by columns are expressed in GMT. Spain belongs to the GMT+1 time zone, but during summertime GMT+2 is applied.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	MEAN
JAN	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟩▤🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟦▤🟨	🟦▤🟨	🟦	🟦	🟦	🟦▤🟨
FEB	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟦▤🟨	🟦▤🟨	🟦	🟦	🟦	🟦▤🟨
MAR	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟦▤🟨	🟦▤🟨	🟨
APR	🟨	🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩▤🟨	🟩▤🟨	🟩
MAY	🟩	🟩	🟩	🟩	🟩▤🟨	🟩▤🟨	🟩	🟩	🟩	🟩	🟩▥🟧	🟧	🟧	🟧	🟧	🟩▥🟧	🟩▥🟧	🟩▥🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩
JUN	🟧	🟩▤🟧	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
JUL	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
AUG	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
SEP	🟧	🟧	🟩▤🟧	🟩▤🟧	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
OCT	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟩	🟩
NOV	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟦▤🟨	🟩▤🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩▤🟨	🟩▤🟨	🟨	🟨	🟦▤🟨	🟩▤🟨
DEC	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟦	🟦	🟦	🟦	🟦

🟦 Cold 🟨 Cool 🟩 Comf 🟧 Hot

In general, in the cold part of the year, daytime hours are *comfortable* or *cool*, while nighttime hours are *cold* or *cool*. During the warm half of the year, daytime hours are mainly *hot* and occasionally *comfortable*, while during nighttime *hot* hours are still common, with a slight increase in the frequency of *comfortable* hours in some months. In June and September *hot* hours are prevailing the major part of the day, however, in the early morning conditions become *comfortable* for a couple of hours. July and August are characterized by *hot* hours all day, without relaxation period in the night. This means general discomfort and continuous increased heat stress on the human body during at least 2 months.

Comparing the suburban and urban stations, a couple of differences should be mentioned. First, looking at the cold part of the year, most of the differences can be seen during nighttime (early night and early morning, depending on the month). The common differences are that the city is one category higher than the suburban, i.e., instead of *cold*, the hourly values belong to the *cool* category, and instead of *cool*, to the *comfortable*. This difference is probably due to the often-occurring intense nighttime heat island effect, that was shown in Fig. 4.5. In November, more than half of the day the city has higher DI values than the airport, indicating milder conditions and less discomfort than outside the city.

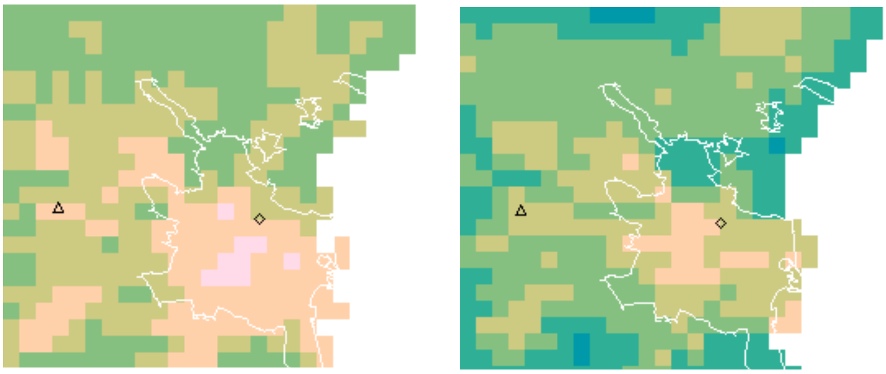
In the warm part of the year, similarly to the rest of the year, the city has higher DI values during nighttime—however only in a few cases. These cases occurred between 1 and 3 GMT, indicating unfavourable conditions, i.e. *hot* in the city instead of *comfortable* outside the city. Nevertheless, during daytime, in some cases (May, late morning and late afternoon) the city had lower DI values than the airport, that suggest more favourable conditions inside the city. This can be partly due to the negative urban heat island effect, that implies lower temperature in urban areas—mainly thanks to the shadows of buildings—, illustrated in Figure 4.7 and 4.8 MODIS images.

4.6 Spatial analysis – the case study

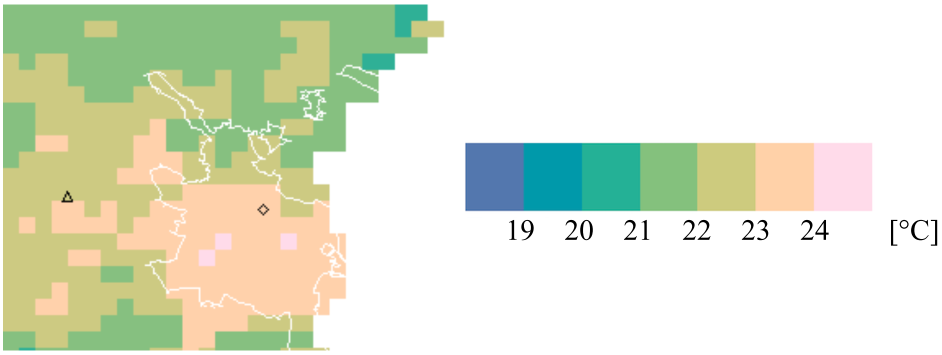
The spatial variability of human thermal comfort in the city was assessed using the DI discomfort index. As the DI formula (Eq. 4.1) originally involves AT and RH data, the index was calculated only at nighttime when the AT and LST were in reasonable agreement (see Figure 4.9 and Sobrino *et al.*, 2013). Accordingly, the index was estimated using the nighttime LST images and the average RH values calculated from the in-situ measurements at Viveros and the Airport (Table 4.2). Although using an average RH value for the entire region introduced a moderated spatial bias to the DI, it did not affect the index significantly as there were only slight differences between the RH values (< 12 %) at the two stations. The DI values throughout the 3 nights of the observed period ranged between 19.5 and 24.2 that fell into the categories of *comfortable* (15.0–19.9 °C) and *hot* (20.0–26.4 °C) (Table 4.3).

On the night 25/26th of August the major part of the region was characterized by *hot* conditions (Figure 4.12a,b). About 4 hours after sunset the DI in the city was around 22.5 and slightly decreased by early morning, while some rural spots had values at the upper limit of the *comfortable* category. The midnight image of the night 26/27 (Figure 4.12c,d) expresses the higher heat stress after a hot day. The inner densely built-up areas of the city (District 1, 2, 3 in Figure 4.1) experienced *hot* conditions characterized with the highest DI (24.2), and the > 23 values extended to the outskirts of the city as well. By early morning the region became less hot, and some *comfortable* rural spots appeared. The night of 27/28 (Figure 4.12e) similar conditions occurred than the night before, probably due to the increased nighttime temperature and humidity.

(**a**) 2014.08.25. 22:40 GMT (**b**) 2014.08.26. 01:15 GMT



(**c**) 2014.08.26. 21:45 GMT (**d**) 2014.08. 27. 02:00 GMT



(**e**) 2014.08.27. 22:30 GMT

*Figure 4. 12. The DI discomfort index during the 3 nights of the examined period (25–27 August 2014). (Diamond: Viveros meteorological station, triangle: Airport meteorological station, white border: administrative border of Valencia, white pixels: missing value/sea). (**a**–**e**): DI based on MODIS nighttime LST images.*

4.7 Extended analysis with high-resolution image of sUHI and DI

As it has been shown in the MODIS images, the values of the sUHI vary throughout the city depending on the different surface materials and building-density, nonetheless, the chosen rural reference point—that is better to define as sub-urban area—also significantly influence its values. Therefore, in this section I add a different estimation of sUHI by changing the reference point to an agricultural field with no buildings in the vicinity—the "huerta" —on the north edge of the city. Furthermore, a thermal image retrieved from ASTER measurements with a resolution of ca. 90 m is compared with the image of MODIS (ca. 1 km resolution), that were taken at the same time (28 June 2014, 22:06 and 22:05 GMT, respectively). Due to the limited number of high-resolution satellite images over the study region (mentioned in section 4.2.4), the only usable nighttime image for this study was the ASTER product on the aforementioned day. Thus, this section offers an example for further work.

Using the airport as reference (Fig. 4.13, first column) the ASTER image presents a detailed "structural map" of the city, highlighting the avenues and highways with wide asphalt cover and high traffic, the industrial zones and the densely built residential areas. The highest UHI values occur on the SE edge of the city indicating the line of highway (+3.2–4.0 °C), the main "ring" avenues around the city (2.1–3.5 °C), the "Bioparc" industrial area (2.5–3.0 °C) and the airport building with its asphalt runways (2.5–3.5 °C). Viveros, the biggest green park of the city, is cooler than most of the inner city and the airport (-0.5– -1.7 °C). Another identifiable object is the new channel of the Turia river on the west boarder of the city that is (-1.0– -1.6 °C) cooler than the reference point. The agricultural belt around Valencia, the "huerta", is also cooler than the rest of the city.

This pattern shows, that even though the airport weather station is set up over bare soil and away from buildings, its surrounding is affected by artificial surfaces that influence the thermal radiance data. Hence, sUHI values were also calculated by using a different reference point that was representative of the agricultural belt (Figure 4.13, second column, asterisk symbol). On the retrieved image the city centre is less distinguished from its surrounding as the reference spot is 2.5 °C cooler than the airport area. On one hand this gives a more realistic image of the temperature contrast in the whole region around midnight (urbanised vs. agricultural fields), but the differences inside the city are blurred. In both of ASTER images some sporadic extreme cold spots (dark blue) are notable, that are originated from the estimation uncertainties of the surface emissivity parameter. “Over-radiated” spots of very light surfaces can cause this type of error that can be ruled out by better estimations of *e*, but it was beyond of the scope of this study.

The MODIS images (Figure 4.13, second row) capture the main pattern of the sUHI, with a “hotspot” on the SW part of the city (+0.7 °C) indicating the highways, and a slightly warmer spot in the vicinity of Viveros (+0.4 °C), compared to the airport. The rest of the city has similar or slightly cooler temperatures than the airport, with the coolest part in the north “huerta” (around -3 °C). Using the “huerta” as reference the city is represented by higher sUHI values (+1.5–3.0 °C) and also the villages on the NW ca. 1 km from Valencia are +2.5 °C warmer. In general, the MODIS images show lower sUHI values as the surface variances are averaged out due to the rougher resolution.

The discomfort index in the city (Figure 4.13, third column) varied following the temperature patterns, mainly characterized by values around 22–23 °C that indicates *hot* category. The large SE highway shows the highest values (around 24.5–25 °C) that is close to the upper limit of the category. The only *comfortable* spot in the inner city around midnight is Viveros, that has some values around 18 °C. The north fresh part of the city is well pronounced in the MODIS image as well, with values around 19–20 °C. The comfortable regions with values of 18–19 °C are generally farther from the city boarder, typically occurring in the agricultural fields.

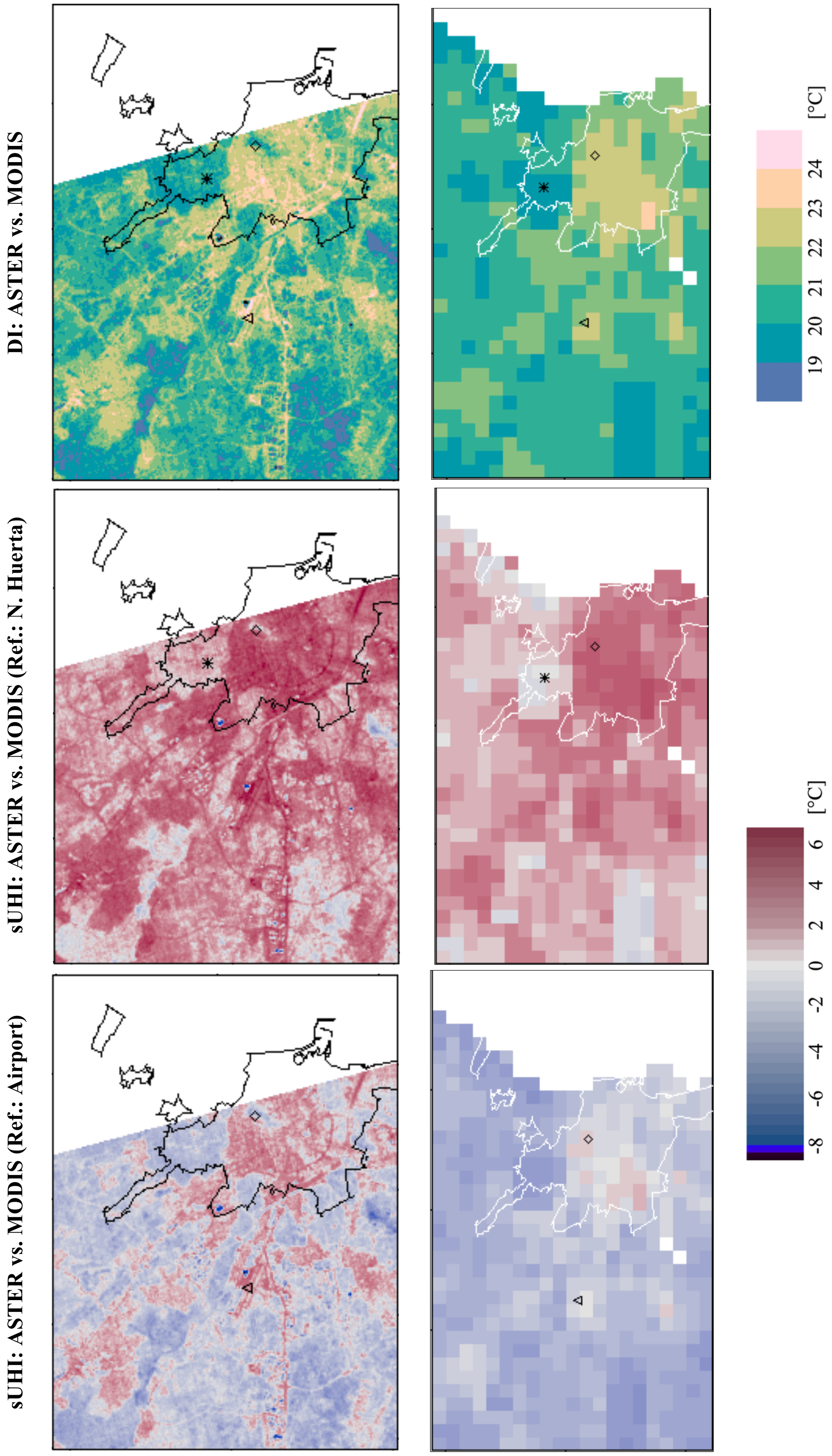


Figure 4. 13 The-high resolution structure of the sUHI and the DI discomfort index during a summer night (28 June 2014).

4.8 Discussion

4.8.1 Long-term heat conditions

A strong local warming trend was identified in the long-term (1906–2014) near-surface temperature time series in Valencia (0.2 °C per decade) as it is expected due to the human induced global climatic changes. This is accompanied by changes in both the cold and warm extremes. The Valencian region has experienced more intense warming than the global average, as the global surface temperatures increased with 0.85 °C between 1880 and 2012 (IPCC, 2013b), that indicates a warming rate of 0.07 °C per decade. This pronounced mean warming in the Mediterranean region has been documented by several studies, e.g., Giorgi, (2006) and Brunet *et al.* (2007). Over mainland Spain warming of 0.1 °C per decade was detected based on an average of 22 stations for the period 1850–2005, and for southeastern and eastern Spain—the region of Valencia—it was 0.13 °C for the period 1901–2005 (Brunet *et al.*, 2007). According to this study—using different methods and extended time period (1906–2014)—the individual station of Valencia showed stronger warming than the rest of the country.

Warm days (1.1 % per decade) and *warm nights* (1.8 % per decade) have become more frequent while the occurrence of *cool days* (-1.5 % per decade) and *cool nights* (-2.3 % per decade) decreased during the studied period 1906–2014. This implies positive shift of frequency distribution of daily Tmin and Tmax, indicating generally warmer conditions. Similar trends in temperature extremes have been observed in the Western Mediterranean region (e.g., Kiktev *et al.*, 2003; Klein Tank and Können, 2003; Brunet *et al.*, 2006; Bartolini *et al.*, 2008; Rodríguez-Puebla *et al.*, 2010), and globally (e.g., Alexander *et al.*, 2006).

As the absolute value of average annual rate of trends in cold extremes was higher than in warm extremes, the rightward shifting of cold tail was bigger than of warm tail in case of both Tmax and Tmin. This is in line with the global trends (Alexander *et al.*, 2006), i.e. a positive shift in the distribution of daily minimum and maximum temperature was observed throughout the globe for the period 1951–2003—but with smaller magnitudes in case of Tmax. Over mainland Spain Brunet *et al.* (2007) found similar tendency, showing that the overall warming during the period 1850–2005 has been more associated with reductions in cold extremes, as opposed to increases in warm extremes.

Significant trends of more *warm days* and fewer *cool nights* over the Iberian Peninsula were connected to large scale-variables by the study of Rodríguez-Puebla *et al.* (2010). According to their results, changes in the *warm days* indicated by *TX90P* are connected with the Scandinavian teleconnection index and a preferred mode of geopotential height at 500 hPa over the North Atlantic. Changes in *cool nights* (*TN10P*) are connected with the East Atlantic teleconnection index and the leading mode of Sea Surface Temperature (SST) variability over the North Atlantic area (Rodríguez-Puebla *et al.*, 2010).

In present work, slightly larger changes were detected in nighttime conditions (increase of *warm nights* and decrease of *cool nights*), than in daytime. This suggest more comfortable (less cold) winter nights but increased heat stress during summer nights as similar studies (e.g., Unger, 1999) discussed this. The latter is an important contextual factor to be considered when discussing the harmful impacts of summer urban heat island effect (see section 4.8.2 and 4.8.3).

The occurrence of cold spells decreased drastically in the second half of the 20th century according to the presented calculations. However, a detailed comparison of results is not possible since there are only a few studies available investigating long-term changes in characteristics of cold spells or cold waves in Europe. In case of the United States, Kunkel *et al.* (2008) found that the country has experienced a general decline in cold waves over the 20th century, with a spike of more cold waves in the 1980s. During the period 1950–2003 a significant decrease of cold spells was documented in the Middle East too, based on data from 52 stations (Zhang *et al.*, 2005). Lhotka and Kyselý (2015) analysed the spatial extent, temperature magnitude and duration of cold spells over Central Europe, however still there is a lack of research on the frequency of cold spells/cold waves from long-term perspective in Europe.

Warm spells have become more common after 1997, with a record number of days in 2003. As Castellà and Brunet (2011) described, the summer of 2003 was unprecedented (at the time of the study) in terms of both warm days and nights, as well as the warm spells along the Mediterranean coast, including Valencia. This remarkable 2003 heat wave and its impact was well-documented all-around Europe, e.g. in France (Poumadère *et al.*, 2005 and De Ridder *et al.*, 2017), in Italy (Conti *et al.*, 2005, 2007) or in Switzerland (Beniston and Diaz, 2004). In general, the increasing number of warm spells is in accordance with the findings of Della-Marta *et al.* (2007a), showing that the length of summer heat waves over western Europe has doubled over the period 1880 to 2005. Heat wave events over western Europe were explained in the context of large scale forcing and teleconnections between atmospheric circulation, sea surface temperature and precipitation by Della-Marta *et al.* (2007b).

4.8.2 Urban heat island

The growing number of tropical nights indicates a general warming trend at both the city centre and the countryside. The temperature contrast between the two sites has not changed in the last 5 decades, suggesting that the intensity of the urban heat island effect is not sensitive to the growth of the city or the warming trend. It is worth noting that the UHI effect is independent of the warming trends experienced by the studied locations in relation to global atmospheric dynamics, as the latter happens independently of the urban or rural nature of the measurement sites. Nevertheless, the Tmin as an indicator of nighttime conditions has limitations, providing more accurate information about the early morning, but less of the early night.

A measurement campaign carried out during two winter nights in 1988 (Caselles *et al.*, 1991) first quantified the UHI in Valencia, taking ground-based air temperature measurements along transects and using remote sensing NOAA data. According to Caselles *et al.* (1991) in a winter morning (5 GMT) 3.0 °C of heat island effect was estimated by transect AT measurements and 4.5 °C by satellite LST data. This agrees with results of this study presenting 2.3 °C of heat island effect estimated by in-situ AT data at 5 GMT and 2.6 °C by remotely sensed LST data at ca. 22 GMT after the record hot summer day. Our slightly lower values—besides the use of improved satellite sensors—were due to the seasonal difference, as the cool winter nights provide more favourable conditions for the development of UHI (Figure 4.5b).

Furthermore, Caselles *et al.* (1991) found that the heat island effect obtained from satellite data is 1–2 °C higher than the value obtained from air temperature measurements. This also supports the findings of this study that in general the nighttime sUHI was higher (with 1.5–2.2 °C, Figure 4.10) than the corresponding UHI. Nonetheless, our results emphasise that the “urban” and “rural” reference locations in an extensively urbanised landscape have a high impact on the estimations of the urban heat island effect (Table 4.3, Figure 4.8), hence should be chosen prudently. The NDVI provides a good base to distinguish surfaces with or without vegetation, however an objective, universally applicable landscape classification scheme is needed for further higher resolution sUHI studies (Stewart and Oke, 2006).

According to an early analysis on the urban climate of Valencia (Pérez Cueva, 2001), the heat island effect of the city decreases the discomfort of winter cold, but it increases the discomfort of summer heat. In the present case study the sea breeze played a main role in refreshing the city after the record hot day. It is notable that the prominent SW continental wind (“Poniente”) blocked from early morning the beneficial sea breeze from E on the 26th of August 2014, resulting in a severe warm advection all day, that was overtaken by the NE sea breeze only in the early evening hours. Consequently, the nighttime UHI after the unusually hot day was more intense as we might expect from other cases, e.g., Birmingham, UK (Tomlinson *et al.*, 2012), Beijing, China (Li *et al.*, 2015), and Madison, USA (Schatz and Kucharik, 2015).

Regarding the sUHI pattern, using low resolution NOAA images Caselles *et al.* (1991) found a similar structure to that identified in the MODIS images, namely higher values in the city centre and the eastern part of the city. They also identified a maximum SW temperature gradient from the city centre, which occurs thanks to the unfragmented agricultural fields and forests on the SW (Figure 4.7). A similar spatial pattern was found in Barcelona, another Mediterranean coastal city, with higher intensity (Moreno-Garcia, 1994), probably due to the larger population of the city. For further spatial assessment of the intra-urban variability of UHI in a district or neighbourhood level spatial resolutions greater than 50 m are needed, and the recommended satellite overpass time is immediately before sunrise, as Sobrino *et al.* (2012) suggests.

4.8.3 Human comfort

The discomfort index is an important indicator to evaluate the heat stress imposed on the human body and well-being. The annual and diurnal cycle of DI shows that urban areas are more temperate than the rural, that is line with studies comparing climatic factors between urban and rural areas, such as Unger (1999) and Toy, Yilmaz and Yilmaz (2007). In the city four months—the second and third months of spring and autumn—belong to the *comfortable* category and four months—summer and early autumn—to the *hot*. Three months (second and third months of winter and the first of spring) are characterized by *cool* conditions, and the first month of winter falls to the *cold* category. In contrast with the mild winter in the city, the suburban areas are attributed by one category less (i.e. they are colder) in January, February and November. Accordingly, during winter the city offers more favourable conditions than the rural region, where people are exposed to less comfortable conditions. A similar study on the city of Erzurum (Turkey, continental climate) found that during winter—considering the number of *cold* and *very cold* months—the most advantageous area is the urban area compared to rural regions (Toy, Yilmaz and Yilmaz, 2007).

I found that in the warm part of the year the DI conditions were similar at both stations. July and August were characterized by *hot* hours all day, without relaxation period in the night. This means general discomfort and increased heat stress on the human body during at least two months. Apart from July and August, there are a couple of cases (occurring between 1 and 3 GMT) when it's *hot* in the city and *comfortable* outside the city, indicating warmer nighttime conditions in the urban area. This implies that people living inside the city—and resting home during night—are exposed more frequently to *hot* conditions, than those having their home outside. The higher exposure time might impose higher heat risk on the vulnerable segment of the population, as Tomlinson *et al.* (2012) showed for the case of Birmingham.

Thermal discomfort on an hourly scale was studied in the Spanish cities of Malaga and Barcelona (Balafoutis, Ivanova and Makrogiannis, 2004), but not in Valencia. Considering the geographical locations of these three cities, all lay along the Mediterranean coast: Barcelona in the north, Malaga in the south and Valencia around half-way between the two. Based on the Relative Strain Index—that applies temperature and relative humidity data similarly to DI—calculated for July 2003, Malaga was more comfortable than Barcelona, where some days had very unpleasant conditions (Balafoutis, Ivanova and Makrogiannis, 2004). However, I need to note, that the more frequent distress conditions in Barcelona compared to Malaga cannot be generalized for all summers, as the 2003 summer had unprecedented heat waves that were more intense on the northern part of the Iberian Peninsula (Castellà and Brunet, 2011) than on the south. For this reason, our results based on the Discomfort Index calculated for the 4-year period 2012–2015 provide a more comprehensive overview of the annual cycle of human comfort in Valencia.

Nevertheless, it is important to mention that non-ideal locations of the meteorological measurements probably influence the DI results. As the airport station is placed close to a medium built-up suburban region and the urban station is installed at the side of a large urban park, both meteorological data are influenced by its surrounding for some degree, as I described in section 4.2.2. Probably, with more and better located stations (for instance one in the surrounding agricultural fields and others in the densely built-up areas such as the old town) more accurate results could be achieved. Furthermore, other indices that take into account more variables (such as wind, sunshine hours, precipitation, etc.) could provide further, sector-specific information of thermal comfort in the city. For example, the Tourism Climatic Index (Mieczkowski, 1985; Perch-Nielsen, Amelung and Knutti, 2010; Kovács and Unger, 2014) and Holiday Climate Index (Scott *et al.*, 2016) are widely used for the tourism sector.

To evaluate the heat stress that the increased nighttime temperatures impose on the urban population the spatial pattern of DI was analysed. It is notable that the inner city and surrounding residential areas (with the highest number of inhabitants in the SW districts of 2, 3, 7, 8, 9, in the N districts 5, 15, 16 and the E districts of 12, 13, 14, Figure 4.1) generally tended to be warmer than the surroundings during the usual sleeping period of night in summer in Valencia (02–08 GMT+2). This increases the discomfort of habitants, and might cause more frequent insomnia events (Vineis, 2010). According to the DI maps, the hot zones with the highest DI were in the densely built-up city centre, while the cooler areas that were categorized as *comfortable* corresponded to non-urban zones. An airborne measurement campaign over Madrid (Sobrino *et al.*, 2013) found similar patterns on a summer dawn, corroborating that most of the *hot* areas are inside the city, while the cooler ones (categories of *comfortable*, *cool* and *cold*) are outside of it.

When looking at the high-resolution ASTER image, a more detailed map of the city can be drawn in terms of sUHI and DI. Based on the map obtained from the ASTER image it can be noticed that the highest values of DI are related to artificial surfaces in general, such as asphalt and densely built-up areas, or the high traffic multi-lane roads (the main arteries of the city transport). The cooler areas—categorized as *comfortable*—correspond to non-urban zones (mainly on the SW) and some spots with extensive green vegetation in the city, such as the park of Turia and Viveros. These findings support the concept that a city with more vegetation is considered to have more comfortable urban climate (e.g., Lafortezza *et al.*, 2009).

According to an urban planning study from 2010 (Lozano Esteban, 2010), an interconnected green area throughout the city and joint to the sea could significantly improve the ventilation of the city. The daytime negative urban heat island in summer is conserved partially thanks to the morning fresh sea breeze. As soon as the morning breeze stops penetrating the city (at around 11–12 h local time), the temperature between the city and the countryside equalizes, as it was shown in Figure 4.7b,f,k. Based on the proven value of the already existing green urban areas throughout Europe (e.g., Dimoudi and Nikolopoulou, 2003; Bowler *et al.*, 2010) as well as the park of the Turia riverbed and the green road Blasco Ibáñez towards the sea in Valencia, the extension of these green lanes would be highly beneficial for a climate-resilient city. As an ecological design research showed on the case of Valencia (Gómez *et al.*, 2013), trees are the best way to protect open spaces against thermal stress and UV rays.

This case study on the urban heat island of Valencia provides essential knowledge to help urban designers mitigate the combined effects of climate change and UHI. As a next step, higher resolution satellite images will be analysed to provide a more detailed thermal map of the city for strategic urban planning and for modelling studies to estimate the effect of the different measures. As the use of green spaces could alleviate the perception of thermal discomfort during periods of heat stress (Lafortezza *et al.*, 2009), increasing the urban greenery as well as promoting light coloured building design are highly recommended (Hoverter, 2012). Moreover, both public opinion and expertise from different municipal departments, literature surveys and life cycle assessments should be considered in an integrated urban planning process (Eliasson, 2000; Andersson-Sköld *et al.*, 2015; Cortekar *et al.*, 2016). This has been already initiated through various cross-sector projects in relation to the Valencia Smart City Strategy (*Valencia Smart City Strategy website*)

4.9 Summary and Conclusions

In present study, the urban heat island effect and human comfort is evaluated in the city of Valencia, in case of hot summer days. To put the results into time context, the temperature conditions of Valencia were analysed from a long-term climatological perspective. Daily mean temperature as well as warm and cold extremes were examined for the 1906–2014 period. Furthermore, a year-round calendar was prepared based on hourly values of the Discomfort Index calculated from 4-year data.

The results are summarized as follows:

- Significant increasing trend in mean temperature (0.23 °C per decade) was detected in Valencia over the studied period 1906–2014. The number of *warm days* and *warm nights* increased, while the number of *cool days* and *cool nights* decreased during 1906–2014. The occurrence of cold spells drastically decreased in the second part of 20th century, while warm spells have become more common after 1997.
- The urban heat island effect in Valencia estimated from AT and LST measurements showed a good agreement regarding the intensity and evolution of the effect during hot summer days. The UHI estimated from AT measured at the two stations was highest just before sunrise (2.3 °C). The sUHI calculated as the difference between the urban and rural region LST was the most intense after sunset on the record hot day (2.6 °C).
- The MODIS satellite images provided valuable insights to the heat conditions over the region of Valencia, but because of its moderate resolution the differences inside the city were blurred. For this reason, as we exemplified by an ASTER image, higher resolution satellite images with more frequent data acquisition time are needed, especially over cities.
- Based on the Discomfort Index the city has milder winter conditions than the rural areas, especially during nighttime. In the warm part of the year the DI is similar at both stations, however, the city was occasionally warmer in the early morning hours. Hot nighttime conditions are prevailing from June to September, that might impose higher heat risk on the vulnerable segment of urban population.
- The spatial analysis of DI in the nighttime MODIS and ASTER images revealed less comfortable areas in the densely built up city centre, main traffic arteries and industrial zones in contrary to the rural regions.

These findings are consistent with previous studies and provide novel contribution to the literature in several specific aspects. By examining the long-term changes in temperature extremes over eleven decades and describing the nighttime temperature contrast between the city and its surroundings over five decades this work offers new, specific information on the climate of Valencian region. As the time series examined here are one decade longer than those in the existing literature, this work is able to update the previous findings. The presented results on the urban heat island effect calculated from in-situ and remote sensing data extend our knowledge on the case of Valencia, due to the simultaneous description of UHI and sUHI and the improved quality of satellite sensors since previous studies. Characterizing the diurnal cycle of thermal comfort throughout the year and the spatial pattern during hot summer nights, resulted in novel information too that can be useful to urban planners in the design and distribution of green areas in the city.

4.10 Practical implications

In order to facilitate the mitigation of urban heat risk, detailed thermal maps of UHI and DI should be considered in urban planning and modelling, and measures need to be taken to reduce the discomfort of the humid heat in the summer period, such as those that improve the natural sea breeze to ventilate the city. Furthermore, more green areas (interconnected parks, rooftops, etc.) as well as high albedo building materials (e.g., cool roofs and cool pavements) need to be installed throughout the city. As an answer to the increasing demand of city scale environmental data, the presented results provide essential information on the urban climate and thermal comfort that can provide a solid foundation for the design of climate change adaptation strategy in Valencia.

Climate Services could contribute to the climate adaptation efforts by providing detailed city maps of sector specific indices, e.g. Tourism Climatic Index or Discomfort Index, as this work showed through the example of thermal comfort. For mid- and long-term strategic planning the region-specific results of climate projections need to be taken into account. To support the urban planning and decision-making processes, user-friendly metrics and maps (as we exemplified) need to be prepared taking into account public opinion and expertise from different municipal departments. To analyse the stakeholders' different needs and perspectives in terms of climate information, market research is recommended. As an example, in the next chapter a cross-sectoral case study is presented mapping the different interests of actors in urban climate adaptation projects.

As adaptation is increasingly conceived of as the management of climate risk, the potential threats, vulnerabilities and impacts need to be assessed hand-in-hand with practitioners. For instance, by identifying the residential areas of vulnerable groups of urban population, and combining this information with the spatial urban climate knowledge, detailed heat risk maps can be produced. Integrating scientific and local knowledge is key in the process. Co-development of these projects is a way of securing that the different perspectives and needs off stakeholders (e.g. urbanists, architects, the municipality, citizens, local businesses, etc.) are included in the planning and decision-making process. The urban thermal comfort information can be combined with other types of high-resolution data from the city (e.g., real-time traffic, air pollution data) tailored to the needs of citizens or other stakeholders.

Chapter 5

Transdisciplinary collaborations in Climate Services: cross-sectoral case study on urban climate adaptation planning

5.1 Introduction

Numerous studies are available on the team science of transdisciplinary (TD) collaborations from the health, business and education sectors (e.g., Aboelela *et al.*, 2007; Klein, 2008; Stokols *et al.*, 2008; Nancarrow *et al.*, 2013), but only a few on the team dynamics of climate-related problem-focused collaborations. Most of the literature on TD collaborations focusing on environmental/climate issues are framed as sustainability science (e.g., Lelea *et al.*, 2014; Leventon *et al.*, 2016) or environmental resources management (Reed, 2008; Reed *et al.*, 2009). Such studies provide useful methodologies for stakeholder analysis in TD research projects. In recent years, various sector-specific multi-stakeholder studies were published, focusing on, for example, food supply chains (Lelea *et al.*, 2014), flood risk management (Morss *et al.*, 2005), water planning and irrigation (Granados *et al.*, 2015; Hall *et al.*, 2016), soil degradation projects (Leventon *et al.*, 2016) or coastal defence research (Merkx and van den Besselaar, 2008). The publication of the BASE project (BASE Project,

2017) also presented a diverse collection of case studies relating to different aspects of climate adaptation planning at a European level (e.g. flood risk and river basin management, urban planning, health impact). Participatory action research approaches have been widely used in different disciplinary and geographical contexts involving multiple stakeholders (Reed, 2008), for example climate adaptation options are examined through participatory action research by Campos *et al.* (2016a,b).

Despite this, there is still a lack of research on stakeholders' needs, interests and motivations, and the barriers that influence the efficiency of climate-related TD collaborations. Because getting to know the needs of climate information users was declared as one of the main priorities of Climate Services research (JPI Climate, 2011; European Commission, 2015; Vaughan *et al.*, 2016), and now that Climate Adaptation Services is a growing market (Goosen *et al.*, 2013), it is considered important and urgent to better understand the dynamics of climate-related TD collaborations, and to map the different perspectives of stakeholders working on climate adaptation. As Pidgeon and Fischhoff (2011) argued, "there is no way to know what information people need without doing research that begins by listening to them".

The present qualitative social research is designed to analyse the factors that influence and foster cross-sectoral collaborations in urban climate adaptation and planning. To evaluate TD collaborations I apply the framework developed by Stokols *et al.* (2008) that helps teams to identify interventions in order to improve or optimise their team work and foster new collaborations. For this, in-depth interviews are conducted with relevant stakeholders (academics and practitioners) involved in climate adaptation planning projects. Furthermore, based on the visual tool of the "Empathy Map" (De Vicente Lopez and Cristian, 2016), I draw the profiles of the different stakeholders and provide novel insights into the market of Climate Services.

Based on the TD literature and the author's practical experience in cross-sector projects (Chapter 6), several questions were formulated, such as "What are the principles of good TD collaborations focusing on climate-related issues?", "What are the incentives and obstacles that climate scientists involved in TD collaborations face?", "What are the benefits of TD collaborations for the academic and practitioner stakeholders?", and "What do practitioners need as users of climate information?". Accordingly, this cross-sectoral case study was designed with the following specific objectives:

(i) analyse the factors that influence and foster transdisciplinary collaborations in urban climate adaptation projects;
(ii) map the voices of academic and practitioner stakeholders regarding their motivations, challenges and needs;
(iii) provide practical insights into building effective TD collaborations in Climate Services.

5.2 Data and Methods

In this section, I provide an overview of data collection and the tools used for the evaluation of data. The conceptual frameworks for this analysis are described in detail in Chapter 2 (section 2.5.5).

This case study on the key determinants of a successful TD collaboration in Climate Services is based on both primary and secondary data; it consists of an extensive literature review (Chapter 2), interviews with key informants and observations in the field. A broad-range literature review provided a foundation for the study and an understanding of the wider context of TD collaborations. During fieldwork in Lisbon and Cascais (Portugal), key informant interviews were then conducted with academics and practitioners working on urban climate and adaptation planning.

5.2.1 The interviews

To carry out these interviews, the qualitative interview method was chosen for the following reasons: a) the research questions need a high degree of freedom so that question could be answered precisely; b) different stakeholders need differently weighted questions; c) it provides space for serendipity (accidental, non-expected findings) (Yates, 2003). The latter is especially important in this study because the dynamics of TD collaborations in relation to climate science have rarely been investigated. The interview questions were designed according to the modified framework of “contextual factors influencing transdisciplinary collaborations” developed by Stokols *et al.* (2008) (Fig. 2.9, Chapter 2). In the discussion section, additional evaluation is based on further key literature: the ten principles of good interdisciplinary (ID) team work by Nancarrow *et al.* (2013) and the roles of researchers by Wittmayer and Schäpke (2014).

Semi-structured interviews—with questions tailored to the different stakeholders—were deemed to be the most appropriate method to explore the core research themes from different perspectives. The interviews were transcribed and the information gathered was classified manually according to six categories—a) intrapersonal, b) interpersonal, c) organisational, d) physical environmental, e) technological and f) other political and societal—of contextual factors that influence the effectiveness of TD collaborations (described in detail in Chapter 2). These factors, both inside the academic research group (*internal*) and in the cross-sectoral context (*cross-sector*), are evaluated separately. Accordingly, in the tables (Table 5.1–5.5) summarising these factors, information is presented—when applicable—in both *internal* and *cross-sector* contexts.

Six in-depth interviews were conducted with key stakeholders, to map the voices of the different actors working on urban climate and adaptation planning projects at local, national and international levels. Because the aim of this study is not to deliver a complete stakeholder network analysis, but rather to examine a specific segment of the TD partnership in line with our research questions, I only considered certain actor groups when selecting key informants. Thus, on one hand, special attention is paid to the academy, in order to explore the researchers' needs, difficulties and motivations in relation to TD collaborations. On the other hand, the interviews with practitioners provided insights into the seldom-described market of Climate Services.

The data collection (carried out in March–April 2017) began by interviewing the head of the academic research team, and the sample group was then added using the snowball sampling technique, based on the working connections of the academic research group in the field of urban climate and planning. Snowball sampling is a commonly used method, meaning that initial contact persons are asked for recommendations of people linked to them through their work (Lelea *et al.*, 2014; Leventon *et al.*, 2016). A major benefit of this approach is being integrated into "trust networks", however for the same reason, the method is heavily influenced by the social networks of the people contacted initially. Using snowball sampling thus requires awareness of its limitations. The interviews lasted about 1–1.5 hours; the questions are enclosed as Appendix A.

Following good ethical practice in social research, the anonymity of interviewees and institutions are protected, and the interviewees participated in the study voluntarily. Only the author of this study dealt with the raw data and carried out the analysis, meaning their confidentiality is protected.

5.2.2 The stakeholders

The academic research group was represented by three researchers at different academic career levels (two senior and one junior). The group has expertise in environmental sciences, such as climatology or geography, as well as urbanism. They all are involved in urban climate research and developing climatic guidelines for urban planners. The group has therefore had collaborations with several municipalities on a national and international level. Here I refer to them as *Academic-A, B* and *C*, where the letters do not correspond to career levels.

As a next step the practitioners were identified that have worked together with the academic group on urban climate and planning projects. The interviewed practitioners represent professionals like urbanists, architects, spatial planners, urban managers and consultants. Two municipality representatives (one from Lisbon and one from Cascais, Portugal) and a representative of a technical consulting company with project coordinating tasks were interviewed. They were chosen based on the relevance of their work to the study, and their experience with various urban planning and land use management projects. In this case study, I refer to them as *Practitioner-A, B* and *C*, where the letters do not correspond to any attribute of the practitioner.

Besides the local scale urban climate adaptation projects with the above-mentioned research group, the practitioners also participated in a nationwide collaboration. (The interviewed research group got involved in this particular nationwide project in a later phase.) Fig. 5.1 shows the partnership structure of the national scale project as an example of multi-level and multi-stakeholder collaboration in urban climate adaptation planning.

The so-called Empathy Map visual tool is used to illustrate stakeholder profiles and to examine the different interests, needs, motivations and challenges they face. The tool was developed by De Vicente Lopez and Cristian (2016) to facilitate stakeholder analysis in projects of sustainability transitions. The map allows us to put ourselves into the stakeholder's shoes and thereby see the common challenges they face from different perspectives. It helps to build a general stakeholder profile that can be of help for further in-depth market research. Hence, the academic and the practitioner profiles were built based on the six interviews, to provide first-hand insights into the market of Climate Services.

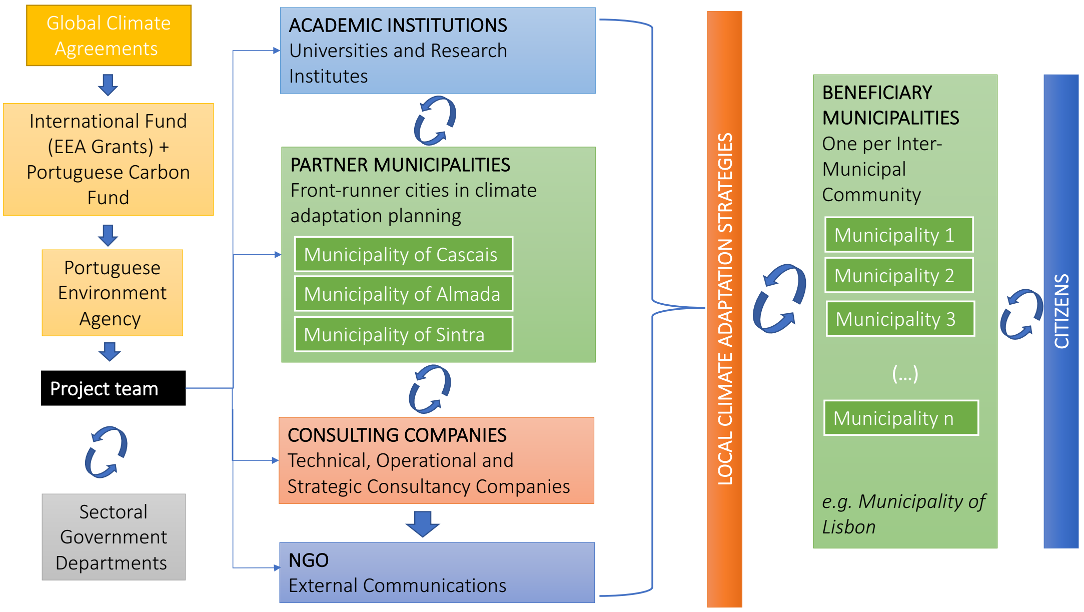


Figure 5. 1 A schematic structure of the multi-level, multi-stakeholder partnership working on the nationwide project of climate adaptation planning. The circular arrows refer to the iterative process of knowledge co-production (the intensity varies throughout the project lifetime and among participants). The figure is developed by the author based on the information given by the interviewees.

5.3 Mapping the voices

In this section, the results are organised into three subsections. Section 5.3.1 analyses the key contextual factors that influenced the TD projects. Section 5.3.2 outlines the challenges and drivers of the TD collaboration, while section 5.3.3 presents the Empathy Maps that help us to understand the similarities and differences in the diverse perspectives of stakeholders as providers and users of CS. Finally, Figure 5.5 provides a schematic representation of CS as a decision-support tool for urban development towards climate-resiliency, as developed by the author.

5.3.1 Key contextual factors influencing the TD projects of urban climate adaptation

In this section, the results are structured based upon the key contextual factors (described in Chapter 2, Fig. 2.9) that influence TD team effectiveness at each (individual, team, socio-political) level of analysis. Through this analysis, we can explore which factors hindered or fostered the success of the TD projects that interviewees have participated in.

5.3.1.1 Intrapersonal Factors

Individuals who are opened to other disciplinary perspectives, who value collaborative teamwork and embrace a culture of sharing, are well-suited for TD teams (Stokols *et al.*, 2008). The intrapersonal factors relevant in the case of the examined collaboration are classified in Table 5.1. In general, both academics and practitioners had a positive ***attitude towards TD collaborations***, for instance the *Practitioner-C* emphasised the need for cross-sectoral cooperation, as “we have a lot of sectoral areas of impact and we need a lot of thematic expertise to prepare a thematic plan”.

The members’ ***collaborative preparedness*** is evaluated based on their previous experience with TD collaborations. Apart from the junior academic, all the interviewees have considerable experience of working on projects involving several stakeholders; one of the academics also had working experience in a geo-informatics service company too. The interviewees expressed similar opinions regarding the principal differences between the partners: “there is a gap between the scientists and the technicians because sometimes there is a lack of information and understanding; our schools [of thought] are different” said the *Academic-A*. The *Practitioner-B* commented that “it was kind of like a [gut] feeling as we went through [...] because there was nobody doing this before us”, also adding that not all the partners were completely ready for such challenging collaboration. All the interviewed stakeholders referred to the projects as a learning process that needed patience and flexibility.

In terms of ***leadership***, both groups found it important to connect with people and empower them: “What I like the most is finding a way that we can open our minds and can talk to everyone without constraint, although it’s very challenging.”, stated the *Academic-A*. The *Practitioner-B* emphasised that working closely with partners is indispensable: “This is so ‘transversal’ [cross-sectoral]; there are a lot of things that are not our responsibility, but that of other institutions. Because of this, I have a meeting every week”. For instance, participatory workshops are frequently organized with local experts in an open-table system; the aim of this is to improve local climate adaptation measures involving the local particular knowledge of stakeholders. The *Practitioner-A* added that “it’s very important to know to how to talk to engineers, with landscape architects, with physicians, geographers, everybody, because we are working for the others”. Creating a common understanding and serving others were therefore considered important qualities of inclusive leadership in the examined TD projects.

Most of the stakeholders mentioned that they built the partnerships based on ***previous work*** relationships and/or a similar vision. For example, the *Practitioner-C* referred to the "confidence with the mayors" that joined the project, the "sympathy" and "the friendly relationship" because "it was very important to us to have some mayors (...) that can also support our flag". Accordingly, the strategic choice of partners based on a previously established positive relationship and/or sharing similar values was important for building a trustful partnership. Note, that the classes of factors have several common points, for example, ***members' collaborative experience with each other*** (Intrapersonal Factor) also implies Interpersonal Factors.

Table 5. 1 Intrapersonal factors based on six interviews with academics and practitioners. "Internal" refers specifically to the studied academic group, i.e. it is a description of the collaboration among the research group members. "Cross-sector" refers to the collaboration between academics and practitioners.

Intrapersonal Factors	Academics	Practitioners
Members' attitudes to collaboration and their willingness to devote substantial time and effort to transdisciplinary activities	*Internal*: members are motivated to collaborate and they often help each other in their research. *Cross-sector*: they are motivated to transfer scientific results into climatic guidelines for urban planners.	*Cross-sector*: they conducted various workshops with stakeholders and organised extra workshops.
Members' preparation for the complexities and tensions inherent in transdisciplinary collaboration	*Internal*: Senior members have considerable experience in collaborating with academics in TD projects, nationally and internationally. *Cross-sector*: Apart from the junior academic, they have various experiences in collaborating with practitioners, as consultants and as a geo-info service provider.	*Cross-sector*: they have vast experience with multi-stakeholder projects, including collaborations with universities and research centres, as well as administrative bodies and decision-makers.
Participatory, inclusive and empowering leadership styles	*Internal*: The members find it important to connect with people, assist in the implementation of the strategic plans and learn from the experience. They feel involved and appreciated. *Cross-sector*: the scientific information provided by academics is appreciated, i.e. plays an active role in developing the policy.	*Cross-sector*: they put huge effort into capacity building and training. They empower mayors and municipality servants to play an active role in climate adaptation planning and sharing their expertise with each other. They all agree that tasks and responsibilities must be shared in the TD project, and that science plays an important role in the process.
Members' collaborative experiences with each other, earlier projects	*Internal*: they have been working together in the same research group for years. *Cross-sector*: a chain of projects on urban climate planning have already been completed.	*Cross-sector*: a chain of projects on urban climate planning have already been completed. All the interviewees emphasised that previous trusting relationships are important when looking for TD project partners.

5.3.1.2 Interpersonal Factors

When examining Interpersonal Factors (Table 5.2), internal communication within the TD collaboration should first be mentioned. Regular interpersonal communication enables members to develop a shared vision and set common goals that drive the TD collaboration in the same direction. The TD partnership established a ***hospitable conversational space*** through ***frequently scheduled personal meetings*** and workshops, which helped to narrow the gap between the "worlds" of academics and practitioners. The members of the academic research group worked closely together, even when they were in different countries. The *Academic-C* explained that social interaction with colleagues was crucial, "I need to meet and talk about science and research often, because this is how I learn." According to the academics, these professional interactions were frequent, and the group members helped each other with various tasks inside the group. In the cross-sectoral context, the frequency of interaction between academics and practitioners depended on the phase of the TD project. The practitioners also found the regular communication with the partners important, because they benefitted greatly from the knowledge and skills of the cross-sector partnership.

Considering the ***qualities*** that the academics and practitioners value in their colleagues (as an indicator of presence/absence of mutual respect and appreciation of diverse perspectives), similar skills and attitudes were mentioned. Both groups referred to honesty, open-mindedness and availability, mutual respect for each other's time and diversity of opinions. The *Academic-B* appreciated when colleagues were "able to discuss about anything without restriction or taboo". The academics also mentioned scientific ethics, capacity and delivering on time, all of which are more related to professional competences (Intrapersonal Factors) than interpersonal relations. On the other hand, the practitioners group mainly talked about soft skills, such as tolerance, attention to others, empathy and straightforwardness. The *Practitioner-A* found empathy especially important, saying that "everybody must be a chief for six months of their lives […] because it's very important to see things from another point of view".

The academic researcher's previous experience in collaborating with practitioners and working in different geographical and cultural contexts helped them to ***adapt to changing circumstances***, be open to different perspectives, and accept the formal and informal rules of the other sectors. The practitioners navigated comfortably in various stakeholder environments, probably due to their considerable experience with various partners and the diverse soft skills they possess. The *Practitioner-C* evaluated the collaboration as a "rich experience". The ***diversity of members' perspectives and abilities*** empowered the partners to surpass obstacles and develop novel local and national frameworks for climate adaptation planning. "I think one of the main values of our partnership was how we connected all these different experiences and skills, and from this, created a common project", stated the *Practitioner-C*.

The familiarity inside the academic group empowered the researchers to openly discuss challenging tasks and request help when necessary. The ***hospitable working environment*** of both stakeholder groups probably helped them develop trustful relationships between the members of the cross-sectoral collaboration. The mutual respect and shared vision among the partners contributed to the creation of a supportive atmosphere, which was indispensable for easing interdisciplinary tensions.

Table 5. 2 Interpersonal Factors. Description same as Table 5.1.

Interpersonal Factors	**Academics**	**Practitioners**
Regular and effective communication among members to develop common ground and consensus about shared goals	*Internal*: personal and e-mail communication on a weekly (or occasionally daily) basis. *Cross-sector*: regular meetings and workshops (depending on the phase of the project).	*Cross-sector*: personal and e-mail communication, regular personal meetings (a couple of times a month) and workshops.
Establishment of a hospitable conversational space through mutual respect among team members	*Cross-sector*: the members value the following qualities in their colleagues: honesty, open-mindedness, availability, scientific ethics, capacity, respectfulness, friendliness, spirit, delivering on time, non-competitive atmosphere.	*Cross-sector*: the members value the following qualities in their colleagues: honesty, open-mindedness, availability, tolerance, long-term vision, attention to others, empathy, straightforwardness, soft skills.
Diversity of members' perspectives and abilities	*Internal*: members have similar scientific background. The group also has international members and projects. *Cross-sector*: They have diverse experience with external collaborators, mainly technicians.	*Cross-sector*: they have various professional competences in project management, technical implementation and policy evaluation. They are able to communicate with various actors, such as mayors, decision-makers, national agencies and academics.
Ability of members to adapt flexibly to changing task requirements and environmental demands	*Internal*: the group has had projects in different geographical and cultural contexts. *Cross-sector*: the senior researchers have worked on non-academic tasks, one of them even had a full-time non-academic job.	*Cross-sector*: they are comfortable in the different working environments of various stakeholders. One of the interviewees is doing doctoral research as well as their everyday job.
Members' familiarity, informality, and social cohesiveness	*Internal*: friendly and hospitable working environment, with regular social activities, forming a community.	*Cross-sector*: friendly and hospitable working environment, ease with informal conversation.

5.3.1.3 Organisational and Institutional Factors

An ***organisation's collaborative readiness*** (Table 5.3) contributes in important ways to the effective TD work. Academics were supported in their TD activities; for example, as the *Academic-A* claims, "Portuguese universities are obligated to open their doors" for cross-sectoral projects. One of the main reasons for such openness is the lack of financing due to the 2009-2010 economic crisis; this prompted inter-sectoral and international transdisciplinary collaborations in scientific research and training—as it happened in the field of public health research too. Thus, the institute is "very supportive of applying things to real life" added the *Academic-A*, thereby acknowledging that academic research with practical applications is more appealing to private and public funding bodies. In this way, a Socio-Political Factor—the economic crisis—fostered TD initiatives through the Organisational Factor.

The examined chain of projects in urban climate adaptation planning includes ***several disciplines/professions***, for example, academic researchers in urban climate, urbanists, architects, spatial planners, urban managers, public servants, politicians, communicators and consultants. As the *Practitioner-C* commented, "it is really important to have a large team with different capacities to answer the questions of climate change adaptation". The ***organisational climate of sharing*** was measured only in terms of sharing information. The research group shared their scientific results in meetings and workshops, as well as helped to apply their methodologies in different geographical contexts (e.g., the urban climatic guidelines are transferred to other cities). They also published their results in scientific journals. The outcomes of the nationwide cross-sectoral urban planning project are available online. Furthermore the sharing of best practices between municipalities was one of the main goals of the project.

During these cross-sectoral projects, ***several workshops*** for various stakeholders (e.g., local companies, citizens, mayors), training activities for public servants, and assemblies for decision-makers and national sectoral agencies were organised. The examined academic research group had workshops with the municipalities too. As part of the nationwide project, different types of workshops were organised: a) local workshops for stakeholders to discuss the local adaptation options/measures and to prepare the local communities for the adaptation challenges; b) regional capacity building workshops for local public servants to prepare them to design and manage the municipal adaptation strategies; c) national seminars at the beginning and end of the project, which were open to everyone, and d) specific workshops to specific stakeholders on themes such as how to finance adaptation—as the practitioners explained.

The academics briefly mentioned that when organising TD workshops/courses in the university, they faced bureaucratic barriers. Further investigation of the types of existing or lacking institutional incentives and administrative routines supporting TD activities was beyond the scope of this study.

Table 5. 3 Organisational and Institutional Factors. Description same as Table 5.1.

Organisational/Institutional Factors	**Academics**	**Practitioners**
Presence of strong organisational incentives to support collaborative teamwork	*Cross-sector*: the university is supportive, there are institutional incentives that foster cross-sector collaborations.	*Cross-sector*: the involved municipal departments (and their directors) are supportive.
Non-hierarchical organisational structures to facilitate team autonomy and participatory goal setting	Not measured.	Not measured.
Breadth of disciplinary perspectives represented within the collaborative team or organisation	*Cross-sector*: the chain of projects involved in urban climate adaptation planning needs several disciplinary perspectives (e.g., urbanism, climatology, geography) that are provided by the research group.	*Cross-sector*: the chain of projects involved in urban climate adaptation planning includes several disciplines and professions (e.g., urbanists, architects, spatial planners, urban managers, public servants, politicians, communicators and consultants).
Organisational Climate of Sharing (e.g. sharing of information, credit and decision-making responsibilities is encouraged)	*Cross-sector*: sharing scientific results and methodology is encouraged. The guidelines are available online.	*Cross-sector*: Sharing best practice between municipalities at a national and international level is one of the main goals of the project. Products are available online.
Frequent scheduling of social events, and other center-wide opportunities for face-to-face communication and informal information exchange	*Cross-sector*: the group has frequent internal social events, and from time-to-time there are professional workshops and afternoons, e.g., with the municipalities.	*Cross-sector*: Workshops for public servants and local stakeholders, general assemblies for decision-makers and national public agencies.

5.3.1.4 Physical Environmental Factors

In the academic setting, the research group was provided with appropriate environmental resources (Table 5.4) that allow for ***distraction-free work***. Most of the members were based in the same building; although some of the researchers were in a different building but at the same campus, and a couple of members were abroad. The academics mentioned that they preferred to be in the same building as all the members of the group, as face-to-face interaction with colleagues helped them in their daily tasks. In terms of the cross-sector collaboration, most of the partners involved in the local projects were in the same city (e.g., Lisbon or Cascais), thus regular face-to-face meetings were feasible. In the case of the nationwide project, even though the national scale meetings and training (e.g. participants from the Portuguese islands were also involved) required more time and resources, they were organised a couple of times.

To facilitate collective activities involving group discussion and brainstorming, ***comfortable meeting areas*** are needed (Stokols *et al.*, 2008). The academic research group was provided with a small meeting room in the department, although this was sometimes overbooked during working hours. To organise wider events, other meeting halls were available in the campus buildings. Most of the work places—in the university and municipality buildings where the interviews took place—were open-plan offices with workstations separated by panels. The interviewees felt comfortable in these settings, however one of them mentioned that sometimes the open-plan office can be busy and noisy.

Table 5. 4 Physical Environmental Factors. Description same as Table 5.1.

Physical/Environmental Factors	Academics	Practitioners
Spatial Proximity of team members' workspaces to encourage frequent contact and informal communication	*Internal:* Most of the members were in the same building; there were some in a different building but on the same campus, and a couple of members were abroad.	*Cross-sector*: To develop local adaptation strategies, local stakeholders worked together, scheduling regular meetings. National level meetings/training activities were organised 4-6 times/year.
Access to comfortable meeting areas for group discussion and brainstorming	*Internal:* There was one small meeting room in the main building of the group, but it was sometimes "overbooked".	Not measured.
Availability of distraction-free work spaces for individualised tasks requiring concentration or confidentiality	*Internal:* There were different types of offices; in the biggest one, the workstations were separated by panels.	*Internal:* Three locations were visited for the interviews. There were both small offices and open plan offices with workstations separated by panels.
Environmental Resources (e.g. workstation panels) to facilitate members' regulation of visual and auditory privacy	*Internal:* Mostly workstation panels.	*Internal:* Mostly workstation panels.

5.3.1.5 Political and Societal Factors

The socio-political landscape (Table 5.5) has a significant impact on the initiation and survival of TD projects. ***Cooperative international policies*** facilitated the exchange of scientific information and co-operation between the different sectors in the nationwide climate adaptation project. One of the main financial instruments that supported the development of the project was a European level international grant that promotes policies for the equity of countries. As it was discussed in the section 5.3.1.3, one of the main reasons that the academic research institutes were opened to cross-sectoral collaborations was the lack of financing as a result of the ***economic crisis***. On the other hand, in recent years, various international funding opportunities have become available for innovation programs that support TD teams working on complex challenges, such as local climate adaptation planning. The administrative and business sector also realised the opportunities available in climate change-related development projects, and started to build public-private partnerships to strengthen their connections with research institutes.

In different ways, all the interviewed stakeholders perceived that there is a momentum for developing climate adaptation measures. As the *Practitioner-A* commented, by the moment that climatic aspects were approved to be included in the master plan, "everything was in place". This was the result of continuous progress made by various initiatives in recent years.

Nevertheless, the ***general political landscape in the country*** also influences the implementation (and continuation) of the projects, since national level policies could support or hinder the development of a new climate adaptation policy. The *Practitioner-A* expressed worries in relation to the upcoming governmental elections, which might pull back the implementation of the strategy, stating that "all this work may be put in the drawer". The *Practitioner-C* argued that the climate adaptation policy is not an ideological approach, it is more a technical question, hence "it is not felt by the politicians as a problem, I don't feel tension". A continuation path for the project is the nationwide network of municipalities that collaborate to develop local climate adaptation measures, to exchange experience, and to help other municipalities to develop their own plan.

The latter factor of the national political landscape was not included explicitly in the key factors identified by Stokols *et al.* (2008), however in this case—and this is true of most of the countries—government politics might have a significant impact on the implementation of national environmental strategies. Thus I found it important to include this aspect in this evaluation.

Table 5. 5 Political and Societal Factors. Description same as Table 5.1.

Socio-political Factors	Academics	Practitioners
Cooperative international policies that facilitate exchanges of scientific information and transdisciplinary collaboration	*Cross-sector:* the group have been involved in several international collaborations and TD projects.	*Cross-sector:* one of the main financial instruments of the climate adaptation project was an international grant.
Environmental and economic crises that prompt inter-sectoral and international transdisciplinary collaboration in scientific research and training	*Cross-sector:* with the economic crisis, the university faced lack of funding, and a good way to finance research activities is to work on cross-sectoral projects.	*Cross-sector*: in recent years, there are a lot of international funding opportunities available for TD projects, such as local planning of adaptation and innovation programmes.
Enactment of policies and protocols to support successful transdisciplinary collaborations (e.g., those ensuring ethical scientific conduct, management of intellectual property ownership, and licensing)	Not measured.	Not measured.
General political landscape in a country. Supporting or counterproductive national governmental policies and local political/civil influence in environmental issues	Not measured.	*Cross-sector:* There is a momentum for the development of climate adaptation plans. The municipalities and decision-makers approved the plans without difficulty. However, governmental elections might influence the implementation process.

5.3.2 Insights into the difficulties and drivers of the TD collaboration

5.3.2.1 Challenges

The question “What was challenging in the collaboration?” was directly asked of the interviewees in order to learn from their personal perceptions of “TD challenge” (Table 5.6). Exploring the difficulties that participants faced during the collaboration helps to identify aspects of TD collaborations that could be managed better, skills that needs to be improved, and collaborators that might need more assistance.

Academics

The academic researchers found it challenging to create a common language and understanding with the collaborating partners; the *Academic-A* for example mentioned at first place the challenge “to create a language that can be useful to urban planning”. They worked to provide understandable, useable and useful tools and metrics (e.g., in the form of maps and indices) for the practitioners—mainly the municipality technicians—that apply the climatic information. The academics referred to this aspect of their role as that of science translators and knowledge brokers, “my goal is to interpret the science and to give the right information to everyone”, as the *Academic-A* commented. The *Academic-B* argued that it was easier for decision-makers to decide on an issue when there is a single number or metric provided; thus “the biggest challenge is to provide an instrument to create a law”. The *Academic-C* found it challenging to demonstrate the relevance of the topic to the stakeholders, and felt that this was a big responsibility.

The academics were concerned with helping the partners, but they admitted that sometimes it was not easy because of the different schools of thought. According to the *Academic-A*, in general, academics did not have problems with the collaboration, indeed, “the difficulty sometimes is to implement the policies”. The academics were aware that the practical implementation of their guidelines is a complex urban planning task; “it’s a process of understanding; it’s like a negotiation”, added the *Academic-A*.

Practitioners

Similar to the academics, the practitioners also found the development of a common understanding both important and challenging. Further specific challenges mentioned by the practitioners are briefly described below in a non-exhaustive overview, without ranking of importance.

One of the main challenges was the development of a strong and coherent policy instrument with a comprehensive document. As the *Practitioner-A* said, “now the real challenge is to put it [the climatic assessment results] in plans”. Another challenging aspect of the project was to connect the different actions that already exist in the city and to develop connections between the different administrative structures, such as between the municipality and the “Juntas Frequesias” (neighbourhood level administrative units). Because the “Juntas Frequesias” have more power than the municipality in certain areas of urban management and maintenance, it is important to reach them.

A further challenge was to convince the municipality decision-makers (i.e. mayors and the executive board) and local stakeholders (e.g., local companies and citizens) about the benefits of climate adaptation measures. According to the *Practitioner-B* the climate strategy is not a priority in the city plans, it is only an additional factor that the decision-makers should take into account. Another difficulty explained by *Practitioner-B* is that municipal structures are not designed to work on climate change: “We don’t have the knowledge, we don’t have the time, we don’t have the resources, so we have to get them from others.”

The lack of public awareness was also mentioned as a barrier to implementing the local climate adaptation strategies. As the practitioners emphasised, there is a lack of understanding on the topic, its relevance to daily life, and the benefits of action. For this reason, the communication strategy of the project was a challenging component. Furthermore, capacity building among public servants was also a key issue, because the municipality employees were not prepared and/or appropriately skilled to work on the climate adaptation strategy.

Table 5. 6 A non-exhaustive list of challenges and barriers that participants faced during the TD collaboration based on the six interviews.

Academics	**Practitioners**
- to create a common language and understanding - to develop understandable, useable and useful tools and metrics - to help technicians and decision-makers - to show the relevance of the topic	- to overcome technical language barriers and differences in interpretation - to develop a strong and coherent instrument - to develop connections between different administrative structures - to connect various actions in the city - to convince decision-makers and stakeholders about the benefits of climate action - to create a completely new policy for climate adaptation - to coordinate between municipalities on a national level - to create public awareness - to work closely with the partners because municipal structures are not designed to work on climate adaptation projects - to upskill public servants that are not prepared to work on projects that involve comprehensive research tasks - to distribute resources between academic analysis and assessing the implementation - to deal with legislation and create new conditions on how the urban space is used - to deal with the complexity of planning and the different realities in terms of municipalities - to change local authorities’ investments

According to *Practitioner-C*, an interesting and challenging phase was the creation of a new climate adaptation policy that had no antecedent; “So we have the freedom to design it”. However, local level legislation was also mentioned as a barrier to the implementation of local climate adaptation strategies, as “these instruments (for climate adaptation) are sometimes not compatible with the existing rights of landowners”, explained the

Practitioner-B. Moreover, the beneficiary municipalities represented quite “different realities” in terms of the complexity of planning and what the local communities expect from the local municipalities. Hence the diversity of the TD project created a range of diverse challenges to be dealt with.

5.3.2.2 Motivations

Positive experiences during the collaboration and the sense of achievement in relation to the accomplished goals are important indicators of a good collaboration. To map the participants’ personal motives, they were asked about what they liked the most about the collaboration.

Both academics and practitioners enjoyed the collaboration, describing it as an interesting and rich learning process. Some of those interviewed mentioned that building relationships and connections between people was essential for them, “What I like the most is finding a way that we can open our minds and can talk to everyone without constraint”, commented the *Academic-A*. The *Practitioner-A* expressed a similar opinion, stating “I like to contact people, to connect things”.

The real-life impact was also mentioned by several stakeholders. The *Academic-B* enjoyed developing solutions to real-life problems, reacting to the question with “I’m very enthusiastic”. The *Academic-C* added that reducing air pollution in cities has a visible impact that drives the research ambitions of the interviewee: “it’s very important to believe in what you are doing”. The practitioners also referred to the noticeable change that the project brings to the city. The *Practitioner-C* was proud of the social transformation that the project generated, especially regarding the communities’ awareness on the topic; stakeholders have started to consider climate change not only as a threat, but also as an opportunity for developments: “I feel that lot of the political representatives want this, they feel it as something with value. (…) It’s interesting how we changed that.”

5.3.2.3 Need for capacity building

The necessity for a diverse range of professional competences and skills was mentioned by all the interviewees. The *Practitioner-C* pointed out that “it’s really important to have a large team with different capacities to answer the questions of climate change adaptation". To develop these competences and to establish a mutual understanding between the partners, "capacity building is key", said the *Practitioner-B*, and "we are depending on others, and vice versa" to deliver the project goals. The practitioners mentioned that the partners were not always completely prepared to deal with the circumstances of the broad-scale project, thus several workshops and training activities were organised (detailed in section 5.3.1.3).

The academics had provided a couple of professional training activities for other partners in previous projects, and had participated in short workshops organised by the municipality. However, they see the need for more capacity building in TD research, especially for students. The *Academic-B* found it necessary to take part in TD training and workshops, because these are the best occasions for conversations with technicians to discuss and clarify roles, tasks, needs and methods. The *Practitioner-A* also believes that training is needed—especially for students—to be prepared for TD collaborations in climate adaptation. The interviewee has built and participated in several cross-sector projects over the course of a long period working on urban planning; thus "I know the cost of it", referring to the long learning process.

The practitioners mentioned public servants' lack of time and preparedness to work on climate assessment as a key issue that the project had to address. (Public servants are trained for administrative type of work.) For this reason, several workshops were organised over the course of the project to upskill the public servants, so that later they could develop the plan with little (or no) support. This was a type of knowledge exchange process, because these capacity building events provided skills and competences to the local public servants, and the locals supported the project with their local territorial knowledge.

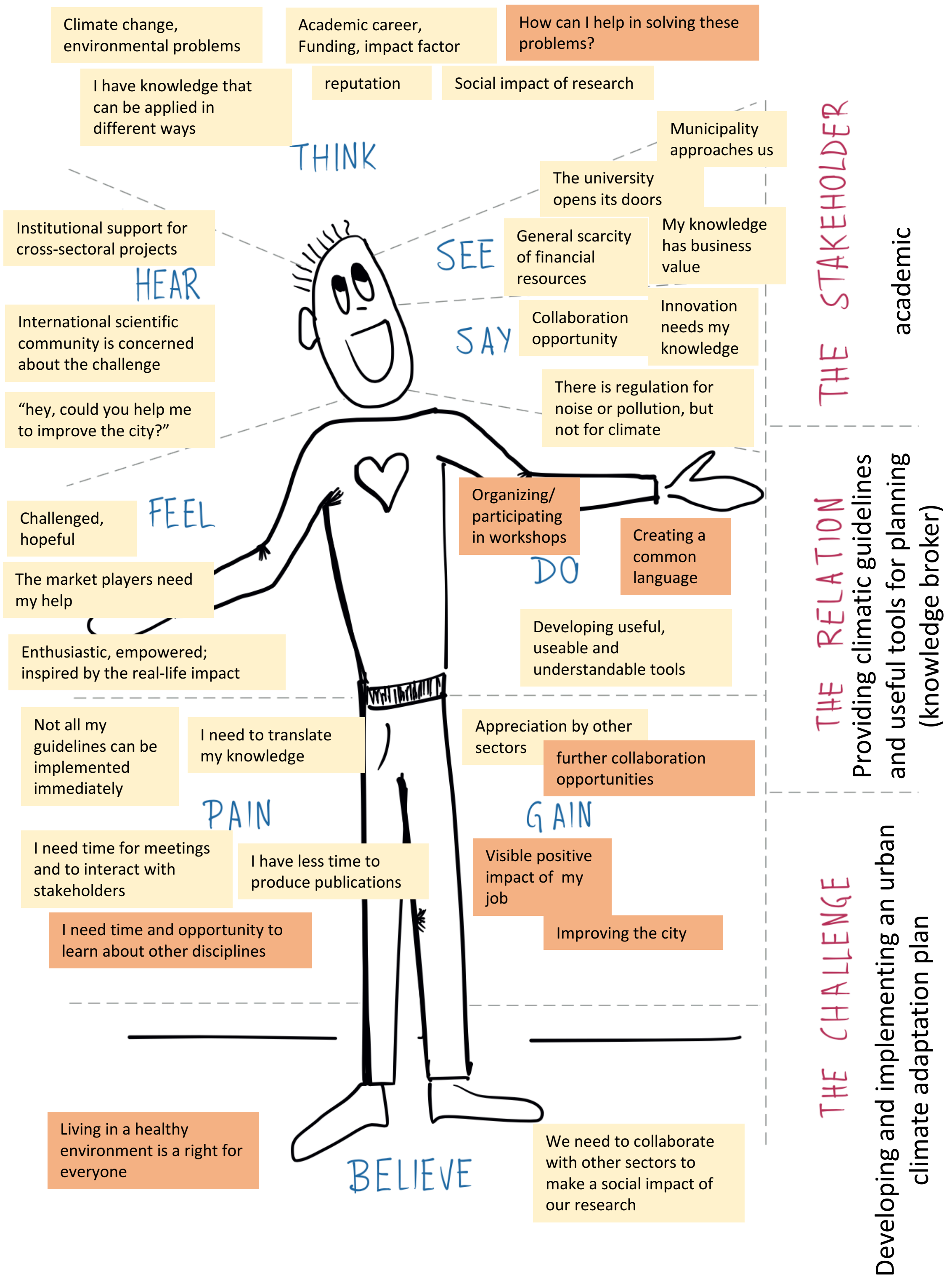
The assurances of long-term funding were essential for capacity building and to have time for building trust between the partners. As the practitioners stated, the international grant that funded the nationwide climate adaptation project provided opportunities for implementing innovation programmes. This financial instrument played an important role in supporting the TD project, "because the ministries will not feel pressed to satisfy some kinds of clients". Interestingly, "some of the main public policy projects were supported by this tool" in recent years, explained the *Practitioner-C*.

5.3.3 Empathy Maps

Empathy Maps help us understand the different interests, needs and priorities of stakeholders, and to find common points of view that can connect their efforts and motivate them to collaborate. First we need to clarify how the stakeholder relates to the challenge: whether the actor is a service provider, a user, or an intermediate player. Following from this, we need to answer the following questions to map the drivers and forces that influence the stakeholder's perspectives and decisions (Table 5.7).

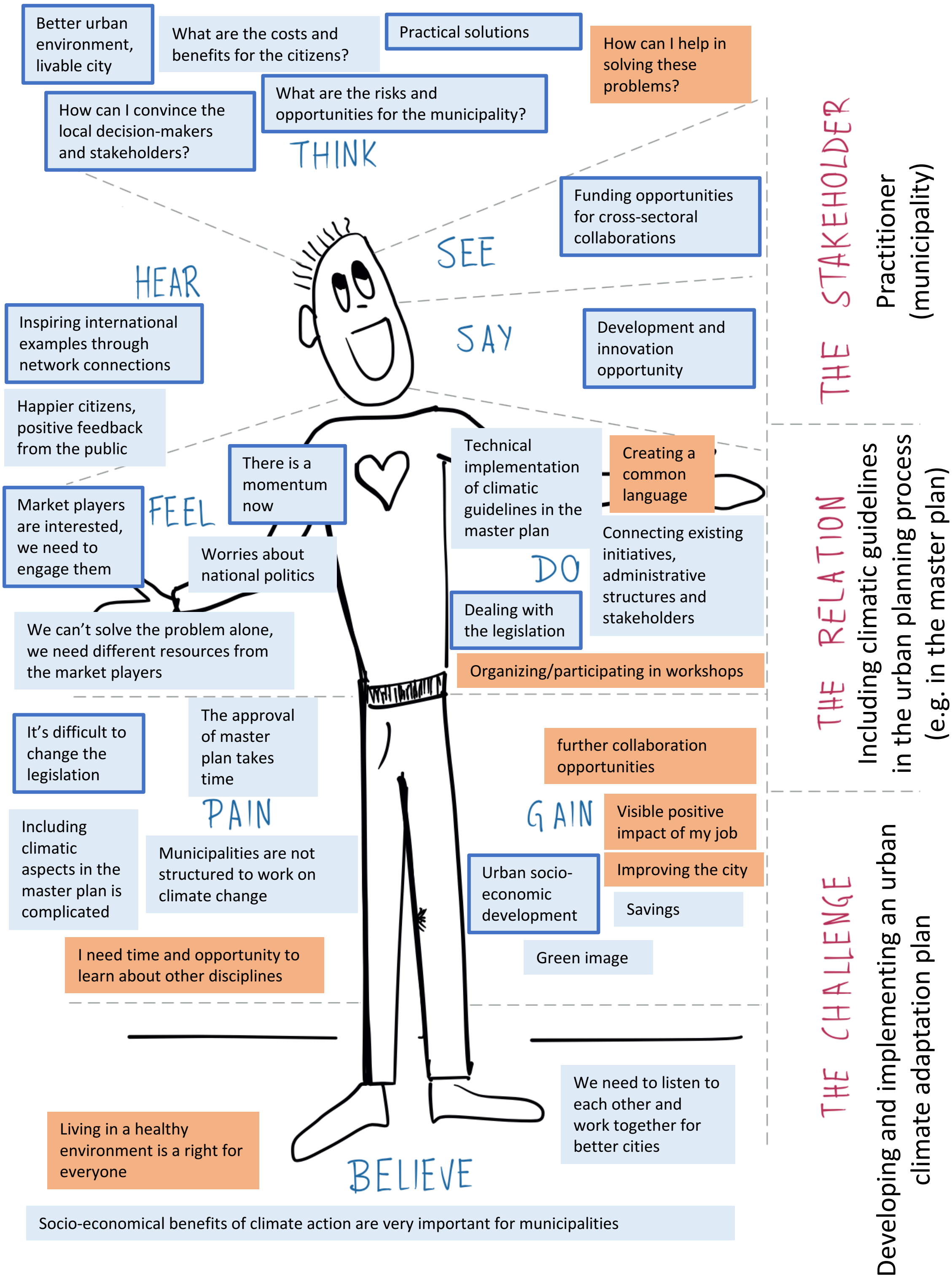
Table 5. 7 Questions for the Empathy Map based on the Visual toolbox for system innovation by De Vicente Lopez and Cristian (2016).

Think "brain"	What do they really care about? What do they think about the challenge and the current market solution?
See "eyes"	What do they see when they face the problem/challenge in their daily life? What is the context/environment they see around them?
Hear "ears"	What do their friends/boss/colleagues... say? What influencers do they follow? What do they hear when other people face the same problem? Are they following the big players?
Say "mouth"	What do they say regarding the challenge in a conversation? What opinions do they state about innovative solutions to the challenge?
Feel "heart"	What do they feel when working on the solution? What are their feelings regarding the players in the market and society, related to the challenge?
Do "hands"	What is their attitude towards the solution? What are their tasks and responsibilities? Are they trying to do anything to defy or modify the status quo?
Pain "back"	What are the barriers they face in their day to day life? What are their pain points when implementing the current solution? What are their concerns?
Gain "legs"	What do they really want to achieve with the solution? What are their actual needs? How do they measure success? What are their expectations regarding the solutions?
Believe "feet"	What do they believe? What are their thoughts rooted in? What are their implicit and explicit assumptions about the challenge? (e.g., how society, decision-makers react...)



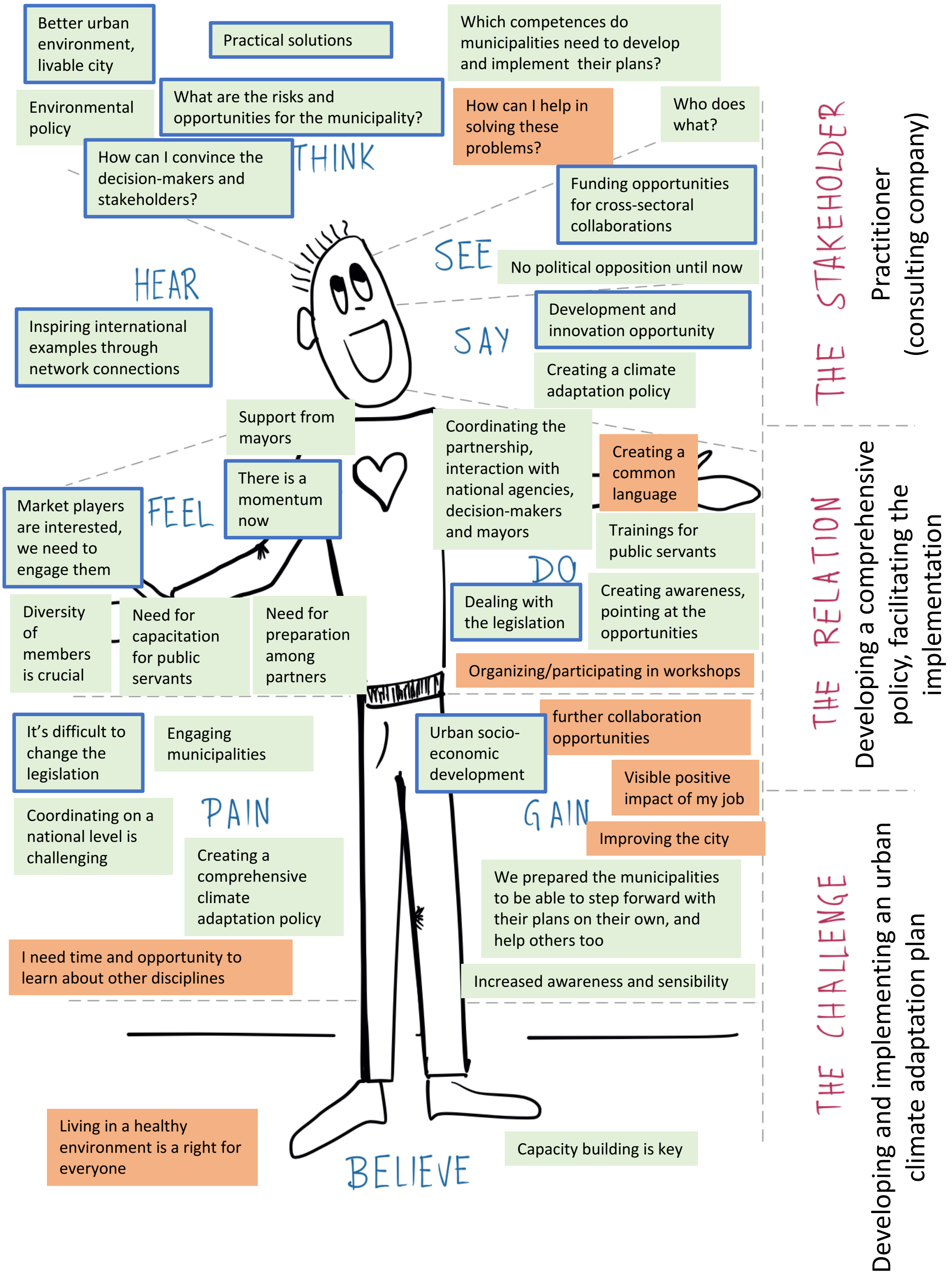
Academics

Figure 5. 2 The Empathy Map of Academics, drawn on the canvas from the Visual toolbox for system innovation by De Vicente Lopez and Cristian (2016). Yellow box: ideas of the academics; Orange box: common ideas of the interviewed academics and practitioners (Fig. 5.2–5.4).



Representative of municipality

Figure 5. 3 The Empathy Map of Municipality Representatives, drawn on the canvas from the Visual toolbox for system innovation by De Vicente Lopez and Cristian (2016). Blue box: ideas of the representatives of municipality; Blue frame: common ideas of the practitioners (Fig.5.3 and Fig. 5.4); Orange box: common ideas of the interviewed academics and practitioners (Fig. 5.2–5.4).



Representative of consulting company

Figure 5. 4 The Empathy Map of the Representative of consulting company, drawn on the canvas from the Visual toolbox for system innovation by De Vicente Lopez and Cristian (2016). Green box: ideas of the representative of consulting company; Blue frame: common ideas of the practitioners (Fig. 5.3 and Fig. 5.4); Orange box: common ideas of the interviewed academics and practitioners (Fig. 5.2–5.4).

5.3.3.1 The Empathy Map of academics

Empathy Maps of three market actors were drawn up based on the six interviews. The general profile of the academic stakeholder group is shown in Figure 5.2. The general profile of Municipality Representative is drawn in Figure 5.3 and the last Empathy Map (Figure 5.4) shows the profile of the representative of consulting company.

The three academics (Fig. 5.2) have several common ideas among them, such as

- **think:** about climate change and environmental problems, academic career, funding, impact factor, reputation, social impact of research; “I have knowledge that can be applied in different ways”
- **see:** general scarcity of financial resources
- **hear:** that the international scientific community is concerned about the challenge; the call “hey, could you help me to improve the city?”
- **do**: developing useful, useable and understandable tools
- **feel:** enthusiastic and empowered; inspired by the “real-life” impact
- have **pain:** “I need to translate my knowledge”.

5.3.3.2 The Empathy Map of practitioners

The ideas that we can find in both practitioner Empathy Maps (boxes with blue frame in Fig. 5.3 and Fig. 5.4) are the following. They

- **think:** about a better urban environment, a liveable city, practical solutions, “What are the risks and opportunities for the municipality?” and “How can I convince the local decision-makers and stakeholders?”
- **see:** funding opportunities for cross-sectoral collaborations
- **say:** development and innovation opportunity
- **hear:** inspiring international examples through network connections
- **do:** dealing with the legislation; organising/participating in workshops
- **feel:** “there is a momentum now”; “Market players are interested, we need to engage them”
- have **pain:** it’s difficult to change the legislation
- **gain:** urban socio-economic development

From the practitioner group, the municipality technicians are responsible for including the climatic guidelines in the urban master plan, thus they have first-hand experience in how problematic it is to deal with local legislations, and how tough it is to convince local decision-makers such as the executive board of the municipality and the mayor. Furthermore, the municipality representative is concerned about high-level political changes that might influence the implementation of the plans, although the representative of the consulting company does not share these worries.

5.3.3.3 Common ideas between academics and practitioners

According to the Figures 5.2, 5.3 and 5.4 (orange boxes), the three market players share several common ideas. They all

- **think:** "How can I help to solve these problems?"
  » practice oriented approach
- **do:** creating a common language, organising/participating in workshops
  » willingness for TD collaboration, crossing disciplinary borders
- **believe:** that living in a healthy environment is a right for everyone
  » shared vision
- have **pain:** they need time and opportunity to learn about other disciplines
  » embracing the need for personal development and extra effort for TD collaboration
- **gain:** further collaboration opportunities, visible positive impact of the job, and improving the city
  » shared goals.

To sum up the results of the Empathy Maps, it first should be mentioned that all the partners were concerned about the same problem, but that they approached it in different ways. They realised the necessity for different resources that they did not possess, hence, to address the complex challenge, they built a cross-sectoral collaboration based on their common vision. They reached their shared goals by creating a common language and understanding between the different disciplines, by sharing their academic and practical knowledge and by embracing the "pain" and stepping out of their personal and professional comfort zone.

5.3.3.4 Climate Services as decision-support tool

As the Empathy Maps (Figures 5.2-5.4) show, the challenge is to develop and implement an urban climate adaptation plan. The relationship to the challenge differs between the stakeholder groups: the academics are the Climate Service providers as their task is to develop climatic guidelines and useful tools for urban planning. From this aspect, they play a *knowledge broker* role (according to the classification of researcher roles by Wittmayer and Schäpke (2014)), and they deliver this service through the co-development of technical and policy instruments in the TD collaboration. The direct users of Climate Services are the municipality technicians, thus the climatic products are tailored to their needs. These climatic tools are co-developed with the urban planners through continuous feedback loops. The schematic representation of CS as a decision-support tool to enhance climate-resiliency of the city can be seen in Figure 5.5, as developed by the author.

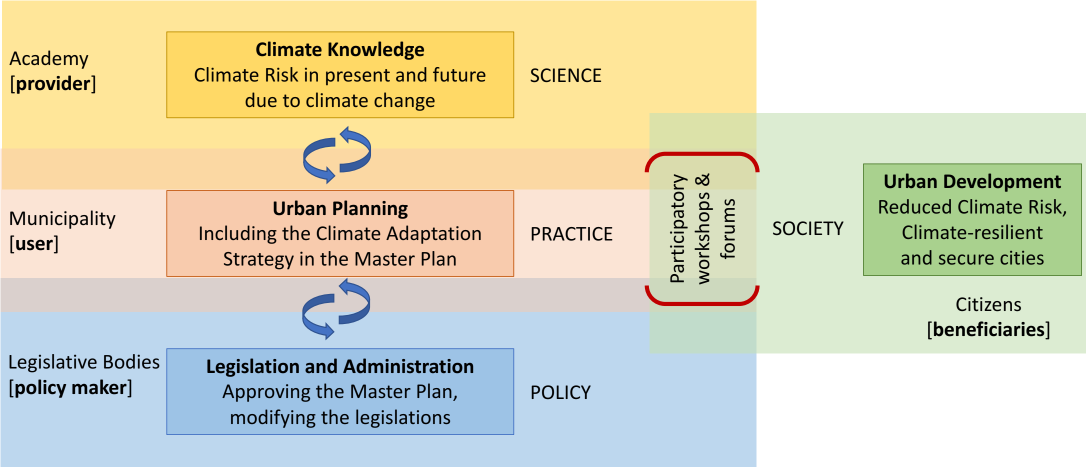


Figure 5. 5 Climate Services as decision-support tool for urban development towards climate-resiliency. Circular arrows refer to knowledge co-production and the red bracket indicates collaborative learning and action. Figure developed by the author.

In the case of the nationwide project, the technical consulting company was an intermediate player that facilitated knowledge transfer and capacity building in the municipalities so that their own climate adaptation plans could be developed. The municipalities were beneficiary users of the products that were co-developed by the academics and the urban planners, with the example and support of front-runner cities (e.g., Cascais, Figure 5.1). The TD collaboration was built to develop innovative solutions for the complex challenge of urban climate adaptation involving the relevant stakeholders.

5.4 Discussion

5.4.1 Understanding roles and competences

Re-framing the role of the academics in Climate Services requires thoughtful examination and lively discussion within and beyond the scientific arena. While the need for TD training and capacity building became clear by analysing the interviews, the role of understanding of the members has been passed over until now. In general, a natural opposition of perspectives was observed between the two main groups—academics and practitioners—that was described as the tension between the "descriptive-analytical and transformational mode" by Wiek *et al.* (2012). In the examined case, the academics focused mainly on the research methodology and outcomes, while the practitioners were concerned with the practical implementation of plans and engaging with the relevant stakeholders. Hence the former group takes on the general role of "descriptive analyst" and the latter, the "activist". As the Figure 2.8 (section 2.5.2) of TD knowledge co-production shows, both types of knowledge are indispensable for developing a viable solution.

The practitioners expressed their appreciation for the scientific knowledge that they applied; they also believed that it adds credibility to their actions. They highly appreciated the results focusing on the risk and opportunities. Most of the stakeholders mentioned that creating a common language and understanding between the various disciplinal perspectives and professional practice was a challenging part of the collaboration. Nevertheless, thanks to the collaborative preparedness and willingness of interviewees, effective communication, and clear leadership and management, these differences were anticipated and handled successfully.

Taking a closer look at the interviewed academics, it is clear that among them, it is not only the *reflective scientist* role that is evident, but the alternative activities represented by the ideal-type roles (Wittmayer and Schäpke, 2014). They acted as *process facilitator* – organising workshops, facilitating the development process and experiments; *change agent* – motivating and empowering participants and supporting policy formulation; and *knowledge broker* – making meaningful climate knowledge in the urban planning context and mediating between different perspectives. It has to be noted that the aforementioned alternative activities are performed by scientists—especially individuals with coordinating and leading responsibilities—in the general climate community, however, the importance of these activities need to be better recognized (NAS/NAE/IM, 2004).

All the interviewed academics emphasised their intention to help the technicians, and they were highly motivated to provide "understandable, usable and useful" climate knowledge (maps, metrics) that would aid the work of urban planners. This kind of approach certainly leads to the baseline of demand-based Climate Services. Similar skills (such as project management, facilitating, building relationships) are included in the Guidelines for Trainers in Meteorological, Hydrological and Climate Services by WMO (WMO, 2013) and are referred to as "transferable skills or core competences"; however, have not yet been discussed in the context of TD teamwork.

Another interesting aspect in terms of roles and professional motivations is the high sense of responsibility and ownership of the problem; these are important attributes for researchers who are active in sustainability transitions, according to Wittmayer and Schäpke (2014) and Loorbach (2010). All the interviewed stakeholders expressed not only professional interest, but also personal motivations for working on the projects. They talked enthusiastically about the topic, felt the positive social impact as a priority, and evaluated their job as more like a vocation than simply a profession. Working on real-life problems empowered the academics to take an active role in the partnership and pursue alternative activities besides the *reflective scientist* role. This approach provides a new insight into the motives of academics to participate in climate-related TD collaborations.

5.4.2 Contextual Factors and Policy

At the beginning of this research, I addressed the question "What were the contextual factors that influenced the dynamics of TD collaboration?". When reviewing the categories, there are none that can be distinguished as the most important based on the collected data. In order to compare the results to the literature of team and TD/ID science, some important factors are highlighted here.

From the Intrapersonal Factors category *members' preparedness* and *positive attitudes toward TD* should be mentioned. These skills and behaviours are mainly due to members' previous experience in TD collaborations and the strategic selection of project participants. From the Interpersonal Factors category, soft skills (including *effective communication*) as well as *member's diverse skills* and their *respect* for each other should be highlighted. According to a review of ID research in the education, business and health care sectors, 61.9 % of papers found “Team factors” such as “Communication/trust/ interpersonal relationships” (54.8 %), “Composition of team/balance of power” (50.0 %), “Shared values and goals” (35.7 %), and “Leadership” (26.2 %) important (Aboelela *et al.*, 2007). In the same review, the “Individual characteristics of team members” factor, for example, commitment, agreeability and flexibility, was found to be important by 19.0 % of the reviewed studies. These team and individual factors have also arisen this study, but obvious comparisons are not possible because the basis of classification is not the same.

Among the Organisational and Institutional Factors, the *presence of strong incentives* to support TD collaborations should be mentioned. The supporting attitude of the university is mainly due to the economic crisis (Socio-Political Factor) that prompted the building of cross-sectoral collaborations as a way of financing research projects. From the Physical Environmental Factors category, the *spatial proximity of team members* who are working on the same tasks (e.g. the researchers in the same academic group) was positively valued. The review by Aboelela *et al.* (2007) combined the environmental and institutional factors. The combination of these factors was found important by 54.8 % of studies, including “Interdisciplinarity explicit in mission” (42.9 %), “Resources for ID work provided” (38.1 %) and “Rewards and promotion related to ID work” (28.6 %). In the present case, none of the interviewed stakeholders mentioned explicitly the latter factors, since the questions were prepared based on different frameworks.

The importance of Socio-Political Factors was also articulated by the stakeholders, especially in terms of *cooperative international policies* that facilitate the exchange of expertise and TD collaborations. Most of them mentioned that there is a momentum for TD collaborations in climate adaptation at both national and international levels, as there are various financial and technical resources available to support these cross-sector projects. Nevertheless, national governmental politics might support or hinder the implementation of environmental strategies, thus I added this aspect to the typology of contextual factors as *general national political landscape*. Due to changing government policies on research funding, the uncertainty of funding continuation can be a real pressing issue (Muscio, Quaglione and Vallanti, 2013). NAS/NAE/IM (2004) and Bennett, Gadlin and Levine-Finley (2010) also emphasised that the assurances of continuous funding are essential to have enough time for trust-building in TD collaborations. Fortunately, in recent years there is a Europe-wide tendency for an increasing number of climate adaptation projects, thanks to international programmes and networks such as the ones mentioned in section 2.2.1.

5.4.3 Shared vision, common goals and outcomes

Shared vision and shared goals are the foundations of high-functioning teams. As the Empathy Maps show, the interviewed academics and practitioners shared views that were important for the project, such as believing that “living in a healthy environment is a right for everyone”. Furthermore, their common perception of benefits—further collaboration opportunities, visible positive impact of the job, improving the city—helped set common goals for the collaboration. Each team member had a deep sense of problem ownership that motivated them to contribute to the development of joint solutions. Stauffacher *et al.* (2008) and Wittmayer and Schäpke (2014) also noted that ownership notions are strongly related to the intensity of stakeholder involvement in TD research collaboration and action for societal transformations.

Even though the team members may each have a slightly different sense of the team’s vision, depending on their roles and responsibilities or their stage of career development (NAS/NAE/IM, 2004; Bennett, Gadlin and Levine-Finley, 2010), it is important that the overall goals and individual responsibilities are understood and that a collective effort is made.

Achieving of balance between research needs and community interests was identified as a key challenge by a public health study on an intersectoral community coalition (Lantz *et al.*, 2001). Other studies (Israel *et al.*, 1998; Stokols, 2006; Stokols *et al.*, 2008) also demonstrated that while practitioners’ goals are more pragmatic and community-oriented, as well as favouring quick decisions and the implementation of problem-solving strategies, researchers generally have a longer-term orientation, and are more concerned with research questions and pursuing publications and grant funds. In this case, as well as the pragmatic approach, practitioners managed to combine the long-term vision with short-term goals and implementation strategies. Academics did not need to worry about seeking highly competitive research grants on the topic, since the international grant was handled by a partner. As well as research focused on methodology, academics embraced the solution-oriented approach, and focused on developing user-friendly climatic products. These findings indicate that the examined cross-sectoral collaboration was able to agree on goals and objectives perceived to be attainable, and was able to narrow the gap between science and practice.

The stakeholders' profiles provided us with interesting insights into the market of Climate Services. The academics were in direct contact with urban planners (represented by the profile of municipality technicians) in order to develop climatic products that are understandable and useful for urban climate planning. The consulting company was an intermediate player that facilitated knowledge transfer, strategic planning and policy development between the municipalities, policy-makers and academic groups. Both academics and practitioners found it challenging to create a common understanding and language, as Aboelela *et al.* (2007) found in other sectors. Nonetheless, they described the collaboration as a rich learning experience that opened up more opportunities for them.

The "think" and "gain" boxes in the Empathy Maps help us to identify what the practitioners—Climate Service users—care about, what they need from the collaborators, and what outcomes they expect from the cross-sectoral collaboration. Analysing the "pain" boxes, we get an overview of what they are concerned about and what barriers they need to overcome. For example, both the practitioners and academics feel the "pain": that they need more time and opportunities to learn about other disciplines and practices. To serve these needs, more TD training and workshop opportunities, as well as stronger institutional support for TD activities (e.g., changing academic procedures, policies and rewarding system) is suggested by several studies (Bennett, Gadlin and Levine-Finley, 2010; Larson, Landers and Begg, 2011).

By focusing on the "gain" box, we can get ideas about what motivates stakeholders to participate in cross-sectoral collaborations concerning climate issues. By promoting the benefits gained via TD work experience, stakeholder groups can be engaged more effectively. The highlighting of successful practices is highly appreciated by those new to the TD field, as was also suggested by graduate students of an ID course (Larson, Landers and Begg, 2011). Even though the Empathy Maps do not provide an exhaustive list of stakeholder attributes, it certainly provides more information about the interests and needs of both the climate service provider and user. Other innovative tools for stakeholder analysis can be found, for instance in De Vicente Lopez and Cristian (2016).

5.4.4 Communication

Communication emerged as an important topic throughout the literature in terms of Intra- and Interpersonal factors of TD collaborations (Stokols *et al.*, 2008), as a principle of good interdisciplinary team work (Nancarrow *et al.*, 2013), as a personal skill in project management (IPMA, 2015), and as a necessity for sectoral innovation (Klein Woolthuis, Lankhuizen and Gilsing, 2005). Rosales Carreón (2015) highlighted that the poor communication between actors led to inefficient multi-stakeholder collaboration in a retrofitting project. Listening and communicating skills were also mentioned in the WMO Guidelines for Trainers (WMO, 2013), referred to as “transferable skills or core competences”. Furthermore, the “Competences for provision of Climate Services” defined by WMO GFCS (WMO, 2015) outlined communication of climatological information in partnership with users, as a core competency for institutions providing CS. Much of what determines success in team communication relies on trust (Bennett, Gadlin and Levine-Finley, 2010); this is further discussed in section 5.4.6.

Regular internal communication (among team members) and external communication (communication beyond the core team, e.g. with end-users) are both important for enhancing team performance (Nancarrow *et al.*, 2013). As well as electronic communication, thanks to frequently scheduled meetings, the studied partnership could build trust among team members, and develop a common understanding of the project. The geographically disperse cross-sectoral collaboration, the diversity of members and the size of the team made it challenging to maintain good team dynamics and efficiency. To overcome these barriers, good communication among team members was key, as this encourages feelings of trust, and enables teams to better manage issues of size, compatibility and cohesion (Edmondson, 1999).

Regarding interactions with decision-makers (e.g. mayors and politicians), the communication strategy included marketing elements and traditional public relations tasks. As the practitioners explained, to convince decision-makers, the direct benefits and financial savings for the municipality was the most relevant information to be communicated. These arguments are commonly used in environmental communication strategies. According to the practitioners, the main interest of the municipality is the development opportunities that come with the climate adaptation project. In addition, the "climate-friendly image" could provide promotional value for the city. For this reason, flexible personal communication skills (soft skills) in various working environments was indispensable for the cross-sectoral collaboration.

Communicating the results to the public was the task of the communication NGO. They kept in contact with local, regional and national media as well as managed the project website and social media platforms. It is important to mention that a separate entity was responsible for the external communication of the project, however analysing their role was beyond the scope of this study.

5.4.5 Capacity building

The importance of capacity building and the need for workshops and training on TD collaboration were articulated by all the interviewees. Their opinion is in line with the findings of Bennett, Gadlin and Levine-Finley (2010) for the biomedical sector, i.e. people are rarely introduced to skill sets that can help them to establish and maintain strong collaborative relationships. Nevertheless, one might question whether ID skills can be taught and learned, or whether the interest and competences in such work were intrinsic to one's personality and value system. Larson, Landers and Begg (2011) develop controversial opinions in their writings. Based on their investigation, there are researchers engaged in collaborative work who believe that ID skills had to be experienced and learned "on the job". On the other hand, Gebbie *et al.* (2008) identified a set of core competences essential to IR teamwork, which Larson, Landers and Begg (2011) argued, can be taught.

Accordingly, Larson, Landers and Begg (2011) developed and implemented a graduate didactic course that is open to students and faculty members in any discipline across the campus (health care sector). From their experience of running the course, they concluded, that the most challenging aspect was working through institutional structures that made it difficult to offer cross-school courses. Furthermore, interpersonal challenges among a diverse group of students from several disciplines also occurred. Bennett, Gadlin and Levine-Finley (2010) also pointed out that the challenges imposed by institutions are among the most difficult to overcome, as making changes in policies and procedures that have been in place for decades takes hard work, negotiation, and lots of meetings. In this case, the academics described a similar situation, stating that the university leadership is very supportive regarding cross-sectoral collaborations; however, the institutional bureaucracy makes it hard to achieve the necessary changes.

As Hall, Stokols and Moser (2008) suggested, to move team science forward, it is vital to develop more effective ways to train scientists. A didactic course such as the one described by Larson, Landers and Begg (2011) is a promising approach to enhancing the ID/TD skills of scholars-in-training in an academic setting, and could also be further developed by adding solution-oriented, practice-based learning experience. The National Academy of Science in its handbook, “Facilitating Interdisciplinary Research”, also recommended immersion courses and IR curricula for undergraduate and graduate students (NAS/NAE/IM, 2004). A study by Borrego and Newswander (2010) identified five categories of learning outcomes for ID graduate education: (1) disciplinary grounding; (2) integration; (3) teamwork; (4) communication; (5) critical awareness.

5.4.6 Building trust

As well as capacity building, fostering trust in a TD collaboration is indispensable. Trust is not a one-dimensional variable, it is based on an assessment of the other member’s honesty, abilities, reliability and intentions (Bennett, Gadlin and Levine-Finley, 2010). When interviewees were asked about the qualities that they find important in each other, most of the ideas (e.g. honesty, open-mindedness, availability, empathy) were related to trust and respect. Trusted partnership also requires the belief that members will be truthful in their communications and in the conduct of their scientific research; this was expressed as “scientific ethic” by the *Academic-A*. Members need to have confidence in the abilities of their colleagues to produce reliable results and to openly share and discuss them. The interviewed persons shared similar ideas on trust and reflected the views provided in the literature (Stokols *et al.*, 2008; Larson, Landers and Begg, 2011; Nancarrow *et al.*, 2013).

I would like to note that some of the findings might seem obvious because the fundamentals of collaborative work are supposed to be common sense. However, self-awareness of these topics is very important. As Bennett, Gadlin and Levine-Finley (2010) explains, sometimes in everyday situations, people act in a very different way than what they would have themselves recommended. Practical guidance such as the one provided by Bennett, Gadlin and Levine-Finley (2010), can aid self-assessment and selfdevelopment as well as the improvement of team dynamics. The framework of factors established by Stokols *et al.* (2008) functions in a similar way, as it helps to design, improve and foster TD collaborations. I found this framework useful tool for evaluating the cross-sectoral case of urban climate planning.

5.5 Summary and Conclusions

Climate change adaptation planning and decisions are made within a complex web that includes local, regional and national government employees, elected officials, technical and strategic consultants, sectoral agencies and associations, business people, members of the public and scientists. In the example of present case study, I explained the differences in opinion of scientific researchers and practitioners when working on the same issue and dealing with different types of knowledge. Informant interviews were conducted to map the voices of various stakeholders and to establish the key determinants that influenced TD collaboration in the context of urban climate planning. By analysing the motivations, challenges and needs of stakeholders, we gained novel insights into the market of Climate Services in the field of climate adaptation. Furthermore, an understanding of roles and competences needed for effective TD collaborations can help academics to analyse their own research practice and to become aware of the kind of roles that fit personal skills and interests, as well as tasks and the situations at hand.

The lessons learnt are summarised as follows:

- Practitioners were constrained by others in the decision-making web of climate adaptation planning. They had to balance the needs and expectations of multiple constituencies—for example the elected board of municipalities, local businesses and citizens—and respond to their decisions and demands.
- Practitioners had to act within national-local regulations and guidelines, and in order to build a new policy for climate adaptation, the already existing sectoral regulations need to be revised and mutually aligned with the new strategy.
- Academics took on various “non-traditional” researcher roles during the co-development of urban climatic products such as *knowledge broker*, *process facilitator* and *change agent*.
- Academics were inspired and motivated by the real-life impact of their research, driving them to engage in cross-sectoral projects aimed at problem-solving. They

showed a great interest in serving practitioners with useful climatic information.
- The university leadership supported cross-sectoral collaborations, however there are still some institutional barriers to overcome, e.g. providing TD training for students/university staff.
- Both practitioners and academics embraced the opportunity and challenge of mutual learning and developing a common language; additionally, they managed to build a trusted partnership that continues to function in the form of further projects.
- The international and national political system enabled for the development of the examined projects, providing professional and financial resources for climate adaptation planning.
- Capacity building was essential among stakeholders. The practitioners needed an update on climate-related risks and opportunities, and the academics needed to learn about the legislative context of climatic planning. To incorporate climate information in municipality strategies, public servants needed technical upskilling.
- Communication was one of the most powerful contextual factors that fostered efficient teamwork. Open-mindedness, availability, honesty and empathy were among the qualities that both academics and practitioners considered important.

Through the real-life case of urban climate adaptation planning, important lessons are being learnt about bridging science and practice; this knowledge then can contribute to other arenas where scientists seek to connect scientific research and information to societal decision-making and sustainability transformations. This study calls for more TD collaborations supporting multi-stakeholder, climate-smart decision-making, incorporating both academic and practical knowledge. The lessons and observations presented here are novel in the context of Climate Services. The practical implications provide recommendations for those academics who wish to engage in TD collaborations focusing on climate-related issues, and for those who create science policy.

5.6 Practical Implications

New insights are provided to Climate Services research through this study by mapping the voices of the different stakeholders, and their attitudes to transdisciplinary collaboration in climate adaptation planning. Based on the results, practical implications and recommendations are formulated to help stakeholders to build and manage efficient cross-sectoral collaborations in the field. Furthermore, we gained novel insights into the market of Climate Services, through analysing stakeholder profiles using the visual tool of Empathy Map.

The following recommendations are formulated:

- Academics and practitioners need to interact on a regular basis to build trust, credibility, common understanding and a shared vision; this is essential for effective TD collaborations that facilitate climate-smart decision-making and societal transformations. If regular face-to-face meeting is not possible, several online tools exist to aid remote teamwork.
- Academic groups need members who facilitate the dissemination and communication of scientific issues, for instance helping interested practitioners avail of new methods and information, and demonstrating that using science has value, and/or it is authoritative.
- Assumptions (originating from the different schools of thoughts) of both academics and practitioners need to be softened by developing interactive relationships based on mutual respect, openness, an appreciation of different perspectives and constraints, as well as a willingness to learn from each other.
- By promoting frequent feedback and long-term partnerships, the iterative approach of knowledge co-production can significantly contribute to overcoming the challenges and barriers of cross-sectoral projects on climate. Building one successful partnership may then open up a range of additional opportunities. A useful practical guide for multi-stakeholder involvement in environmental problem-solving is e.g., Lelea *et al.* (2014).
- Integrated TD research is indispensable to advancing climate-smart planning and decision-making, thus the participation of various disciplines as well as participatory action research and transition management approaches need to be encouraged. A recommended network to learn more about the TD methodology is the Swiss td-net (*td-net website*).
- Education and Training programmes play an important role in developing personal competences to aid cooperation in TD teams. TD capacity building also prepares persons/groups for the role of intermediaries who facilitate knowledge

co-development. The WMO provides Guidelines for Trainers in Meteorological, Hydrological and Climate Services (WMO, 2013) and also defines competences for the provision of CS targeting institutions (WMO, 2015). To develop personal and team competences in TD collaborations, for example the well-written practical guide by Bennett, Gadlin and Levine-Finley (2010) is recommended.

- Inside academies, stronger institutional support is needed. Changing procedures and policies to enable TD activities is hard work, but is necessary. The rewarding system for academic achievements and the evaluation system for career advancements need to be revised in order to support TD and cross-sectoral activities.
- The exchange of experiences and best practice need to be encouraged inside the TD team as well as between projects, on both national and international levels. What can we learn, for example, from other cities or communities that face similar challenges? Recommendable international platforms and programmes in the field of local climate adaptation and sustainability include C40 Cities Climate Leadership Group, ICLEI Local Governments for Sustainability, Mayors Adapt, Climate-ADAPT, EIT Climate-KIC, Future Earth, etc.
- Climate Services function as an interface between science and society, thus following the “demand-driven and science-informed” approach (European Commission, 2015), further market research and the co-development of climatic products need to be encouraged. This requires more intense communication across sectors and embracing alternative researcher roles and tasks.

As Climate Services literature echoes, generating useable scientific information requires connecting academic research to practical applications and decision-making. Hence, academics and practitioners need to co-develop climate information products that clearly apply to practitioners’ specific decision-making settings, in this example of urban climate adaptation, such as climatic guidelines, metrics and maps. This requires long-term partnerships among scientists, product developers, and different groups of stakeholders to mutually learn about opportunities and needs, develop trust, and build credibility. It is hoped that the offered recommendations based on informant interviews and the literature review can help facilitators of transdisciplinary research processes, and academics who wish to develop more efficient Climate Services.

Chapter 6

Practical projects relevant to the thesis

6.1 Overview

As the thesis aiming to facilitate the development of actionable climate information (Objective 4), I took part in various TD projects. These short projects provided practical experience in co-developing solutions and the opportunity to explore the perspectives, priorities and needs of a diverse set of stakeholders. This chapter briefly summarizes the aims and outcomes of three projects.

Section 6.2 describes the individual project related to an Innovation & Knowledge Lab that served as a real-life example of "science-society" interfaces. Here practical experience is gained on conducting market research and stakeholder mapping. In section 6.3 a multi-expert project is presented that addressed urban complex issues through enhancing sustainable mobility and greening the city. Section 6.4 introduces a project that addresses climate adaptation via improved asset management in the intelligent city.

6.2 Executive Summary: Knowledge & Innovation Lab

Individual fieldwork, LDE Centre for Sustainability (joint institute of Universiteit Leiden, Delft University of Technology and Erasmus University Rotterdam), Pioneers into Practice Programme Climate-KIC, the Hague (the Netherlands), 1–31 October 2016

Project title: Demand-driven innovation and knowledge lab on Circular Cities of the future

Living labs are defined as "user-centered, open innovation ecosystems based on a systematic user co-creation approach in public-private-people partnerships, integrating research and innovation processes in real-life communities and settings" (ENoLL, 2006; Steen and van Bueren, 2017). In recent study the Knowledge and Innovation Lab is considered as a science-society interface that connects real-life urban sustainable challenges with the goals of practice-oriented Climate Services. There are several examples especially from Northern European countries that these interfaces create successful synergies between the participating stakeholders (academics, NGOs, municipalities, entrepreneurs, companies). Furthermore, such co-creation spaces e.g. urban living labs, green offices and impact hubs offer great potential for climate-innovation in form of multi-stakeholder collaborations.

The Happy City Lab (*HCL website*) was set up in 2014 providing honour courses for students from three universities (TU Delft, Erasmus University Rotterdam and Leiden University) under the umbrella of the Centre for Sustainability (CfS). Since then it has been growing successfully and a new lab was going to be set up by the end of 2016 focused on Circular Economy. The HCL connects outstanding students, researchers in philosophy, human geography, urban sociology, positive psychology and urban design, as well as innovative start-ups, aiming to link positive design with science that engages in designing for subjective well-being and happiness, with contemporary urban issues.

In order to improve the communication and marketing strategy, as well as to foster community building around the HCL, this work focused on the question: "How to engage students, academics and NGOs to participate in a living lab?" Three groups of stakeholders were interviewed in accordance with the research scope: a) student based organizations/green university groups, b) academics (scientists and PhD students), c) civil initiatives, NGOs. The interviews provided insights into the different motives and needs of stakeholders and also highlighted the underlying barriers and institutional incentives that influence the engagement of stakeholders in co-designed projects. Finally, the work specifically aims at affording recommendations to advance the set-up and development of the Knowledge and Innovation Labs. Here the outcomes are briefly summarised by stakeholder groups.

In terms of student based organizations/green university groups (6 interviews) the most surprising finding was the lack of communication and collaboration between these organisations. In some cases, even when they are based in the same building, they do not know much about each other’s activities. Furthermore, almost all of them commented that they suffer from poor internal communication and the unclear/undefined short- and long-term vision of the group. In order to eliminate these drawbacks more conscious networking and well-organized PR is needed. Using social media and promotion on the campus screens, as well as expositions at campus proved to be the most efficient communication channels in many cases.

The interviewed academics (scientists and PhD students, 4 interviews) considered the lack of time as one of the main barrier to participate in living lab activities. Other main concern is that the academic rewarding system is immensely based on indicators that do not take into account cross-sectoral activities (e.g., the number of published papers), furthermore in several research institutes still negative connotation surrounds those researchers who start their own business or any collaboration with the industry, or pursuing outreach activities. PhD students are often overloaded by academic obligations, and sometimes does not find the proper organisations when they want to do extracurricular activities. For these reasons changes are needed at both sides: on one hand the academics need to be positively evaluated for cross-sector collaborations (change of the academic rewarding system), on the other hand academics need to be provided with special trainings or courses to help them link their research with the needs of the industry (offering help to improve certain skills). In the latter task the living lab could play a significant role, for example providing practical courses for the academics and students to improve their TD skills.

Finally, a couple of civil organisations were involved in the research (2 interviews), that confirmed the fact that urban living labs definitely need to include such bottom-up initiatives, as they provide real-life challenges for student/company projects and academic research. All in all, urban living labs provide unique networking opportunity for all the stakeholders, and also create a growing community working for better city life via circular cities. This is undoubtedly a win-win situation for all actors.

I was responsible for the design and implementation of the market research. I conducted the interviews and explored interested stakeholders to extend the network around the kick-starting Happy City Lab.

6.3 Executive Summary: Sustainable Mobility and Green City

Multi-expert teamwork, Pioneers into Practice Programme Climate-KIC, Valencia (Spain), 16 May – 16 November 2016

Project title: Bike Generation – how to improve the sustainable mobility in the city of Valencia?

Most of European cities have not been planned taking into account energy and environmental aspects that are crucial to sustainable urban mobility. Considering the social, economic, technological and environmental aspects of the multifaceted challenge, we propose some strategic changes in the transport system by adding new smart features built upon the already existing innovations in the city of Valencia. The developed joint solution is aligned with the goals of the Sustainable Urban Mobility Plan, Sustainable Energy Action Plan, the 2020 Strategy, the Adaptation Plan to Climate Change and the Smart City Strategy.

The aim of the project is to develop innovative solutions to tackle urban issues addressing the following specific topics, proposed by the Valencian InnDEA Foundation (*InnDEA website*): a) reduce CO_2 and NO_x emissions; b) reduce urban heat island and noise; c) promote sustainable alternatives in mobility; d) change user mobility pattern; e) claim the public space for people and improve the quality of life.

The challenge

Based on the above described urban sustainability challenges we addressed the following specific questions:

(i) How to reduce the traffic congestion and daily use of cars in the city?

(ii) How to attract more people to enjoy every day a healthy and fun biking experience?

(iii) How to improve the biking infrastructure while making the city greener and reducing heat stress and air pollution?

Problem approach

In order to reduce the GHG emissions due to the daily movements of citizens using their private cars, we foster the use of bikes and public transport. To reduce heat stress and to enhance the interconnectivity of different parts of the city, new green and safe bike lanes are proposed. It would not only create more inclusive society but also engage people of any age to do more exercise and enjoy riding their bike through gamification.

To tackle the complex challenge of building a more sustainable urban mobility system, we developed a joint solution that can be implemented separately or jointly. In our idea we integrated the theme of Mobility, Energy, Climate and Environmental Awareness that are key elements in the urban development agenda of InnDEA and the Municipality of Valencia.

Thus, our joint solution (Fig. 6.1) is as follows:

A) Gamification using a bonus based system to reward using the bike. A virtual currency will be created that users could change for tickets to public transport, access to cultural activities in the city, parking hours out of the city, local shops and restaurants, etc.

B) Bike = Transport + Energy Generation. A removable battery element will be designed to a) charge the user's devices and b) supply energy to the grid to illuminate bike lanes.

C) Improved and extended bike lanes: a) more secure lanes and bike sheds b) innovative lighting system with special pavement that utilizes solar energy and c) green corridors with vegetation cover.

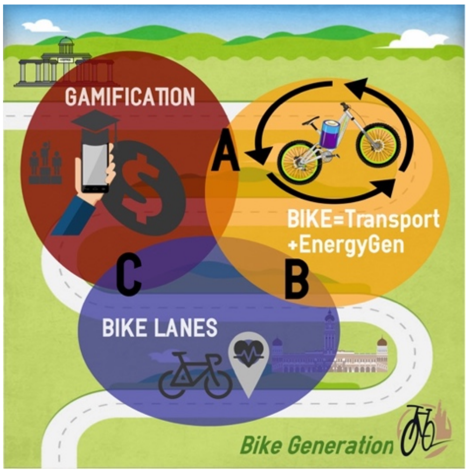


Figure 6. 1 The joint solution of BIKE GENERTION (Credit: Áxel Pena López, team member)

Additional benefits of the idea are self-sustaining bright lanes (additional energy supply not needed), enhancing the green image of the city, economic revitalization in the vicinity of the bike lanes, improving social cohesion and community building through gamification, R&D in batteries and supercapacitors, awareness raising: e.g. the user appreciates the value of energy by seeing what it costs to generate it.

We cannot just change the existing transport system to a "green transport" without the citizens. Awareness raising on the benefits of a sustainable mobility system is key besides the improvement of infrastructure. We believe that Valencia can be a biking city just as for instance Copenhagen, but we need to make the routes safer and comfortable to provide an enjoyable cycling experience for everyone.

The project has been presented to InnDEA (16 November 2016) and in the Innovation Festival of Climate-KIC in Frankfurt, Germany (7-9 November 2016).

Team members: Maribel Cano Domínguez (Architect), Áxel Pena López (Industrial Engineer), Vicente Ramón Tomás López (Computer Science Engineer) and the author of this thesis. I took part in the co-development of creative ideas through systems thinking, and I was responsible for providing climatic information on the urban thermal comfort and managing public relations.

6.4 Abstract: Addressing climate adaptation through intelligent cities

Advising the project of PMM Business School, May–August 2017

Title of conference paper (originally in Spanish): Climate change adaptation strategy through the development of intelligent and sustainable cities

Climate change has emerged as one of the defining global issues of today, but negotiations to deliver a supra-national climate change mitigation strategy post-Kyoto have been progressing slowly. The Paris Agreement formulated at the COP21 (Conference of Parties) in Paris, 2015 was a breakthrough event, as 195 countries adopted by consensus the main aim of the convention: „holding the increase in the global average temperature to well below 2 °C above pre-industrial levels".

Urban municipalities play a leading role in the implementation of the Paris Agreement through sustainability projects and programs in various fields, e.g., urban mobility, health, energy, water, transport infrastructure. These cities vision themselves as intelligent or smart cities, including sustainability and enhanced physical/digital connectivity in their development agenda. However, still there is a gap in connecting the various projects with the strategic plan of the municipality.

For this reason, it is necessary to develop a conscious Asset Management, aligned to ISO 55001 and UNE 178303:2015 – Smart Cities. The Asset Management of the City—in terms of projects developing new infrastructure and improving the already existing one—is need to be aligned with life-cycle models (Amendola, 2016) and embedded in the Philosophy of Cradle-to-Cradle (C2C) (McDonough and Braungart, 2002). This philosophy describes that from the conception and design of any product (that can also mean strategy or policy), the entire life cycle of the product has to be taken into account, optimizing material health, recyclability, renewable energy use, water efficiency and quality, as well as social responsibility.

Adaptation to climatic changes in cities is a necessity, and require radical social and economic transformation. Front-runner cities have already realised that „climate change adaptation is an opportunity for social reform, for the questioning of values that drive inequalities in development and our unsustainable relationship with the environment"

(Pelling, 2011). Thus, enhancing adaptive capacity of a city is essential and can be addressed through improved Asset Management of the City.

Reference: Sánchez, A.; Amendola, L.; Depool, T.; **Lehoczky, A.** (2017): Estrategia de Adaptación al Cambio Climático a Través del Desarrollo de la Ciudad Inteligente y Sostenible. XIX Congreso Internacional de Mantenimiento y Gestión de Activos, Bogotá, Colombia, 16-18 August 2017. Full article in the conference issue, 8 p.

I was responsible for translating the goals of the Paris Agreement into locally relevant information that supports urban climate adaptation through asset management in the city. The paper was presented in the XIX International Congress on Maintenance and Asset Management. Bogotá, Colombia, 16-18 August 2017, and can be accessed here: http://www.aciemmantenimientoygestiondeactivos.org/home/files/Trabajos/17090_TRA_USA_A_SANCHEZ_CIMGA2017.pdf

Chapter 7

Summary

7.1 Overview

In this chapter, the main results and conclusions of the core chapters are summarised to provide a comprehensive overview of the interdisciplinary work. Each chapter individually offers interesting results, but it is the combination of multiple data from a variety of disciplines in this thesis that has enabled novel research on the climate information distillation challenge. To link science and practice, practical insights are formulated at the end of Chapters 3, 4 and 5 supported by practical experience. This chapter reviews the outcomes of the project, describing the results in relation to the four research objectives outlined in Chapter 1. Further potential research lines are also discussed.

The overall aim of this thesis was to pave the way for the integration of regional and local scale climate information into Climate Services that support climate adaptation planning and policy-making. Regional and local scale climate information was produced via analysing climate model projections over the Iberian Peninsula (IP) and the urban heat island (UHI) in the city of Valencia (Spain). This work has been carried out using various datasets, including remotely sensed land surface temperature, ground measured meteorological data and climate simulations from a high resolution regional climate model that has no urban component. To learn about the needs of climate information users and the challenges that academics and practitioners face in climate-related transdisciplinary (TD) collaborations, in-depth interviews were conducted with relevant stakeholders involved in urban climate adaptation projects in Portugal.

7.2 Fulfilment of the objectives of the thesis

The hypothesis, i.e. “through the development and use of Climate Services along with transdisciplinary approaches urban climate adaptation and planning can be improved” was supported by the results of the climatological analysis and the qualitative social study. Each of the four main objectives, introduced in section 1.4, is detailed below, with a short discussion summarising the outcomes in relation to this thesis. This thesis was sure to explicitly discuss the uncertainty related to data and methodologies to ensure readers are aware of the situation. Critique of research is also formulated for each objective below.

7.2.1 Objective 1

Assess climate projections over the Iberian Peninsula via a high-resolution regional climate model ensemble and evaluate model performance to provide scientifically solid and easily understandable illustrations of future temperature change and its uncertainties.

This thesis evaluated the performance of a regional climate model (RCM) ensemble and described the future changes in seasonal mean near surface temperature over the IP for the mid-term (2041–2070) and long-term (2071–2100) future in Chapter 3. The high spatial resolution (12.5 km) RCM simulations with the Rossby Centre model RCA4 were provided by the EURO-CORDEX framework. First, the thesis analysed the simulated temperature for the period 1981–2005 both when forced by “perfect boundary conditions” and when forced by boundary data from five different General Climate Models (GCM). Various evaluation metrics and maps were used to reveal geographical details in the bias pattern compared to different observational and reanalysis data.

The GCM-driven RCA4 simulated the seasonal mean features of the temperature patterns over the IP reasonably close to the observations, however, a prevailing cold bias was found, similar to the performance of other RCMs over the IP in general. Given “perfect boundary conditions” from ERA-Interim, the RCA4 systematically underestimated the mean temperature over most of the IP, except summer, when warm and cold biases were equally present. The seasonal absolute bias value was typically 1–2 °C, with larger bias values (up to 5–8 °C) over complex terrain, e.g., the Pyrenees. In general, the GCMs introduced additional cold bias to the RCA4 simulations, increasing the absolute bias values of RCM with about 0.5–1.0 °C, especially in the warm half of the year. The summer warm biases of RCM were additionally turned into cold biases over most of the domain. The ensemble of five GCM-driven RCA4 simulations had a well-pronounced cold bias over most of the IP throughout the year, compared to the observations (E-OBS). The seasonal overall absolute bias value was typically 1–3 °C.

To fulfil the second part of the Objective 1, future change maps of seasonal mean temperature (using the so-called delta-approach) were produced. To address model and scenario uncertainty, an ensemble of RCA4 simulations driven by five GCMs were analysed under a stabilization (RCP4.5) and a high-end scenario (RCP8.5). As expected, each projection showed a gradual warming trend over the whole IP in every season throughout the 21st century. Under both scenarios, summer and autumn seasons were projected to experience the highest temperature rise (up to 3–6 °C by the end of century), but also the highest spread of simulations (0.5–0.9 °C) was projected in these seasons. This implies that summers are becoming longer and warmer while winters are becoming shorter and milder over the IP. The warming signal was strongest in the central and southeastern mountainous part of the peninsula and in the Pyrenees according to most of the simulations, but there were some differences in the amplitude and pattern across seasons, scenarios and time scales.

The work demonstrated the capabilities of RCA4 to reproduce the mean temperature features over the IP as well as its systematic errors. The identification of the possible reasons for the model-specific bias characteristics would require a deeper and dedicated analysis that was not the aim of this thesis. Furthermore, to fully explore the uncertainty ranges a larger ensemble is needed containing more RCMs, forcing GCMs, emission scenarios and ensemble members initiated with slightly different conditions and/or modified physical parameters (to sample the internal climate variability).

The user-focused development of climate change maps for the Iberian Peninsula has started only recently, in spite of the growing demand for future climate information from different sectors. The thesis presents the future temperature changes in the form of seasonal maps, including the spread of projections, based on the good practices applied in Climate Services by SMHI. A strength of this study is that future projections are produced by the high-resolution version of the RCA4, which can be regarded as an added value of regional climate simulations over the IP.

7.2.2 Objective 2

Evaluate the intensity and spatial pattern of the urban heat island and thermal comfort over the city of Valencia to create solid foundations for urban climate change adaptation planning. Analyse the locally observed temperature extremes.

The urban heat island effect and human comfort in the city of Valencia was quantified in case of summer hot days, detailed in Chapter 4. To provide context to the case study, the mean temperature conditions of Valencia were analysed from a long-term climatological perspective using homogenised daily observations. Temperature extremes that might contribute to the heat risk in the city were also investigated. The work revealed a significantly positive trend in mean temperature (0.23 °C per decade) as well as a significant increase in warm extremes (*warm nights*, *warm days*, *tropical nights*) and decrease in cold extremes (*cool nights*, *cool days*, *cold spells*) over the period 1906–2014.

The magnitude and spatial extents of the Valencia urban heat island is quantified during three consecutive summer hot days based on MODIS remotely sensed land surface temperature (LST) data and in-situ air temperature (AT) measurements at two meteorological stations. The UHI estimated from AT measured at the urban and rural stations was highest just before sunrise (2.3 °C). The sUHI calculated as the difference between the urban and rural region LST was the most intense after sunset on the record hot day (2.6 °C).

A year-round calendar was produced to describe the thermal comfort in the city based on hourly values of the Discomfort Index (DI). The city had milder winter conditions than the rural areas, especially during nighttime. In the warm part of the year the DI is similar at both stations, however, the city was occasionally warmer in the early morning hours. Hot nighttime conditions are prevailing from June to September, which might impose higher heat risk on the urban population. The spatial analysis of DI in the nighttime MODIS and ASTER images revealed less comfortable areas in the densely built up city centre, main traffic arteries and industrial zones in contrary to the rural regions.

Compared to previous studies this work used satellite data measured with improved sensors, however a limitation of the study is that due to the moderated resolution of MODIS (approx. 1 km), the details inside the city were blurred. Thus the 1 km scale and the variety of groundcover in a heterogeneous urban area is a limitation of the current approach. However, in spite of the moderated resolution of the MODIS LST product, the high temporal resolution of MODIS made it reasonable for the present UHI study. This highlights the need for higher spatial resolution satellite images with more frequent data acquisition time, especially over cities. Due to the limited availability of higher spatial resolution satellite images (e.g., LANDSAT, ASTER) over the study region during nighttime, a more detailed study could not be pursued.

Another limitation to the approach of this study is the non-ideal locations of meteorological stations that probably had an influence on the quantification of UHI and DI. As the airport station (used to represent rural conditions) is placed close to a medium built-up suburban region and the urban station is installed at the side of a large urban park, both sets of meteorological data are influenced by its surrounding for some degree. Probably, with more and better located stations (e.g., one in the surrounding agricultural fields and others in the densely built-up areas such as the old town) more accurate results could be achieved. Thanks to the spatial coverage of satellite images and the availability of NDVI data, regions with predominant urban and natural surfaces could be defined, that enabled an accurate calculation of surface UHI.

This part of the thesis also provides novel information on the long-term changes in temperature extremes in the city of Valencia, partly thanks to the extended time series with over a decade since previous studies on the subject. The use of ETCCDI climate indices makes the results comparable with any other region around the globe. Furthermore, this section illustrates the importance of including the UHI in climate models as it can make a significant difference to urban temperatures, where the majority of people live. The work also extended our knowledge on the diurnal cycle of thermal comfort throughout the year that complements the results of other studies in the city limited in time (e.g., limited field works). The illustration of spatial variability of increased heat and discomfort via the UHI and DI maps can be useful to urban planners in the design and distribution of green areas in the city.

7.2.3 Objective 3

Analyse the factors that influence and foster transdisciplinary collaborations in urban climate adaptation projects and map the voices of stakeholders in regard to their motivations, challenges, needs.

In Chapter 5 the thesis explores the social dimension of transdisciplinary (TD) collaborations focusing on urban climate adaptation. The work presented the view differences and similarities of scientific researchers and practitioners working on the same climate-related issue and dealing with different types of knowledge explained in Chapter 2. The case study based on informant interviews with various stakeholders identified the key determinants that influenced the TD collaboration in the context of urban climate adaptation and planning. Furthermore, it revealed the different interests, motivations and needs of stakeholders to provide insights into the market of Climate Adaptation Services. Several lessons were learnt through the case study (detailed in section 5.5), here the novel contributions to CS research are summarised.

In TD collaborations, academics took various researcher roles beyond the *reflective scientist* such as *knowledge broker*, *process facilitator* and *change agent* during the co-development of urban climatic products. They were inspired and motivated by the real-life impact of their research, driving them to engage in cross-sectoral projects aimed at problem-solving. They showed high interest in serving practitioners with useful and useable climatic information.

Capacity building was essential among stakeholders. The practitioners needed updates of climate risks and opportunities, and the academics needed to learn about the legislative context of climatic planning. To incorporate scientific results in municipality strategies, public servants needed technical upskilling. Both practitioners and academics embraced the opportunity and challenge of mutual learning and developing a common language. As expected, open communication was one of the most powerful contextual factors that fostered efficient teamwork. Open-mindedness, availability, honesty and empathy were among the qualities that both academics and practitioners considered important.

This study demonstrated that integrating climatic guidelines in the master plan of a city or formulating a new policy concerning climate adaptation is as challenging as providing climate knowledge in a user-friendly form. Practitioners were constrained by others in the decision-making web of climate adaptation planning. They must balance the needs and expectations of multiple constituencies, for instance, the elected board of municipalities, local businesses, citizens; and respond to their decisions and demands. Furthermore, they must act within national-local regulations and guidelines, and to build a new policy for climate adaptation the already existing sectoral regulations should be revised and mutually aligned with the new strategy.

At the time of the study (spring 2017) the international and national political system was enabling for the development of the climate adaptation projects, providing professional and financial resources. I added the national political landscape to the contextual factors separately, as practitioners made important explicit comments on it. According to the academics, the university leadership supported cross-sectoral collaborations, however there were still some institutional barriers to overcome, for example, providing TD trainings for students/university staff. This is a common problem in other TD fields too, for example in health research. Nevertheless, recent years more and more TD initiatives and partnerships aim to fill this gap at both regional and global scale.

The qualitative method applied in this chapter allowed space for some degree of subjectivity, however, to avoid researcher bias and to maintain as much objectivity as possible, all the interviews were conducted by the author following a semi-structured interview guide. In contrast to multiple choice survey questions the interview method with predominant open-ended questions enabled the interviewees to better explain their opinions and ideas relevant to their expertise as well as provided space for serendipity (accidental, non-expected findings). This was essential to explore such a barely touched research area that Objective 3 addressed.

Through the real-life case of urban climate adaptation planning, important lessons are learnt on bridging science and practice, that can contribute to other arenas where scientists seek to connect scientific research and information to societal decision making and sustainability transformations. The thesis calls for more TD collaborations to support multi-stakeholder, climate-smart decision-making, incorporating both academic and practical knowledge.

7.2.4 Objective 4

Provide practical insights to facilitate the development of actionable climate information based on user-focused Climate Services research and practical experience.

The overall aim of thesis was to pave the way for the integration of regional and local scale climate information into Climate Services that provide easily understandable and useful climate products to the users. Thus, as well as the rigorous scientific studies the thesis formulated practical implications at the end of Chapter 3, 4 and 5. The recommendations were addressed to academics interested in Climate Services in general, and besides the academics, Chapter 3 provided additional insights concerning the sector of urban planning. Chapter 4 outlined some recommendations to practitioners too.

Chapter 3 presented "traditional" climate change information in the form of maps that not only show the ensemble means, but the spread between the different simulations as well, for different time-scales and under different scenarios. The way of illustrating the seasonal changes in temperature and the uncertainty of future projections was inspired by the SMHI climate scenario web pages (*SMHI website*). As Kjellström *et al.* (2016) also recommended, the communication of uncertainty in future climatic changes is better through discussing "spread" and "robustness" of climate projections rather than referring only to "uncertainty". One can get an indication of the robustness of the results by assessing the main direction and amplitude of climate change as well as the spread of projections around the mean value of change. Other ways of visualising robustness (e.g., integrating the information into the same climate change map) are available in the literature, however their appropriateness for CS purposes have not been tested and documented yet.

As an answer to the increasing demand of city scale environmental data, Chapter 4 provided essential information on the urban climate and thermal comfort in the city of Valencia to be considered in climate adaptation planning. To support the urban planning and decision-making processes, user-friendly metrics and maps need to be produced on sufficiently high resolution (e.g., LANDSAT and ASTER images), as exemplified in the thesis. In designing measures to reduce the thermal discomfort (e.g., greening the city, using high albedo building materials) a wide range of relevant stakeholders (e.g., urbanists, architects, the municipality, citizens, local businesses, etc.) need to be involved to ensure the integration of scientific and local practical knowledge as well as the alignment of interests.

Pursuing the CS research agenda, to explore science-society interfaces and users' needs, Chapter 5 mapped the voices of different stakeholders, and their attitudes towards transdisciplinary collaboration in climate adaptation planning. The formulated practical implications in section 5.6 aim to help stakeholders to build and manage efficient cross-sectoral collaborations in the field, and encourages both academics and practitioners to engage in co-development of climatic products. This requires more intense communication across sectors and embracing alternative researcher roles and tasks.

I participated in practical projects that additionally helped to better understand the tasks of Climate Services. The Knowledge & Innovation Lab project highlighted the importance of thorough market research to find and engage relevant stakeholders. The project on sustainable urban mobility and green design demonstrated that multi-expert collaborations are essential to create innovative climate solutions that address various co-benefits (social-economic-environmental) at the same time (e.g., reducing air pollution and urban heat, improving citizens' lives, vitalising neighbourhood businesses). The project on linking intelligent cities and climate adaptation showed how the asset management of the city can actually facilitate and deliver adaptation strategies.

7.3 Future work

Following the results presented in this thesis, there is considerable scope for further work in the growing research area of Climate Services.

Regarding regional climate projections, further work can consider sector-specific variables and indicators (e.g., indices of vegetation period or heat waves) on different time-scales, in order to tailor the climatic products to the exact needs of users. The chosen variables and indices should represent features for which the RCM performance has been evaluated. To ensure that the climate products are customized, frequent interaction between service providers and users as well as opportunities for co-development of products need to be facilitated.

Considering urban climate products, besides high-resolution satellite images with more frequent time resolution, other indices that take into account more variables (such as wind, sunshine hours, precipitation, human activities, etc.) could provide further, sector-specific information on the thermal comfort in the city. For example, the Tourism Climatic Index or Holiday Climate Index are widely used for the tourism sector as well as the physiologically equivalent temperature (PET) for more specific human thermal comfort. Climate model projections integrating an urban climate module could further enhance our knowledge on what we can expect locally due to global climatic changes.

As adaptation is increasingly conceived as the management of climate risk, the potential threats, vulnerabilities and impacts need to be assessed hand-in-hand with practitioners. For instance, by identifying the residential areas of vulnerable groups within the urban population, and combining this information with the spatial urban climate knowledge, detailed heat risk maps can be produced. This could provide useful information for example to the health and insurance sector.

To develop more efficient Climate Services there is an increasing need to explore the market and its actors, as well as cultivate cross-sectoral partnerships. Both academics and practitioners need to be prepared for such TD activities that requires skills different than the *reflective researcher* role or the one-direction provider-customer interaction.

7.4 Final remarks

In an increasingly urbanised world, the urban influence on temperatures and its associated effect on health are significant issues, especially in light of the general warming trend. Cities are strongly threatened by the harmful impacts of climate change, nevertheless, they have high potential to turn these risks into opportunities for development and innovation. Offering reliable and useful climate information is an important first step towards climate-resilient urban planning. This thesis demonstrates that integrating different disciplines and perspectives is vital to efficient Climate Services.

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APPENDIX

Appendix A: Interview Guide for the academics

Brief introduction and signing the letter of consent.

General Data
Name:
Contact Information: (e-mail)
Age:
Background (profession):
Position (and years in this position):
Nationality (and ethnic group):

1. What is your current position?
2. Since when do you hold that position?
3. What are your recent research interests?
4. Do you have non-academic work experience?
5. (If yes) where and when?
6. You are involved in various urban climate projects with your [research group]. I'm especially interested in those that you worked together with stakeholders outside of the academy. Could you please describe these projects briefly?
7. What is your contribution to the project?
8. With which different institutions/companies have you been in contact during the project?

9. How did you find the collaboration with different professionals?
10. Did you face any difficulties during the collaboration? If yes, how did you deal with it?
11. What is the most challenging for you in this project?
12. What do you like the most in it?
13. Do you feel supported by your research unit/institute?
14. Do you think that TD collaborations are good for your career? Could you please explain your answer?
15. Have you ever participated in any workshop/training involving different professionals? If yes, could you please share your experience?
16. Do you think you have enough training/workshop/networking events in this field? Do you need more or different ones?
17. How do you communicate with each other (e-mail, personal contact, phone call, messaging app, etc.)?
18. How frequently do you have meetings with the team?
19. Are you satisfied with your working environment? (Facilities of the office, common areas, cafeteria, building services, technological)?
20. Do you spend leisure time (lunch, coffee break, weekend activity, etc.) with team members?
21. What qualities do you consider important in your colleagues?

Appendix B: Interview Guide for the practitioners

Brief introduction and signing the letter of consent.

General Data

Name:

Contact Information: (e-mail)

Age:

Background (profession):

Position (and years in this position):

Nationality (and ethnic group):

1. What is your current position?
2. Since when do you hold that position?
3. What is your academic background?
4. Have you ever done academic research?
5. (If yes) where and when?
6. You are involved in various urban climate projects collaborating with the [research group]. Could you please describe these projects briefly?
7. Could you please tell me about your contribution to these projects?
8. How did you find the collaboration with different professionals? academic researchers)?
9. Did you face any difficulties during the collaboration? If yes, how did you deal with it?
10. What is the most challenging for you in this project?
11. What do you like the most in this project?
12. Do you feel supported by your institute/company?
13. Have you ever participated in any transdisciplinary workshop/training that involved different professionals? If yes, could you please share your experience?
14. Do you think you have enough training/workshop/networking events in this field? Do you need more or different ones?
15. How frequently do you have meetings with the project members?
16. What qualities do you consider important in your colleagues?