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European climate change : co-development of local climate services and clustering approaches

Florentin Breton

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Florentin Breton. European climate change : co-development of local climate services and clustering approaches. Climatology. Université Paris-Saclay, 2021. English. NNT : 2021UPASJ012 . tel-03512518

HAL Id: tel-03512518

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European climate change: co-development of local climate services and clustering approaches

Changement climatique en Europe :
co-développement de services
climatiques locaux et approches de
classification non-supervisée

Thèse de doctorat de l'université Paris-Saclay

École doctorale n°129 : sciences de l'environnement
d'Île-de-France (SEIF)

Spécialité de doctorat : Océan, atmosphère, climat et
observations spatiales

Unité de recherche : Université Paris-Saclay, CNRS, CEA, UVSQ,
Laboratoire des sciences du climat et de l'environnement, 91191,
Gif-sur-Yvette, France.

Référent : Université de Versailles-Saint-Quentin-en-Yvelines

**Thèse présentée et soutenue à Paris-Saclay, le 27 septembre
2021, par**

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*In loving memory of Jacques Breton, or "Grand-papa" as we called him,
who passed away during the making of this thesis.*

*Former researcher and professor of physics at the University of Bordeaux,
he was always passionate about science and devoted to his family.*

Acknowledgements

This thesis has a long backstory. The journey to the field of climate change started on my first year at university, with lectures on paleoclimatic changes and the reading of books on global change. I was intrigued by an formidable issue in both scientific and societal dimensions, and its sheer scale and complexity would reveal themselves later.

My gratitude goes to Gilles Ramstein for introducing me to the world of climate models at the end of my bachelor's degree. This first experience at LSCE gave me a taste for climate research and the desire to pursue a master in climatology. I thank Camille Risi for taking me into the clouds, and Diana Ruiz-Pino and Alejandro Bianchi for making me dive into ocean acidification. My thanks also to Matthieu Roy-Barman for his help and advice during the master degree (and PhD thesis).

I met Mathieu Vrac at the end of my master and he was kind enough to introduce me to research in statistical climatology and climate services. Mathieu and Jean-Paul offered me a fascinating PhD topic, at the interface between climatology, social science and territorial decision-makers. I cannot thank them enough for their guidance during the thesis. They have been extremely available, helpful and insightful during the various stages (literature, experiments, articles, conferences, manuscript, defence), while also encouraging my gradual autonomy. I have been very lucky to have them, and to learn from their experience in statistical climatology, climate services and local adaptation.

My deep appreciation goes to Christophe Cassou and François Géménne for reviewing my thesis, and to Sylvie Joussaume and Daniela Jacob for participating to my defence committee. They raised many interesting points on the thesis that greatly improved the manuscript and opened additional paths for future work. I also thank Benjamin Sultan and Aglaé Jézéquel for their ideas and suggestions during the meetings of my PhD council, and Nicolas Vuichard (my PhD godfather) for our informal talks about the thesis.

I am indebted to my colleagues in the CoCliServ project for their invaluable collaboration and contributions. Thank you to Birgit Gerkenmeier and Insa Meinke for their enormous work and our many discussions on climate services. Thank you to Charlotte da Cunha for taking me into the social fieldwork of climate change, and for making me simplify and clarify my climate knowledge. Thank you to Ana Paula Rocha, Marianne Cardon and Caroline Amrom for your contributions and the friendly experiences shared on the Gulf of Morbihan. Thank you to Laurent Labeyrie for helping me to better understand the context of the Gulf, inviting me to an event with local stakeholders, and suggestions on

my manuscript. Thank you to Juan Baztan and Scott Bremer for their important contributions on Brest and Bergen. Thank you to Zhiwei Zhu for the coffee and informal discussions at CEARC. I also thank all the people in the different case studies of CoCliServ that took time and effort to work with us on adaptation.

I will greatly miss the company of many colleagues at LSCE, especially in the ESTIMR, CLIM and MERMAID teams. Thank you to Pascal Yiou, Soulivanh Thao and Flavio Pons for our scientific, statistical and technical discussions. Thank you to Pradeebane Vaithinada Ayar and Aglaé Jézéquel for suggestions on my study of atmospheric circulation regimes. Thank you to Philippe Naveau for courses in statistical analysis, and Florence Gerry for administrative help that permitted a smooth last year despite adversity. Thank you to Bastien François for the PhD brotherhood, and John Bazire for the thumb camaraderie. Thank you to Mathieu for having led this beautiful ESTIMR team that is like a family, and now to Davide Faranda for taking the relay baton and experimenting new activities.

Thank you to Robert Vautard, Didier Paillard and Sébastien Fromang for answering my questions on climate change attribution, Atlantic oceanic circulation and atmospheric jetstreams. Thank you to Bruno Lansard for letting me teach at the university. Thank you to Jean-Yves Peterschmitt for the food support that permitted computer coding and scientific writing after sunset. Thank you to Jerome Servonnat and Cédric Bacour for the experience of touch rugby and interlaboratory relay race. Thank you to Fanny Lhardy for supporting each other in the ultimate moments of thesis writing and defence preparation.

I am grateful for having participated in the laboratory council, this rich experience revealed unnoticed components of the inner workings of science. Thank you to Anne Cozic for the tremendous work of coordination and to Cyril Caram for the complicity in the many meetings and outside. Thank you to Alizée Chemison and Stella Bourdin for taking the relay baton and fighting for the collective of non-permanents in an evolving research environment.

This PhD experience was greatly enriched by the company and complicity of my "thesis brothers": Linh Nhat Luu, Vincent Labarre and Cyril Caram. We shared much of work and life during these few years: office space, discussion of results and articles, teaching experience at the university, thesis writing, defence preparation, post-thesis prospects, sports, food, movies and music. I will cherish those memories forever.

A special mention to many other colleagues (interns, PhD students, postdocs) who made this PhD more enjoyable around lunch, (coffee) breaks, and computer code. I trust that you will recognize yourselves (Meriem K., Clément D. and D., Yann C., Alizée C. and D., Fanny P., Mathis L., Robin N., Camille C., Germain B., etc.). Thank you also to my friends at the athletic club and first-aid association of Orsay, and calisthenics parks of Gif and Orsay.

Finally, this PhD thesis would probably not have seen the light without the continuous and unwavering support of my family since many years. Thank you dad and mom, for everything you have taught me in life (and still teach me).

Sorry to those I may have forgotten to include here. I also apologize to everyone for my stubbornness and too many questions. Can curiosity kill the cat?

Abstract

Climate change has various impacts on society, but future changes are uncertain and a wide gap remains between the scientific knowledge and societal action (mitigation, adaptation). The gap in climate adaptation was partly addressed by the recent growth of climate services, but their local usability is associated to many barriers. France is an example of lacking climate adaptation at territorial level, and this thesis focuses on the Gulf of Morbihan as a case study. My research aims first to identify the role of climate change in the territory, second to support the local development of adaptation planning, and third to explore future climate change through the angle of clustering approaches.

To identify the local role of climate change, I analyze the literature (grey and academic) and engage in field interviews with various stakeholders. Particular features of the territory emerge: the coastal-inland contrast (economy, demography), the socioeconomic life organized seasonally, and the dependence and conflict between agriculture and tourism. The local role of climate change is complex, impacting emblematic activities (oyster farming, salt production), overlapping with existing issues (socioeconomic imbalance, land-use conflict), and affecting agriculture negatively (warmer and drier summers) but tourism positively (longer summer weather). The local experiences are generally consistent with scientific knowledge (ongoing changes, link to climate change), although some elements are scarce in local perceptions (heatwaves).

To assist local adaptation, I participated to the experimentation of different foresight activities (scenario workshop, art-science exhibition, conference-debate) with local stakeholders, based on an assessment of climate services and on creative art-design tools (e.g. poker design cards). The main outcomes are two long-term scenarios, multiple short-term actions and several hinge points on which the scenarios depend. The two scenarios represent divergent visions of the territory: continued occupation of the coast despite increasing risks, or withdrawal from the coast and densification of urban areas inland. The scenarios depend on the issue development of urbanization and spatial planning, food and energy autonomy, and demographic balance. The theme of food and energy autonomy concentrates conflicting views between inhabitants, highlighting fears and desires about long-term territorial choices.

My investigation of the territory highlighted several climatic themes (e.g. seasonality of weather conditions) that are linked to atmospheric circulation, but future circulation changes are highly uncertain. To investigate the future seasonality of atmospheric circulation, I classify year-round patterns of geopotential height at 500 hPa (Z500) from a

reanalysis and several climate models. Despite their biases, climate models reproduce similar evolution of circulation seasonality as the reanalysis. During the last decades, winter conditions have decreased while summer conditions have increased, and these changes strengthen under future climate change. Yet circulation seasonality remains similar relatively to the increase in average Z500, and the same happens for surface temperatures associated to the circulation patterns. I additionally developed the perspective of a new approach to study the local evolution of weather seasonality, based on the classification of multiple variables (temperature, precipitation, windspeed).

In addition to the effects from future climate change, the Gulf of Morbihan will probably welcome new populations, and an active collective strategy of adaptation is required. Several routes have been featured in my research to address the local needs in climate adaptation, including perspectives inspired from existing climate services in other countries. The findings from this thesis highlight the physical and social dimensions of climate change.

Résumé

Le changement climatique a diverses conséquences sur la société, mais les changements futurs sont incertains et un gouffre subsiste entre les connaissances scientifiques et l'action sociétale (atténuation, adaptation). L'écart en adaptation a été comblé en partie par l'essor récent des services climatiques, mais leur utilisation à l'échelle locale est liée à de nombreux obstacles. La France est un exemple de manque d'adaptation climatique au niveau territorial, et cette thèse se concentre sur le Golfe du Morbihan comme cas d'étude. Ma recherche vise premièrement à identifier le rôle local du changement climatique, deuxièmement à soutenir le développement local de l'adaptation, et troisièmement à explorer le changement climatique futur avec des approches de classification (non-supervisée).

Pour identifier le rôle local du changement climatique, j'ai analysé la littérature (grise et académique) et engagé des entretiens de terrain avec différents acteurs. Le territoire est particulier : contraste littoral-intérieur (économie, démographie), vie socio-économique organisée saisonnièrement, dépendance et conflit entre agriculture et tourisme. Le rôle local du changement climatique est complexe, impactant des activités emblématiques (ostréiculture, production de sel), se superposant à des problématiques existantes (déséquilibre socio-économique, conflit d'usage des terres), et affectant négativement l'agriculture mais positivement le tourisme. Les expériences locales sont généralement conformes aux connaissances scientifiques, mais certains éléments sont rares dans les perceptions locales.

Pour soutenir l'adaptation locale, j'ai participé à l'expérimentation de différentes activités de prospective (atelier de scénario, exposition art-science, conférence-débat) avec des acteurs locaux, basées sur un inventaire des services climatiques et sur des outils créatifs d'art-design (par exemple, des cartes à jouer). Les principaux résultats sont deux scénarios à long terme et de multiples actions à court terme. Les deux scénarios représentent des visions divergentes du territoire : occupation continue de la côte malgré l'augmentation des risques côtiers, ou retrait de la côte et densification des zones urbaines à l'intérieur des terres. Les scénarios dépendent de l'urbanisation et de l'aménagement du territoire, de l'autonomie alimentaire et énergétique, et de l'équilibre démographique. Le thème de l'autonomie alimentaire et énergétique concentre les points de vue contradictoires entre les habitants.

Plusieurs thèmes climatiques locaux sont liés à la circulation atmosphérique, mais ses changements futurs sont très incertains. Pour étudier la saisonnalité future de la circulation, je classifie des champs de hauteur géopotentielle durant toute l'année, à partir d'une réanalyse et plusieurs modèles climatiques. Les modèles climatiques, malgré

leurs biais, reproduisent une évolution de la saisonnalité de la circulation qui est similaire à la réanalyse. Au cours des dernières décennies, les conditions hivernales ont diminué tandis que les conditions estivales ont augmenté, et ces changements se renforcent dans le futur. Néanmoins, la saisonnalité de la circulation reste similaire par rapport à l'augmentation moyenne du géopotential. J'ai par ailleurs développé une perspective de nouvelle approche pour étudier l'évolution locale de la saisonnalité météorologique, basée sur la classification de multiples variables (température, précipitations, vitesse du vent).

En plus des effets du changement climatique à venir, le Golfe du Morbihan va probablement accueillir de nouvelles populations, et une stratégie collective active d'adaptation est nécessaire. Plusieurs pistes ont été évoquées dans mes recherches pour répondre aux besoins locaux en matière d'adaptation climatique, notamment des perspectives inspirées des services climatiques existants dans d'autres pays. Les résultats de cette thèse mettent en évidence les dimensions physiques et sociales du changement climatique.

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List of Abbreviations

ADEME	Agence de l'environnement et de la maîtrise de l'énergie
AMO	Atlantic Multidecadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
BRGM	Bureau de recherches géologiques et minières
CAUE	Conseil d'Architecture, d'Urbanisme et de l'Environnement
CCKP	Climate Change Knowledge Portal
CCVA	Conseil communautaire de Vannes Agglomération
CDM	Conseil départemental du Morbihan
CEARC	Cultures · Environnements · Arctique · Représentations · Climat
CKH	Climate Knowledge Hub
CMIP	Coupled Model Intercomparison Project
CSEB	Conseil Scientifique de Bretagne
DDTM	Direction départementale des Territoires et de la Mer
DREAL	Direction régionale de l'environnement, de l'aménagement et du logement
EDSS	Environmental Decision Support System
EEA	European Environment Agency
ENSO	El Niño Southern Oscillation
EU	European Union
GCM	Global Circulation Model

GFCS	Global Framework for Climate Services
GHG	Greenhouse gas
GMVA	Golfe du Morbihan - Vannes Agglomération
IA	Indicator Assessment
INSEE	Institut national de la statistique et des études économiques
IPCC	Intergovernmental Panel on Climate Change
IPSL	Institut Pierre Simon Laplace
KNMI	Royal Netherlands Meteorological Institute
LSCE	Laboratoire des Sciences du Climat et de l'Environnement
MNHN	Muséum National d'Histoire Naturelle
NAO	North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
ODEM	Observatoire Départemental de l'Environnement du Morbihan
OEB	Observatoire de l'environnement en Bretagne
PCAET	Plan Climat Air Energie Territorial
PNR	Parc Naturel Régional
RCP	Representative Concentration Pathway
RISA	Regional Integrated Science and Assessment
SSP	Shared Socioeconomic Pathway
SST	Sea surface temperature
SMVM	Schéma de Mise en Valeur de la Mer
UVSQ	Université de Versailles Saint-Quentin-en-Yvelines
WMO	World Meteorological Organization
WR	Weather regime

“Dr. Ian Malcolm: The lack of humility before nature that’s being displayed here... staggers me.

- Donald Gennaro: Thank you, Dr. Malcolm, but I think things are a little bit different than you and I had feared.

- Dr. Ian Malcolm: Yeah, I know. They’re a lot worse.”

Jurassic Park

Introduction

This thesis addresses various themes and topics, but will focus on climate change, climate adaptation and climate services. These three themes are closely linked, since society needs to adapt to the various impacts from climate change, and climate services support this adaptation by facilitating the use of scientific knowledge by societal decision-makers. The research presented in my thesis contributes to these three fields, mainly through:

- an empirical study of the localization of climate science in a territory
- the experimentation of participative processes to develop local climate adaptation
- the development of clustering approaches to study climate change

The Introduction will first present the climate system, its complexity and natural variability through time and space. Second, we will turn to the human influence on this system and the resulting impacts. Third, I will cover the nature and purpose of climate services, and the main motivations for the present research.

Complexity and variability of the climate system

Climate is the long-term pattern of weather conditions in any particular place. Understanding how the climate can change is important to prepare for the future, since nearly all activities in society and in the environment are affected by weather conditions in some way. The climate system is complex but scientists have found various methods to understand its inner workings (components, variability, causes and effects). For instance, we now know that climate varies in multiple scales of space and time.

Studying a complex system

Earth’s climate system is composed of six interacting components: atmosphere (air), hydrosphere (water), cryosphere (ice), land surface (ground), biosphere (life) and geosphere (rocks and inner Earth). These components exchange matter and energy through various fluxes (e.g. cycles of water and carbon; Cubasch et al. (2013)). Solar radiation brings to the system most of the energy, which is then redistributed through the atmospheric and oceanic circulations.

The atmospheric and oceanic circulations are composed of various cells (Figure I.1) that overall transport (vertically and horizontally) the solar energy excess from the tropics to the poles. The atmospheric greenhouse effect increases the total energy of the climate system, providing sufficiently warm conditions for life.

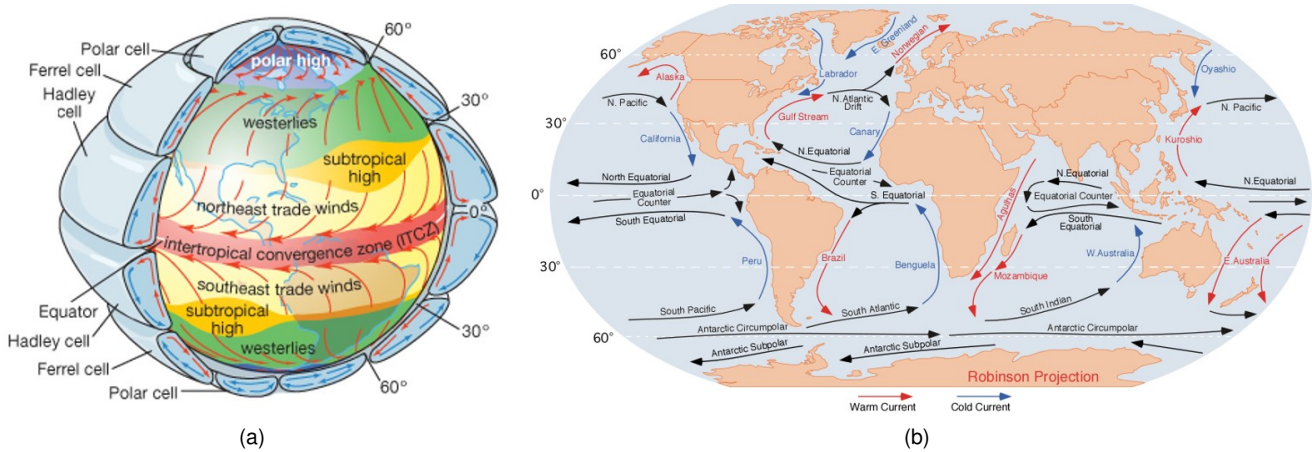


Figure I.1: Current global patterns of atmospheric circulation (a) and surface oceanic circulation (b). Adapted respectively from Encyclopaedia Britannica (2010) and Pidwirny (2006). Note that the vertical atmosphere is not to scale in (a) and that the oceanic circulation also has important subsurface currents (not shown here).

The climate system is studied through various sources of data: paleoclimate proxies (e.g. ice cores, marine sediments), observational measurements (e.g. weather stations, satellites), climate simulations (past, future), and atmospheric reanalyses. Paleoclimate records serve to reconstruct climate evolution before the instrumental period, and to evaluate climate models. The current observational networks monitor and analyze weather and climate continuously and worldwide (although some regions lack data). Measurements come from various instruments (WMO, 2015): atmospheric (radiosondes, planes), terrestrial (e.g. weather stations), oceanic (argo floats, cruise campaigns), and space-based (satellites).

Climate simulations are used to test hypotheses and to investigate past and future climate variability in virtual Earths. Climate models share many similarities with weather models, but the latter are more precise on smaller spatio-temporal scales (processes) and don't include climatic components acting on longer timescales (e.g. ice-sheets). Atmospheric reanalyses are hybrid tools based on both simulation and observation. They are model simulations (weather) that assimilate observations (incomplete coverage in space and time) to produce continuous maps of variables (e.g. temperature, rainfall, wind).

The variability of the climate system is studied through the analysis (e.g. statistical) of these different data sources (paleo, observations, simulations, reanalyses). For instance, the analysis of warm periods in the past can provide a glimpse of our future under global warming. The main way to anticipate future climate change is to "project" scenarios of GHG emissions onto the climate system and see how it evolves. A way to understand the separation between human influence and natural variability is to study how human activities affect the processes inside the climate system. Doing so requires first to understand the natural state and variability of the system.

Natural variability through time and space

For practical purposes, climate is often defined as the mean of the weather conditions in a given location over a few decades, typically about 30 years (a human generation). However, the climate system undergoes ample fluctuations through time and space. These variations range in time (Figure I.2) from weather to geological, and in space (Figure I.3) from turbulence to global change (Mitchell Jr, 1976; Nese, 1996; Stocker, 2014; Anna et al., 2020). Short-term climate variability (day to decades) is dominated by the seasons (annual orbital cycle), diurnal cycle (day and night), variability modes (large-scale oscillations), and sometimes volcanic eruptions (Barnston and Livezey, 1987; Wallace et al., 1993; Robock, 2000; Ghil, 2002; Christensen et al., 2013; Ahrens and Henson, 2021; Sjolte et al., 2021).

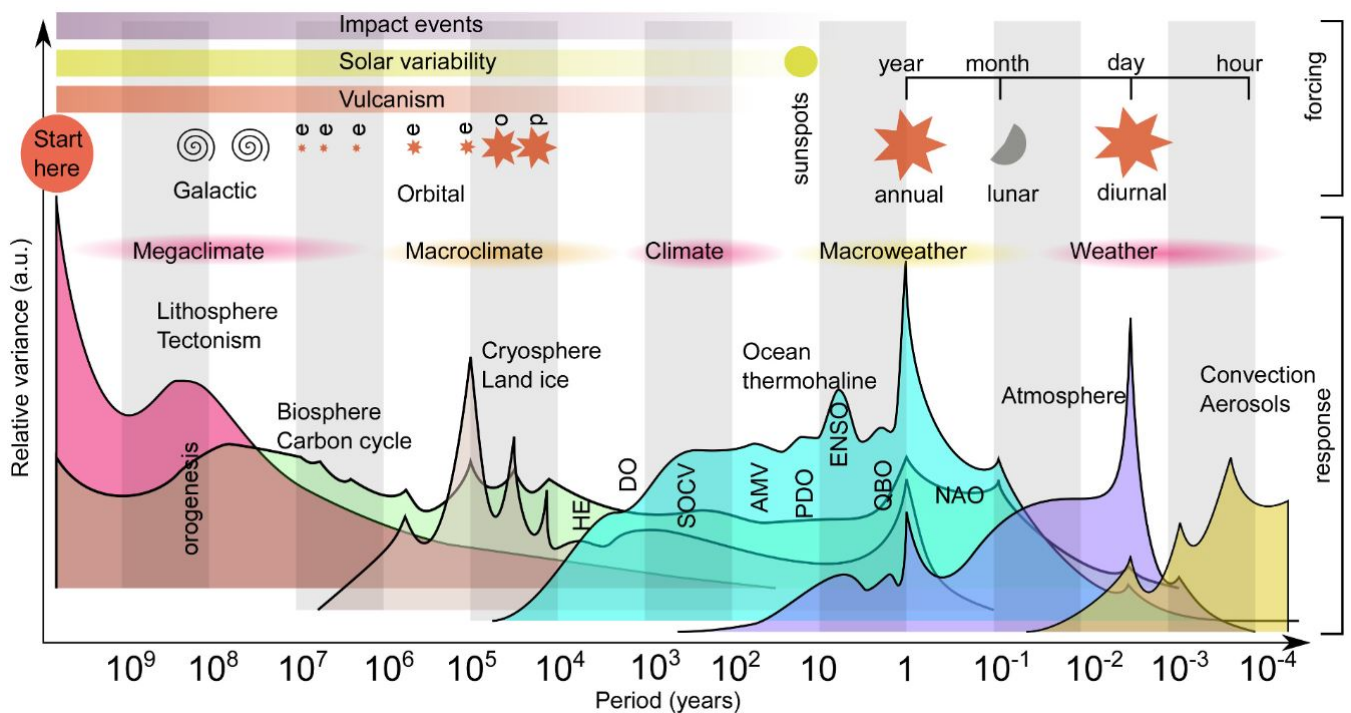


Figure I.2: Conceptual landscape of the typical cycles in the climate variability of the Earth (Anna et al., 2020).

Our daily weather is mostly made of the passage from weather fronts, resulting from the interaction of air masses with different temperature and humidity. Weather fronts evolve in close association with atmospheric cyclones (centers of low pressure), anticyclones (centers of high pressures) and jetstreams (strong air currents in altitude; Figure I.4; Ackerman and Knox (2012); Woollings (2019); Ahrens and Henson (2021)). These dynamical structures are part of the atmospheric circulation, which interacts largely with the oceanic circulation (Cubasch et al., 2013). Large-scale fluctuations in both atmosphere and oceans are associated to climate variability modes, which play a key role on regional climate (e.g. Europe) on a scale of months to decades.

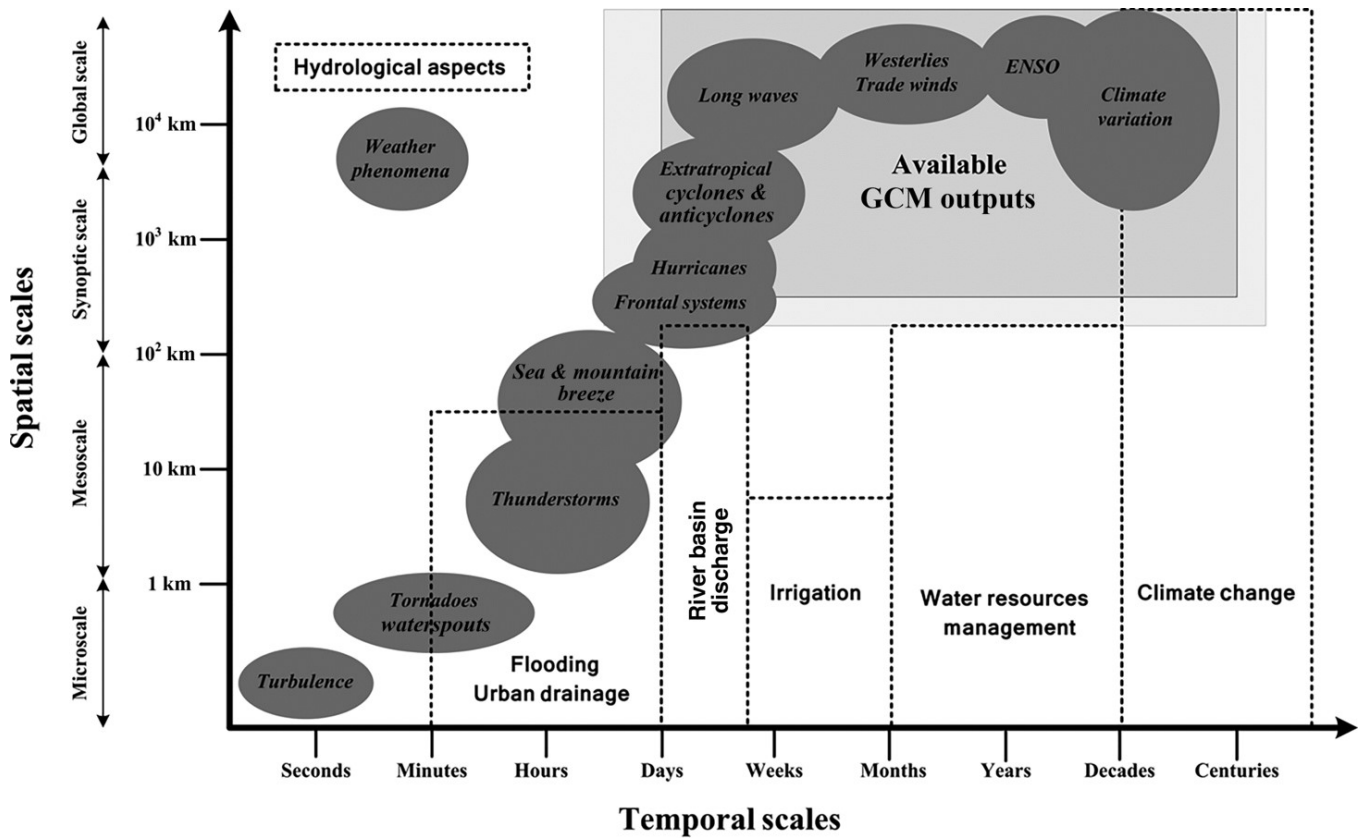


Figure I.3: Spatial and temporal scales of weather phenomena (Tavakolifar et al., 2017).

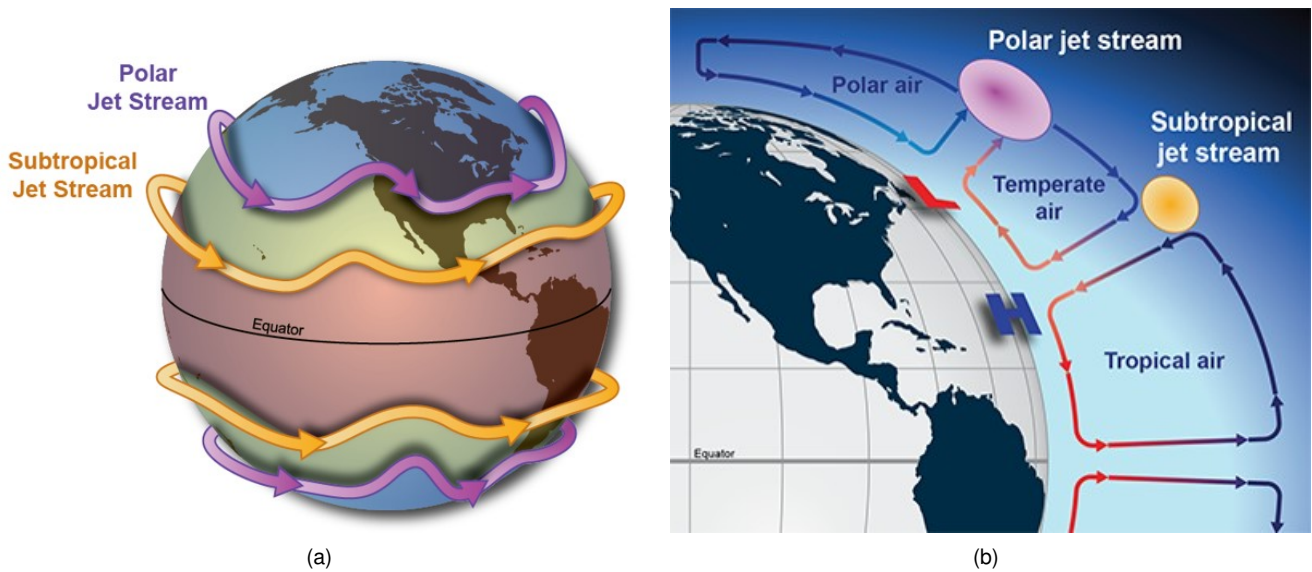


Figure I.4: Conceptual overview (zonal, meridional) of atmospheric jetstreams (National Weather Service, 2021). On the right, the red "L" corresponds to a cyclone, and the blue "H" to an anticyclone.

Examples of climate variability modes: ENSO, NAO and AMO

The largest climate variability mode is El Niño Southern Oscillation (ENSO). ENSO is an interannual phenomenon of ocean-atmosphere coupling over the tropical Pacific, influencing global mean temperature and affecting severe weather worldwide (Christensen et al., 2013). The positive (negative) phase of ENSO is El Niño (La Niña), corresponding to warmer (cooler) sea surface temperatures (SSTs) in the equatorial eastern Pacific, associated to weaker (stronger) easterly trade winds and weaker (stronger) oceanic upwelling along the coast of Peru (Wang et al., 2017). These ENSO phases induce weather anomalies in many regions of the world (Figure I.5) through atmospheric teleconnections (Sun et al., 2015; Li et al., 2020; Luo and Lau, 2020; Taschetto et al., 2020).

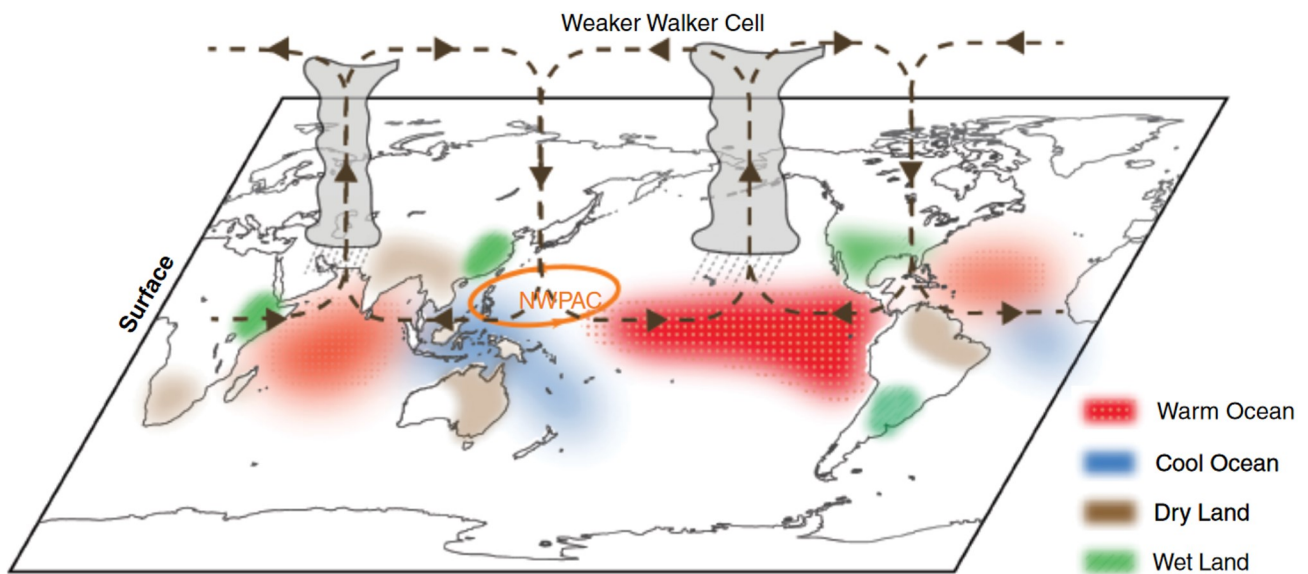


Figure I.5: Schematic depiction of regional covariations during El Niño (adapted from Taschetto et al. (2020)). Sea surface temperature anomalies (red: warm, blue: cold), Walker Circulation anomalies (brown dashed arrows), Northwest Pacific Anticyclone (orange contour), and precipitation anomalies (brown: dry, green: wet).

In the North Atlantic, climate variability is more directly influenced by the North Atlantic Oscillation and by the Atlantic Multidecadal Oscillation (Christensen et al., 2013). The North Atlantic Oscillation (NAO) describes the main regional variations in atmospheric circulation, with important effects on European weather. For instance, the 2019/2020 winter was especially warm in Europe due to a strongly positive NAO (WMO, 2021). A common way to quantify the NAO is to measure the strength of the westerly atmospheric flow (pressure difference, Figure I.6) between Iceland (semi-permanent cyclone) and the Azores (semi-permanent anticyclone; Hurrell and Deser (2010); Christensen et al. (2013); Norel et al. (2021)).

The positive phase (NAO+) corresponds to a higher pressure difference than average (i.e. stronger Westerly flow), and the negative phase (NAO-) to the opposite. NAO+ generally corresponds to a northward shift of the storm-tracks, leading to a more maritime influence over northwest Europe (e.g. warmer and wetter in winter) and less over southern Europe (e.g. cooler and drier in winter; Hanna and Cropper (2017)). The storm-tracks usually shift southward during NAO-, with opposite effects on Europe. The NAO phase can also be affected by ENSO (Bengtsson et al., 1996;

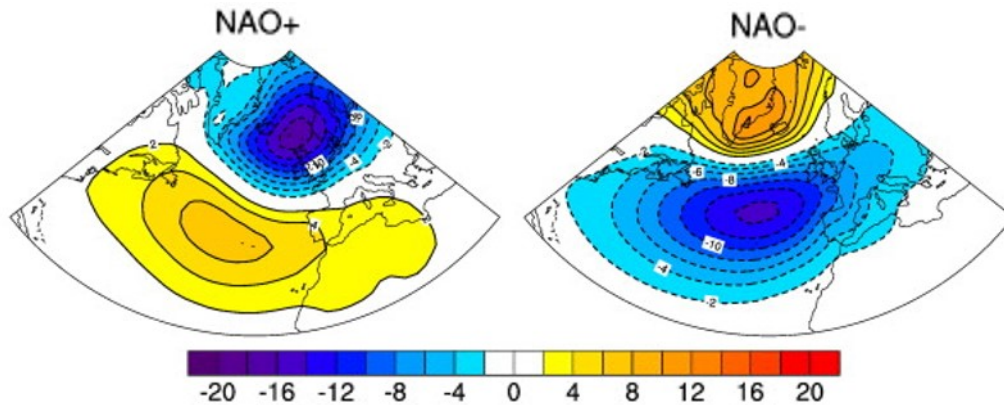


Figure I.6: North Atlantic Oscillation defined through the clustering of sealevel pressure (hPa) in winter over 1950-2006 (adapted from Hurrell and Deser (2010)). The NAO anomalies of sealevel pressure correspond to the difference with the winter mean.

Roeckner et al., 1996; Martineu et al., 1999; Cassou and Terray, 2001; WMO, 2021).

The other main variability mode of the North Atlantic is the Atlantic Multidecadal Oscillation (AMO). The AMO is a fluctuation of sea surface temperatures (SSTs) over several decades, with a phase (positive, negative) lasting typically about three to four decades (Christensen et al., 2013; Alexander et al., 2014; Drinkwater et al., 2014). The positive AMO phase (AMO+) corresponds to warmer SSTs (Fig. I.7) and reduced sea-ice cover in the North Atlantic, and the negative phase (AMO-) to colder SSTs and increased sea-ice cover (Deser et al., 2010; Alexander et al., 2014; Drinkwater et al., 2014).

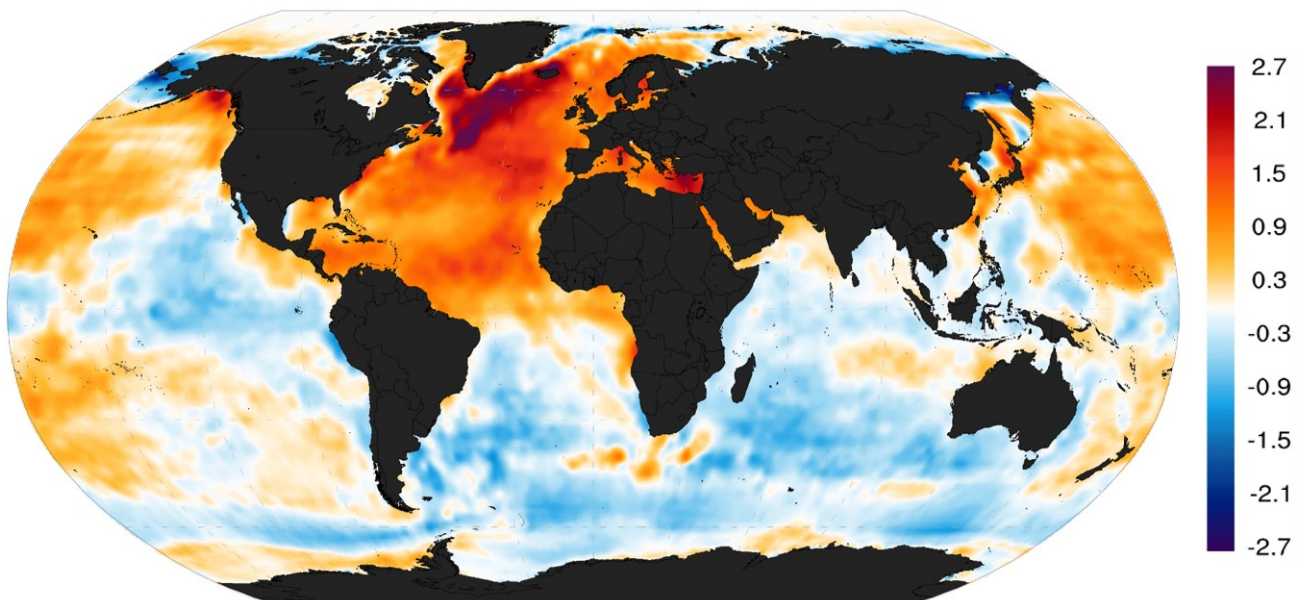


Figure I.7: Spatial pattern of the Atlantic Multidecadal Oscillation in the warm phase (from Wikimedia (2014), similar to Deser et al. (2010)). Map obtained as the regression pattern of monthly SSTs on the AMO index over 1870-2013 (observation dataset from HadISST; Met Office Hadley Centre (2021)). The AMO index corresponds to the average monthly SST anomalies over the North Atlantic minus the global mean monthly SST anomaly. The regression pattern is unitless ($^{\circ}\text{C}/^{\circ}\text{C}$) since it represents SST anomalies per standard deviation of the AMO index.

The AMO is linked to the variability of the oceanic thermohaline circulation, and influences the multidecadal variability of European climate (Christensen et al., 2013; Yamamoto and Palter, 2016; Qasmi et al., 2020). Through their links to changes in the North Atlantic atmospheric circulation, these climate variability modes (AMO, NAO) also influence European weather extremes (more on this in Chapters 1 and 6). Beside the large natural variability of the climate system in space and time, human activities exert various influences.

Human-caused climate change: causes, consequences, mitigation and adaptation

The growing environmental impact of humankind has reached every component of the climate system. Human-caused climate change now affects weather variability and extremes in many regions, with increasing impacts on human and natural systems. Although many uncertainties and unknowns remain, future climate change would be catastrophic if unmitigated and not adapted to. However, current efforts of mitigation and adaptation are insufficient.

From local influence to planetary force

People have believed that human activity might alter a local climate (e.g. through deforestation and farming) at least since antiquity, but not to affect the planet overall (Neumann, 1985; American Institute of Physics, 2021). During the nineteenth century for instance, the conversion of forests to croplands in North America brought obvious change (e.g. warmer and drier conditions) within a human lifetime (Fleming et al., 1990; American Institute of Physics, 2021). Also during the nineteenth century, the compilation of observational data led national weather agencies to discover large natural variations, turning scientific opinion against belief in a current human influence on global climate (Fleming et al., 1990; American Institute of Physics, 2021).

At about the same time however, scientists began to hypothesize about a potential warming resulting from human activities (Arrhenius, 1896; Uppenbrink, 1996). The growing understanding of the greenhouse effect, along with the development of human activities (e.g. burning of coal), gradually led to the suggestion that modern civilization might cause global warming, sometime far in the future (Neelin, 2010; American Institute of Physics, 2021). The proof arrived during the second half of the twentieth century, with the combined unfolding of human-caused global climate change, and progress of meteorology and climatology (Lynch, 2008; Edwards, 2011; Cubasch et al., 2013; Haupt et al., 2018; Molina and Abadal, 2021).

The global environmental footprint of humans increased abruptly from the 1950s onwards (Figure I.8), in what is termed the "Great Acceleration", taking us into a new geological era: the Anthropocene (i.e. the era of man; Steffen et al. (2015); McNeill (2016); DellaSala et al. (2018)). Human activities now affect every component of the climate system, disrupting the natural cycles of carbon, water and energy (Bindoff et al., 2013). The main cause

SOCIO-ECONOMIC TRENDS

EARTH SYSTEM TRENDS

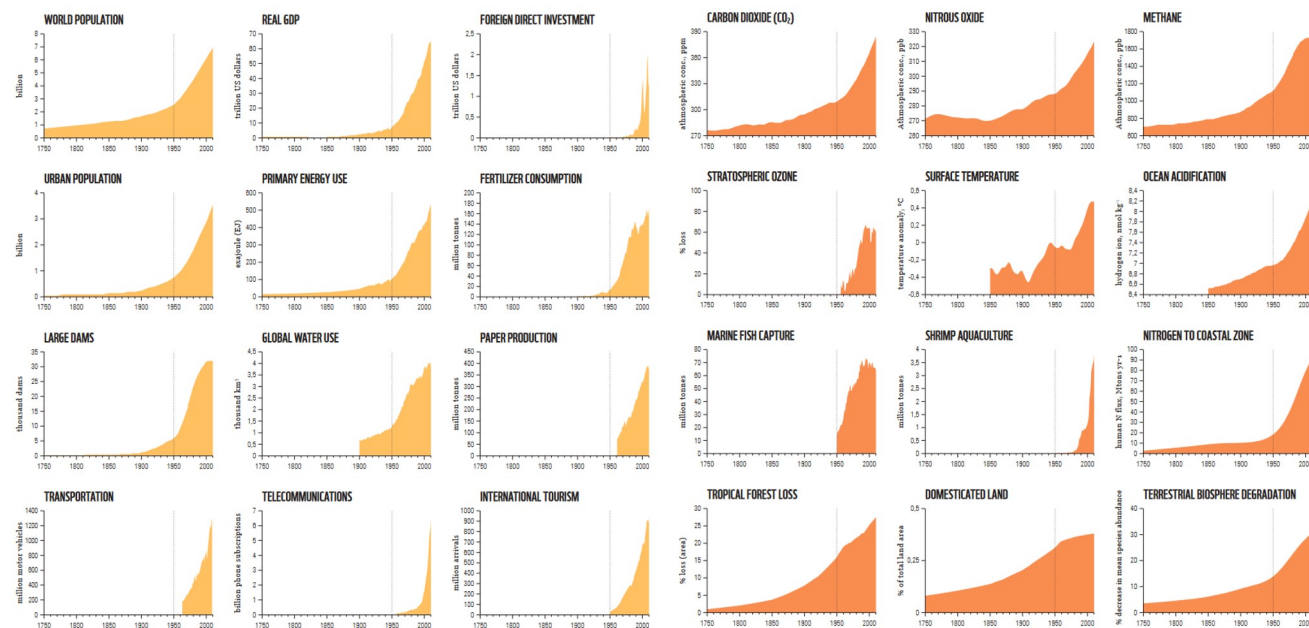


Figure I.8: The Great Acceleration: exponential growth of human activities since the 1950s (left), and interference with the Earth system (right; adapted from Steffen et al. (2015)).

of anthropogenic climate change is the emission of GHGs (e.g. CO₂, CH₄, N₂O) from human activities (fossil fuel burning, agriculture, etc.) to the atmosphere (Stocker et al., 2013).

This perturbation (CO₂, CH₄, N₂O) is partly absorbed by natural sinks, but most of it stays in the atmosphere and increases the greenhouse effect (Stocker et al., 2013; Friedlingstein et al., 2020; Saunio et al., 2020; Tian et al., 2020). The human influence on the energy balance of the Earth also includes negative factors (e.g. aerosols have an overall cooling effect), but the net result is additional energy in the system (Stocker et al., 2013; Ramaswamy et al., 2019). Although it is simpler to think of the human influence in terms of global scale, the individual and historical responsibilities vary considerably between human generations, countries, and social classes (Friman and Strandberg, 2014; Rocha et al., 2015; Macey, 2018; Singer, 2018; Bou-Habib, 2019; Olhoff and Christensen, 2020).

Impact on the mean state, weather extremes, society and environment

The main effect of the additional energy is to put the climate system out of equilibrium, and to warm the atmosphere (also slightly expanding it vertically), land and oceans (Stocker et al., 2013; Ramaswamy et al., 2019; Loeb et al., 2021; Gillett et al., 2021). This atmospheric warming accelerates the global water cycle (more evaporation and precipitation), which is also perturbed by other human activities (irrigation, dams, groundwater extraction; Boucher et al. (2004); Wada et al. (2011); Hegerl et al. (2015); Allan et al. (2020)).

In the hydrosphere, warmer waters can hold less oxygen, and the increased surface absorption of atmospheric CO₂ (anthropogenic) leads to water acidification (Gattuso and Hansson, 2011; Stocker, 2014; O'Reilly et al., 2015;

Levin, 2018; Oshlies et al., 2018; Limburg et al., 2020; Jane et al., 2021). In the oceans, sealevel rise is accelerating, driven by the melting of the cryosphere in addition to the thermal expansion of water and to groundwater extraction (Oppenheimer et al., 2019; Frederikse et al., 2020; Hugonnet et al., 2021).

More broadly, anthropogenic climate change is modifying weather patterns and extremes in many regions, with deep consequences for society and the environment (Stocker, 2014; Hoegh-Guldberg et al., 2018; Jia et al., 2019; Pörtner et al., 2019). Changes in the mean climate state and in the patterns of variability can have strong implications for weather extremes. For instance, a small increase in the average temperature or in the temperature variability can be associated to a multiplication of hot extremes (Figure I.9).

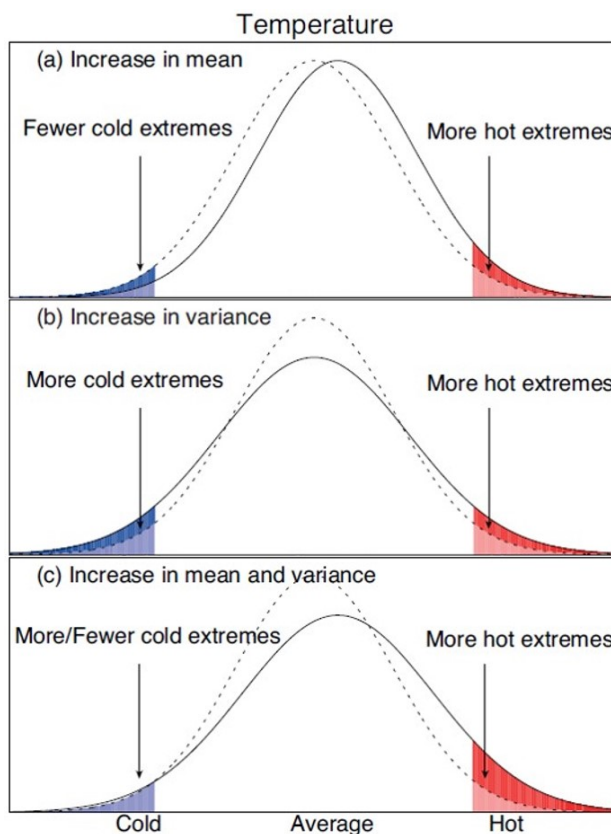


Figure I.9: Statistical relationship between weather and change in climate (Zhang and Zwiers, 2013).

A main consequence of anthropogenic climate change is a general increase (at the global scale) in the frequency, and or intensity of many extreme events (Figure I.10), sometimes in addition to changes in other features (e.g. spatial extent, duration, co-occurrence with other extremes):

- heatwaves (Fischer and Knutti, 2015; Perkins-Kirkpatrick and Gibson, 2017; Oliver et al., 2018; Perkins-Kirkpatrick and Lewis, 2020; Woolway et al., 2021)
- droughts (Dai et al., 2004; Dai, 2011, 2013; Trenberth et al., 2014; Mukherjee et al., 2018)
- wildfires (Huang et al., 2015; Jolly et al., 2015; Duane et al., 2021)

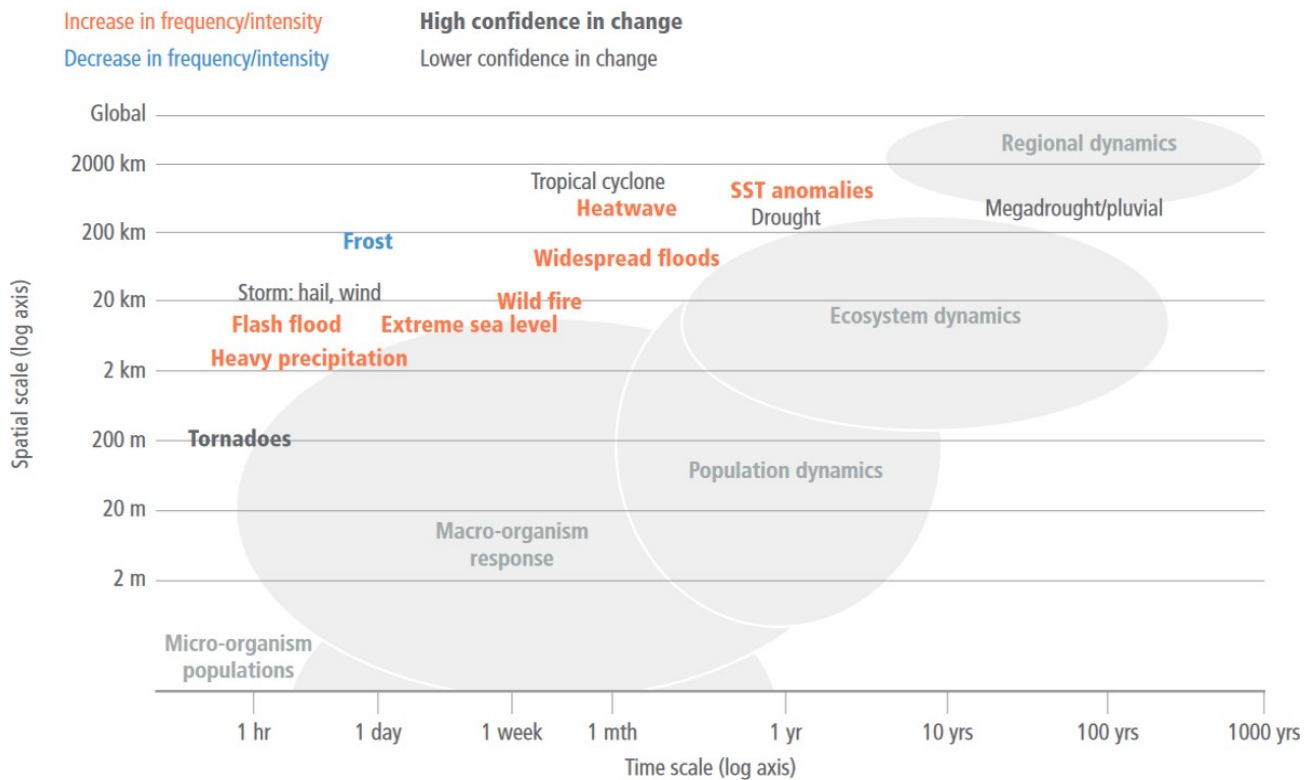


Figure I.10: Effect of climate change on extreme weather events at different spatio-temporal scales (Jia et al., 2019).

- heavy rainfall (Min et al., 2011; Trenberth, 2011; Fischer and Knutti, 2015; Donat et al., 2016; Fischer and Knutti, 2016; Myhre et al., 2019; Fowler et al., 2021)
- flooding (Kundzewicz et al., 2014; Eccles et al., 2019)
- storm surges (Rahmstorf, 2017; Resio and Irish, 2018; Collins et al., 2019; Ji and Li, 2020)
- compound events (Zscheischler and Seneviratne, 2017; Vogel et al., 2019; AghaKouchak et al., 2020; Zscheischler et al., 2020; Wu et al., 2021)

In addition to the raw effects from changes in extreme events, climate change has many indirect consequences on society:

- health risks (McMichael et al., 2012; Kim et al., 2014; Mora et al., 2017; Rossiello and Szema, 2019; Lemery et al., 2021; Vicedo-Cabrera et al., 2021; Zhang et al., 2021)
- the distribution of diseases (Wu et al., 2016; Liang and Gong, 2017; Caminade et al., 2019)
- freshwater availability (Firth and Fisher, 2012; Eekhout et al., 2018; Rodell et al., 2018)
- food security (Dwivedi et al., 2013; Misra, 2014; Myers et al., 2017; Ray et al., 2019)

- energy production (Mideksa and Kallbekken, 2010; Pryor and Barthelmie, 2010; Schaeffer et al., 2012; Khan et al., 2013; Gernaat et al., 2021)
- transportation (Koetse and Rietveld, 2009; Love et al., 2010; Macarthur et al., 2012; Moretti and Loprencipe, 2018; Wang et al., 2020)
- infrastructure (Wilbanks et al., 2012; Shiklomanov and Streletskiy, 2013; Vardon, 2015)
- the overall economy (Ebele and Emodi, 2016; Batten, 2018; Kompas et al., 2018; DeFries et al., 2019; Andersson et al., 2020)
- social conflicts (Swain and Öjendal, 2018; Froese and Schilling, 2019; Krieger and Panke, 2020)
- human migrations (Faist and Schade, 2013; Burrows and Kinney, 2016; Berchin et al., 2017; Internal Displacement Monitoring Center, 2021; Balsari et al., 2020)

Similarly to the unequal social responsibility in the causes of climate change, the social distribution of the consequences (and of resources to adapt) is also highly unequal between countries (e.g. UK and Bangladesh) and social classes (Ciplet et al., 2015; Islam and Winkel, 2017; Singer, 2018). Beyond society, natural ecosystems are also deeply impacted by climate change, for instance through the shifts of climate zones (towards the poles and higher elevation) and in phenology (i.e. timing of biological cycles; Jia et al. (2019); Piao et al. (2019); Menzel et al. (2020)).

Projections of future change suggest that the situation (mean change, extremes, societal and environmental effects) will mostly continue in the same direction under further warming (Stocker, 2014; Hoegh-Guldberg et al., 2018; Zscheischler et al., 2018; Arnell et al., 2019; Jia et al., 2019; Collins et al., 2019; Lynas, 2020; Wallace-Wells, 2020). Despite these general insights, many uncertainties and unknowns remain about future regional climate changes, hinting at possible "climate surprises".

Uncertainties, feedbacks and tipping points

Although the progress of climate change attribution has allowed to quantify an human influence in many aspects of the climate system (Bindoff et al., 2013; National Academies of Sciences, Engineering, and Medicine, 2016; Otto, 2017; Pörtner et al., 2019; Jia et al., 2019), some recent and future changes remain attached to wide uncertainty, such as regional changes in atmospheric circulation (Woollings et al., 2018; Zappa, 2019; Stendel et al., 2021). The uncertainty in projections of future climate change can generally be derived from three sources (Figure I.11): societal scenario of GHG emissions, model bias and response to a change in climate forcing (e.g. increased atmospheric CO₂), and natural variability of the climate system.

An example of the high uncertainty and high impact of natural variability is the pause in global warming observed during the 2000s, which has been linked to changes in oceanic heat uptake due to multidecadal variability modes

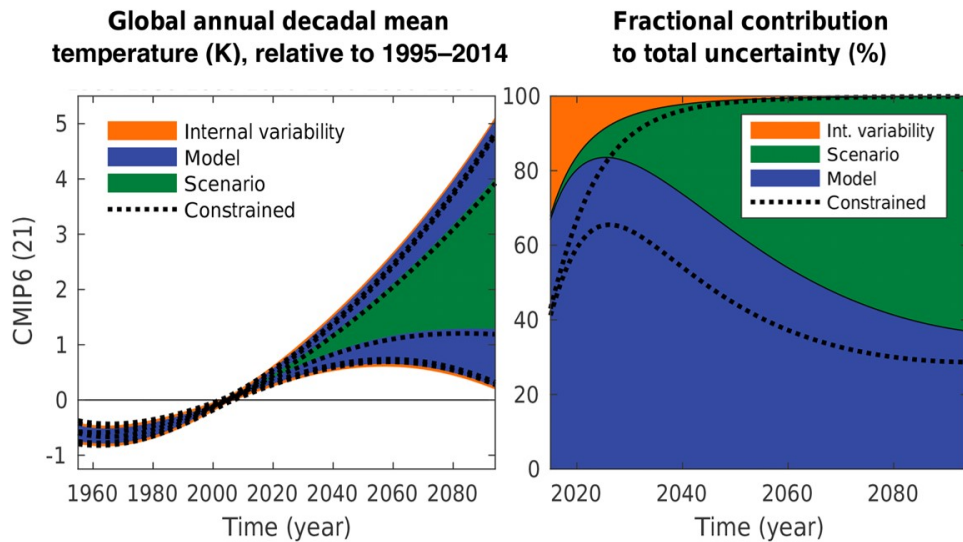


Figure I.11: Sources of uncertainty in mean projection of global mean temperature in CMIP6 models (adapted from Lehner et al. (2020)). Projections constrained by observations are indicated by the dotted lines.

(Medhaug et al., 2017; Xie and Kosaka, 2017; Xu et al., 2020). More concerning is the presence of tipping points in the climate system (indicated by paleoclimate evidence), which are key elements (e.g. the Arctic) that can undergo critical transitions when pushed beyond a given threshold (Lenton, 2021; Ritchie et al., 2021). Once pushed over the edge, their role in the system can change drastically and potentially tip other elements in a domino-like manner (Dekker et al., 2018; Klose et al., 2019; Krönke et al., 2020). Several climate tipping points have been identified (Figure I.12), which could transition under higher levels of global warming (Steffen et al., 2018; Lenton et al., 2019; Wang and Hausfather, 2020).

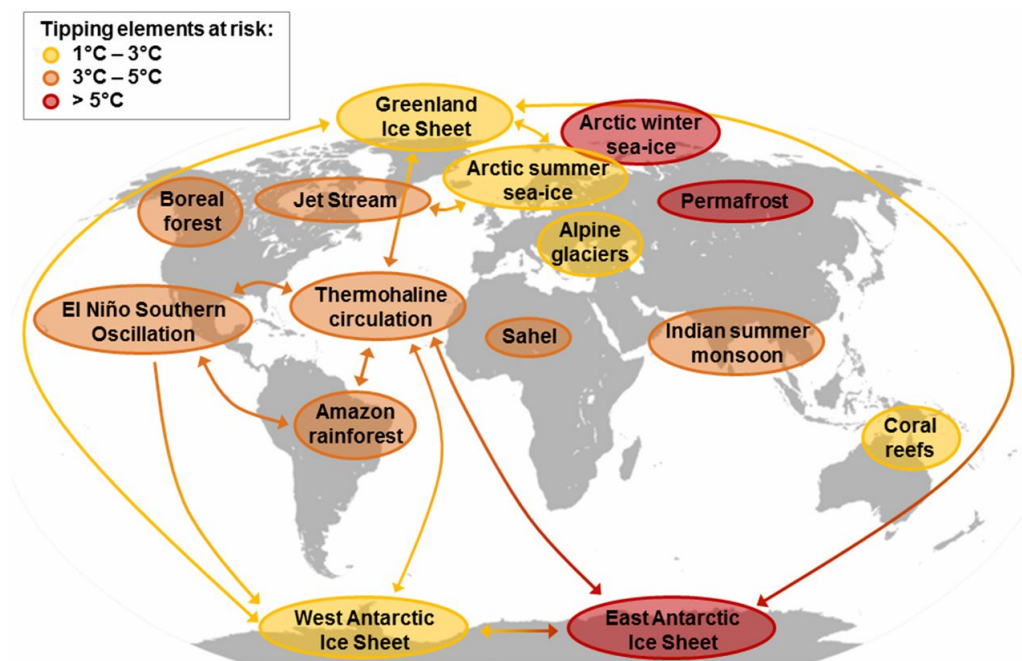


Figure I.12: Global map of climate tipping points and potential cascades (adapted from Steffen et al. (2018)).

The tipping of some elements would warm the Earth further, regardless of human actions. For instance, the long-term melting of ice in the Arctic (e.g. sea-ice and Greenland ice-sheet) would lead to lower albedo and higher surface solar absorption, further increasing "Arctic amplification" (i.e. the fact that the Arctic warms much faster than the global average) in a "positive feedback". A warmer surface would lead to higher atmospheric pressure and more water evaporation (ice-free oceanic surface), with strong repercussions on the water cycle, energy cycle, and circulation (atmospheric, oceanic).

Between the complexity of the climate system and the risks implied by feedbacks and tipping points, the safest course would be to limit global warming (Buchanan, 2020). Similarly, impact cascades may become more likely under further climate change, overwhelming the capacity of society to respond due to the recurrence of climate extremes and associated social crises (Lawrence et al., 2020; Lynas, 2020; Wallace-Wells, 2020). Therefore, reducing both the causes (mitigation) and the consequences (adaptation) of climate change appears necessary.

Insufficient mitigation and adaptation

Despite a brief dip in CO₂ emissions due to the Covid-19 crisis, the world is still heading (based on current policies) for about two additional degrees of global warming by the end of the century (Olhoff and Christensen, 2020). In the three decades since the first report from the Intergovernmental Panel on Climate Change (IPCC), global GHG emissions (including land-use) have increased by about 50 % (from about 38 to 59 Gt of CO₂ equivalent), following approximately the RCP8.5 scenario (Knutti, 2019; Olhoff and Christensen, 2020; Schwalm et al., 2020). The degree to which global GHG emissions will cause further climate change depends largely on the climate sensitivity of the Earth (i.e. response of the system to additional GHGs; Stocker (2014)).

This sensitivity of the Earth system appears strongly related to the behaviour of clouds (Zelinka et al., 2017; Frey and Kay, 2018; Zhu et al., 2019), and the increased climate sensitivity in the new generation of state-of-the-art climate models (CMIP6) has been linked to the different representation of clouds and aerosols, by comparison to the last (CMIP5) generation of models (Meehl et al., 2020; Schlund et al., 2020; Zelinka et al., 2020). However, the range of climate sensitivity remains highly debated in paleoclimatology and climatology (Goodwin, 2018; Nijssen et al., 2019; Sherwood et al., 2020; Zhu et al., 2020; Cesana and Del Genio, 2021)). Although more efforts are needed to decrease GHG emissions, the inertia of the climate system implies that historical emissions will trigger further climate change in the next decades, even if we stopped emitting today (Matthews and Weaver, 2010; Masson-Delmotte et al., 2018a).

Recent experiments have nonetheless suggested that the climate system inertia could be lower than previously thought, with a stabilization of global temperature a few decades after anthropogenic CO₂ emissions would virtually stop (MacDougall et al., 2020), and a recovery of the AMOC (Atlantic branch of the thermohaline circulation) over a century after the global temperature would stabilize (Sigmond et al., 2020). Anyhow, adaptation to current and future

climate change is needed, in combination with mitigation. However, many of the adaptation responses implemented to decrease the impacts from climate change are based on experienced disasters or on current risk (Daniels and Endfield, 2009; Measham et al., 2011; Oppenheimer et al., 2019).

This situation can result in maladaptation, for instance people feeling safe behind a coastal defence, which was not built high enough for the next storm surge. In France for instance, climate change adaptation is lacking at the territorial level, to prepare for current and future risks (Sénat, 2019; Simonet and Leseur, 2019). Understanding future changes is important for adaptation, but mitigation is also needed since long-term adaptation would become unfeasible under unmitigated climate change. New tools have emerged during the last decade to facilitate adaptation, by making the scientific knowledge of climate change more accessible. And usable?

The role of climate services in climate change adaptation: progress and barriers

The gap has widened between scientific knowledge and societal action about climate change (mitigation, adaptation). How to better link science and action? The field of climate services has emerged in recent decades to address the gap in climate change adaptation. Alongside the progress of climate services, their limited usability has come to light as a key issue. Nevertheless, approaches including social science can address this issue by better connecting the development of climate services (producers) with its use (decision-makers).

The journey from weather services to climate services

Weather services have existed since the end of the 19th century, measuring the evolution of weather conditions and forecasting short-term changes so that society can prepare in advance (Teague and Gallicchio, 2017; Anduaga, 2019). By contrast with weather services, climate services aim to facilitate the preparation of society to climate variability and change, on timescales longer than a few weeks (Figure I.13).

Historically, climate services appeared during the 1970s-1980s in the form of climate data and information products, provided predominantly by public climate research institutes (Changnon et al., 1990; Vaughan and Dessai, 2014). The initial goal was to improve the access (e.g. for scientists) to climate data that was scarce in quantity and scattered broadly, and to disseminate this data to a broader audience outside the scientific community (Vaughan and Dessai, 2014). Since the field of climate services is at the interface between science and society, it depends on progress achieved in climate research.

On the supply side of climate services, crucial scientific and technological breakthroughs since the 1980s (satellites, radar, telecommunications, supercomputing, model improvement) enabled increasingly skilled prediction (short-term) and improved projections (long-term), leading to the production of better knowledge about future climate

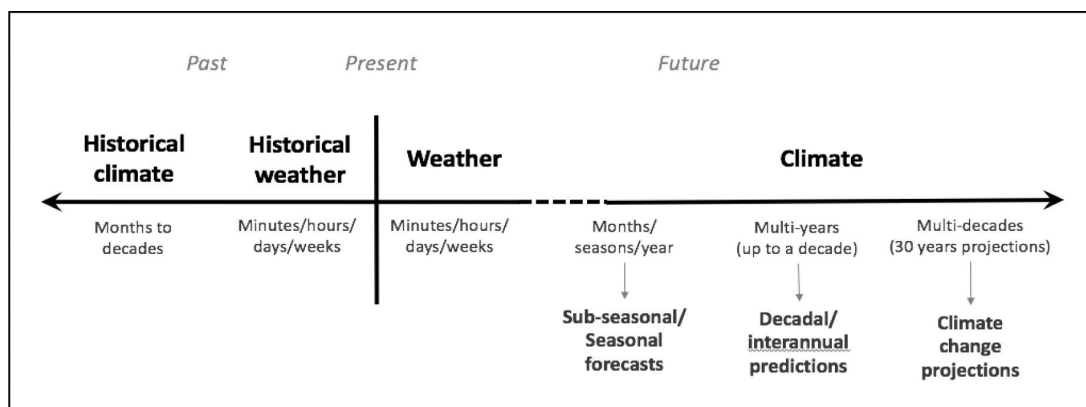


Figure I.13: Main types of weather and climate information (Soares et al., 2018).

(Troccoli, 2010; Edwards, 2011; Cubasch et al., 2013). On the demand side, the advance of global change combined with an increase in the frequency and costs of climate-related disasters prompted various societal decision-makers to seek climate information (Council et al., 2009; Changnon and Changnon, 2010; Hellmuth et al., 2011). These two developments (supply and demand) can explain the great proliferation in the quantity of climate services during the last decade, and the implementation of the Global Framework for Climate Services (GFCS) by the World Meteorological Organization (WMO) in 2012 (Vaughan and Dessai, 2014).

Welcome to the jungle: the plurality of climate services

Beyond the vast objective of facilitating adaptation to climate variability and climate change, climate services represent a collective term bundling a broad range of products, tools, activities and processes. The rapidly evolving field is also the place of many debates within the community, such as regarding what climate services are (Vaughan et al., 2018; Bessembinder et al., 2019; Bruno Soares and Buontempo, 2019; Weichselgartner and Arheimer, 2019), how they are made (Vaughan et al., 2016; Alexander and Dessai, 2019; Krauß, 2020), for which purpose (Harjanne, 2017; Webber and Donner, 2017; Raaphorst et al., 2020), and for who (Brasseur and Gallardo, 2016; Tall et al., 2018; Baztan et al., 2020).

Nevertheless, a common aspect between climate services appears to be the aim to provide “climate-related knowledge that can be used to reduce climate-related losses and enhance climate-related benefits” (Vaughan and Dessai, 2014). More broadly, the objective of many climate service activities is to facilitate the production, translation, transfer, and use of climate information and knowledge for climate-informed decision-making and an improved society’s resilience at large (Vaughan and Dessai, 2014). Climate services involve different types of providers (e.g. research institute, meteorological agencies), users (e.g. government, NGOs, private sector), services (e.g. seasonal, projections), and sectors (e.g. agriculture, water, energy; Soares et al. (2018); Vaughan et al. (2018)). The typical climate service appears to not have changed substantially in three decades (1980s to 2010s), and to remain the (now online) delivery of seasonal predictions for agriculture (Changnon et al., 1990; Vaughan et al., 2018).

The usability gap

Climate services were supposed to connect scientific knowledge to societal applications by facilitating the use of climate information (Vaughan and Dessai, 2014; Lúcio and Grasso, 2016), but they have remained largely science-driven and user-informed (McNie, 2012; Lourenço et al., 2016). In other words, climate information is provided by scientists but with little connection to specific regional and local issues, thereby impeding its relevance and ultimately its use by societal actors such as territorial decision-makers (Krauss, 2010; Lemos et al., 2012; Kirchhoff et al., 2013). Additionally, climate information is usually required at “local” level (e.g. city), but small-scale aspects of the climate are not well simulated by climate models (Collins et al., 2020), which have coarse resolutions (e.g. 10-100 km) that are not suited to the study of local phenomena (e.g. flash floods).

Techniques of downscaling can bring climate information at more local scale, but they imply strong assumptions between large-scale climatic variables (e.g. atmospheric pressure) and local variables (e.g. wind speed), and add a layer of uncertainty (Gutowski and Giorgi, 2020; Kotamarthi et al., 2021). Similarly, the biases of climate models can be corrected by comparison to observations but this step also adds a layer of uncertainty (Maraun, 2016; Maraun and Widmann, 2018). Once brought at the right scale, the climate information has to be robust (reliable) enough for decision-making, which is rarely the case. Climate information can become more suitable for decision-making through the evaluation and intercomparison of models and scenarios, through probabilistic approaches, and through the use of impact models and user-relevant indicators (Collins et al., 2020).

Yet even if all these conditions are met, and the “perfect” climate service has been produced, nothing guarantees that it will be used. It would therefore seem that we arrive at the societal boundaries of climate science. Therefore, new ways have to be explored about how to connect the users and producers, so that actionable knowledge is produced and used. A whole subfield of the climate service literature corresponds to the experimentation of approaches (e.g. workshop activities, evaluation surveys) to reduce the usability gap with potential users (e.g. water managers) of climate knowledge (Jacobs et al., 2009; Koldunov et al., 2016; Vogel et al., 2017; Tall et al., 2018). More broadly, social science and transdisciplinary approaches can provide key insights for the development of climate services and for bridging the climate adaptation gap (more on this in Chapter 2).

The road ahead and the CoCliServ project

Many scientific and societal barriers remain regarding climate change. Better anticipating the future requires to improve the understanding of how climate is likely to evolve regionally, but also the understanding of the societal and environmental consequences. In parallel, we have to connect this knowledge to adaptation decision-making at different levels of society, in order to bridge the usability gap of climate services, and ultimately the societal adaptation gap. Both top-down and bottom-up assessments of climate risks and adaptation are needed, in order to cater relevant information for immediate decisions at the territorial level (Conway et al., 2019).

The CoCliServ project was born in this sense, to co-develop with local stakeholders climate services that are place-based for action, in five European case studies. An important challenge facing climate adaptation is finding how to root climate change in the territory, and how to contextualize climate science with local stakeholders (Krauss, 2010; Owen et al., 2019). How does one identify, localize and select the information for action in the face of uncertainty, and based on the latest science? There already is a lot of information out there, regarding climate change. Does local climate information, tailored to local needs and interests, necessarily require new simulations, improved downscaling processes, and progress in meteorology and climate change science?

Moreover, how does one connect the existing climate information, in all forms, with local needs? How would one conduct a gap analysis, with and for local communities? What would then be selected as locally relevant climate information? Beyond the concept of information provision, these questions push the notion of climate service further to new possibilities (and activities). To tackle all these questions, the international team of social and climate scientists of CoCliServ engaged in an exploratory process about ways to render climate science actionable and to assess the discrepancies between currently available science and future needs for climate information. We went along devising approaches to connect what exists (climate knowledge) to what might be needed now and in the future (local issues).

Objectives and outline of the thesis

During the thesis, I worked on three case studies: two in France (Gulf of Morbihan, Kerourien district in Brest) and one in Norway (Bergen). For the purpose of conciseness, this manuscript will only cover the case study of the Gulf of Morbihan, although a brief comparison with the two other case studies is provided at the end of Chapter 5.

My research objectives were:

- To understand the local role (physical, societal) of climate change in the territory (past, present, future)
- To connect the territorial situation to the existing scientific knowledge and climate services, and to support the participative development of local adaptation planning
- To investigate climate change through the angle of clustering approaches

The associated research questions are:

- How does climate change locally affect the life and activities of inhabitants?
- Are there consistencies or inconsistencies between scientific knowledge and local experiences?
- How does climate change influence the future(s) envisioned by inhabitants for the territory?
- Are the current science and services enough to support local adaptation?

- Can clustering approaches bring additional insights about future climate change, and about making scientific knowledge more usable?

Chapter 1 will describe the climatic, environmental and social context of the case study. Chapter 2 will cover the methodological approach used in this thesis and situate it in the field of climate services. Chapter 3 will investigate the local role of climate change as experienced by inhabitants and their future visions for the territory. Chapter 4 will assess local climate change based on the existing scientific knowledge and climate services. Chapter 5 will explore the experimentation of foresight processes with inhabitants based on climatology, art and design, and deduce implications for climate services. Chapter 6 will investigate future climate change through the lens of clustering approaches. Finally, the Conclusion will summarize the research carried out in this thesis and discuss the implications and perspectives.

Summary of the Introduction

Context and motivation:

Climate change has various impacts on society, but future changes are uncertain and a wide gap remains between the scientific knowledge and societal action (mitigation i.e. reducing the causes, and adaptation i.e. reducing the consequences). Even when adaptation exists, it is often based on experienced disasters or on current risk (without an outlook in the future). This adaptation gap was partly addressed by the recent growth of climate services, but their local usability is associated to many barriers. France is an example of lacking climate adaptation at territorial level, and this thesis focuses on the Gulf of Morbihan as a case study. How is climate changing locally and how to prepare societally for these changes?

Objectives and questions:

- Identify the role of climate change in the territory. How does climate change affect the life and activities of inhabitants? Is local experience consistent with scientific knowledge?
- Support the participative development of adaptation planning. What are the visions of inhabitants for the territory? Are the existing climate science and services sufficient to enable local adaptation?
- Explore future climate change with clustering approaches. Can these approaches improve our understanding of future climate change, and facilitate territorial adaptation?

Outline of the thesis:

- Climatic, environmental and social context of the case study (Chapter 1).
- Methodological approach and situation in the field of climate services (Chapter 2).
- Investigation of the local role of climate change as experienced by inhabitants, and of their future visions for the territory (Chapter 3).
- Assessment of local climate change based on the existing scientific knowledge and climate services (Chapter 4).
- Experimentation of foresight processes with inhabitants based on climatology, art and design, and deduction of implications for climate services (Chapter 5).
- Investigation of future climate change with clustering approaches (circulation regimes, climate analogs) (Chapter 6).

"Harry Dalton: My 9th grade science teacher always said that if you put a frog in boiling hot water, it would jump out. But put it in cold water, and heat it up gradually, it would slowly boil to death.

- Nancy: What's that Harry? Your recipe for frog soup?

- Harry Dalton: It's my recipe for a disaster."

Dante's Peak

Chapter 1

The Gulf of Morbihan case study

1.1 Environmental and societal background

1.1.1 Physical environment and recent history

The Gulf of Morbihan is a natural harbour in Western France, on the coast of the Morbihan department in Southern Brittany (Figure 1.1). The harbour is about 8 km from North to South and 18 km from West to East (Direction départementale des Territoires et de la Mer, hereafter DDTM, 2020). Five rivers meet there and the harbour contains around 40 islands (DDTM, 2020); Morbihan means "little sea" in Brittonic language (Cagnard, 2009). The entry to the Atlantic Ocean is narrow (about 900 m wide) and associated to strong local currents (up to 4-4.5 m/s) and large tides (3-4 m; DDTM (2020)). The marine environment of the Gulf was formed over the last several kyrs by the combination of geological subsidence (i.e. ground sinking locally) and sealevel rise (Perez-Belmonte, 2008; Météo-France, 2012; DDTM, 2020). Both processes were driven by the warming of global climate and melting of Northern European glaciers since the last Ice Age. The coastal lowland was inundated progressively (present subsidence rate of about 1 mm/yr), with previous rivers becoming submarine valleys (20-25 m of depth).

This marine area has been attractive for several civilizations during the last thousands of years (Krauß et al., 2018b). During the megalithic period, the population cleared areas of trees to grow crops and livestock (Visset et al., 1996). This society also set up large megalithic monuments (menhirs, dolmens, cairns, cromlechs), some of which are remarkable witnesses of sea level rise (Gouezin, 1991). Remnants of luxurious villas on the coast indicate the presence of gallo-roman society during Antiquity, and the commercial ports of Vannes and Auray (two biggest towns) were important trade centers during the Middle Ages (DDTM, 2020). A manufacturing hub developed around the port activity of Vannes (Ville de Vannes, 2021b), meanwhile novel agricultural activities surfaced such as salt marshes in the 12th century and oyster farming in the 19th century (Le Gars, 1991; Ville de Vannes, 2021a). Industrial agriculture developed during the second half of the 20th century (Daucé et al., 1983), followed more recently by the development



Figure 1.1: Location (top) and geography (bottom) of the Gulf of Morbihan. Vannes is the biggest city in Morbihan (and the Gulf), visible as the large grey patch in the upper part of the bottom panel. Auray is the second largest city in the Gulf, visible as the smaller grey patch at the West of Vannes. About half of the Gulf population lives in these two towns.

of organic farming (Conseil départemental du Morbihan, hereafter CDM, 2021).

The area is attractive to humans, but also to many species of plants and animals. The Gulf is a complex and diversified natural system (e.g. mudflats, marshes and swamps rich in fauna and flora) supported by the abundance of eelgrass beds. This ecosystem is home to many rare and threatened species, under growing pressure from human activities (DDTM, 2020). For example, the population of winter migratory birds was about 100,000 at the start of the 1990s but has since decreased by 30 % (Office National de la Chasse et de la Faune Sauvage, 2018). A coastal law was voted in 1986 to protect rare species, limit the spread of urbanization, and make the shoreline more accessible to the public (Communes, 2021). Additionally, the coastal protection agency has bought and transformed about 15,000 hectares into a special conservation zone (réseau Natura 2000; DDTM (2020)). A natural park was also created in 2014 (Parc naturel régional du Golfe du Morbihan, hereafter PNR) to increase the protection of natural habitats

while developing the economic activities (PNR, 2020). Since 1986, the coastal law The coastal law also played an important role since more than two decades, by blocking "Loi Littorale" also played an important role since more than twenty years

1.1.2 Economy and seasonality

The urban area of the Gulf counts 34 towns and about 170,000 inhabitants over 800 km² (Conseil communautaire de Vannes Agglomération, hereafter CCVA, 2020). The corresponding intercommunality (Golfe du Morbihan - Vannes agglomération) was created in January 2017 (Figure 1.2). Vannes is the main town of the Gulf (and Morbihan) with about 53,000 people, followed by 13,500 people in Auray (Institut national de la statistique et des études économiques, hereafter INSEE, 2020). Vannes and Auray concentrate a large part of the Gulf economy (almost 50,000 jobs). The population is younger around urban centers (e.g. Vannes and Auray) but older on the islands and Atlantic shore (DDTM, 2020).



Figure 1.2: The intercommunality "Golfe du Morbihan - Vannes agglomération" created in January 2017.

The coastal population is largely seasonal and towns can host about ten times more people in summer than winter (e.g. x6 in Sarzeau and x14 in Arzon; bottom left in Figure 1.2). This seasonality is caused by the extent of secondary housing and tourism in the region; some towns are almost empty in winter (Krauß et al., 2018b). Young people struggle to settle and work in the Gulf, since there is little work outside the touristic and holiday seasons. The

strong pressure to urbanize more area in the Gulf (especially around Vannes and Auray) is another issue, due to the growth of the residential and touristic populations. Agriculture and tourism are important economic activities in the Gulf, but for very different reasons. Tourism drives the local economy while agriculture drives the local culture. The coastal fringe is mostly dedicated to tourism, while the rural hinterland is largely devoted to agriculture. The overall economic activity in 2017 (DDTM, 2020) was:

- 2.1 % agriculture
- 16.2 % industry and construction
- 45.4 % commercial (services, trade and transportation)
- 35.6 % non-commercial (administration, education, health, and social action)

1.1.3 Contrast between agriculture and tourism, between coastal and inland territory

Agriculture, industry and construction are declining, while the commercial and non-commercial sectors are growing (DDTM, 2020; INSEE, 2021). The growth of commercial activities is driven by tourism, and the growth of non-commercial activities is driven by the ageing of the population (especially human and medical services; DDTM (2020)). The main agricultural activity (about 2/3 or 400 jobs) is the aquaculture of shellfish, mostly oysters in the harbour DDTM (2020)). Morbihan represents about 1/3 of shellfish aquaculture area in France. Despite these strengths, the sector is declining due to three factors:

- Access to essential areas is becoming more difficult because coastal land is becoming too expensive (due to tourism and secondary housing)
- Conditions necessary for oyster development (water quality, predation, mitigation of diseases) are becoming less favourable. For instance, about half of oyster production was lost due to excess mortality between 2007 and 2012
- Lack of replacement for departures and retirements

Shellfish farmers have adapted their activity by importing oysters from other areas (e.g. Arcachon Bay), by breeding oysters in elevated spots (tables, cages, and "Australian baskets"), and by organizing visits and tasting (associated to tourism). Fishing represents about 1/6 of agriculture in the Gulf (90 jobs; DDTM (2020)). It is done by boat in the middle and Western area of the harbour, and on foot in the Eastern and norwesternmost areas. The fishing fleet counts 65 boats and most boat fishermen have other jobs (aquaculture, fishing on foot). The ageing of boats and fishermen is an issue. Marine food exploitation is influenced by many determinants: population dynamics, water quality, climate change, and human factors. Gulf authorities consider that the general state of marine resources

is in intermediate conditions, some species in a favorable state (clams and sea breams), and others in an unfavorable state (cuttlefish and sea urchins). The coexistence of fishing is rather easy with aquaculture, but more difficult with recreational activities (e.g. kite surf, leisure fishing). The supervision of professional fishing becomes increasingly complicated due to the combination of law and environmental factors: tranquillity zones, protected marine areas, and special conservation zone (Natura 2000).

Land farming also represents about 1/6 of agriculture (105 jobs), concentrated around Vannes and Auray (DDTM, 2020). The activity is dominated by the breeding of cattle (associated to milk production), with smaller roles for the breeding of pigs and chickens. Other similar activities include the farming of fish (land hatchery), algae, flowers, and salt. The shore has little space available for agriculture due to natural and urbanized areas, but more area is available inland. The quantity of land used by farming (cattle, pigs, chickens) is stable, in contrast to aquaculture (oysters). About half of land farmers take part in short circuits of distribution for their products, increasing their direct sales locally. The PNR started a program in 2015 to help farmers adapt their practices to environmental challenges (water, soils, biodiversity, climate, natural risks, etc.). Farmers have also been involved with the coastal protection agency in conservation efforts of natural sites in marshes and on islands. A local association ("CAP 2000") of land farmers, shellfish farmers and fishermen aims at preserving water quality and sensitive areas (aquaculture, swimming), while supporting primary activities (studies and expertise, technical support to producers).

Tourism enriches coastal towns, but it benefits less to small inland towns suffering from decaying industry and agriculture. Morbihan was the fifth touristic department in France during 2014, hosting 4.8 million tourists (half of them in the Gulf; DDTM (2020)). Most tourists come between June and September, resulting in marked seasonal activities. For instance, tourism employed about 13,000 people on average in 2016 (6 % of Morbihan jobs) but 21,000 in August. The Gulf contains about 130,000 beds for tourists, more than for the permanent population. Vannes and Auray mostly have permanent housing for locals, whereas the Atlantic coastline and harbour islands are dominated by second homes and touristic accommodations. About half of accommodations are commercial, mostly hotels in Vannes and Auray, and campings in the rest of the Gulf. The number of touristic beds in commercial accommodations decreased between 2006 and 2017 (from 34 % to 25 %), but secondary housing is increasing.

The nautical sector of the Gulf represented about 3200 jobs in 2015: nautical and seaside activities, trade and services, industry, and port facilities (DDTM, 2020). The Gulf has about 12 main ports and anchorage areas. All ports cater to recreational boating, and six ports connect the shore to the main islands of the harbour. Vannes also has a trading port. Recreational sailing (motor boats and sailboats) is increasing, mostly in July and August (about 3000 registered sailors). There is a lot of traffic between islands, and at the oceanic entry of the harbour, but navigation is forbidden in several sectors to protect birds and fragile marine habitats. Recreational fishing on foot is largely practiced by locals and tourists during high tide (up to about 1,000 people), but is forbidden in some areas to protect ecosystems and oyster farms. Other nautical (leisure) activities include rowing, sea kayaking, paddle, kite surf, and scuba diving. Hiking on the coastal path is also highly attractive. The coastal path corresponds to 3 meters of land

situated above high tide round the harbour. This path is protected by the coastal law and guarantees free passage to pedestrians on about 71 km.

Many cultural and sport events take place in the Gulf, mostly in summer (DDTM, 2020). Some events are festivities and celebrations of Brittonic culture and history (e.g. music festivals). A famous event is the "Week of the Gulf", gathering over a thousand boats every two years in association to open-air entertainment and exhibitions, oyster tasting, and nighttime shows (music concerts, village dances, fireworks). About 125,000 people took part in events within the Natura 2000 area (water and land) in 2015, with potential consequences on local ecosystems. The largest events (over 1,000 participants) undergo impact assessment based on a Natura 2000 framework.

Overall, a significant portion of the Gulf activities (e.g. agriculture, tourism) depend on the local climate and are largely seasonal. Climate change could therefore play an important role in the next decades. Large human impacts are already happening on the coastal environment in summer, with many consequences (social, environmental, economic; DDTM (2020)). For instance, water access becomes challenging during the touristic season for drinking, irrigation, and other uses (Krauß et al., 2018b). It could become more challenging with an increasing population and drier summers.

1.2 Climate

1.2.1 Main features

Climate in France is mostly temperate and oceanic (Figure 1.3) due to the intermediate latitude, proximity of the North Atlantic Drift (warm boundary current), and dominance of Westerly winds (Météo-France, 2012, 2020d). The oceanic influence is stronger on Brittany, famous for the frequent rain showers (Météo-France, 2012).

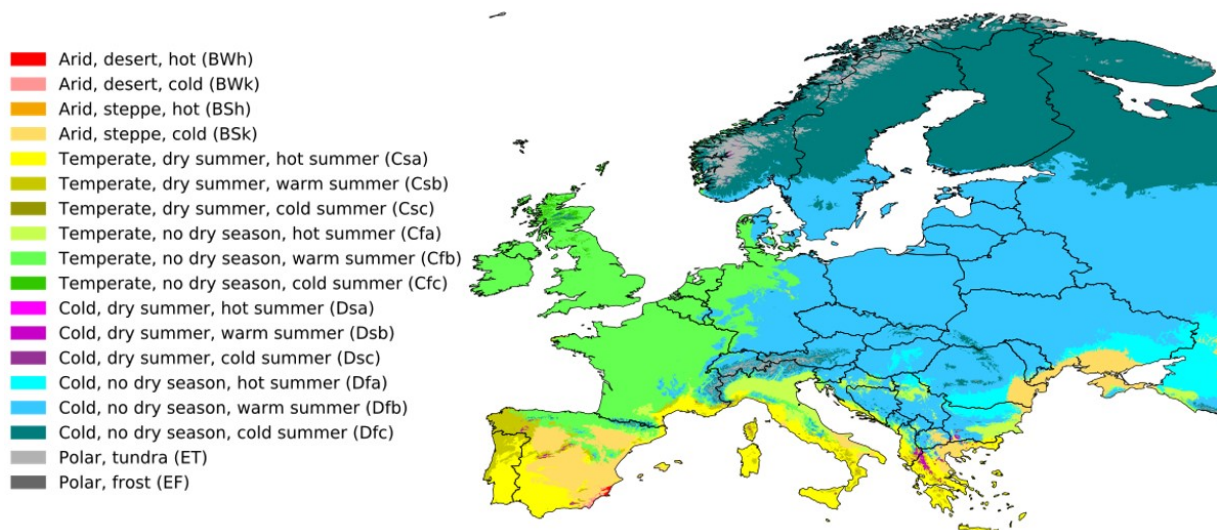


Figure 1.3: Present climate classification of Europe. Map of Köppen-Geiger climates in Europe over 1980-2016, adapted from Beck et al. (2018).

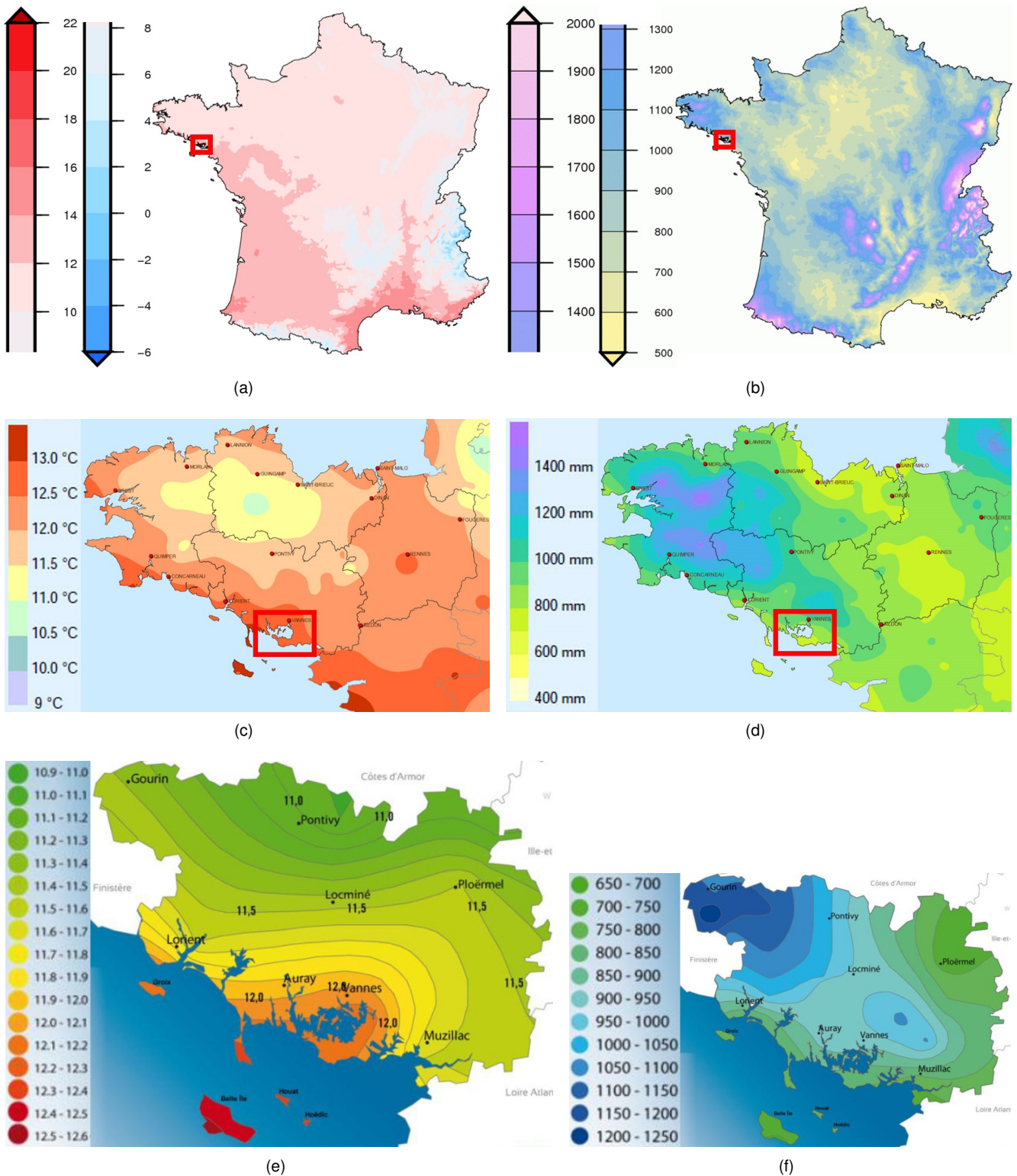


Figure 1.4: Maps of mean annual temperature (left) and cumulated precipitation (right) in France (top), Brittany (middle) and Morbihan (bottom). France over 1981-2010 (adapted from Météo-France (2020d)). Brittany over 1981-2010 (adapted from OEB (2020a)). Morbihan over 1971-2000 (adapted from ODEM (2012)). The Gulf of Morbihan is indicated by the red box.

Brittany is generally warm, wet and windy due to the frequent weather disturbances coming from the Atlantic Ocean (Figure 1.4a-b and Météo-France (2012, 2020c)). For instance, the average temperature in Brest (at the tip of Brittany) draws near 7 °C in winter and 17 °C in summer (Météo-France, 2012). The accumulated precipitation in Brittany varies between about 600 and 1500 mm over the year, depending on the location (Figure 1.4d). The Breton climate varies along different parameters (Météo-France (2012); Observatoire de l'environnement en Bretagne, hereafter OEB (2020b)):

- Longitude (less oceanic influence eastwards)
- Latitude (sunnier and warmer southwards)
- Continentality (less temperature variability on coastline)
- Topography (more precipitation and cooler temperatures in elevation)

The Gulf of Morbihan is warmer (Figure 1.4c), drier (Figure 1.4d), sunnier and less windy than Brittany (Conseil d'Architecture, d'Urbanisme et de l'Environnement, hereafter CAUE, 2011). The "microclimate" of the Gulf is produced by two local features. First, high rocky hills (about 100 m high) create a natural barrier dividing the climate of Morbihan along a Northwest-Southeast axis (CDM, 2020). These elevated lands increase the local precipitation that is weaker seaside and eastwards (Figure 1.4f and Météo-France (2012)). Second, the inner sea of the Gulf increases the "coastal effect" that tends to warm the Breton shoreline and decrease its temperature variability (Figure 1.4c; Observatoire Départemental de l'Environnement du Morbihan, hereafter ODEM (2012); CDM (2020)). The Gulf is therefore warmer seaside than inland (Figure 1.4e). For example, Vannes is approximately at the center of the Gulf with about 12.5 °C and 900 mm on average over the year (Figure 1.5a-b). By contrast, Locminé (about 20 km North of Vannes) is cooler and wetter: 11.7 °C and 1010 mm (Figure 1.5c-d). The island of Belle-Île (about 50 km Southwest of Vannes) is warmer and drier: 12.7 °C and 700 mm (Figure 1.5c-d).

1.2.2 Seasonal variability

The oceanic influence reduces climate variability during the day and between seasons (Météo-France, 2012). This is due to the prevalence of cloudy weather, strong winds, and inflow of oceanic air that is mild and wet (Météo-France, 2012). Summers are fresh and winters are warm in the Gulf by comparison to the continental interior (ODEM, 2012; CDM, 2020). For instance, the variation in temperature and precipitation between different seasons (i.e. seasonality) is smaller in Belle-Île, but higher in Vannes and near Locminé (Figure 1.5c-d). Since the shore is warm and has low seasonality, frost days are rare there. Hot days (above 25 °C) are also rare on the shore. The number of frost days and hot days increases with the distance to the sea, and both are more frequent inland (OEB, 2020a; CCVA, 2020).

Most of the precipitation in Brittany occurs during winter, and about 2/3 from October to March i.e. season of hydrological recharge or "recharge season" (Figure 1.5d and Météo-France (2012)). In winter, Brittany is

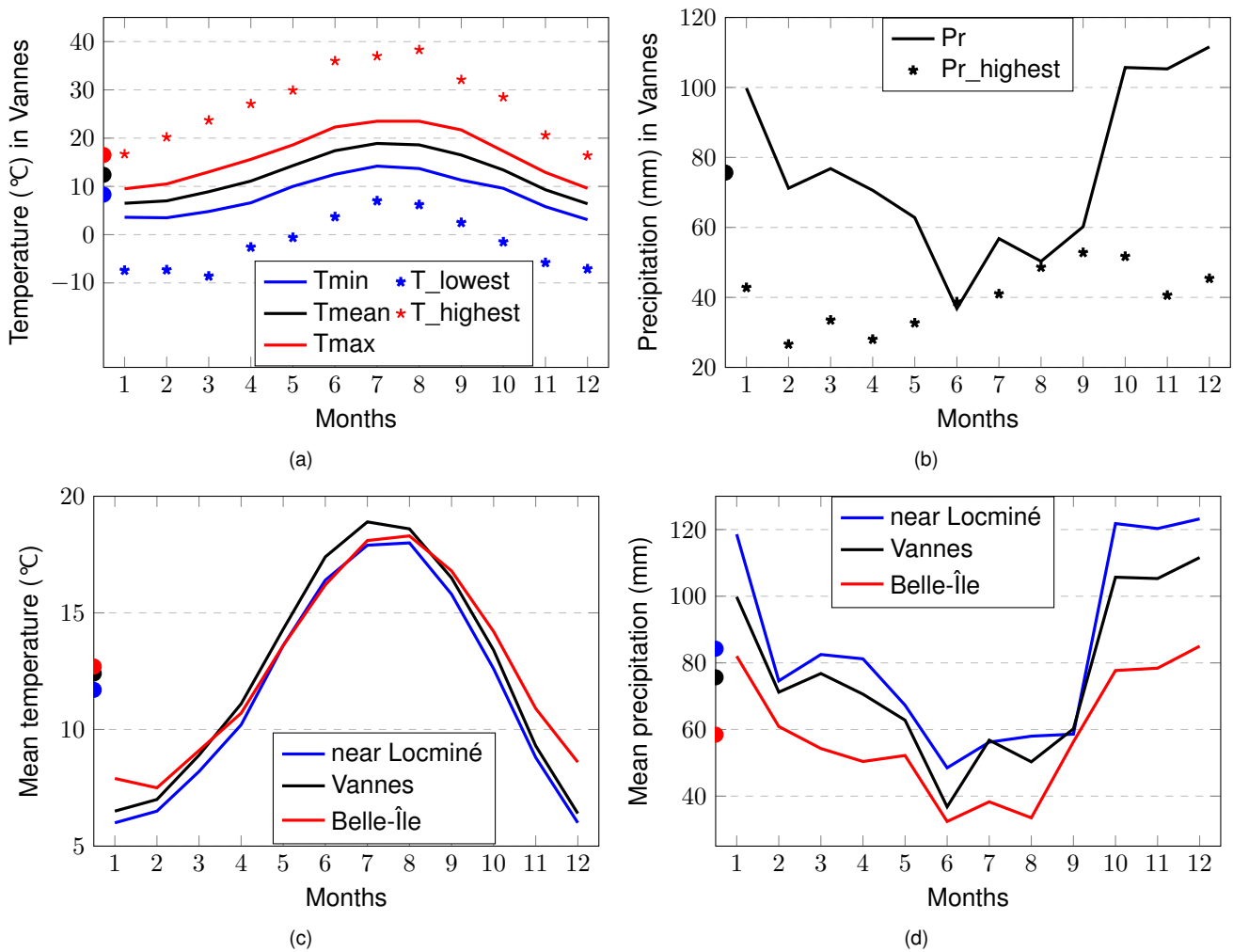


Figure 1.5: Seasonal and spatial variability of temperature (left) and precipitation (right) in the Gulf of Morbihan (adapted from Météo-France (2020a)). Top panels: monthly means (lines), annual means (dots), and extreme daily records (stars) of temperature (a) and accumulated precipitation (b) measured in Vannes-Séné. Bottom panels: monthly means (lines) and annual means (dots) of temperature (c) and accumulated precipitation (d) recorded near Locminé (blue), in Vannes (black) and in Belle-Île (red). Mean values recorded over 1997-2010 (near Locminé), 1998-2010 (Vannes-Séné), and 1981-2010 (Belle-Île). Extreme values in Vannes-Séné measured over 1998-2021.

swept massively by cyclonic systems flowing from the Atlantic storm track (Météo-France, 2012). The associated precipitation is essential to refill groundwater and rivers for the local ecosystems and human activities (DDTM, 2020). The remaining 1/3 (approximately) of the precipitation occurs between April and September i.e. "low-flow season". In summer, the storm track moves North and Brittany receives less weather disturbances (Météo-France, 2012). Brittany receives ample precipitation throughout the year, but this precipitation fluctuates strongly between years and seasons (CCVA, 2020). There is sometimes a factor of two or more between amounts of accumulated precipitation from consecutive years, recharge seasons, or low-flow seasons (CCVA, 2020; Météo-France, 2012).

Winds in Brittany mostly blow from the West ("Westerlies") and Southwest (Figure 1.6a), year-round but more strongly in winter (Météo-France, 2012). Weak winds sometimes blow from the Northeast (1/5 of situations) and bring cold and dry weather, usually during spring (Météo-France, 2012). Anticyclonic conditions (about 1/10 of situations)

are rarer and associated to very weak winds (Météo-France, 2012). Winds are stronger on the coast (over 8 m/s) than inland (about 1.5 to 4.5 m/s) due to the continental topography slowing winds more than the ocean surface (Figure 1.6a). Brittany is associated to a high variability of winds and gusts from year to year, and is at the forefront of Western Europe regarding the path of cyclonic systems (Météo-France, 2012). The wind climate in the Gulf of Morbihan is similar to Brittany: mostly blowing from the West and Southwest (Lemasson, 1999), and faster in Belle-Île than in Vannes (Figure 1.6c).

The Gulf of Morbihan is the sunniest part of Brittany with about 2000 hours per year on average (Figure 1.6b). The amount of sunlight in Vannes is lowest in winter (about 3 hours/day; Figure 1.6d) and highest in summer (about 8 hours/day). This contrast is due to the variation of the Earth's orbit in relation to the Sun (Thomson, 1995; Donohoe and Battisti, 2013), and to the seasonality of the cloud cover (Chiacchio and Vitolo, 2012). Sunlight also varies largely

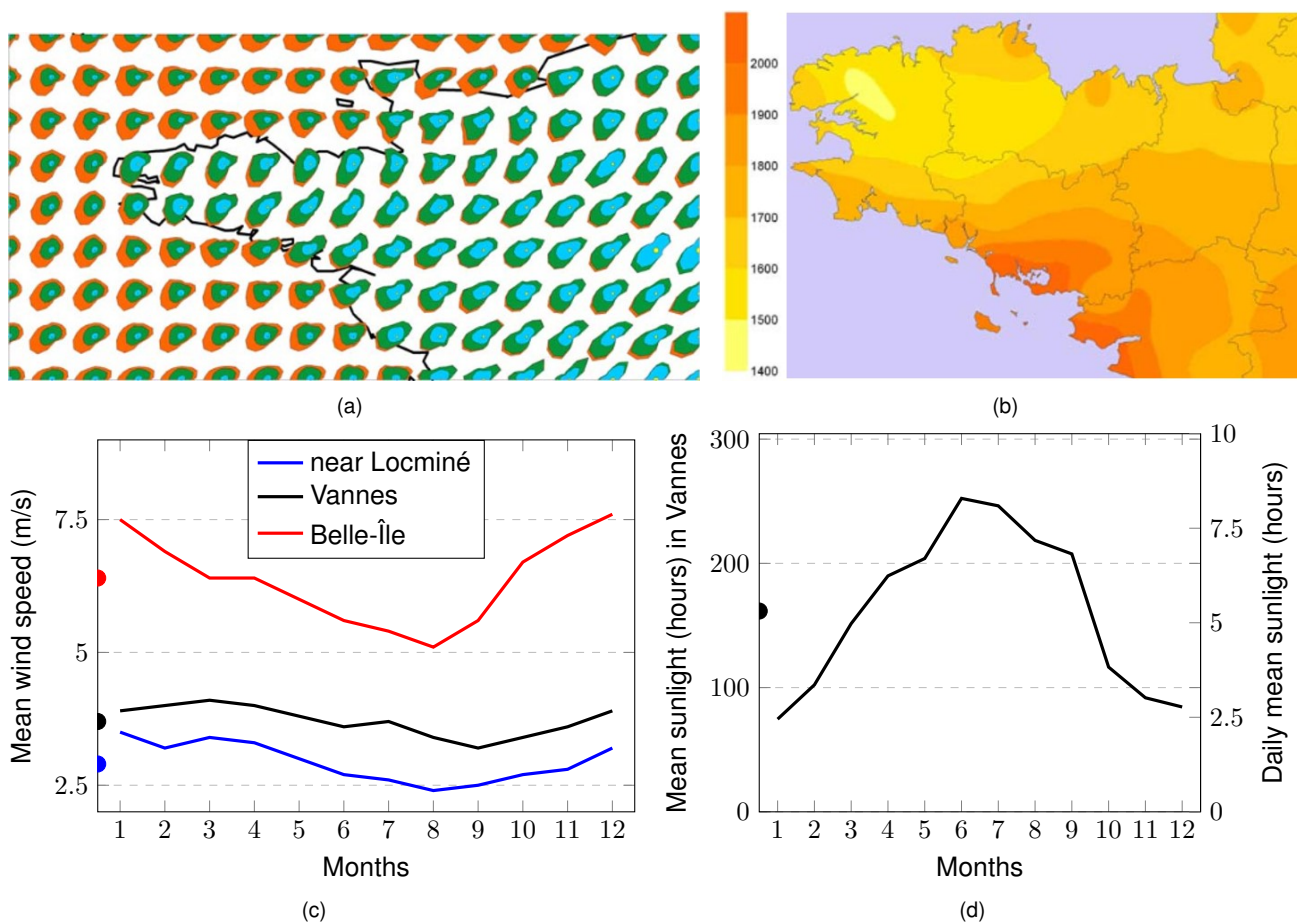


Figure 1.6: Spatial and seasonal variability of wind speed (left) and sunlight (right) in Brittany (top) and the Gulf of Morbihan (bottom). Top left: map of average wind speed at 10 meters of altitude in Brittany from the numerical model Aladin over 1999-2008 (adapted from Météo-France (2012)). Slow winds in blue (1.5 to 4.5 m/s), intermediate winds in green (4.5 to 8 m/s), and fast winds in orange (over 8 m/s). Top right: map of average sunlight in Brittany from ground measurements and Meteosat satellites over 1997-2006 (adapted from Météo-France (2012)). Bottom left: monthly mean wind speed measured at different weather stations in the Gulf of Morbihan (adapted from Météo-France (2020a)): near Locminé (1997-2010; blue), in Vannes-Séné (1998-2010; black), and Belle-Île (1981-2010; red)). Bottom right: mean sunlight measured in Vannes over 1998-2010 (adapted from Météo-France (2020a)): annual mean (dot), monthly means (line) and daily equivalent (right y-axis).

from year to year in Brittany (Météo-France, 2012).

1.2.3 Weather regimes

More generally, the variability of meteorological parameters (temperature, precipitation, wind, sunlight) is linked substantially to the occurrence of specific weather situations (Plaut and Simonnet, 2001; Schwander et al., 2017; Pasquier et al., 2019; Météo-France, 2020f). The Gulf microclimate depends on the local physical features but also on the larger context of atmospheric circulation over Europe and the Atlantic. A way to describe this larger context is through the pattern of occurrence from specific atmospheric situations. Since the variability of the atmosphere is chaotic at short timescale, an exact atmospheric situation never repeats twice. However, similar situations can happen occasionally in this chaos. We can then distinguish the emergence of patterns from the repeated occurrence of a given type of situation. Many of these recurrent atmospheric situations, or "**weather regimes**" (WRs, also named weather patterns or weather types; Ramos et al. (2015)), exist in Europe (Fernandez-Granja et al., 2021). WRs are generally associated to particular configurations of meteorological parameters (hot or cold, rainy or dry, windy or calm), but these configurations depend on the season and location. There are four or five main WRs for France (Figure 1.7; Plaut and Simonnet (2001); Sanchez-Gomez et al. (2009); Météo-France (2020f)). They happen year-round but follow some seasonality:

- Westerly or "zonal" flow (Figure 1.7 top row) is the most frequent WR (Hoy et al., 2013; Météo-France, 2020f; Fernandez-Granja et al., 2021). It brings numerous storms to France from the Atlantic (Hurrell et al., 2003; Météo-France, 2020f). This flow is produced by the combination of a cyclonic system (i.e. center of low atmospheric pressure or "Low") near Iceland, and an anticyclonic system (i.e. high-pressure center or "High") near the archipelago of the Azores. The winds generally flow clockwise around the High and counterclockwise around the Low in the Northern Hemisphere, directing them towards Europe in the present case (Hurrell et al., 2003). Westerly flow is more frequent in winter than in summer (Sanchez-Gomez et al., 2009; Plavcová and Kyselý, 2019; Fernandez-Granja et al., 2021) since both High and Low tend to migrate South in winter and North in summer (Barnston and Livezey, 1987; Portis et al., 2001; Hurrell et al., 2003). This WR is generally associated to wet and mild weather in France (fresh summer, warm winter; Hoy et al. (2013); Hurrell et al. (2003); Planchon et al. (2009); Vicente-Serrano et al. (2016); Pasquier et al. (2019)). Temperature extremes are less likely to occur during Westerly flow (Plavcová and Kyselý, 2019).
- Anticyclonic or "blocking" conditions (Figure 1.7 second row) occur when the usual Westerly flow is deflected by a High in Western Europe, steering the North Atlantic storm-track towards the British islands and Scandinavia (Météo-France, 2020f). A High over France is usually associated to calm weather (clear sky) and dryness due to the sinking air from the upper atmosphere (Trigo et al., 2004). This apparently nice weather can turn to nightmare if it persists for too long. In summer, heat can accumulate due to strong sunlight and adiabatic

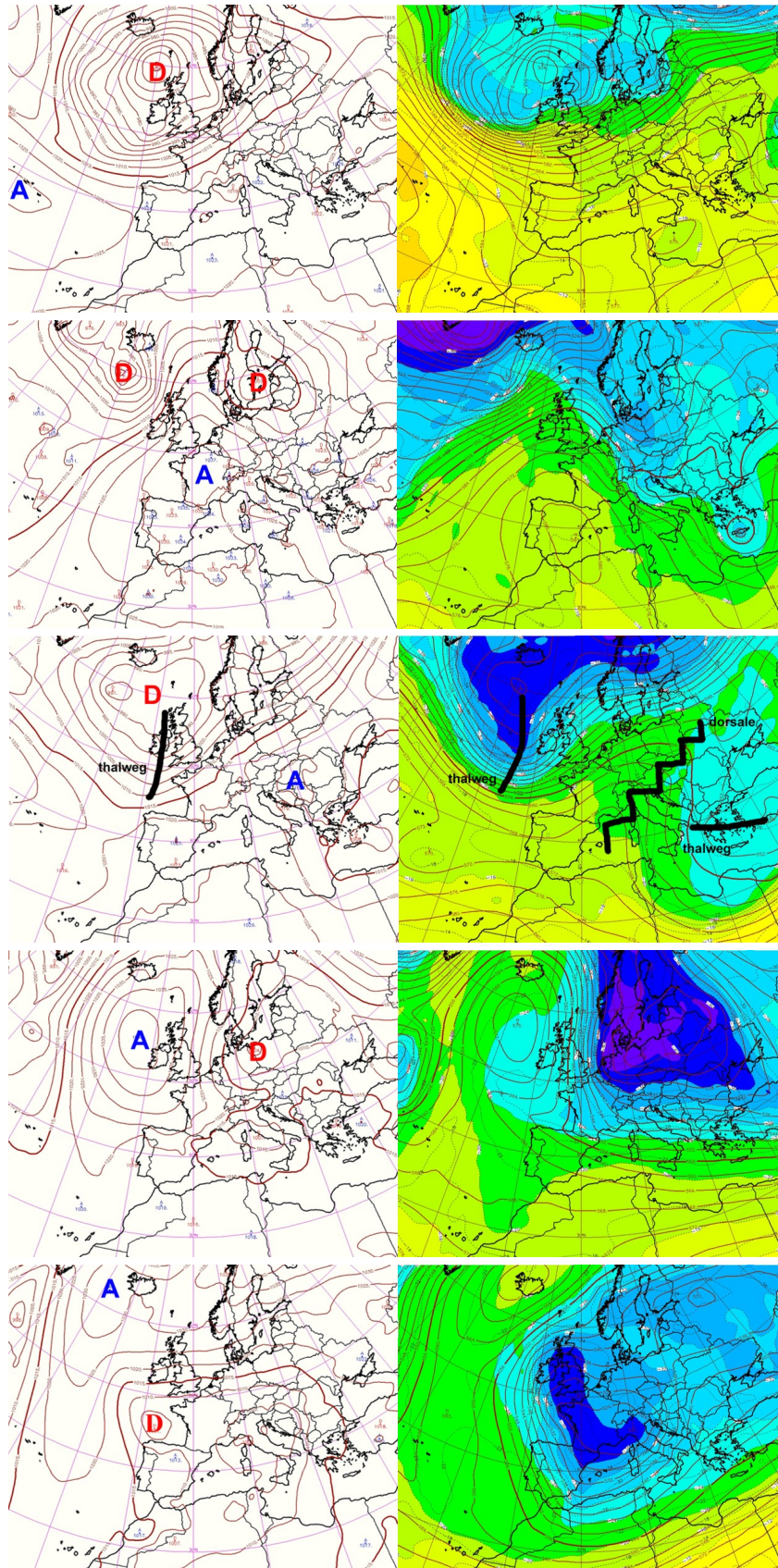


Figure 1.7: Five main weather regimes in France, adapted from Météo-France (2020f). Example of mean sealevel pressure (left panels) and 500 hPa temperature (right panels) associated to each weather regime (top to bottom). The position of Highs is indicated by "A" and Lows by "D". Warm areas are indicated in yellow and cold areas in blue.

heating, sometimes leading to a heatwave (Pfahl and Wernli, 2012; Bieli et al., 2015). The persistence of dry air can amplify the local heat accumulation (Miralles et al., 2014; Rasmijn et al., 2018; Schumacher et al., 2019). It can also produce a drought (Mukherjee and Mishra, 2020), a wildfire (Gudmundsson et al., 2014), or both (Sutanto et al., 2020). In winter, heat loss due to weak sunlight and enhanced radiative cooling (weak cloudiness and humidity, sometimes snow) can lead to a cold spell (Trigo et al., 2004; Buehler et al., 2011; Sillmann et al., 2011). Regarding the occurrence of anticyclonic conditions, Sanchez-Gomez et al. (2009) found that they were more frequent in winter than summer, but Fernandez-Granja et al. (2021) found the opposite.

- Southern flow or "Greenwich Trough" (Figure 1.7 middle row) happens with a Low near Iceland and a High near Central Europe, orienting the airflow northwards from the Mediterranean sea. The arrival of subtropical air (warm and wet) in France brings warm and rainy weather during winter (Planchon et al., 2009; Hoy et al., 2013), and thunderstorms in summer (Météo-France, 2020f). Southeastern France can experience intense rain when this subtropical air climbs the Southeastern French mountains (Massif Central, Alps), sometimes pouring hundreds of mm in a few hours or days (equivalent to several months of rain; Météo-France (2020f)). Southern flow and extreme rain are more frequent in autumn (Luu, 2020; Fernandez-Granja et al., 2021), when the Mediterranean sea is still warm but air masses are colder.
- Northwestern flow or "Atlantic Ridge" (Figure 1.7 fourth row) occurs with a Low near Scandinavia and a High near Iceland. This atmospheric flow brings cold Northerly (subpolar) air that the ocean surface tends to slightly warm and moisten. The arrival of this air creates a large difference in the vertical profile of temperature. This instability produces strong ascending winds associated with unstable clouds (cumulus, cumulonimbus) that bring rain in summer, snow in winter, and mixed showers in spring ("giboulées de printemps"; Météo-France (2020f)). The Northern air accelerates when passing between mountains (Pyrenees, Massif Central, Alps), producing strong local winds (mistral and tramontane) in Southeastern France (Météo-France, 2020f). This WR is less frequent in winter and autumn, but more in summer (Sanchez-Gomez et al., 2009; Fernandez-Granja et al., 2021). It is associated to colder and drier conditions in winter (Plaut and Simonnet, 2001; Hoy et al., 2013; Sousa et al., 2018), and fewer atmospheric rivers and precipitation extremes in autumn (Pasquier et al., 2019).
- Eastern flow or "Greenland High" (Figure 1.7 bottom row) happens when a High is further North (e.g. near Greenland) and a Low further South (e.g. near Spain) than usual. The air then flows eastwards and brings dry air from the continental interior that is rather cold in winter and warm in summer (Hoy et al., 2013). The persistence of this pattern can lead to a European cold spell in winter or heatwave in summer (Pfahl and Wernli, 2012; Plavcova and Kyselý, 2016; Plavcová and Kyselý, 2019). Eastern flow is generally associated to a cold zone in altitude over France that can produce clouds and winds by interacting with the warm wet air of the Mediterranean region (Météo-France, 2020f). This interaction can also facilitate snowfall in winter

(Météo-France, 2020f). Greenland High does not always lead to Eastern flow since the circulation also depends on the position of the Low. If the Low is located more to the North or West of France, the air will flow from the West or South. Eastern flow is therefore less frequent than Greenland High (Sanchez-Gomez et al., 2009; Fernandez-Granja et al., 2021). Greenland High happens more often in summer than winter (Sanchez-Gomez et al., 2009), and Eastern flow is more frequent in spring and less in autumn (Fernandez-Granja et al., 2021).

European WRs are therefore useful to describe local atmospheric variability (Plaut and Simonnet, 2001; Simonnet and Plaut, 2001) and especially weather extremes (Yiou and Nogaj, 2004; Cassou et al., 2005; Yiou et al., 2008; Van den Besselaar et al., 2010; OrtizBeviá et al., 2011). This strong atmospheric influence of WRs combined to their "slow" evolution (days to weeks) provides a path to weather predictability and forecasting (Hannachi et al., 2017; Lavaysse et al., 2018; Matsueda and Palmer, 2018; Cortesi et al., 2021). For instance, European atmospheric blockings can persist for weeks, while largely affecting the local occurrence of extreme temperatures and precipitation (Sillmann et al., 2017; Brunner et al., 2018; Sousa et al., 2018; Lenggenhager and Martius, 2019).

1.2.4 Extreme events

In the Gulf, the effect of the inner sea on weather extremes is less clear-cut than for instance on annual and seasonal temperature (Figures 1.4e and 1.5c). In the case of temperature extremes, major heatwaves (e.g. 1976, 1989, 2003) and cold spells (e.g. 1954, 1963, 1985) were less intense in Brittany than in more continental regions of France (Météo-France, 2012). Similarly, heatwaves and cold spells tend to be rarer in the Gulf near the sea (similarly to hot days and frost days). Temperature extremes tend to be more intense near Locminé and in Vannes than in Belle-île (Figure 1.8a-b). The strongest cold spells appear to be less intense in the Gulf than in Brest (none below -10°C in Figure 1.8a vs. four events below -10°C in Météo-France (2020b)). This can be due to the shorter temperature records in the Gulf (1997-2021 vs. 1945-2021 in Brest), since stronger events could appear in longer time series from the perspective of extreme value theory. However, the strongest heatwaves tend to be more intense in the Gulf than in Brest (about 38°C in Figure 1.8b vs. 35°C in Météo-France (2020b)).

Climate is rainy in Brittany but droughts can be severe (e.g. 1949, 1976 and 2011; Météo-France (2012)). Brittany and the Gulf are especially prone to precipitation extremes due to the large interannual variability of precipitation, hydrological features (isolated watersheds, soil impermeability) and enhanced evaporation (sunny, warm and windy climate; ODEM (2012)). Precipitation extremes appear to be more intense in Belle-île than in the two Gulf locations inland (Figure 1.8c). This can seem odd since precipitation is higher inland on average (Figure 1.5d), but can be explained by the lower variability of precipitation inland (CAUE, 2011) and longer measurement records of Belle-île's weather station (almost a century vs. about two decades for Vannes and Locminé; Météo-France (2020a)). Floodings are the main natural risk in Brittany (population exposure, potential damage), happening mostly in winter due to high precipitation, river overflow, and sometimes storm surges (especially for rivers reaching the sea; Météo-France

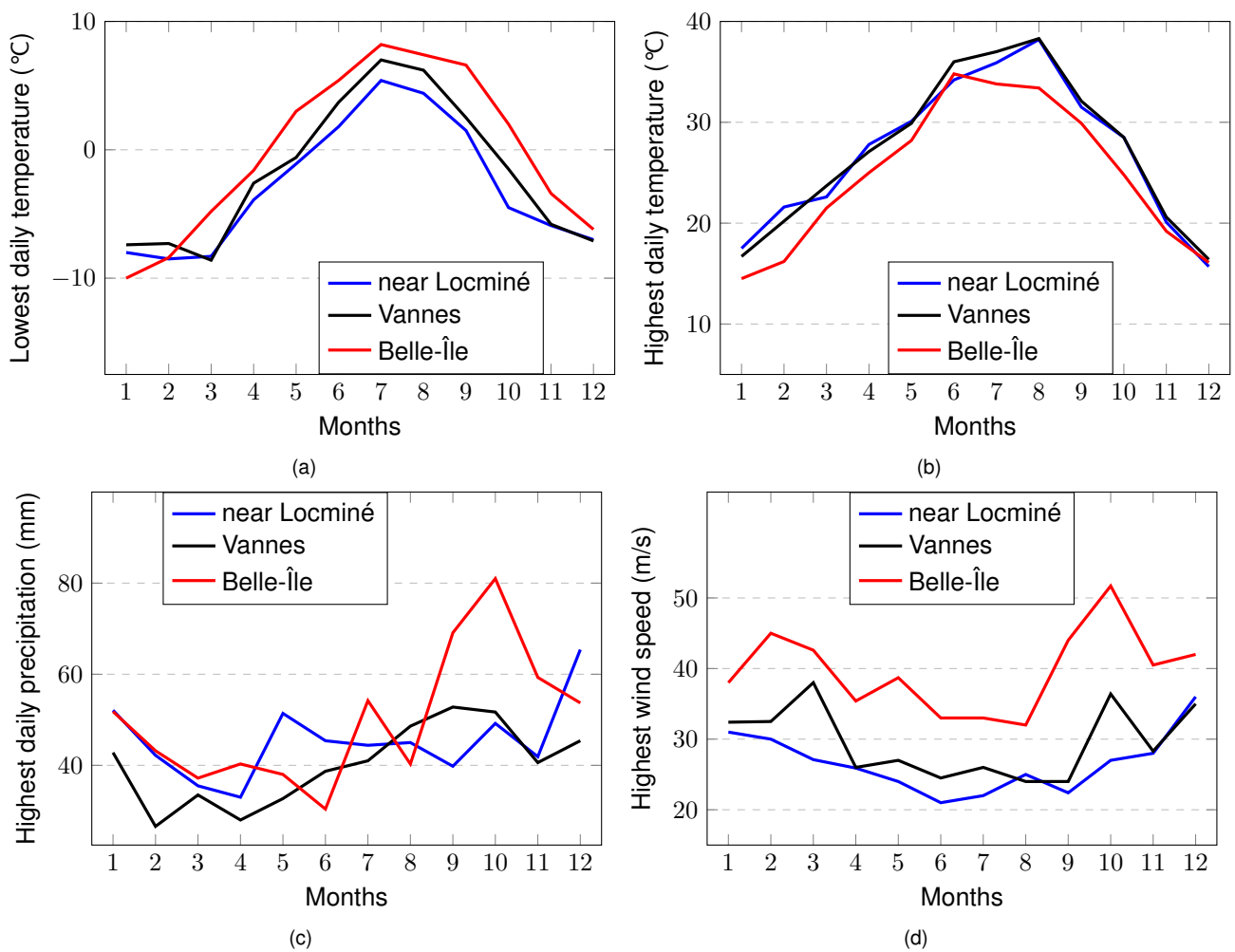


Figure 1.8: Seasonal variability of extreme temperature (top), precipitation (bottom left) and wind speed (bottom right) in the Gulf of Morbihan (adapted from Météo-France (2020a)). Top left panel: lowest daily temperature measured near Locminé (blue), in Vannes (black) and in Belle-Île (red). Top right: same for highest daily temperature. Bottom left: same for highest daily precipitation. Bottom right: same for maximum wind gust. Values recorded near Locminé over 1997-2021, in Vannes-Séné over 1998-2021, and in Belle-Île over 1930-2021 (except wind gusts over 1981-2021 in Belle-Île).

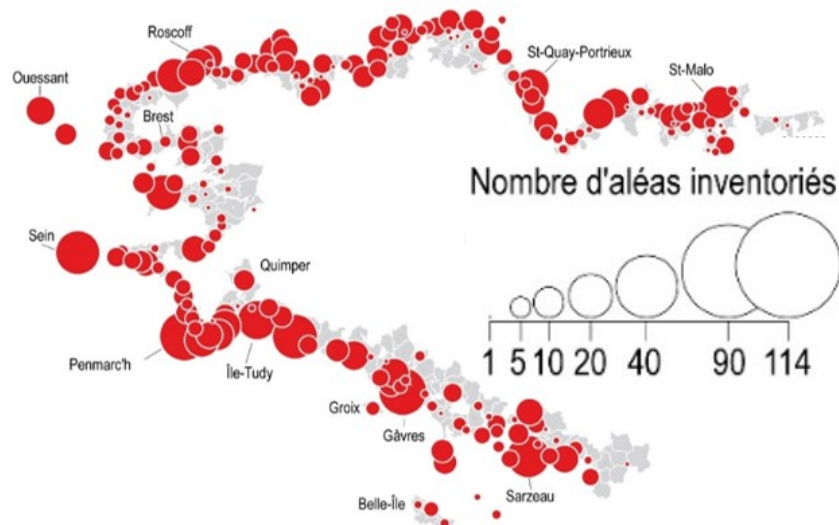


Figure 1.9: Number of coastal hazards counted on Brittany's coastline over 1790-2010, adapted from Henaff et al. (2018).

(2012)).

Many coastal hazards have occurred in Brittany over the last two centuries (Météo-France, 2012, 2020g), rather on the southern side (e.g. Sarzeau in the Gulf; Figure 1.9). The Gulf is mainly exposed to Southwestern storms (Henaff et al., 2018), but is protected from winds by the peninsulas of Rhuys (South) and Quiberon (Southwest; DDTM (2020)). The Xynthia storm for instance (February 2010) produced a sea surge of about 0.5-0.6m along the Rhuys peninsula, eroding some of the foredunes and displacing sediments to neighboring beaches (Dubois et al., 2014). During storms, extreme winds are faster (reaching up to 50 m/s) on islands and the shore than further inland (Figure 1.8d and ODEM (2012)). The area of Vannes is especially prone to flooding from storm surges and river overflow (DDTM, 2020). The shore of the Gulf is largely composed of small cliffs (rarely more than 5-6 m high), some of which have retreated by about 1-4 m over 1952-2004 (DDTM, 2020).

1.3 Climate change

1.3.1 Local influence and warming

Climate change can change local weather patterns (e.g. temperature and precipitation) and the occurrence (frequency, intensity, length) of extreme weather events (heatwaves, cold spells, droughts, heavy rainfall, etc.). Through changes in atmospheric thermodynamics (heat and moisture), in atmospheric dynamics (circulation), and in land-atmosphere interactions (Vautard et al., 2016; Chen et al., 2018; Catto et al., 2019; Jia et al., 2019). These atmospheric changes can also, combined with sealevel rise, influence coastal hazards (e.g. storm surges; Collins et al. (2019)). The influence of climate change on extreme weather events is generally more difficult to estimate than on "normal" indicators (e.g. average temperature). Due to the very large variability of these events (e.g. long return period of floods), complexity of processes (thermodynamic, dynamic, feedbacks) that combined to trigger them, and short observation records (usually a few decades).

Brittany has warmed about 1 °C over 1946-2006 (Conseil Scientifique de Bretagne, hereafter CSEB (2012)), and neighboring Atlantic waters (e.g. Iroise Sea near Brest) have also warmed since the end of XXth century (ODEM, 2012). The warming of Brittany corresponds to about 0.2-0.3 °C/decade over 1959-2009 (CCVA, 2020), occurring similarly in Lorient (CCVA, 2020) near the Gulf (about 50km from Vannes). This warming is stronger in autumn and summer, and in minimum daily temperatures, detectable despite a large interannual variability of temperature (especially in winter; Météo-France (2012)). Similarly, the warmest summers have occurred in recent decades (1976, 1983, 2003) while cold spells have decreased (frequency, intensity, length) and the number of hot days has increased (CSEB, 2012; Météo-France, 2012; ODEM, 2012).

1.3.2 Precipitation, sealevel rise and coastal hazards

The detection of climate change trends in the evolution of precipitation is more difficult than for temperature, because these trends are weak and can reverse due to the large variability of precipitation from year to year (linked to fluctuations in ENSO and NAO; CSEB (2012); Météo-France (2012)). The location of Brittany complicates this detection further, situated between opposing precipitation responses to climate change: annual decrease in the Mediterranean and increase in Northern Europe (CSEB, 2012; Hartmann et al., 2013). Observations indicate that annual precipitation increased in Brittany over the last decades (e.g. in Lorient over 1959-2009; Météo-France (2012); CCVA (2020)), due to the intensification of the hydrological cycle (evaporation, precipitation) and increase in frequency of heavy rainfall events (Météo-France, 2012).

This annual increase corresponds to weak seasonal trends (winter, summer) that depend on the location and are small by comparison to the interannual variability (CSEB, 2012; ODEM, 2012; CCVA, 2020). In Morbihan, the evolution of precipitation shows an increase in winter and small decrease in summer (CCVA, 2020). The full attribution of causes for these evolutions remains difficult due to the overlapping roles of climate change, natural variability (ENSO, NAO), and local anthropogenic factors (e.g. land-use change; CSEB (2012); ODEM (2012)). Similarly to precipitation, droughts follow large natural variability and are recurrent in Brittany since the start of the XXth century (CSEB, 2012). The evolution of soil conditions (humidity, drought extent) since 1959 does not show the emergence of trends in droughts (CCVA, 2020).

Sealevel rise is a more robust indicator of global warming, measured at about 1 mm/year over 1906-2006 in Brest (ODEM, 2012). This rise accelerated in the last decades, now about 3-4mm/year (Oppenheimer et al., 2019). This acceleration combined to the subsidence of Southern Brittany (about 1mm/year; DDTM (2020)) and increase of extreme weather events (heavy rainfall, storm surges) leads to an increasing risk of marine submersion in the Gulf (DDTM, 2020). An increase of coastal hazards (frequency, intensity) at the end of XXth century was found by Henaff et al. (2018) but the scientific literature diverges on the interpretation of this trend in Northwestern Europe. In particular, the influence of climate change on the local occurrence of storms is difficult to determine due to large interannual variability (intensity, direction, frequency) and short observation records (CSEB, 2012).

1.3.3 Local effects and future changes

The effects of climate change are already perceptible in the Gulf of Morbihan on the natural environment and economic activities, especially on the shore or in relation to water (CCVA, 2020). Examples are changes in hydrology and heatwaves for tourism and health, seasonal changes in temperature and precipitation for agriculture, and increase in extreme events for infrastructure (CCVA, 2020). Brittany is projected to experience further climate change and increasing consequences on the environment and society. The warming of Brittany is projected to continue until 2050 regardless of the GHG emission scenario (CCVA, 2020).

Beyond 2050, this warming largely depends on the choice of scenario. Anticipating local impacts in Morbihan is difficult due to the uncertainty in location and magnitude of changes (ODEM, 2012). However, some general trends of future climate change emerge, modulated by scenario, time horizon, and climate model. Future warming is associated to more hot days, hot nights, and heatwaves, and fewer frost days and cold spells (Météo-France, 2020e; CCVA, 2020). Projections show little evolution of annual precipitation (ODEM, 2012), but an increase of atmospheric and soil droughts (frequency, intensity, length; ODEM (2012); Météo-France (2020e)), and in the intensity of extreme rainfall (Météo-France, 2020e).

In essence, thermodynamical changes are rather reliable, but dynamical changes are more uncertain as well as the associated extremes (e.g. storm surges). Despite this uncertainty, the present pattern of observed effects from climate change is expected to intensify in the future as climate change progresses (CCVA, 2020). The present adaptation of the Gulf to future climate change is therefore necessary. This adaptation depends on the reliability of anticipated changes (atmospheric thermodynamics), associated uncertainties (atmospheric dynamics, extreme events, modeling flaws, climate surprises), and societal factors (socioeconomic trajectory, ability to adapt).

1.4 Climate change adaptation

1.4.1 Land-use planning

A major avenue for the local adaptation of the territory to climate change is through the planning of the land-use. In the Gulf of Morbihan, the local context of land-use planning is complicated due to the overlap of numerous policies from multi-scale governance: European, French, Breton, and Vannes-Agglomération (CCVA, 2020; DDTM, 2020). The main planning tools at the local level are:

- The SMVM (Schéma de Mise en Valeur de la Mer) since 1983 for the planning, risk management and economic development of the coastal territory
- The Charter of PNR since 2014 for sustainable development
- The PCAET (Plan Climat Air Energie Territorial) since 2015 for climate change mitigation and adaptation, air and energy
- The SCOT (Schéma de Cohérence Territoriale), PLU (Plan Local d'Urbanisme), PLH (Plan Local de l'Habitat), and PDU (Plan de Déplacements Urbains) for urban planning
- The SAGE (Schéma d'Aménagement et de Gestion des Eaux) and SDAGE (Schéma Directeur d'Aménagement et de Gestion des Eaux) for water management
- The PPRL (Plan de Prévention des Risques Littoraux) for the management of coastal risks through land-use planning

- The GEMAPI (Gestion des Milieux Aquatiques et Prévention des Inondations) and PAPI (Programme d'Actions de Prévention des Inondations) for the management of water environments and risks

Originally, local climate policy and adaptation planning were directed in France by top-down national and European strategies (Bertrand, 2013; Reckien et al., 2014; Richard, 2016). Until climate planning became compulsory at city level in 2012 (da Cunha et al., 2020). In the same year, a local report in the Gulf recommended to raise the awareness of the inhabitants to climate change, to start the overall adaptation of society, and to prioritize adaptation measures (urgency, uncertainty, risks vs. benefits; ODEM (2012)). Currently, the climate planning of the Gulf is contained essentially in the PCAET and SMVM reports from 2020 (CCVA, 2020; DDTM, 2020). This local planning is however dedicated much more to climate change mitigation (e.g. energetic transition) than to climate change adaptation, as was the case a decade ago (Queffelec, 2009). The preference for mitigation over adaptation was also the viewpoint of the Gulf inhabitants in 2011 (ODEM, 2012).

1.4.2 An adaptation gap?

This situation is not singular, since the focus in France for the last decades has been to mobilize society on climate change mitigation (Sénat, 2019). The focus on mitigation, combined to the practical complexity of local adaptation measures, resulted in a vast adaptation gap nationwide (Simonet, 2017; Sénat, 2019; Simonet and Leseur, 2019). The gap was made evident on the Atlantic coast when the Xynthia storm in 2010 caused large damages and tens of death in unprepared territory (Genovese and Przulski, 2013; Chadenas et al., 2014; Creach et al., 2015; Madelenat, 2019). Yet the local adaptation has increased only slowly since a decade, based on the PCAET and SMVM reports. An additional indicator of the low priority given to climate lays in the Atlas de l'environnement (online knowledge base from Morbihan) that dates back to 2010 (Département du Morbihan, 2021).

The description of climate change and adaptation plans in the 2020 PCAET are important to consider. The recent evolution of climate is based on data from the weather station of Lorient (50km from Vannes), while the future evolution of climate is at the scale of Brittany (CCVA, 2020). The effects of climate change on the Gulf are then assessed through a SWOT analysis (strengths, weaknesses, opportunities, threats) for each part of the environment (e.g. water) and economy (e.g. tourism). The PCAET finally gives a roadmap of 47 planning actions (several about adaptation) for the territory over 2020-2025, articulated with other planning tools (SCOT, etc.). Therefore, the low precision of the climate change assessment, and the low priority given to climate change adaptation, can be considered shortcomings in the current land-use planning.

The research presented in the following chapters addresses the gaps identified above (climate change assessment, adaptation planning) and was conducted over 2018-2020, mostly before the release of the new PCAET and SMVM. Chapter 2 will present the research approach, and the subsequent chapters will describe the application, results and discussion of this approach.

Summary of Chapter 1

Context and objectives:

The goal of this chapter was to provide the general context of the case study area (social, environmental, climatic) and to highlight potential gaps regarding climate change and adaptation.

Methods and results:

I analyzed the scientific and grey literature about the Gulf of Morbihan. This analysis revealed several particularities of the area:

- There is a sharp contrast (economy, demography) between coastal and inland territory
- The population and socioeconomic activity are strongly seasonal (tourism, agriculture)
- The inner sea and rocky hills generate a microclimate (milder temperature, higher precipitation)
- The coastal area concentrates both societal stakes (population, urban infrastructure) and climate change risks (weather extremes, marine submersion)

The local climate is generally warm, wet, windy and sunny. The oceanic peninsulas are affected by coastal hazards, and Vannes is prone to flooding from storm surges and river overflow. Climate change has already affected Brittany in several ways over the last decades (warming, precipitation, sealevel rise), and some effects have also been perceived in the Gulf (seasonal temperature and precipitation, coastal erosion). In the future, the region is expected to warm further and to experience more extremes (heat-waves, droughts, heavy rainfall).

Two issues emerged from my literature analysis of the situation in the Gulf. First, the low precision of the local assessment of climate change, based on nearby weather stations (e.g. Lorient at about 50km of Vannes) for the past, and based on Brittany for the future. Second, the low priority given to climate adaptation in local planning, where the focus is rather on climate mitigation.

Perspectives and link to next chapters:

The gaps identified in this chapter (climate change assessment and adaptation) are addressed in the next chapters. In chapter 2, I will present the overall research approach, and the following chapters will describe the application, results and discussion of this approach.

"Elizabeth Swann: This is madness.

Jack Sparrow: This is politics."

Pirates of the Caribbean: At World's End

Chapter 2

A localization approach to co-develop climate services supporting local adaptation

2.1 Barriers to the use of climate science for adaptation

2.1.1 The climate usability gap

The expression "Valley of death" depicts the abyss laying between original research in a scientific field and its translation to derived operational products and services (Barr et al., 2009; Brooks, 2013; McIntyre, 2014). The manifestation of this abyss in the case of anthropogenic climate change is the "climate usability gap" persisting between scientific understanding and societal action. This usability gap corresponds to the fact that climate science remains underused and/or inappropriate to inform adaptation action (Lemos et al., 2012; Kirchhoff et al., 2013; Hewitt et al., 2017; Jagannathan, 2019; Griggs et al., 2020).

This remains true despite the global progress of climate change and of the underlying science (Masson-Delmotte et al., 2018a; Jia et al., 2019; Pörtner et al., 2019). Climatologists have focused on increasing the supply and quality of the scientific knowledge on climate change. However, many decision-makers do not seem to find most of this information relevant enough or useful for practice (e.g. Jones et al. (2017)). Their specific needs often go unmet; they might not even know of the existence of potentially useful information (e.g. McNie (2007)). A growing body of the literature in social science has identified the reasons for this gap, with barriers on both the demand's and supply's sides (Table 2.1).

Table 2.1: Examples of barriers to the use of climate science for adaptation.

Side	Barriers	References
Demand	Institutional and governance issues	Ekstrom and Moser (2014)
	Institutional risk aversion	Rayner et al. (2005); Lemos et al. (2012); Kuhlicke and Demeritt (2014)
	Limited resources and scientific capacity within organizations	Tribbia and Moser (2008); Lemos et al. (2012); Wilby and Keenan (2012); Porter et al. (2015); Jones et al. (2017)
	Perceived relevance to institutional mandates and priorities	Tang and Dessai (2012); Archie et al. (2014); Porter et al. (2015); Jones et al. (2017); Flagg and Kirchhoff (2018)
	Attitudes, values, and motivations of actors	Ekstrom and Moser (2014)
	Perceived risk that is low or absent	Lemos et al. (2012)
	Not knowing where to find or how to use the information	Kiem and Austin (2013a); Soares and Dessai (2016)
	Inappropriate information (format, detail)	Kiem and Austin (2013a)
	Scale mismatch (temporal, spatial)	Rayner et al. (2005); Archie et al. (2014); Jones et al. (2017)
	Low reliability and skill of the information	Soares and Dessai (2016)
	Confusion about scientific uncertainty	Meah (2019)
	Excessive uncertainty	Lemos et al. (2012)
	Terminology mismatch and unrealistic expectations	Briley et al. (2015)
	Convenience and accessibility	Demeritt and Langdon (2004); Jones et al. (2017)
	Trust and familiarity	Demeritt and Langdon (2004); Kiem and Austin (2013a); Archie et al. (2014); Jones et al. (2017)
Scientific competence and familiarity	Tang and Dessai (2012)	
Supply	Cognitive and institutional divide between science and policy	Porter et al. (2015)
	Divide between policy and context of scientific knowledge production	Sarewitz and Pielke Jr (2007)
	Widespread belief that science automatically translates to societal benefits	Sarewitz and Pielke Jr (2007); Meyer (2011))
	Prioritization of curiosity-driven research over policy-maker concerns	McNie (2007); Meyer (2011)
	Ignorance of decision-making context	Kolstad et al. (2019)
	Struggle of experts to respond to non-experts	Porter and Dessai (2017)

2.1.2 Climate services to the rescue?

The progress of the relatively new and rapidly evolving field of climate services is increasingly bridging this gap between science and action (Hewitt et al., 2012; Vaughan and Dessai, 2014; Hewitt et al., 2020). Many definitions of climate services exist; in this work we will use the following (which is frequently adopted since its formulation in Vaughan et al. (2018)): "the production, translation, transfer, and use of climate knowledge and information in climate-informed decision-making and climate-smart policy and planning". Despite the growth of the climate service field, and progress in reducing the usability gap, the use of climate science by decision-makers remains limited (Brasseur and Gallardo, 2016; Weichselgartner and Arheimer, 2019; Raaphorst et al., 2020).

This limit has been framed in the literature on climate services as an issue of accessibility and usability, in

addition to the barriers regarding the use of climate science by decision-makers (Table 2.1). That situation can appear paradoxical, since climate services initially emerged to make climate science more accessible and usable by non-scientists. The multitude and diversity of climate services can make them hard to navigate and might have contributed to this situation. Although recent efforts have helped by mapping the sources of climate information (Hewitson et al., 2017; Swart et al., 2017; Vaughan et al., 2018; Miranda Espinosa et al., 2020), it remains difficult for the layperson to cross the Valley of Death from his or her side.

Yet it is also difficult for climate service producers (often climatologists) to cross the Valley from their side (Table 2.1). This list of barriers (Table 2.1) to the use of climate science for adaptation is long but not exhaustive (Amundsen et al., 2010; Moser and Ekstrom, 2010; Fieldman, 2011; Gifford, 2011; Hamilton, 2011; Measham et al., 2011; Fressoz and Bonneuil, 2016; Bushell et al., 2017). However, the identification of these barriers is a first step towards overcoming them and the scientific literature has identified opportunities to do so (Dilling and Lemos, 2011; Lemos et al., 2012; Kirchhoff et al., 2013; Vaughan and Dessai, 2014; Vaughan et al., 2016, 2018; Kolstad et al., 2019; Palutikof et al., 2019). Accordingly, many approaches have been developed in the last two decades, some in the most recent years, in order to increase the usability of climate science.

2.2 A classification of climate service approaches

Different approaches can be distinguished in the field of climate service practice (e.g. Beier et al. (2017)). These approaches can be classified (Table 2.2) according to the situation of the provider (first category), and to the nature and trajectory of the climate knowledge (second category).

The first category of approaches corresponds to the variety of circumstances associated to the functions of the climate service provider. The second category corresponds to the different ways of making and sharing knowledge between the producers and users of climate services. The range of approaches in both categories follows a gradient of connection between producers and users, from disconnection towards coupling. The following paragraphs will describe each approach.

2.2.1 Based on the situation of the provider

The first approach of the first category (according to the provider situation) is contractual research, in which scientists are contacted by users to deliver a specific product that may be used later (Beier et al., 2017). Contractual research can also be understood another way, as in the example given by Biggs (1989) of scientists contracting farmers to use their land for experiments. In this case, contractual research is conducted academically with the intention of developing real-world applications, but not to answer user-driven questions (Meadow et al., 2015). Regarding the general purpose of climate services, we will consider mostly the first perspective, such as a regional agricultural

Table 2.2: A classification of climate service practices.

Category	Approach	Short description	Example	References
Provider situation	Contractual research	Scientists are contracted by users to deliver specific products	Climatologists contracted by farmers about temperature and rainfall for the next seasons	Biggs (1989); Changnon et al. (1990); Meadow et al. (2015); Beier et al. (2017)
	Training scientists to work with users	Providing scientists with user-oriented skills (e.g. assessing user needs, engaging stakeholders and collecting feedback, activities of tailoring, translation and dissemination)	NOAA scientists getting trained to provide technical information to local users	Jacobs et al. (2005); Dilling and Lemos (2011); Timofeyeva and Mayes (2011); Pathak and Lúcio (2018); Mahon et al. (2019)
	Boundary organizations	Intermediaries between science and practice, facilitate the interaction between producers and users and stabilize the science-policy interface	RISAs support research focusing on water resource problems in specific regions, linking scientists with policy-makers and water resource managers	Gieryn (1999); Cash (2001); Guston (2001); Cash et al. (2002); Feldman and Ingram (2009); Dilling and Lemos (2011); Kirchhoff et al. (2013); Meadow et al. (2015); Zulkafli et al. (2017); Franklin et al. (2019)
	Embedding scientists in agencies	Scientists working in agencies and doing research that directly supports policy-making, decision-making or resource management	Water management organizations in the US Southwest hiring scientists since 2006 to incorporate climate information into decision-making	Pagano et al. (2001); Lowrey et al. (2009); Pouyat et al. (2010); Dilling and Lemos (2011); Jenkins et al. (2012); Cook et al. (2013)
Knowledge nature and trajectory	Loading dock model	Information is produced and made accessible by scientists who assume it will be useful to potential users	"National Weather Services, in general, have... the loading-dock approach to forecasting. You take it out there, and you leave it on the loading dock and you say, there it is. And then you walk away and go back inside."	Cash et al. (2006); Feldman and Ingram (2009); Johnson and Weaver (2009); Dilling and Lemos (2011); Garfin (2014); Bremer and Meisch (2017); Jacobs and Street (2020)
	User-inspired research	Focus on end-use and on advancing fundamental scientific understanding	Basis of programs from agencies (e.g. NOAA, RISAs) to develop usable science	Dilling and Lemos (2011); Stokes (2011); Lemos et al. (2012); Kirchhoff et al. (2013); Wall et al. (2017)
	Knowledge exchange	Bring together the different types of knowledge and experiences between users and producers, to shape the production of new (improved) knowledge	Experimented in the Swedish forestry sector and by NOAA programs to integrate locals for building trust, shaping climate information, and improving knowledge usability	Hegger et al. (2012); Fazey et al. (2013); Archie et al. (2014); Klenk et al. (2017); Kruk et al. (2017); Zulkafli et al. (2017); Gerger Swartling et al. (2019)
	Social learning	Iterative exchange and learning of knowledge and practices between diverse users and producers, leading to the co-creation of new knowledge and changes in practices, from the scale of individuals to communities or systems	Used in the CLIMAS program to situate science within the social context of the complex issues related to climate change	Harvey et al. (2012); Kristjanson et al. (2014); Ensor and Harvey (2015); Owen et al. (2019)
	Co-development	Collaboration (often iterative) between scientists and users to transform scientific knowledge into actionable information, e.g. collective framing of analysis (research questions, methods, findings)	Ouranos climate scenarios in Canada, UK climate programme (predictions and projections), a Canadian energy company (forecasts and projections for hydroelectric power management), Australian sugar industry (forecasts of seasonal risks)	Lemos and Morehouse (2005); McNie (2012); Huard et al. (2014); Meadow et al. (2015); Vaughan et al. (2016); Hewitt et al. (2017); Bremer et al. (2019b)

committee asking climatologists about key climate parameters (e.g. temperature, rainfall) over the next seasons (Changnon et al., 1990).

The second approach is scientists getting trained to improve their ability to work at the interface with users (Timofeyeva and Mayes, 2011; Pathak and Lúcio, 2018). My PhD thesis is carried out in this sense. This training provides scientists with skills similar to those of knowledge brokers who are fluent in both worlds of production and use (Jacobs et al., 2005; Dilling and Lemos, 2011). Evidence shows that there is currently little room for user-oriented aspects of climate services (such as assessing user needs, stakeholder engagement and translational activities) in the training of personnel within the centers of National Meteorological and Hydrological Services (NMHSs) of many countries (Mahon et al., 2019). Examples of training exist however such as in the National Oceanic and Atmospheric Administration (NOAA) and in the projects participating to the Global Framework for Climate Services (GFCS). Since 2002, NOAA has offered communication training to scientists on the provision of technical information to local users (Timofeyeva and Mayes, 2011). Similarly, many GFCS projects have trained both producers (to better tailor, disseminate, and collect feedback about climate information) and users (to access and use weather and climate information) of climate services (Pathak and Lúcio, 2018).

Boundary organizations represent the third approach, filling the gap between science and decision-making. They act in this context as science-policy intermediaries between different organizations, disciplines, and practices (Gieryn, 1999; Cash, 2001; Guston, 2001; Cash et al., 2002; Dilling and Lemos, 2011; Meadow et al., 2015; Franklin et al., 2019). Boundary organizations facilitate the interaction between science producers and users at different scales (Zulkafli et al., 2017), and stabilize the science-policy interface against the influence of external factors such as politics (Guston, 2001; Kirchhoff et al., 2013). Two examples of boundary organizations are the Regional Integrated Sciences and Assessments (RISAs), and the Environmental Decision Support Systems (EDSSs). RISAs encourage targeted research on highly focused problems of water resource in specific regions, linking scientists, policy-makers and water resource managers (Feldman and Ingram, 2009). EDSSs can take the form of web tools, they support decision-making and can be tailored to different decision contexts (McIntosh et al., 2011; Zulkafli et al., 2017).

The last approach of the first category is to directly have research scientists embedded in organizations (policy, decision-making, resource management). For instance, having scientists inside federal agencies (e.g. Pouyat et al. (2010); Cook et al. (2013)) can increase the likelihood that their research findings are implemented, while providing opportunities for them to learn from management action (Jenkins et al., 2012). In some cases, organizations even hired people explicitly to incorporate climate information into decision-making, such as water management organizations in the Southwest of the United States' (US) since 2006 (Lowrey et al., 2009). Having scientists inside the organization can institutionalize the use of forecasts since managers tend to put more trust in internal products than external ones (Pagano et al., 2001).

2.2.2 Based on the nature and trajectory of the knowledge

The first approach of the second category (according to the nature and trajectory of the knowledge) is the loading dock model. This approach is dominant in science and climate services, with scientists preparing information (e.g. models, products, forecasts) for general use and making it accessible, with the expectation that potential users will find the information useful (Cash et al., 2006; Feldman and Ingram, 2009; Johnson and Weaver, 2009; Dilling and Lemos, 2011; Garfin, 2014; Bremer and Meisch, 2017; Jacobs and Street, 2020). However, this information is generally prepared without consulting the anticipated user, or understanding his or her needs. The "stovepipe" and "pipeline" mindsets (Feldman and Ingram, 2009) are siblings of the loading dock model where the information tends to flow in narrow channels or, taking the analogy of oil, from the well head (scientists) to the storage tanks (the brains of those who need it). This kind of approach is summed up nicely by the following quote:

"National Weather Services, in general, have... the loading-dock approach to forecasting. You take it out there, and you leave it on the loading dock and you say, there it is. And then you walk away and go back inside." (Cash et al. (2006), p.20)

The second approach, user-inspired research (Figure 2.1), goes beyond the loading dock model by largely engaging the end-users in the research process in order to produce information that supports decision-making (Wall et al., 2017). Use-inspired research has been the basis of many programs from agencies (e.g. NOAA, RISAs) for developing usable science, and can be characterized by a multi-directional flow of information and knowledge where the multiple perspectives from the different participants are considered (Wall et al., 2017). This approach resembles

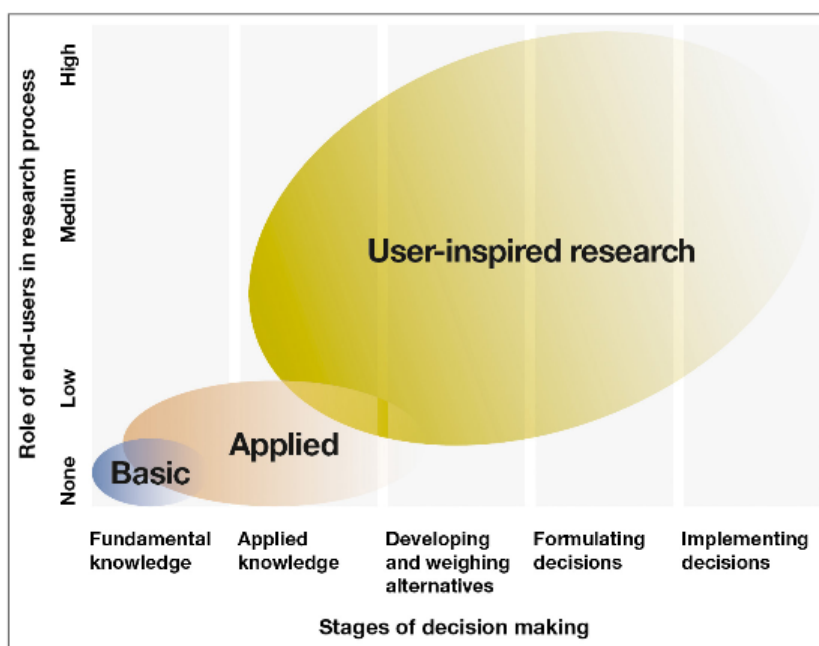


Figure 2.1: Schematic representation of three types of research (basic, applied, and user-inspired) in relation to the roles of end-users in the research process, and the types of decisions being made. From Wall et al. (2017).

applied research in the importance that is given to the end-use of the research. Yet, it differs in also prioritizing the advancement of fundamental scientific understanding (Stokes, 2011; Kirchhoff et al., 2013). Scholars argue that user-inspired knowledge is useful but that additional steps are needed from users and producers to make this knowledge usable (Dilling and Lemos, 2011; Lemos et al., 2012).

Knowledge exchange is the third approach, based on the exchange of different types of knowledge (e.g. tacit, traditional or indigenous, citizen science, academic research) between users and producers (Zulkafli et al., 2017). It was proposed by scholars to outperform "one-way" approaches of knowledge transfer (e.g. contractual research, loading dock model) for expanding and improving the field of knowledge production (Fazey et al., 2013; Klenk et al., 2017; Gerger Swartling et al., 2019). Knowledge exchange is gaining momentum in the scientific realm (transdisciplinary research between disciplines; Leavy (2016)), between science and policy in environmental sciences (Hegger et al., 2012; Fazey et al., 2013; Reed et al., 2014; Thompson et al., 2017; Hansson and Polk, 2018), and in climate adaptation (Klenk et al. (2017); Gerger Swartling et al. (2019)). A few definitions of knowledge exchange have been suggested in the literature, such as:

- The sharing of knowledge, experiences and opinions based on open communications within collaborative environments (e.g. workshop, conference or meeting; Brandt et al. (2013))
- Processes that generate, share and/or use knowledge through various methods appropriate to the context, purpose, and participants involved (Fazey et al., 2013). Such as including local communities through interviews, surveys, focus groups, and participatory workshops (Fazey et al., 2010)
- The way knowledge is produced, shared with and between those who might use it, translated and/or transformed at it is shared, and the social context in which people learn about new knowledge (Reed et al., 2014). An example given by Reed et al. (2014) of effective knowledge exchange is the long-term relationship of trust and exchange between researchers and stakeholders to produce new knowledge for environmental management
- The process of producing usable or actionable science through collaboration between scientists and those who use science to make policy and management decisions (Meadow et al., 2015). Meadow et al. (2015) suggest that researchers should pick the most effective mode of engagement and research approach depending on the decision-makers (questions, context and resources)

This co-production of knowledge was experimented in the Swedish forestry sector (Gerger Swartling et al., 2019) and by NOAA programs (Kruk et al., 2017) to reframe the science-society interface (by better including the local and cultural contexts) and to improve the knowledge usability. Knowledge exchange also built trust between the scientific and user communities, and empowered local communities to shape climate information products. The deliberative quality (i.e. capacity to debate) and the engagement of actors (e.g. through iterative dialogue) are critical aspects for joint knowledge production. They can improve the long-term commitment of actors and the environmental

effectiveness of a research project (Hegger et al., 2012). While climate adaptation research is increasingly mobilizing local knowledge, a large part of this mobilization is however happening as "extraction" rather than a tangible exchange of knowledge (Klenk et al., 2017).

The fourth approach is social learning applied to climate adaptation (Harvey et al., 2012; Ensor and Harvey, 2015). Social learning can be defined as cycles of knowledge sharing and joint action to co-create knowledge, relationships, and practices among diverse stakeholders (Ensor and Harvey, 2015). These cycles result in learning and change going beyond the individual into communities, networks, or systems (Kristjanson et al., 2014). This approach expands on the concept of knowledge exchange by explicitly seeking to engage stakeholders in a process of knowledge creation that induces behaviour change through a shared process of learning by doing (Harvey et al., 2012). Social learning can enable the emergence of new shared knowledge that leads to changes in practices (Kristjanson et al., 2014; Ensor and Harvey, 2015). It can also support local-level climate adaptation since adaptive practice is often closely linked to the everyday practices of local communities (Harvey et al., 2012). Social learning was for instance used in the Climate Assessment for the Southwest (CLIMAS) program of the United States in order to better situate science within the social context of the complex issues related to climate change (Owen et al., 2019). Scholars involved in CLIMAS lamented the scarce use of social learning in climate services.

2.2.3 Co-development: an hybrid approach

The last approach of the second category is the co-development (also termed co-production or co-construction) of climate services. This co-development builds on knowledge exchange and social learning, by producing usable (or actionable) science through collaboration (often iteratively) between scientists and those who use science (e.g. decision-makers, policy-makers, resource managers). It has become a promising way to develop usable climate knowledge (McNie, 2012; Meadow et al., 2015; Vaughan et al., 2016; Hewitt et al., 2017; Bruno Soares and Buontempo, 2019). This collaboration between scientists and users aims at framing the research questions, choosing how to answer these questions, and analyzing the findings, all in a collective way (Lemos and Morehouse, 2005). The co-development of climate services is therefore suitable to address problems involving multiple scales (spatial, temporal), where one does not know in advance the information that is needed (Beier et al., 2017).

It is also appropriate for users needing guidance on a variety of decision-making contexts (Beier et al., 2017). For instance, climate services were tailored through co-development with users for the UK climate programme (climate predictions and projections), a Canadian energy company (climate forecasts and projections for hydroelectric power management), and the Australian sugar industry (forecasts of seasonal climate risks; Hewitson et al. (2017)). Another example of climate service codevelopment is the tailoring of climate scenarios by Ouranos (Canadian nonprofit consortium) with users of the impact and adaptation communities (Huard et al., 2014). This tailoring allowed to develop scenarios that are suited to the needs and levels of climate expertise from the end users. Although I have

defined co-development here in a general way, there are diverse ways to co-develop depending on the context and research questions at play (e.g. Bremer et al. (2019b)).

2.2.4 Recommended practice

We can draw general recommendations for climate service practice (Table 2.3), based on the overview of the barriers in the use of climate science for adaptation, and on the review of climate service approaches. Table 2.3 aims to work as a guidance sheet, summarizing negative and positive elements of practice for different aspects of a climate service.

Table 2.3: Guidance for climate service practice.

Climate service aspect	Practice	Recommended practice
Design	<ul style="list-style-type: none"> • Unclear who will use the service • Developed without involving users 	<ul style="list-style-type: none"> • Contact with potential users • Produced with potential users
Accessibility	<ul style="list-style-type: none"> • Information difficult to find and/or to understand 	<ul style="list-style-type: none"> • Online (and free) service • User-friendly (and interactive) • Information suitable to user level of expertise
Transparency	<ul style="list-style-type: none"> • Methods difficult to find and/or to understand • Unclear mission of service provider 	<ul style="list-style-type: none"> • Accessible and clear methods and uncertainties • Provider trustworthiness
Relevance and usability	<ul style="list-style-type: none"> • Irrelevant variables and/or scale (spatial, temporal) • Uncertainty too large 	<ul style="list-style-type: none"> • Appropriate information and format for user need • Amount of uncertainty allows decision-making
Feedback and improvement	<ul style="list-style-type: none"> • Non-existent 	<ul style="list-style-type: none"> • Contact possibility • Activities with users • Service updates

2.3 Localization: a place-based practice of co-development

2.3.1 Objectives, challenges and limits of co-development

The co-development of climate services has several specific advantages but also disadvantages (Table 2.4). In addition to these disadvantages, the perspective of co-production as an iterative interaction between producers and users has been so dominant (Lemos and Morehouse, 2005; Cash et al., 2006; Dilling and Lemos, 2011; Kirchhoff et al., 2013) that scarce alternative practices have emerged (e.g. Lövbrand (2011); Hegger et al. (2012); Bremer et al.

(2019b)). This situation is illustrated by the ADAM research project (Adaptation and Mitigation strategies: Supporting European Climate Policy) where the co-production was framed too restrictively:

"By granting a small and powerful group of EU policy-makers the mandate to determine what counts as useful knowledge, the policy appraisal process gave the participants little room to imagine things differently." (Lövbrand (2011), p.10)

Table 2.4: Examples of benefits and challenges in the co-development of climate services.

Co-development	Examples	References
Benefits	Versatility and flexibility	Beier et al. (2017)
	Customization and usability	Dilling and Lemos (2011); Kirchhoff et al. (2013)
	Users better informed and skilled about science and impacts	Kruk et al. (2017)
	Tailored service and access to climate expertise	Buontempo et al. (2018)
	Credible, salient and legitimate knowledge	Vincent et al. (2018)
	Improve the integration of multiple knowledge systems into decision-making processes	Cvitanovic et al. (2019)
	Stimulate learning among participants	Cvitanovic et al. (2019)
Challenges	Managing user engagement (time, effort, resources, continuity)	Rickinson et al. (2011); Kruk et al. (2017); Lemos et al. (2019)
	Power imbalances in the participation process	Few et al. (2007); Balvanera et al. (2017); Blythe et al. (2017)
	Compromising the perceived scientific integrity of the output	Mausser et al. (2013); King and O'Meara (2019)
	Antagonizing scientific peers	Polanyi and Cockburn (2003); Porter and Dessai (2016)
	Usability gap wider than anticipated	Kolstad et al. (2019)
	Dealing with uncertainty cascades	Briley et al. (2015)
	More expensive than conventional modes of knowledge production	Lemos et al. (2014)
	Risks becoming an end in itself, rather than the means for better engagement and knowledge use in decision-making	Lemos et al. (2018); Suldovsky et al. (2018)

In the trade-off between research co-produced for the knowledge needs of societal decision-makers, and co-produced for seeking to challenge and transform existing ways of thinking, the former took over the latter. Lövbrand (2011) argues that co-production should question the meaning and value of knowledge while exploring ways to make research applicable to societal problem-solving. Similarly, Hegger et al. (2012) suggest that research projects should not be framed too restrictively, but rather have room for reflexivity and space for making mistakes and learning (trial-and-error process).

Beside the limited framing of climate service co-production and the scarce emergence of alternative practices, some scholars have identified a lack of empirical inquiry (Moss et al., 2013) and a need for more analysis of the practice of co-production (Bolson and Broad, 2013; Porter et al., 2015; Lorenz et al., 2017). Another main challenge in the co-construction of climate services is the need to "localize" climate science (Krauss, 2010, 2016; Krauß and

Bremer, 2020). These five shortcomings could be tackled by experimenting the co-development of climate services through the localization of climate science.

2.3.2 The localization of climate science

In the co-production of climate services, localization is the process of integrating the local-level context (cultural, economic, etc.) of climate change for the users. During localization, scientists must interact with local populations in specific places to renegotiate the definitions of "local" and "global". These negotiations also have to extend the understanding of climate change from a scientific concept towards a locally meaningful one. In this manner, localization supports the co-development of "place-based" climate services for users in a particular location, such as local communities in a territory. The localization of climate services can include the need to situate them in the broader context of the ongoing local activities (economic and social e.g. da Cunha et al. (2020)).

Table 2.5: Examples of issues in climate adaptation and objectives for the localization of climate science.

	Examples	References
Climate adaptation issues	Gap between climate change science and local perceptions and concerns from population	Krauss (2010); Krauß and Bremer (2020)
	Gap between climate services and local experience and action regarding climate change	Krauss (2010); Krauß and Bremer (2020)
	Mismatch between measures suggested by global experts and action taken by locals	Hooke and Pielke Jr (2000); Kirchhoff et al. (2013); van der Sluijs and Wardekker (2015); Haque et al. (2017); Lorenz et al. (2017); Bremer et al. (2019a)
Localization objectives	Focusing on environmental matters that matter to local communities	Baztan et al. (2017)
	Rooting climate science in the local context of society	Von Storch et al. (2011); Buizer et al. (2016); Flagg and Kirchhoff (2018); Owen et al. (2019)
	Climate change stops being an abstract fact and becomes a legitimate concern for communities	Bremer et al. (2020); Krauß (2020); Marschütz et al. (2020); Vanderlinden et al. (2020)
	Rooting climate risk governance in local experience, knowledge and practices of populations	Krauss (2010); Krauß and Bremer (2020)

Localization is a bottom-up approach contrasting with the usual top-down science-based approach (Bremer et al., 2019b). It addresses a few issues in climate adaptation (Table 2.5). Climate change can be seen as a multi-level challenge of governing policy action (local, regional, national; Jensen et al. (2020)). However, climate risk governance appears rather like a patchwork of connected activities that are partially linked to climate science (Krauß and Bremer, 2020), and partially appropriated by communities to their local places, concerns and purposes (Ryghaug, 2011; Bremer et al., 2019a). Trust is an important aspect for climate risk governance and local appropriation, as it can influence concrete action through the feeling of individual responsibility and the support for policy measures (Bodor

et al., 2020). Moreover, the identification of what counts as salient climate information locally, for now and tomorrow, remains the subject of an active debate (Krauss, 2010; Lemos et al., 2012; Porter et al., 2015; Cortekar et al., 2016; Hackenbruch et al., 2017).

Bridging the divide between the scientific description and the local experience of climate change is not easy. On one hand, the scientific account of climate change deployed by global science and policy networks is powerful (Krauβ and Bremer, 2020). It influences public decision-making, spatial planning, and how we behave as individuals (Miller, 2004; Hulme, 2008; Bravo, 2009; Farbotko and Lazrus, 2012). But on the other hand, climate change remains abstract for many people (e.g. Krauβ (2020)). They do not live in an abstract climate but in "weatherworlds that structure the rhythm of life, shape everyday practices, and are woven into dreams of the future" (Ingold, 2010). One way to localize climate change is to use local narratives of change and storytelling.

2.4 The role of narratives and vision-based scenarios to localize climate science

2.4.1 Narratives in interdisciplinary climate research

Narratives are an emerging field in interdisciplinary climate research, broadening the methodology of climate research and challenging the research frame separating climate and society (Paschen and Ison, 2014; Moezzi et al., 2017; Krauβ and Bremer, 2020). They can be defined as a narrator's account of a sequence of events occurring in a defined time and place, and involving the action or interaction of characters (Bremer et al., 2017). Narrative research can also be understood more simply as the study of stories (Jones et al., 2014a; Kim, 2015). Bremer et al. (2017) has identified four areas of research in the literature on climate narratives, and I will focus on the last three:

- Historical development of dominant climate narratives at the global scale
- Critical analysis of how global narratives impact public and policy discourses in particular places
- How narratives can be used to improve the quality of what is produced by the community of climatologists
- Role of narratives as cultural context in a place for climate adaptation

Climate change research has only started recently to intersect with narrative research but there is a long history of climate narratives in society. There are a multitude of global narratives regarding climate change, some of which have divided people and nations (Liverman, 2009; Bushell et al., 2015, 2017). Moreover, the social memory of impacts from extreme weather has largely conditioned the way some communities have dealt with climate risks (Daniels and Endfield, 2009). Narratives provide a different set of tools to connect diverse societal actors, and to foster imaginative forms of collaboration and collective action (Moezzi et al., 2017). They connect the scientific and local perceptions of

the "weatherworld" (Ingold, 2010), as well as the private and public realms (Arendt, 2013). Narratives have been used to:

- Study the indigenous climate knowledge contained in stories (Krupnik and Jolly, 2002; Janif et al., 2016)
- Reconnect scientific knowledge and indigenous knowledge (Alexander et al., 2011; Whyte, 2018)
- Discuss the use of metaphors in climate change science (Jasanoff, 2010; Mayer, 2012)
- Examine how the communication of climate change science to the public can be improved (Boykoff, 2007; Wardekker et al., 2009; Nerlich et al., 2010)
- Understand how communities respond to weather events (Carmichael et al., 2020)
- Characterise climate uncertainty (Dessai et al., 2018)
- Analyze how to increase climate mitigation (Evans et al., 2014) and adaptation (Köpsel et al., 2017; Coulter et al., 2019)

For instance, narratives can support scientific production by making future climate scenarios more lifelike (Wilby and Dessai, 2010; Kok et al., 2015). They can also make scientific communication more accessible to the public (Kearney, 1994; Bushell et al., 2015). An example is popular culture (e.g. books or movies) that could reframe the perspective of the climate change problem from scientific and detached to personal and immediate (Trexler and Johns-Putra, 2011; Kaplan, 2015; Bulfin, 2017; Onyekuru et al., 2020). While popular culture has been argued to raise public concern, it is sometimes at the price of generating negative emotions (Schneider-Mayerson, 2018) or reducing public understanding (Balmford et al., 2004; Lowe et al., 2006).

The main role of narratives for climate communication and climate service co-production is recognized by the Intergovernmental Panel on Climate Change (IPCC). The IPCC acknowledges that narratives provide a social and environmental context for modelled futures, connect scientific and local forms of knowledge, and reframe the attitude towards risk and uncertainty (Jones et al., 2014b). Climate adaptation can benefit from narratives through the mobilization of context-specific knowledge of climate impacts and adaptation capacities (Lejano et al., 2013; Paschen and Ison, 2014). The lack of narrative approaches in the literature on climate adaptation has been lamented by Paschen and Ison (2014) who argued that narratives can support policy making for climate change adaptation. Several features of narratives can be relevant for climate risk governance (Krauß and Bremer, 2020):

- Materializing climate change by situating weather events (Krauß and Bremer, 2020), since people make sense of climate through their experience of the weather and seasons (Ryghaug, 2011)
- Reframing climate risks and assigning responsibilities, for instance with characters acting either as heroes, villains or victims (Jones, 2010, 2014; Fløttum and Gjerstad, 2017; Bremer et al., 2020). In this frame, climate change acts as a complication that amplifies the "old" risks (Bremer et al., 2019a)

- Facilitating the translation of climate ideas and information into action. By giving meaning or morals that motivate and legitimate local action (e.g. Bremer et al. (2020); Wildschut and Zijp (2020)). Or by inspiring a practical or emotional response (Cronon, 1992). Or through the contribution of culture to the perception of climate change (Von Storch and Krauss, 2005)
- Capturing the local cultural identity and senses of place (e.g. da Cunha et al. (2020); Marschütz et al. (2020)). Embedding community values in the narratives of science through association to art forms (e.g. Baztan et al. (2020); da Cunha et al. (2020))
- Serving as cognitive scripts for handling complexity in the context of climate and other rapid changes (Bruner, 1991; Herman, 2003). Eliciting the thoughts of people on climate risk governance through their narration of stories (Lejano et al., 2013)
- Empowering marginalised groups to contribute to a public decision-making process. By sharing people's knowledge in a way that challenges existing power structures (Bremer et al., 2017), as narratives can differ between city-level decision makers and inhabitants from vulnerable neighbourhoods (Marschütz et al., 2020)

The general narratives of climate carry a lot of influence over everyday life (Krauß, 2020) and social actors (Bremer et al., 2017), but they are politically contested. There are few similarities (e.g. Bremer et al. (2020)) and many divergences (e.g. Krauß (2020); Marschütz et al. (2020)) between local narratives along spatial scales, past and future (e.g. da Cunha et al. (2020)), institutions and social groups (e.g. Jerneck (2014)). The nature of climate change contributes to this situation with high stakes, large uncertainties, disputed values (Bushell et al., 2017), and the "struggle of traditional science" to legitimize climate change in society (Kloprogge and Van Der Sluijs, 2006; Daniels and Endfield, 2009; Hulme, 2010).

The perspective of general climate narratives can be shifted by integrating the narratives from local communities (Moezzi et al., 2017). This new perspective might be more locally relevant, by "zooming in" to better understand micro-dynamics and how things work at the local level. And by "zooming out" to analyse assumptions, beliefs and possibilities. Narrative research is not considered in this context as an extractive method of social research (Paschen and Ison, 2014). Rather as an holistic approach to better understand social and environmental systems, and to support the participatory design of local adaptation policies.

2.4.2 Local narratives of climate change

In the quest of reconnecting climate information and everyday experience in the real world, giving local meaning to climate change facts is a key challenge for narrative research. Based on the same set of scientific facts, narratives may imply different worldviews and understandings of adaptation (Thomas et al., 2016). Or a competition can occur

between local knowledge and scientific knowledge, where the reconciliation of the two knowledge systems must be negotiated for the emergence of place-based sustainability (Bremer and Funtowicz, 2015).

Abstract scientific concepts of climate change must be given contextual meaning before they can matter to local communities. Similarly to countries, regions or cities can be seen as "imagined communities" with a collective identity and meta-narratives bringing a sequential and causal order to the chaos of geophysical, meteorological, and socio-political history (Anderson, 2006). This collective identity is in permanent construction, built in part on memories and official representations of weather and climate. Therefore, local narratives connect stories and events in people's lives with the social identities and discourses that define places (such as a city; Marschütz et al. (2020)). These narratives also show how people perceive their capacity to make decisions (Bravo, 2009; Adger et al., 2013; Moser, 2014).

Local narratives can root climate governance in social life (Krauss, 2010). For instance by revealing social visions of "desirable futures" as well as the actions preferred to attain these (Somers, 1994; Paschen and Ison, 2014; Bremer et al., 2017). Or by facilitating the involvement of different actors (from communities, science and policy) in collective experimentation and learning (Paschen and Ison, 2011). Proactive adaptation in developed nations, with typically high adaptive capacity and low vulnerability to climate change, may be difficult without future-oriented narratives supporting individual and community-based adaptation (planning and practice). This is because many adaptation barriers come not from climate impacts but social constraints; social norms and time constraints can prevent to share knowledge or to discuss the problems associated to climate change and which solutions might be acceptable (Coulter et al., 2019).

Narratives are powerful: they link social history to climate (weather events and history of climate changes) and turn places into entities. Meta-narratives are even more powerful, they can change the direction of politics. However, narratives are like butterflies, momentary and difficult to catch (e.g. they can disappear and resurface). Furthermore, narratives have to be placed in the context of their construction to be understood, since they are only a snapshot of people in a given place at a given time. Scholars have identified and analyzed narratives through diverse means: stories from people, everyday conversations, metaphors, legends and myths, newspaper articles, archives, conflicts (Marcus, 1998).

The previous paragraphs have emphasized the importance of places in narratives. Time is also important, in relation to the human experience of weather and climate (Krauß et al., 2018a). There is a rich literature painting the human experience of time: in geography (Thrift, 1977a,b), history (Bender and Wellbery, 1991), anthropology (Orlove and Strauss, 2003; Douglas, 2013), and sociology (Bourdieu, 1977). A few aspects of the human experience of time are important for narratives of climate. Strauss and Orlove (2003) distinguish between the weather of everyday life, seasons that structure agriculture cycles, and climate associated to generational knowledge. But things get more complex.

Time is humanly perceived in multiple dimensions and at multiple scales, rather than strictly in the universal

dimension from physics (Thrift, 1977a,b; Gosden and Gosden, 1994). These dimensions are biological (e.g. circadian cycle that paces our body daily functions), psychological (e.g. memories and stories), and social (e.g. collective events;). The scales of time perception are individual, social, and cultural. Time is closely associated with the natural and social orders, for instance with the rhythm of seasons organizing how an agricultural community spends time over the year (in the fields and at home). Time is also dynamic. For example, climate knowledge can be considered as a knowledge aggregate from many sources at diverse timescales (Rayner, 2003; Hastrup, 2016). Also, the human experience of time can be altered by socio-physical dimensions, such as young adults induced to "behave old" and old adults induced to "behave young" (Nowotny, 1975).

Time is often framed differently between local communities and scientists (Krauβ et al., 2018a). This allochronism (i.e. different perception of time) can be settled by narratives. Narratives offer specific configurations of intersections between time and space, and can reconcile different concepts of time and complementary ways of understanding climate. These specific configurations, or "chronotopes", are locations that are charged with personal and social meaning (e.g. a river or a road; Blommaert (2015)). These chronotopes are identity markers with symbolic meaning; they give power to the landscape through the stories that people tell about particular locations. Chronotopes can provide insights into the richness of social life and record the passage of weather events (e.g. flood stones; Krauβ et al. (2018a)). In this landscape, climate change is part of the weatherworld we inhabit (Ingold, 2010) rather than a threat coming from outside (Krauβ et al., 2018a).

Catachronism, the idea of reframing the present and past in terms of a projected future (Aravamudan, 2013), is another interesting time concept for the co-construction of local climate services. This future is often designed in scientific and technical terms, with smaller roles for social and cultural dimensions. However, the adaptation of cities and territories to climate change is worth including local citizens in the process of decision-making (Wiseman et al., 2010; Preston et al., 2011). The actor-network theory can support this integration. This theory in social research assumes that the social and natural worlds are systems with elements that are interacting constantly. This assumption serves to explore hidden assumptions behind the concepts used by people (Mol, 2010).

Actor-Network Theory can help to understand the stakes at play (e.g. construction of a dike), and which people (e.g. administrators, activists, citizens) and things (e.g. rain, sea, a district) are included or excluded from the situation. This methodological stance can also help to situate climate locally, from an abstract scientific concept to a deeply local process where people and things are dynamically involved (Krauβ et al., 2019). Desired futures can play a role in this localization of climate, with interventions imagined or desired by people. The goal of adding social science to climate science in the co-development of climate services is to concretize climate knowledge in an open process with local communities. Another way to consolidate the understanding of the present (narratives of change) and future (projected climate, socially desired futures) situation is to co-construct local scenarios of future climate change with local communities.

2.4.3 Local vision-based scenarios

Many localities still assume a stable climate in the planning of their territory (e.g. Measham et al. (2011)), or they don't consider the wider implications of climate change on society and the environment (e.g. Wilson (2006)). In the quest of making science more locally meaningful, scenario approaches can complement local narratives to achieve a common framing of the changes (including climate) affecting a place. The climate research community recognizes the need to make climate change scenarios more regionally relevant for local users (O'Neill et al., 2020).

Many benefits have been identified from the use of scenario approaches for climate adaptation at global and national scales (Hulme and Dessai, 2008; Girod et al., 2009; O'Neill et al., 2014; Rothman et al., 2014). However, the currently dominant climate scenarios correspond to a relatively large scale while many societal applications require information at smaller scale (Cubasch et al., 2013; Hoegh-Guldberg et al., 2018). The empowering nature of such an approach for local communities is debated (Ensor and Berger, 2009; Shaw et al., 2009). An alternative is to develop local-level scenarios rooted in the concerns and desires of local communities, and to coalesce them with quantitative climate scenarios (Bizikova et al., 2009). The local and participatory co-construction of scenarios can be valuable to help communities facing environmental issues:

- Safe deliberation space (to express viewpoints and values; Kane et al. (2014)) and empowerment (Tattersall, 2010)
- Building trust (Van Der Sluijs et al., 2005) and joint learning (apprehending each other's framing of problems, solutions, and uncertainties; De Boer et al. (2010))
- Learning about planning priorities and the local impacts from climate change
- Unique context to identify knowledge gaps (Van Der Sluijs et al., 2005; Kloprogge and Van Der Sluijs, 2006; Bremer, 2013; Bremer and Funtowicz, 2015)
- Identifying adaptation options that are relevant and desirable (Bizikova and Hatcher, 2010)
- Producing creative visions and desires contained in the long-term future (Kok et al., 2006)

Climate plans developed in partnerships with communities are more likely to be implemented (Wiseman et al., 2010). This can be especially useful in the case of rural communities facing multiple social and economic issues alongside climate change (e.g. Kiem and Austin (2013b)). Participatory approaches show promise for climate adaptation and mitigation at the local level (Laukkonen et al., 2009). For instance, the global Shared Socioeconomic Pathways (SSPs) have been extended to sub-national scale based on a collaboration between experts (scientists) and societal stakeholders to explore migration and adaptation in three deltas of West Africa and South Asia (Kebede et al., 2018).

Visualizations can be key to support these local scenarios, such as showing different possibilities of how the future landscape could look like under climate change (Dockerty et al., 2006; Sheppard, 2012). These visualizations should be realistic and dramatic enough to attract and retain interest, while staying defensible in terms of data and methods (Sheppard, 2012). Moreover, local climate change scenarios need to be framed so that the choices are explicit between alternatives over the short and long-term, to provide clear options for action in the community (Sheppard, 2012). Another exercise that can be applied is backcasting. Backcasting starts from a future desired situation of society, and goes back in time for developing visions of future climate-adapted society decades ahead of time (Carlsson-Kanyama et al., 2013; Flynn et al., 2018).

Top-down visions have been appropriated locally in Grenoble (France) by combining downscaled climate scenarios with precise local dynamics informed by stakeholders to support land planning (Vannier et al., 2019). In Flensburg (Germany), the global SSPs have been combined with local socioeconomic narratives through a multi-scale coproduction to build "local SSPs" supporting local mitigation and adaptation to climate change (Reimann et al., 2021). Strategic scenarios have been used to integrate existing adaptation planning into future visions in Phoenix (United States) for exploring synergies and tradeoffs (Iwaniec et al., 2020). Since the social response to a changing climate is very uncertain, participatory scenarios can also be used as "learning machines" for assessing the impact of climate change on socio-economic future (Berkhout et al., 2002). Tales of future weather have also been proposed, based on the numerical prediction of weather events projected in a future climate (Hazeleger et al., 2015). They allow to explore the consequences associated with a set of similar weather events in the past, present and future.

Knowledge gaps can be captured and translated into climate information needs through the design of policy scenarios that are incremental (Wardekker et al., 2020). Policy scenarios describe futures that are desirable (visions) and the plans of action (paths) to reach them (Dammers et al., 2013; Haasnoot et al., 2013; Vervoort et al., 2014; Vanderlinden et al., 2015; Dammers, 2017). Incremental scenarios assume that the journey from present to future is not a straight line but hinges on points where trajectories might diverge between desirable and undesirable directions (Figures 2.2 and 2.3; Vanderlinden et al. (2015); Wardekker et al. (2020); van den Ende et al. (2021)).

Incremental scenarios can serve local adaptation planning through "future visioning" (Beaulieu et al., 2015). They can also serve to plan under deep uncertainty through the exploration of adaptation pathways with transient scenarios (Haasnoot et al., 2011) and dynamic adaptive policy (Haasnoot et al., 2013). Policy scenarios can be combined with environmental scenarios (external influences on societal system; e.g. climate scenarios) to be more effective for achieving concrete impacts for decision-makers (Vervoort et al., 2014; Kok et al., 2015). Another interesting approach for climate risks and policy-making is gaming (Mayer, 2009; Terrado et al., 2019; Marome et al., 2021).

The next chapters will describe how we developed a co-constructed foresight process to support the local adaptation of municipalities in the Gulf of Morbihan with the involvement of the population. This foresight process was based on local narratives of change (Chapter 3), an analysis of scientific knowledge and climate services (Chapter 4), and different foresight activities (Chapter 5). The goal was to identify the local changes ongoing in the territory, and

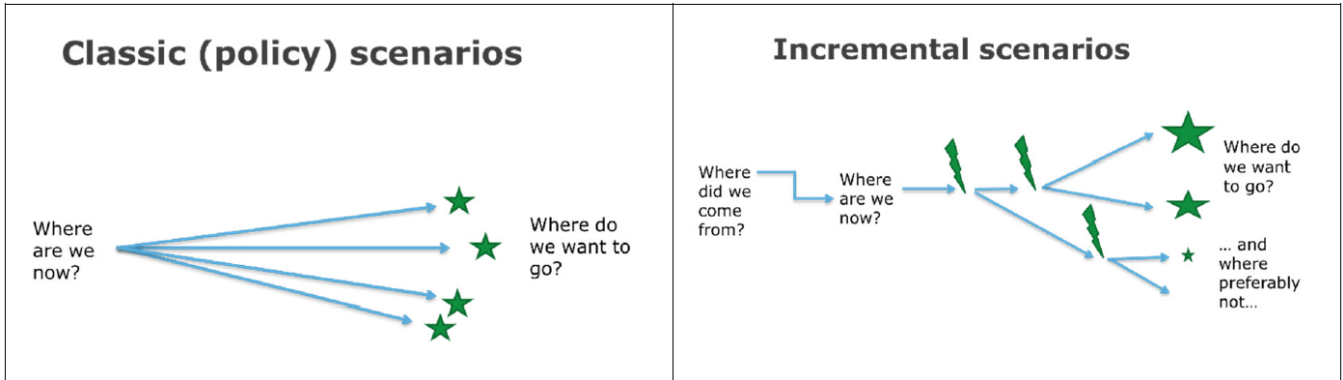


Figure 2.2: Classic policy scenarios (left) and incremental scenarios (right). Future situations are represented by stars, and hinge points are represented by thunderbolts. Hinge points are pivotal moments on which depend the following course of events, dividing the scenario in two subsequent paths or "branches". From Wardekker and Marschütz (2018).

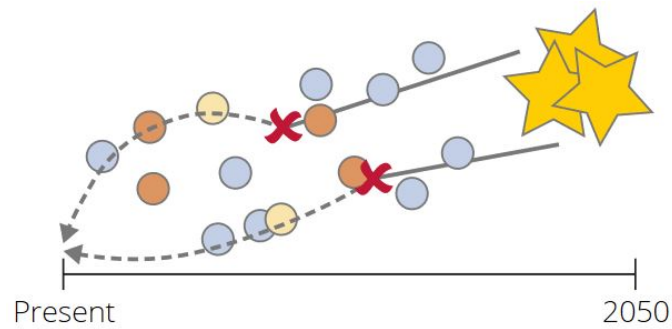


Figure 2.3: Set of incremental backcasting pathways. Backcasting allows to identify pathways (lines) to desirable futures (stars) based on tangible local actions (dots). Incremental pathways can be adjusted (dashes) in the face of disturbances or new opportunities (crosses). From van den Ende et al. (2021).

how the available science and services could assist in the preparation for these (climate) changes.

Summary of Chapter 2

Context and objectives:

The first goal of this chapter was to describe the general approach used in my thesis, based on the co-development of climate services with territorial actors. The second goal was to situate this approach in the field of climate services, which emerged recently to make climate science more accessible and usable by societal decision-makers.

Methods and results:

I reviewed the scientific literature of climate services, highlighting two issues:

- The limited use of scientific knowledge (about climate change) by decision-makers, due to many barriers between supply (scientists) and demand (users)
- The limited usability of climate services for territorial adaptation, due to the disconnection between the information (accessibility, relevance) and local issues (context, needs)

I classified the climate service approaches in two ways, based on the situation of the provider and on the trajectory of the climate knowledge. The approaches follow a gradient of connection between producers and users, and co-development (i.e. continuous collaboration with users) appears suitable to make climate knowledge usable for various decision-making contexts. I also draw general recommendations for climate service practice, based on positive and negative elements identified in the literature.

Alongside co-development, the localization of climate change (i.e. integration in local context) can bridge the disconnection between scientific knowledge and territorial action. This localization can be enabled by narratives of change (i.e. storylines) and vision-based scenarios (i.e. collectively visualized and constructed futures). The narratives can give local and practical meaning to scientific climate change, reconnect scientific with indigenous knowledge, and root climate governance in social life. The vision-based scenarios can make climate change scenarios more relevant for local users, help to identify desires and adaptation options over the long-term future, and highlight planning priorities and knowledge gaps.

Perspectives and link to next chapters:

The next chapters will describe how I co-developed (in collaboration with colleagues and inhabitants) a foresight process to support the adaptation of municipalities in the Gulf of Morbihan. This co-development is built upon local narratives of change (Chapter 3), an analysis of scientific knowledge and climate services (Chapter 4), different foresight activities (Chapter 5), and additional climate research (Chapter 6).

Chapter 3

Investigating the local narratives of change, chronotopes and future visions

This chapter is based on collaborative work with social researchers from the CoCliServ project, and local partners from the Gulf (PNR and Clim'actions Bretagne Sud). Clim'actions is a local association developing initiatives (ideas and projects) to anticipate climate change and engage actions of mitigation and adaptation (Clim'actions Bretagne Sud, 2021). The investigation of the local narratives was led by Charlotte da Cunha (researcher at CEARC in adaptation planning), with the assistance of Ana Paula Farias Rocha (student at CEARC in adaptation planning) and me. The analysis of the narratives was a focus of Ana's internship.

Some of the research presented in this chapter (and Chapter 5) has been published in the journal *Climate Risk Management*, in the article *Adaptation planning in France: Inputs from narratives of change in support of a community-led foresight process (da Cunha et al., 2020)*.

The scientific contribution of this chapter is triple. First, our methods that combine local narratives, chronotopes and visions serve the novel co-development approach by revealing the local matters and interests within the territory and how climate change plays a role. Second, these methods aim to uncover new knowledge about the local effects from climate change, potentially missing from previous assessments. Third, this new description of the situation in the territory provides a basis for the construction of local scenarios and climate services.

3.1 Methods: materials and analysis

3.1.1 Preliminary materials from local partners and literature review

The preliminary materials consist of a set of data (field data, reports, academic literature) in part supplied by the local partners, and in part drawn from a preliminary literature review focused on the Gulf of Morbihan. Several local narratives can already be identified in the Gulf based on these preliminary materials (Krauß et al., 2018b). Clim'actions for instance has organized various events about the future of the Gulf, such as different activities (exhibitions, conferences, questionnaires, expression tree) during a forum discussion on marine energies (Figure 3.1a; Franchet (2018)). Additionally, the group "Singulier collectifs" has collected feelings, experiences and stories of inhabitants about global warming (Brulavoine et al., 2016).

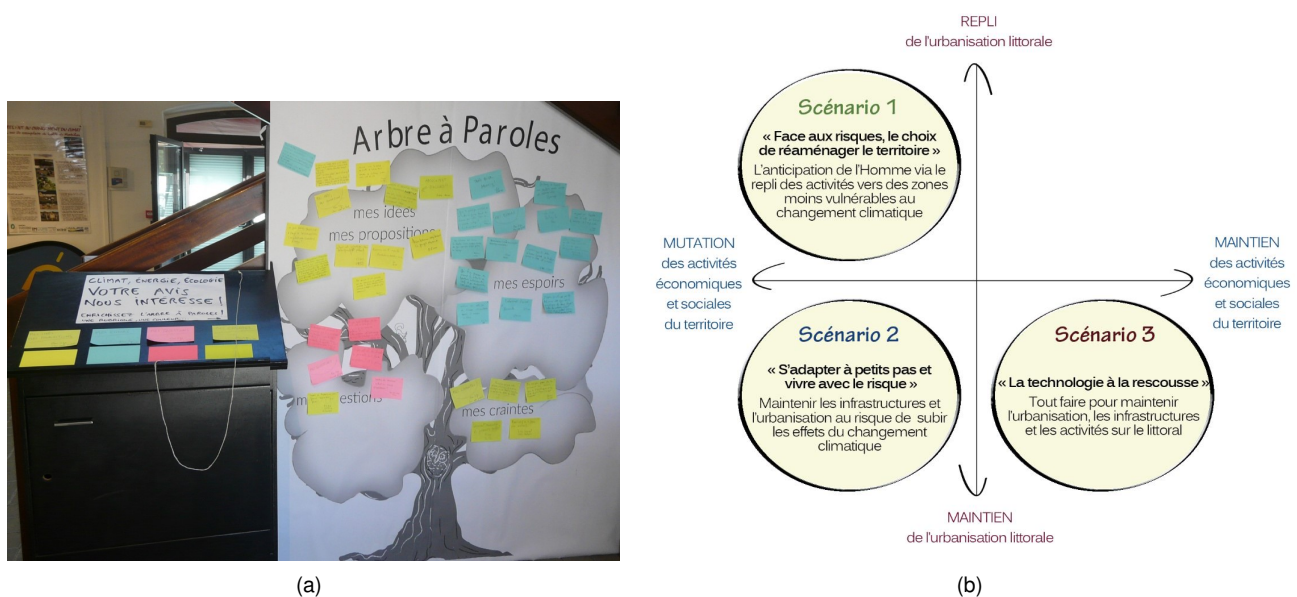


Figure 3.1: Examples of preliminary materials: expression tree and IMCORE scenarios. Left: expression tree during the forum on marine energies in the Gulf (Franchet, 2018). Right: scenarios developed during the IMCORE project (PNR, 2021).

The PNR of the Gulf is also engaging the population about climate change impacts, mitigation and adaptation. Three scenarios of future evolution of the Gulf (Figure 3.1b) were developed during the IMCORE project in 2008-2011 collaboratively with the PNR (UBO and SIAGM, 2016). The PNR also carried out several filmed interviews in 2015 about how the environment is changing and the effects on the life of local inhabitants (PNR, 2016). Other narratives can be found within the institutional website of the Gulf (Vannes Tourisme, 2021): promotional (to attract visitors and economic opportunities), and romantic (showcasing the wealth of history in the region).

3.1.2 Field interviews

To complement the preliminary materials and scrutinize the local situation in depth, we collected additional information through two sets of field interviews. The purpose of the first fieldtrip in February 2018 was to explore the site and collect life stories, with the aim of gathering a basic understanding of changes in the Gulf of Morbihan (past, present, future), to identify community priorities, and to reveal potential gaps laying within the preliminary materials. We conducted four exploratory interviews with professionals from traditional agricultural activities (labeled "lifestory" in Table 3.1) to better understand the changes of the primary sector in the context of tourism development. The exploratory interviews were based on three main questions, and a few other optional questions:

- "How is it like to be an oyster farmer in the Gulf today?" (matched to each profession)
- Same question but referring to the past
- Same question but referring to the future
- If the interviewees did not spontaneously mention climate change, we asked them if they observed any changes over the past 20 years, if they perceived these changes to be linked to climate change, and if they considered to need more information about these changes.

A second set of fields interviews was carried out between February and May 2019 to further investigate the local matters and widen our scope to other dimensions (administrative, political, civic). We conducted 28 individual semi-structured interviews with diverse stakeholders (Table 3.1). The structure of the interviews encompassed the following purposes:

- Study the relation of the participants to the territory and associated emotions (e.g. what is the Gulf for you today?)
- Identify the activities and actions of the participants in the territory
- Expand our knowledge of the changes in the Gulf
- Reveal the visions of the participants about the future of the territory

3.1.3 Analysis of the data

Two sets of data (or "corpus") resulted from the previous steps of collecting materials. The first corpus is made of the preliminary materials (from local partners and literature review) and the exploratory interviews. The semi-structured interviews constitute the second corpus. The analysis of the data was based on grounded theory, a method using inductive reasoning to identify patterns in field data (Strauss and Corbin, 1997). Grounded theory attempts to

Table 3.1: Stakeholders interviewed in the Gulf of Morbihan (adapted from da Cunha et al. (2020)).

Socio-professional category	Stakeholders
Primary activities	Traditional farmer (lifestory) Salt mine worker (lifestory) Oyster farmer (lifestory) Local shop selling direct (lifestory) Organic farmer Oyster farmer and entrepreneur
Public officers	Deputy for scientific initiatives at the local Fishing and Aquaculture Departmental Committee (CDPMEM 56) Project manager at the Regional/Departmental Sustainable Development Governmental Agency (DREAL) Project manager at the PNR of the Gulf of Morbihan Local-level facilitator at the Chamber of Agriculture Deputy for organic agricultural practices at the Chamber of Agriculture Deputy for Sustainable Development at the Departmental Committee of Tourism Director of the Tourism Office of the Gulf of Morbihan - Vannes Manager for Territorial Development at the Gulf of Morbihan Regional Natural Park (PNR) Manager for communication and pedagogic activities at the PNR of the Gulf of Morbihan Director of the PNR of the Gulf of Morbihan
Elected officials and administrative staff	Mayor of Sarzeau Deputy for Culture and Economy, Sarzeau Member of municipal council, Sarzeau Manager of urban planning and development projects, Sarzeau Regional Vice-president of environment, water and sanitation (Gulf of Morbihan - Vannes)
Business and services	Professional guide – fishing Professional guide – aquatic sports Administrator of an ecotourism facility Naval architect and businessman Architect
Academia	Student (high school level) Student (university level) University associated professor University professor
NGOs and associations	Member of a local environmental association (Eau et Rivières de Bretagne) Entrepreneur in the Social and Solidarity Economy

decipher an empirical situation by classifying the data into groups based on links between elements, in order to infer assumptions and extract meaning (Paillé, 1994; Glaser and Strauss, 2017).

The analysis of the first corpus aimed to determine the climate-related storylines, practices, community priorities, forms of governance and notions related to foresight (da Cunha et al., 2020). A software for the analysis of qualitative

data (Atlas.ti) was used to translate and process the second corpus. Text quotes from the second corpus were classified according to categories defined on the first corpus, and were supplemented using inductive reasoning as relevant elements emerged from the transcriptions. We then adopted another approach based on a multi-level structure for the analysis of specific narratives in time and place. For instance, Braudel (1949) separates processes on different timescales: very long (geographical), intermediate (social), and short (individual). The refinement of our classification with the multi-level structure resulted in the emergence of four narratives of change, two chronotopes, and a few future visions of the territory, which are described thereafter.

3.2 Results: local narratives of change (past, present, future), chronotopes and future visions

3.2.1 Geo-social narrative: from estuary to inner sea

The landscape of the Gulf of Morbihan has been shaped by the neighboring ocean and the rise of sea level over the last ten thousand years. Today, the Gulf contains a small inner sea with islands and is bordered by a coastal pathway. This territory is exposed to increasing risks from coastal erosion, marine submersion (storm surges, sea level rise), and flooding (heavy rainfall). As a natural barrier to Southwestern storms (e.g. Xynthia), the Rhuys peninsula is at the forefront of coastal risks. Natural erosion of the shore is exacerbated by local activities, such as urban development that increases soil impermeability, and recurrent walks on the coastal footpath that increase soil compaction (Commune d'Arzon, 2021).

3.2.2 Historical narrative: economic shift from traditional agriculture to tourism

The growth of tourism has reshaped the Gulf (economy, land-use, daily life) over the modern period. This development has been ambivalent towards agriculture, increasing the direct sales (products from organic farming, oysters, salt) but leading to conflicts of use regarding land (tidal zones, rural occupation and maintenance) and summer access to water (drinking, irrigation, oyster farming). Tourism has also increased the number of secondary homes in coastal villages, driven up the price of housing, and made the Gulf host to many recreational boats (e.g. in Vannes, Auray and Arzon). The port of Crouesty was built during the 1980s to accommodate this increasing number of boats (Krauß et al., 2018a). Meanwhile, part of the coastal infrastructure and households lay in flood risk area, protected by dikes and dunes but imperiled by the increasing coastal risks. Additionally, episodes of heavy rainfall often lead to water overflows due to inadequate river management owing to the recent urban expansion. In this situation, one can question the risk perception of people who decide to build and live in these risky areas.

3.2.3 Seasonal narrative: winter vs. summer

The four climatic seasons pace the year in Europe, and weather changes interest local populations as much or more than scientific announcements about climate change (Krauβ et al., 2018a). Seasonality is socially evident in the Gulf, with an economic slowdown in autumn-winter and bloom in spring-summer. Many houses and shops are closed during winter (e.g. about 80 % of houses in Arzon are secondary homes) and the population increases tenfold (between seven and 17 depending on the town) in summer with tourists and secondary residents (Krauβ et al., 2019).

Three issues arise: temporary inhabitants are not interested to socially invest in the locality over the long-term, permanent residents feel invaded in summer, and tourism has led to an unbalanced development of the shore. Some infrastructure choices are questionable and disconnected from the needs of local residents. Examples include land storage for boats that are rarely used, or a soccer field for the French national team (da Cunha et al., 2020). Tourism drives the economic activity during summer, and young people struggle to find work outside this season (Krauβ et al., 2018b). Most permanent residents of the coast are seniors (e.g. 57.6 % of retirees in Arzon), creating demand for service workers but these workers cannot live there year-round due to the price of land (Cazenave, 2016; Goutard et al., 2018; Krauβ et al., 2019).

3.2.4 Climate effect narrative: socioeconomic impacts

The effects of climate change are already manifest in the Gulf. Local stakeholders experience climate change mostly through their professional activity. Climate change is perceived to varying degrees through a shift in the timing of seasons, disturbances of the weather, and summers that are longer and hotter (Krauβ et al., 2018a). Oyster farmers spontaneously evoked climate hazards and warming of water, when asked about their current work. To adapt to the ongoing changes, they must diversify their practices (e.g. algaculture, adding value to products, offering activities to tourists). The fast and negative shift in their activity represents a worrisome future for the next generation of the profession. In the case of salt workers, their activity is paced by the tides, sun and wind. Other agricultural activities such as farming are mainly concerned by seasonal changes, water scarcity and drying soils.

Tourism is also directly affected by climate change through warming and seasonal changes. The local summer weather begins earlier and finishes later than previously, lengthening the peak season of tourism from July-August to June-September. This longer summer brings economic opportunities but also leads to conflicts of use with other activities (primary) in terrestrial and marine areas. Many stakeholders, such as tourism and regional planning experts, suggest that the Gulf could evolve into a new Côte d'Azur. The Côte d'Azur is a very attractive touristic region on the French Mediterranean shore, famous for its warm weather and affluent ageing population.

This region is hotter than the Gulf and more directly concerned by climate change (warming and drying), a heatwave for instance reached 45.9 °C in July 2019 (HuffPost, 2019). The Gulf therefore represents a viable substitute, with milder temperatures and well established touristic infrastructure. For example, about nine out of ten

tourists visiting the Gulf are French, 28 % from Paris for vacations or retirement (Morbihan Tourisme, 2018). However, this process of substitution would represent an additional demographic shift in the Gulf, thereby intensifying the already vast socioeconomic contrast. This situation highlights the necessity of policies to improve the social and generational mix (e.g. housing).

3.2.5 Chronotope of sealevel rise: the double cromlech of Er Lannic

During our investigation of the narratives, we also identified chronotopes i.e. elements of the landscape that are charged with historical meaning. Megaliths are an example of chronotopes, they are ancient monuments marking the landscape and testifying about the history of a place (Joyce and Preucel, 2002; Goldhahn, 2015). Thousands of cairns and menhirs date back to the megalithic period, when the Gulf of Morbihan was a major civilization center (Audouard, 2014). Some of the megaliths were submerged by the rise of sea level during the last thousands of years.



Figure 3.2: Illustrated aerial view of the double cromlech of Er Lannic, a geo-social chronotope (Thomas, 2015). Modified to show the location of submerged parts (Burl, 2005).

An exemplar case is the double cromlech of megaliths on the island of Er Lannic (Figure 3.2). This monument is composed of two half circles of stones upraised on the southeastern sloping ground of the island. Only the uppermost part of the cromlechs is emerged today (partly submerged at high tide), and the southern stones lay permanently underwater. The presence of two cromlechs has raised theories, such as the use of stones from the southern cromlech as it was being submerged to build the northern cromlech, or that the southern cromlech represented a symbolic protection against the rising ocean (Mohen, 2009; Sévère and Lorin, 2021). The cromlechs of Er Lannic exemplify the rise of sealevel during the Neolithic period and are omens for future changes.

3.2.6 Chronotope of erosion: the coastal pathway

Another chronotope is the coastal pathway of the Gulf, which is relatively recent and embodies the ongoing coastal erosion (Figure 3.3). Walking along the entire coastline was previously difficult, and the national walking trail (GR34) was created in the Gulf shortly after the implementation of a new law (1976) regulating the coastal right-of-way (da Cunha et al., 2020).



Figure 3.3: The coastal pathway (GR34; red line) around the Gulf of Morbihan (Morbihan Tourisme, 2021).

The law guarantees a 3-m wide right of way on private property along the shoreline, and most owners tend to fence their property close to the trail. Erosion is therefore visible clearly in the changing width of the trail, and has in some cases forced homeowners to move back their fences to respect the right of passage.

3.2.7 Future evolution and divergent visions of the territory

Several insights and visions have appeared in the narratives regarding the future evolution of the territory (Krauß et al., 2018b, 2019). Climate change affects many economic activities and especially emblematic ones (e.g. oyster farming, salt production, crop and livestock farming). Oyster farming is affected by water warming and mortality increase, salt production depends on salt crystallization and precipitation patterns, livestock farming requires available grass and moderate precipitation (not overly dry in summer and not excessively wet in winter). The viability of these activities depends on weather hazards and future climate evolution.

More generally, the local decision-makers have to urgently address the national demand for territorial planning against the future effects of climate change (Krauß et al., 2018a). Coping with this demand requires knowledge on local future scenarios including the changing parameters of the territory (e.g. urban planning and economic activities), the impact of extreme events (e.g. heatwaves, flooding, storms), and a mapping of "climate hot spots" (i.e. degree of positive/negative sensitivity to climate changes). Another important variable is the future demand for drinking water in

the touristic summer period and consequence on groundwater resources.

Climate change exacerbates issues of land-use planning and risk management: the urbanization of highly populated risk areas, the ageing of the coastal population, and the widening socioeconomic gap. The maintenance of the coastal urban area could become increasingly difficult under future climate change, but withdrawal from the coast appears difficult and territorial adaptation is considered through the lens of technical and technological means (Krauβ et al., 2018b). However, the traumatic impact from past storms nourishes the consideration of withdrawing activities to less vulnerable areas (Krauβ et al., 2018b). Securing the territory would then result in the transfer of population and goods in anticipation of future risks. Yet the planning and development capacity of the territory can be limited with a temporary and ageing population, emphasizing the role of place attachment in the decisions of individuals and decision-makers regarding adaptation and withdrawal (Krauβ et al., 2019).

3.3 Discussion

The use of local narratives and chronotopes facilitated our understanding of the present local context, to a degree further than enabled by the preliminary literature review. The framework of the analysis enabled us to investigate the short and long-term changes that are ongoing in the Gulf from an historical perspective. The narratives also allowed us to look at the territory from different viewpoints (multiple histories of people and places), letting us grasp the experience of people living there.

The different narratives and chronotopes painted a more complex territory than previously assumed, such as regarding the choices of urban development during the last decades, the contrasts in the population and economic activities, the current impacts of climate change and the diverging future visions. We reached a deeper knowledge of the ongoing changes with the analysis, such as the different socio-economic issues facing the Gulf and the complex role of climate change on the way people occupy and transform the territory (Krauβ et al., 2021). Although we have categorized the different narratives in order to facilitate the understanding of ongoing changes, they remain deeply intertwined (Figure 3.4).

From the many elements that emerged during the field interviews, a few remarkable or surprising findings include:

- The various facets of tourism: positive (economy), contentious (coastal urban development) and negative (land-use conflicts, socioeconomic imbalance)
- The ambivalence of farmers towards tourism (product sales, territorial consequences)
- An abundance of local climate knowledge from some actors (e.g. farmers)
- A few actors are disappointed by IPCC findings and recommendations (information too general for them)
- Many actors (e.g. farmers) follow a pragmatic adaptation (« au fil de l'eau »)

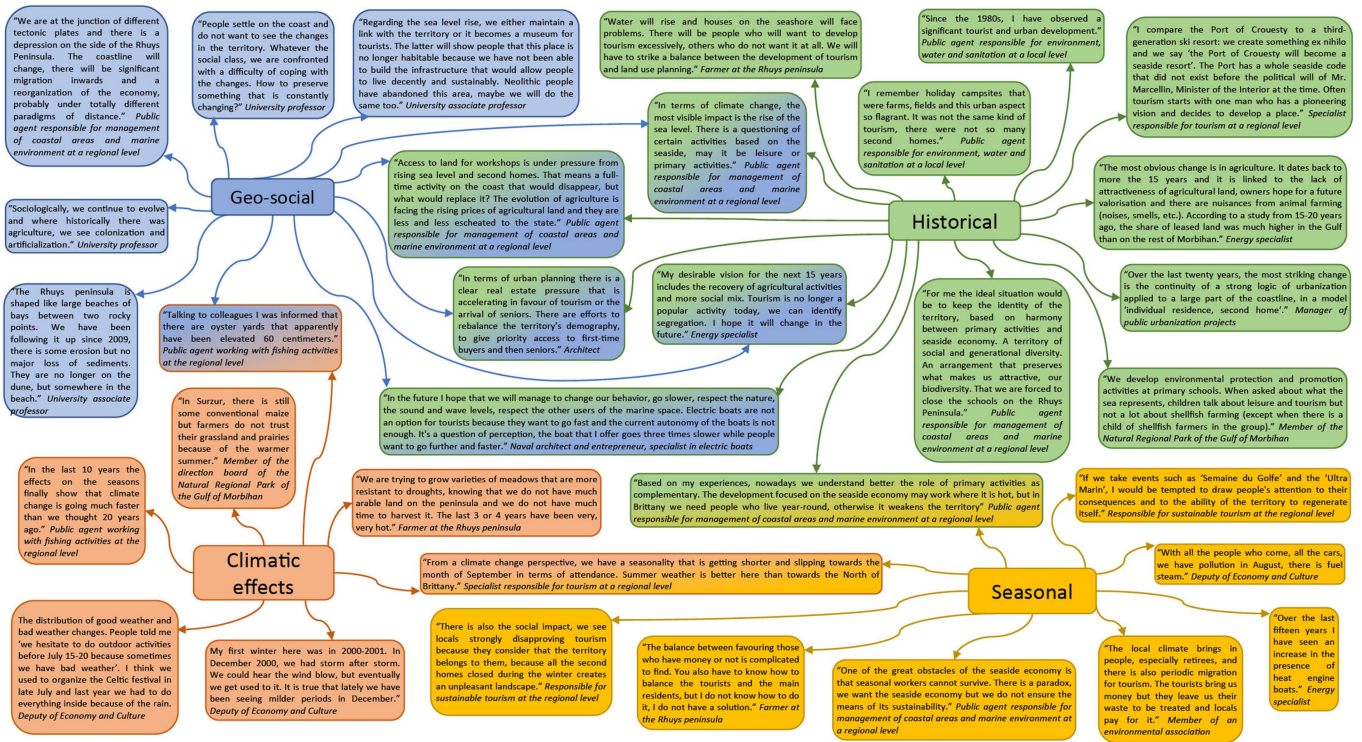


Figure 3.4: Examples of quotes from stakeholders and relation to the four main narratives (da Cunha et al., 2020).

- A few actors are very pessimistic about the future, and struggled to envision positive things for the territory

Several entry points have been identified for the development of future scenarios and local climate services. These entry points are contained in the present and future issues (socio-economic, climate change), the contrasting viewpoints (agriculture, tourism), and the future visions (coastal adaptation, withdrawal) of the territory. Additionally, the mapping of narratives and chronotopes in the context of climate planning permitted to convert scientific knowledge into local matters of concern (Krauß et al., 2021). This provides a foundation for the experimentation through art and science of possible future narratives.

Now that we have obtained a good understanding of the ongoing changes in the Gulf (social context and societal role of climate change), another step is needed before we can experiment foresight processes and construct local future scenarios based on physical evidence. We previously need to precise the scientific understanding and available tools regarding present and future climate change locally in the Gulf. For this, I will determine the existing scientific knowledge and available climate services in Chapter 4.

Summary of Chapter 3

Context and objectives:

The first goal of this chapter was to investigate the local context and issues more in depth, and the second goal was to determine the local experience of climate change.

Methods and results:

The investigation was based on the analysis of different materials (collaborative work):

- Preliminary materials from local partners and literature review
- Field interviews with various stakeholders

The analysis revealed additional features of the territory and climate change:

- Multiple territorial evolutions and stakes at different timescales (geo-social, historical, climatic, seasonal)
- Physical markers of change, such as the coastal pathway (coastal erosion) and Er Lannic cromlech (sealevel rise)
- Ambivalent relationship between agriculture and tourism (dependence and conflict)
- Ambivalent effects of climate change (negative for agriculture, positive for tourism)
- Exacerbation of local issues by climate change (socioeconomic imbalance, water access, land-use problems)

Three climatic themes also emerged from the analysis (seasonal changes, extreme events, marine submersion).

Perspectives and link to next chapters:

Although we conducted about thirty interviews with diverse stakeholders, the mapping of the local experience of climate change is not exhaustive. Additional interviews with other actors and in different seasons could bring more insights. In the next chapters, I assess if the local experience is consistent with scientific knowledge (Chapter 4), use the narratives and scientific knowledge in foresight activities with territorial actors (Chapter 5), and conduct further climate research in relation to the three themes identified above (Chapter 6).

Chapter 4

Assessment of local climate change based on current scientific knowledge and climate services

While this assessment may seem a standard step in the writing up of a thesis that is centered on a specific geographic area, or even a standard step in climate service provision, this work had a precisely defined status in the co-production process being developed within the CoCliServ project.

First, identifying relevant existing knowledge has been understood as part of dialogical process - this was not only about "knowing what is out there" in terms of scientific knowledge. It was also about identifying how current scientific knowledge sheds a light on the local narratives identified in Chapter 3.

Second, when developing the project the CoCliServ consortium considered that identifying existing knowledge source is in itself an important part of what co-produced climate services may become - co-produced climate knowledge becomes a place where the "old and the new" are explicitly informing each other - and this deserves a method-centered enquiry.

Third, the identification of climate information needs centered on narratives and scenarios (Chapters 3 and 5) was expected to reveal blind spots in climate science - this is particularly true in order to inform the development of local scenarios (Chapter 5). The assessment described in the present chapter was about mapping these blind spots and preparing scenario designs as well.

4.1 Methods: determining the current scientific knowledge and climate services

4.1.1 Published scientific knowledge on local climate change

To document the current scientific knowledge of climate change in the Gulf of Morbihan, I complemented the previously identified sources (from local partners and narrative materials) by a search on a scientific literature browser (Google Scholar) with several combinations of keywords (e.g. "Morbihan" + "climate" + "change"). The resulting documented materials include various sources from the scientific literature (e.g. scientific articles, PhD theses), and grey literature (e.g. assessment reports, project reports).

4.1.2 Available climate services relevant for the case study

In a first phase, I documented the available climate services based on:

- Previous knowledge of activities at various levels e.g. from the World Meteorological Organization (global), Copernicus (European) and Météo-France (national).
- Existing mappings of climate services (e.g. Figure 4.1) in scientific articles (Hewitson et al., 2017; Swart et al., 2017; Vaughan et al., 2018) and assessments reports (Medri et al., 2012; Clean Air Partnership, 2018).
- A database of climate service providers in Europe (Figure 4.2): the Climate Knowledge Hub (thereafter CKH; Cortekar (2016)). Due to the very large number of registered providers in CKH (over two hundred at the time of writing), I focused on those in France.
- A search on browsing engines (Google, Google Scholar) to find other services (e.g. Van Den Besselaar et al. (2015); Preuschmann et al. (2017)).
- A monitoring of the climate service literature to detect new services (e.g. Lajarín et al. (2021); Photiadou et al. (2021)) and assessments (e.g. Cortekar et al. (2020); Leal Filho and Jacob (2020); Miranda Espinosa et al. (2020)).

In a second phase, I developed an analytical framework with colleagues in CoCliServ to categorize the documented climate services (Gerkenmeier et al., 2018). The purpose of this documentation is to conduct an empirical study of climate service practices, aiming to provide an overview of the service landscape and to identify emergent features. To build the analytical framework, we drew on the current discussion in the scientific literature about the assessment and evaluation of climate services (e.g. Soares et al. (2018); Vaughan et al. (2018)), and on the practical experiences from CoCliServ researchers as climate service providers (e.g. Meinke (2017a,b)). A large body of the literature regards the development of climate services and tools, whereas a minor but increasing part involves climate service

Characteristics/Portal Name	Website	Institution in charge	Scale	Main scope
DRIAS	www.drias-climat.fr	Météo France	National	Downloadable data and exportable maps. Multi-model forecasts (CNRM, IPSL, EURO-CORDEX) under IPCC's SRES (CMIP3) and RCP (CMIP5) scenarios
UKCP09 (UK Climate Projections)	ukclimateprojections.metoffice.gov.uk	Met Office	National	Climate projections for land and marine regions + observed (past) climate data for the UK. "The most comprehensive source of future climate information for the UK"
Climate Change Knowledge Portal	sdwebx.worldbank.org/climateportal	World Bank	Global	Generic climate indicators, impact-oriented indicators for Agriculture, water and natural hazards
Climate4impact (IS-ENES)	climate4impact.eu	ENES	Global	Downloadable data and exportable maps. Multi-model forecasts (CORDEX) and RCP (CMIP5) scenarios, SPECS. Downscaling, uncertainties. Part of CLIPC and Copernicus Climate Change Service (C3S)
Climate Explorer	climexp.knmi.nl/	KNMI	Global	Web application to analysis climate data statistically. Daily, monthly & seasonal data available. Station, gridded & climate indices. Time series and field calculations, downloadable data and maps
Climate.gov	www.climate.gov	NOAA (USA)	National + Global	Maps & data. Climate data + sectorial "actionable information": Agriculture & Fishery, Air quality, Civil Infrastructure, Coasts, Energy, Extreme events, Human Health, Insurance, Marine ecosystems, National Security, Tourism, Transportation, Water
Climate Adapt	climate-adapt.eea.europa.eu	EEA	Regional	Guidelines, maps, graphs, datasets (spatial time series, incl. projections), case studies, adaptation support tool + sectoral tools for Health
GCM Data Portal	ccaifs-climate.org	CIAT	Regional	Downscaled climate model data of various scenarios and RCPs
ECA & D	www.ecad.eu	KNMI	Regional	Observations: stations and gridded datasets. Climate Impact Indices, Indices of extremes. Downloadable data and exportable maps

Figure 4.1: Example of a previous mapping of climate services (information portals), adapted from Swart et al. (2017).

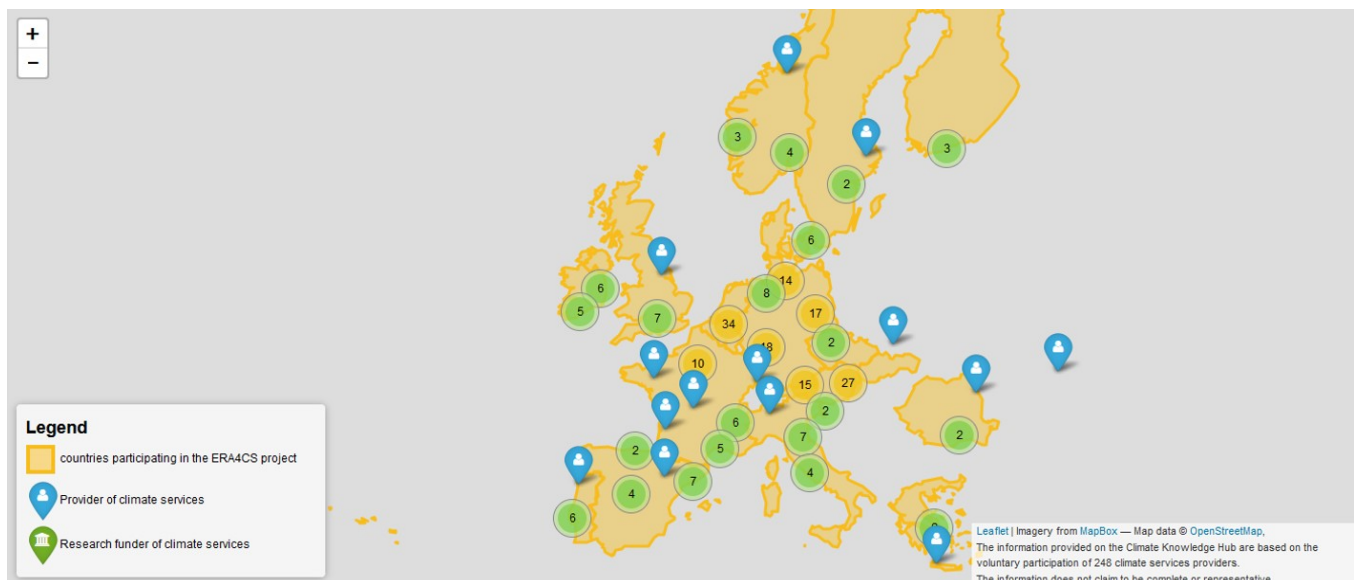


Figure 4.2: The Climate Knowledge Hub: a database of climate service providers in Europe (CKH, 2021)

assessment and evaluation. Only a small part of climate services and research projects include evaluation, even fewer based on stakeholder criteria (e.g. Vaughan et al. (2018)).

Several criteria for the assessment of climate service content (knowledge/information/data) are mentioned and discussed, contrasting with a lack of activities on the assessment of formats and processes (Göransson and Rummukainen, 2014; Máñez et al., 2014; Meinke, 2017b; Vogel et al., 2017). The literature on climate service evaluation contains criteria relevant for our analysis, such as the service value (economic in Clements et al. (2013)), the process of service development (knowledge exchange in Fazey et al. (2014), co-development in Kirchhoff et al. (2013)), the usability (Dilling and Lemos, 2011; Ford et al., 2013; Wall et al., 2017), and the impacts on decision-making and policy (Cash et al., 2002; Evely et al., 2011; Meinke, 2017b). Scarce literature assesses specific climate

service formats, except Swart et al. (2017) who reviewed web portals.

The original analytical framework (Table 4.1) was designed to analyze each climate service based on different

Table 4.1: Analytical framework to assess climate services, adapted from Gerkenmeier et al. (2018).

Criterion	Indicators	References
Provider	Who established the service? Who runs the service?	Göransson and Rummukainen (2014)
Service development	How was the user requirement collected? Long-term maintenance or tied to project duration? To what extent does local contextualization play a role? Who financed the service?	Swart et al. (2017) Göransson and Rummukainen (2014)
Type of service	Information provision or interactive format? What is the product that the user receives? Aim of the service (knowledge transfer, knowledge exchange, presenting scientific results...)	Vaughan and Dessai (2014); Meinke (2017b)
Content	Diversity or focus on individual parameters/topics/scenarios? What is provided (data/products)? Method of data processing: is a description of the method available? Which method has been used? Is the goal of enabling users to act on climate change formulated?	Göransson and Rummukainen (2014) Meinke (2017b)
Format and process	Information or participation? Which methodology? How does the communication take place between provider and user? What is known about the development processes? How is the service disseminated to the user? How is the service promoted?	Fazey et al. (2014); Swart et al. (2017) Lemos et al. (2012); Fazey et al. (2014); Swart et al. (2017) Göransson and Rummukainen (2014) Göransson and Rummukainen (2014); Vaughan and Dessai (2014) Göransson and Rummukainen (2014); Vaughan and Dessai (2014)
User-provider communication	Are there a few special users or many users (from many sectors)? Is there a possibility of feedback? Is there or was there an evaluation of the service? Do we know something about the use/query or similar? Is there a reproduction of the service? At other locations or in other sectors Is there a long-term contact point?	Swart et al. (2017); Vaughan et al. (2018) Swart et al. (2017) Meinke (2017b)

Table 4.2: Revised framework for climate service assessment, adapted from Gerkenmeier et al. (2018).

Category	Criterion	References
Provider	Who established the service?	Göransson and Rummukainen (2014)
	Who runs the service?	
Service development	Long-term maintenance or tied to project duration?	Swart et al. (2017)
	Who financed the service?	Göransson and Rummukainen (2014)
Type of service	Information provision or interactive format? What is the product that the user receives?	Vaughan and Dessai (2014); Meinke (2017b)
	Aim of the service (knowledge transfer, knowledge exchange, presenting scientific results...)	
Content	Diversity or focus on individual parameters/topics/scenarios?	Göransson and Rummukainen (2014)
	What is provided (data/products)?	
	Method of data processing: is a description of the method available? Which method has been used?	Meinke (2017b)
	To what extent does local contextualization play a role?	
	Is the goal of enabling users to act on climate change formulated?	

criteria. We tested the framework on the climate services pertaining to the five European case studies of CoCliServ. However, some criteria had limited applicability in practice, so we simplified the framework to essential questions that are practically feasible to answer (Table 4.2). The incentives for the exclusion of each criterion are given in Gerkenmeier et al. (2018). The revised framework is versatile and transferable outside the CoCliServ areas, it also provides a concept design for the co-construction of local climate services.

4.2 Results: synthesis of climate knowledge and services for the local case study

4.2.1 Overview of main sources

I found numerous sources of published scientific knowledge (Table 4.3), and about fifty climate services (Table 4.4). They form together a broad range of available climate knowledge at national, regional and sometimes almost local level. From this landscape of climate services emerge several interesting features (Table 4.5). For instance, with services at many geographic levels (global, European, national, regional) come varying degrees of specificity (contextualization) and detail (uncertainty).

Overall, three types of providers can be identified, each focusing on different missions. With these different missions come different understandings (conceptions) of climate services for providers and users. Commercial

Table 4.3: Documented sources of published scientific knowledge.

Type	Number of sources	Example of source
Journal articles	Hundreds	Large-scale changes of the semidiurnal tide over the North Atlantic coasts from 1846 to 2018 (Pineau-Guillou et al., 2021)
PhD theses	2+	Impact of climate change on the frequency and intensity of droughts in Brittany (Lamy, 2013)
Project reports	12+	The new climate projections DRIAS 2020 for France (Météo-France, 2020e)
Assessment reports	9+	Characterization and evolution of climate in Brittany (CRPF Bretagne-Pays de la Loire, 2019)

Table 4.4: Documented climate services.

Level	Number of services	Example of service
World	14	Climate Information (Swedish Meteorological and Hydrological Institute, 2021): <ul style="list-style-type: none"> • Summary reports of climate change for any site worldwide • Access to pre-calculated climate indicators • Guidance on how to link global changes to local observations
Europe	14	Products for climate change adaptation (EEA, 2021o): <ul style="list-style-type: none"> • Data, charts, maps and indicators • Interactive data and maps
France	31	Climat HD and DRIAS (Météo-France, 2021a,b): <ul style="list-style-type: none"> • Observed evolution of climate • Future projections of climate

enterprises or corporations (e.g. ARIA Technologies or the Climate Data Factory) provide climate services often tailored to specific client needs. Climate services from the private sector are scarcely represented in the scientific literature (Gerkenmeier et al., 2018), and mapping them was more difficult than for public providers (especially service types). Public availability of relevant information is an important requisite for broad societal adaptation, but private climate services are rarely made freely available and their specificity reduces their broader usability. For these reasons, we rather considered public climate services for the construction of a common adaptation basis (e.g. for laypeople and public stakeholders).

The two other types of providers have very different mandates by comparison to commercial enterprises. Research institutions and universities must conduct basic research in natural sciences, contribute to solve societal challenges, and educate society. They can therefore provide climate services that are scientifically extensive (e.g. explain causes for complex phenomena) and identify broad societal risks and challenges for society. Some research institutions focus specifically on climate services or have departments specialized in their development (e.g. IPSL and KNMI). Governmental agencies and public authorities (e.g. Météo-France and BRGM) are usually mandated to provide operational services supporting the functional capacity of societal activities (e.g. forecast and early warning of

Table 4.5: Characteristics of the documented climate services.

Feature of the service	Types
Scope	<ul style="list-style-type: none"> • Global • European • National (France) • Regional (Brittany, Morbihan)
Provider	<ul style="list-style-type: none"> • Commercial enterprises/corporations • Research institutions/universities • Governmental agencies/public authorities
User	<ul style="list-style-type: none"> • Laypersons or the public at large • Stakeholders/decision-makers/policy-makers • Scientists/researchers
Nature/format	<ul style="list-style-type: none"> • Data provision and management • Data-based products • Text-based products • Dialogue and educational formats • Advisory services and products
Topic	<ul style="list-style-type: none"> • Climate (research) • Disaster risk • Agriculture and forestry • Tourism • Water • Energy • Health • Urban planning

extreme weather).

As a whole, the documented climate services represent a great variety of formats. These formats and the level of user-provider interactivity are framed by boundary conditions set by providers and users (e.g. funding source, service purpose, required contextualization). We classified the climate service formats into five groups: data provision and management, data-based products, text-based products, dialogue and educational formats, and advisory services and products (Gerkenmeier et al., 2018).

Data provision and management is the most frequent group of climate services, involving the acquisition of raw data, data management, data processing, and the distribution of data via online platforms (or through particular requests). Climate data includes observations, reanalyses and simulations (forecasts, predictions and projections). The second group, data-based products, corresponds to processed data at different stages of analysis and interpretation. This climate service is very frequent, often taking the form of digital web applications. These applications can be differentiated between digital solutions for experts (e.g. software programs and models), and user-friendly web

tools. Web tools (e.g. climate atlas) address a broad user group and provide interactive access to analyzed data with accessible interpretation.

Another very frequent group of climate services is text-based products. This format gives easy access to contextualized scientific knowledge, ranging from popularization work to specialized materials for experts. Examples of text-based products are story maps (e.g. EEA (2021p)), understandable summaries, information brochures, and assessment reports. Understandable summaries and information brochures use plain language for the general public and user groups outside the scientific community. Assessments reports are systematic documentations of published knowledge (e.g. scientific reports and peer-reviewed articles) on certain aspects of climate change, they address an audience with a basic knowledge in climate science (e.g. professionals in activities related to science).

Dialogue and educational formats represent the fourth group of climate services, with a focus on in-person activities. These services include direct solicitations from users, stakeholder events (discussion rounds, conferences, workshops, exhibitions), and courses (recurrent and specific trainings). The fifth group is advisory services and products, providing support to decision-makers and policy-makers that implement regulations and policies. The associated products are tailored specifically (for sectors, authorities or municipalities), and they relate to activities of conceptualisation, implementation and monitoring (e.g. impact studies, climate change mitigation and adaptation).

To summarize, a climate service can be understood in many ways: as data (e.g. raw observations), a product (e.g. downscaled maps), a tool (e.g. web portal), advice (e.g. consultancy), or a process (e.g. series of courses on climate risks). Climate service activities can be associated to research projects (limited in time) or be long-term (continuous source). The climate service landscape is dominated in quantity by data and text products (data services, web applications, printed media) over in-person formats (advisory, education). Many of the climate services focus on the transfer of scientific knowledge to increase societal awareness on climate change impacts, mitigation and adaptation. For additional details, a more thorough analysis at the European scale is available in Gerkenmeier et al. (2018).

The following sections describe the results from my assessment of climate change, and will cover the main scientific insights and climate services that I found. This assessment was guided by the topics identified in the local case study (Chapters 1 and 3), which I organized in three climatic themes (seasonal changes, extreme events, marine submersion).

4.2.2 Warming, seasonal changes and water resource

A major way in which climate change manifests itself locally in the Gulf of Morbihan is through warming, changes in weather seasonality, and the modulation of the water resource. Warming inland affects the timing of crop harvest, while the warming of seawater damages the aquaculture of oysters, both due to the exceedance of temperature thresholds. Inhabitants also notice changes in the seasonality of the weather (e.g. more frequent rainfall in winter,

summers getting drier), which matter for agriculture and tourism. Tourism is a special case because the effects of climate change are ambivalent (positive and negative). Both tourism and agriculture are highly dependent on the evolution of the water resource, sometimes competing for water use in summer. Future changes in summer rainfall are critical for the vegetative phase of crops, for salt production and for touristic activities.

Brittany has warmed by about 1 °C on annual average over a thirty-year period (1959-1988 to 1989-2018), with all temperatures (minimum, mean, maximum) increasing in all seasons (CRPF Bretagne-Pays de la Loire, 2019). Morbihan has warmed more, about 1 to 1.2 °C annually in the Northwest, and 1.2 to 1.4 °C in the East during summer (CRPF Bretagne-Pays de la Loire, 2019). Although the occurrence of frost decreased over the last three decades in Brittany, no shift has been detected in the timing of frost during spring and autumn (CRPF Bretagne-Pays de la Loire, 2019). The Atlantic coastal waters have also warmed, about a few tenths of °C in mean annual temperature (DREAL Bretagne, 2015; l'Hévéder et al., 2017; Charria et al., 2020), in association to warmer summer nights over Brittany's coastline (CRPF Bretagne-Pays de la Loire, 2019). Oyster mortality events have been linked to high wintertime anomalies of seawater temperature, associated to the prevalence of NAO+ during winter (Thomas et al., 2018).

More generally, warming has also resulted in shifts of climate zones worldwide, with an expansion of dry climates and reduction of polar climates (Jia et al., 2019). Another consequence of climate change and surface warming is the modification of seasonality, such as the annual cycle of temperature (Santer et al., 2018; Yettella and England, 2018; Chen et al., 2019; Wang et al., 2021), and a lengthening of the summer weather (Vrac et al., 2014; Peña-Ortiz et al., 2015; Cassou and Cattiaux, 2016). The phenology of plants is deeply linked to climate, especially to transitions of weather conditions between seasons, although there are many other non-climatic factors at play in plant development (Cleland et al., 2007). As a result of recent climate changes, the seasonal activities of many species of plants and animals have changed (Jia et al., 2019).

Crop development in temperate regions is influenced by climate change through various effects. Warming leads to increases in heat stress, crop water demand (increased evapo-transpiration) and night respiration, in addition to a longer growing season and a shortening of crop cycles (Tubiello et al., 2007; Teixeira et al., 2013; DREAL Bretagne, 2015; Jia et al., 2019; Menzel et al., 2020). Higher atmospheric CO₂ facilitates photosynthesis and reduces plant water needs, but climate change also has negative effects on the evolution of water availability (DREAL Bretagne, 2015). The acceleration of phenology has been observed in French vineyards in association with warming since the 1980s (CSEB, 2012). The relationship between warming and advance of harvest date is almost linear for various types of vineyards in France (ONERC, 2018b), for example grape harvest (about 1 month in 50 yrs) and fruit maturity (1-2 weeks in 30 yrs) in southeastern France (Hébert et al., 2011).

The seasonality of precipitation has changed less spectacularly than temperature. Precipitation fluctuated largely in Brittany over 1959-2018, with no significant trend emerging, except a small decrease in spring (less than 5 %) and small increases in other seasons (CRPF Bretagne-Pays de la Loire, 2019). The number of raining days increased in Western Brittany during summer, resulting in +20 to +40 mm in 30 years (10-20 % increase; CRPF Bretagne-Pays

de la Loire (2019)). This evolution of precipitation is paralleled by increased evaporation due to surface warming. Eastern Brittany is getting drier during the extended summer season (April to October), with an additional 100 mm difference in water balance (precipitation minus evaporation; CRPF Bretagne-Pays de la Loire (2019)). Morbihan is included in the area where evaporation is increasing faster than precipitation, possibly leading to issues of water use. An analog can be found about 100 km southeast of Morbihan, in Vendée which is already exposed and vulnerable to water scarcity (DREAL Bretagne, 2015).

A few uncertainties are attached to the current situation. Although climate change has been linked to modifications of the seasonality of temperature, water cycle, and plant development, the attribution of the evolution of crops remains tricky because of changing agricultural practices that are also due to other factors alongside climate change (CSEB, 2012). Similarly, the current impact of climate change on touristic activities through the reduction of water availability has not been quantified clearly based on current data (DREAL Bretagne, 2015). Another issue is the lack of local long-term observations of the warming of coastal waters in Brittany (CSEB, 2012), and at the scale of the natural harbour in the Gulf.

The future warming of France depends substantially on the scenario, with the Northwest projected to heat up less than the Southeast (Figure 4.3), and a warming stronger in summer but weaker in spring (Météo-France, 2020e). By 2030, the mean annual temperature of Western France is projected to increase by about 0.8-1.4 °C (vs. 1971-2000), but as much as 1.8 °C in Morbihan during summer (DREAL Bretagne, 2015). The contrast in warming widens between scenarios and seasons over the second half of the century (DREAL Bretagne, 2015; Météo-France, 2020e). By the end of the century (RCP8.5), Western France has warmed up to 5.5 °C during summer in some territories but only 1.4-3 °C in winter (DREAL Bretagne, 2015). Brittany will warm less than the rest of Western France (Figure 4.3), about 3-4 °C by the end of the century according to a high-emission scenario (CRPF Bretagne-Pays de la Loire, 2019; Météo-France, 2020e)). Exceptional mortality events of oysters are likely to become the norm by approximately 2035 (without adaptation), even under moderate global warming (e.g. +2 °C relative to preindustrial; Thomas et al. (2018)).

Projections of future precipitation show a small annual increase over France, between 2% and 6% depending on the time horizon and scenario (Météo-France, 2020e). This evolution differs regionally (Figure 4.4), with a tendency of increase over northern France and decrease over southern France, and seasonally with an increase in winter (often more than 10%) and decrease in summer (RCP8.5 median of about 20% by end of century; Météo-France (2020e)). These projections vary largely between climate models (Figure 4.4), and the ensemble envelop (5% to 95% of models) corresponds to a range of -6% to +15% of annual change in precipitation by the end of the century (Météo-France, 2020e). In Brittany, a small evolution of annual precipitation is projected during the century (CRPF Bretagne-Pays de la Loire, 2019), hiding contrasting trends of increase during winter and decrease during summer (DREAL Bretagne, 2015). The decrease of precipitation during summer in Brittany will be associated to an increase in droughts (Kovats et al., 2014; DREAL Bretagne, 2015; Jacob et al., 2018; CRPF Bretagne-Pays de la Loire, 2019)).

The exposure of Morbihan's coast to droughts will increase significantly in the short to medium term (DREAL

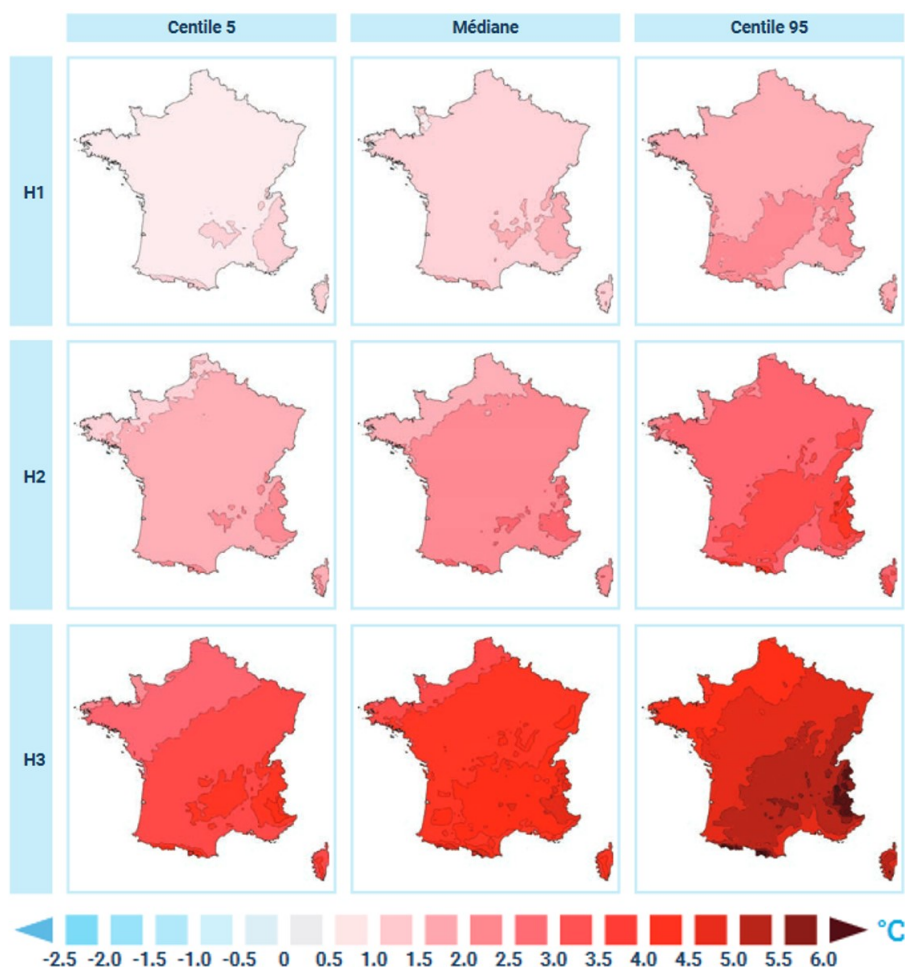


Figure 4.3: Projected increase of annual mean temperature in France according to the RCP8.5 scenario, adapted from Météo-France (2020e). The temperature change is relative to the mean over 1976-2005, for an ensemble of regional climate models and for three time horizons (30-year mean). From left to right: percentiles of the distribution (5th, median, 95th) of results from models. From top to bottom: time horizons (2021-2050, 2041-2070, 2071-2100).

Bretagne, 2015), while the inland territory will see declining river streamflows, more severe low flows, and a degradation of the water resource (ODEM, 2012). For ecosystems and cultivated crops in Europe and the entire world, the ongoing warming is projected to shift climate zones further towards the poles and upward in elevation (Jylhä et al., 2010; Jia et al., 2019). In other words, whole regions and cities will continue to migrate equatorward with reference to historical climate conditions (Beck et al., 2018; Bastin et al., 2019; Fitzpatrick and Dunn, 2019; Cui et al., 2021). These shifts will expose ecosystems to increasingly different climate conditions (e.g. Figure 4.5) than they are adapted to, possibly altering their constitution and functions (Jia et al., 2019). In conjunction with these shifts, the seasonal cycle of surface temperature will change further (Figure 4.5 and Santer et al. (2018); Yettella and England (2018); Chen et al. (2019)) while summer weather expands during the year (Cassou and Cattiaux, 2016; Ruosteenoja et al., 2020).

In Western France, the main impacts of climate change on agriculture and forestry are projected to be less water availability (Brisson and Levraut, 2010), changes in crop productivity, the evolution of production (species, varieties)

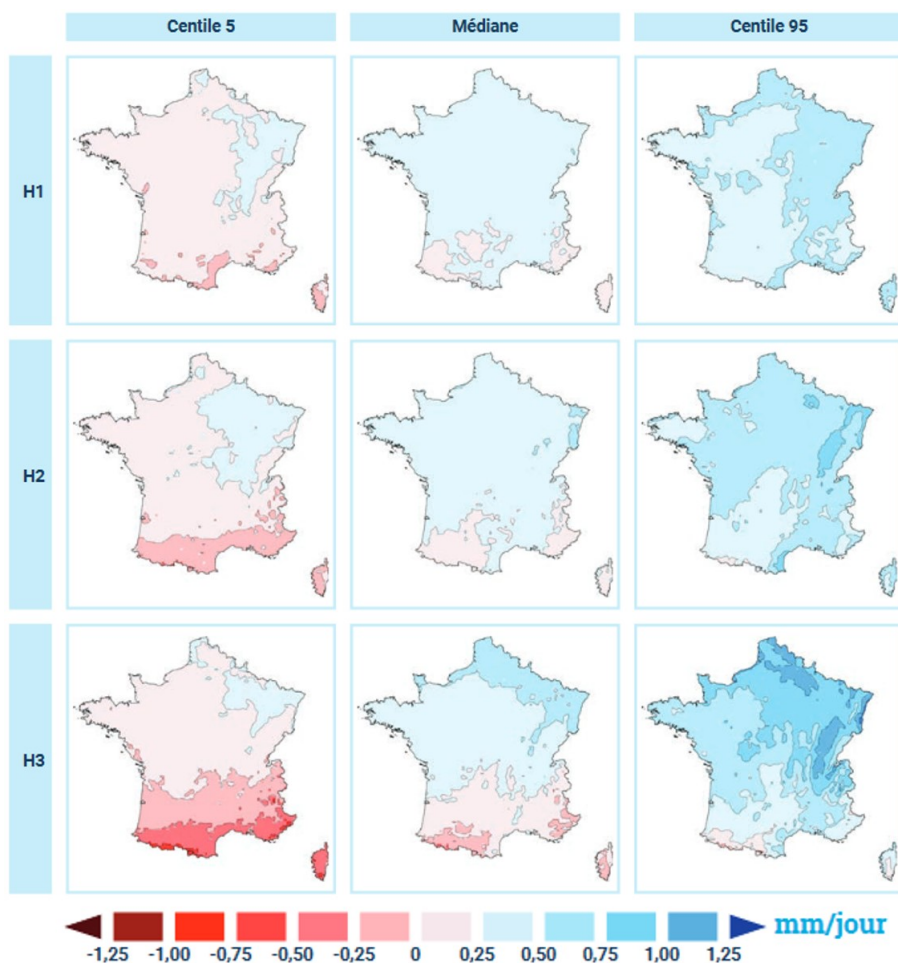


Figure 4.4: Projected changes of annual mean precipitation in France according to the RCP8.5 scenario, adapted from Météo-France (2020e). The precipitation change (mm/day) is relative to the mean over 1976-2005, for an ensemble of regional climate models and for three time horizons (30-year mean). From left to right: percentiles of the distribution (5th, median, 95th) of results from models. From top to bottom: time horizons (2021-2050, 2041-2070, 2071-2100).

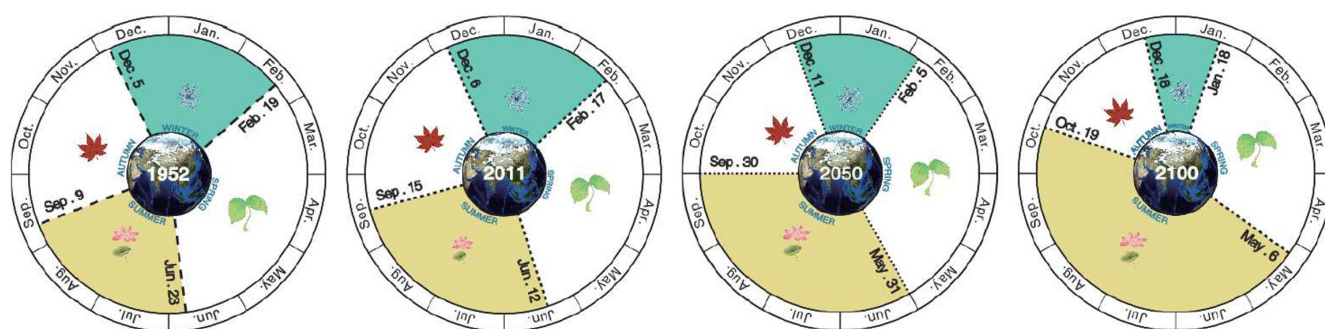


Figure 4.5: Onsets and lengths of the four thermal seasons in the Northern Hemisphere midlatitudes in 1952, 2011, 2050 and 2100 (adapted from Wang et al. (2021)). The four thermal seasons are defined by the passage of a temperature threshold based on historical conditions, calculated on data from observations and multimodel ensemble simulations.

as well as dates of sowing and harvesting (Massu and Landmann, 2011). A pursued advance in the phenological stages of crops and in the timing of harvest is projected for most cultures (especially in spring) at Rennes, about

100 km northeast of Vannes (CSEB, 2012). The positive effects from climate change could be outweighed by the reduction of precipitation and increase of droughts during the vegetative stage of crops, in spring and summer (DREAL Bretagne, 2015). By 2050, the water needs from agriculture could rapidly increase in Western France due to the increase in droughts and strong warming in summer (DREAL Bretagne, 2015).

Water stress appears especially threatening for crops that need a lot of water, that are located on soils with low water availability, or that depend on irrigation (DREAL Bretagne, 2015). Water scarcity in summer could lead to restrictions of use, degradation of waters inland and on the coast (lower river flows and aggravation of algal blooms), and increased conflict of use between activities (e.g. tourism and agriculture) as is already the case in other regions today (e.g. in Vendée; ODEM (2012); DREAL Bretagne (2015)). An odd feature of climate change in Europe is that it could benefit tourism in the Western part, with a decrease in climate comfort over the Mediterranean coast and small increase on the Atlantic coast (Jacob et al., 2018). For instance, the increase of mean temperature and reduction of precipitation during summer appear as opportunities for tourism in Brittany. Climate change might therefore lead to a redistribution of touristic fluxes during summer and new opportunities for inter-seasonal tourism (DREAL Bretagne, 2015).

The future also holds possible surprises that are not well represented in climate models, and two wild cards could alter the fate of future projections in drastic ways: the climate migration of diseases and a slowdown of the Atlantic Meridional Overturning Circulation (AMOC). The present exposure and vulnerability of Brittany's population to vector-borne and infectious diseases are small, but climate change could lead to more favorable conditions for their development. In particular, the warming of surface waters and the increase of heavy rainfall episodes can facilitate the development of bacteria, pathogens, or toxic algae (DREAL Bretagne, 2015). However, future changes in vector-borne and infectious diseases are very uncertain (e.g. at Brittany's scale) due to their dependency on climate change and various human activities (DREAL Bretagne, 2015).

The AMOC plays a central role in European climate, with the North Atlantic Drift (AMOC tributary) bringing cities of Western Europe several °C of warmth (especially in winter) by comparison to cities of North America at similar latitudes. The strength of the AMOC has reduced since a century due mainly to increasing anthropogenic GHG emissions, driving the North Atlantic "warming hole" (Drijfhout et al., 2012; Sgubin et al., 2017; Chemke et al., 2020; Keil et al., 2020). If this reduction was to strongly intensify in the future, a net effect would be a cooling (and drying) of Northwestern Europe (Figure 4.6 E-F), competing with the ongoing warming (Drijfhout, 2015; Jackson et al., 2015; Sgubin et al., 2017; Liu et al., 2020). The AMOC will likely weaken during the century, and while a complete collapse remains unlikely, a strong weakening is physically plausible (Collins et al., 2019).

Relevant climate services for adaptation to warming and seasonal changes (temperature, precipitation, water resource) include Climat HD and DRIAS from Météo-France, the Indicator Assessment (IA) from the European Environment Agency (EEA), and the Climate Change Knowledge Platform (CCKP) from the World Bank. These four climate services address changes in surface air temperature annually, by season (Climat HD, IA), and monthly

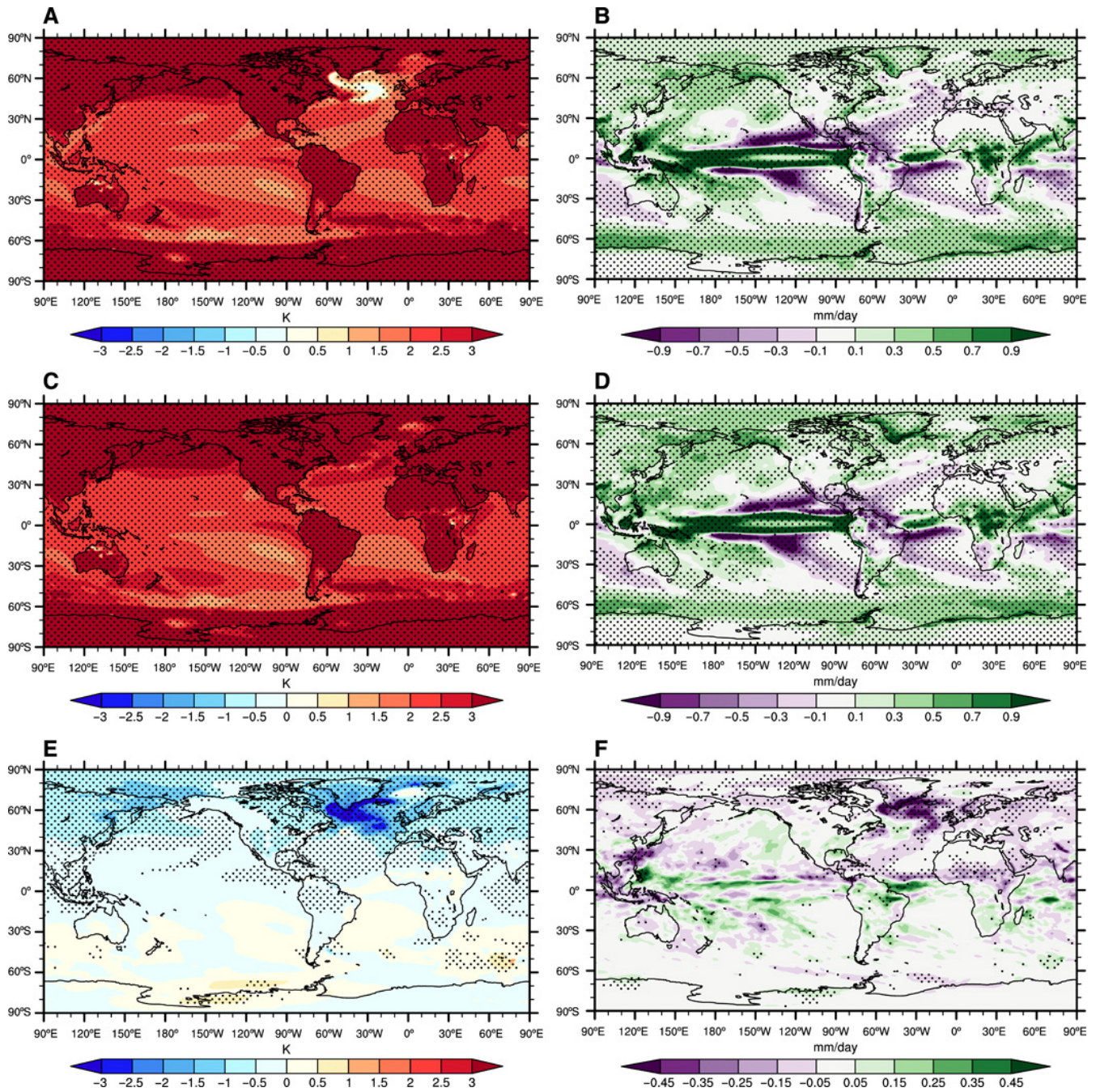


Figure 4.6: Surface temperature and precipitation projections and AMOC impacts (Liu et al., 2020). Left column: relative to 1961–1980, annual mean surface air temperature changes (K) during 2061–2080 based on the ensemble means of CCSM4 RCP8.5 simulation (panel A) and AMOC_{fx} (panel C). In the AMOC_{fx} simulation, the same forcings are used as in the historical and RCP8.5 simulations, but the AMOC strength is maintained. Panel E shows panel A minus panel C. Right column: similar to left column but for annual mean precipitation changes (mm/day). Panel F shows panel B minus panel D. In all the panels, stippling indicates that the response is statistically significant at the 95% confidence level of Student’s t-test. AMOC impacts on surface temperature and precipitation are revealed in panels E and F.

(DRIAS, CCKP) at various scales (from Europe to the region of the Gulf). The warming of surface waters is less covered by climate services in general, but IA provides summaries about the warming of European seas (EEA,

2021k), rivers and lakes (EEA, 2021m), and so does Copernicus about lakes (Copernicus, 2021b). This information is not local however (e.g. Gulf's innea sea).

Some climate services cover future changes (e.g. mean temperature and rainfall) within the meteorological seasons (e.g. winter) but scarce services consider changes in the structure of seasonality. Nevertheless, future changes in seasonality can be explored through DRIAS (Météo-France, 2021b) and CCKP (World Bank, 2021), covering changes in the annual cycle and monthly amounts of various climate variables (e.g. mean and extreme temperature and rainfall) and agricultural indicators (e.g. length of growing season, timing of frost occurrence). Additionally, IA indicates changes in the growing season and timing of phenological events across Europe (EEA, 2021c,i). Regarding the future evolution of the water resource, the four climate services (Climat HD, DRIAS, IA, CCKP) cover future precipitation but also changes in droughts, soil moisture, crop water demand, and river flow (EEA, 2021e,f,l,a,j).

4.2.3 Extreme weather events

Local decision-makers and stakeholders need to prepare the activities and infrastructure of the Gulf for future climate change, and especially for extreme events. Climate change is affecting extreme weather and new extreme events might take place (e.g. unprecedented heatwaves). Additionally, droughts could add pressure on the water resource during summer, while episodes of heavy rainfall could increase the risk of flooding during winter. The warming of air and soil due to climate change leads to more hot extremes (heatwaves), but is also associated to an acceleration of the water cycle causing more humidity extremes (droughts, heavy rainfall; (Jia et al., 2019)). Accordingly, the frequency and intensity of some weather extremes (e.g. droughts and heatwaves) has increased in many parts of the world (Jia et al., 2019).

Similarly in Europe, the number, intensity and damage of weather disasters has increased during recent decades (Kron et al., 2019). Heatwaves and droughts are associated to increased mortality (cardiovascular, respiratory), wildfires to increased morbidity (respiratory and mental health), and floods to increased mental health morbidity (Weilhammer et al., 2021). 2020 was the warmest year on record in Europe, breaking historical high temperatures in many locations (including France) during two heatwaves in June-July 2019 and another in August 2020 (WMO, 2020, 2021). Without climate change, the European heatwaves of 2019 would have been colder and less likely to happen (Vautard et al., 2020). Hot extremes have almost tripled in most large European cities during the last two or three decades, with Northern cities experiencing higher warming in winter and Southern cities in summer (Founda et al., 2019).

Warming also leads to more soil evaporation but the pattern of droughts is divided over Europe due to changing precipitation patterns, towards a desertification of the Mediterranean and wetting of Northern Europe. Drought frequency has decreased over Northern Europe over 1950-2014, whereas drought intensity has increased over

Southern Europe (Spinoni et al., 2015, 2019). Over the past 60 years, droughts have increased in frequency, intensity and duration in the Mediterranean, western, south-eastern, and central Europe (Spinoni et al., 2016). The frequency and severity of droughts particularly increased in Southern and Eastern Europe in summer and autumn, and particularly decreased in Northern Europe in winter and spring (Spinoni et al., 2017). Additionally, the increasing likelihood of occurrence from both heatwaves and droughts leads to an increasing probability of combined dry and hot events during summer (Manning et al., 2019).

Although extreme events carry a high environmental and societal impact, in some cases the influence of climate change can be difficult to determine. The field of climate change attribution has progressed tremendously over the last decade, but several limitations and gaps remain in the assessment of recent changes, attribution of individual events, and projection of future changes (Sillmann et al., 2017; Chen et al., 2018). Weather and climate extremes are influenced by small- and large-scale weather patterns, modes of variability, thermodynamic processes, land-atmosphere feedbacks, and antecedent conditions (Stocker, 2014). There is low confidence in how large-scale modes of variability will respond to a warming climate (Jia et al., 2019).

Extreme events are by definition highly variable, and their triggering mechanisms and underlying processes are not yet fully understood (e.g. Zwiers et al. (2013)). High-quality and long-term data (rarely available) is needed to detect and attribute whether regional changes or individual events fall outside the range of natural variability (Rummukainen, 2012; Stocker, 2014; Easterling et al., 2016). With proper data, there are also limitations in the ability to describe the natural variability of extremes with models and statistical tools (Zwiers et al., 2013). Additionally, there is a lack of consistent definitions of extreme events in the scientific community (McPhillips et al., 2018). Despite these scientific limitations, several features of future changes in extremes can be projected with confidence, from Europe to France.

Europe is projected to face increasing climate hazards: heavy precipitation events (Figure 4.7), heatwaves (Figure 4.8), droughts, and wildfires (Beniston et al., 2007; Lenderink and Van Meijgaard, 2008; Kovats et al., 2014; Forzieri et al., 2016). The European population will be increasingly affected by weather-related disasters, potentially up by an order of magnitude by the end of the century, and similarly for the number of fatalities (Forzieri et al., 2017). As in most of the world, heatwaves are projected to increase in frequency, intensity and duration, affecting an increasing part of the population (Dosio et al., 2018; Dosio and Fischer, 2018; Jacob et al., 2018; Lehner et al., 2018; Lhotka et al., 2018; Jia et al., 2019). In southern Europe by the end of the century under a high GHG emission scenario, extreme heatwaves may happen every two years and last two months (Russo et al., 2014).

European metropolitan areas will become more vulnerable to extreme heat and less to extreme cold in the coming decades, cold spells might almost disappear by the end of the century (Smid et al., 2019). Droughts are also likely to become more frequent, more intense and longer in Southern Europe, and the opposite for Northern Europe (Spinoni et al., 2016). The risk of wildfires will also increase in Southern Europe (Liu et al., 2010). However, episodes of heavy precipitation are also projected to increase in Europe (high confidence; Stocker (2014)), and the increasing

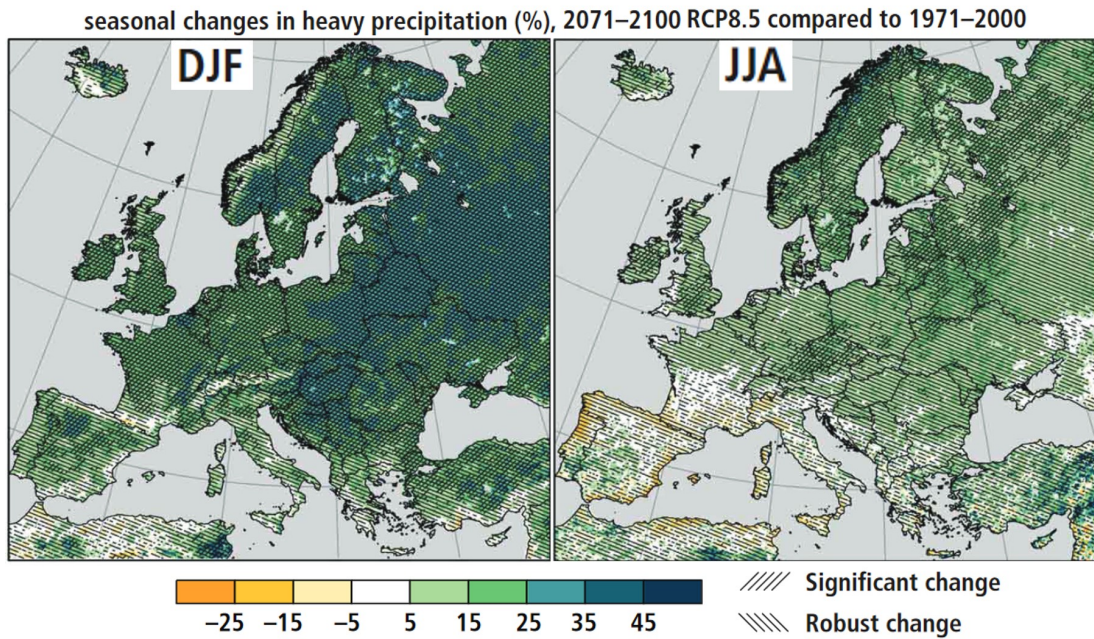


Figure 4.7: Projected seasonal changes in heavy precipitation over Europe, adapted from Kovats et al. (2014). Heavy precipitation is defined as the 95th percentile of daily precipitation (only for days with precipitation >1mm) for the period 2071 compared to 1971–2000, shown in % for winter (left) and summer (right).

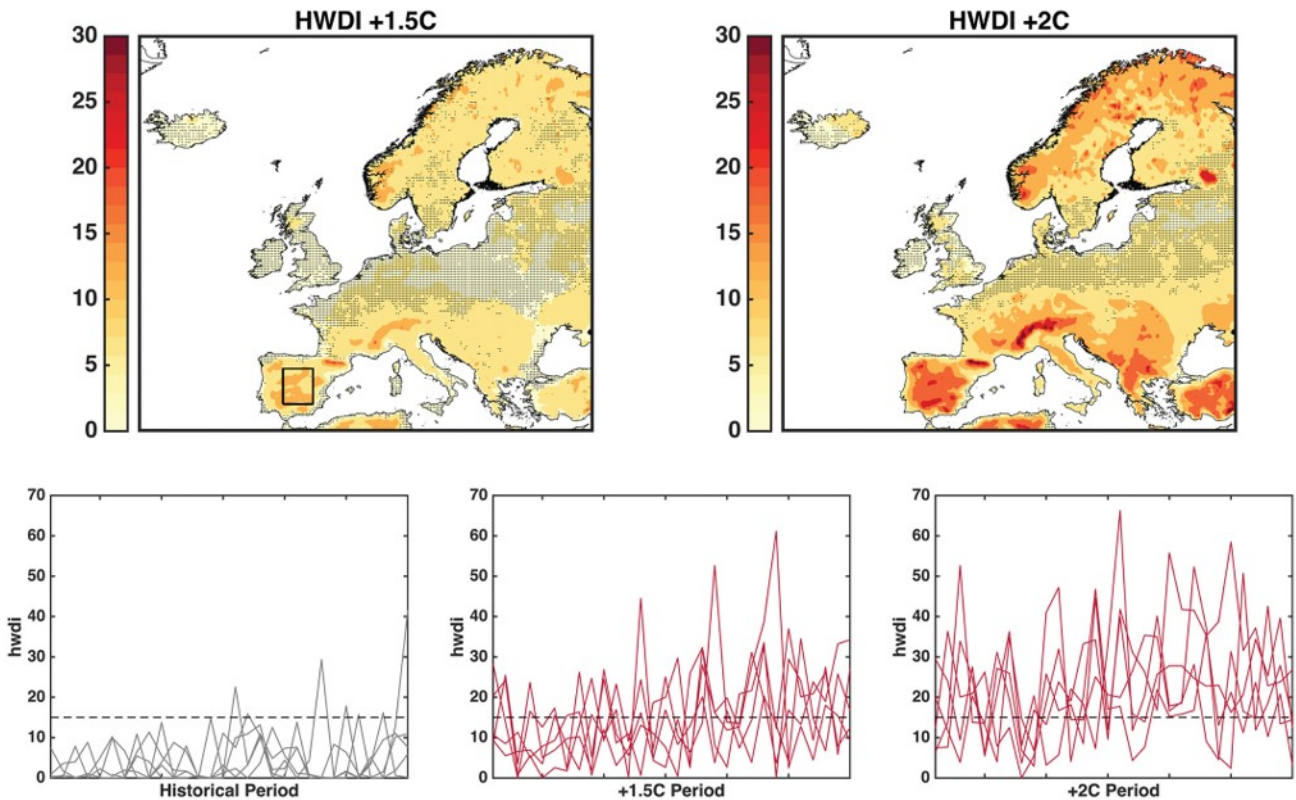


Figure 4.8: Response of an ensemble of models in heatwaves depending on the level of warming, adapted from Jacob et al. (2018). The heat wave duration index (HWDI) is defined as the number of days in May–September where, in intervals of 6 days, the maximum daily temperature exceeds the climatological daily maximum temperature of 1971–2000 by at least 5°C. Top panels: bias-adjusted five-member RCP4.5 ensemble mean response under +1.5°C (left) and +2°C (right), with areas of non-significant trends shown in stipples. Bottom panels: area-averaged time series for each ensemble member of the historical (left), +1.5°C (middle) and +2°C (right) periods, with the historical 95th percentile marked by the dashed line.

intensity of extreme rainfall could lead to a higher risk of flash flooding, land-slides, and erosion (Vergara-Temprado et al., 2021). Under a high-end scenario, the frequency of rare (50- and 100-year return periods) sub-daily events of extreme precipitation could triple (Hosseinzadehtalaei et al., 2020).

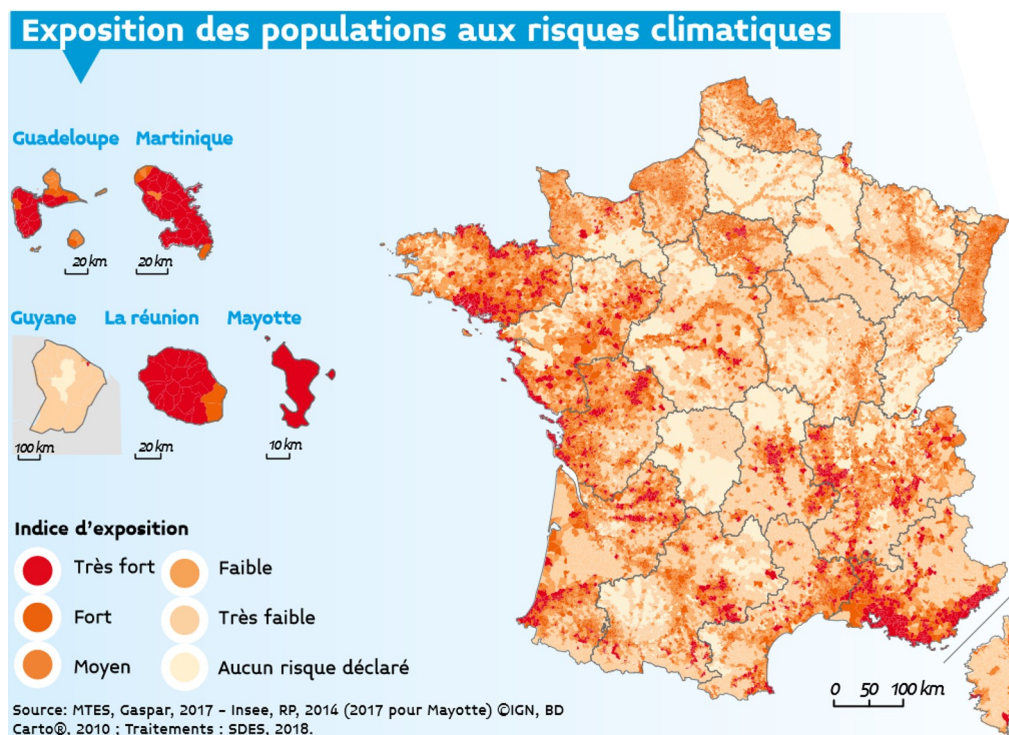


Figure 4.9: Current exposure of French territories to climate risks (ONERC, 2018a). Climate risk exposure increases with the population density and the number of identified natural hazards that are directly or indirectly influenced by climate change. This indicator is calculated based on the current knowledge of these hazards' occurrence, including avalanches, cyclones and storms, forest fires, floods, and land movements.

In France, the Gulf of Morbihan is currently a hotspot: an area of high to very high exposure to climate risks (Figure 4.9). Climate projections indicate that the number of days of heatwaves will increase in France while the opposite happens for cold spells. Both depend substantially on the scenario and time horizon, with for instance two times more days of heatwave under RCP2.6, three to four times under RCP4.5, and five to ten times with RCP8.5 (Météo-France, 2020e)). In the period 2021-2050, summer heatwaves become more frequent, more intense and longer, but the 2003 summer heatwave would still be exceptional (ONERC, 2018b). Cold spells are becoming less frequent, less intense, and shorter, but do not disappear completely (ONERC, 2018b). Similarly to heatwaves and cold spells, the duration of meteorological droughts depends largely on the scenario and time horizon (Météo-France, 2020e), but they have already increased by 2030, especially in Brittany (DREAL Bretagne, 2015).

The increase of droughts is due more to soil moisture deficit (warming increases evaporation) than to lack of precipitation (ONERC, 2018b). In 2050, droughts are aggravating in Brittany, and the number of days of heatwaves has increased in Morbihan (DREAL Bretagne, 2015). By 2080, droughts are becoming generalized in Western France and days of heatwave have largely increased (DREAL Bretagne, 2015). During the end of the century in France,

drought conditions have increased by about 5 to 10 days (RCP4.5 and RCP8.5), and episodes of extreme rainfall are more intense, while the summer heatwave of 2003 would have become common (ONERC, 2018b; Météo-France, 2020e). The increase of heatwaves is projected to increasingly affect the health of fragile people (e.g. senior, children, sick) in combination with an ageing of the population, and with an increase of droughts will increasingly affect crops and livestock (DREAL Bretagne, 2015).

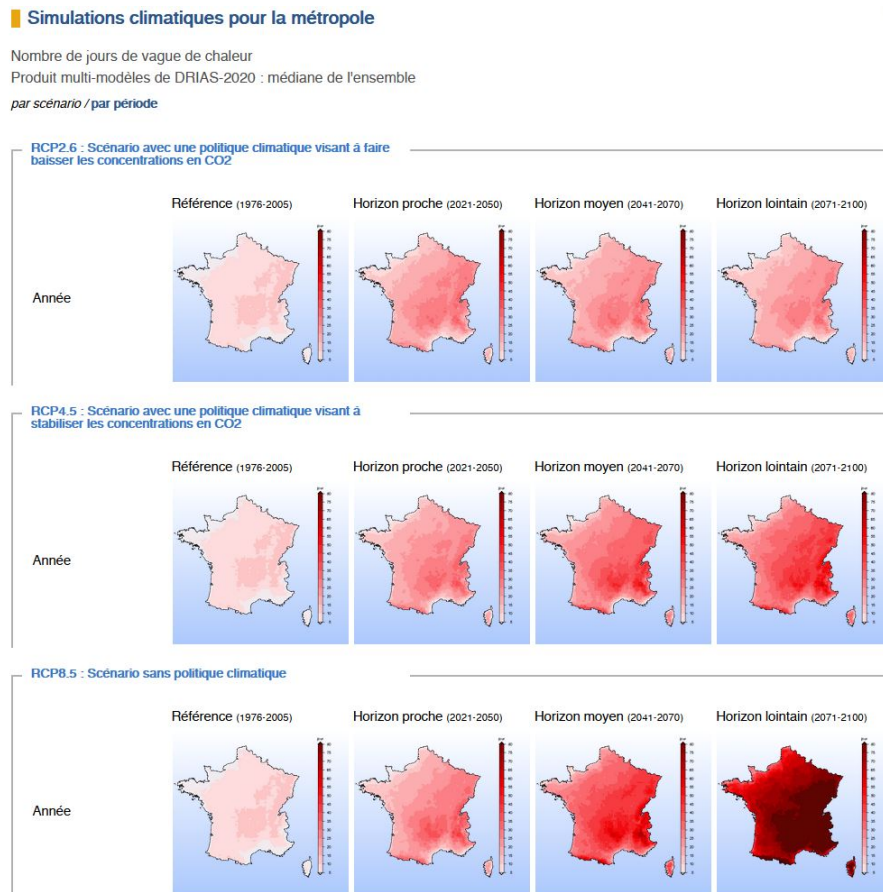


Figure 4.10: DRIAS: number of days of heatwaves over France (Météo-France, 2021b).

Relevant climate services for adaptation to extreme events include Climat HD and DRIAS (Météo-France), the Indicator Assessment (EEA), and the Climate Change Knowledge Portal (World Bank). Climat HD describes heatwaves, droughts and cold spells at the scale of Brittany in the past and at the scale of France in the future (droughts also at the scale of Brittany). This information includes the year, length (days) and intensity ($^{\circ}\text{C}$) of heatwaves and cold spells, and the fraction of territory affected by droughts per year. DRIAS is more difficult to use but much more flexible in terms of climate information (annual to monthly, multi-model, multi-scenario) and provides maps of many extremes (e.g. heatwaves, cold spells, droughts, heavy rainfall) over France at different time horizons (Figure 4.10).

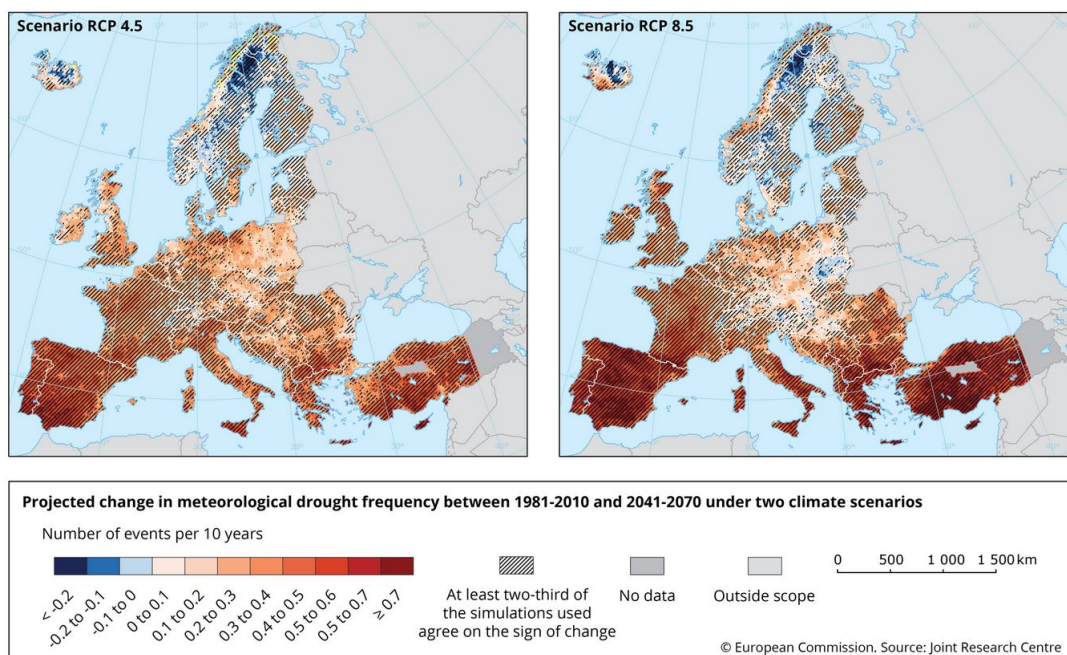


Figure 4.11: Indicator Assessment: future changes in droughts over Europe (EEA, 2021f).

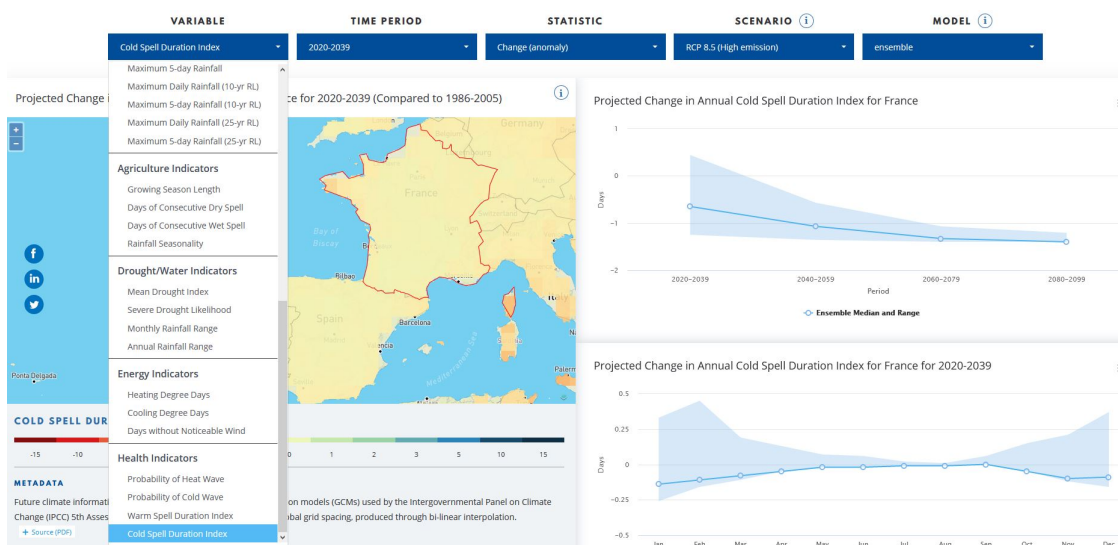


Figure 4.12: Climate Change Knowledge Portal: projected changes in various climate-related variables (World Bank, 2021).

The Indicator Assessment (IA) provides a summary and maps of recent and future changes in extremes related to temperature and precipitation in Europe, including heatwaves, meteorological and hydrological droughts (Figure 4.11), heavy precipitation and river floods (EEA, 2021h,f,d,g). The Climate Change Knowledge Portal (CCKP; World Bank (2021)) provides the observed seasonal cycle, the projected future seasonal cycle and associated map over European areas for various climate variables (Figure 4.12), indicators for society, time periods, scenarios and models. It is also possible to access more local information but requires to do data analysis (extraction, plotting of maps and

time series, etc.) with data available from DRIAS or other free online platforms such as the Copernicus Climate Data Store (Copernicus, 2021a).

4.2.4 Marine submersion

The Gulf is vulnerable to marine submersion and coastal risk management will become more difficult with climate change and a retreating coastline. To develop future projection of shoreline changes, a good understanding of the driving coastal processes is needed (roles of sealevel, waves, tides and storm surges) as well as how they are affected by climate change (Toimil et al., 2020). For instance, the effect of sealevel rise on marine submersion is not linear, since the odds of exceeding water-level thresholds increase exponentially (Taherkhani et al., 2020). Sealevel rise has accelerated globally in the last decades (up to about 3.3 mm/yr since 1993), but with large regional variations due to various factors (oceanic dynamics and thermal expansion, melting of land ice, anthropogenic groundwater extraction; Oppenheimer et al. (2019); Hamlington et al. (2020); Todd et al. (2020); Buzzanga et al. (2021); WMO (2021)).

The current sealevel rise is well comprehended but future projections are very uncertain (especially in high-end scenarios) chiefly because of future GHG emissions, scientific gaps, and model limits (Stocker, 2014; Oppenheimer et al., 2019). Projections of sealevel rise have increased since the last generation of climate models, due to the discovery (and increasing integration in models) of new ice-sheet processes and interactions with a warming atmosphere and ocean, tending to make ice-sheets more sensitive to climate change than previously assessed (Kopp et al., 2017; van den Broeke et al., 2017; Bell et al., 2018; Gudmundsson et al., 2019; Oppenheimer et al., 2019; Robel et al., 2019; Ryan et al., 2019; King et al., 2020; Pattyn and Morlighem, 2020; Seroussi et al., 2020; Slater et al., 2020; DeConto et al., 2021; Edwards et al., 2021; Joughin et al., 2021; Pan et al., 2021). These ice-sheet processes are intensely debated in the scientific community (e.g. DeConto and Pollard (2016); Edwards et al. (2019); Gilford et al. (2020); Smith et al. (2020)).

The last IPCC report provides estimations of 0.84 m global sealevel rise projected by 2100 (likely range of 0.61 to 1.10 m) according to a high-emission scenario (Oppenheimer et al., 2019). However, estimations of sealevel rise from expert surveys and upper-tail projections can be substantially higher than IPCC estimates, reaching between about one and three meters at the end of the century (Kopp et al., 2017; Bamber et al., 2019; Abadie et al., 2020; Horton et al., 2020; Vega-Westhoff et al., 2020; Dayan et al., 2021). To explore the uncertainty of future sealevel rise, various probabilistic projections have been developed (e.g. Le Cozannet et al. (2017); Vousedoukas et al. (2018b); Jevrejeva et al. (2019); Nicholls et al. (2021)), sometimes for particular locations (e.g. Nauru and New York in Figure 4.13). Projections of European shoreline retreat have also been developed, reaching up to two hundred meters in some locations (Figure 4.14) based on a high-emission scenario (Athanasίου et al., 2020). In some cases, a better representation of coastal processes and their interaction can reduce sealevel rise projected on Western European

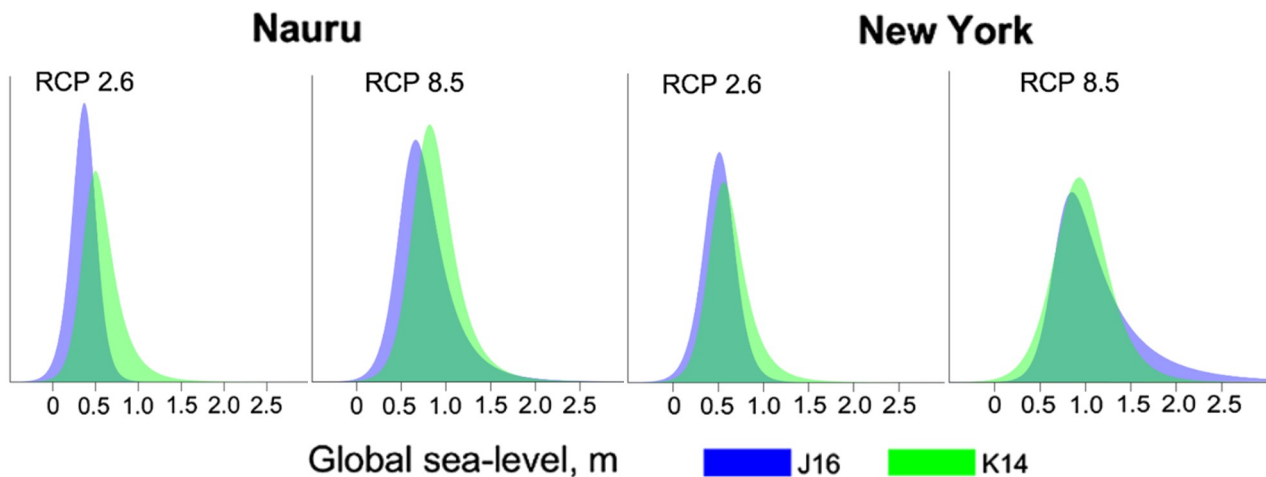


Figure 4.13: Probabilistic projections of sea level rise, adapted from Jevrejeva et al. (2019). Probability density functions for sea level in Nauru (Pacific island) and New York in 2100 for RCP2.6 and RCP8.5. Green colour (K14) corresponds to the results from Kopp et al. (2014), and blue (J16) to the results from Jackson and Jevrejeva (2016).

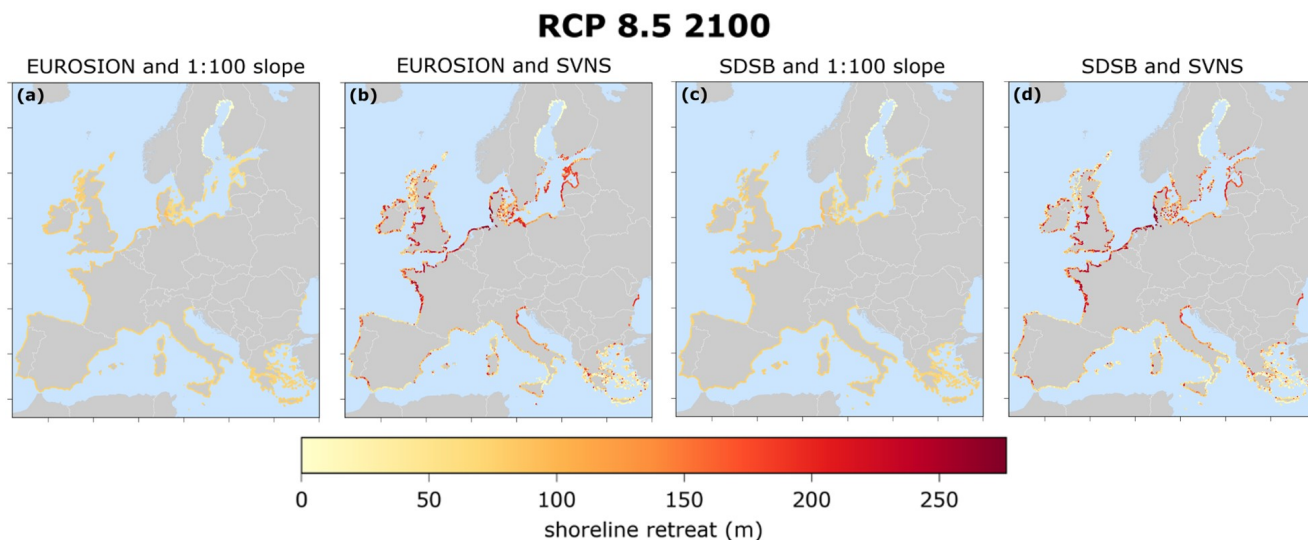


Figure 4.14: Projections of European shoreline retreat, adapted from Athanasiou et al. (2020). Potential shoreline retreat (m) projections at sandy beaches for the median projected sea level rise at 2100 under RCP8.5 (in the absence of ambient shoreline changes), relative to the baseline year 2010. Each map represents an assessment with a specific combination of geophysical data (sandy beach location and nearshore slope).

coasts (Arns et al., 2020; Hermans et al., 2020).

The most immediate way that sea level rise will be felt is not the slow-paced retreat of the coastal land, but rather the exacerbation of storm surges. A storm surge is an anomalous rise of the sea level induced by low atmospheric pressure and strong winds during intense cyclones (Vousdoukas et al., 2018a; Fernández-Montblanc et al., 2019). The vast majority of cyclones reaching Europe arises in the midlatitudes, but a small fraction comes from the tropics ("post-tropical") and tends to have higher windspeed (Sainsbury et al., 2020; Baker et al., 2021; Haarsma, 2021). Tropical cyclones rarely reach Europe (Figure 4.15), about one in ten over the last four decades (Baker et al., 2021), but this might change in the future with warmer conditions. The temperature of surface waters in the tropical Atlantic

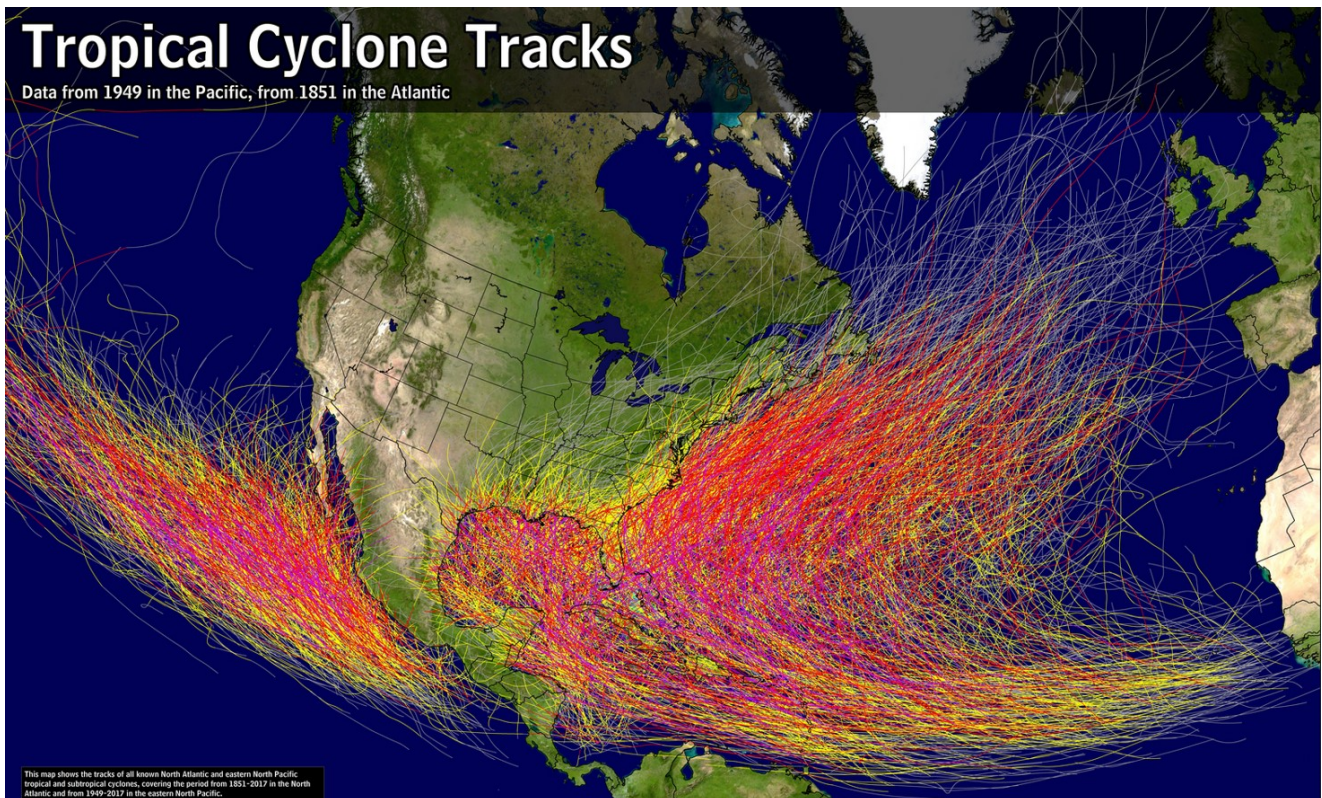


Figure 4.15: Tropical cyclone tracks in the Atlantic over 1851-2017 (National Hurricane Center, 2021). Tropical and subtropical storms in yellow (63-118 km/h), hurricanes in red (119-177 km/h), and major hurricanes in purple (>177 km/h). In grey are shown depressions, disturbances, lows or systems that have transitioned to extratropical.

is a key factor in the formation of tropical cyclones (McTaggart-Cowan et al., 2015; Tory and Dare, 2015; Mei et al., 2019), with higher SSTs fueling their development (Murakami et al., 2018).

The number of tropical cyclones in the North Atlantic has increased in the last decades (Figure 4.16 and Zhao et al. (2018); Murakami et al. (2020)), as well as their intensification rates (Bhatia et al., 2019), with the strongest cyclones becoming more intense (Elsner, 2020). However, there appears to be a trade-off between the intensity and frequency of tropical cyclones at the global scale, with overall fewer but more intense cyclones due to ocean warming (Kang and Elsner, 2015). The wave climate of the North Atlantic has also changed, with increases over 1985-2018 in wind speed (about +0.3 cm/yr), significant wave height (about +0.3 cm/yr), and extreme wave heights (about +0.8 cm/yr; Young and Ribal (2019)). In this case, significant wave height is the average height from trough to crest of the highest one-third of waves, and extreme wave heights correspond to the the 90th percentile of wave height. However, the strong natural variability of wave climate in the North Atlantic may still mask the signal from global warming (Odériz et al., 2021).

Some tropical cyclones are associated with more precipitation (medium confidence), faster winds (low confidence), and higher extreme sea level events (high confidence) due to climate change (Collins et al., 2019). Extreme storm surges on European shorelines appear to have increased in magnitude over 1979-2016 above 50°N, and decreased

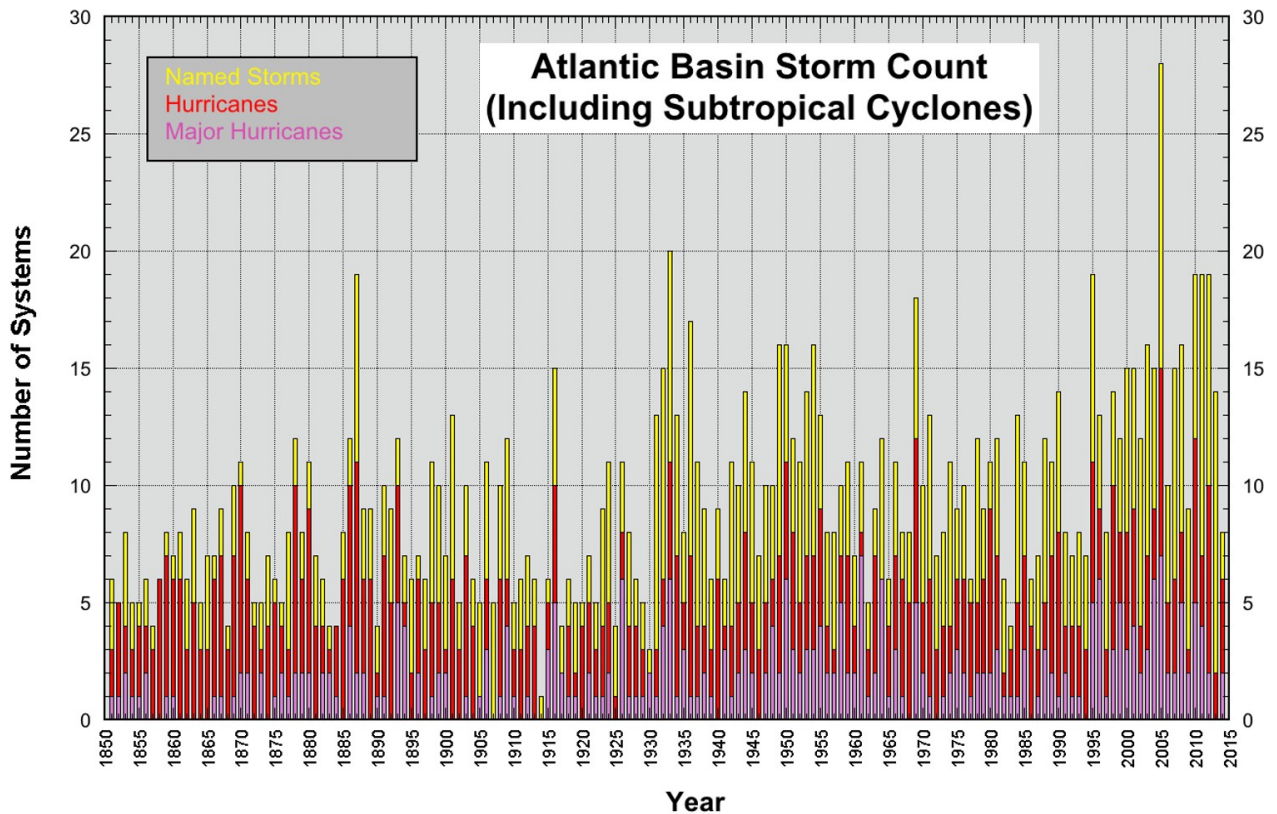


Figure 4.16: Evolution of the number of named cyclones in the Atlantic over 1850-2014 (National Hurricane Center, 2021). Named storms in yellow, hurricanes in red (119-177 km/h), and major hurricanes in purple (>177 km/h).

at lower latitudes (Fernández-Montblanc et al., 2020). Historical data suggests detectable changes in the activity of tropical cyclones over some regions, but their analysis (intensity, frequency) is complicated by issues of data quality and quantity (Knutson et al., 2019). The future evolution of coastal hazards is more uncertain, with low confidence in projected regional changes of storm activity in the North Atlantic (Collins et al., 2019; Oppenheimer et al., 2019), associated to uncertainty in SST warming patterns (Yoshida et al., 2017). Météo-France states the same conclusion for the future evolution of storms concerning the French coasts, with no consensual direction of change (intensity, number, trajectory) due to the sensitivity of the results to the model and method used (Météo-France, 2021d).

However, other changes in coastal hazards can already be identified in projections. The key factor controlling the activity of Atlantic major hurricanes appears to be the degree to which the tropical Atlantic warms relative to the rest of the global ocean (Murakami et al., 2018). This local warming will likely lead to even higher numbers of major hurricanes in the future (Murakami et al., 2018). The intensity of tropical cyclones and proportion of major hurricanes (category 4 and 5) are projected to increase with further global warming (Collins et al., 2019; Knutson et al., 2020). Due to the observation of very strong category 5 Atlantic hurricanes, and to the potential for more intense hurricanes in the warming climate, scientists have suggested to extend the current scale of hurricane intensity (Category 1-5) with a category 6 and even 7 (e.g. >314 km/h and >370 km/h; Livescience (2006); Daily Express (2017); Tampa Bay Times (2018); The Guardian (2018)).

Category 6 hurricanes have already been observed, while category 7 have been simulated to be physically plausible in the future (ABC News, 2006; Lin and Emanuel, 2016; Lin et al., 2017; CBS News, 2018). Tropical cyclones will be associated to higher extreme sea levels (very high confidence) and storm surges, as well as more precipitation rates (medium confidence; Collins et al. (2019); Knutson et al. (2020)) due to increased cyclone intensity and environmental water vapour (Liu et al., 2019). Significant wave height is projected to decrease in the North Atlantic (high confidence; Collins et al. (2019)), with the same for mean wave heights but the most severe wave heights are projected to increase (Wolf et al., 2020). The risk of compound flooding from heavy precipitation and storm surges in Europe is also projected to increase (Bevacqua et al., 2019).

A lower confidence is associated to the following projections of tropical cyclones: decrease of global frequency, increase in global frequency of major hurricanes (category 4–5), and slowdown in motion speed (Knutson et al., 2020). In a warmer world, some projections show a reduction of tropical cyclone motion, a poleward shift of storm tracks, an increased latitudinal propagation of midlatitude storms, and an increased occurrence of extratropical storms in the Eastern North Atlantic (Liu et al., 2017; Tamarin-Brodsky and Kaspi, 2017; Wolf et al., 2020; Zhang et al., 2020). In the North Atlantic, the amount and intensity of post-tropical cyclones might increase due to warmer oceans, stronger tropical cyclones, and the extension of genesis regions for tropical cyclones poleward and eastward (Haarsma, 2021). These changes would increase the windstorm risk from post-tropical cyclones and their potential to cause high-impact weather in Western Europe (Haarsma, 2021; Jung and Lackmann, 2021).

The literature on coastal adaptation contains many types of strategies and measures (Figure 4.17). Coastal management might require different types of information such as probabilistic sea level rise and exploration of

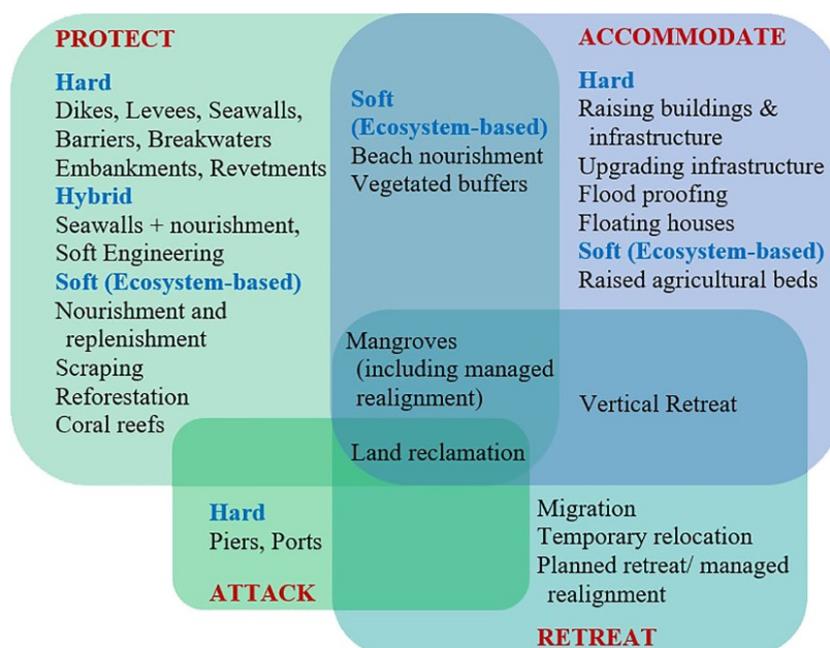


Figure 4.17: Types of strategies and measures in the literature on coastal adaptation (Dedekorkut-Howes et al., 2020).

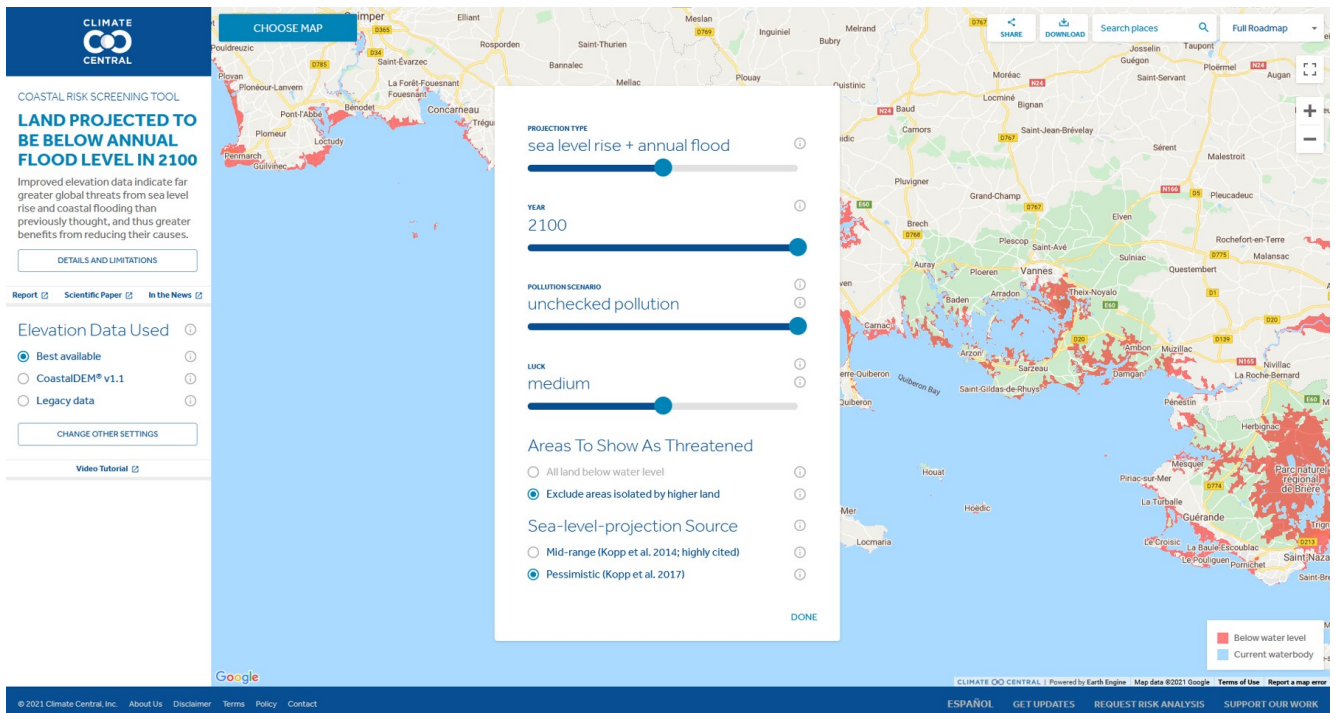


Figure 4.18: Example of a climate service for the analysis of future local marine submersion (Climate Central, 2021a).

uncertainty in coastal flood hazards (Le Cozannet et al., 2017; Stephens et al., 2017) at regional and city scale (Dayan et al., 2021). Relevant climate services for coastal adaptation include Tempêtes and Climat HD (Météo-France), the Indicator Assessment (EEA), and Surging Seas (Climate Central). Tempêtes and Climat HD provide knowledge about past storms. Tempêtes (Météo-France, 2021e) provides a historical database of storms over 1980-2020 (occurrence, intensity, trajectory), including maps and summary sheets (e.g. for Xynthia).

Climat HD (Météo-France, 2021a) gives a summary of the evolution of storms in France and Brittany over 1980-2018, such as the high interannual variability and unclear link with climate change. The Indicator Assessment (IA) provides an assessment of past and future changes in sealevel rise (EEA, 2021b) and wind storms (EEA, 2021n) for Europe. Finally, Surging Seas (Climate Central, 2021a) provides maps and tools (e.g. Figure 4.18) for regional and local analysis of future sealevel rise and land submersion depending on various parameters (inclusion of flood level, year, pollution scenario, luck, elevation data, projection source).

4.3 Discussion

This assessment of the landscape of climate knowledge and services was limited by my resources and is not exhaustive. It was nonetheless based on the state of the art of existing mappings, and was updated continuously during my PhD. The assessment indicates an abundance of climate services, with a large diversity of services but majority of non-interactive formats, and a strong distinction between public and private services. It also reflects the

growth of the sector of climate service production, also suggested by the rising number of providers listed on CKH. The regional climate services were also presented to stakeholders during the 2019 field interviews (February, March and December). The local actors did not know these services existed (despite their online accessibility) but showed a keen interest in the information especially regarding the short-term future (seasonal forecasts).

I also identified the scientific knowledge, uncertainties and gaps in terms of climate change at the local scale of the case study (Gulf of Morbihan). The assessment allowed to precise the local future changes, which can be quantified with varying level of detail and uncertainty based on the documented materials. Table 4.6 summarizes the changes for each climatic theme and topic. The future evolution of some variables in the next decades are deeply uncertain (e.g. storm surges and rate of sealevel rise) while others are nearly certain (e.g. seasonal warming). The Gulf of Morbihan is already substantially affected by climate change, but most of the ongoing changes will strongly increase in the future. These changes will have mostly negative effects (e.g. heatwaves on health, droughts on agriculture), despite rare positive effects (e.g. summer tourism).

Table 4.6: Synthesis of the assessment of local climate change. An increase is indicated by an upward arrow (\nearrow), a decrease by a downward arrow (\searrow), and an unclear trend by an approximation (\simeq).

Theme	Topic	Past	Future
Seasonal changes	Temperature	\nearrow all seasons (especially summer)	\nearrow (especially summer)
	Precipitation	\searrow spring and \nearrow other seasons	\nearrow winter and \searrow summer (large uncertainties)
	Water resource	\searrow summer	\searrow continue
	Seasonality	Shift of climate zones, longer summer weather	\nearrow continue
	Crops	Shift of phenology, longer growing season. Shortening of crop cycles?	\nearrow continue
Extremes	Heatwaves	\nearrow (frequency, intensity, duration) especially summer	\nearrow continue
	Cold spells	\searrow (frequency, intensity, duration)	\searrow continue
	Droughts	\simeq depends on sources (e.g. Météo-France: no, EEA: yes)	\nearrow summer
	Heavy rainfall	\simeq (trend significancy)	\nearrow continue
Marine submersion	Sealevel rise	\nearrow	\nearrow continue
	Storm surges	\simeq depends on sources (\nearrow windspeed, wave height, surge level?)	\simeq depends on sources

Overall, these results suggest that climate change will have wider consequences than previously assessed (Chapters 1 and 3), implying a larger adaptation gap. The local perceptions identified in Chapter 3 are mostly consistent with the current state of scientific knowledge, both in terms of the ongoing local changes (coastal risks, seasonal changes, extreme events) and their link to climate change. There are also a few discrepancies however. Some elements are absent of local perception (e.g. cold spells) although they will matter in the near future. A striking disparity is the topic of heatwaves, prevalent in scientific assessments but severely under-represented in the

narratives, possibly due to the timing of the interviews (outside summer).

Finally, the materials documented in my assessment can serve as a basis for further activities: exploring and building foresight processes in support of local adaptation. The current assessment could therefore, by a conceptual stretch, be considered as a form of climate service. These foresight activities will be key to analyse how the present state of scientific knowledge and climate service address local adaptation needs, and whether there are gaps and options for improvement. In addition, it could be interesting to investigate further some of the research gaps that I have identified in climate change science.

Summary of Chapter 4

Context and objectives:

The first goal of this chapter was to assess the scientific knowledge of local climate change (to compare with the perception of actors), and the second goal was to map the existing climate services (to support adaptation activities in the Gulf).

Methods and results:

I first reviewed extensively the literature (scientific and grey) about climate change for the Gulf of Morbihan. This assessment varies in detail and uncertainty depending on the climatic topic and information source, but it shows that the Gulf is already broadly affected by climate change. The effects are mostly negative (e.g. warmer and drier summer for agriculture) despite rare positive effects (e.g. longer summer weather for tourism), with a projected general increase of the changes (e.g. warming, seasonality) in the future. This picture is consistent with the local experience in the Gulf (ongoing changes, link to climate change), despite disparities such as the rare mention of heatwaves and cold spells in interviews.

Second, I mapped the existing climate services that cover the case study, based on previous mappings (literature, Climate Knowledge Hub) complemented by an extensive search and an analytical framework (built collaboratively). This mapping revealed an abundance (50+) and diversity (data, text, tool, advice, process) of climate services. The services vary extensively in scope (from global to regional), provider (corporation, public agency, etc.), user (from layperson to researcher), format (cf. above), and topic (disaster risk, urban planning, etc.). However, the majority of services are not interactive (data, text). Some services were presented to local actors during the interviews, but they did not know about them (despite their online accessibility).

Perspectives and link to next chapters:

The literature review and mapping of services are not exhaustive, and in some cases it would be interesting to precise the changes at local scale (e.g. uncertainty of precipitation) when the information is at regional scale. In the next chapters, the scientific knowledge, climate services and local narratives will serve as a basis for adaptation activities (Chapter 5), and I will conduct new studies to address knowledge gaps associated to the three local climatic themes (Chapter 6).

Chapter 5

Experimentation of foresight processes (climatology-art-design) and implications for climate services

This chapter is based on collaborative work with social researchers from the CoCliServ project, local partners from the Gulf (PNR and Clim'actions Bretagne Sud), a designer and artists. The main goal of the following community-led activities was to make local inhabitants take ownership of the issue of climate change, and to engage them into thinking about local adaptation. We have organized a foresight workshop, an art-science exhibition, and a conference-debate. Charlotte da Cunha led the experimentation of the workshop and exhibition, assisted by Ana Paula Farias Rocha (workshop), Caroline Amrom (exhibition), Marianne Cardon (workshop and exhibition), me (workshop and exhibition) and Laurent Labeyrie (exhibition). Laurent led the conference-debate on local adaptation with my assistance. Caroline was a student in adaptation planning at CEARC, Marianne is a local designer, and Laurent Labeyrie is a local emeritus climatologist engaged into the work of Clim'actions. The analysis of the results from the prospective workshop was a focus of Ana's internship, while the internship of Caroline focused on the art-science exhibition and on the link between CoCliServ results and the new PCAET under construction for the Gulf.

Some of the research presented in this Chapter (and Chapter 3) has been published in the journal *Climate Risk Management*, in the article *Adaptation planning in France: Inputs from narratives of change in support of a community-led foresight process* (da Cunha et al., 2020).

The climate change basis for the three foresight activities (workshop, exhibition, debate) was drawn from the assessment of climate services and scientific knowledge (Chapter 4). As I updated this assessment continuously during my PhD (i.e. detection of new materials), the climate change basis was less comprehensive when the foresight activities occurred. This basis was nevertheless already substantial and included the main relevant climate services (i.e. Climat HD, DRIAS, IA, Surging Seas) for the task of developing a local scenario of future climate change.

5.1 Local vision-based scenarios

5.1.1 Methods: prospective workshop based on a "poker design" approach

Making the Gulf of Morbihan more climate-resilient will be a multifaceted endeavor, because of the divergence of future visions and controversial character of land-use choices (Chapter 3). The objective of the first foresight activity was to gather local stakeholders and make them seize climate change adaptation. By defining collectively their priorities for the territory and how these actions could be achieved, in light of the risks from climate change and extremes.

The prospective workshop was the occasion to collectively design a desired future (visions and scenarios) for the Gulf, associating short-term actions and long-term plans, to produce a more climate-resilient trajectory. We coupled long-term scenarisation with short-term planning so that we could identify the matters of concern for the community, adaptation pathways, hinge points, and potential needs of additional climate knowledge. The foresight workshop took place in March 2019, and gathered twenty local stakeholders (among the available interviewees from Table 3.1, and two members of Clim'actions), representing a sample of various activities from the territory (e.g. agriculture, tourism, land-use planning, research).

A main challenge for the workshop was the relative proportion of overlap and conflict in the future visions, so we tried to create conditions favouring the emergence of main scenario lines, so that pathways could be framed (plans, actions, hinge points). The workshop was therefore organized in collaboration with the local designer, devising creative tools to facilitate the participation of stakeholders, and to encourage them to consider multiple possibilities for the future of the territory. Lasting about three hours, the workshop consisted of different activities (Figure 5.1):

- 2pm - Introduction and roundtable
- 2.45pm - Scenarization - creative session
- 3.30pm - Coffee break
- 3.45pm - Collective creation of a 2200 vision
- 4.30pm - Conclusions



Figure 5.1: Different activities during the prospective workshop (adapted from Wardekker et al. (2020)). Topleft: participant taking poker design cards. Topright: collective deliberation of the visions for 2200. Bottom: scenarization phase in groups of four.

Before the introduction to the prospective activity, the organizers and each participant introduced themselves to the group (roundtable). During the introduction, the researchers then presented the scientific basis for future climate change, and the identified narratives of change, aiming to give participants a common basis for the issues at stake. The use of narratives of change can support the act of thinking about the future, as narratives help to structure the uncertainty and to guide actions (Frittaion et al., 2010; Miller et al., 2015; Milojević and Inayatullah, 2015; Wittmayer et al., 2019). The long times (45 minutes) of individual reflection (creative session) and then discussion (collective creation) aimed to allow each participant to enter a proper process of active thinking and deliberation in the co-construction of desired scenarios.

The proposed time horizon for the future vision is distant: 2200. Four reasons motivated this choice by the research team:

- avoiding the preference of stakeholders for short-term issues
- letting go of the constraints of the present
- clear-cutting the effects from climate change
- allowing to consider more imaginative perspectives and actions

The desire of a long-term physical scenario was also driven by the geo-social narrative, which interrogated the impact of sealevel rise over the last several thousand years. A disadvantage from such a long timeframe is the large

part of unknown and uncertainty (questioned by a few participants), but this limitation was overcome with the creative tools during the prospective activity (see Discussion in 5.1.3).

The future physical scenario was built on the basis of the regional information assessed previously (part of Chapters 3 and 4), briefly outlining the relative certainty and uncertainty in the future evolution of temperature, precipitation, sea level, seasons, and extreme events (Figure 5.2). This physical scenario was presented before the foresight activity in order to provide elements of boundary conditions in the prospective thinking (i.e. what is likely to happen or almost impossible in the future). We considered a mean warming of 6.5°C based on AR5 multimodel projections (Figures 12.5 and 12.11 from Collins et al. (2013)), and a conservative estimate of 2.5 m of sealevel rise based on projections from Kopp et al. (2017) and on local subsidence (1 mm/yr).



Figure 5.2: Examples of introductory slides during the prospective workshop (adapted from Amrom et al. (2020)).

A map of the territory (Figure 5.3) was devised by the designer (with the software Illustrator), based on the coastline projection from Surging Seas (Climate Central, 2021a) using the previous sealevel rise estimation. This map compares the current distribution of land-use and infrastructure (e.g. cities and roads) with the future coastline according to projection. To put the future sealevel rise in historical context, we illustrated the past coastline evolution with maps (devised by geologists) showing the approximate 90-meter increase in water level over the past 15,000 years. Participants could see that Vannes was several tens of kilometers inland and Belle-Île-en-Mer (an emblematic local island) was once an inland hill. Similarly for future warming, we highlighted how the projected future annual cycle of mean temperature in Vannes would resemble the present one of a Southern city with a warmer climate.

These representations of the possible territory in 2200 helped to establish what the forthcoming geo-social narrative could become. In addition to the climatic elements of context, socioeconomic elements (Figure 5.4) were also given to the participants in the form of factsheets summarizing current trends and future projections (demography,

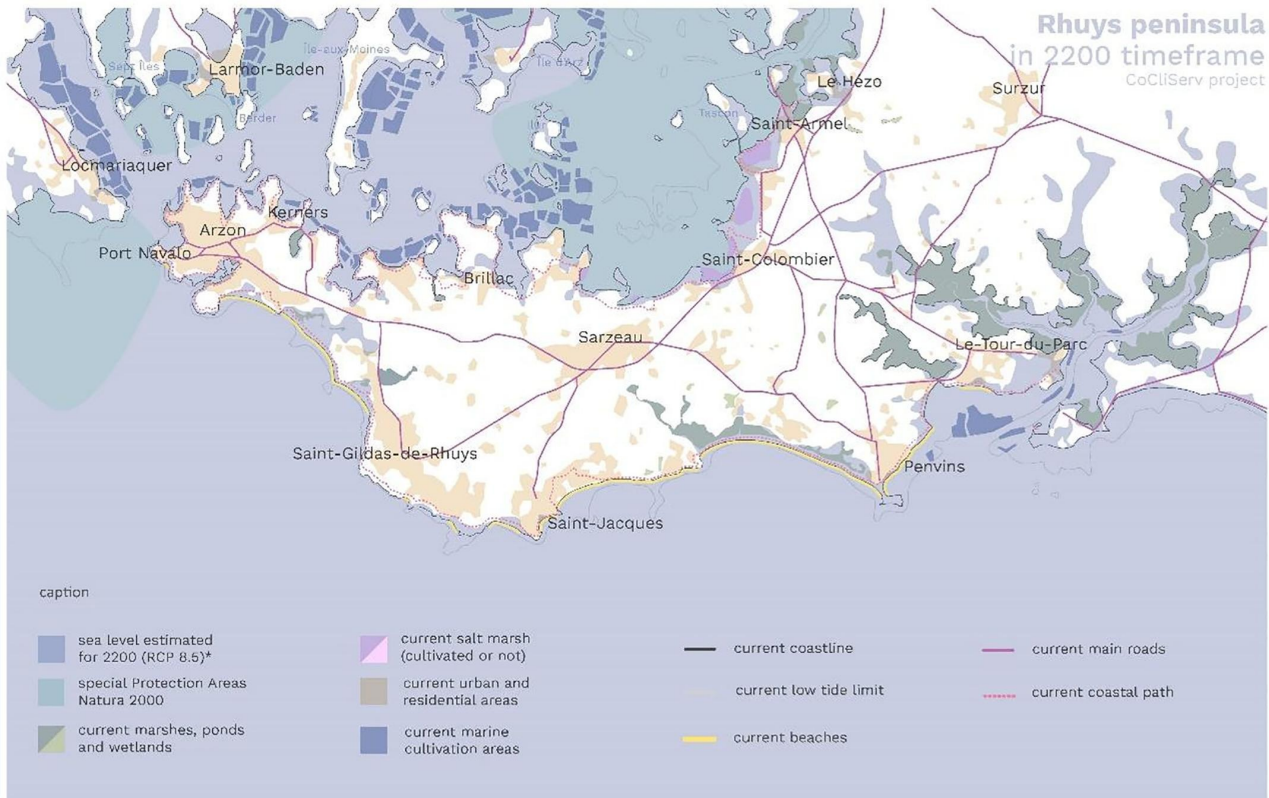


Figure 5.3: 2200 physical scenario map of the Rhuy peninsula (da Cunha et al., 2020).

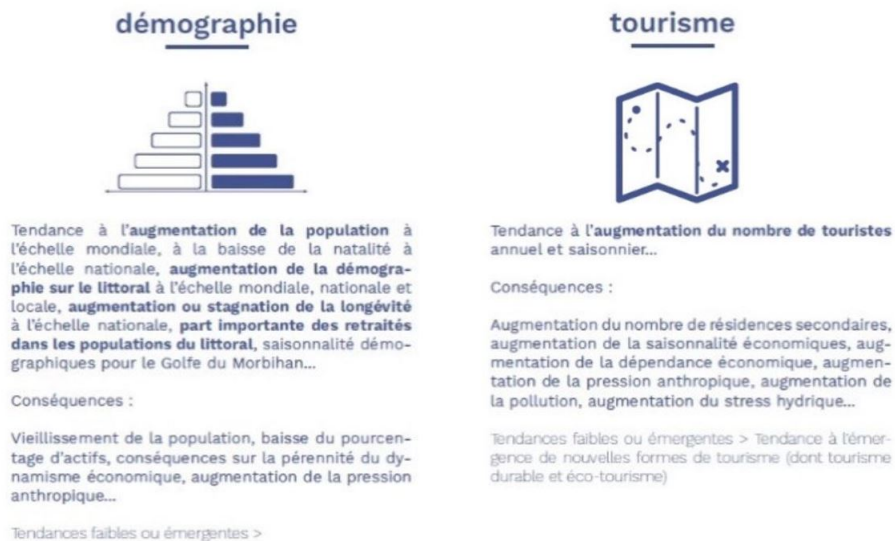


Figure 5.4: 2200 socioeconomic scenario elements for demography and tourism (adapted from Wardekker et al. (2020)).

tourism, urbanization, housing, employment, energy, environment, natural resources, etc.). The scenarization phase took place after the introductory session on future trends for the Gulf and Rhuy Peninsula. This creative exercise was supported by tools devised specifically for the event, and based on Design Thinking. Design Thinking is an

ideation process prioritizing the needs of stakeholders in the elaboration of a concept or product (McKim, 1972; Faste, 1995; Brown et al., 2008).

Table 5.1: Examples of poker design cards according to three categories and the four narratives of change (da Cunha et al., 2020).

Poker design category	Geo-social	Historical	Seasonal	Climatic effects
Climatic changes and hazards	<ul style="list-style-type: none"> • Submersion • Flooding • Erosion 	<ul style="list-style-type: none"> • Drying soils • Sealevel rise • Ocean acidification 	<ul style="list-style-type: none"> • Warmer summer and spring periods • Colder winters 	<ul style="list-style-type: none"> • Storms • Heatwaves • Droughts
Infrastructure and territory	<ul style="list-style-type: none"> • First nautical mile • Subsidence • Beaches 	<ul style="list-style-type: none"> • Oyster farms • Coastal pathway • Salt mines 	<ul style="list-style-type: none"> • Second homes • Ports • Water treatment systems 	<ul style="list-style-type: none"> • Historical sites • Urban areas • Routes
Resources and actors	<ul style="list-style-type: none"> • Island owner • Intra-gulf nautical transport network 	<ul style="list-style-type: none"> • Farmers and oyster farmers • Direct selling • Tourists 	<ul style="list-style-type: none"> • Office of tourism • Retired population • Seasonal workers 	<ul style="list-style-type: none"> • Measuring instruments • Scientific community

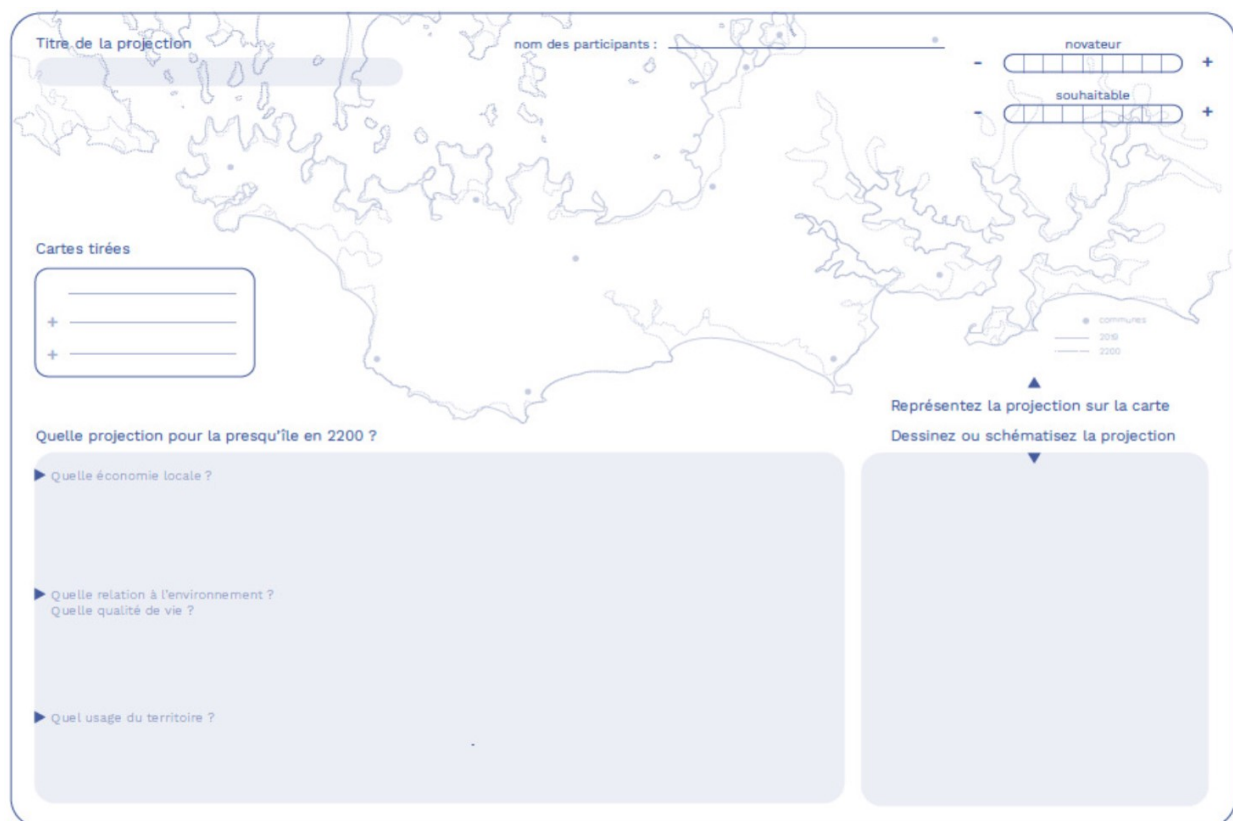


Figure 5.5: Note-taking support used by participants during the prospective workshop (Wardekker et al., 2020).

The designer and CEARC team created the poker design exercise, consisting of a series of cards combined in three categories (Table 5.1). The poker design cards represent key contextual elements of the territory (places, concepts, actors and issues), connecting elements of the narratives to the projection exercise. This connection incited the participants to reflect more deeply about the territory, while being inventive in their proposal of visions for the future. Participants in groups of four were instructed to randomly combine cards from each category, and to imagine how these unlikely combinations could work. This exploration of the range of possibilities encouraged the participants to consider multiple alternatives (desires, scenarios) for the territory.

An innovative media was also conceived specially for the event, a note-taking support helping the participants to collate and present their ideas (Figure 5.5). On this support including a map of the territory, the groups of participants represented their created scenarios and were incited to imagine how these scenarios might fit in the social, economic and environmental context. They then evaluated how innovative and desirable the various propositions were, and debated initial proposals of short-term actions (2030 horizon), and started to deduce the points on which the newly created scenarios hinge.

5.1.2 Results: long-term visions and scenarios, hinge points and short-term actions

After the foresight workshop, we articulated the results to define a long-term vision and to identify preliminary actions to trace back the trajectory leading to the desired future outcomes. This analysis, also based on past and present narratives, produced future narratives that demonstrate mutual aspirations as well as conflicts and contradictions. Table 5.2 shows the most frequently mentioned topics in future narratives. Since changes in the territory (past, present, future) and desirable events were the building blocks of the workshop activities, they naturally appear at the top of issues in the future narratives built by local stakeholders.

Table 5.2: Top 5% most frequent code combinations referring to the past, present and future (da Cunha et al., 2020). NA*: code combination outside of the top 5% range.

Issues	Future changes	Past or ongoing changes	Related narratives
Regional planning/Urbanization	30	22	Geo-social; Historical
Primary activities	20	25	Geo-social; Historical; Seasonal; Climatic effects
General climatic and environmental changes	15	15	Seasonal; Climatic effects
Tourism and recreational activities	14	14	Geo-social; Historical; Seasonal; Climatic effects
Sustainable mobility	14	NA*	Geo-social; Historical
New economic models	14	NA*	Geo-social; Historical; Seasonal
Demographic rebalancing	10	12	Geo-social; Historical; Seasonal
Biodiversity and environmental protection	NA*	12	Historical; Climatic effects; Seasonal

Stakeholders agree to varying degrees about the local need to adapt, and to prepare the territory for future changes (including climate). They concurred in a single long-term vision for the territory for the majority of the proposed issues (Table 5.3). They are however divided about the land-use of the coastline and role of tourism in the region. Some participants prefer to maintain housing on the coast, living with water by adapting habitats to become climate-resilient (or submersible). For other participants, the density of urban areas could increase with taller buildings, and an expanded no-build zone on the coast would let the original vegetation recover. While some visions entail a drastic reduction in touristic activities, other visions favour their development in association to a shift towards more sustainable practices and with the parallel development of local economic activities that do not depend on tourism.

Table 5.3: Incremental scenarios co-developed during the prospective workshop (adapted from Wardekker et al. (2020)).

Local issues	Shore-centred adaptation scenario	Country-side adaptation scenario
Regional planning/Urbanization	Population continues to occupy coastal areas, leading to intense adaptation efforts against climate change hazards.	Population retreat and densification of inland urban areas. Recovery of the natural coastal landscape.
Primary activities	Implementation of sustainable practices in the primary sector. Short circuits bring together producers and consumers. Harmonious co-evolution of primary activities and the landscape.	
Soft and low carbon mobility	A territory that favours soft and shared mobility, through development of infrastructure for already existing technologies (bicycles, buses, boat buses) and investment in the sectors of the future (shared, electric, autonomous means of transport).	
Housing	Adapting local habitat in terms of construction (techniques, materials, etc.) and usage (seasonality, sharing, etc.).	
Innovative economic models	Development of an active economy all seasons, evolution towards economic models of sharing and service. Short circuits between producers and consumers.	
Demographic balancing	A territory accessible to permanent residents as well as tourists, rich in generational, social and demographic diversity.	
Energy and food autonomy	Incentivizing food autonomy by promoting primary activities and short circuit in the territory, as well as a model of energy autonomy based on renewable energies.	
Cleaner environment	Reducing production and improving waste treatment. Improving water quality and focusing air quality, especially during the summer months due to boats and cars with thermal engines.	
Biodiversity conservation and environmental protection	Preservation of fragile ecosystems and endangered species.	

Therefore, the two desired futures considered during the workshop (Visions A and B) overlap substantially except for coastal land-use (Table 5.3). The first scenario (Vision A): "Shore-centred adaptation", corresponds to a continued occupation of the coasts, and the integration of increasing adaptation efforts in policies of land-use planning and urbanization. By contrast, the second scenario (Vision B): "Countryside-based adaptation", coincides with the densification of urban areas and recovery of natural landscape on the coasts. The next step of the analysis is the backcasting of potential actions according to the scenarios. In other words, we will specify which actions can put the territory on the trajectory towards a given desired future. We identified 25 actions in the compilation proposed by

participants, which can be linked to one or multiple local issues (Table 5.4 below, and Tables A.1-A.2 in Appendix).

Table 5.4: Actions (1-10) of the backcasting trajectory, adapted from Wardekker et al. (2020)). The other actions (11-25) can be found in the Appendix (Tables A.1-A.2).

Reference	Action	Description	Local issues
1	Develop infrastructure for irrigation in agriculture	Invest on polders and dykes to control water flow for the irrigation of lands and crops.	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Primary activities
2	Protect oyster farming infrastructure from the effects of real estate market and touristic pressures.	Develop regulatory tools reinforcing the preemption rights of Safer (land development and rural establishment public societies) aiming to prevent oyster farming infrastructure from being reconverted for non-agriculture related purposes.	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Primary activities
3	Build vertical villages	Conceive vertical villages based on aggregated multi-purpose spaces (schools, offices, housing, etc).	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Demographic balance
4	Remedy coastline retreat	Develop technical solutions to coastline retreat, such as artificialisation, elevation of beaches, etc.	<ul style="list-style-type: none"> • Urbanisation and spatial planning
5	Regulate circulation during peak season	Set up rules regarding the circulation of boats and vehicles powered by combustion engines during summer.	<ul style="list-style-type: none"> • Cleaner environment • Tourism • Primary activities
6	Define a chart for the different navigation modes	Make a chart concerning the different users of the maritime space (motorboats, sailing boats, paddles, swimmers, etc). Identify their constraints and needs to incentivize their harmonic coexistence.	<ul style="list-style-type: none"> • Soft and low carbon mobility • Tourism • Primary activities
7	Invest in a boatbus network	Invest in a boatbus network, favouring electric boats, aiming to utilize the inland sea as an alternative for roads for passenger transport.	<ul style="list-style-type: none"> • Soft and low carbon mobility • Demographic balance
8	Sensitize the local community about nuisances related to sustainable agriculture	Sensitize farmers and habitants of areas around farms about nuisances related to sustainable agriculture. For instance, farmyard manure might produce odours but they replace chemical fertilizers effectively.	<ul style="list-style-type: none"> • Cleaner environment • Primary activities
9	Develop short circuits for agricultural products	Favour short circuits and direct sale for products from farming, fishing and oyster farming.	<ul style="list-style-type: none"> • Innovative economic models • Primary activities
10	Decrease the use of chemical fertilizers	Reduce the use of chemical fertilizers in agricultural lands to reduce nitrate and phosphate levels in local water bodies, thus preventing eutrophication and algae bloom.	<ul style="list-style-type: none"> • Cleaner environment • Primary activities

The analysis of the results from the workshop (and previous interviews) also revealed 23 mentions of hinge points.

After excluding the redundancies, 11 unique hinge points emerged: eight past and three future (Table 5.5). The past hinge points are worth mentioning since they allowed participants to imagine similar (or opposite) possibilities in the future and to identify potential actions. The three future hinge points are linked to the local issues of urbanisation and spatial planning, food and energy autonomy, and demographic balance.

Table 5.5: Hinge points of the backcasting trajectory (Wardekker et al., 2020).

Description	Chronology	Origin	Local issues
Creation of the Natural Regional Park of the Gulf of Morbihan	Past	Institutional	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Biodiversity conservation and environmental protection • Primary activities
Decision by the PNR to prohibit changes in land-use in agricultural areas	Past	Institutional	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Primary activities
Enforcement of the Coastal Act	Past	Institutional	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Demographic balance • Primary Activities
Decision to plant exogenic trees on cliffides, which lead to an acceleration of erosion processes	Past	Urbanisation and spatial planning	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Biodiversity conservation and environmental protection
Development of tourism and construction of the Crouesty Port	Past	Urbanisation and spatial planning	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Tourism
Regulatory changes following the Xynthia storm	Past	Climatic effects (storm)	<ul style="list-style-type: none"> • Urbanisation and spatial planning
Parking interdiction in fragile areas of the coastline (e.g.: dunes, bird nesting sites)	Past	Institutional	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Biodiversity conservation and environmental protection
Restructuring of main roads and creation of bicycle lanes	Past	Institutional	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Soft mobility
Hardening of the Coastal Act following changes in the coastline	Future	Climatic effects (changes to the coastline)	<ul style="list-style-type: none"> • Urbanisation and spatial planning
Amendment to the Coastal Law allowing installation of renewable energy infrastructure where construction is currently forbidden	Future	Institutional	<ul style="list-style-type: none"> • Food and energy autonomy
Increase in migration flow to the Gulf of Morbihan as a consequence of temperature rise in other regions	Future	Temperature rise	<ul style="list-style-type: none"> • Demographic balance

The co-constructed scenarios are summarized in Figure 5.6 where moving from left to right is the equivalent of advancing in time (no scale). The identified local issues are displayed on the left (present time) as the framework used by stakeholders to reflect on the desired future. An horizontal line indicates the pathway for each issue from

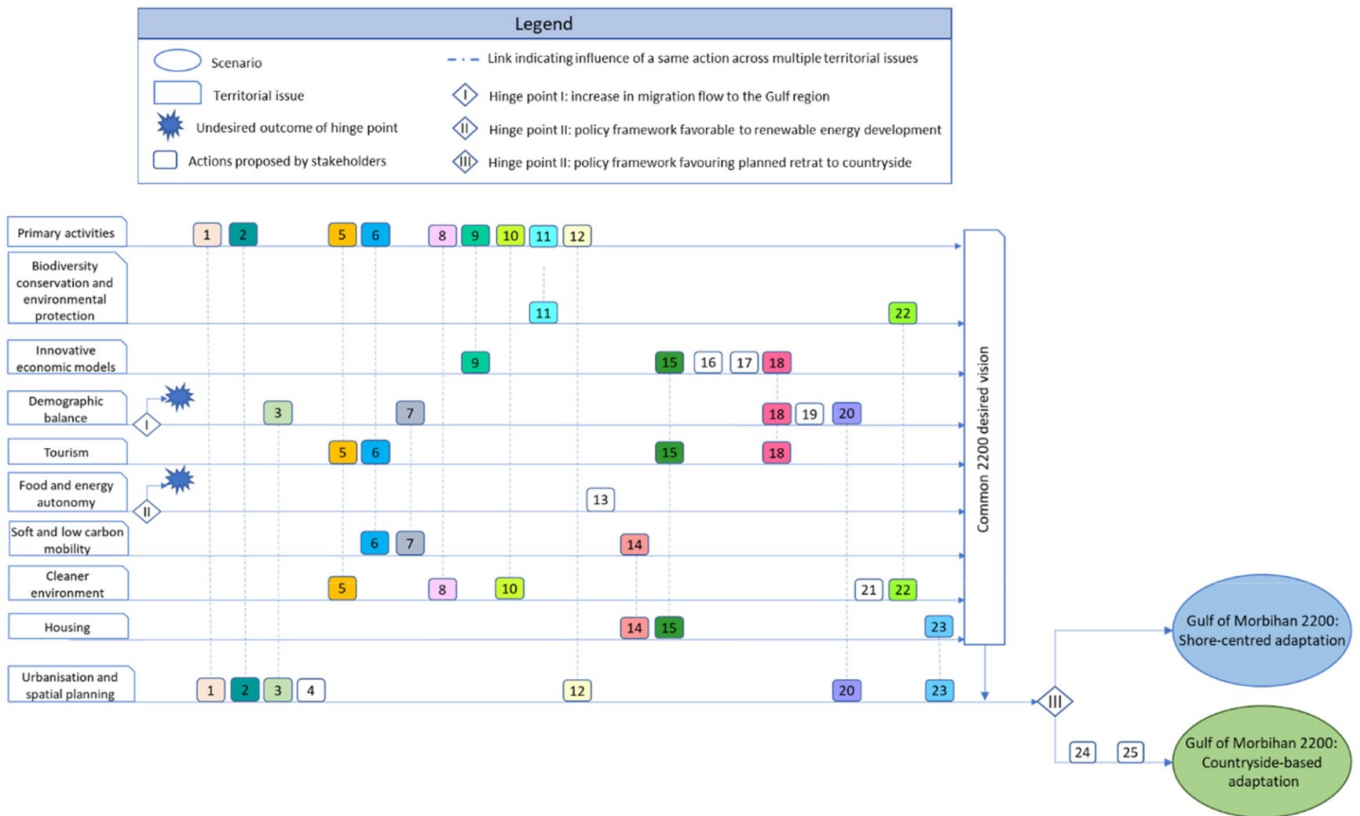


Figure 5.6: Integrated incremental scenarios, adapted from Wardekker et al. (2020).

2019 to 2200. The adaptation actions proposed by stakeholders are represented in small rectangles in association to the local issues (referenced according to Tables 5.4 and A.1-A.2), without any prioritization or order of implementation. Hinge points are represented by diamonds on the adaptation pathways leading to the visions.

5.1.3 Discussion

Two societal questions associated to climate change are the perception of impacts and the consideration of adaptation modalities. They can be addressed by the use of narrative approaches for foresight processes (e.g. Wittmayer et al. (2019)), but researchers must also understand which insights are brought to the table (i.e. discussion about the future) by the narratives. Our empirical results suggest several advantages from the use of past and present narratives of change to guide the creation of future narratives, scenarios, hinge points and actions.

In the context of planning for climate adaptation, narratives of change can pinpoint the crucial traits of a given territory, and give meaning to climate change science through the association to local matters of concern. The issues represented in the local narratives constituted an appropriate framework to develop new narratives of change for the future, by stimulating future thinking anchored to the territory within the creative experimentation. Local narratives also facilitated the dialogue between stakeholders, by portraying scientific and non-scientific elements (values, fears, desires, etc.) of the discussion. The exchange of ideas and scenarization process were also facilitated since the

stakeholders could draw on shared references based on the narratives, regardless of disagreements about desired futures.

Alongside the narratives, the choices of time horizon and physical scenario were the foundation of the prospective activity. Both were associated to a large part of unknown and uncertainty. We presented 2200 as a timeframe where close generational links would no longer be the main motivation for change, since stakeholders' children, grandchildren or even great grandchildren are unlikely to be alive to experience this imagined future. Reactions to this proposal were mostly positive, although some participants considered this exercise as "too abstract" and the long-term nature of this reflection to be anxiety-inducing for two reasons. First, because it moves beyond the timeframe of individual human-life (some participants reacted negatively to this timeframe, particularly the oldest), and secondly because projecting far into the future is challenging due to uncertainties related to current environmental changes (including climate).

These reservations decreased during the foresight workshop, in association to the collective dimension of the activity and to the elements offered as creative supports (poker design cards, socioeconomic and climatic trends, etc). The participants quickly integrated the principles of the exercise and began to think long term, freeing themselves from the present. In the end, taking 2200 as timeframe allowed the participants to overcome current restrictions and to propose innovative, even disruptive solutions, addressing both climate change (mitigation, adaptation) and sustainable development. Using a local physical scenario (maps and coastline) to represent the baseline of the future territory proved as a powerful means of communicating climate change to the participants, as well as the perspective brought by the (pre)historic sealevel rise.

The foresight workshop also became a learning experience for the researchers and designer, having co-constructed and adapted their methods and working tools to the specificity of the local issues and foresight exercise. To reach the objectives of a creative exercise in a foresight workshop, designers can have to fully reinvent and tailor their methods, in a way similar to how participative practices must be continuously reconceived to fit local specificities (Ostrom et al., 2007). In our case, the use of drawings, playing cards and other creative forms helped the animation team (researchers) to access elements that are generally excluded from scientific enquiry (e.g. effect of using creative supports on the resulting scenarios and actions), in order to convey a more complete picture of the challenges at hand.

The creative tools were fundamental in facilitating the collective work of participants who had never worked together before, and had to reflect on long-term issues that are potentially sensitive for their own environment and lifestyle (e.g. employment and economic activities, mobility and transportation, relationship with nature). The poker design cards stimulated the engagement of participants, and produced a lighthearted atmosphere during the session. The artistic dimension of the activity also helped to mobilize the participants' creativity, contributing to the quality of the results. This combination of favourable conditions allowed a relevant strategy of community-led adaptation to emerge, built upon the academic results on narratives and climate change.

The discussions about long-term visions were carried out simultaneously with initial reflections on hinge points and potential actions, in order to profit from the creative dimension of the poker design exercise (combinations of cards), and to optimize the work during a session limited to three hours. This methodological choice brought satisfying results, based on the quality of the discussions and relevance of scenarios, actions and hinge points produced. Another interesting feature of the methodology is that the current socioeconomic issues and the climatic aspects of the projections were analysed simultaneously by participants. For instance, the main distinction between the scenarios appears to be the priority given to humans (staying on the coast and facing rising waters) or nature (recovery of natural coastal ecosystems).

However, an additional element of the "countryside-based adaptation" is the concern about public access to the coastal pathway, in opposition to the private nature of the second homes and the socioeconomic imbalance they represent. This element was not mentioned by promoters of "shore-centred adaptation", although participants agreed on the desired vision addressing the local issue of demographic balance, including the problem of beach houses and second homes. These apparent contradictions reflect the capacity of narratives to make room for nuance and multiple human experiences. Considering the adaptation strategy of managed retreat from the shore, the opposition between social inequality and territory resilience appears to be a common feature in urbanized coastal France (Long et al., 2021). More generally, coastal managed retreat is becoming increasingly considered as climate risk management approach (for instance in the United States), and the societal benefits must be emphasized in parallel to the drawbacks, since the topic is highly controversial (Dundon and Abkowitz, 2021).

When debating long-term complex issues such as climate change, scientific data is generally the dominant discourse, presented as accurate and indisputable (unbiased). The biases and uncertainties are however ubiquitous (i.e. hidden), and this communication strategy is not optimal when social changes are needed and dialogue with local stakeholders is essential. The collaboration between social and climate scientists allowed researchers to convey to the participants a consistent picture of the issues at hand, composed of climatic and socioeconomic dimensions. This set of information set the tone of the collective discussions during the workshop, and needs for climate knowledge started to emerge from the scenarization, for the realization of desirable visions and adaptive actions.

These results indicate the advantages of taking an integrated approach combining art, social science and climatology to co-construct locally relevant actions for climate change adaptation. They also suggest that artists and designers can help in the development of a method to challenge existing narratives, and to explore pioneering future narratives. We presented our initial results to local authorities and several insights from the foresight workshop can be linked to the PCAET under construction for the following themes:

- to support stakeholders in the adaptation of the territory to climate adaptation
- to start actions of adaptation as soon as possible for sectors that are sensitive and for structuring activities
- to further the understanding of local climate change effects and carbon storage mechanisms

- to preserve the natural resources of a territory weakened by the aforementioned changes

For broad adaptation, the ideas co-produced with the Gulf stakeholders can feed the PCAET, such as in housing and development by "considering a mixed and seasonal use of spaces and habitats". Concerning the water resource, the solutions mentioned in the PCAET are mainly related to infrastructure investments, but the daily experience of several stakeholders includes the monitoring of water (including temperature) through their professional or personal activities. These stakeholders could therefore participate to observation networks and citizen science, such as the "Habitants Sentinelles" initiated by Clim'actions (Clim'actions, 2021b). Both the PCAET and workshop scenarios address the topic of food autonomy in the Gulf, and the capacity to ensure sufficient agricultural production despite the decline of the activity and the increasing adverse effects from climate change.

Food autonomy implies that enough support is given to present farmers, that the activity is made more attractive for new farmers, and that farmland speculation is managed better. The active preservation of agricultural and forest areas, in combination to carbon storage, requires a special and long-term commitment but there is a network of agricultural actors mobilized and interested in these issues. Another topic mentioned in the PCAET and motivating many stakeholders is energy autonomy, potentially accompanied by a decrease in energy needs. Although all stakeholders agree on the need to make the Gulf more sustainable in the face of future demographic and urban growth, some projects can come into conflict. For example, the development of tidal turbines is at the crossing of energy autonomy and ecosystem preservation.

This experience in progress demonstrates that mobilizing art and science to interact with stakeholders in a territory undergoing transformation (partly due to climate change), and to establish future narratives of change can empower people and stimulate local action. The ideas that arose from participants are innovative, practical, and generally unite inhabitants from a territorial perspective. The power of art forms to represent climate information and engage local stakeholders presents both challenges and opportunities for increasing awareness of climate-related issues, and for the development and use of climate services at local level. We are still involved in this co-development process, with the objective of helping municipalities in the Gulf to improve their thinking about the future while engaging the population. Many actions were devised during the workshop to achieve the desired futures, and we gathered these actions in a "Local Utopia Plan" that we submitted online to the vote of inhabitants (CoCliServ, 2021d).

This participatory process will select which actions should be further detailed during a second prospective workshop. The first workshop focused on brainstorming possibilities and collecting ideas, while the specifics and implementation of selected actions will be discussed in the second workshop (using 2030 as timeframe). This second workshop would be longer (a day), and use methods based on backcasting to explore one or two incremental scenarios and their hinge points. Since the second exercise is more strategic, we aimed to involve more of the neighbourhood (inhabitants, organisations, municipalities), and to use popular educational tools in collaboration with local associations. This activity will involve, once the details of the actions have been defined, the discussion of climate information and services that may be useful for adaptation planning to occur. However, the Covid-19 health

crisis shattered the organization of this second workshop (planned in March 2020), which could not be conducted.

5.2 Art-science exhibition on climate change

5.2.1 Long-term

After using narratives to connect the science of climate change to the local matters of concern, we wanted to explore another approach to represent climate change at the intersection of culture and emotions. This approach would take the form of an art-science exhibition on climate change. The content of the exhibition is based on climate change science (e.g. future projections) and on the collectively-built narratives of past, present and future changes (e.g. coastal retreat). In other words, this art-science experimentation is science fiction, inspired from current trends and future projections (physical and socioeconomic), but also nourished from artistic extrapolations.

The underlying goal is to convey the transformations of the territory to people through elements of artwork acting as markers of future changes (e.g. chronotope of sealevel rise). From the collaboration with the designer about the project of a long-term exhibition, emerged the idea of realizing a small itinerant exhibition with vulgarization panels of climate change science and a comprehensive storytelling exercise. This is the "Pathway of possibles" (Figures 5.7-5.8 and CoCliServ (2021f)), originating from the chronotope of the coastal pathway and positive response of local

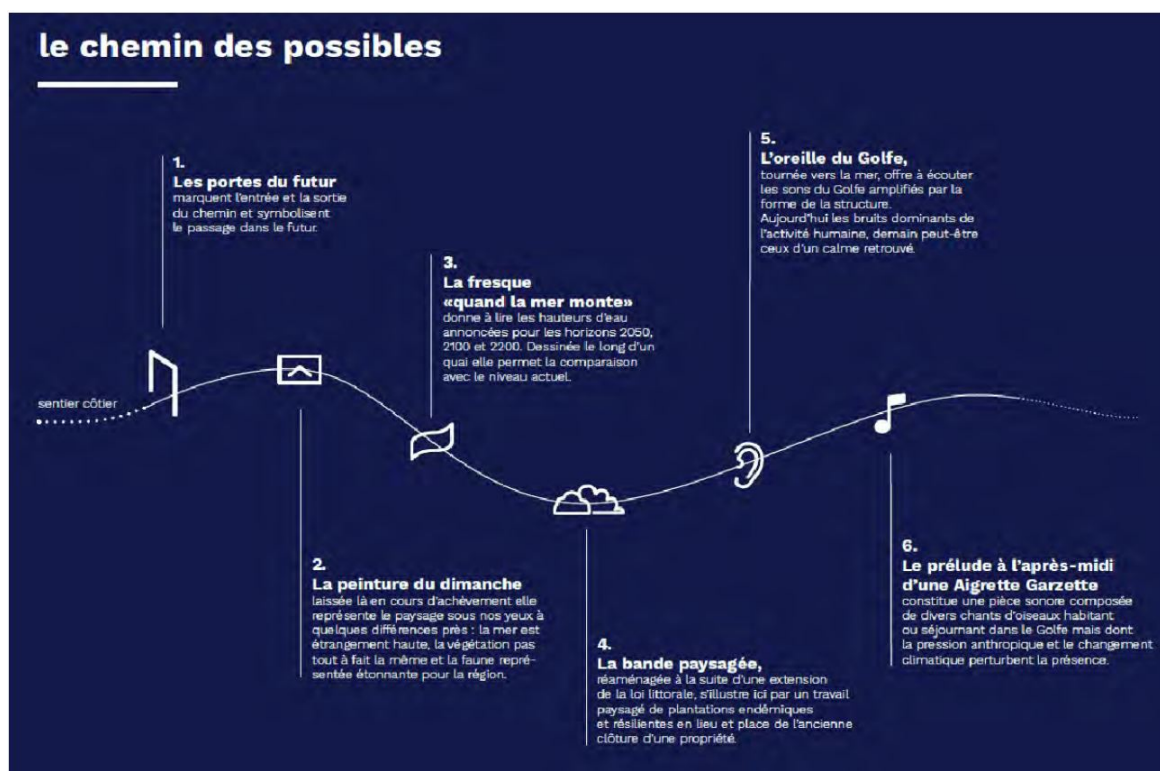


Figure 5.7: First part of the long-term art-science project on the coastal path (Wardekker et al., 2020).



Figure 5.8: Second part of the long-term art-science project on the coastal path (Wardekker et al., 2020).

stakeholders to this concept. The proposition is an immersion exercise for visitors over a large stretch of the coastal pathway, offering successive encounters and emotions in the fragile environment of the shore.

Starting from the present situation, the "possibles" represent reflections of what is likely to happen based on current trends, and of other outcomes that might be desirable or not for people taking this path. Several artists would make a piece of art to convey the climate change issue in its local dimension, their creative process inspired by the previous scientific results. Most of the artists involved have already created sculptures in the past to raise awareness about the environment and climate. In addition, this pathway of future possibles would further the role of the coastal pathway as a chronotope. However, it would require a long time of creation for the artists (beyond summer 2020), a larger financial budget than the research project allows, and the authorization from local authorities for a permanent installation. The solution was to make a temporary exhibition that would prepare the greater one to come.

5.2.2 Short-term (summer 2020)

The objective of both short- and long-term exhibitions is to immerse visitors in a feeling of "here and now", while facing outlooks of the future. The short-term exhibition will stir up questions and suggestions from visitors, in preparation of the larger exhibition along the coastal path to be co-constructed within two years. The artistic work will invite visitors to contemplate how the future could look like in parts of the Gulf, simultaneously foreseeing potential impacts and

bold adaptation options.

Multiple animation activities were planned to accompany the exhibition, seizing the occasion of the immersive experience to discuss with spectators about climate change perception and adaptation actions for the territory. These participatory exercises would include a second foresight exercise, the collection of ideas from visitors (adaptation actions, future directions that are desirable or not), and maybe an artwork proposal for the Pathway of possibles. Unfortunately, we could not carry out these animations due to administrative and human complications associated to the Covid-19 health crisis.

The exhibition, initially named "La Cataravane", aims to access the sensitivity of the spectators by illustrating several visions and questions that inhabitants have for 2050. The illustrations would take the form of a piece of art-design, display panels that present local information (scientific and artistic), and an auditory narration to complete the immersive experience. The artistic committee selected two elements of art-design (Figure 5.9) during the collective creation process: a "Cataravane" (mixture between caravan and catamaran) and a buoy. The artistic committee imagined the Cataravane surrounded by barriers of construction sites, serving as support for the scientific and artistic panels (right part of Figure 5.9). In addition to the Cataravane inspired from our research results, we associated to the exhibition the multiple elements of art-design produced previously by the artists (Figure 5.10).

For the communication purposes of the exhibition, we chose to focus on both short-term and long-term perspectives in the representation of local climate change. The 2050 horizon was problematic to raise awareness (create a sense of urgency and need of action), since projections of climate change give similar results according to different

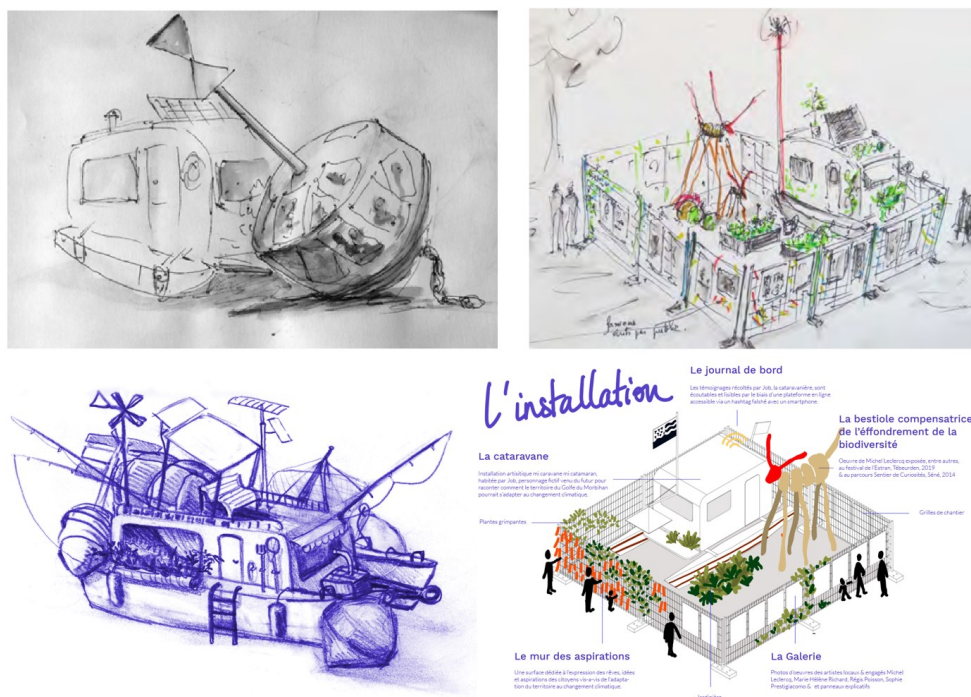


Figure 5.9: Artistic sketches of the exhibition, adapted from Wardekker et al. (2020) and Cardon, M. (2020).

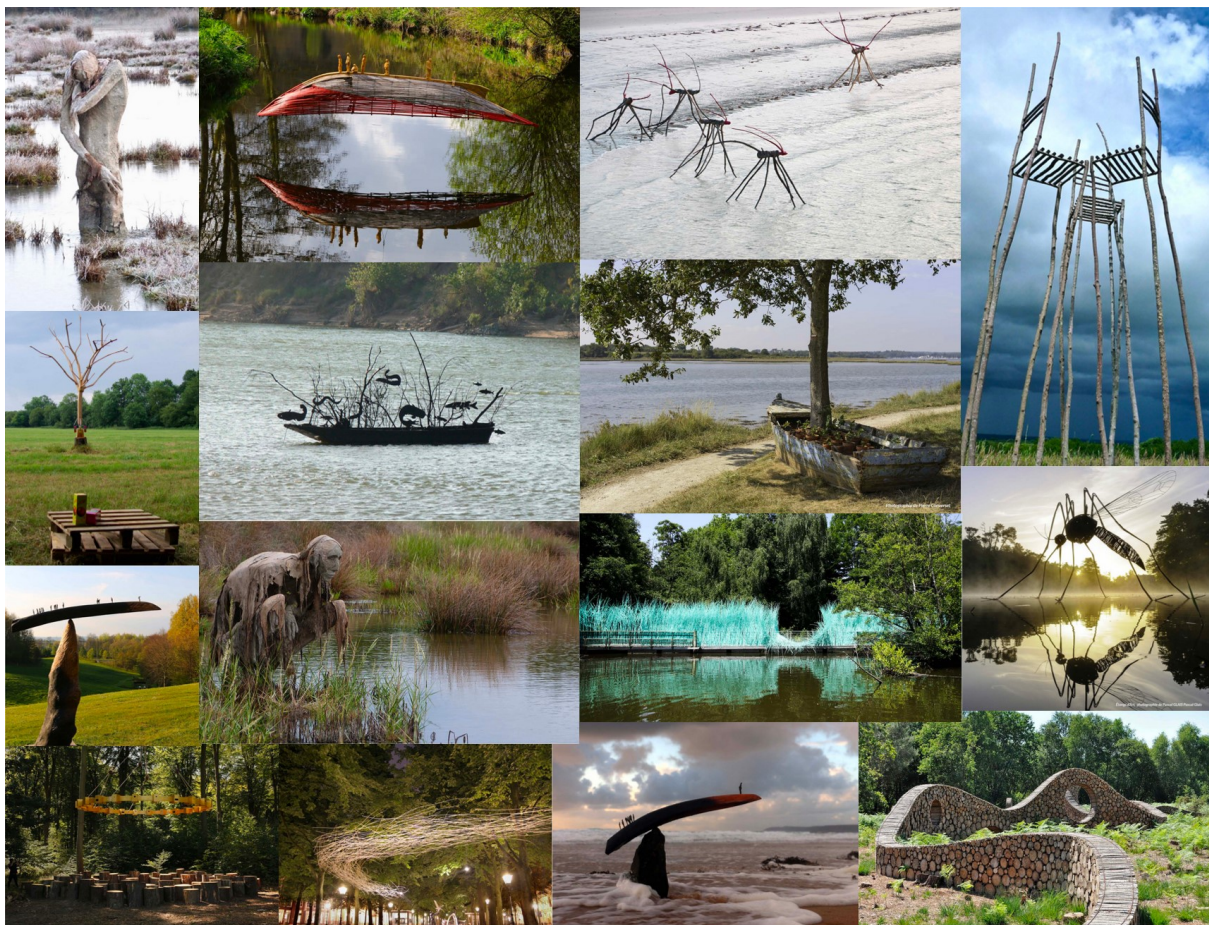


Figure 5.10: Artistic productions in the Gulf associated to the exhibition, adapted from CoCliServ (2021a).

scenarios until 2050, and because the Gulf is not likely to undergo abrupt changes in the next three decades. On the other hand, these scenario differences and abrupt changes become more evident in the second half of the century. The 2100 horizon showcases both the long-term evolution of climate and the consequences of actions taken today.

Therefore, we synthesized the climatic changes according to two time horizons: 2050 (in one human generation) and 2100 (long-term changes), and two scenarios: RCP4.5 (active mitigation) and RCP8.5 (passive). The name of the exhibition finally became "Ça Baigne?" (French wordplay), hinting at the rescaping of the territory by sealevel rise. The collective of scientists, artists and designer produced 25 panels presenting the manifesto, scientific information, and artworks (CoCliServ, 2021a). These panels also invited visitors to propose their own suggestions of artworks, needs of climate services, and visions of the Gulf for 2050.

A strong storytelling exercise has also been developed to complete the immersive experience of the visitors. Different characters would narrate their stories from the future in 2050 and illustrate the actions developed in the Local Utopia Plan (Table 5.6). This narration is the result of a co-writing process between the social scientists, designer, and an author. The exhibition invites the visitor to discover the life of "Job la Cataravanière", fictitious inhabitant of the territory in 2050. Job is a young girl from Vannes who traveled through time to meet the citizens of 2020, and tell

Table 5.6: Relation between the storytelling characters and future visions (adapted from Wardekker et al. (2020)).

Local topic	Storytelling character					
	Job	Nimby	Gaïa	Diogène	Cresus	Diatomée
Primary activities		X		X	X	X
Soft mobility	X	X	X			X
Habitats/lodging	X	X	X	X		X
New economic logics	X	X	X	X	X	
Demographic balance		X	X	X		
Energy and food autonomy	X	X	X		X	
Less polluted environment	X		X	X	X	X
Biodiversity conservation				X	X	X
Tourism		X	X			
Landscape management	X		X		X	



Figure 5.11: Locations of the fictitious 2050 characters (red circles) in the Gulf (CoCliServ, 2021c).

them the importance of art to change society and adapt to climate change.

Carrying with her the testimony of a future time, she depicts a territory (Figure 5.11) where the inhabitants would have adapted to the consequences of climate change by changing much of their lifestyle. Beside the short-term exhibition, a short-version of the character narrations was submitted to a radio contest of sci-fi stories. We wanted to put the exhibition in a busy public place, and the city of Vannes proposed the site of the music conservatory. Since this place was already enclosed by a fence, we used it for our display panels (Figure 5.12). The exhibition lasted from



Figure 5.12: Art-science exhibition in Vannes during summer 2020, adapted from Wardekker et al. (2020). Topleft: flyer, topright-middle: photographs of the exhibition, bottom: examples of scientific panels.

July 15 to August 20 in 2020 (Clim'actions, 2021a), and remains available online (CoCliServ, 2021e) where visitors are invited to propose their visions for the future of the Gulf (CoCliServ, 2021b).

5.2.3 Discussion

The committee of the artistic project involved researchers, artists and designer, and aimed at a genuinely collective construction and integration of art with science. There was no previously established plan for the development of

the art-science activities and they all evolved from the continuous interdisciplinary exchange within the committee. The project took several forms and routes, bringing challenges and surprises, but ultimately valorized the knowledge produced from the social and climate research (local narratives and assessment of climate change).

As we developed the artistic project based on the materials from interviews and workshop, the weak presence of a few high-stake topics became problematic (e.g. biodiversity loss, ocean acidification, rainfall trends). However, the committee debated about the mission of the art-science project and concluded that it should only illustrate the concerns raised by interviewed stakeholders (supposed to be representative of interest for the Gulf population), and add topics identified as essential by the scientific or artistic teams (to extend the perspective of visitors). Additionally, the uncertainty of the location for the exhibitions (short- and long-term) was perceived as difficult for the artists since they produce in-situ creation. The research team also learned that artistic products are the result from a complex combination between the message to convey, creator perception or interpretation, and crafting know-how.

Our process did not aim to use arts to communicate scientific findings, but to develop a strong connection between art and science to enable the re-articulation of the scientific description of the world (Latour, 2017). In this case, art play the role of a "Distant Early Warning system" addressing the cultural problem of climate change between current actions and future consequences (Buckland, 2012). The previous workshop activity suggested that the development of artistic works is an effective way to convey messages of future narratives. The products of both workshop and exhibition may themselves become chronotopes of the territory, integrating different dimensions of ongoing changes (climate, biodiversity, migration etc.).

This preview of the future could inspire community-led transformative practices. The productions from the art-science exhibition address the goal from the PCAET to make the population (including decision-makers) aware of recent and future climate issues, especially through the deployment of awareness tools. The scientific panels and artworks that we developed will remain available through the territory and online, will keep arousing questions and discussions, and can stimulate the production of new awareness tools. The coastal path had a fundamental role as location for artworks, and could later serve in a long-term (or permanent) exhibition to further exemplify sealevel rise and coastal erosion.

5.3 Conference-debate on local adaptation in Elven

I had the opportunity to co-organize a conference followed by a roundtable about the topic of "preparing Morbihan to climate change" with Laurent Labeyrie in mid-September 2020. The event took place in Elven (about 15 km northeast of Vannes), was attended by about thirty inhabitants and several local decision-makers, and lasted about two hours. The objectives of the event were:

- to present the local effects of climate change

- to highlight the insufficiency of current plans to prepare for territory for future climate change
- to introduce climate services and how they can support the preparation for future changes
- to start the discussion towards the co-construction of local transition scenarios for the adaptation of the territory

Before the roundtable, a conference served as introduction to the debate and lasted about an hour (including Q&A).

5.3.1 Introductory conference

General context

Laurent and I explained our role as climatologists, to study the causes and effects of climate change at different spatio-temporal scales. An emerging aspect of our work is to work out with the decision-makers and population how territories, sectors and activities can prepare for future climate change. After a brief historical background of climate change science, we highlighted the large disconnection between current scientific knowledge and societal action, and how social science could help to bridge this gap (e.g. the CoCliServ research project). The conference-debate aims to serve as a participative workshop to exchange about how to do the transition of adapting the territory to climate change.

This transition is difficult because our society is based on an ancient model (energy, transportation, etc.), but many stakeholders are interested in action and experimentation. The main goal of the event was to discuss which strategies to adopt for the transition, with examples from the roundtable participants. Brittany is relatively privileged regarding climate change (i.e. less affected than e.g. Southern France), and appears to be on the path to become the new “Côte d’Azur”. Climate change will nevertheless induce many impacts with economic consequences to manage. The transition to adapt the territory is a huge challenge, and existing efforts (e.g. PCAET) are insufficient compared to the magnitude of the problems to come. We can in this situation identify which problems will arise from climate change, which solutions exist, and build prospective scenarios to deduce adaptive actions.

From global climate change to local daily weather

Climatologists determined with confidence that human activities are causing global climate change, mainly through the emission of greenhouse gases and by deforestation. Global warming is the main consequence, with the long-term warming trend superposed to short-term fluctuations of the climate system (Figure 5.13). Global climate change has many other consequences: modification of precipitation patterns (frequency, intensity) and weather extremes (heatwaves, droughts, floods, storms), the melting of ice (sea ice, glaciers, continental ice sheets), the acidification of oceans, etc.

Global warming relative to 1850-1900 (°C)

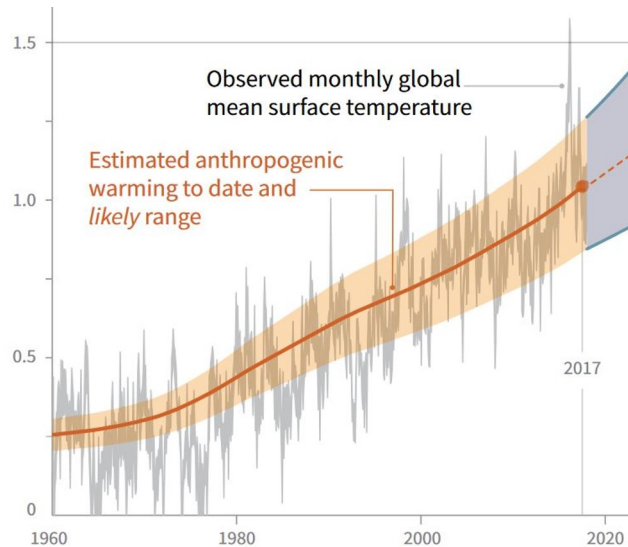


Figure 5.13: Estimated global warming over the last decades (adapted from Masson-Delmotte et al. (2018b)).

Beyond affecting large-scale patterns, climate change also affects the local daily weather. Climate is often defined as the average of the weather over a few decades, so a shift in climate is generally associated to a shift in the average weather. The effects of climate change on weather patterns and especially on extremes, is therefore how climate change affects our daily lives. Despite tremendous progress in meteorology and climatology, the current scientific and numerical capacity allows only to skilfully forecast the weather system a few weeks in advance. How then can we anticipate the future further down the road?

Anticipating the future despite complexity

The system is too complex (and we don't fully understand all processes) to simulate it directly with computers, so we have to use many simplifications (gridding, step calculation, parametrizations, averages) to make the computation feasible. All these simplifications do not account appropriately for the short-term fluctuations (energy cascades, oscillating frequencies, resonance) which make the variability of the weather. Therefore, the climate simulations that we use represent a limited variability of the weather, especially extremes since they occur in specific conditions (locally in space and time, driven by various processes).

This smoothing of the variability is amplified by the low ratio of signal to noise in the data, and by the bias of climate models (compared to the real system), so we often have to use averages from multiple models to extract the signal of interest (i.e. climate change). However, climate simulations are our main tools (assisted by statistical and empirical models) to anticipate changes from the future decades. This information gap between the future weather and the climate simulations is yet where the value is for the territory in terms of predicting what will happen, especially for extremes (rare but high impact). Bridging this gap remains a dream for climatologists and meteorologists, but the existing tools already bring ample information about the future, despite their limitations.

CC et Morbihan

- Effet CC : migration climatique vers hautes latitudes

- Effet local : on migre vers le Sud !
Comment ? A quelle vitesse ?

- Conséquences :

- Changements conditions (température, eau, vent, extrêmes)
- Dépendent forçages climatiques, humains, naturels

- Que fait-on pour agir ?!

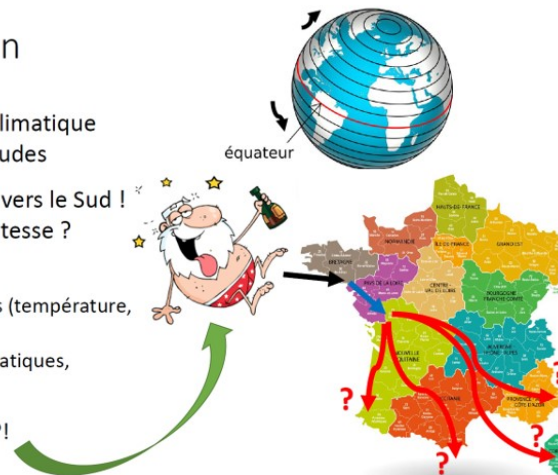


Figure 5.14: Presentation slide highlighting the migration of climate zones and uncertainty about future changes.

Local changes, uncertainties and action

We know for instance from past observations and future simulations that a broad effect from climate change is the slow and general migration of climate zones towards the poles. This means that we are locally moving to the South! But how much to the West or East, and how fast? The uncertainties are big, so we chose a drunkard to represent our territory (Figure 5.14). He is traveling generally towards the South but does not know precisely where and how fast he is getting there. He has also roamed in the past decades in association to changes in his surrounding conditions (temperature, water, wind, extremes). His future trip depends on climatic, human and natural forces.

We however already know with some certainty that he will encounter warmer conditions, with more summer heatwaves and droughts, more winter floods and stronger storms. So what can we do locally about it? We could start by reducing the causes of climate change, by decreasing our emissions of greenhouse gases and the pace of deforestation. However, the next twenty years or so of climate change are already approximately predetermined by our activities from the previous decades, due to the inertia of the climate system. Therefore, even if today we stopped all human activities, we would still suffer the consequences of past actions. Hence the need to adapt locally to the consequences, in addition to mitigation for reducing the causes.

Adaptation, scenarios and climate services

Existing efforts are a first step (e.g. PCAET, PLU) but are insufficient and must be reinforced. Action plans must consider the large uncertainties of different natures about the future: physical (e.g. natural variations, tipping points, unknowns), environmental (e.g. ecosystem functions), and human (societal choices). With local decision-makers, we can strengthen the existing tools planning the adaptation of the territory. For action, one must select the right information, for example through the definition of strategic scenarios. A scenario is an hypothesis to explore the future in terms of unknowns and uncertainties. Scenarios allow to test different roads of climate and society, and to

measure the short-term against the long-term costs and benefits of action choices. For example, tourism generates money for the region but increases the pressure on the water resource and leads to additional pollution.

The ADEME explored different scenarios at the scale of France about measures to decarbonize society, decreasing the environmental footprint of the population, transitioning to a greener energetic mix, and the effect on people's livelihood (ADEME, 2014a,b, 2017a,b). Similar scenarios could be made at a local level, involving the environmental constraints and those of territorial stakeholders to determine what is possible to do or not. To define strategic actions, local stakeholders could rely on scientific knowledge but the scientific literature is complex, technical, and difficult to use. Recent tools have emerged to make this information more accessible and usable, such as in the form of climate services.

Another possibility is to train local stakeholders about the climate change effects on the territory, and the associated constraints for their practical choices at local level. Examples of climate services are Climat HD and DRIAS from Météo-France, CACTUS from the PNR, and the climate adaptation indicators from the European Environment Agency. However, climate services have two weaknesses: the non-local scale of the information, and the limited interaction and iteration with users. Our aim is therefore to identify with local stakeholders their territorial issues and information needs to prepare the future, and to determine if existing climate services (and scientific knowledge) are sufficient to support local adaptation efforts.

5.3.2 Roundtable debate: how to transition towards a sustainable territory?

Overview

A roundtable discussion of about an hour followed the conference, with the participation of a few local decision-makers (from left to right in Figure 5.15):

- A representative from PNR
- The vice-president in charge of climate and biodiversity at GMVA (Golfe du Morbihan - Vannes Agglomération)
- The mayor of Elven
- An organic farmer of Elven
- An honorary professor of the MNHN (National Museum of Natural History)

The discussion aimed to focus on:

- How to prepare Morbihan to climate change?
- What are the local urgencies at the level of the territory?
- Which role for climate services in supporting the local actions?



Figure 5.15: Roundtable discussion during the conference in Elven (Le Télégramme, 2020). Note that the cited press article selected parts of the discourse and mixed together separate aspects in a way that may appear confusing, between the role of natural variability and climate change, and between storms and warming.

Role and issues of the stakeholders

Each roundtable participant introduced his identity, role and issues of interest in the Gulf. The representative from PNR works on energy and climate for the shore, him and his colleagues have worked on climate adaptation since 2007. They have created the CACTUS tool (PNR, 2021) about two to three years ago to support public decision-makers in the regional planning of the territory with regard to climate change. The vice-president of GMVA is a Météo-France engineer and former head of Morbihan's weather center for 15 years (since 2004). Awareness about climate change started several years ago in the Gulf of Morbihan, when an IPCC representative visited the local activity centers and outlined the stakes of climate change and sustainable development.

The vice-president is now in charge of the PCAET, and intends to show how this strategic tool can be used to plan the territory from now to 2030 and 2050. The PCAET is an operational plan that includes the NEGAWATT strategy (sober, efficient and green energy; Association négaWatt (2021)). GMVA supports the transition towards a more sustainable territory but this transition must involve all the local actors (e.g. partners and companies). An ambition is to increase the renewable energy production, currently low (about 5%), to reach 32% in 2030. Energy consumption must also decrease to help the proportion of renewable production to increase. A whole set of subsidies exist to renovate housing, which are also supported by the French State.

GMVA diagnosed the potential of Morbihan to produce renewable energies (e.g. for wind turbines) but the topic of energy remains complicated because of the reactions from inhabitants. A mapping was made of the solar potential for house roofs, so that inhabitants can know how much solar energy they could produce. Solar energy is also an economic opportunity for companies. GMVA can help inhabitants to identify available subsidies and honest installation offers (to avoid fraudulent offers). Individuals can self-consume or produce on the network (e.g. rent their

roof to Morbihan Energie). GMVA identified various partners but the production must also be controlled at the level of electrical networks. Data is an important aspect for all types of renewable energies, and is also used by large private groups.

The adaptation to climate change is linked to the PNR, and the vice-president communicates with the mayor of each district to determine what the climate plan takes into account, and how to include inhabitants in the making of the plan. The mayor of Elven says that he is interested in the topic of territory transition. Land management is an important ecological and economic issue for farmers (conventional and organic), and requires coordinated discussion between all actors. Elven's PLU (local plan of urbanization) was revised during the first term of the mayor, and Elven has since rehabilitated buildings and installed photovoltaic panels with the help of PNR.

Plans of future development at local level include the promotion of cycling. The organic farmer says that he is concerned by climate changes, both personally and professionally, as his activity is directly affected (e.g. by droughts). The professor from MNHN reminds to the room that biodiversity should also be considered when talking about climate change, since the two affect each other. Climate change will lead to a reduction in biodiversity, in turn having an effect on climate change. Climate change is only the fourth cause of the current biological crisis, after the destruction of environments (1), the overexploitation of resources (2), and the use of chemicals/pollutants (3).

Ecosystems are affected by climate change in many ways, such as the proliferation of invasive alien species with the migration of wildlife due to the warming of large areas. Another example is caterpillars hatching earlier, in March, while birds still arrive in April to eat them. We have to be careful about solutions to climate change, since they can sometimes clash with biodiversity conservation. For example, the development of solar power plants on mountain sections in France harms the ecosystems underneath the solar panels. Another example is wind turbines disrupting the circulation of birds. Additionally, sealevel rise will lead to the disappearance of species habitats, although people do not worry about this.

Territorial decision-making: example of the CACTUS tool from the PNR

Laurent mentions that beside sealevel rise, the warming of water decreases its oxygen content and kills animals. This phenomenon is increasingly happening in the territory, where we find skeletons of crabs and fish in rivers, covered by large trails of green algae that made the water anoxic. One of the big current fights in the Gulf is about farmers who want to continue cultivating corn and irrigating more, although water reserves are scarce. The installation of dams could increase these water reserves, but would alter the water tables and biosphere. Everything we do has an impact, so we have to discuss among specialists whether it is worth it or not.

These matters should be discussed much more, and each municipality should have its own permanent workshop to think collectively about the future. The PNR representative says that the CACTUS tool was created in this sense, inspired from a European research project about coastal climate adaptation around 2010. Three scenarios were developed during the project: defending the coast, adapting, or letting happen. Three people of PNR worked with two

researchers from Brest to describe the consequences of these scenarios (economic, social, environmental, etc.), and made sixty or so information sheets for different sectors (city planning, agriculture, fishing, etc.). When learning about the information sheets, elected officials said those brought the answers for the questions that they had. This was a delicate situation, since the makers of the sheets do not have innate knowledge and the information in the sheets is general.

To be careful, the makers converted the points of each information sheet into questions, ultimately becoming the CACTUS tool. This tool aims to help the public authorities, or anyone who has a project in the territory, to think about the possible consequences from a decision (e.g. to bury electrical systems in one place). Questioning the impacts of a decision is the way to choose the best possible decision. The tool acts as a reminder of the right questions to ask, rather than wasting weeks, months or years. The topic of renewable energy is complicated and cultural since we want these energies but not near anybody's house and without harming ecosystems. The role of PNR is to provide cultural support and explain why certain actions can or not be done.

Renewable energy production: tidal, solar, wind

A tidal turbine project is for instance underway, with the installation of two turbines in the harbour in 2022. More turbines would be installed (10-20 in the next 10 years) if this project succeeds. The work of PNR is to set up a consultation stage so that ordinary inhabitants can take a position and give an opinion. The pros and cons of each decision have to be weighted, as putting tidal turbines at the bottom of the harbor will have constraints and advantages. The tidal turbines would produce 7% of the energy consumed by the inhabitants of the harbour's border, and help to achieve the ambition of 32% renewable energy production by 2030. Another example is the building on the Ilur island, covered by about 70 m² of photovoltaic panels.

The building has to self-consume, since the island is not connected to the mainland for water and electricity. Getting the authorization from the architect was difficult, as he preferred to put the panels on the ground. He got convinced by a visit to the site, and architects now take this building as example when they have to work on photovoltaic projects in Morbihan. A participant in the audience gives his own example of installing photovoltaic panels on his house roof in 2009. His nephew did the same in Arradon (on the border of the harbor) and recouped the cost in six years. By contrast, the audience participant estimates that he should only recoup his cost in the twelfth year.

Producing solar energy inland is more difficult than near the harbour, due to the different conditions of weather and sunshine. The vice-president of GMVA answers that twelve years is a normal payback period for photovoltaic panels. The energy that will be the most profitable is anaerobic digestion, then wind, and finally solar. These considerations are factored in the plan to achieve the production goals of renewable energy. The installation of green energy will however not lead to immediate results, since the energy system has a long period of inertia. An issue now raised by people and companies is the recycling of solar panels, becoming more interesting as the number of panels increases

and the recycling rates are high (e.g. a subsidiary company manages to recycle 95-97%).

Laurent adds that recent panels are cheaper and lose less energy. An inhabitant can self-consume and sell the unused energy. When for instance the production of photovoltaic electricity is large due to strong sunshine but the local consumption is low, the excess can be exported to the North of Brittany or elsewhere (or even converted into hydrogen). These strategies require a systematic view of the energetic system, while self-consumption works separately from the network. The vice-president of GMVA considers hydrogen as the solution ahead for storing energy. Morbihan Energie already has a car running on hydrogen, and we can anticipate that hydrogen will store the solar energy produced during the day so that it can be used at night. If hydrogen is now made mainly from hydrocarbons, this production will eventually be replaced by the hydrolysis of water.

A second audience participant has a question. Projects of wind power take more time due to administrative appeals, which could counter the goals of renewable energy production. For example, a project of wind power set up today would only be productive around 2030. The vice-president of GMVA answers that the delay between the start of the project and the installation of wind turbines is usually about two years. The territory has wind power potential, although there is scarce territory North of Vannes to produce wind energy. GMVA aims to coordinate the installations of wind turbines, so that they are put in the best spots and do not bother neighbours. Medium-sized wind turbines are now producing as much as large turbines from a few years ago. Laurent adds that their blades turn slower, and are therefore less dangerous for birds.

Energy mix

The whole community of the territory needs to think together and identify the obstacles, in order to solve any basic problem. Otherwise, it becomes easy to oppose a decision coming from above (e.g. GMVA) for various reasons (e.g. lack of information or discussion). The future transformation of the territory is nothing like what we have ever experienced. Recalling the drunkard from the conference, we have some ideas about the future but do not know exactly where we are going. We have to gather all of our knowledge and desire, and to experiment solutions. A number of experiments will turn out wrong, but some will work.

The goal is to gather the elements for the decision that will be taken by our elected officials, as they control the funding and relations with various constraints (laws, regulations, etc.). A third audience participant intervenes, he has concerns about renewable energies. The production of photovoltaic panels uses a lot of energy (e.g. oxidation of silica) and this solution can not cover all our needs, even in a territory as small as the Gulf. The overall energy consumption for the production of renewable energy installations should be included in the energetic balance, for the planning goals of the territory, and we should consider solutions that are more diffuse.

The vice-president of GMVA answers that solar energy was just an example, and that an energy mix is needed. This mix would start with solar, wind, and anaerobic digestion, to be later supplemented by hydrogen. The SCOT (land development plan) includes this energy mix and experimentation projects are underway, such as an eco-district with

an imposed solar production. Hydrogen systems could one day support an entire city. Due to the slow development of renewable energies in the territory (e.g. wind, hydrogen), a mixture of them is needed in a program, and all types are studied (e.g. tidal power) to achieve the objectives set for the future.

Laurent mentions an example of simple energy source. By putting a water heater on the roof of your house during summer, you can quickly heat the water up to about 80 °C. Wind power is difficult to harness but solar power is a lasting source. It is however less interesting for a technician to replace a conventional system (of hot water production) by another system mixed with solar, because the operation of replacement is not profitable enough (e.g. few or no electronic materials).

Urbanization and housing

The critical problem that we will have by insulating more our houses is that they will cool less at night. People will be roasted and need air conditioners. To manage hot and cold (air, water), you need a heat exchanger and a coupled exchange system with the undersoil. The sun provides everything we need during the day; we are not progressing enough on these things. An audience participant disagrees, since a house gets cooler the more insulated it is (e.g. old farms do not take the heat). A well-insulated house retains 24-25 °C indoors even during a heatwave, and air conditioning is not needed if someone knows how to ventilate during the night.

Laurent agrees but the proper insulation is expensive to keep a house cold even after multiple hot days. For old farms, the soil is kept cool by evaporating moisture. Andalusian houses are an example of architectural solution, implying a dedicated design with caps outside and scarce glass surface. The issue is that houses are already built in the Gulf, and we are currently funding the isolation of the present housing instead of building houses that are tolerant to heat. A house can be adapted to warming, with ventilation inside (e.g. Canadian well) and outside (e.g. air drafts by grouping houses).

Does GMVA think about the reconstruction of heat-tolerant houses? The vice-president of GMVA answers that houses will be rehabilitated based on the year of construction, and that the economic reality makes renovation more relevant than rebuilding in some cases (e.g. in districts of Vannes). The permissions to build houses are given by GMVA, and the Gulf will need more housing given the projected increase in population. Construction permits consider different things, and while insulating and producing energy are positive aspects, they are not viable alone (e.g. energy loss with hydrogen).

We have to stop spending so much energy, such as on air conditioning. The Mayor adds that before PLUs were put in place, construction was sprawling anywhere. Urbanization is now denser, and the trend is to rebuild the new city upon the old one. A program of wood-based construction is underway in Elven. The city is mixing ecology and economy but the process takes time. For example, wind turbines could be installed around Elven but would also have negative (cultural) effects. The program of anaerobic digestion must first go through, and then the situation can be reassessed.

Agriculture and forestry

Laurent mentions another situation where transitions are difficult, between the activities of traditional and organic agriculture. The human pressure on the biosphere has increased over the last thousands of years, accelerating in the last decades. The issue of biosphere management and impacts must be considered, since it is also complicated further by climate change. Researchers can learn by listening to the specialists, to deepen their understanding and reflection about these issues, and to lay the ground for future research. Does someone have questions or concerns about how the environment and agriculture will evolve?

The MNHN professor adds that agriculture is implied in climate change and biodiversity, and would like to know how farmers are approaching this problem. The organic farmer describes the current situation for him and his colleagues. He witnesses changes in operation and practices of farmers on the field, accelerating over the past ten years. Farmers are adapting gradually in the region, each in his own way, with solutions that are individual or collective (e.g. anaerobic digestion). Farmers are for instance using smaller quantities of industrial products (fertilizers, phyto-sanitary), which are already minimized in organic farming. Laurent asks how the farmers are preparing for the next 10-20 years in association to climate change.

The farmer clarifies that he cultivates crops but does not breed animals, and therefore has very different constraints than breeders for managing the farm. Most of his farm is irrigated, which could alleviate climate change. Creating water reserve areas is complicated because doing so affects the ecosystems, so only few permissions are given by authorities. Farmers tend to intervene at specific spots, but we have to see the situation at the scale of the territory. If a stream flows next to a farm and a small dam is built, everything will be modified but not all negatively. There can also be positive impacts, and farmers need to be aware of all these impacts (negative and positive) to know which way to go, where to stop, what to ask, from whom and when.

Practices are changing among all farmers; tractors for example use a smaller engine and consume less fossil fuel. We do not realize that a whole bunch of solutions are already in place, at the level of people who work on the field. They are forced to adapt through the choice of crop varieties and sowing dates. You cannot sow corn now like you used to in the past. The farmer witnessed some people sowing earlier and harvesting later in order to increase yields, but this was not ideal as spring was very dry and winter very wet. Farmers must be reasonable and think about these things continuously. There is a popular/common impression that depicts farmers in a runaway intensification of agriculture, regardless of the impacts. This is not possible in practice, because of the economic impact from the waste of materials and energy.

Laurent gives the example of climate change effects on corn and woods. Wood is widely used to build and heat houses in Brittany, but much of the lumber comes from the North (e.g. Scandinavia). Tropical deforestation is commonly discussed, but the forests providing the wood to build houses are also disappearing. The Swedes are not stupider than others, and they know that they will be able to grow corn better than us in 10-20 years with the effects of

climate change. Their land will be warm enough, and supplied by plenty of water to grow productive species. When corn was cultivated in Mexico, the species were less productive and used less water, but these are not the species that we use in France.

Highly productive corn will be grown in Norway or Sweden, and we will not be able to do this at the same price in France. The whole system is evolving, and you have to constantly experiment, being a farmer is an extraordinary job for the future. An increasing number of farmers is starting to try varieties from the South (e.g. Spain, Italy) and some even start to consider African varieties. The organic farmer says that we must think about why we grow corn, which is a question faced by every farmer. What is the point of doing it, if we perpetuate an endless and unsustainable practice?

Corn is grown to feed cows, but cows are also given imported supplements, to breed an hermaphrodite that will be eaten here or exported elsewhere. This is not an economic or technical problem since we will always find a temporary solution, such as growing corn varieties from the South. Maybe we could work differently instead of always look for a short-term solution, like looking for corn in Spain, then Morocco, and then Senegal. One day, where are we going to find it? We will have tried everything but it does not work anymore. This is stupid, because we did not need any of that. But it will not matter and we will just start something else.

For consumption in general, many solutions are imported, such as for food or for buildings materials. The consumer will always be the one to choose, and he will always be right. Laurent mentions that we must also plant trees, but need to plant them now since they usually come from the South and take decades to grow. The MNHN professor suggests the role played by large companies in the current situation of farmers. By locking down a number of processes, these companies make difficult for farmers to get out of the system, because the farmers have lost part of their freedom to decide (due to contracts or loans). Therefore, the transition to a more sustainable territory requires changes at different levels.

Meat production

The mayor mentions a big project of chicken production. The developers obtained the building permits but could not start producing because the law had changed. The mayor is surprised that people are happy with importing chicken from other countries (Poland, Ukraine, Brazil), rather than to have a self-sufficient territory (i.e. local chicken production). We have to be coherent if we want the territory to be sustainable. The law-makers should consider this issue, because it makes no sense for a local project to be blocked by the law after waiting to start for years. An audience participant disagrees and ask why we want to produce so many animals.

Chickens are for instance fed proteins often associated to tropical deforestation (e.g. Amazon). The assumption that human beings need to eat meat everyday is also something to question. Laurent says that the two people are not talking about the same thing. One is the issue of importing chicken (industrial) because the local production is insufficient, and the other is the still excessive need for meat. We should eat less meat, but our meat consumption is

not going to drop dramatically tomorrow or in 5 years. We could also increase the quality (organic) and decrease the quantity of meat, by producing chicken in open-space instead of having factories importing proteins linked to deforestation.

The mayor's question could be interpreted on a much broader issue than just reducing meat consumption. For instance, if there is compatibility between the project that an entrepreneur is trying to develop, and the way the law is evolving? Other audience participants say that we should also talk about employment if we discuss animal farming. Many people are going to arrive in Morbihan, and the current jobs are in other countries (e.g. chicken production in Poland). For the MNHN professor, the problem is one of scale. France is a large exporter of chicken so feeding the French people with imported chicken is a system walking on its head.

Several large projects of animal farming are envisioned in Brittany, but they will lead to deep issues. While small-scale (organic) farming is rather beneficial for natural environments (e.g. grasslands), a farm with thousands of animals has serious environmental consequences. Regarding the state of law, the legislator does what he can but anyone can appeal against a project. Laurent highlights the importance of the mayor's question as an illustration of contentious topics for the evolution of the territory. Two choices are possible for industrial farming in the territory, so we should explore all the advantages and disadvantages associated to this project over the next five years for instance.

Conclusion

To prepare for a transition that will affect all of us in the next years or decades, we can no longer stay at the stage of "I am right and you are wrong". Everyone must exchange their arguments and we can build a consensus. By exploring different strategies instead of just one, while posing the pros and cons of each, so that there can be a democratic vote. This way, we can favor a solution if we have money to do so, without doubts regarding the advantages and disadvantages. The PNR representative mentions that someone was hired recently at PNR to work on food transition and agroecology.

The approach "from the landscape to the plate" is emerging, as well as short distribution circuits. What do inhabitants want to consume, and which landscape is going to result from these food choices? A global vision is needed of these food desires, and a clue used by the newly hired person is "what the consumer wants" (if the consumer knows what he/she wants). The idea is to apply this approach in canteens, so that farmers produce the food preferred by inhabitants. The wife of the organic farmer intervenes in the audience, mentioning that farming in Elven is a pleasure and that they employ young people from the surroundings.

Her husband was a conventional farmer and he converted to organic. The neighboring conventional farms reflect on their own practices by witnessing the operations in the organic farm. Organic farmers coordinate their efforts to provide their products with a single truck to local organic shops. They think continuously about the global vision around organic farming, and how to do things (individually and collectively). The mayor thanks everyone for

participating to the event. He mentions the importance of the theme (transitioning to a more sustainable territory) for local citizens, and that the territory is at a turning point.

5.3.3 Discussion

This conference-debate was the first on the theme of transition scenarios in the region, involving local decision-makers and inhabitants. The group was small (about thirty-five people) due to the constraints from the health crisis (Covid-19), but this small number facilitated the discussion. Although we tried to focus the conference and debate on climate change adaptation, the debate also covered various themes (Table 5.7), including sustainable development and climate mitigation. The relation of the territory to climate change was centralized through two topics, the energy autonomy (consumption, production, installation of renewables) and food autonomy (crop cultivation, meat production,

Table 5.7: Overview of the main points for each theme raised during the debate.

Theme	Situation	Efforts	Challenges
Climate adaptation	<ul style="list-style-type: none"> Climate change awareness started recently Transition to sustainable territory supported by GMVA and PNR 	<ul style="list-style-type: none"> PCAET (2030-2050) Cactus tool with information sheets to support decision-making Coordination of climate plans with mayors 	<ul style="list-style-type: none"> Involve local actors (partners, companies, etc.) and inhabitants in the making of the climate plans
Energy	<ul style="list-style-type: none"> Decrease energy consumption and increase renewable energy production An energy mix is needed but the energy system has a large inertia 	<ul style="list-style-type: none"> Diagnosis of the territory potential for renewable energy production Support and coordinate the installation of renewable power (solar, wind) Experimentation projects (hydrogen, tidal power, anaerobic digestion) 	<ul style="list-style-type: none"> Cultural reactions from inhabitants Production must be controlled at level of electrical grids Lower solar potential inland than near harbour (long pay-back period)
Urbanization and housing	<ul style="list-style-type: none"> More housing is needed given the projected population increase Need to make the buildings more tolerant to heat 	<ul style="list-style-type: none"> Renovation and rehabilitation of buildings Consider architectural design for heat tolerance (caps, ventilation) 	<ul style="list-style-type: none"> Insulating the buildings will decrease their potential to cool at night
Agriculture and biodiversity	<ul style="list-style-type: none"> Direct impacts from climate change Warming of water decreases the oxygen content and kills marine animals 	<ul style="list-style-type: none"> Changes in practices of farmers (e.g. crop varieties, sowing dates) Gradual adaptation (individual and collective), some solutions are imported and temporary (e.g. Southern varieties) Emergence of short distribution circuits 	<ul style="list-style-type: none"> Land management requires coordinated discussion between all actors Some farmers want to keep cultivating corn and irrigating more, although water reserves are scarce Creating water reserves is complicated (permission from authorities, alteration of ecosystems)

distribution circuits).

This relation is complicated since these two topics also concentrate conflicting views between inhabitants. The emotional interventions from both inhabitants and stakeholders about these topics demonstrate how people react instinctively to their culture, reflecting the fears and desires they have for their future territory. To build a common future, we have to express disagreement but also to explore several strategies and compare them, making it possible to distinguish the actions and problems that will concretely emerge. Our desire is to continue pushing for climate adaptation and participative processes in collaboration with the GMVA and PNR. Everyone must be able to feel as an actor in Morbihan, and in the transition of the territory.

A GREC (local group of scientific climate experts) is under construction in Brittany, inspired from other regional GRECs in France (e.g. Acclimaterra in Nouvelle-Aquitaine; AcclimaTerra (2021)). A mission of this GREC would be to build scenarios of evolution for climate and society in Brittany, based on multidisciplinary scientific expertise and supported by climate services. In addition to environment and climate, the panel of experts would include scientists from the social, economic and health fields. The first report of the Briton GREC is expected by end of November 2021.

5.4 Climate services for local adaptation: gaps and perspectives

One of the objectives of this PhD thesis was, in conjunction to the activities with local stakeholders (interviews, workshop, exhibition, debate), to determine the usability and limitations of available climate services for supporting the local adaptation. An initial ambition was to compare the local needs in climate knowledge with the existing climate science and services, in order to deduce gaps and potential demand for more locally accurate data, that could then be addressed by the research team (e.g. through methods of regionalization).

The co-development activities with stakeholders took longer than expected, to understand the local issues and build trust with inhabitants. Therefore, the stage of qualifying and quantifying the required knowledge for relevant actions of adaptation was not reached. Nonetheless, I carried out the gap analysis as far as allowed by the level of detail from previous results. This analysis was complemented by an evaluation of the climate services with the leader of the case study, aiming to better understand how climate services can support local adaptation, and to deduce potential strengths and weaknesses, as well as limitations and perspectives.

5.4.1 Evaluation

The evaluation of climate services in the Gulf of Morbihan is based on an interview with the case study leader, supported by a framework of evaluation criteria (Table 5.8). The framework aimed to provide an easily applicable (short, simple, and fast) list of user-oriented criteria. The criteria and subcriteria are based on a brief literature review

about climate service evaluation (e.g. Meinke (2017b)).

Table 5.8: Evaluation framework for climate services (Meinke et al., 2019).

Criteria	Sub-criteria
Accessibility	<ul style="list-style-type: none"> • Information easy to find? • Information easy to understand?
Credibility	<ul style="list-style-type: none"> • Trust in producer? • Transparency of data, methods and uncertainties?
Usability	<ul style="list-style-type: none"> • Appropriate format to address the question/problem? • If uncertainty is included, does it increase the usability of the information/knowledge for decision-making?
Relevance	<ul style="list-style-type: none"> • Relevant spatial and temporal scales? • Can this service cover all aspects of the initial question? • Uncertainty of the information allowed (small enough) or not allowed (too large) by decision-making?
Additional criteria and remarks mentioned by the interviewee	What is not covered above but is important from your perspective to evaluate available climate services for specific issues

We focused on climate services under the form of free online tools because they are the most accessible, interactive, and flexible. In the preparation of the evaluation, I gathered the most pertinent climate services according to the local issues. The evaluation focused on the two services Climat HD and DRIAS, developed by Météo-France, since they are very relevant to address most of the issues. The main results from the evaluation are shown in Tables 5.9 and 5.10. The full analysis by criteria is not shown due to redundancy between climate services on different issues.

The evaluation indicates that the key strengths of the climate services used are their accessibility, understandability, credibility and transparency. Their key weaknesses are the lack of information about variables (e.g. seasons and water surface temperature), spatial distribution (e.g. storms and extreme events), spatial scale (e.g. extreme events), past (e.g. attribution to climate change), future (e.g. storms), and uncertainty (represented through different climate models and scenarios in about half of the cases). The combined strengths and weaknesses of these climate services make their use possible in some cases but very limited in most cases, although the combined use of multiple climate services can partly remedy the gaps of individual services.

Table 5.9: Main results (part 1) from the evaluation of climate services (Meinke et al., 2019).

Topic	Climate service	Strengths	Weaknesses
Warming (air and water) for primary activities, tourism and, to some extent, territorial planning	Climat HD	<ul style="list-style-type: none"> • Time series can partially answer the question • Uncertainty considered (between climate models and scenarios) 	<ul style="list-style-type: none"> • Unclear which temperature is considered (soil surface, air surface) • No information on water surface temperature • No maps
	DRIAS	<ul style="list-style-type: none"> • Maps more precise than Climat HD • Uncertainty considered (between climate models and scenarios) • Spatial and semi-temporal information to answer the questions 	<ul style="list-style-type: none"> • No time series
Rainfall changes for agriculture	Climat HD	<ul style="list-style-type: none"> • Information on annual, summer and winter precipitation • Clear maps and explanation • Complementarity between time series of Brittany and maps of Morbihan over different scenarios and time horizons 	
	DRIAS	<ul style="list-style-type: none"> • Maps more precise than Climat HD • Uncertainty considered (between climate models and scenarios) • Spatial (maps) and semi-temporal (time horizons) information are helpful to answer questions 	<ul style="list-style-type: none"> • No time series
Seasonal changes for primary activities and tourism	Climat HD and DRIAS	<ul style="list-style-type: none"> • Lot of information on changes of climate variables in seasons • Appropriate format for seasonal changes but assuming the structure of seasons doesn't change with climate change 	<ul style="list-style-type: none"> • Lot of information on changes of climate variables in seasons, but not on seasons themselves • Need to know the effect of climate change on the structure of seasons and condition the climate variables by changing seasons to determine the impact on agriculture and tourism

Table 5.10: Main results (part 2) from the evaluation of climate services (Meinke et al., 2019).

Topic	Climate service	Strengths	Weaknesses
Occurrence of extreme events for agriculture, tourism and territory planning	Climat HD	<ul style="list-style-type: none"> Information on droughts, hot and cold days at the scale of Brittany Didactic 	<ul style="list-style-type: none"> Information on heatwaves and cold-spells but only at the scale of France Format supportive of action but not precise enough to know what to do in Brittany Uncertainty not considered Unknown location of extremes, information at the scale of Brittany would be useful
	DRIAS	<ul style="list-style-type: none"> Spatial information (maps) more precise, and easier visualization than Climat HD Uncertainty considered (between climate models and scenarios) Spatial (maps) and semi-temporal (time horizons) information are helpful to answer questions 	<ul style="list-style-type: none"> More difficult to use and to answer questions than with than Climat HD Credible but not very transparent (data and methods) No time series No local data (Brittany)
Impact of storms, sea level rise and marine submersion for coastal risk management	Climat HD	<ul style="list-style-type: none"> Accessible, understandable, credible, and transparent information Scale of Brittany is sufficient 	<ul style="list-style-type: none"> Information only on past storms Little information on future coastal risks Little information about uncertainty No information about storm intensity
	Copernicus	<ul style="list-style-type: none"> Accessible and credible but less than Climat HD 	<ul style="list-style-type: none"> Information not usable (coarse scale)
	Surging Seas	<ul style="list-style-type: none"> Didactic Usable for sea level rise (relevant spatial and temporal scales) Uncertainties considered 	
Attribution of weather changes to climate change (outside natural variability)	Climat HD	<ul style="list-style-type: none"> Visible, understandable, and credible attribution of temperature, precipitation and soil humidity according to scenario Uncertainty considered (between climate models and scenarios) Small divergence between scenarios in 2030 makes planning less uncertain The different scenarios make attribution more evident in the future but the attribution is less clear in the past (natural vs. anthropogenic) 	<ul style="list-style-type: none"> Attribution of past storms but not future
	Clim4energy demonstrator	<ul style="list-style-type: none"> Credible Many climate variables and projections from different models 	<ul style="list-style-type: none"> Difficult to access, understand and use Spatial scale too coarse (no local detail)

5.4.2 Limitations and perspectives

The first climatic theme for the case study is about warming, seasonal changes and the water resource. The evaluation activity suggests that the topic of surface air warming is sufficiently covered by available climate services to support local adaptation. However, we do not know if there is sufficient information about the warming of surface water, since this topic is scarcely covered by climate services, and since local observations (long-term) are lacking in the Gulf.

The evaluation also suggests that future precipitation is sufficiently covered by climate services to support local adaptation. However, projections of future seasonal precipitation in climate models are associated to large uncertainties, and sometimes even contradicting trends between different scenarios or models. From the angle of water resource management, future groundwater availability could be assessed on the short-term based on seasonal meteorological forecasts (Rubio-Martin et al., 2021), and on the long-term based on stochastic modelling of system dynamics (Terzi et al., 2021).

Many changes in the seasonality of climatic variables (e.g. temperature, precipitation) have been identified in the scientific literature, as well as associated changes in the phenology of crops, although changing agricultural practices complicate the attribution to climate change. Most climate services dealing with seasonality focus on phenology, while others use static meteorological seasons. A new service could investigate how the seasonality of different indicators (selected with stakeholders) might evolve in the future, although DRIAS already includes many agro-climatic indicators.

The second theme is the occurrence of extreme events. The main scientific limits regarding extreme weather events are:

- their enormous variability
- the understanding of the diverse underlying processes
- the lack of high-quality and long-term data to detect and attribute the influence of climate change
- the lack of consistent definitions
- the limitations of the tools used to analyse these events

The observational record of rare events also matters for future projections, since the skill of models to simulate extremes is generally assessed based on this record. The attribution of individual events to climate change is covered by some climate services (e.g. World Weather Attribution (2021)), and the attribution findings for new weather events often become available through research papers in the following months (and disseminated more broadly through media coverage). Providing attribution statements shortly after an event remains challenging for the scientific community, although weather services and climate centers are working towards the near real-time attribution of extreme weather (e.g. Tradowsky et al. (2021)).

The evaluation indicates that the scale of the information (Climat HD, DRIAS) could be insufficiently precise to support local action, for example regarding the timing and location of extremes. However, we do not know whether this really constitutes a knowledge gap for local adaptation. There is the possibility to access more local information about future extremes but this requires to do data analysis (using free online data platforms). For the determination of future extremes at local scale, a service could also be considered that shows the aggregated variability (spatial and temporal) between different events and types, accounting for uncertainty (models, scenarios), and including the derivation of local impacts (e.g. on sectoral activities). More exotic options of service development could also be imagined:

- an early-warning system for heatwaves (including mortality forecasts) to prepare local heat-health actions plans (Lowe et al., 2016).
- a methodological approach to guide citizens moving in the city when extreme temperatures occur (Madureira et al., 2021)
- a multisector identification of flood risk, including the cascading effects of drainage system failures (Almeida et al., 2021)
- a simulator of flood evacuation scenarios (Shirvani and Kesserwani, 2021), combined with realistic images and animations of simulated flood occurrence at street level (Siegel and Kulp, 2021)

The third theme is the adaptation of the shore to coastal risks (marine submersion). The main associated knowledge gaps are:

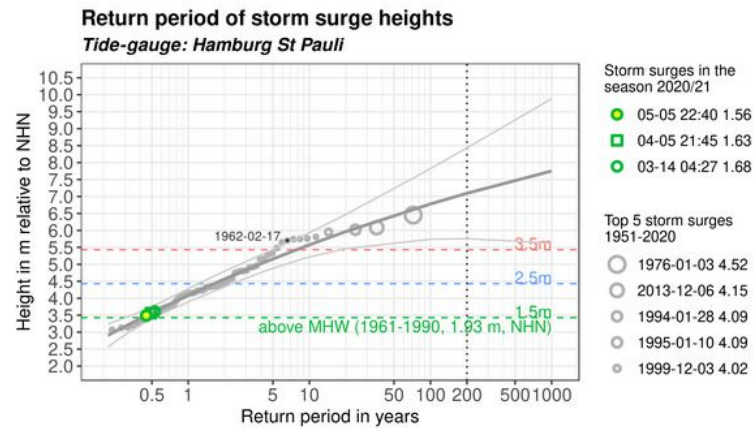
- the large uncertainty in future coastal hazards
- the lacking representation of local features (hazard, vulnerability, exposure) in assessments and simulations
- the lacking translation of coastal risks for adaptation measures

Options would be to include local subsidence in the assessment of future flood hazards (e.g. Miller and Shirzaei (2021)), and to navigate the incertitude of future coastal impacts with uncertainty frameworks and probabilistic projections (Stephens et al., 2017; Jevrejeva et al., 2019; Toimil et al., 2021). There are also approaches to deal with deep uncertainty in decision-making for marine submersion, such as no-regret strategies for coastal protection measures (Adaptation Community, 2021).

An additional possibility is the inspiration from climate services in other countries (e.g. United States, Germany). These existing tools illustrate how to situate recent and future coastal hazards in the context of long-term climate variability and societal vulnerability. In Germany, the Northern German Coastal and Climate Office contextualizes the current conditions (sealevel, windstorms and storm surges) in view of long-term variability (Helmholz-Zentrum hereon, 2021d,b; Liu et al., 2021), as well as coastal vulnerability and exposure (Figures 5.16-5.17).

Interpretation of the figure

Is the height in the current storm surge season unusual?



The higher the storm surges the less frequent the events. Heights of storm surges of the current season are denoted by colored symbols. They show how long it will take on average until an event of similar height may be observed again (x-axis).

Data from the current season are preliminary and reflect the present status of the ongoing season.

Figure 5.16: The service of storm surge monitoring from the Northern German Coastal and Climate Office (Helmholz-Zentrum hereon, 2021c).

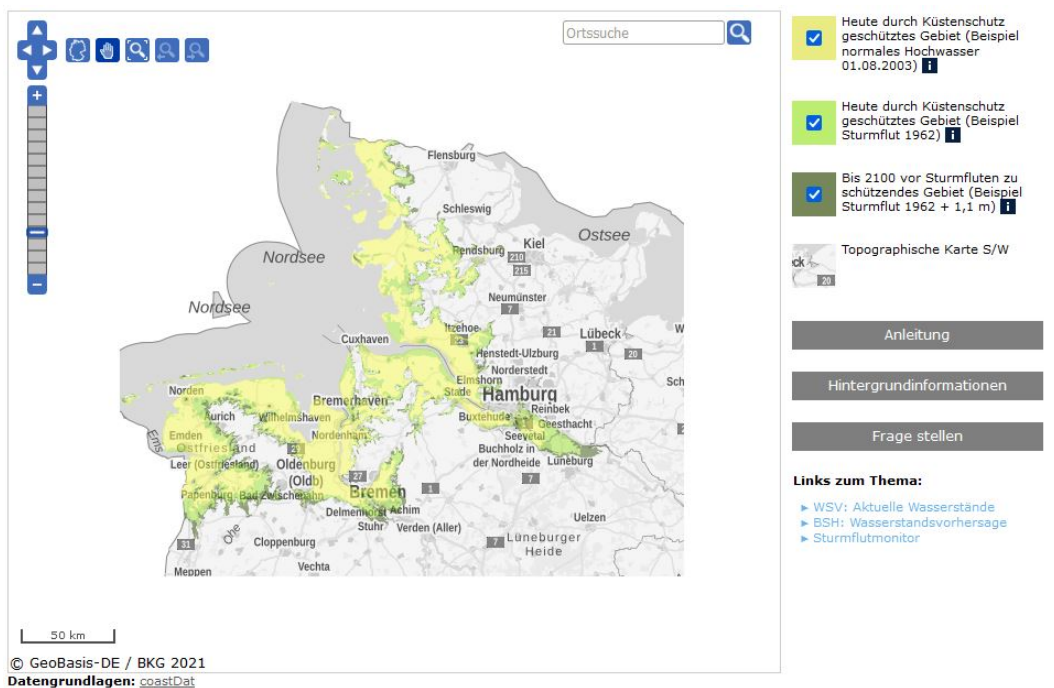


Figure 5.17: Existing coastal protections and future needs in the Northwestern coast of Germany (Helmholz-Zentrum hereon, 2021a).

In the United States, Surging Seas displays social variables (vulnerability, population, income, etc.) alongside sealevel rise and flood risk (Figure 5.18).

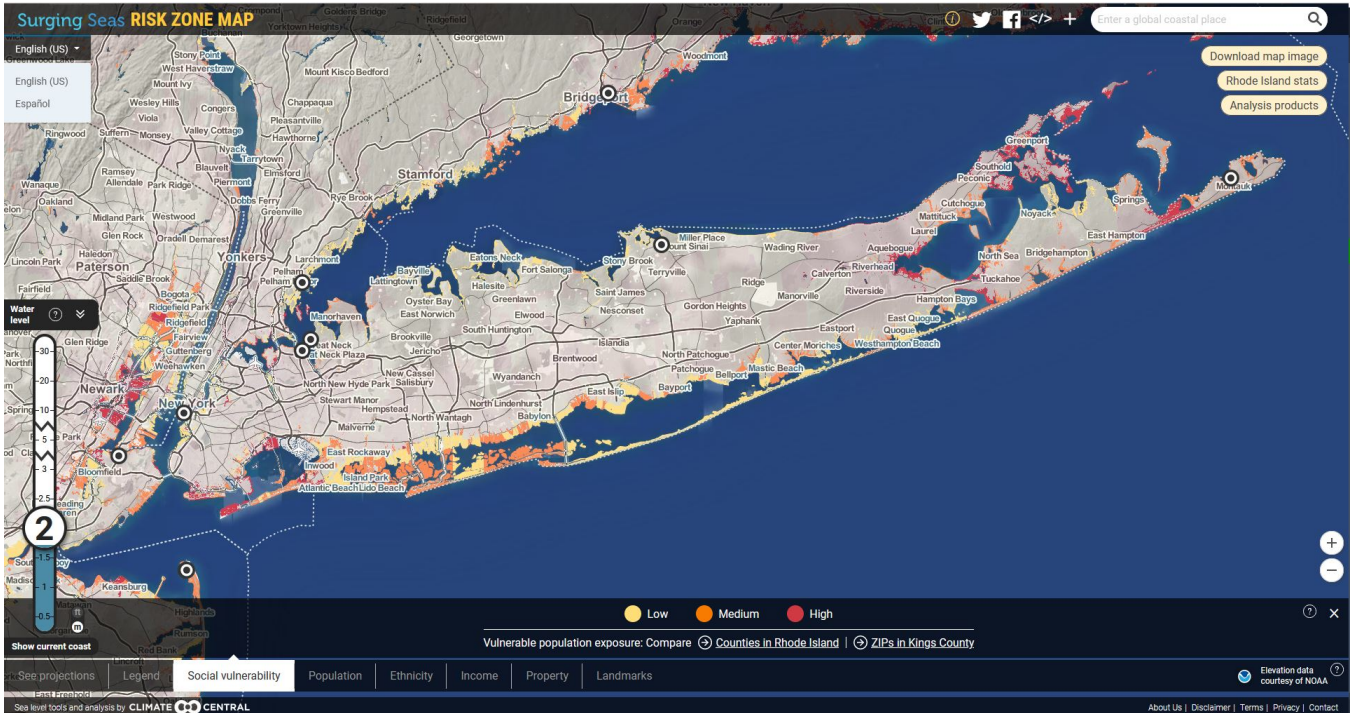


Figure 5.18: Mapping of social vulnerability for a given rise of sealevel in New York (Climate Central, 2021b).

In summary for climate services, general directions of improvement are:

- To further precise locally the historical and future evolution of climate-related hazards (e.g. heatwaves, droughts, storm surges), including a reduction of scientific uncertainties (e.g. precipitation, sealevel rise)
- To better derive these hazards into societal impacts (e.g. on agriculture, infrastructure), and translate with stakeholders these impacts into potential adaptation measures (e.g. coastal protection)
- To reach new users (e.g. territorial decision-makers), and keep exchanging with the community of users about their issues, needs, the improvement of existing services and possible development of new services

A big question remains the necessary level of detail (spatial, temporal, uncertainty) needed for decision-making. An example of climate service prototype at city-scale is the "City Pack" that was developed for Bristol in the UK, co-produced to become a highly tailored and user-relevant tool (Fuller et al., 2021). Additionally, new demonstrators of climate services have become available on DRIAS in the last months, for instance regarding the urban planning of cities, the evolution of the water resource, or the coastal adaptation to marine submersion (Météo-France, 2021c).

To summarize the situation of climate service development in the Gulf of Morbihan, we can draw elements of comparison (Table 5.11) from the two other case studies (Brest in France, Bergen in Norway). In the case of Bergen as for the Gulf of Morbihan, climate is integrated in the local culture and climate change directly affects local issues, with options for adaptation and climate service development (Bremer et al., 2020). However, the case of Brest is particular since climate has low priority in the local context and issues, questioning how to include climate change

Table 5.11: Comparison of the situation in the Gulf of Morbihan with the two other case studies (Brest, Bergen).

	Gulf of Morbihan (France)	Kerourien district, in Brest (France)	Bergen (Norway)
Context	<ul style="list-style-type: none"> • Seasonal socioeconomic activities • Territorial contrast (inland vs. coast) • Ambivalent relationship between agriculture and tourism 	<ul style="list-style-type: none"> • Poverty, crime, marginalization • Social work has high priority • Low interest in weather and climate 	<ul style="list-style-type: none"> • Europe rainiest city (culture) • Torrential rain and landslide risk (nearby mountain)
Climate change	<ul style="list-style-type: none"> • Perception consistent with science • Complex role in territory (negative, positive) • Exacerbates local issues 	<ul style="list-style-type: none"> • Indirect link to local issues (e.g. building squalor, air quality) 	<ul style="list-style-type: none"> • Perception consistent with science • Exacerbates local issues (e.g. water and sewage management, landslide risk)
Adaptation	<ul style="list-style-type: none"> • Agreement of actors on most issues • Disagreement about coast and tourism • Possibilities for climate service development 	<ul style="list-style-type: none"> • Low priority, how to put on community agenda? • Need to broaden the definition of climate service? e.g. community development activities 	<ul style="list-style-type: none"> • Need of meetings (e.g. "climate café") to discuss adaptation between scientists and actors • Possibilities for climate service development (seasonality, landslide impacts)

adaptation in the community agenda (Baztan et al., 2020).

Going back to the Gulf of Morbihan, the three climatic themes discussed (seasonal changes, extreme events, marine submersion) are closely connected to atmospheric circulation. For instance, the seasonality of weather conditions is associated to that of atmospheric flow patterns (Vrac et al., 2014; Cassou and Cattiaux, 2016), extreme weather events can be triggered by the persistence of weather systems (Martineau et al., 2017; Brunner et al., 2018; Wolf et al., 2018), and the variability of windstorms and oceanic waves depends strongly on dynamical factors (Camus et al., 2017; Morim et al., 2018; Markina et al., 2019). Additionally, both atmospheric circulation and extreme events have strong seasonal features (Wallace et al., 1993; Cattiaux et al., 2012; Brunner et al., 2018; Iqbal et al., 2018), but future circulation changes are highly uncertain (Woollings, 2010; Shepherd, 2014; Chen et al., 2018; Woollings et al., 2018).

The effects of climate change on atmospheric circulation and weather extremes have been investigated extensively through the use of circulation regimes (Hannachi et al., 2017). Circulation regimes have for instance served to detect long-term trends in circulation patterns (e.g. Horton et al. (2015)), and to study the processes leading to extreme weather events (e.g. Vautard et al. (2016)). The effects of climate change on European circulation regimes could therefore be interesting for the local case study, based on the potential of these regimes to address the three climatic themes of importance for adaptation. This is the focus of the next chapter, which reviews the literature on circulation regimes (links to variability modes and effects of climate change) and presents a new study on the role of climate change in the seasonality of atmospheric circulation (and surface temperature).

Summary of Chapter 5

Context and objectives:

The first goal of this chapter was to experiment foresight activities with territorial actors (to identify adaptation options). The second goal was to evaluate whether the existing climate services can provide the information needed for adaptation (to identify gaps in services or knowledge).

Methods and results:

I engaged in four different activities (collaborative):

- A scenario workshop to develop a collective adaptation strategy
- An art-science exhibition to convey the territorial transformations through artworks
- A conference-debate to discuss territorial sustainability (climate adaptation and mitigation, etc.)
- An evaluation of climate services to determine how to support local needs

Two scenarios of long-term planning (2200) emerged from the workshop, as well as several hinge points (eight past and three future) on which the scenarios depend, and 25 actions for 2030. Actors agreed on one vision for most issues except for tourism and coastal land-use. The first scenario represents a continued occupation of the coasts (increasing adaptation efforts), and the second the densification of urban areas inland (recovery of coastal natural landscape). The exhibition immersed visitors in the future of the Gulf (potential impacts, adaptation options), and imaginary characters from 2050 illustrated the results of the 2030 actions in the future territory. The conference-debate addressed various topics but climate change was centralized through food and energy autonomy, which concentrated conflicting views between inhabitants. The evaluation highlighted the main strengths and weaknesses of key climate services, and discussed the implications for the development of local climate services, as well as directions of improvement for climate services in general.

Perspectives and link to next chapter:

The 2200 horizon was very uncertain, and another workshop is needed to finalize the 2030 actions (details, implementation). It remains unclear whether existing science and services suffice for local adaptation, but options for local services exist (also inspired from other countries) for each climatic theme. Since the three climatic themes (seasonal changes, extreme events, marine submersion) are linked to climate change effects on atmospheric circulation and seasonality, I conduct new studies in Chapter 6 to investigate these effects (with circulation regimes and the perspective of climate analogs).

"Marion Ravenwood: You're not the man I knew ten years ago.

- Indiana Jones: It's not the years, honey, it's the mileage."

Raiders of the Lost Ark

Chapter 6

European circulation regimes under climate change: towards new seasonality?

As prerequisite knowledge for this chapter, the main European modes of climate variability (NAO, AMO) have been developed in the Introduction (cf. section "Examples of climate variability modes: ENSO, NAO and AMO"), and the main European circulation regimes have been introduced in Chapter 1 (cf. section "1.2.3 Weather regimes").

Some of the research presented in this Chapter has been submitted to the *International Journal of Climatology*, in the article *Seasonal circulation regimes in the North Atlantic: towards new seasonality?* (Breton et al., 2021). The article is currently under revision.

6.1 Association to variability modes and effects from climate change

6.1.1 Relation to the jetstream, NAO, AMO and ENSO

Since circulation regimes are a representation of atmospheric variability, they are naturally closely related to other similar concepts in meteorology and climatology, such as jetstreams, variability modes (patterns, oscillations), and teleconnections (Christensen et al., 2013; Hannachi et al., 2017). The European weather regimes (WRs) are for instance representative of the variability from the boreal polar jetstream, since both concepts characterize the direction, strength, and persistence of the atmospheric flow in the North Atlantic. Moreover, the four classical weather regimes found in winter correspond to three preferential positions of the polar jetstream, and a fourth situation of

atmospheric blocking (Woollings et al., 2010; Madonna et al., 2017). This fourth situation can be decomposed into two configurations of atmospheric blocking, with a jet that is either tilted or split (Dorrington and Strommen, 2020).

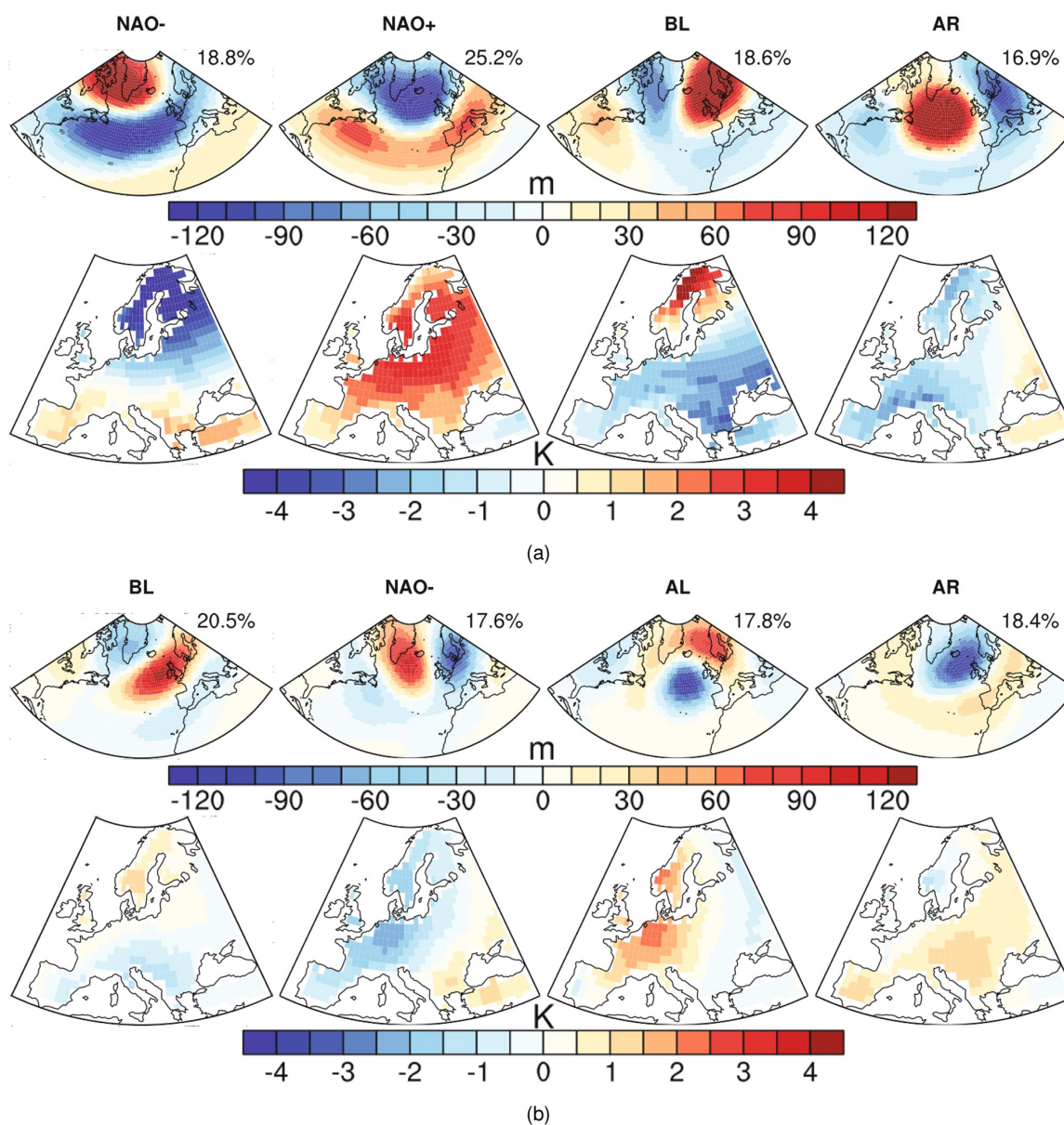


Figure 6.1: Four main weather regimes in the North Atlantic, during winter (a) and summer (b) (adapted from Cattiaux et al. (2013)). Composite maps of seasonal anomalies of Z500 (top) and surface temperatures (bottom) corresponding to each weather regime. Wintertime (December to March) weather regimes: NAO- and NAO+ (negative and positive phases of the North Atlantic Oscillation), BL (Blocking) and AR (Atlantic Ridge). Summertime (June to September) weather regimes: BL, NAO-, AL (Atlantic Low) and AR. Note that in summer, the BL regime corresponds to NAO+, and the AL regime resembles the Scandinavian Blocking.

Alongside boreal atmospheric jetstreams (polar, subtropical), the North Atlantic Oscillation (NAO) is another climatic component linked to European WRs. In winter, the positive NAO phase (NAO+) corresponds approximately to strong Westerly flow, and the negative phase (NAO-) to Greenland High (Figure 6.1a). The summertime NAO differs largely from the wintertime one, in terms of spatial signature and effects on weather conditions (Figures 6.1

and 6.2). Summer NAO+ is associated to less oceanic influence over Northwest Europe (warmer, drier, cloudless) and more oceanic influence over Southern Europe (cooler, wetter, cloudier; Folland et al. (2009)). Diving more in depth, the NAO is actually more diverse than just the typical NAO+ and NAO- phases. Many sub-types of NAO reflect the range of locations for the action centers (Icelandic Low and Azores High), with diverse effects on European climate (Rousi et al., 2020). These NAO flavors correspond in turn to multiple weather regimes.

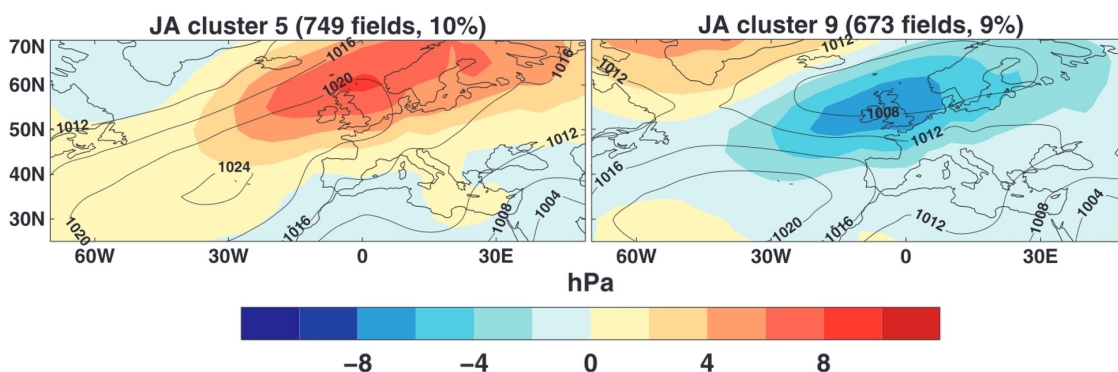


Figure 6.2: Positive (left) and negative (right) phases of the summer NAO (adapted from Folland et al. (2009)). Summer (July-August) monthly fields of sea level pressure (seasonal anomalies) associated to each NAO phase, averaged over 1881-2003 (based on cluster analysis of data from Ansell et al. (2006)).

On longer timescales than the jetstreams and NAO (days to years), North Atlantic climate is paced by the Atlantic Multidecadal Oscillation (AMO). The AMO influences European climate on decadal scale through the influence of large-scale North Atlantic SST anomalies on the oceanic and atmospheric circulation. The positive phase of the AMO (AMO+) is associated to the following changes (usually opposite for AMO-, with exceptions):

- displacing the Icelandic Low towards North America and the Azores High towards Europe (Börgel et al., 2020)
- displacing the eddy-driven jetstream southward (Davini et al., 2015; Simpson et al., 2018)
- contracted Atlantic storm-track (less extended poleward), low-level jet shifted toward the equator in the eastern Atlantic (Ruggieri et al., 2021)
- more frequent NAO- in winter (Peings and Magnusdottir, 2014; Davini et al., 2015; Gastineau and Frankignoul, 2015) and summer (Semenov and Cherenkova, 2018).
- more frequent Euro-Atlantic blocking in winter (Häkkinen et al., 2011; Peings and Magnusdottir, 2014; Rimbu et al., 2014) and summer (Ghosh et al., 2017)
- two specific weather regimes in spring and summer (Zampieri et al., 2017)
- warmer European summers (Sutton and Hodson, 2005; Sutton and Dong, 2012; O'Reilly et al., 2017) and the facilitation of summer heatwaves (Zhou and Wu, 2016; Gao et al., 2019)
- facilitating cold spells in winter (Peings and Magnusdottir, 2014; Rimbu et al., 2014)

- more summer precipitation in Northern and Western Europe but less in Southern Europe (Sutton and Hodson, 2005; Sutton and Dong, 2012; O'Reilly et al., 2017; Zhang et al., 2019).
- more precipitation over large parts of Europe in winter and autumn (Knight et al., 2006)
- reduction in glacier mass and spring snowfall (Huss et al., 2010; Zampieri et al., 2013)
- increased frequency of Atlantic hurricanes (Knight et al., 2006; Zhang and Delworth, 2006; Nigam and Guan, 2011)

The link between El Niño Southern Oscillation (ENSO) and European WRs can also be mentioned, although the teleconnection is complicated (cf. section "Examples of climate variability modes: ENSO, NAO and AMO" in the Introduction). El Niño appears to be generally associated with a strong pattern resembling NAO-, while La Nina appears to be generally associated to a weak pattern resembling NAO+ (Bengtsson et al., 1996; Roeckner et al., 1996; Martineu et al., 1999; Cassou and Terray, 2001).

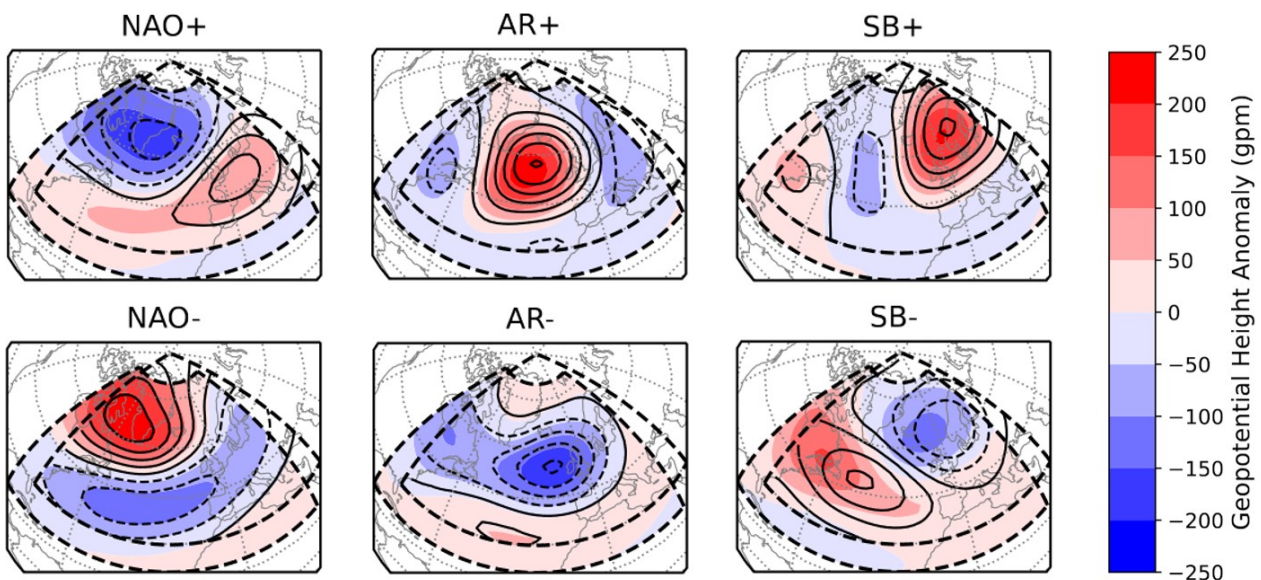


Figure 6.3: Six wintertime weather regimes identified by k-means clustering in the ERA-Interim reanalysis for two domains (adapted from Falkena et al. (2021)). The two domains are indicated by the dashed boxes, and correspond to a sensitivity test of the results to the choice of region. The anomalies of geopotential height (m) associated to the regimes are indicated in shading for the first domain (20-80N, 90W-30E), and in contours for the other domain (30-90N, 80W-40E).

To identify the relation between WR occurrence and ENSO at interannual scale, Falkena et al. (2021) used six wintertime regimes (instead of the four commonly used), and captured a more detailed circulation response. In addition to the negative NAO-like pattern associated to the four usual regimes, they found a new pattern (SB-: the opposite of the usual pattern of Scandinavian Blocking) of cyclonic anomaly over the Norwegian Sea (Figure 6.3). They also found that El Niño is associated to a more frequent SB- pattern, and La Niña to a less frequent AR- pattern. With this understanding of the relations between these climate components (WRs, jetstream, NAO, AMO, ENSO), we

can now turn to the effects of climate change on this interrelated system.

6.1.2 Past and future changes, scientific gaps

The past effects of anthropogenic climate change on ENSO are not consensual. This ambiguity is due to the large ENSO variability (pattern, amplitude) over the instrumental period, and because simulations can reproduce similar evolutions without incorporating anthropogenic factors (Christensen et al., 2013). The ENSO teleconnections are modulated by internal variability and low-frequency variability modes (Taschetto et al., 2020), in the North Atlantic for instance by the state of Arctic sea-ice and large-scale SSTs (Ivsić et al., 2021). The increase of SSTs and reduction of sea-ice could have weakened the ENSO-Atlantic teleconnection since the 1970s, from an NAO-like pattern to almost non-existent (Ivsić et al., 2021).

In the past century, North Atlantic temperatures (air and sea) have alternated between warm and cold phases lasting about three decades, in strong correlation with the AMO (Drinkwater et al., 2014). The AMO is associated to the North Atlantic warming faster in recent decades than implied by other climate forcings (natural and anthropogenic; Knight (2009); Polyakov et al. (2010)), and could possibly explain recent changes in the NAO. The increase in NAO index (winter, summer) between the 1960s and 1990s was previously thought to be linked to anthropogenic GHG forcing, but the trend has reversed since the 1990s with the NAO more negative in summer and more variable in winter (Hanna and Cropper, 2017).

These recent NAO changes are related to an increase in the summer Greenland Blocking Index (i.e. high-pressure over Greenland) and a more variable Greenland Blocking Index in December, possibly due to changes in solar radiation, North Atlantic SSTs and Arctic sea-ice (Hanna and Cropper, 2017). Reduced Arctic sea-ice was also linked to a higher frequency of Scandinavian Blocking (December and February) and NAO- (February and March; Crasemann et al. (2017)). In addition to a general warming of most circulation regimes in all seasons (Jones and Lister, 2009; Hoffmann and Spekat, 2021), the warming of Europe in winter has been linked to an increasing frequency of westerly flow and decreasing frequency of easterly flow (Hoy et al., 2013).

The response of the polar jetstream to anthropogenic climate change is ambivalent. Jet-streams and storm-tracks are strongly coupled to large-scale circulation, and can shift in response to a change in the meridional temperature pattern (Lorenz and Hartmann, 2003; Robinson, 2006; Gerber and Vallis, 2007; Raible, 2007; Athanasiadis et al., 2010). The surface meridional gradient is weakening due to Arctic amplification, and a weakened jet-stream has been hypothesized to be “wavier” (i.e. higher probability of atmospheric blocking; Stendel et al. (2021)). However, global warming also acts to cool the polar lower stratosphere and heat the tropical upper troposphere, which should strengthen the jet (Stendel et al., 2021). Therefore, jet-streams are currently experiencing a “tug-of-war” between these opposing effects, and it remains unclear which effect dominates now or in the future (Woollings, 2019; Stendel et al., 2021).

Many of the future effects of anthropogenic climate change on ENSO are highly uncertain. The response of ENSO (frequency, intensity, pattern, teleconnections) to future warming is unclear because of large natural variability and model differences (Christensen et al., 2013; Yang et al., 2018; Taschetto et al., 2020). The future of ENSO depends on tropical mean conditions and coupled ocean-atmospheric feedbacks, which are model-dependent (Christensen et al., 2013; Taschetto et al., 2020). However, some projections of the ENSO response to global warming are robust. ENSO will for example remain the dominant global mode of interannual variability (Christensen et al., 2013).

The response of lower tropospheric humidity will amplify under future warming (even with similar tropical SSTs), resulting in a major reorganization of atmospheric circulation, temperature and rainfall (Hu et al., 2021). The Pacific mean-state is projected by most models to evolve towards an El Niño-like pattern (Figure 6.4 and Taschetto et al. (2020)), while the frequency of extreme El Niño and La Niña events are projected to increase (Yang et al., 2018). The ENSO-related rainfall variability will intensify because of higher moisture availability (Christensen et al., 2013), in association to a higher risk of extreme precipitation (and flooding) across high northern latitudes, although this risk varies spatially among models (Sun et al., 2017).

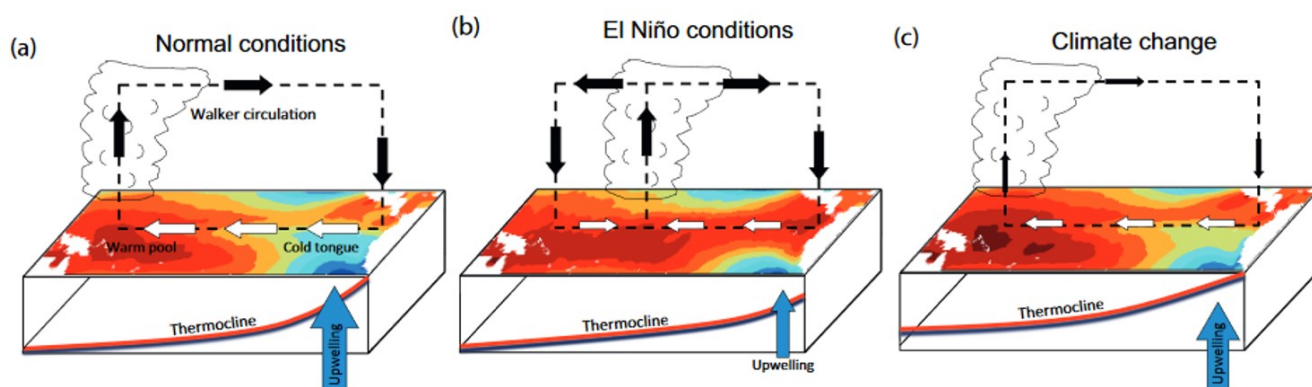


Figure 6.4: Idealized representation of the ocean-atmosphere interaction in the tropical Pacific, under normal conditions (a), El Niño conditions (b), and in a warmer world (c). Adapted from Christensen et al. (2013).

The behaviour of the AMO is unlikely to change under future warming, and the natural AMO fluctuations are likely to influence regional climate nearly as strongly as human-induced changes (Christensen et al., 2013; Chylek et al., 2016). The current warm AMO phase may end in the next few decades, which would cool the North Atlantic and partly offset effects from global warming (Christensen et al., 2013). Likewise, the behaviour of the NAO is likely to continue similarly (natural variations and trends) in the future as observed in the past (Christensen et al., 2013). Recent research suggests potential skill for seasonal NAO predictions, and possibly long-range weather forecasts (up to several months) for northwest Europe (Hanna and Cropper, 2017).

Over the longer-term, the NAO is projected to become slightly more positive (winter, summer) on average (Folland et al., 2009; Christensen et al., 2013). Long-term warming would shift the pressure centers (Icelandic Low and Azores High) towards the northeast, in association to circulation changes that increase drought risk in northwest Europe (Rousi et al., 2020; Vietinghoff et al., 2021). Beyond these average changes, the future evolution of the NAO remains

a large source of uncertainty in climate model projections for Europe (Christensen et al., 2013; Deser et al., 2017; Hanna and Cropper, 2017). The same is true for the jet-stream, although its changes have important implications for extreme weather in the future warmer climate (Stendel et al., 2021).

Back in 2013, the North Atlantic storm-track was considered unlikely to respond to future warming by simply migrating northward, and there was limited scientific confidence in regional projections of storm-track changes and associated climate impacts (Christensen et al., 2013). Scientific confidence is also low for future changes in atmospheric blockings, due to lack of comprehensive theory and to model underestimation of blocking occurrence (Woollings et al., 2018). While models generally agree on a future decline in blocking frequency, changes in intensity and persistence are more uncertain (Christensen et al., 2013). Annual blocking frequency is overall projected to decrease, especially in winter, but regional increases are possible in summer (Barnes et al., 2012; Cattiaux et al., 2013; Dunn-Sigouin and Son, 2013; Masato et al., 2013). This decreasing blocking frequency could be partially explained by the projected strengthening of zonal wind, combined to a potential small northward shift of the jet (Barnes and Hartmann, 2012; Dunn-Sigouin and Son, 2013). A decrease in blocking frequency would be associated to fewer weather extremes. However, fewer blockings in winter would lead to further warming, since blockings are typically associated to anomalously cold conditions (Barnes et al., 2012). Weather regimes could paint a different picture. Some research points to a decrease in the frequency of the Scandinavian Blocking regime in winter and summer (Cattiaux et al., 2013; Fabiano et al., 2021), while some other points to an increase in the annual frequency of atmospheric blockings (especially during spring; Lemos et al. (2021)), associated to decreasing storm activity in midlatitudes.

Future changes in other WRs are more robust. Lemos et al. (2021) found decreasing occurrence of weather types associated to the NAO- pattern, and Cattiaux et al. (2013) found a NAO- regime frequency decreasing in summer but increasing in winter. The NAO+ regime is projected to become more frequent (annually and seasonally; Cattiaux et al. (2013); Lemos et al. (2021)), and more persistent during winter (Fabiano et al., 2021). Lemos et al. (2021) suggests that the changes in regime occurrence of NAO+ and NAO- correspond to decreasing storm-track occurrence at lower latitude (below 50° N), and increasing at higher latitude. Finally, the frequency of the Atlantic Ridge regime is projected to decrease in winter and increase in summer (Cattiaux et al., 2013; Fabiano et al., 2021). The spread of model projections in changes of WRs (i.e. atmospheric circulation) can be traced back to the jetstream tug-of-war (strengthening vs. weakening factors), dependent on the relative warming between lower and higher atmosphere in the tropics and poles (Fabiano et al., 2021).

In summary, future changes in atmospheric circulation are highly uncertain (e.g. intermodel spread for jetstream and blockings), although a few general changes seem to emerge (e.g. more positive NAO). However, we also saw previously that the key climatic themes of the Gulf (seasonal changes, extreme events, marine submersion) are linked to atmospheric circulation. The biased representation of atmospheric circulation in climate models can therefore add uncertainty to the future evolution of these themes (Shepherd, 2014). The next section presents a study that aimed

to evaluate how models reproduce the seasonality of atmospheric circulation over a historical time period, before exploring future changes in seasonality under further climate change.

6.2 Seasonal circulation regimes: towards new seasonality?

The following study has been presented at the General Assembly of the European Geosciences Union in May 2020. The associated article has been submitted to the International Journal of Climatology and is currently in revision. The main figures can be found at the end of the article, and the supplementary figures can be found in the Appendix (A.2 Supplement of research article "Seasonal circulation regimes: towards new seasonality?"). The technical details of the methods can be found in the appendix of the paper, immediately after the main figures.

ORIGINAL ARTICLE

Seasonal circulation regimes in the North Atlantic: towards new seasonality?

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Funding information

The authors acknowledge financial support from the CoCliServ and EUPHEME projects that are part of ERA4CS, an ERA-NET initiated by JPI Climate and co-funded by the European Union.

European climate variability is shaped by atmospheric dynamics over the North Atlantic and local processes. Better understanding their future seasonality is essential to anticipate changes in weather conditions for human and natural systems. We explore atmospheric seasonality over 1979-2017 and 1979-2100 with seasonal circulation regimes (SCRs), by clustering year-round daily fields of Z500 from the ERA-Interim reanalysis and 12 CMIP5 climate models (historical and RCP8.5 runs). The spatial and temporal variability of SCR structures and associated patterns of surface air temperature are investigated. Climate models have biases but reproduce structures and evolutions of SCRs similar to the reanalysis over 1979-2017: decreasing frequency of winter conditions (starting later and ending earlier in the year) and the opposite for summer conditions. These changes are stronger over 1979-2100 than over 1979-2017, associated with a large increase of North Atlantic seasonal mean Z500 and temperature. When using more SCRs (more freedom in definition of seasonality), the changes over 1979-2100 correspond to a long-term swap between SCRs, resulting in similar structures (annual cycle and spatial patterns) relative to the evolution of seasonal mean Z500 and temperature.

* Design of the research, gathering of the data, analysis, interpretation and discussion of findings, drafting the article, article revision.

† Design of the research, interpretation and discussion of findings, drafting the article, article revision.

‡ Interpretation and discussion of findings, article revision.

To understand whether the evolution of SCRs is linked to uniform warming, or to changes in circulation patterns, we remove the calendar trend in the Z500 regional average to define SCRs based on detrended data (d-SCRs). The temporal properties of d-SCRs appear almost constant whereas their spatial patterns change, indicating that the calendar Z500 regional trend drives the evolutions of SCRs, and that changing spatial patterns in d-SCRs account for the heterogeneity of this trend. Our study suggests that historical winter conditions will continue to decrease in the future while historical summer conditions continue to increase. It also suggests that according to an increasing seasonal mean, the seasonality of atmospheric conditions would not change in a major way.

KEYWORDS

Seasonality, atmospheric circulation, North Atlantic, surface temperature, spatial patterns, annual cycle, past, future

1 | INTRODUCTION

Are seasons changing? If so, are those changes due to climate change or to natural variability? It appears that the answers might strongly depend on the definition of season. Indeed, many investigations of seasonality have been carried out based on different definitions of the seasons (see literature reviews in Stocker et al. (2013); Bindi et al. (2018); Jia et al. (2019)). These investigations found changes both regarding variables in climatological seasons (e.g. decreasing winter and spring frost, decreasing summer Arctic sea ice) and regarding the seasonality of variables themselves (e.g. longer growing season, longer fire weather season). The meteorological seasons are a prominent feature of climate variability, experienced by human systems (e.g. health, transportation, energy) and natural systems (e.g. phenology) through the seasonality of surface weather conditions. In Europe, these conditions mostly result from the combined effects of large-scale circulation dynamics over the North Atlantic and local-scale processes that reduce or amplify dynamic effects (Cattiaux, 2010). In this paper, we will define and investigate seasonality based on synoptic atmospheric circulation.

North Atlantic atmospheric patterns are the results of physical phenomena operating at different scales: “low-frequency” quasi-static structures such as the Icelandic Low and the Azores High (Angell and Korshover, 1974; Marshall et al., 2001; Wang, 2002; Hurrell and Deser, 2010) and “high-frequency” eddies or propagating synoptic waves such as cyclones and anticyclones (Price and Maggaard, 1986; Barnston and Livezey, 1987) associated to the eddy-driven jet stream (Blackmon et al., 1984; Woollings et al., 2010; Franzke et al., 2011; Stendel et al., 2021). Due to these low-frequency and high-frequency components, the atmospheric dynamic variability of the North Atlantic is organized into preferential configurations (i.e. modes of variability) despite having a stochastic nature. One way to study these modes of variability or weather patterns is through weather regimes (WRs), defined as recurring atmospheric patterns (Vrac and Yiou, 2010; Hertig and Jacobeit, 2014). Since their first use in the middle of the XXth century in

meteorology (Lamb, 1950; Rex, 1950), WRs have been reintroduced in the beginning of 1980s (e.g. Reinhold and Pierrehumbert (1982)) and largely used to better understand the variability of atmospheric dynamics (e.g. Vautard (1990)) and weather extremes (Hannachi et al., 2017), but also to evaluate climate models (Sanchez-Gomez et al., 25 2009; Díaz-Esteban et al., 2020; Fabiano et al., 2020a).

Extratropical climate variability is largely seasonally dependent (Wallace et al., 1993), and both climate dynamics (Woollings et al., 2010; Iqbal et al., 2018) and weather extremes (Cattiaux et al., 2012; Lhotka and Kyselý, 2015; Brunner et al., 2018) have strong seasonal features. For instance, atmospheric blocking conditions facilitate cold spells in winter (Sillmann et al., 2011) and heatwaves in summer (Schaller et al., 2018). Furthermore, the seasonality of atmospheric dynamics has changed in the last decades with a lengthening of the period with summer conditions, starting earlier and ending later, and a shortening of the period with winter conditions (Vrac et al., 2014). When defining seasons based on the relationship between sea level pressure and surface air temperature, Cassou and Cattiaux (2016) found that the earliness of summer conditions should continue to increase in the future while no trend is found for winter conditions. One limitation is that these results strongly depend on the definition of the seasons and on the 35 good representation of these seasons in the climate models. More generally, we have limited confidence in the representation of atmospheric circulation in models, and the confidence in the understanding of dynamic aspects of climate change is lower than for thermodynamic aspects (Shepherd, 2014). Therefore, it is essential to evaluate how models reproduce seasonality over a historical time period. This is a necessary step prior to investigating future seasonality changes based on a non-stationary definition of seasons.

In the present paper, we investigate synoptic climatological seasonality in the North Atlantic region through the use of seasonal circulation regimes (SCRs, as in Vrac et al. (2014)) that are defined by the probabilistic clustering of daily conditions of atmospheric circulation over a given time period without a priori separation of seasons. The evolution of circulation seasonality is then investigated through the variability of SCRs (structures, trends). SCRs were developed to investigate non-stationary circulation seasonality through their ability to represent the evolution of atmospheric 45 circulation modes (Vrac et al., 2007) with season-like behavior (Vrac et al., 2014). The large-scale increase in geopotential height at 500 hPa (Z500) due to human influence is expected to drive SCR evolutions (Christidis and Stott, 2015). To test if SCR evolutions are driven by this increase, or by changes in spatial patterns of circulation, we also look at SCRs obtained from detrended geopotential height data. This investigation allows us to remove the effects of the large-scale average Z500 increase and therefore to disentangle the potential causes of the temporal and spatial 50 SCR evolutions. The scientific objectives of the present study are to answer the following questions:

- How are climate models able to represent past seasonal variability over 1979-2017 with respect to reanalyses?
- What is the temporal and spatial evolution of seasonal structures over 1979-2100?
- What are the causes of seasonal evolutions?

The paper is organized as follows: Section 2 describes the reanalysis and climate model data used in this study, as well as the clustering method to define seasonal circulation regimes; Section 3 displays the results; and in Section 4, 55 we discuss the findings and conclude.

2 | METHODS

2.1 | Data and preprocessing

We use daily fields of geopotential height at 500 hPa (Z500) as a proxy of atmospheric circulation from the ERA-
 60 Interim (hereafter ERAI) reanalysis dataset (0.75° x 0.75° spatial resolution; Dee et al. (2011)) and simulations from 12
 climate models of the Coupled Model Intercomparison Project fifth phase (CMIP5; Taylor et al. (2012)) over the North
 Atlantic region (22.5 to 70.5°N, 77.25°W to 37.5°E) from 1979 to 2017, and then from 1979 to 2100 (the datasets
 are briefly described in Table 1). The methodological choice of Z500 is motivated by its intermediate representation
 of atmospheric circulation between low (weather systems) and high-level (jet-stream) dynamics, and its smoothness
 65 relative to other proxies of atmospheric circulation for facilitating the identification of the emergence (signal) of long-
 term changes in the climate system (e.g. sea level pressure is noisy). Daily surface air temperatures (TAS) from the
 same datasets are also extracted to study temperature features of SCRs.

Raw year-round data is used rather than seasonal (e.g. summer or winter) data or deseasonalized anomalies to capture
 both the year-round seasonal cycle and any long-term trend. In order to make the analyses and comparisons easier,
 70 all datasets are first given the same format. Calendars are standardized to 365 days per year ignoring bisextile years
 except for the Hadley Center simulations (year of 360 days). Historical experiment runs from climate models over
 1979-2005 are concatenated to RCP8.5 experiment runs over 2006-2100 (respectively 1981-2005 and 2006-2099
 for the Hadley Center model). The choice of the RCP8.5 scenario is motivated by its approximate representation of
 the current climate trajectory and its plausibility for future climate trajectory (Schwalm et al., 2020a,b), as well as its
 75 large magnitude of scenario forcing for facilitating the emergence of long-term changes in the climate system. The
 spatial grids of data from climate model simulations are bilinearly interpolated to the ERAI grid.

A principal component analysis (PCA) is applied to the regridded Z500 fields in order to reduce the dimension of the
 data while keeping most of the variability and seasonality. The raw Z500 data are scaled by the square root of the
 cosine of the latitude to give equivalent weight to all grid cells when performing the PCA (as in e.g. Cassou (2008)).
 80 Only the first principal component (PC1) is kept and used for clustering because it captures between about 49% and
 60% of the variance and between about 95% and 99% of the annual cycle (spectral power at a frequency of 1/365
 days; 1/360 days for the Hadley Center model) over 1979-2017 for ERAI (similar to Vrac et al. (2014) on another
 reanalysis) and all climate models (not shown). A large part of the long-term variability is also contained in PC1 (Figure
 S1), while the spatial pattern (eigenvectors) and statistical distribution (pdf) of PC1 are generally similar between ERAI
 85 and models over 1979-2017 (Figures S2-S3). Including more PCs in the analysis provided similar results (not shown)
 but brought more noise (more variance but only little more seasonality).

2.2 | Definition of seasonal circulation regimes

We use the Expectation-Maximization (EM) algorithm (Dempster et al., 1977) based on a Gaussian mixture model
 (GMM; Peel and McLachlan (2000)) to classify probabilistically the 14235 days (13320 for the Hadley Center model) of
 90 the 1979-2017 period into Seasonal Circulation Regimes (SCRs). The EM algorithm estimates a multivariate probability
 density function (pdf) f of the data (here, daily PC1 values) as a weighted sum of K Gaussian pdfs f_k ($k = 1, \dots, K$)
 (Pearson, 1894):

$$f(x) = \sum_{k=1}^K \pi_k f_k(x; \alpha_k) \quad (1)$$

where α_k contains the parameters (means μ_k and covariance matrix Σ_k) of f_k and π_k is the mixture ratio corresponding to the prior probability that x (i.e. PC1 value) belongs to f_k . The parameters α_k and π_k ($k = 1, \dots, K$) of the GMM are unknown and must be estimated (cf. Appendix). Finally, each cluster C_k of days is defined based on the Gaussian pdfs, according to the principle of posterior maximum:

$$C_k = \{x; \pi_k f_k(x; \alpha_k) \geq \pi_j f_j(x; \alpha_j), \quad \forall j = 1, \dots, K\} \quad (2)$$

In other words, each day is assigned to the cluster for which the probability of belonging is maximum, and the obtained clusters are SCRs which correspond to a classification of the daily data. The freedom of EM in the definition of the SCRs strongly depends on the number K of clusters and on the constraints applied to the covariance matrices (constraining the geometry of the clusters, cf. Appendix). We tried different values for K (from $K = 1$ to $K = 15$) and evaluated them through the Bayesian Information Criterion (BIC; Schwarz et al. (1978)). Optimizing the BIC achieves a compromise between overfitting the observations with the model and the complexity of the model (cf. Appendix). Four SCRs (hereafter SCR4) correspond both to a plateau of BIC (Figure A1 in Appendix) and to the traditional (astronomical) number of seasons. The GMM with the best BIC is selected. Different clustering methods can lead to different results (e.g. Philipp et al. (2010)) so we tested the sensitivity of the SCR results to using the k-means clustering algorithm (more popular but less flexible; Estivill-Castro and Yang (2000); Lior and Maimon (2005); Han et al. (2011)) instead of EM, which brought very similar results (not shown). EM can be seen as a generalization of k-means with less constraint on the shape of clusters and better ability to account for structures of arbitrary shape (Lior and Maimon, 2005; Han et al., 2011). We also tested the sensitivity of the clustering results (spatial patterns, annual cycle) to the number of PCs included (PC1 to PC5), there was a small influence of additional PCs on the results (reanalysis, models) over 1979-2017 and very small influence over 1979-2100 (increasing with the number of PCs; not shown). This reinforced our choice of using only PC1, considering that additional PCs represent little additional seasonality and difference in the long-term response of atmospheric circulation to climate change.

2.3 | Seasonal circulation regimes based on detrended data

The goal is now to remove the large-scale increase of Z500 to further investigate changes in Z500 patterns. This requires to preserve both the spatial structures and the seasonality while removing the large-scale effect. Calculating and removing the trend by gridpoint would result in losing the spatial structures while doing so without a year of reference would result in losing the seasons. Therefore, the trend is calculated on the spatial mean of the whole area for each calendar day, with reference to 2017 (last year contained in both reanalyses and models). This means that for each specific day of the calendar year (1 Jan, 2 Jan, ..., 31 Dec), the trend is calculated with the 122 values (from 1979 to 2100) of the spatial mean for this specific day. The trend was estimated best by using a cubic smoothing spline. Therefore, for each gridpoint and calendar day, we remove the spatial trend estimated by the spline from the raw Z500 (or TAS) values, and add the seasonal value of 2017 (also estimated by the spline) to obtain the detrended data.

The detrended SCRs (d-SCRs) are then obtained by applying the same method as before, of principal component analysis followed by clustering, to the detrended data. We heuristically chose to detrend TAS for this part of our analysis, similarly to Z500. We emphasize that the detrending removes the regional (large-scale) trend per calendar day so that the resulting local trend of the detrended data is the residual of the regional trend. A negative residual trend at a given gridpoint means that its Z500 values are increasing less than the regional average, or even are decreasing, whereas a positive residual trend means that the local trend is higher than that of the regional average.

3 | RESULTS

The first part of the results focuses on the SCRs in ERAI and in the climate models over 1979-2017 to assess how the models perform with respect to the reanalyses. The second part examines SCRs in climate models over 1979-2100 to detect evolutions in the temporal and spatial structures. The third part explores the possible causes for the evolution of SCRs over 1979-2100, such as uniform large-scale Z500 increase, or changes in Z500 spatial patterns.

3.1 | Evaluation of past seasonal circulation regimes in climate models (1979-2017)

We start by looking at the spatial patterns of the regimes as shown by the composites maps in Figure 1. Each composite map is calculated by averaging the values of the Z500 fields corresponding to the days that belong to the regime, with color shading representing the seasonal anomalies and contour lines representing the raw values. Seasonal anomalies correspond to the raw values minus the average seasonal cycle over 1979-2017. The average seasonal cycle is calculated by averaging the Z500 values per calendar day (1 Jan, ..., 31 Dec) over the 39 years. For climate models, each regime composite map is determined individually (i.e. average map) and the multimodel composite is calculated as the mean of the distribution of the twelve composites. The spatial patterns of the four average regimes found in the models are very similar to those from ERAI, and to those from Vrac et al. (2014) based on NCEP (National Center for Environmental Prediction) reanalyses. These patterns also share similarities and differences (detailed below) with the usual North-Atlantic weather regimes from the literature (e.g. Yiou and Nogaj (2004); Cassou (2008); Cattiaux et al. (2013); Hertig and Jacobeit (2014); Hannachi et al. (2017)).

The first regime (R1) corresponds to strong cyclonic conditions northward of 35°N and weakly anticyclonic southward (i.e. anomalously strong Westerly flow), and the second regime (R2) to the opposite (weaker Westerly flow). R1 resembles the positive phase of the North Atlantic Oscillation (NAO+) and R2 its negative phase (NAO-; Hurrell et al. (2003)), but Z500 anomalies are weaker and more zonal than in the usual Iceland-Azores dipole (North/South and East/West, as in e.g. Yiou and Nogaj (2004); Cassou (2008)). The third regime (R3) yields weak anticyclonic conditions over the Northwestern Atlantic and cyclonic from the Southwest towards the Northeast (biased in climate models), corresponding to a wavy jet stream, similarly to the Atlantic Ridge (AR) pattern but lacking the cyclonic conditions over Europe present in AR (Yiou and Nogaj, 2004; Cassou, 2008). The fourth regime (R4) yields strong anticyclonic conditions over Northwestern Europe, resembling the Scandinavian Blocking (SB) pattern except that SB is also associated to cyclonic conditions between Greenland and Northeastern America (Yiou and Nogaj, 2004; Cassou, 2008; Cattiaux et al., 2013).

The temporal patterns of our SCRs are based on full years (like Vrac et al. (2014)), unlike the literature considering weather patterns either in winter (e.g. Yiou and Nogaj (2004); Cassou (2008); Hertig and Jacobeit (2014); Fabiano et al. (2020b)), or in summer (e.g. Folland et al. (2009); Guemas et al. (2010); Cattiaux et al. (2013)). Thus, if our SCRs share similarities with the usual weather regimes, they however present large differences in their definition and properties. Indeed, our regimes correspond rather to the variability of the seasonal cycle of atmospheric conditions, while the usual regimes correspond rather to the intra-seasonal variability of these conditions. The annual cycle of our regimes' monthly frequencies over 1979-2017 is shown in Figure 2. Climate models reproduce an annual cycle of SCRs similar to ERAI, with regime 1 (hereafter R1) representing a winter-like season, R4 a summer-like season, and R2 and R3 transitional seasons (R2 around winter and R3 around summer).

In general, the climate models reproduce atmospheric patterns (Z500, TAS) that are very similar to ERAI (Fig. 1 and Fig. 3), but individual models are less successful (see Table 2 and Figures S4-S11). For example, the circulation patterns associated with R1 and R3 in MIROC5 are very different from other climate models and ERAI (Figures S4 and S6),

despite happening at the same period in the year (Fig. 2). All other climate models show R1 patterns similar to ERAI albeit with diverse intensities (Figure S4). Several climate models (e.g. bcc-csm1-1-1-m and MRI-ESM1) overestimate R1 seasonal anomalies of Z500 (negative in the North and positive in the South; cf. Figure S4), corresponding to a more positive North-to-South gradient (i.e. stronger Westerly flow) than observed in the reanalysis (also visible on
175 Fig. 1) during December to March (Fig. 2). Models overestimating Westerly flow in R1 also tend to have larger surface temperature anomalies (Figure S8), more negative than observed (reanalysis) over North America, Greenland and Scandinavia, and more positive over parts of Europe.

In the case of R2 and R4, ERAI and all climate models agree on the circulation pattern but differ in intensity (Figures S5 and S7). The spatial patterns of R2 (Z500 and TAS) are almost symmetrical to those of R1 (Fig. 1 and 3), with several
180 models overestimating positive anomalies in the North and negative anomalies in the South (Figure S5), corresponding to a more negative North-to-South gradient (i.e. weaker Westerly flow) than observed (also visible on Fig. 1) during March to May and October to December (Fig. 2). Models underestimating Westerly flow in R2 also tend to have larger surface temperature anomalies than observed (Figure S9), more positive over North America and Greenland, and more negative over parts of Europe. The biases of individual models (e.g. bcc-csm1-1-m and MRI-ESM1) in the
185 spatial patterns of R2 (Z500 and TAS) are also symmetrical to R1 biases (Figures S4-S5 and S8-S9).

For R4, several models underestimate anticyclonic conditions in the North or overestimate cyclonic conditions in the South (Figure S7), corresponding to weaker Westerly flow in June to September (Fig. 2). The overestimation of cyclonic conditions by models in R4 is associated to a cold bias (e.g. over Spain for bcc-csm1-1-m and MRI-ESM1; cf. Figure S11), while the overestimation of anticyclonic conditions is associated to a warm bias (e.g. over Northern Europe in bcc-csm1-1-m).
190

The representation of R3 in climate models appears inaccurate (location and intensity of pressure centers) by comparison to ERAI (Table 2 and Figure S6) in April to June and September to November (Fig. 2). Models also tend to have biased R3 TAS patterns (location and intensity; Figure S10), with for instance Greenland that is warmer in ERAI but colder in GFDL-CM3 and MIROC5. A few models (e.g. bcc-csm1-1-m and MRI-ESM1) overestimate the TAS anomalies over Greenland (positive) and Europe (negative).
195

The variability between climate models, represented here by the standard deviation over the 12 values (one per regime composite of climate model), appears larger (Fig. 1) for regimes deviating from the seasonal mean atmospheric circulation (e.g. R1 with intense colors) than for regimes following it (e.g. R3 with pale colors). The same holds true for TAS spatial patterns associated to the regimes (Fig. 3).

200 After looking at the seasonal structure of the regimes, we investigate if and how the temporal organisation of these regimes changes during 1979-2017 through (i) the regime monthly frequencies, (ii) the first (start) and last (end) days of regime occurrence, and (iii) the regime persistence (i.e. average number of consecutive days). Most changes in ERAI and in the average of the models are similar (not shown) to the results from Vrac et al. (2014): R1 (i.e. winter conditions) decreasing in frequency, starting slightly later, ending slightly earlier, and being less persistent, and the
205 opposite for R4 (i.e., summer conditions).

3.2 | Future changes in seasonal circulation regimes (1979-2100)

We now use the same method as before to define SCRs but based on the full simulation datasets over 1979-2100 to detect potential future changes. The first approach is to use four regimes (SCR4). Between the first three decades (1979-2008) and the last three decades (2071-2100) of the period, R1 occurs less often but is more intense for both
210 Z500 and TAS (Figures S12-S13). We emphasize here that the regimes are defined over 1979-2100 and that we investigate their main properties (spatial patterns, annual cycle) over the subperiods (1979-2008 and 2071-2100) by

selecting the results of the full-period clustering over these subperiods. The seasonal anomalies are calculated with reference to the average seasonal cycle of the subperiod (1979-2008, 2071-2100). In the case of R4, it occurs more often with less intense patterns, i.e. becoming closer to the seasonal mean. R2 occurs more often but is less intense, while R3 occurs slightly less often but is more intense. Note that these patterns are relative to the seasonal mean, which increases substantially over the North Atlantic between the first and last three decades (averaging about +90 m for Z500 and +4°C for TAS; not shown).

A shift happens in the annual cycle of SCR4 over 1979-2100 with R4 growing, R2 and R3 moving towards the winter period of the year, and R1 shrinking in time (Figure S14). GFDL-CM3 stands out from the other GCMs (Global Circulation Models) by showing the emergence in the future of a new summer regime that almost did not exist in the past (one day of very wavy jet stream and large temperature anomalies, not shown). This emergence means that in the case of GFDL, the difference between historical and future Z500 conditions in summer is so large that a new regime was created in the clustering. As the clustering has little freedom with 4 clusters (i.e. large constraints on the definition of the regimes), this emergence is even more interesting, but it is consistent with stronger increase of Z500 and TAS in this climate model by comparison to other models (not shown). However, since future R4 in GFDL is very similar to future R4 from other models (annual cycle and spatial pattern, respectively shown in Figure S14 and not shown), and since R4 was already well established in the past for other models, this emergence of R4 in GFDL does not represent the emergence of a new regime from a general perspective.

Monthly frequencies show R2 taking the place of R1 in the December, January and February months (hereafter DJF) starting from the middle of the 21st century, and R4 taking the place of R3 in June around 2025 (not shown). Although the average between models shows a clear direction of SCR evolution, the timing of this evolution differs up to a few decades between individual models. In consistence with the seasonal shift of regimes, the average of climate models between 1979 and 2100 shows R1 starting about one month and a half later while ending about two months earlier, and persisting less, whereas R4 starts about one month earlier while ending about one month and a half later, and persists more (Figures S15-S16).

Over 1979-2100, the spatial patterns of SCR trends of Z500 and TAS are in agreement among GCMs (Figures S17-S18) and are more robust than over 1979-2017. These maps of linear trends are obtained by calculating the linear regression of the evolution of the variable (raw values) by gridcell, grey areas correspond to trends that are not significant (p -value > 0.05). The unconditional trend corresponds to the linear fit over the whole period (all days), whereas the regime-conditional trends are calculated by multiple linear regressions to account for the distribution of days between regimes (cf. Appendix). Both regression coefficients and p -values are calculated individually by climate model, and then averaged over the twelve values. However, these spatial patterns of SCR trends show different spatial evolutions between Z500 and TAS within regimes, hence partially decoupled evolutions of atmospheric dynamics and surface temperature.

Even if using four regimes allows us to explore the future with a traditional number of seasons, the low number of clusters limits the freedom of the clustering to allow the appearance or disappearance of significant structures. Therefore, we applied a second approach to overcome this limit. We tested different numbers of regimes (up to 10) and chose seven regimes as a showcase because it corresponds to an optimization of the BIC (Figure S19) and illustrates the clearest transitions between the disappearance of past structures and appearance of future (new) structures.

With seven regimes (SCR7), the patterns of atmospheric circulation are very similar to those of surface temperatures (i.e. cyclonic associated to cold, anticyclonic to warm) in both past (1979-2008) and future (2071-2100) (Fig. 4-5). Regime patterns seem to follow the seasonal cycle (pale colors) except for R1, R2 and R7. Past (1979-2008) R7 corresponds to rare and very intense anticyclonic conditions over the Northern half of the region in association with summer heatwaves over the continents of the North Atlantic region (except North Africa and northernmost Canada).

255 Future (2071-2100) R1 corresponds to rare and very intense NAO+ conditions associated with cold spells over North-eastern America, Greenland and Scandinavia. Here, we use the terms "cold spell" and "heatwave" to designate robust anomalies (average of more than 50 days i.e. 50 values) over large areas (continents) of about 3°C relative to the average seasonal cycle.

Overall, we observe a shift in the spatial patterns (Z500 and TAS) of the regimes (Fig. 4-5) with past R1 patterns
260 becoming future R2 patterns, past R2 patterns becoming future R3 patterns, and so on until R6, while the R1 pattern becomes seasonally more extreme (rarer and more intense pattern) and the R7 pattern becomes seasonally more normal (more frequent and less intense pattern). We calculated the average monthly frequency of the seven regimes in a similar way to Fig. 2 but over the first three decades (1979-2008) and the last three decades (2071-2100), shown in Figure 6. R7 is a new summer regime almost absent in the past period (1979-2008) that replaces R6 and "pushes"
265 all the other regimes towards the winter calendar days while R1 (past or old winter regime) disappears. This shift in the annual cycle of the regimes between past and future appears very consistent with the shift in the regimes' spatial patterns.

The timing of these changes in regime occurrence during the year can be investigated through the monthly frequencies of the regimes over 1979-2100 (winter months in Fig. 7 and summer months in Fig. 8). Figure 7 shows the
270 collapse of R1 happening throughout the 21st century. R2 takes the place of R1 in the beginning of the 21st century, and becomes replaced by R3 at the end of the 21st century. Symmetrically, R6 is replaced by R7 during the second half of the 21st century (Fig. 8). The evolution of the starting and ending dates as well as persistence of all regimes are consistent with the evolution of their annual cycle and monthly occurrence (Figures S20-S21). Summertime regimes (R5 to R7 in June to September; Fig. 6) start earlier and end later over 1979-2100, while other regimes start later and
275 end earlier (Figure S20). The average persistence of R1 and R6 decreases over 1979-2100, while that of intermediary regimes remains about 5-10 days, and that of R7 increases dramatically (Figure S21).

All regimes except R7 show a similar pattern of Z500 change over the region: increase in the Southern part and decrease in the Northern part, whereas R7 shows widespread increase that is stronger in the South and not robust among climate models in the North of the region (Figure S22). Interestingly, these changes in circulation patterns seem
280 to be opposite to the expected effects from Arctic amplification, such as amplified warming and geopotential height increase over circulation dynamics that are linked to midlatitude weather (Cohen et al., 2014; Barnes and Polvani, 2015; Overland et al., 2015). The strongest warming over the region is observed in R1 and R7, whereas R3 to R6 show (unexpected) cooling over the continents (Figure S23). The origin of this cooling is investigated later in the discussion of the paper (Section 4.3). The appearance and disappearance of regimes observed in SCR7 over 1979-2100
285 is absent from the 1979-2017 period where we tested with four up to seven regimes.

3.3 | Seasonal circulation regimes based on detrended data (1979-2100)

The increasing trend of Z500 over the North Atlantic region, mainly due to human influence (Christidis and Stott, 2015), is expected to be driving the evolution of the SCRs but changes in spatial patterns could also play a role. To investigate this, we use SCRs based on detrended data (d-SCRs) and focus on the average d-SCRs of climate models.
290 This detrending corresponds to removing the trend of the regional average Z500 (or TAS, see Methods 2.3) for each calendar day individually. By comparison to SCRs, the temporal structures of d-SCRs over 1979-2100 appear almost stationary and remain very similar to those of ERAI (Fig. 9). However, spatial structures of d-SCRs present some minor variability for Z500 (Fig. 10) but major changes for TAS in which case future patterns are almost symmetrically opposite to past patterns (Fig. 11). This small evolution of Z500 spatial patterns in d-SCRs can be explained by trends
295 that are either not significant in individual climate models or in disagreement between climate models, as shown by

large greyed areas in Figure S24. However, most of the TAS trends in d-SCRs are robust and show warming over continents and cooling over oceans (Figure S25). This warming contrast can be explained because of the higher heat capacity and evaporative cooling potential of ocean surface than land surface, and ocean mixing (Dai, 2016). These trends also show Arctic amplification (i.e. warming stronger at the pole than at lower latitudes), especially in winter (R1 to R3).

To further understand the roles of the large-scale increases in Z500 and TAS (hereafter LSI), and of the seasonal shift of regimes (driven by the large-scale Z500 increase) in the changes of Z500 and TAS patterns within SCRs and d-SCRs, we examine the spatial patterns of regimes' trends with LSI but without the seasonal shift (Figures S26-S27), and with the seasonal shift but without LSI (Figures S28-S29). The contribution of the large-scale increase of Z500 and TAS is investigated through the regime composite maps calculated based on Z500 (or TAS), conditionally to the clusters defined on detrended Z500 (i.e. clusters with almost constant temporal structures). The contribution of the seasonal shift of regimes is investigated through the regime composite maps calculated on detrended Z500 (or detrended TAS), conditionally to the clusters defined on Z500. The contribution of LSI corresponds only to widespread increasing Z500 and TAS in all regimes whereas the shift of SCRs towards winter corresponds to widespread decreasing Z500 and TAS in most regimes (except R1, R2, and unconditionally to regimes). The two opposing effects of LSI and the seasonal shift can explain the existence of decreasing trends of Z500 and TAS observed earlier within SCRs.

4 | CONCLUSIVE DISCUSSIONS

We used seasonal circulation patterns (Vrac et al., 2014) by clustering Z500 from the ERAI reanalysis and 12 CMIP5 climate models to study past (1979-2017) and future (1979-2100) seasonal structures of mid-troposphere atmospheric dynamics (Z500) and air surface temperature (TAS) over the North Atlantic region and their evolutions in time.

4.1 | Ability of climate models to represent past seasonal variability

The comparison of climate models with ERAI over 1979-2017 showed small biases in the four seasonal circulation regimes (spatial pattern, time of occurrence). On average, the circulation regimes from the climate models are very similar to those from ERAI. However, we identified larger biases in individual climate models. For instance, several models (e.g. in bcc-csm-1-1-m and MRI-ESM1) overestimate the meridional gradients in R1, corresponding to an overestimation of wintertime (December-March) Westerly flow. This wintertime tendency of models to overestimate Westerly flow leads to the overestimation of surface temperatures (as in Wójcik (2015)). Similarly, the underestimation of Westerly flow in R2 by several models (during March-May and October-December) leads to overestimated temperature anomalies. These biases in atmospheric flow and surface temperatures are commonly linked to the overestimation of the wintertime jetstream (strength and stability) in GCMs due to their coarse horizontal resolution (Scaife et al., 2010; Dawson et al., 2012; Iqbal et al., 2018).

R3 is the most biased atmospheric regime in climate models, with several models simulating inaccurate patterns (location, intensity) of Z500 and TAS in April-June and September-November. These biases are likely due to the tendency from models of simulating a jetstream (or storm track) that is too zonal and underestimating its frequency of meandering (Scaife et al., 2010; Cattiaux et al., 2013; Zappa et al., 2013; Iqbal et al., 2018), in consistence with stronger Z500 meridional gradient and faster zonal wind in models than observed (Hassanzadeh et al., 2014; Wójcik, 2015; Cattiaux et al., 2016). In the case of R4, the overestimation of cyclonic conditions (cold bias) and underestimation of anticyclonic conditions (warm bias) by several models can be linked to a model tendency of underestimating summertime

(June-September) Westerly flow and jetstream windspeed (Iqbal et al., 2018).

335 Despite biases in the climate model representation of Z500 and TAS seasonal variability, the general evolution of
the four seasonal circulation regimes (SCR4) over 1979-2017 was consistent between models and ERAI: decreasing
frequencies of historical winter conditions and increasing frequencies of historical summer conditions of atmospheric
dynamics. Most of the results agree with the findings of Vrac et al. (2014), except that we detect a more pronounced
winter evolution. This is probably because their reanalysis dataset covered 1948-2011 while our data covers 1979-
340 2017, which is more recent and better captures global warming (section 2.4.1.1 and Table 2.4 in Stocker et al. (2013)).
The structures (spatial, temporal) and evolution (timing) of SCRs differ between climate models over 1979-2017 and
even more over 1979-2100.

4.2 | Projected evolutions of seasons

When looking at future (1979-2100) evolutions of SCRs with both four and seven regimes, the frequency of histori-
345 cal winter conditions decreases while that of historical summer conditions increases and occurrences of transitional
regimes move towards the winter period. These changes are attached to large increases in the seasonal mean of
Z500 and TAS over the North Atlantic. The results for summer (lengthening) are consistent with those of Cassou and
Cattiaux (2016) but not the results for winter (shortening), which could be due to the very different methods used to
define seasonality. Moreover, allowing for more freedom in the definition of the SCRs by using seven regimes rather
350 than four, we find a collapse of the regime associated to past winter conditions, corresponding to rare cold spells at
the end of the 21st century, and the growth of a new summer regime corresponding to past heatwaves that becomes
dominant in summer by the end of the 21st century.

These results suggest that past winter conditions are becoming shorter in time and past summer conditions are broad-
ening and intensifying, in consistence with changing thermal seasons (Peña-Ortiz et al., 2015; Ruosteenoja et al., 2020;
355 Wang et al., 2021). However, in our case the apparent changes in seasonality seem to correspond rather to a swap
between regimes since occurrences of past R1 are replaced by R2 in the future, past R2 are replaced by R3, and so
on until R6. Note that R1 conditions correspond to the past winter pattern that almost disappears at the end of the
21st century. Hence, for the future projections, R1 corresponds to extreme winter (rare intense Westerly flow) with
respect to the “normal” future seasonality. Therefore, this regime swap, with symmetry between spatial patterns and
360 annual cycle, suggests that the seasonality of the atmospheric patterns does not change in a major way relative to the
evolution of the raw seasonal cycle of Z500 and TAS.

Over the last three decades (2071-2100) respectively to the first three decades (1979-2008), SCR4 had about 75%
fewer days (on average between climate models) of enhanced Westerly flow (R1) and about 10% of wavy jetstream
(R3) but about 54% more days of weakened Westerly flow (R2) and 135% more days of anticyclonic conditions (R4).
365 Under future warming, this increasing frequency of weakened Westerly flow in winter and anticyclonic conditions
over Europe in summer is consistent with the findings from Cattiaux et al. (2013), associated to a reduction of snow
cover in winter and of cloudiness in summer. The increase in the frequency of anticyclonic conditions during May,
June, September and October could have consequences for extreme events, such as heatwaves and dry spells as Röth-
lisberger and Martius (2019) found a strong positive effect of atmospheric blocking conditions on the persistence of
370 simultaneously occurring hot and dry spells over Europe between May and October.

Additionally, the findings from Pfleiderer et al. (2019) that summer weather becomes more persistent in a warmer
world, although they consider summer in June-July-August, can be linked to our finding of an increase in summer
regime persistence. SCR4 over 1979-2100 also revealed a weakening in the patterns of weakened Westerly flow
and anticyclonic conditions (R2 and R4), and a strengthening in the patterns of enhanced Westerly flow and wavy

375 jetstream (R1 and R3) at the end of the 21st century by comparison to the end of the 20th century. This future
strengthening of the enhanced Westerly flow (R1) pattern in the winter period is consistent with a decrease of cold
spells over Europe (Peings et al., 2013) as they are facilitated by anticyclonic conditions in winter (Buehler et al., 2011).
The strengthening of the wavy jetstream (R3) pattern and weakening of anticyclonic (R4) pattern can be put in relation
with the suggestion from Christidis and Stott (2015) that the relative Z500 increase between polar and mid-latitude
380 regions in the Northern Hemisphere could moderate the westerly flow over the North Atlantic and affect the posi-
tioning of the North Atlantic jet stream, especially with a change in the sinuosity of the midlatitude atmospheric flow
(Cattiaux et al., 2016).

4.3 | Drivers of the evolution(s)

The appearance and disappearance of regimes over 1979-2100 do not happen in 1979-2017, probably due to the
385 smaller scale of change in Z500 in this period by contrast to the future where the full extent of the emission scenarios
kick in inside the climate model simulations. We found that the trends of increasing and decreasing Z500 within
regimes, generally associated respectively to TAS warming and cooling trends, are the result of two opposite processes:
the large-scale increase of Z500 due to human influence, and the seasonal shift of regimes towards the winter period,
where Z500 and TAS are lower than during the rest of the year. This seasonal shift explains the decreasing Z500
390 trends, generally associated with cooling, which are observed in several regions within SCRs and would otherwise
not be possible. This explanation also covers the cooling trends reported by Vrac et al. (2014), understood here as a
temporal shift of the regimes' occurrences towards the winter period with cooler conditions rather than a seasonally-
stationary cooling.

The d-SCRs results (i.e., SCRs obtained from detrended Z500) showed almost no temporal evolution between past
395 and future, which means that the Z500 large-scale increase is the main cause for the evolution of SCRs. Christidis and
Stott (2015) reported that the large-scale Z500 increase during 1979-2012 was mostly due to human forcings. So,
although climate models overestimate the surface warming and Z500 increase over the past period (Jones et al., 2013;
Christidis and Stott, 2015), there might be a strong link between the human forcings and the shift in seasonality of the
regimes that we detect here, since most of the evolution of the regimes disappears when we remove the large-scale
400 Z500 increase for each calendar day individually.

4.4 | Limitations and perspectives

Even though the regimes and their evolutions in climate models in the past period are similar to those from ERAI, we
note a few limitations and sources of uncertainty. The representation of the climate in ERAI and models has uncer-
tainties and errors, especially in atmospheric dynamics (Shepherd, 2014) and surface temperature in models (Jones
405 et al., 2013). Bias correction methods could lead to more realistic seasonal atmospheric regimes but could imply other
issues such as modifications of spatial and temporal structures (and trends) that could possibly generate physical in-
consistencies (Vrac, 2018; François et al., 2020).

Overall, although our study highlights the value of a clustering approach for comparing (and evaluating) models as well
as seasonal structures, the apparent consistency that we find between climate models on the future evolution of sea-
410 sonal dynamics seems at odds with other studies where the projected circulation response differs strongly between
models (e.g. Barnes and Polvani (2015)). Indeed, clustering approaches might hide inter-model variability, or seasonal
variability (depending on the number of clusters). Additional sources of uncertainty include the choice of RCP8.5
for the future emission scenarios and the choice of Z500 (i.e., mid-troposphere atmospheric circulation) rather than

surface, lower or higher troposphere.

415 Similar methods to those that we used could be applied to explore changes in weather seasonality at a more local scale by downscaling meteorological variables (e.g. humidity, wind speed, temperature) based on large-scale weather regimes (Vrac and Yiou, 2010) in order to bring more locally-relevant insights for social matters related to the weather. Understanding recent and future changes in seasonality is important to anticipate future changes in weather conditions and the consequences for nature and society.

420 **supporting information**

Figures S1 to S29 can be found in the Supporting Information associated to this article.

code and data availability

The ERAI data is available at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>. The CMIP5 data is available at <https://esgf-node.ipsl.upmc.fr/search/cmip5-ipsi/>. The computations were done using the free statistical package mclust (Scrucca and Raftery, 2015) on the R software (www.r-project.org).

acknowledgements

The authors thank Soulivanh Thao, Ara Arakelian, and Flavio Pons for technical assistance.

conflict of interest

The authors do not have competing interests to declare.

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TABLE 1 Characteristics of data used.

Dataset	Period	Spatial resolution (lon x lat)	Institute	Reference
ERA-Interim	1979-2017	0.75° x 0.75°	ECMWF (Europe)	Dee et al. (2011)
HadGEM2-ES	1981-2005 (historical) and 2006-2099 (RCP8.5)	1.875° x 1.25°	MOHC (UK)	Jones et al. (2011)
ACCESS1-3	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.875° x 1.25°	CAWCR (Australia)	Collier and Uhe (2012)
bcc-csm1-1-m	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.125°	BCC (China)	Wu et al. (2014)
CanESM2	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.8125° x 2.7906°	CCCma (Canada)	Chylek et al. (2011)
CNRM-CM5	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.40625° x 1.4008°	CNRM (France)	Voldoire et al. (2013)
GFDL-CM3	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 2°	GFDL (USA)	Griffies et al. (2011)
IPSL-CM5A-MR	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 1.2676°	IPSL (France)	Dufresne et al. (2013)
IPSL-CM5B-LR	1979-2005 (historical) and 2006-2100 (RCP8.5)	3.75° x 1.8947°	IPSL (France)	Dufresne et al. (2013)
MIROC5	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.40625° x 1.4008°	CCSR, NIES, JAMSTEC (Japan)	Watanabe et al. (2010)
MPI-ESM-MR	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.875° x 1.8653°	MPI (Germany)	Giorgetta et al. (2013)
MRI-ESM1	1979-2005 (historical) and 2006-2100 (RCP8.5)	1.125° x 1.12148°	MRI (Japan)	Adachi et al. (2013)
NorESM1-M	1979-2005 (historical) and 2006-2100 (RCP8.5)	2.5° x 1.8947	BCCR, NMI (Norway)	Bentsen et al. (2012)

TABLE 2 Coefficients of pattern correlation between the regimes from ERAI and each climate model over 1979-2017.

Model	R1	R2	R3	R4
Average	0.901	0.869	0.518	0.9
ACCESS1-3	0.944	0.888	0.275	0.805
bcc-csm1-1-m	0.928	0.842	0.757	0.959
CanESM2	0.935	0.888	0.781	0.931
CNRM-CM5	0.937	0.933	0.589	0.962
GFDL-CM3	0.934	0.868	0.486	0.932
HadGEM2-ES	0.926	0.879	0.887	0.916
IPSL-CM5A-MR	0.908	0.874	0.529	0.948
IPSL-CM5B-LR	0.912	0.859	0.65	0.933
MIROC5	0.553	0.674	-0.397	0.824
MPI-ESM-MR	0.968	0.934	0.59	0.837
MRI-ESM1	0.913	0.86	0.753	0.815
NorESM1-M	0.95	0.925	0.319	0.941

figures

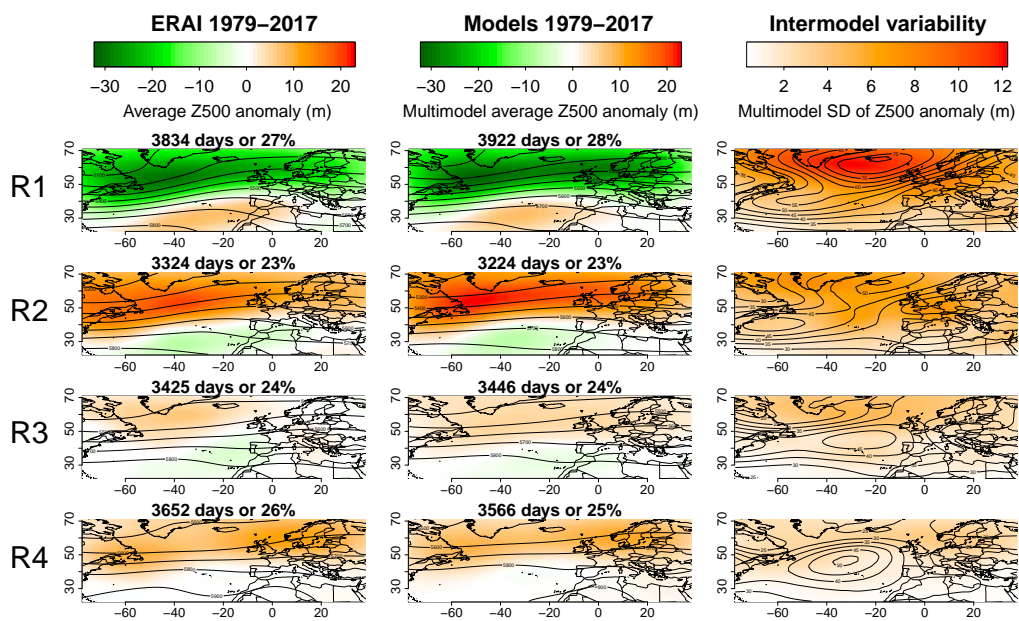


FIGURE 1 Composite maps of the four regimes (one per row) for ERAI (first column) and climate models (second column; each map shows the average of 12 composite maps; third column shows standard deviation of Z500 between the 12 composites). The maps are calculated by averaging the seasonal anomalies (shading) and raw values (contour lines) over the days belonging to the regime. Seasonal anomalies correspond to the raw values minus the average seasonal cycle. The number of days per regime is shown above each map (average of 12 values for the climate models).

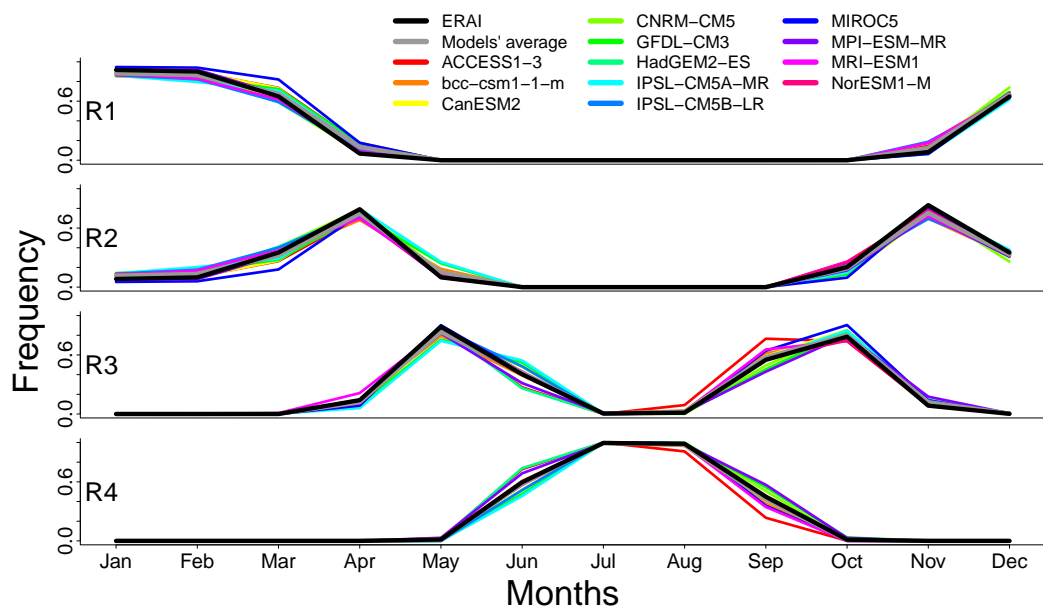


FIGURE 2 Average annual cycle of the frequencies of occurrences for the four regimes of ERAI and the 12 climate models, over 1979-2017. Monthly frequencies correspond to the number of days of regime occurrence divided by the number of days in the month.

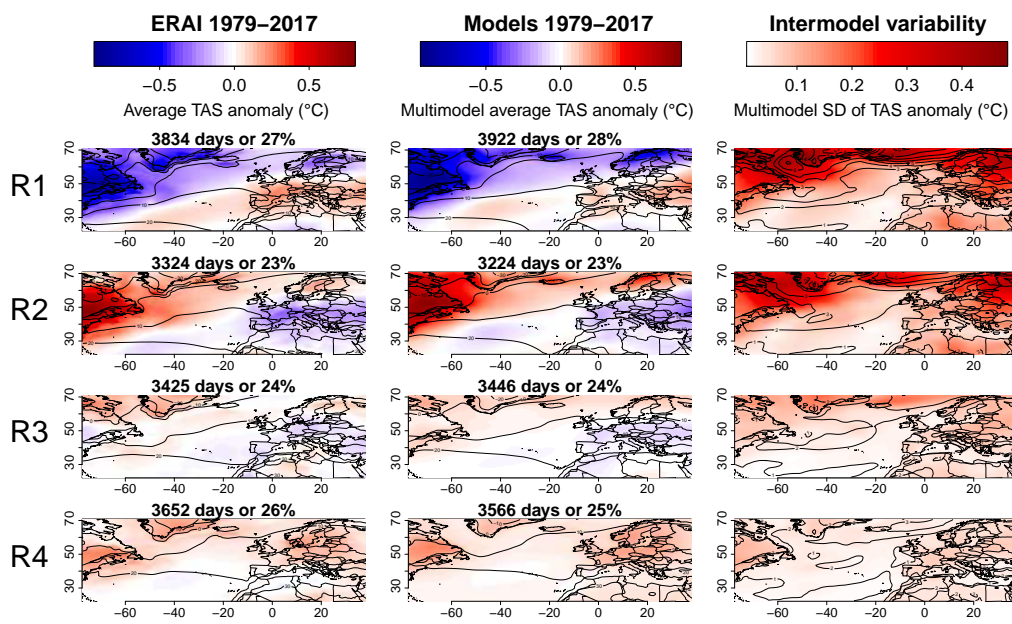


FIGURE 3 As in Fig. 1 but for TAS conditionally to each regime.

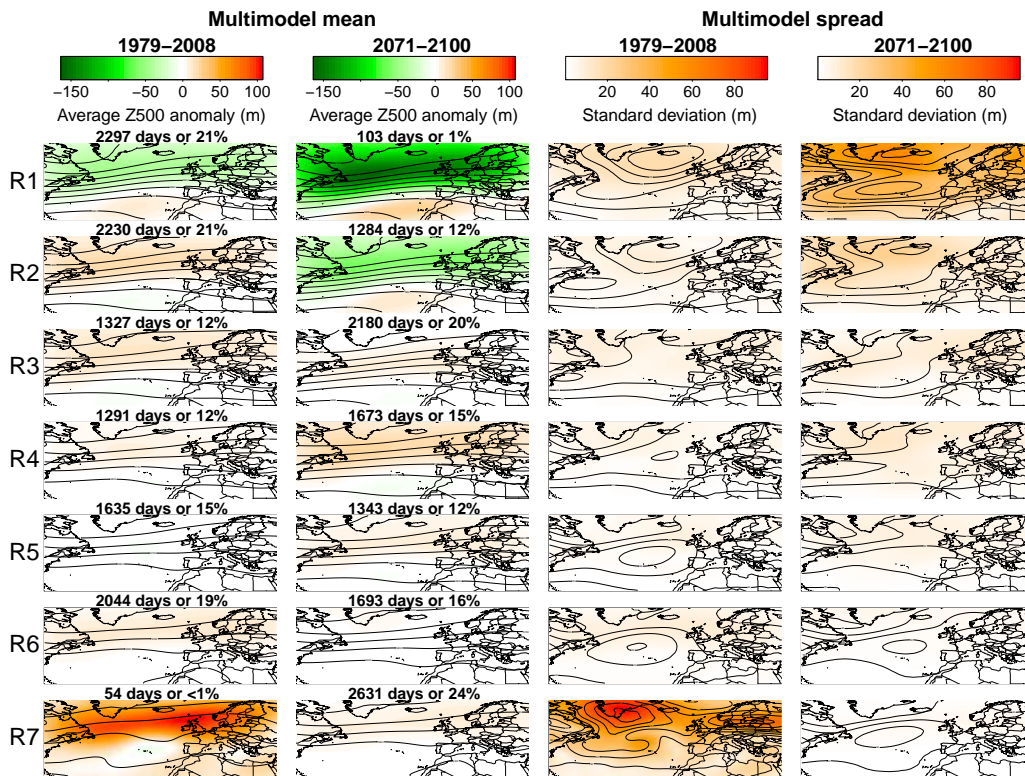


FIGURE 4 Same as Fig. 1 but for the climate models (without ERAI) and seven regimes over 1979-2100. The seasonal anomalies are calculated with reference to the average seasonal cycle of the subperiod (1979-2008, 2071-2100).

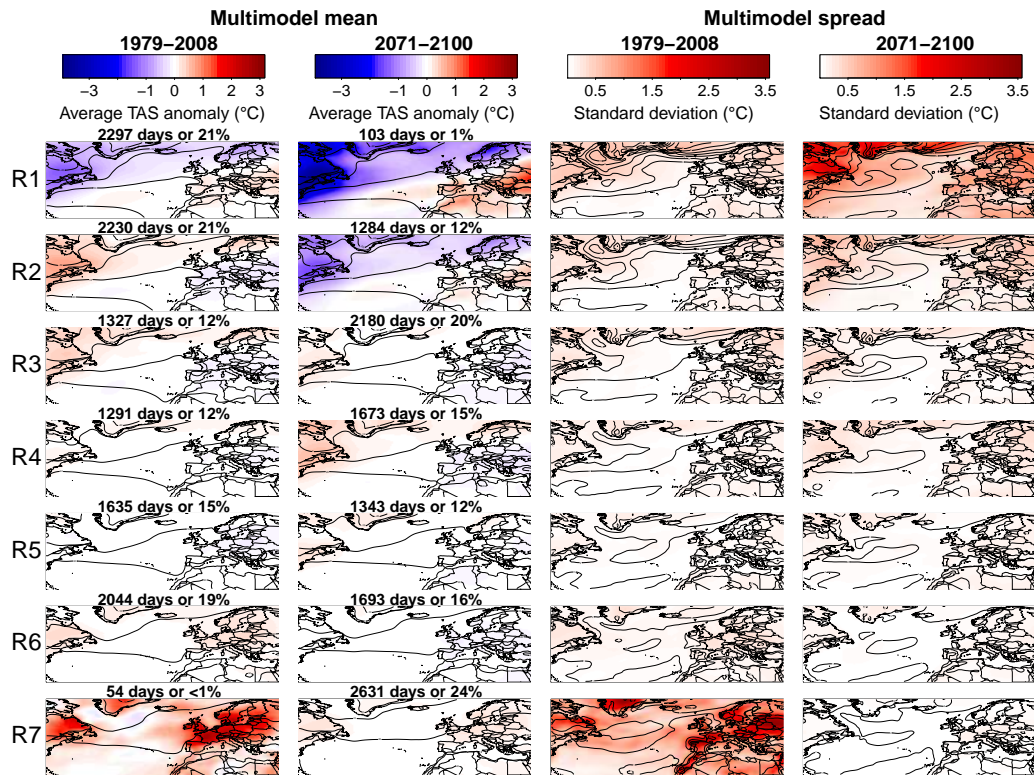


FIGURE 5 As in Fig. 4 but for TAS anomalies conditionally to the regimes.

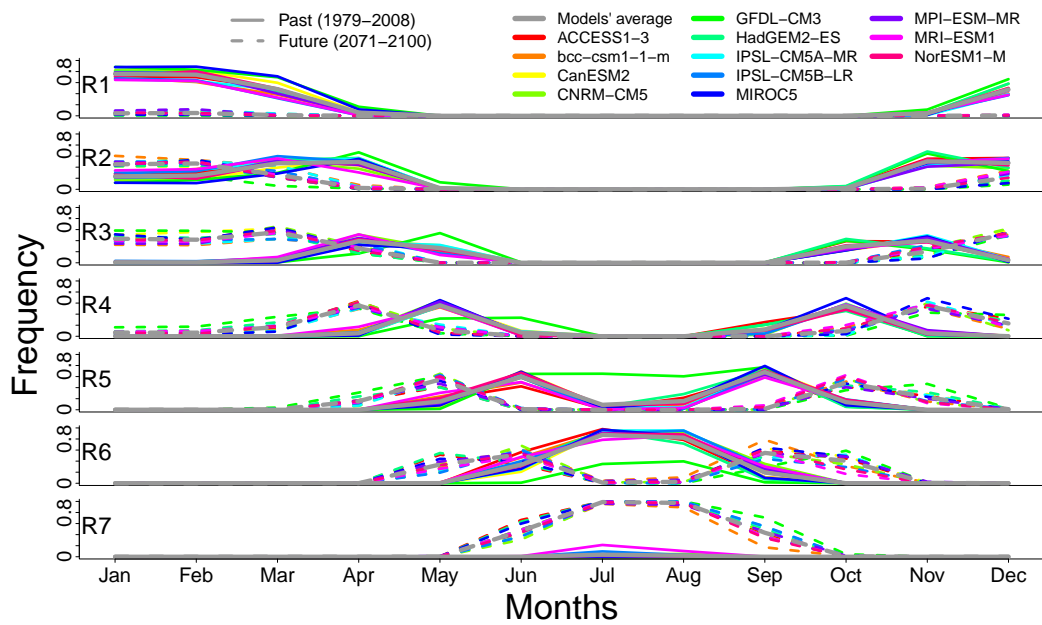


FIGURE 6 Average annual cycle of the seven regimes for the 12 climate models in the past (1979-2008) and future (2071-2100).

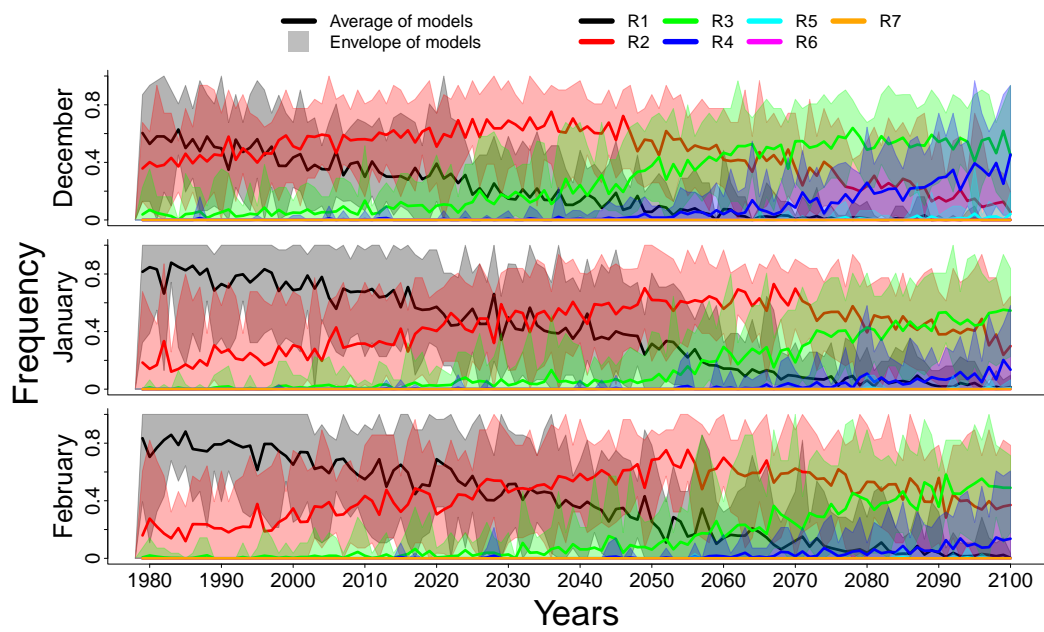


FIGURE 7 Frequency of the regimes per year in December, January and February for the 12 climate models.

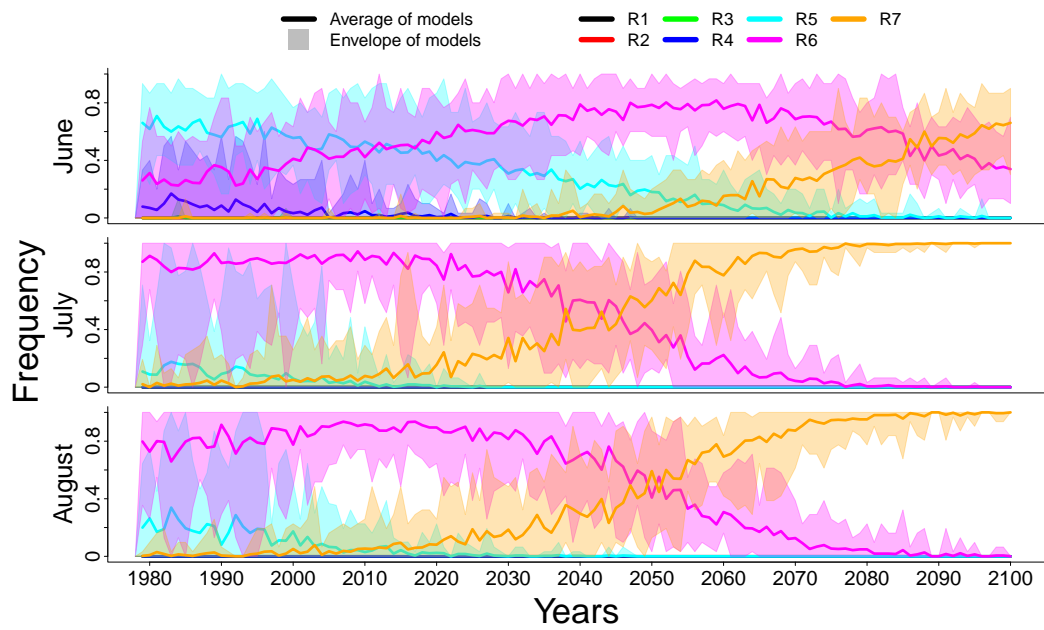


FIGURE 8 As in Fig. 7 but for June, July and August.

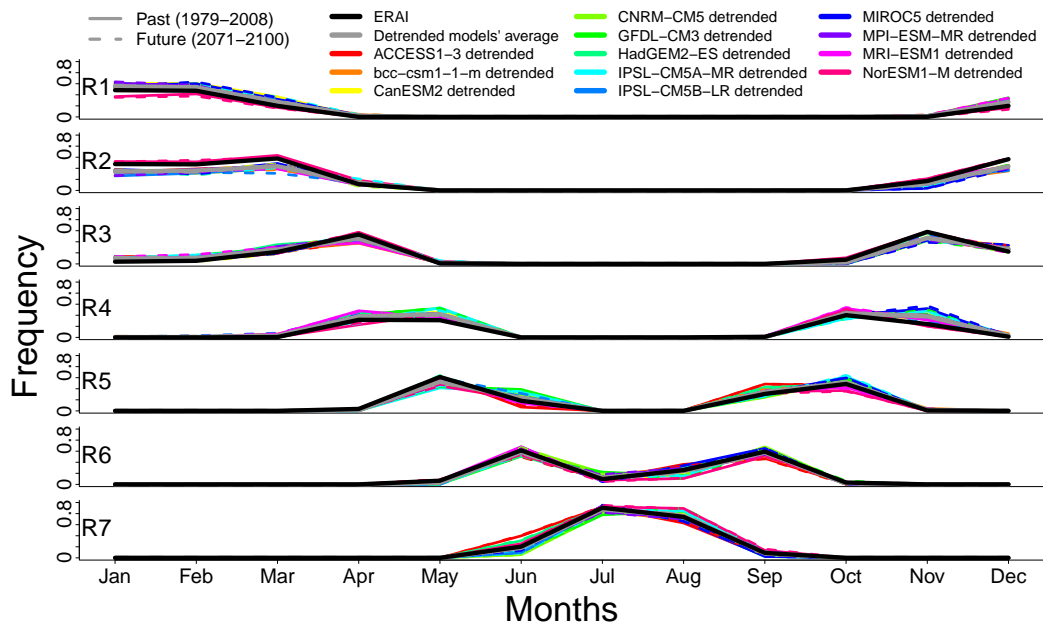


FIGURE 9 As in Fig. 6 but after detrending the data from climate models.

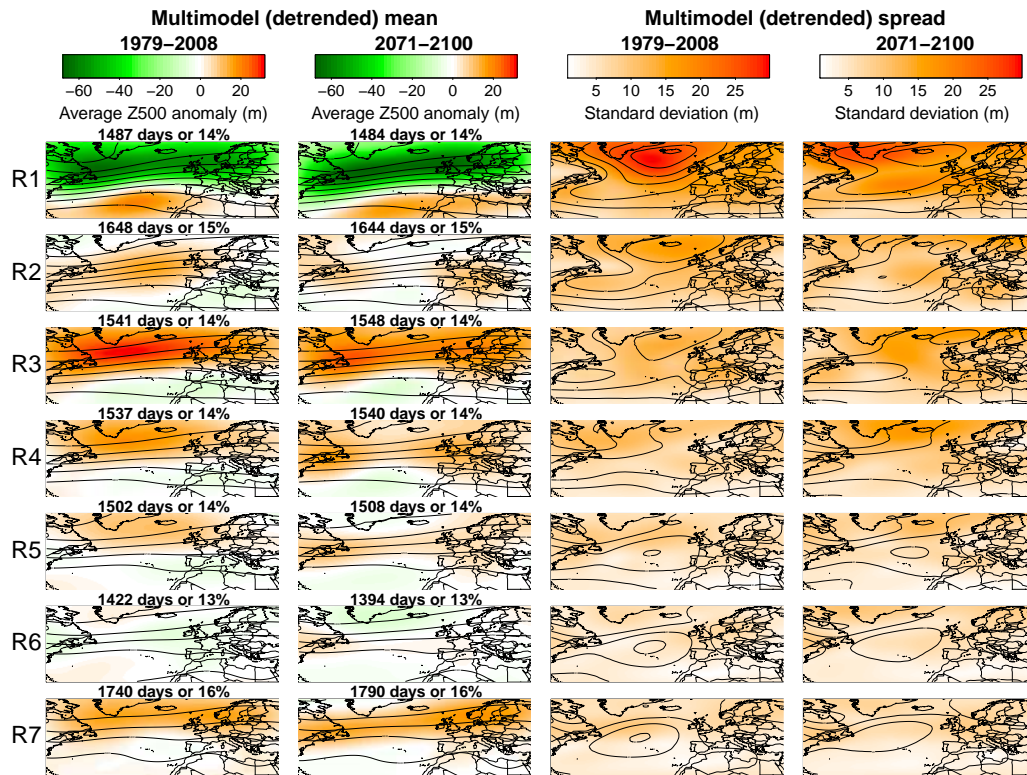


FIGURE 10 As in Fig. 4 but after detrending the data from climate models.

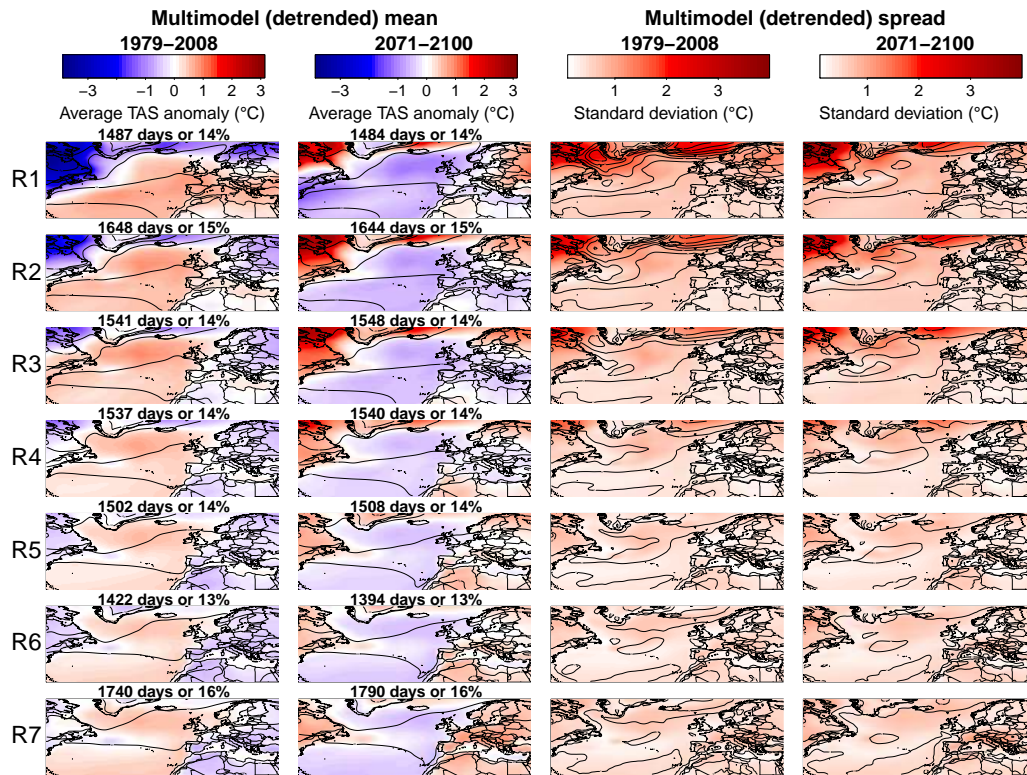


FIGURE 11 As in Fig. 5 but after detrending the data from climate models.

610 appendix

| Density estimation via Gaussian Mixture Model

Gaussian distributions are ellipsoids in space determined by the mean (location) and covariance matrix (geometric features: volume, shape, orientation). The parameters of the Gaussian Mixture Model (GMM) are the means μ_k , covariance matrix Σ_k , and mixture ratio π_k , describing the K ($k = 1, \dots, K$) Gaussian distributions. The estimation of the GMM parameters is done iteratively in the Expectation Maximization (EM) algorithm by maximizing the likelihood that the current statistical model represents the observed data (Fraley and Raftery (2002)). Before being optimized, the GMM parameters are initialized by the result of a hierarchical model-based agglomerative clustering (multivariate), or by separation in quantiles (univariate), rather than random initialization. This approach avoids poor initial partitioning leading to the convergence of the likelihood function to a local maximum rather than a global one (e.g. Scrucca and Raftery (2015)). The principle of EM is based on the possibility to calculate π when knowing α (μ and Σ) and vice-versa, thus enabling the optimization of both. After the initialization, the Expectation-step (or E-step) estimates the posterior probability p_{ik} (update of π_{ik}) that the observation x_i belongs to f_k with the current parameter estimates (at stage t):

$$p_{ik}^t = \frac{\pi_k^t f_k(x_i, \alpha_k^t)}{\sum_{k=1}^K \pi_k^t f_k(x_i, \alpha_k^t)} \quad (3)$$

Then, the Maximization-step (or M-step) uses the posterior probabilities to improve the estimates of GMM parameters (stage $t + 1$):

$$\pi_k^{t+1} = \frac{1}{n} \sum_{i=1}^n p_{ik}^t \quad (4)$$

$$\mu_k^{t+1} = \frac{1}{n \pi_k^{t+1}} \sum_{i=1}^n x_i p_{ik}^t \quad (5)$$

$$\Sigma_k^{t+1} = \frac{1}{n \pi_k^{t+1}} p_{ik}^t (x_i - \mu_k^{t+1})' (x_i - \mu_k^{t+1}) \quad (6)$$

where n is the number of observations. The algorithm repeats the E- and M-steps iteratively until termination when model parameters converge and the maximum likelihood is reached (convergence of the log-likelihood function) or after a maximum number of iterations.

| Model selection with the BIC and covariance matrix

The Bayesian Information Criterion (BIC) is a criterion for model selection that helps to prevent overfitting by introducing penalty terms for the complexity of the model (number of parameters). In the calculation of the BIC, these penalty terms compete with the likelihood function which determines whether adding parameters improves the model by better fitting the observed data. In our case, minimizing the BIC achieves a good compromise between keeping the

model simple and a good representation of the observed data.

$$BIC(K) = p \log(n) - 2 \log(L) \quad (7)$$

where K is the number of clusters, L the likelihood of the parameterized mixture model, p the number of parameters to estimate, and n the size of the sample (e.g. 14235 days over 1979-2017). An additional constraint on the definition of clusters is on the covariance matrix. Our GMM is univariate (since we only use PC1) so the variance can be equal (E model) or different (V model) between clusters (i.e. constraint on volume but not on shape or orientation of clusters).

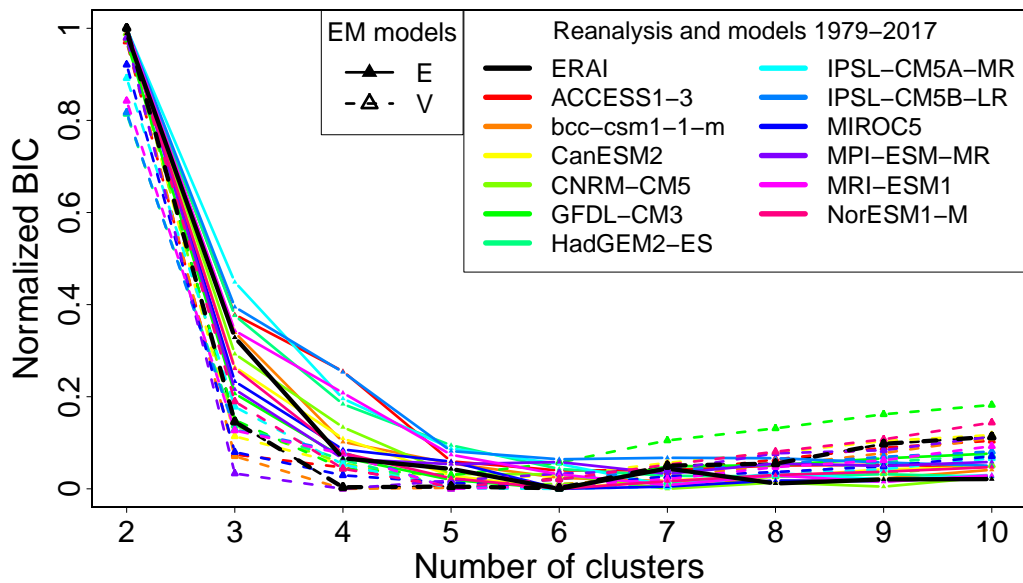


FIGURE A1 Bayesian information criterion (BIC) of the clustering models in function of the number of clusters and model type for ERAI and each climate model over 1979-2017 (exception of HadGEM2-ES: 1981-2017). The BIC values are normalized between 0 (best EM model) and 1 (worst EM model). E: equal variance, V: variable variance.

| Regime conditional trends

The maps of linear trends by regime are obtained by using multiple linear regressions. At each gridpoint, the model of multiple linear regression estimates the contribution of each regime ($k = 1, \dots, K$) to the evolution of the variable (Z500 or TAS):

$$y_t = \alpha_0 + \left[\sum_{k=1}^K \mathbb{1}_{t,k} (\alpha_k + \beta_k t) \right] + \varepsilon_t \quad (8)$$

645 with

$$\alpha_1 = 0 \quad (9)$$

and

$$\mathbb{1}_{t,k} \begin{cases} 0, & \text{if regime } \neq k \text{ at time } t \\ 1, & \text{if regime } = k \text{ at time } t \end{cases} \quad (10)$$

where y_t is the value of the daily variable, α_0 is the general intercept of the multiple regression model, $\mathbb{1}_{t,k}$ is the conditional attribution of days per regime, α_k is the intercept of the regression per regime, β_k is the slope of the regression per regime, t is time, and ε is the error. The intercept of the regression for regime 1 is used as the general intercept (α_0) of the multiple regression model. The intercept (α_k) of the regression for each regime ($k = 1, \dots, K$) is the intercept difference with α_0 , this difference being 0 for regime 1 (α_1). The multiple linear regression estimates the parameters (intercepts, slopes) while taking into account the temporality of the regimes (non-continuous), and while minimizing the error (residual sum of squares). The decadal trends are obtained by multiplying the regression slope per regime by the number of days per decade (3600 in the Hadley Center model and 3650 in the 11 other models).

6.3 Perspective: local climate analogs?

6.3.1 Main findings and prospects of the study on seasonal circulation regimes

I investigated the ability of an ensemble of CMIP5 climate models to represent the past seasonal variability of atmospheric circulation in the North Atlantic, by comparison to a reanalysis (ERA-Interim). I also studied the future evolution of the seasonal structures, and the causes of seasonal changes. The large-scale increase in seasonal mean Z500 (and temperature) causes the continued decrease of historical winter conditions but increase of historical summer conditions. However, the seasonal structures remain similar in the future (annual cycle, spatial patterns) relatively to the increasing seasonal mean (Z500, temperature).

Additional steps could be taken in the evaluation of the climate models, and in the multimodel analysis of the changes in circulation regimes. First, the model biases in circulation regimes could be compared directly to the model mean biases in the climatology of the atmospheric flow, and to the future changes in circulation regimes. This would allow to better constrain the model dependency of the identified changes in atmospheric circulation. Second, the changes in circulation regimes could be linked to the climate sensitivity (warming levels) of the models. In other words, does higher warming correspond to earlier and stronger changes in circulation seasonality during the century?

These insights are interesting at the scale of the North Atlantic and Europe over the century, but have limited implications for the local issues of the French case study (Gulf of Morbihan), since the link between the large-scale structures and local-scale conditions is not clear. How could an approach combine the seasonal and local aspects of the circulation regimes? Methods similar to that used in my study could be applied to explore changes in weather seasonality at a more local scale, by downscaling meteorological variables (e.g. humidity, wind speed, temperature) based on large-scale circulation regimes (Vrac and Yiou, 2010). An alternative is the use of climate analogs, a promising approach emerging in the scientific literature and climate services.

6.3.2 Climate analogs in the scientific literature and climate services

What are climate analogs? They may seem like novel tools in climatology, but have been used extensively in ecology to assess the shift of ecoregions due to climate change (and associated impacts on species; Rohat et al. (2018)). The climate analogs of a given area of study are regions that today have a climate that is very similar to that predicted in the future of the study area (Horváth et al., 2009). The mapping of climate analogs therefore consists in connecting the expected future climate at a location with the current climate at other locations (Figure 6.5), and to measure their similarity (Fitzpatrick and Dunn, 2019; Yin et al., 2020). Climate analogs can be useful in several ways:

- to characterize the climate shift of cities (Rohat et al., 2018). For instance, will one city experience climate conditions not currently experienced by any existing city?

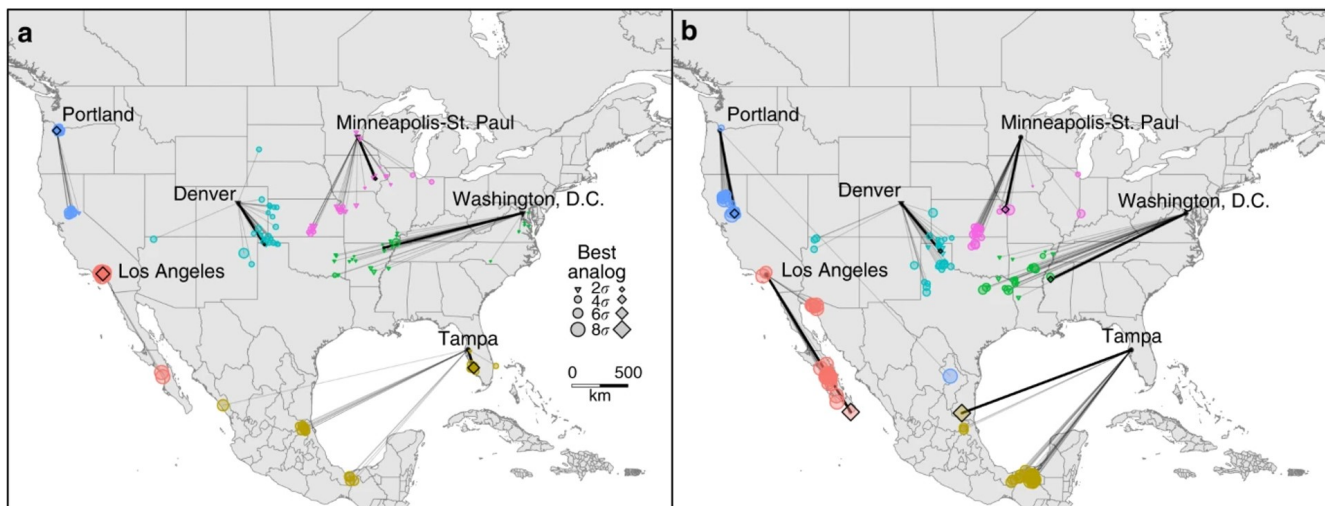


Figure 6.5: Climate analogs of major American cities in the 2080s' climate (2070–2099 mean) for two scenarios (left: RCP4.5, right: RCP8.5). Good analogs are represented by triangles, while the quality of analogs decreases with larger circle size. The ensemble mean of climate model projections (27) is shown by the diamond and bold line. Adapted from Fitzpatrick and Dunn (2019).

- to simplify the understanding of complex climate model predictions (Yin et al., 2020), and provide a place-based (i.e. more relatable) assessment of climate change (Fitzpatrick and Dunn, 2019)
- to raise the awareness of stakeholders and urban dwellers about the pace, magnitude and dynamics of climate change (Rohat et al., 2018)
- to help land managers and city planners visualize the climate futures of their respective cities, in order to facilitate decision-making under climate change (Bastin et al., 2019)
- to support the identification of future climate impacts, vulnerabilities, and available adaptation options, as well as strengthening cities' cooperation within climate-related networks (Rohat et al., 2018)

Climate analogs have already been applied in several analyses: global (Rohat et al., 2017; Bastin et al., 2019), North America (Ordonez and Williams, 2013; Fitzpatrick and Dunn, 2019), Europe (Horváth et al., 2009; Jylhä et al., 2010; Rohat et al., 2018), and China (Yin et al., 2020). They also exist in the form of climate services: global (Barbu, 2020), for the United States (Fitzpatrick, 2019), and for Australia (CSIRO, 2020) .

6.3.3 Study objective, methods and preliminary results

The main goal of the study is to determine the evolution of European local climate regimes (LCRs) under climate change, from the last decades to the end of the century. This goal is associated to the investigation of LCR changes (pattern, frequency, persistence) at the level of Europe, and in the CoCliServ case studies.

Calculating climate analogs at a fine resolution in a large area and over the lapse of decades is computationally intensive. The area size also strongly affects the way climate analogs are defined, since a larger area corresponds to

a higher number of points on which the "climate distances" are calculated. We therefore chose to focus on Western Europe because it contains all the CoCliServ case studies. Instead of calculating climate distances as is commonly done in the literature, we will use a multivariate clustering approach to define local regimes. Our LCRs are defined based on three daily variables: surface temperature, precipitation, and 10m windspeed.

Our dataset of reference for the past climate (Table 6.1) is the ERA-land reanalysis (9 km resolution) over 1981-2019 (Muñoz-Sabater et al., 2021). To represent the future, we use the bias-corrected EUROCORDEX simulations at 12 km resolution (Bartok et al., 2019) over 1971-2005 (historical) and 2006-2100 (RCP8.5). A subset of climate models was selected in the ensemble based on performance criteria (Bartok et al., 2019), we use the 5-member selection for our purposes (Table 6.1). The climate simulations were bias-corrected according to observation-based datasets of reference (Bartok et al., 2019), using the CDF-t method (Vrac et al., 2012).

Table 6.1: Characteristics of data used.

Type	Dataset	Period	Spatial resolution	Reference
Reanalysis	ERA5-Land	1981-2020	9 km	Muñoz-Sabater et al. (2021)
Bias-corrected EUROCORDEX simulations	CNRM-CERFACS-CNRM-CM5 and CNRM-ARPEGE51	1971-2005 (historical) and 2006-2100 (RCP8.5)	12 km	Bartok et al. (2019)
	ICHEC-EC-EARTH and RACMO22E	1971-2005 (historical) and 2006-2100 (RCP8.5)	12 km	Bartok et al. (2019)
	IPSL-CM5A-MR and IPSL-INNERIS-WRF331F	1971-2005 (historical) and 2006-2100 (RCP8.5)	12 km	Bartok et al. (2019)
	MOHC-Hadgem2-ES and SMHI-RCA4	1971-2005 (historical) and 2006-2098 (RCP8.5)	12 km	Bartok et al. (2019)
	MPI-M-MPI-ESM-LR and MPI-CSC-REMO2009	1971-2005 (historical) and 2006-2100 (RCP8.5)	12 km	Bartok et al. (2019)

We define the LCRs based on the multivariate clustering of the three climate variables (temperature, precipitation near-surface windspeed). K-means clustering allows to experiment with the initial settings of the methods (fast computation), while Expectation-Maximization clustering could be applied in a later stage (slow computation) to obtain clusters that are more robust. Since the datasets are too large for clustering directly, we have to simplify them through statistical means.

A matrix is constructed in the pre-processing step, containing six columns (annual mean and standard deviation per climate variable) and one row per year and gridpoint. Since K-means functions with euclidean distances, the matrix must be normalized so that climate variables weight the same importance in the clustering. A centering and scaling is therefore applied to each column.

A proof-of-concept was conducted with 10 clusters and the full data (1981-2020) from the reanalysis (ERA5-Land). The choice of 10 clusters and 40 years of data was to give enough freedom to the clustering, while also facilitating the analysis of the results. The resulting clusters display remarkable spatio-temporal characteristics (Figures 6.6-6.7) but present little evolution from year to year (Figures 6.7-6.8). To increase the sensitivity of the clusters, the pre-clustering

matrix could instead be constructed by month (instead of year).

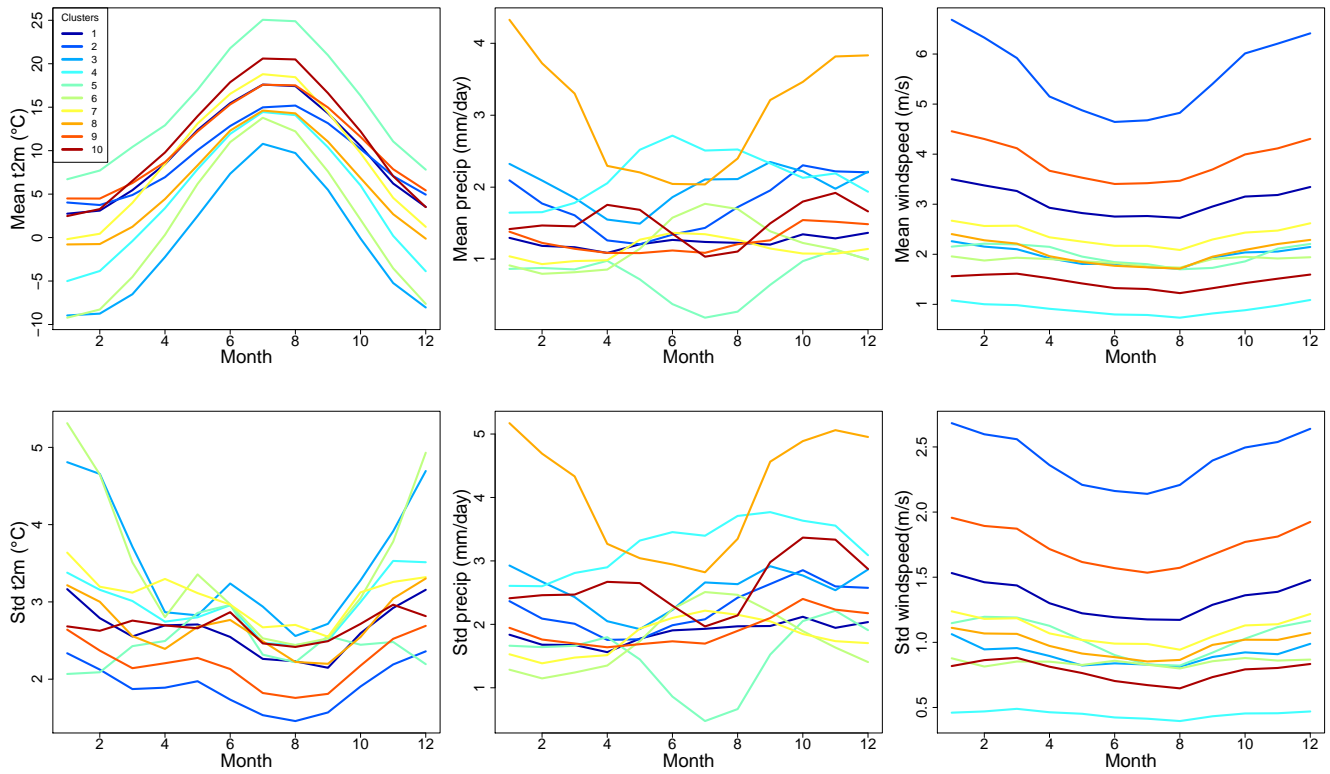


Figure 6.6: Cluster properties for the data sample (40 years of data from ERA5-Land). Top panels: mean monthly value per cluster. Bottom panels: monthly standard deviation per cluster. Each color corresponds to a cluster.

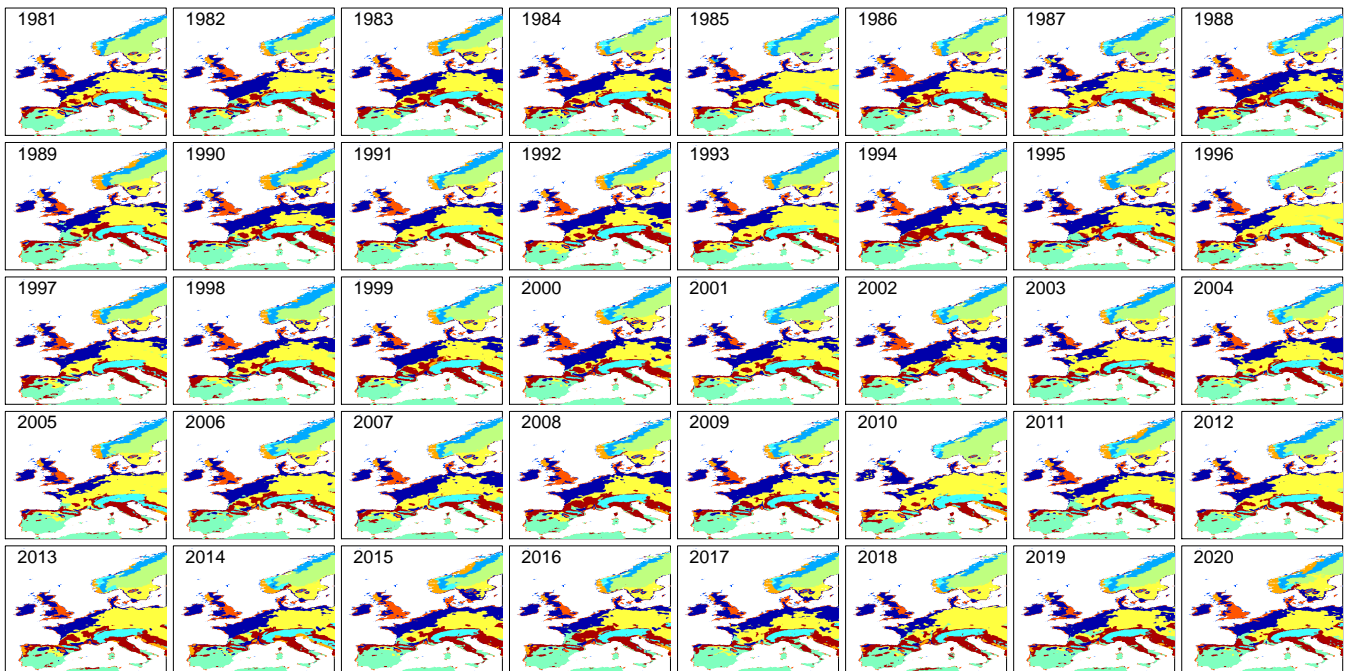


Figure 6.7: Annual spatial distribution of the clusters from 1981 to 2020. Each cluster corresponds to a color as defined in Figure 6.6.

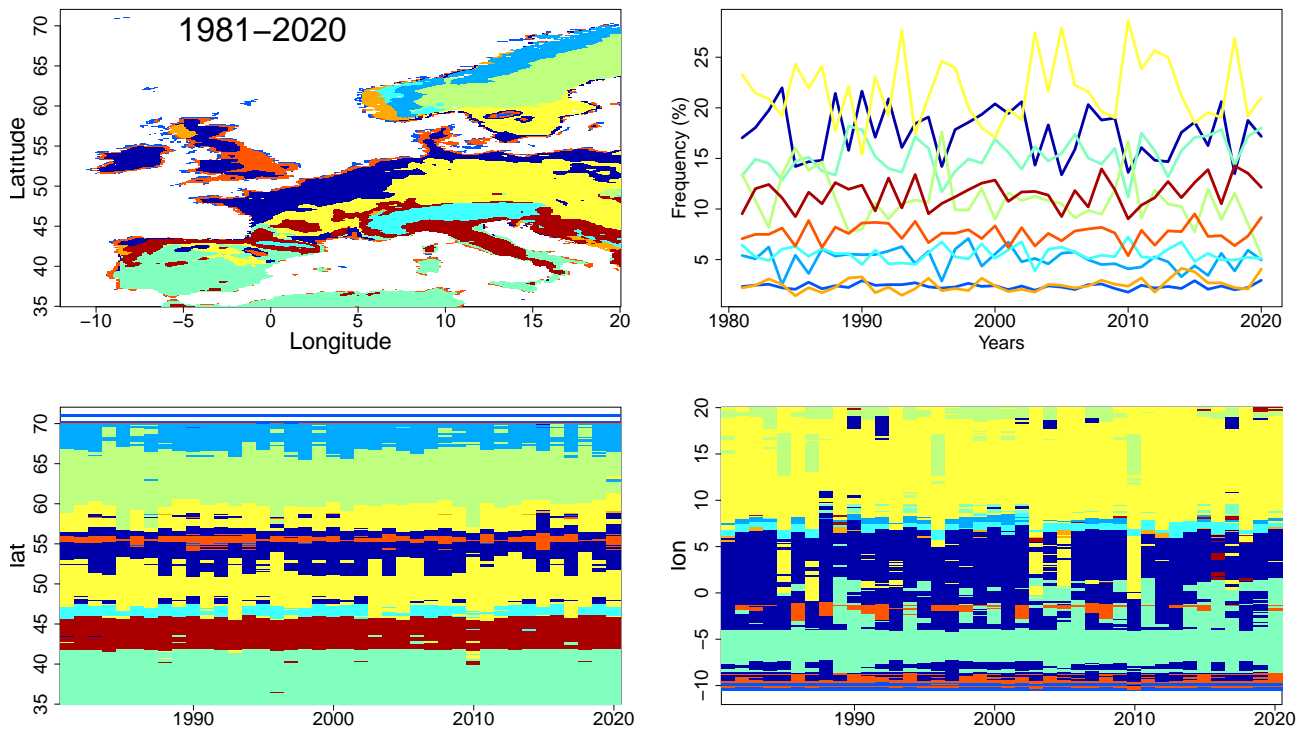


Figure 6.8: Evolution of the clusters in frequency, latitude and longitude from 1981 to 2020. Topleft panel: dominant cluster per location over 1981-2020. Topright panel: cluster frequency per year over the domain. Bottomleft panel: dominant cluster per latitude and year. Bottomright panel: dominant cluster per longitude and year. Each cluster corresponds to a color as defined in Figure 6.6.

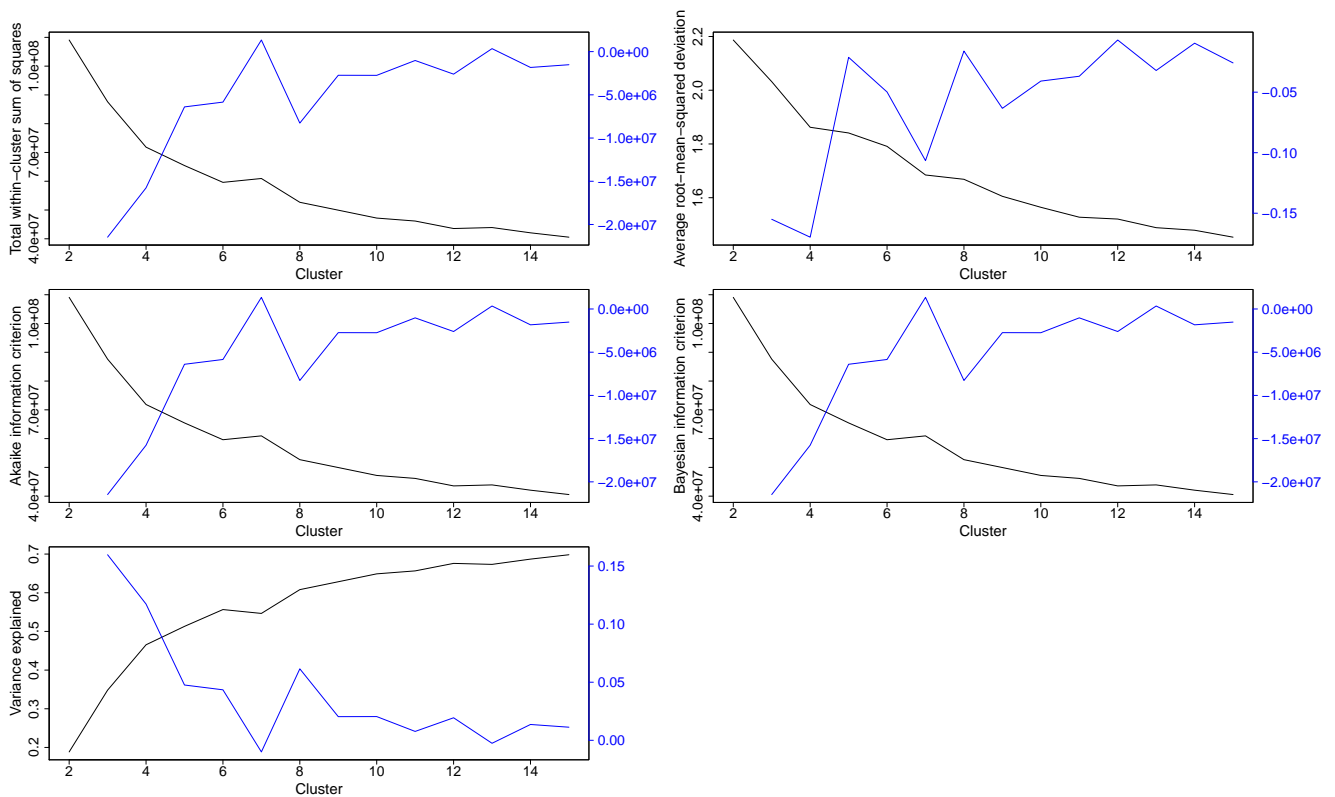


Figure 6.9: Example of criteria to determine the optimal number of clusters. For each panel, the raw value of the criteria is shown in black (left axis), and the difference in criteria value (by adding a cluster) is shown in blue (right axis).

In any clustering, the optimal number of clusters is a central question. This question is related to finding a balance in the way data is assigned to clusters, in order to maximize similarity within clusters and minimize similarity between clusters (Wilks, 2011). This optimization can be examined through different means (Figure 6.9) such as the elbow method (AIC, BIC, variance explained), cluster separation, and silhouette coefficient (Ritter, 2014; Hennig et al., 2015).

6.3.4 Discussion and future research

To summarize this preliminary analysis, the multivariate approach combines both the seasonal and local aspects of climate regimes. These local climate regimes can therefore be used to track the future evolution of weather seasonality in specific locations (e.g. Figures A.1-A.4), by comparison to historical conditions (and regional analogs). The previous study on seasonal circulation regimes found a decrease in winter conditions and increase in summer conditions, but similar seasonality (annual cycle, spatial patterns) relatively to the increasing seasonal mean (Z500, temperature). It would therefore be interesting to compare these circulation changes identified at large-scale, with the evolution of surface weather conditions (temperature, rainfall, wind speed) at local scale.

Further perspectives include:

- identifying the relative roles of natural variability (e.g. NAO, AMO) and climate change in the evolution of the LCRs (e.g. natural vs. anthropogenic features of the regimes)
- assessing the potential extinction of historical regimes and emergence of new regimes (where, when, how)
- examining the behavior of extreme regimes

These new insights could in turn serve to better characterize the climate shift of cities (Rohat et al., 2018), to help inhabitants and decision-makers visualize their climate futures, and to support the identification of future climate impacts, vulnerabilities, and available adaptation options (Rohat et al., 2018; Bastin et al., 2019).

Summary of Chapter 6

Context and objectives:

My investigation of the territory highlighted local themes (seasonal changes, extreme events, marine submersion) that are linked to climate change effects on atmospheric circulation and seasonality. However, climate models have large biases in the representation of atmospheric circulation and local climate, and future circulation changes are highly uncertain. The goal of this chapter is therefore to explore future changes in the structure of local climate seasonality (atmospheric circulation, meteorological conditions). My approach is based on the clustering (i.e. unsupervised classification) of atmospheric conditions (circulation, weather), which defines seasonality in a non-stationary way.

Methods and results:

I first conducted a study with circulation regimes to evaluate the ability of climate models to represent the past seasonality of atmospheric circulation, and to explore future changes in circulation seasonality. The circulation regimes were defined daily over 1979-2017 and 1979-2100 by clustering year-round patterns of daily geopotential height at 500 hPa (Z500), separately for a reanalysis and each of twelve climate models. Despite biases in the climate model representation of circulation regimes, the multimodel average of regime structures (spatial patterns, annual cycle) and their evolution is similar to the reanalysis.

During the last decades, winter conditions have decreased while summer conditions have increased, and these changes strengthen in the future. However, circulation seasonality remains similar, relatively to the increase in average Z500, and the same happens for surface temperatures associated to regimes.

I then developed a follow-up method based on climate analogs to study changes in local weather seasonality. The climate analogs are defined annually by clustering several meteorological variables (temperature, precipitation, windspeed) at high scale (about 10 km), separately for one reanalysis (over 1981-2020) and for each of five bias-corrected model simulations (over 1971-2100). Preliminary results indicate that the method can capture the variability of local weather seasonality in Western Europe.

Perspectives:

Since the link between the circulation regimes and local-scale conditions remains unclear, meteorological variables could be downscaled at a more local scale based on the large-scale structures. The preliminary results showed a small evolution of climate analogs, but this evolution could become more sensitive with a monthly definition (instead of annual). The number of clusters could also be optimized to reach an optimum between information size and accuracy. Finally, the evolution of the clusters could serve to investigate future changes in weather seasonality for the local case study.

“Rita Vrataski: What do we do now?”

- William Cage: I don't know, we've never made it this far.”

Edge of Tomorrow

Conclusion

The Introduction outlined how human-caused climate change is a great challenge facing society worldwide today. Without a change in the global current trajectory, to reduce the causes (mitigation) and consequences (adaptation) of climate change, all regions could become less habitable due to cascading impacts on society and environment. New ways have to be invented to bridge the wide gap between scientific knowledge and societal action towards climate change.

This thesis aimed to address this gap, focusing on a single case study: the Gulf of Morbihan in France. The first goal of my thesis was to understand how climate change affects the local case study. The second goal was to support the participative development of local adaptation planning. My third goal was to develop clustering approaches that could address the two previous objectives. These three goals are associated to several questions:

- What is the local role of climate change in the life and activities of inhabitants?
- Are local experiences consistent with scientific knowledge?
- What is the role of future climate change in the visions of inhabitants for the territory?
- Are the existing climate science and services sufficient to enable local adaptation?
- How can clustering approaches serve to navigate the uncertainty of future climate change, and make climate science more usable for territorial adaptation?

Due to the transdisciplinary and societal dimensions of this thesis, part of the research was conducted in collaboration with local partners from the case study, climatologists and social researchers. This collaborative aspect is reflected in the following sections by the occurrence of "we".

The local role of climate change in the territory: scientific and societal dimensions

In Chapter 1, I analysed the literature (grey and academic) to describe the climatic and societal context of the Gulf of Morbihan. This analysis highlighted the particular features of the case study: the organization of the economy

(e.g. tourism, agriculture) and social life (e.g. population size) around the seasons, the ambivalent relationship (dependence and conflict) between agriculture and tourism, and the contrast (economy, demography) between coastal and inland territory. Climate change can take various forms in a given territory as outlined in the Introduction: changes in mean conditions (e.g. warming) and in weather extremes (e.g. heatwaves), and impacts on society (e.g. freshwater availability) and natural ecosystems (e.g. phenology). Chapter 1 confirmed that several changes had been observed in Brittany over the last decades in relation to climate change, and some of their effects perceived in the Gulf.

I reviewed the scientific literature of climate service practices in Chapter 2, to identify approaches that could reconnect the scientific knowledge of climate change to the everyday experience of local inhabitants. Evidence from the literature indicates that the use of chronotopes and local narratives of change can facilitate this connection. We therefore utilized these two conceptual tools in Chapter 3 to reveal the (hidden) role of climate change in the life of inhabitants. We collected materials from local partners and conducted about thirty field interviews with diverse stakeholders, and analyzed this data with two approaches (grounded theory, multi-level structure). Four narratives of change emerged (geo-social, historical, seasonal, climatic effects) as well as two chronotopes (sealevel rise, coastal erosion). This analysis deepened our knowledge of the ongoing changes (socioeconomic and climate) in the Gulf, and enabled us to link climate change to the local matters of concern.

The narratives and chronotopes allowed to unravel the complex and multifaceted local role of climate change, impacting emblematic activities (e.g. oyster farming, salt production) and overlapping with existing issues (socioeconomic imbalance, water access, urban development, land-use conflicts). A peculiar finding is the overall positive effect of climate change on tourism (lengthening of peak touristic season with summer weather), by contrast to the negative effects on agriculture (drier conditions in summer, water warming). In addition to these findings, Chapters 1 and 3 highlighted the importance of three climatic themes that are connected to the activities in the Gulf: seasonal changes, extreme events, and marine submersion. After linking climate change to local matters of concern, I examined whether the local experience of climate change is consistent with scientific knowledge.

For this, I first assessed in Chapter 4 the current scientific knowledge of climate change (recent, future, uncertainties, gaps), as well as the available climate services. This double assessment was guided by the local issues and three climatic themes. My assessment of scientific knowledge relied on the sources identified previously, complemented by an extensive literature review of specific topics. For climate services, my inventory was based on personal knowledge of available services, on existing mappings, on a search with browsing engines, and on a monitoring of the literature. I additionally developed with CoCliServ colleagues an analytical framework to conduct an empirical study of climate service practices. The double assessment identified hundreds of sources of published scientific knowledge, and about fifty climate services, constituting a broad range of climate knowledge pertaining to the local issues (with varying degree of relevance).

While climate services were abundant and diverse, the majority of formats was non-interactive, and private

services were difficult to analyze. My assessment indicated that the Gulf is already largely affected by climate change, and that most of the ongoing changes will increase in the future, with many negative effects (e.g. heatwaves on health, droughts on agriculture), despite rare positive effects (e.g. summer tourism). The assessment also suggested that climate change has wider consequences in the Gulf than previously assessed, entailing a broader adaptation gap. The assessed scientific knowledge was generally consistent with local experiences (ongoing changes, link to climate change), although some elements are scarce in local perceptions (heatwaves) or absent (e.g. cold spells). However, the discrepancy about heatwaves could be due to the timing of the interviews outside summer. Another limitation is the non-exhaustivity of the assessment, constrained by my resources.

The assessment nevertheless allowed to characterize many of the local future changes, which can be quantified further with the documented materials. Many scientific uncertainties and gaps were also highlighted by my assessment, and while some changes are nearly certain in the next decades (e.g. seasonal warming), others are deeply uncertain over the rest of the century (e.g. storm surges and sealevel rise). I was particularly interested in the influence of climate change on the atmospheric circulation, due to the large uncertainties of the changes and to the overlap with the three local climatic themes.

Circulation regimes have been extensively used to study the variability of atmospheric circulation, so I employed them to describe local weather situations in Chapter 1 and again in Chapter 6 to investigate the dynamical effects of climate change. Since circulation regimes are closely related to atmospheric jetstreams and climate variability modes (e.g. North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO)), Chapter 6 started with a literature review of the effects from climate change on the three. This review highlighted the large natural variability of atmospheric circulation (e.g. fluctuating with NAO and AMO) in both past and future, and the large uncertainty (intermodel spread) in the atmospheric response (e.g. jetstream, blockings) to climate change, although a few general changes were identified (e.g. past warming in most circulation regimes, more positive future NAO).

The uncertain response of atmospheric circulation to climate change, in addition to the large biases (thermodynamic, dynamic) of climate models and the limited understanding of future changes in seasonality, motivated the study in Chapter 6. The goal was to evaluate the ability of climate models to represent the past seasonality of atmospheric circulation (by comparison to a reanalysis), and to explore future changes under further climate change (RCP8.5). I defined seasonal circulation regimes (SCRs) over 1979-2017 and 1979-2100 by clustering (i.e. unsupervised classification) year-round daily fields of geopotential height at 500 hPa (Z500), separately for the reanalysis and each of twelve climate models. Despite biases in the climate model representation of Z500, the general evolution of SCRs over the past was similar to the reanalysis: decreasing frequency of winter SCRs and increasing frequency of summer SCRs.

In the future, the frequency of winter SCRs continued to decrease (their occurrence would start later in the year and finish earlier), while the opposite happened for summer SCRs. A more surprising result is that the seasonality of circulation patterns remained similar in the future, relatively to the increasing seasonal mean of Z500 (i.e. according to

the new circulation "average"). The same similarity in seasonality was found for future patterns of surface temperature associated to the SCRs. Changes in weather seasonality could be explored at a more local scale, by downscaling meteorological variables based on large-scale circulation regimes, or by using climate analogs. Climate analogs were the focus of the follow-up study, at the end of Chapter 6.

The goal of this preliminary study was to investigate the evolution of local weather conditions in Western Europe under climate change, for instance at the level of the Gulf of Morbihan. For this, I defined local climate regimes (LCRs) at a scale of about 10 km from the multivariate clustering of surface temperature, precipitation and near-surface windspeed, separately for one reanalysis (1981-2020) and for each of five bias-corrected model simulations (1971-2100, with historical and RCP8.5). Due to lack of time, this is for the moment only a preliminary analysis, but I found promising early results indicating that the approach works, and that it can be improved to track the future evolution of weather seasonality in specific locations.

With all this gathered knowledge of recent and future climate change, we now go back to the second goal of my thesis, which was to support the participative development of local adaptation planning. This climate knowledge can provide a physical basis for the development of foresight processes supporting local adaptation, which is the focus of the next section.

The participative development of local adaptation planning: making climate science usable?

The Introduction outlined two important gaps: that of climate adaptation, and that of the usability of climate services. The first gap corresponds to the divide between the scientific knowledge of climate change, and the societal preparation to the impacts from climate change. The second gap corresponds to the disconnect between climate services and territorial issues, although climate services aim to facilitate the societal use of scientific knowledge on climate change. We saw in both Introduction and Chapter 1 that France is an illustration of the lack in climate adaptation at the territorial level, as is the Gulf of Morbihan (despite existing efforts). I then reviewed in Chapter 2 the general barriers to the use of climate science for adaptation, and highlighted the challenge of "localizing" climate science with local populations for territorial issues.

At the same time, Chapter 2 identified approaches to integrate the role of climate change in the societal context, for example by using participatory processes that include local stakeholders in the co-construction of future scenarios. Exotic approaches such as gaming and future visions can also support local climate adaptation in association to scenario-building exercises. We investigated in Chapter 3 the future visions that inhabitants have for the Gulf, and identified divergent visions of the territory. While the maintenance of the coastal urban area could become increasingly difficult under future climate change, withdrawal from the coast appears difficult for some stakeholders,

and territorial adaptation is considered through the lens of technical solutions. For other inhabitants, the traumatic impact from past storms nourishes the consideration of withdrawing activities to less vulnerable areas.

Chapter 3 also identified several entry points for the development of future scenarios and local climate services. These entry points are contained in the present and future issues (socio-economic, climate change), the contrasting viewpoints (agriculture, tourism), and the future visions (coastal adaptation, withdrawal) of the territory. Entry points also provide a foundation for the experimentation through art and science of possible future narratives. To support the development of local future scenarios, I identified a large set of climate knowledge (scientific literature, climate services) in Chapter 4. This climate knowledge would provide a physical basis for adaptation foresight processes, and foresight activities would in turn be key to analyze how the current state of scientific knowledge and climate service can address local adaptation needs.

We then experimented in Chapter 5 different ways to conduct foresight processes (scenario workshop, art-science exhibition, conference-debate), aiming to engage the population and help municipalities in the Gulf to improve their thinking about the future (climate). The first experiment was a prospective workshop based on a poker design approach to develop local vision-based scenarios. We gathered twenty local stakeholders from various backgrounds (e.g. agriculture, tourism, land-use planning, research) for three hours to collectively define their priorities for the territory (long-term plans and short-term actions), in light of the risks from climate change and extremes. An initial challenge was the proportion of conflict in the future visions (identified in Chapter 3), so we devised creative tools to facilitate the participation of stakeholders and to encourage them into considering multiple future possibilities.

The foresight exercise was based on the local narratives, the scientific knowledge of future climate change, two time horizons (2030 and 2200) and the creative tools (poker design cards, map of future territory with sealevel rise). Two scenarios, 25 short-term actions and 11 hinge points (eight past, three future) resulted from the outcomes of the foresight activity. Stakeholders agreed on a single long-term vision for the majority of the proposed issues, except for coastal land-use and for the role of tourism in the region. The first scenario ("Shore-centred adaptation") represents a continued occupation of the coasts, and the integration of increasing adaptation efforts in policies of land-use planning and urbanization. The second scenario ("Countryside-based adaptation") corresponds to the densification of urban areas inland, and to the recovery of natural landscape on the coasts. The three points on which the future scenarios hinge are linked to issues of urbanization and spatial planning, food and energy autonomy, and demographic balance.

Our empirical results suggest advantages from the use of creative tools and local narratives to develop future narratives, scenarios, hinge points and actions. The creative tools and local narratives stimulated the engagement of stakeholders on long-term sensitive issues (e.g. economic activities, relationship with nature), facilitated their discussion, and allowed a relevant strategy of community-led adaptation to emerge. The 2200 horizon of the physical scenario was associated to large uncertainty, initially considered by a few participants as too abstract and anxiety-inducing. However, these reservations decreased during the collective activity with the use of the creative tools,

and participants proposed innovative solutions addressing climate change (mitigation, adaptation) and sustainable development. We presented our initial results to local authorities (several insights can be linked to the PCAET), and submitted the actions devised during the workshop to the online vote of inhabitants.

While the first workshop focused on brainstorming possibilities and collecting ideas, the specifics and implementation of the selected actions would be discussed in a second workshop. This second workshop would have involved more of the neighbourhood (inhabitants, organisations, municipalities) to decide on the details of actions for the 2030 horizon, but had to be cancelled (March 2020) due to the Covid-19 health crisis. Instead, the second foresight experiment was an art-science exhibition on climate change, to convey the transformation of the territory through elements of artwork and scientific panels. The initial project was a long-term exhibition over a stretch of the coastal pathway, which was not currently possible under present constraints.

We therefore opted for a short-term exhibition aiming to immerse visitors in reflections of how the future could look like in parts of the Gulf, simultaneously foreseeing potential impacts and bold adaptation options. Multiple animation activities were planned to accompany the exhibition but had to be canceled due to the Covid-19 health crisis. The exhibition included display panels presenting local information (scientific and artistic), an auditory narration, and multiple elements of art-design. We synthesized in the display panels the climatic changes according to two time horizons (2050 and 2100) and two scenarios (RCP4.5 and RCP8.5). The auditory narration consisted of stories from characters of 2050, illustrating the actions developed previously in the prospective workshop. Their testimonies of the future depict a territory where the inhabitants would have adapted to the consequences of climate change by changing much of their lifestyle.

The panels also invited visitors to propose their own suggestions of artworks, needs of climate services, and visions of the Gulf for 2050. The scientific panels and artworks that we developed will remain available through the territory and online, and can stimulate the production of new awareness tools. The coastal path could later serve in a long-term (or permanent) exhibition to further exemplify sealevel rise and coastal erosion. The third foresight experiment was a conference-debate on local adaptation, attended by several local decision-makers and about thirty inhabitants, and lasting about two hours. An one-hour conference introduced the debate by presenting the local effects of climate change, the insufficiency of current plans to prepare the territory, how climate services can support this preparation, and how to co-construct adaptation scenarios.

The following one-hour debate covered various topics, but climate change was centralized through two themes: energy and food autonomy. These two themes coincide with the future hinge point that emerged from the previous foresight workshop. During the debate, they concentrated conflicting views and emotional interventions between inhabitants, reflecting their fears and desires for the territory. Overall, this debate highlighted the cultural dimension of climate change for the inhabitants of the territory, when long-term territorial choices are discussed (e.g. local production of food and energy). After examining how climate change influences the visions of inhabitants for the territory, we go back to another main question of my thesis: are the existing climate science and services sufficient to

enable local adaptation?

Implications and perspectives for the development of local climate services

An initial ambition of my research was to compare the local needs in climate knowledge with the existing science and services, and to deduce gaps and potential demand for more local information. The research team could then address these gaps with methods of regionalization. However, the co-development activities with stakeholders took a long time, in order to understand the local issues and to build trust with inhabitants. The stage of qualifying and quantifying the required knowledge for relevant actions of adaptation was not reached. I nonetheless attempted to carry out the gap analysis as far as allowed by the level of detail from my previous results. This analysis aimed to further understand how climate services can support local adaptation, and to deduce their potential strengths and weaknesses, as well as limitations and perspectives.

The first step of this analysis was an evaluation of climate services with the case study leader, supported by a list of user-oriented criteria. I gathered the most relevant climate services according to the local issues, focusing on services in the form of free online tools (e.g. Climat HD and DRIAS). The evaluation highlighted the key strengths (accessibility, understandability, credibility, transparency) and the key weaknesses of the selected climate services. These weaknesses include the lack of information about variables (e.g. seasons and water surface temperature), spatial distribution (e.g. storms and extreme events), spatial scale (e.g. extreme events), past (e.g. attribution to climate change), future (e.g. storms), and uncertainty (multimodel and multiscenario). The second step of the gap analysis was to discuss the implications and perspectives for the local development of climate services addressing the local issues, based on my previous findings (including the evaluation) and on existing services abroad.

For instance, it remains unclear whether there is sufficient information about the warming of surface water, since this topic is scarcely covered by climate services and local observations (long-term) are lacking in the Gulf. Likewise, the evaluation suggested that future precipitation is sufficiently covered by climate services to support local adaptation, but projections are associated to large uncertainties and sometimes contradicting trends between scenarios or models. From the angle of water management, future groundwater availability could be assessed on the short-term based on seasonal meteorological forecasts, and on the long-term based on stochastic modelling of system dynamics. Similarly, a new service could investigate how the seasonality of different indicators (selected with stakeholders) might evolve in the future, although DRIAS already includes many agro-climatic indicators.

In the case of extreme events, the evaluation indicated that the scale of the information (Climat HD, DRIAS) could be insufficiently precise to support local action, for example regarding the timing and location of extremes. A service could show the aggregated variability (spatial and temporal) between different events and types, accounting

for uncertainty (models, scenarios), and including the derivation of local impacts (sectoral). More exotic options of service development could also be imagined. For heatwaves, an early-warning system (including mortality forecasts) could prepare local health action plans, and a service could guide the movement of inhabitants towards cooler areas of the city when extreme temperatures occur.

For flooding, a multisector identification of risks and cascading effects from drainage system failures could be combined with a simulator of flood evacuation scenarios, and communicated with realistic animations of (simulated) flood occurrence at street level. Regarding marine submersion, local subsidence should be included in the assessment of future flood hazards, and the uncertainty of future coastal impacts can be navigated through uncertainty frameworks and probabilistic projections. Another way to deal with deep uncertainty is the use of no-regret strategies for coastal protection measures. Existing climate services in other countries (e.g. United States, Germany) illustrate how to situate recent and future coastal hazards (sealevel, windstorms, storm surges) in the context of long-term climate variability and societal vulnerability and exposure (coastal protections, population, income, etc.).

More generally, directions of improvement for the development of climate services include:

- to further precise locally the historical and future evolution of climate-related hazards (e.g. heatwaves, droughts, storm surges), including a reduction of scientific uncertainties (e.g. precipitation, sealevel rise)
- to better derive these hazards into societal impacts (e.g. on agriculture, infrastructure), and translate with stakeholders these impacts into potential adaptation measures (e.g. coastal protection)
- to reach new users (e.g. territorial decision-makers), and keep exchanging with the community of users about their issues, needs, the improvement of existing services and possible development of new services

A big question remains the necessary level of detail (spatial, temporal, uncertainty) needed for decision-making. An example of climate service prototype at city-scale is the "City Pack" that was developed for Bristol in the UK, co-produced to become a highly tailored and user-relevant tool. New demonstrators of climate services have also become available on DRIAS in the last months, such as for the urban planning of cities, the evolution of the water resource, or the coastal adaptation to marine submersion. Additionally, Chapter 6 highlighted the value of local climate analogs as a climate service. Climate analogs have already been applied in several studies (global, continental), and can serve to better characterize the climate shift of cities, to help inhabitants and decision-makers visualize their climate futures, and to support the identification of future climate impacts, vulnerabilities, and available adaptation options.

The nexus between climatology, social science and society

Climate change is a problem that is highly social. By addressing past and future developments in the Gulf of Morbihan, the activities carried out in this thesis allowed to discuss a large number of issues and themes. Several routes and responses have been identified to address the question of the need of climate services for local stakeholders. The tools, insights and perspectives developed in this research remain available to continue the adaptation of the Gulf to future climate change. Additionally, the overall approach used in my thesis to localize climate change could also be applied to other territories, adjusted to their own specificities (socioeconomic context, etc.).

Due to its mild climate, the Gulf of Morbihan will probably become a welcoming land for new populations. These changes require strategic thinking and an adequate strategy must also include the effects from climate change. To meet the future challenges to come, an active and collective approach of adaptation is needed, such as that initiated by the activities of the PNR, Clim'actions and in this thesis. A local group of scientific climate experts (GREC) is currently under construction in Brittany, who will build local scenarios of evolution for climate and society, based on multidisciplinary scientific expertise and supported by climate services.

In addition to the research outlined in this thesis, I participated to a summer school in 2019 about multidisciplinary research on climate change. The resulting insights from the summer school activities have been published in the journal *Natures Sciences Sociétés*, in the article *The challenges of interdisciplinary research and training courses on climate change: the Summer Seminar "About the 2 °C"* (Mathy et al., 2021).

A particularity of my thesis was the broad interaction between climatology and social science, and between academia and society. Due to the wide-ranging nature of climate change, both academia and society have to deploy new ways to deal with its multiple factors. Social science can act as a facilitator between climatology and societal action, in order to address climate change at all levels of society. For instance, localizing climate science was difficult in my thesis but raised new questions of climate research (local analogs). Yet the interaction between the three communities remains limited today. The question remains: if we want to completely address climate change, how to increase the interaction between the three communities (climatology, social science, society)? I hope that my thesis will highlight the value of conducting climate change research that is interdisciplinary and societally relevant.

Appendix

A.1 Actions 11-25 of the backcasting trajectory

Table A.1: Actions (11-17) of the backcasting trajectory (Wardekker et al., 2020).

Reference	Action	Description	Local issues
11	Technical innovation in favour of primary activities	Develop technical solutions and implement sustainable practices in the primary sector (permaculture, agroforestry, oyster culture in open sea, climate-resilient species, algae as a substitute for meat, etc).	<ul style="list-style-type: none"> • Biodiversity conservation and environmental protection • Primary activities
12	Protection of agricultural lands	Assure sufficient agricultural land is available by means of spatial planning regulation.	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Primary activities
13	Develop renewable energy in the territory	Invest on renewable energy systems (solar, wind, marine, hydrogen from algae, etc), as well as in desalination and valorisation of by-products.	<ul style="list-style-type: none"> • Food and energy autonomy
14	Implement the energy transition	Implement and accelerate the energy transition, notably in the housing sector. Reduce residential energy consumption and improve thermal insulation.	<ul style="list-style-type: none"> • Housing • Food and energy autonomy
15	Reflect on seasonal and mixed use of spaces and infrastructures	Develop voluntary schemes of house sharing, notably during off-season (winter). Develop sensitizing tools concerning rational and multipurpose use of spaces and infrastructures for primary and tertiary activities.	<ul style="list-style-type: none"> • Tourism • Housing • Innovative economic models
16	Promote innovative and low carbon construction	Favour low carbon, innovative, climate-resilient construction, which values local resources.	<ul style="list-style-type: none"> • Housing
17	Incentivize the use of a local currency	Develop awareness raising actions and incentives to the use a complementary local currency, such as the Bizh, aiming to promote the local economy and strengthen ties between local stakeholders.	<ul style="list-style-type: none"> • Innovative economic models

Table A.2: Actions (18-25) of the backcasting trajectory (Wardekker et al., 2020).

Reference	Action	Description	Local issues
18	Create Social and Solidarity Economy Investors Clubs	Create "Investors Clubs" to finance and support projects developed in the Social and Solidarity Economy model, especially initiatives concerning sustainable development and the fight against climate change.	<ul style="list-style-type: none"> • Innovative economic models
19	Develop service and functional economy	Imagine new professions and work possibilities linked to service and functional economy, aiming to create local, long-term employment. Some possibilities are barter exchange platforms, objects and material sharing, rental of boats and mooring points, as well as reuse and recycling initiatives.	<ul style="list-style-type: none"> • Innovative economic models • Tourism • Demographic balancing
20	Reinforce housing policy and programmes	Develop more housing programmes regarding buying and renting options, favoring social, generational and demographic balance in the territory.	<ul style="list-style-type: none"> • Demographic balancing
21	Increase young people's interest in the territory	Invest in public infrastructure (such as public spaces for collective activities, transport networks, etc.) in order to create an attractive territory for younger generations	<ul style="list-style-type: none"> • Urbanisation and spatial planning • Demographic balancing
22	Increase the capacity of wastewater treatment stations	Increase the capacity of the wastewater treatment stations located in the Rhuys peninsula, aiming to manage seasonal peaks and to efficiently treat pollutants such as heavy metals, medicines, phosphate and nitrate.	<ul style="list-style-type: none"> • Cleaner environment
23	Develop programs of environmental education	Create programs of environmental education and awareness raising for publics of all age, including kids.	<ul style="list-style-type: none"> • Cleaner environment
24	Increase coastal reserve areas	Increase the coastal reserves registered in spatial planning documents, in order to protect a larger area of the coastline. This could possibly be conceived to set the basis for a future governmental buyback program.	<ul style="list-style-type: none"> • Urbanisation and spatial planning
25	Set limits to urban sprawl	"Redensify" and vegetate cities, especially by favoring the construction of higher buildings in downtown areas.	<ul style="list-style-type: none"> • Urbanisation and spatial planning

A.2 Supplement of research article "Seasonal circulation regimes: towards new seasonality?"

ORIGINAL ARTICLE

Supporting information of "Seasonal circulation regimes in the North Atlantic: towards new seasonality?"

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† Design of the research, interpretation and discussion of findings, drafting the article, article revision.

‡ Interpretation and discussion of findings, article revision.

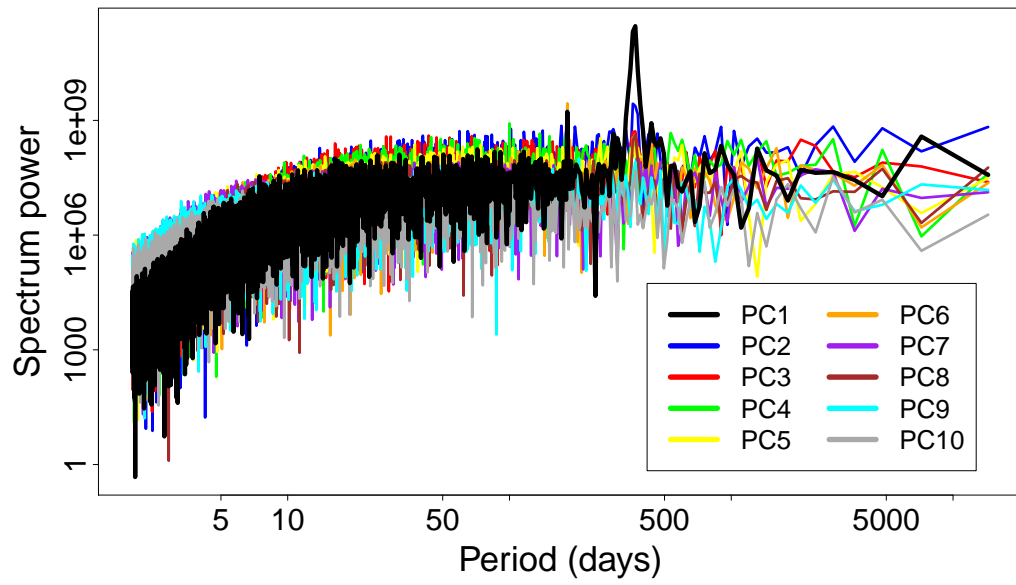


FIGURE S1 Spectral power captured by each PC in function of the period for Z500 from ERAI over 1979-2017.

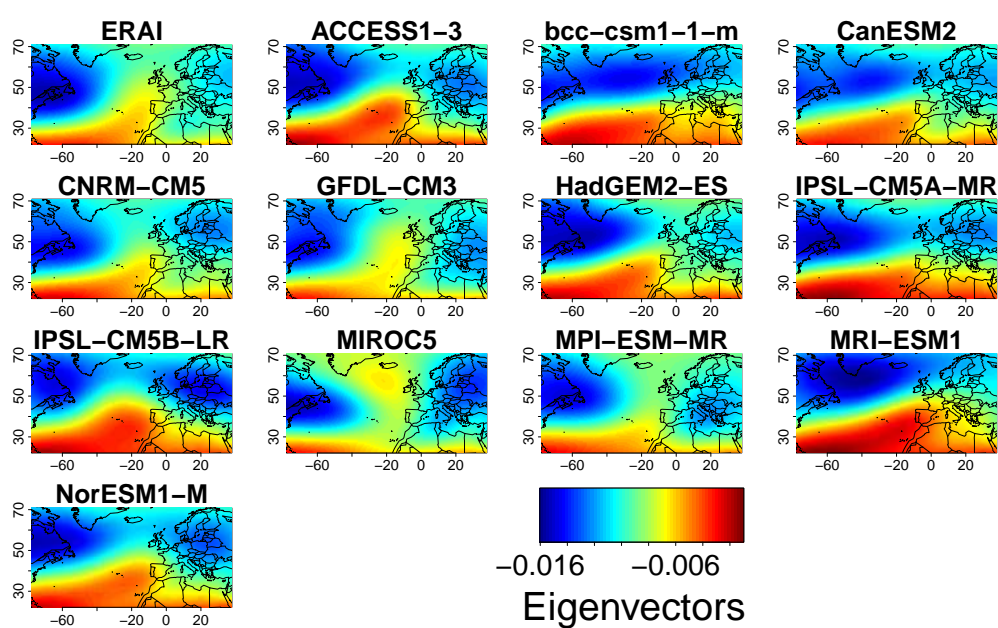


FIGURE S2 Maps of PC1 eigenvectors for ERAI and each climate model over 1979-2017 (exception of HadGEM2-ES: 1981-2017).

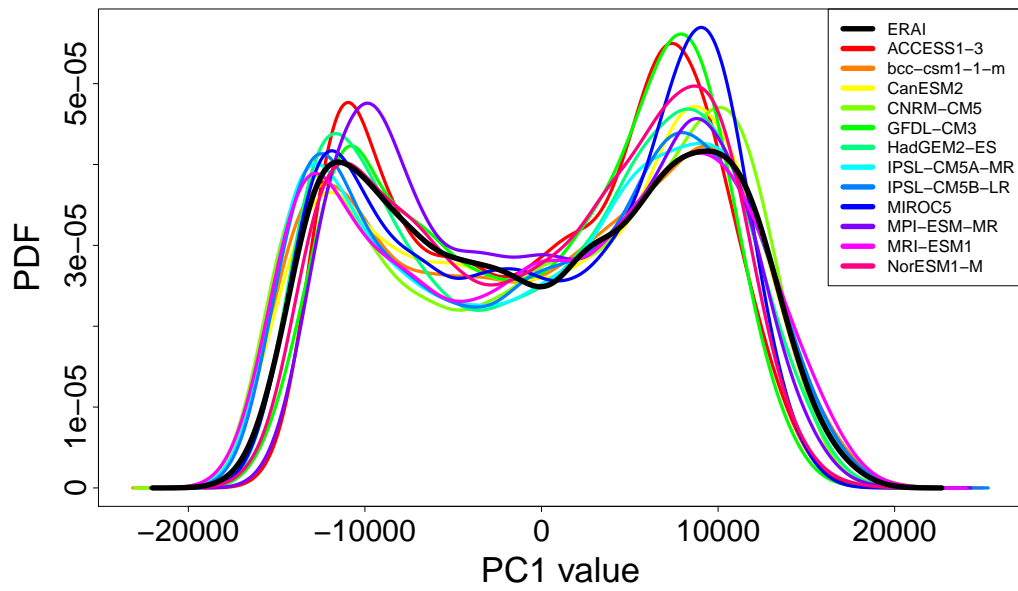


FIGURE S3 Probability distribution function of PC1 for ERAI and each climate model over 1979-2017 (exception of HadGEM2-ES: 1981-2017).

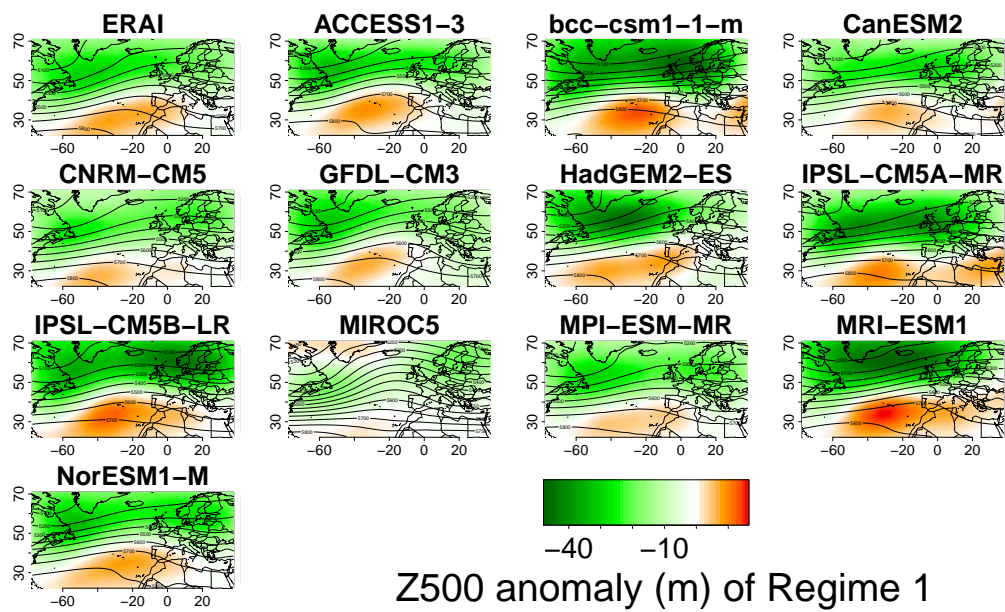


FIGURE S4 Composite maps of the first regime for ERAI and each climate model. Color shades show Z500 seasonal anomalies (raw Z500 minus the average seasonal cycle) and contours show raw Z500 values according to the regimes.

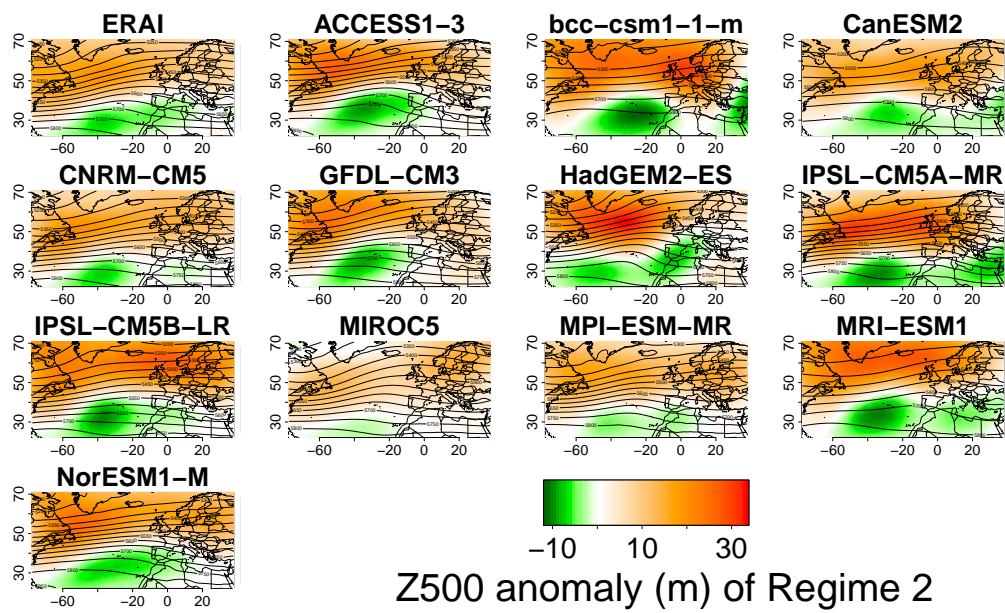


FIGURE S5 As in Figure S4 but for the second regime.

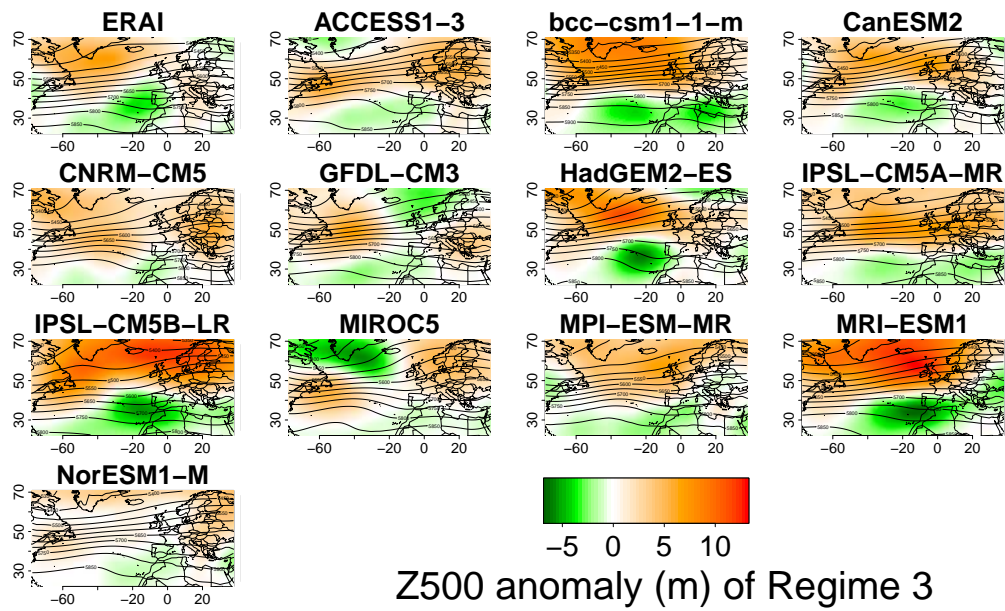


FIGURE S6 As in Fig. S4 but for the third regime.

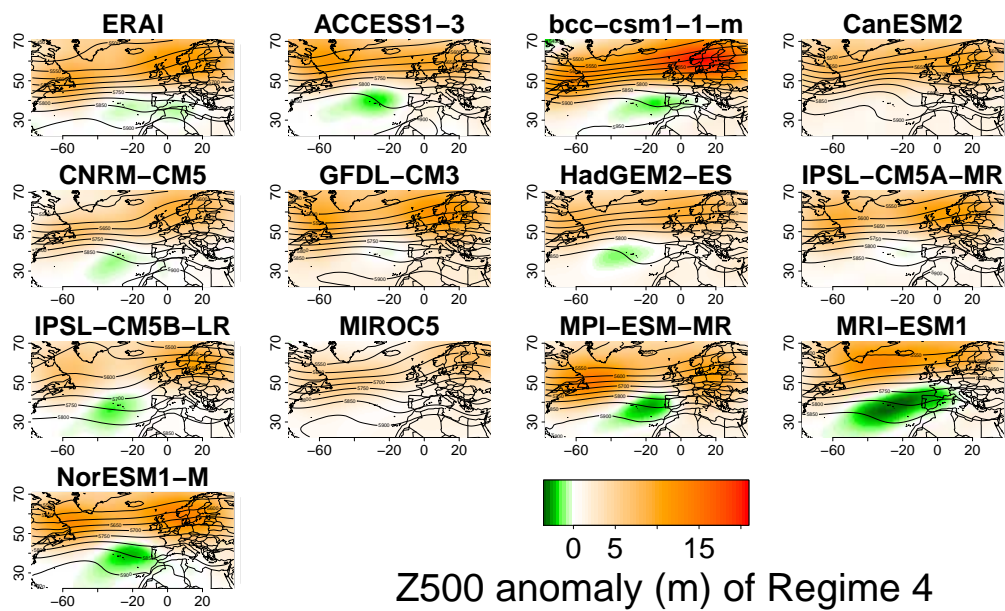


FIGURE S7 As in Fig. S4 but for the fourth regime.

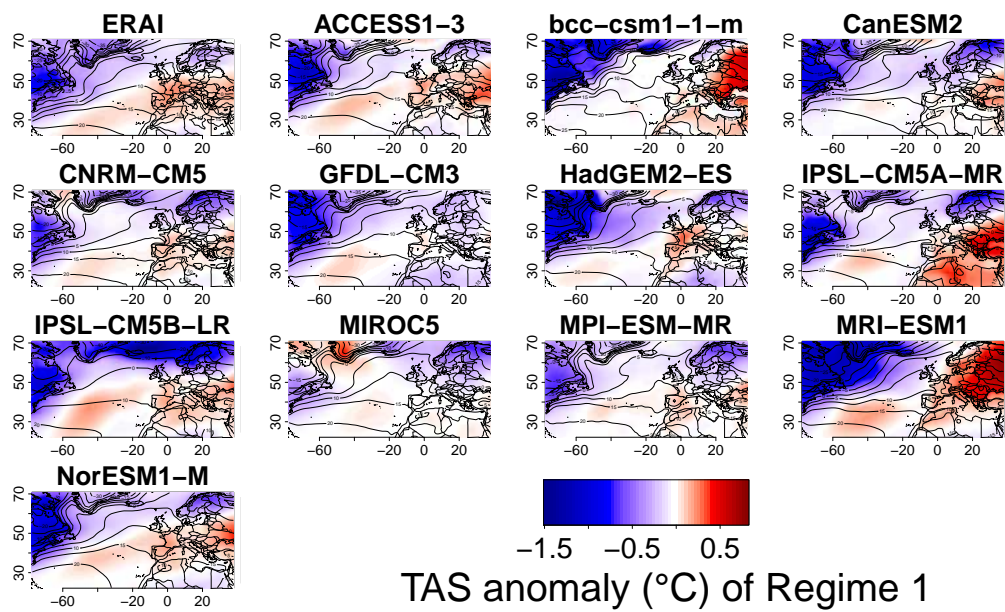


FIGURE S8 Composite TAS maps conditional to the first regime for ERAI and each climate model. Color shades show TAS seasonal anomalies (raw TAS minus the average seasonal cycle) and contours show raw TAS values according to the regime.

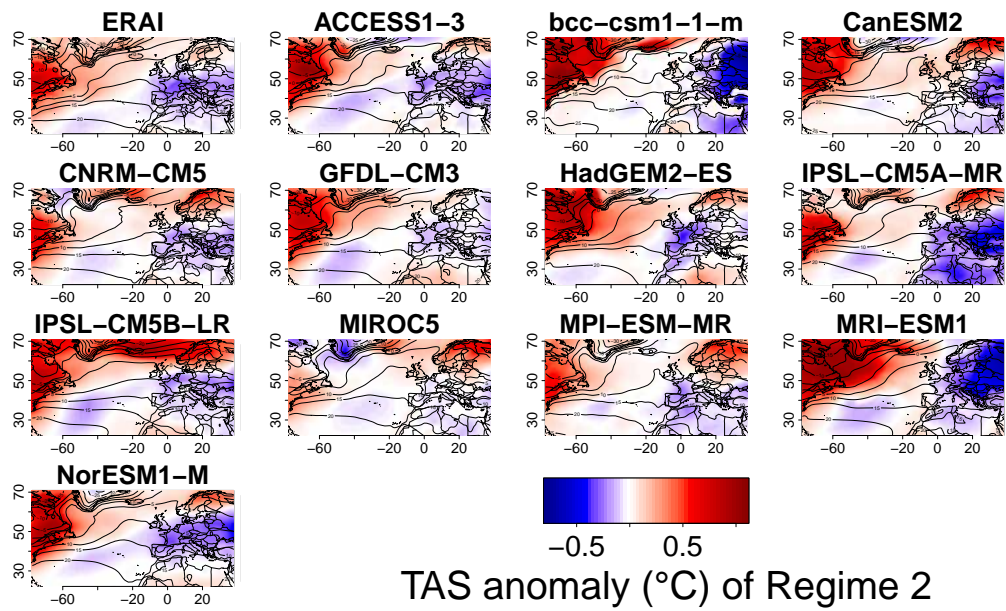


FIGURE S9 As in Fig. S8 but for the second regime.

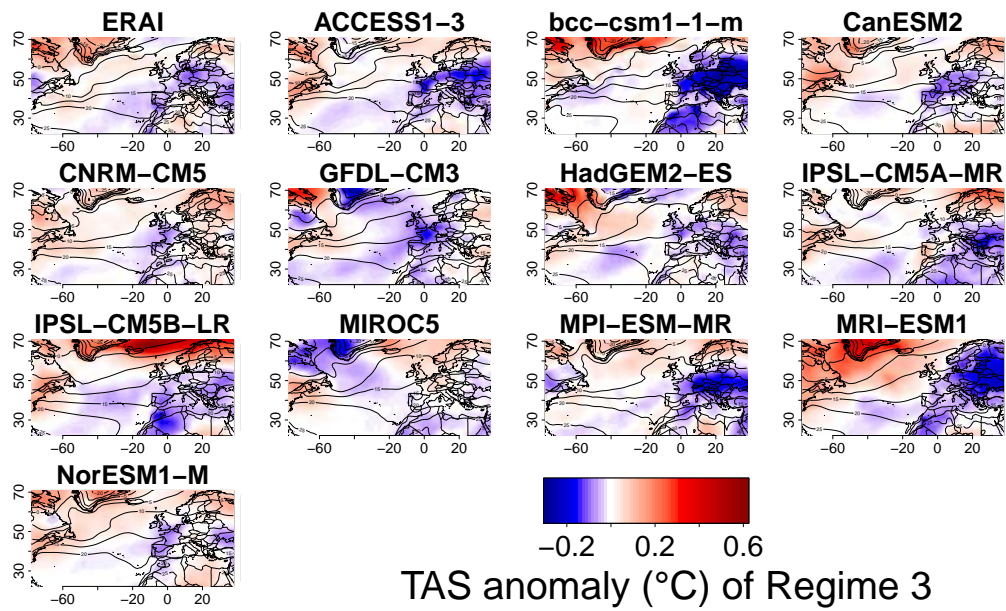


FIGURE S10 As in Fig. S8 but for the third regime.

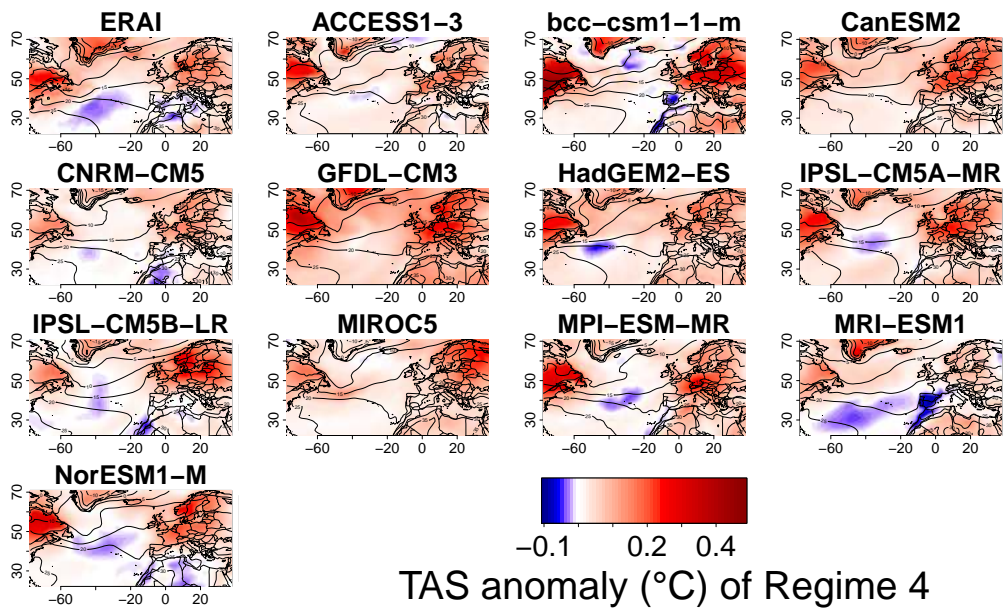


FIGURE S11 As in Fig. S8 but for the fourth regime.

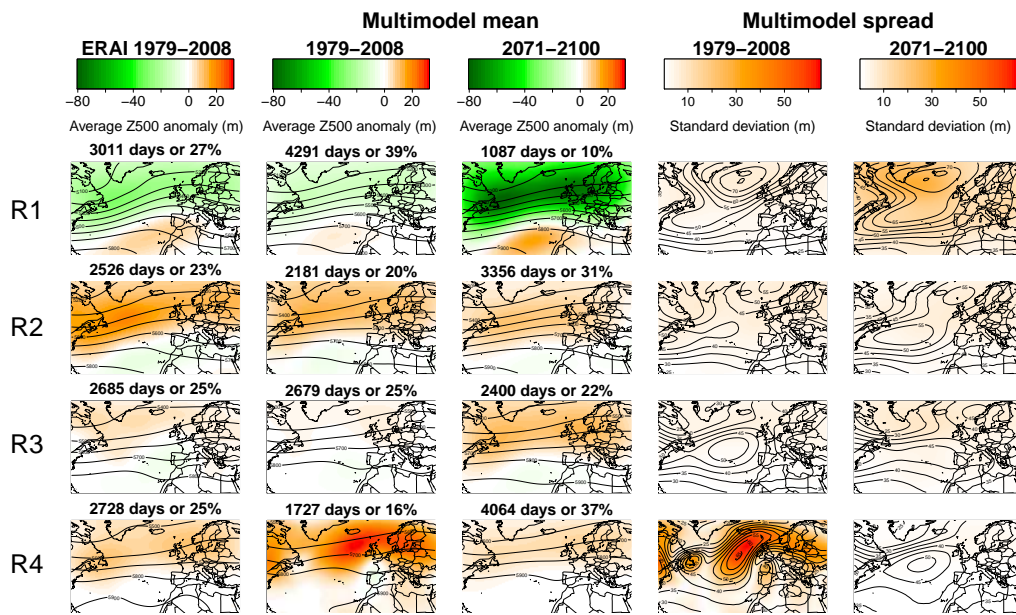


FIGURE S12 Composite maps of the four regimes (one per row) in the past (1979–2008) for ERAI (first column) and the 12 climate models (second column), and future (2071–2100) for climate models (third column). Color shades show Z500 seasonal anomalies (raw value minus the 30-year average seasonal cycle) and contours show raw Z500 values. The composite maps for climate models are averaged over the 12 composites (the standard deviation is shown for the past (fourth column) and future (fifth column)). The number of days per regime is shown above the maps (average of 12 values for the models). The clustering was done over the full time period (1979–2017 for ERAI, 1979–2100 for 11 climate models and 1981–2099 for Hadley). The clustering and calculation of raw Z500 values and seasonal anomalies was done individually for each dataset.

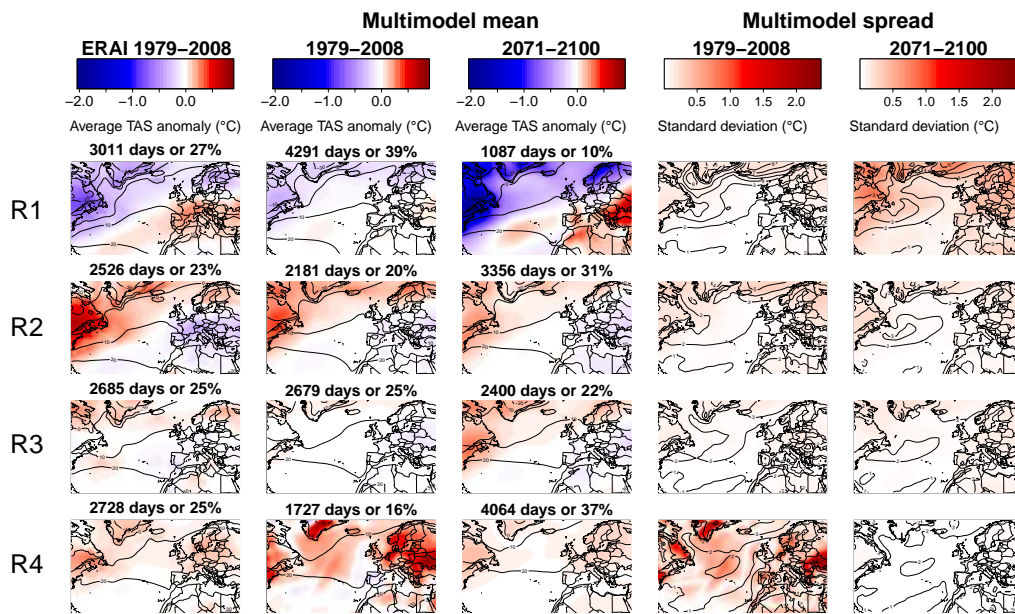


FIGURE S13 As in Fig. S12 but for TAS conditionally to the regimes.

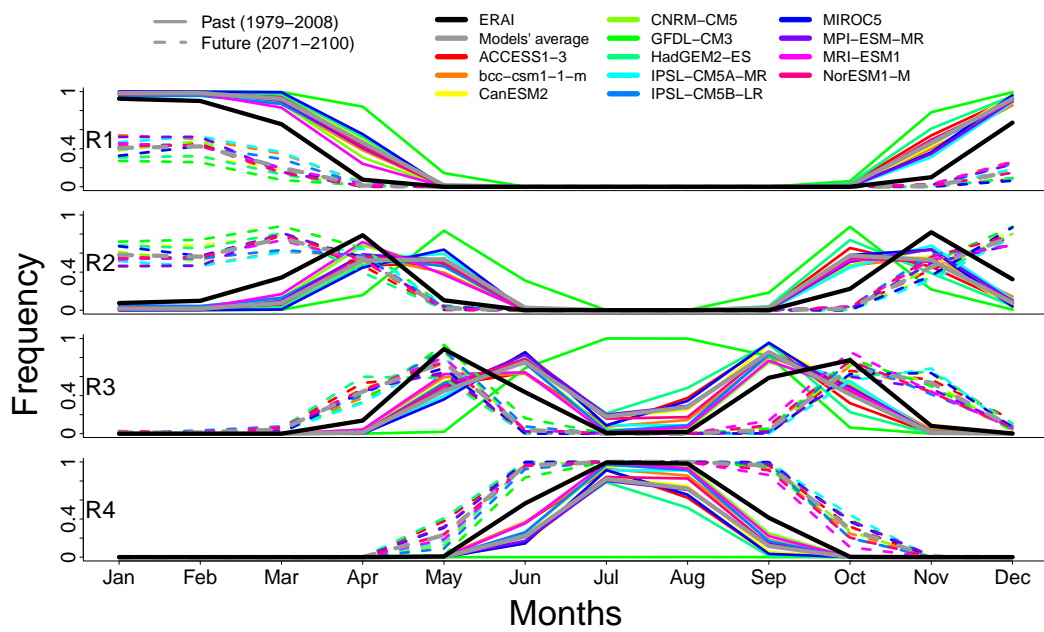


FIGURE S14 Average annual cycle of the four regimes for ERAI and climate models in the past (1979-2008) and future (2071-2100).

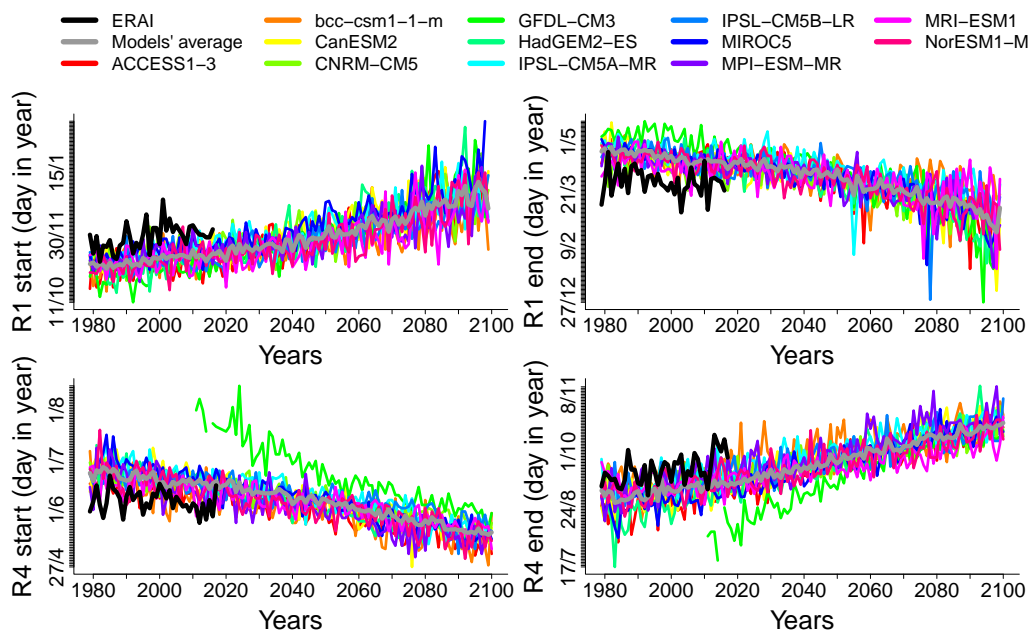


FIGURE S15 First and last dates of R1 (winter conditions) and R4 (summer conditions) occurrence in ERAI (1979-2017) and climate models (1979-2100).

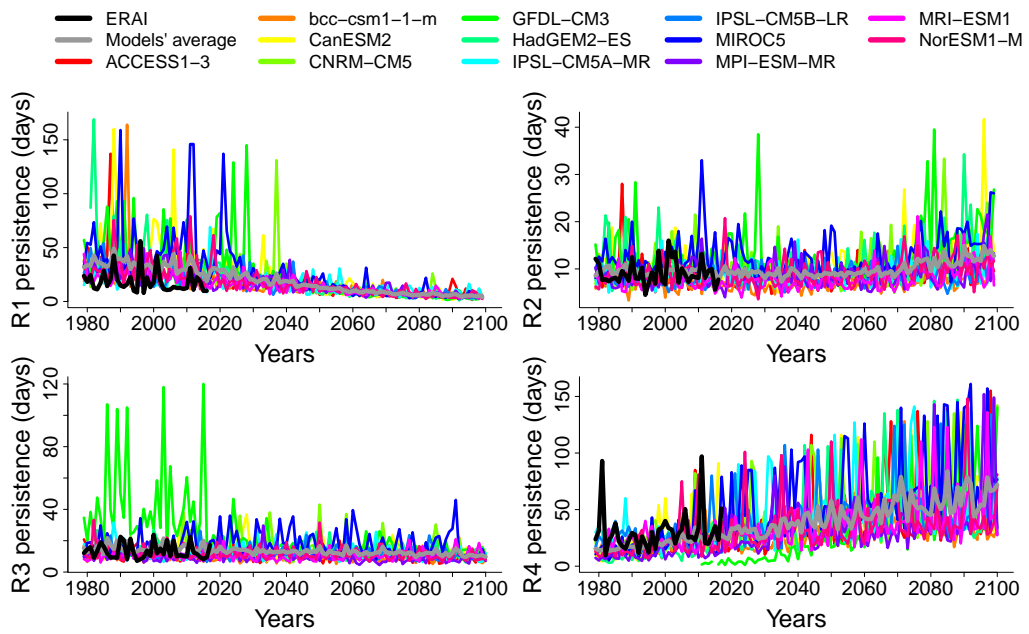


FIGURE S16 Average persistence of the four regimes in ERAI (1979-2017) and climate models (1979-2100).

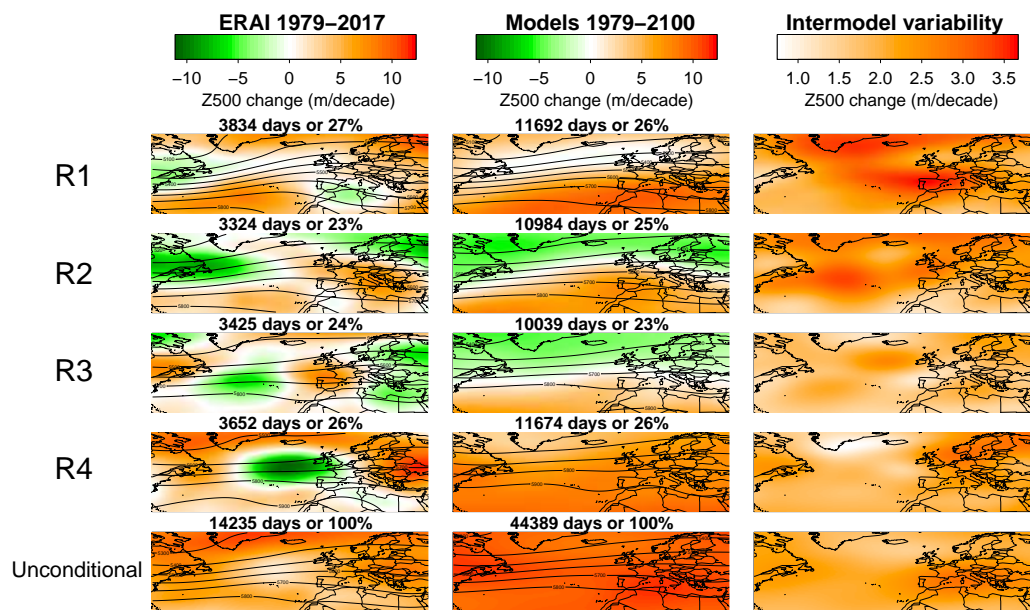


FIGURE S17 Maps of linear trends by regime (one per row) for ERAI (first column) and climate models (second column; third column: standard deviation). Color shades show trends and contours show raw Z500 values according to the regimes. The number of days per regime is shown above the maps (average of 12 values for the climate models). Multimodel results are represented through the mean of the trends (slope and p-value). Grey areas correspond to trends that are not significant (p -value > 0.05).

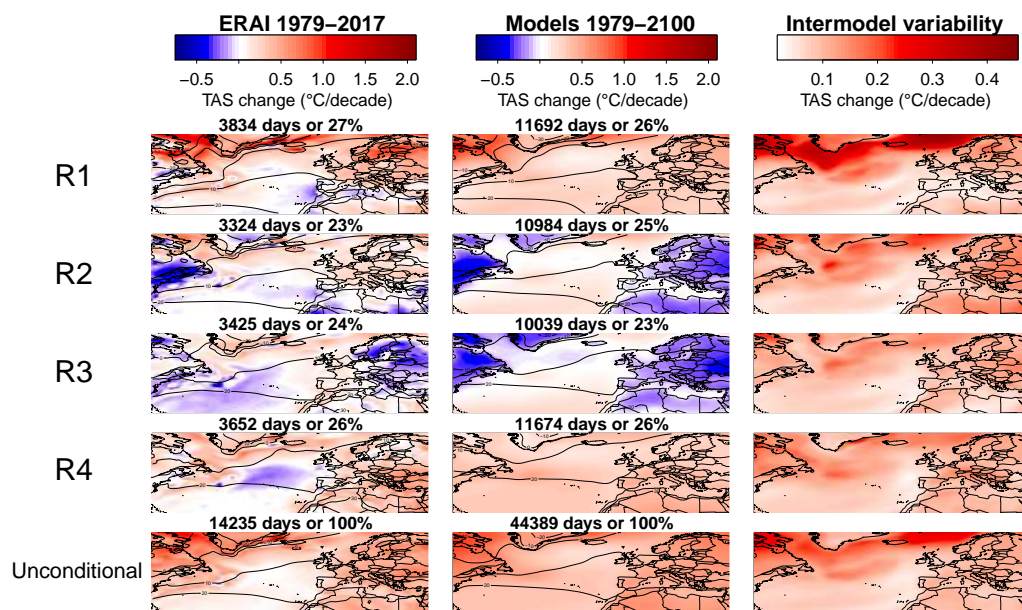


FIGURE S18 As in Fig. S17 but for TAS.

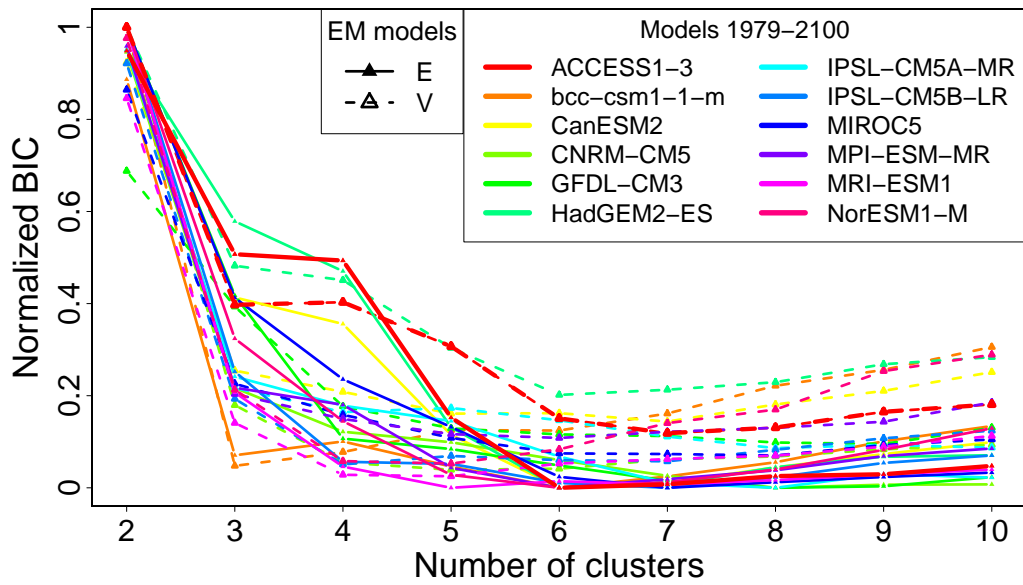


FIGURE S19 Bayesian information criterion (BIC) of the clustering models in function of the number of clusters and model type for each climate model over 1979-2100 (exception of HadGEM2-ES: 1981-2099). The BIC values are normalized between 0 (best EM model) and 1 (worst EM model). E: equal variance, V: variable variance.

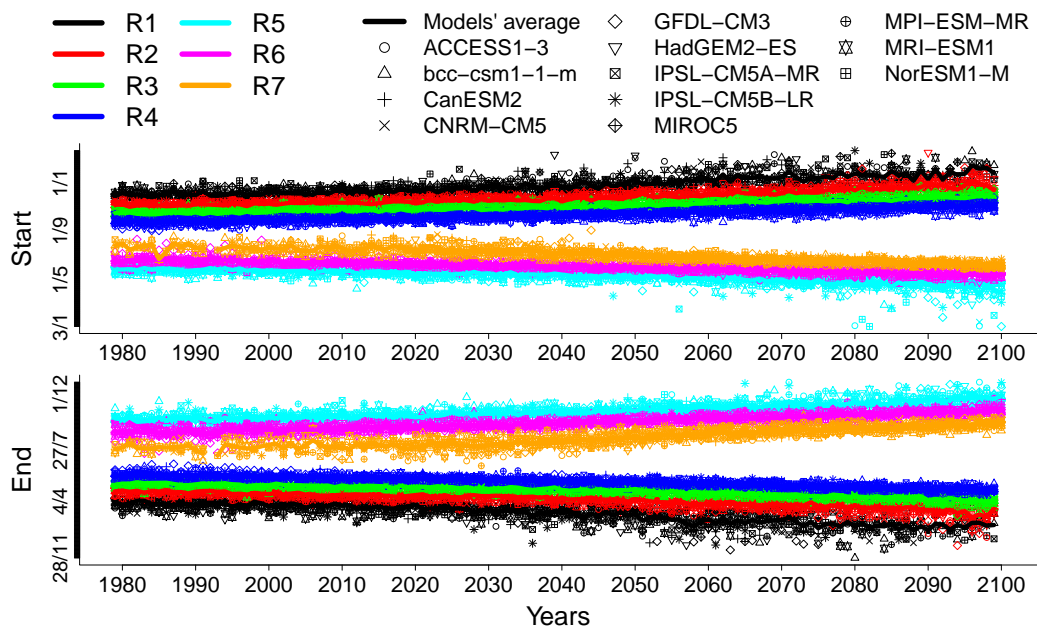


FIGURE S20 As in Fig. S15 but with seven regimes for climate models (without ERAI). Regimes are indicated by color and climate models by symbol.

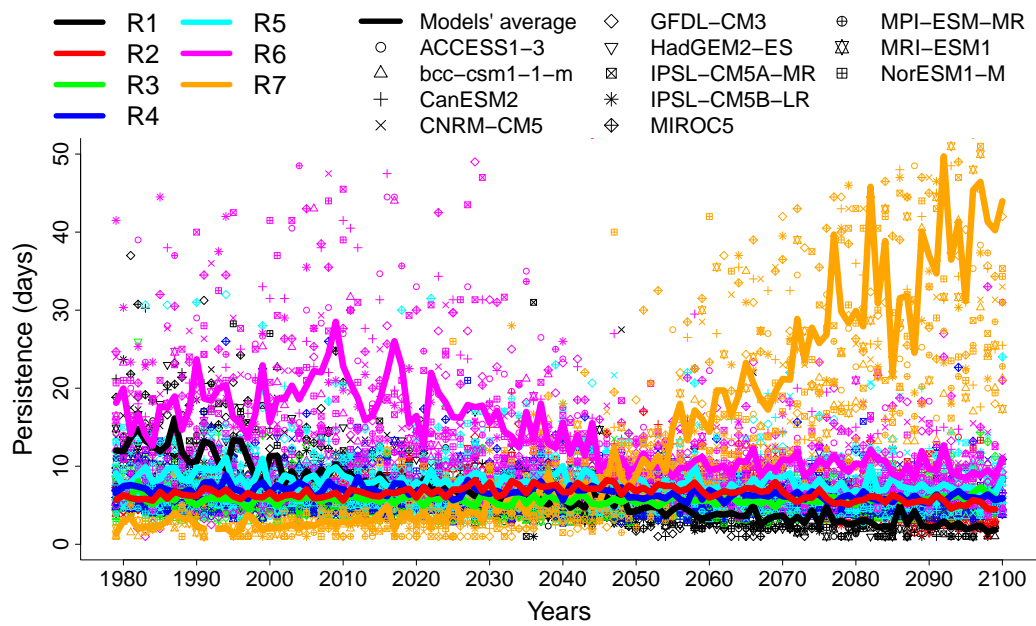


FIGURE S21 As in Fig. S16 but with seven regimes for climate models (without ERAI). Regimes are indicated by color and climate models by symbol. This figure emphasizes the average model evolution and regime persistence can exceed 50 days in individual models (not shown here).

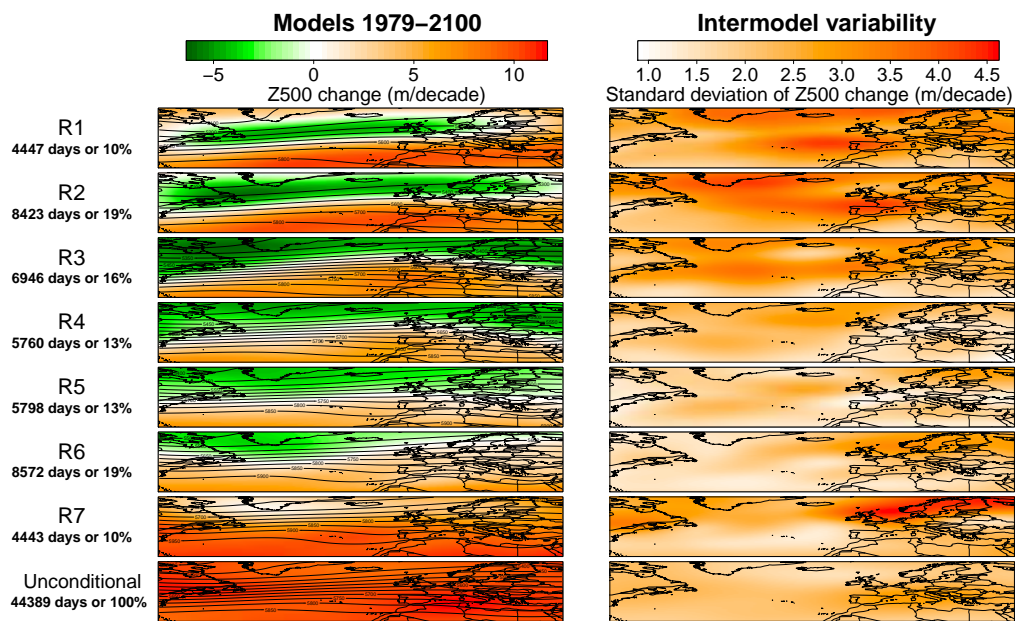


FIGURE S22 As in Fig. S17 but with seven regimes for climate models (without ERAI).

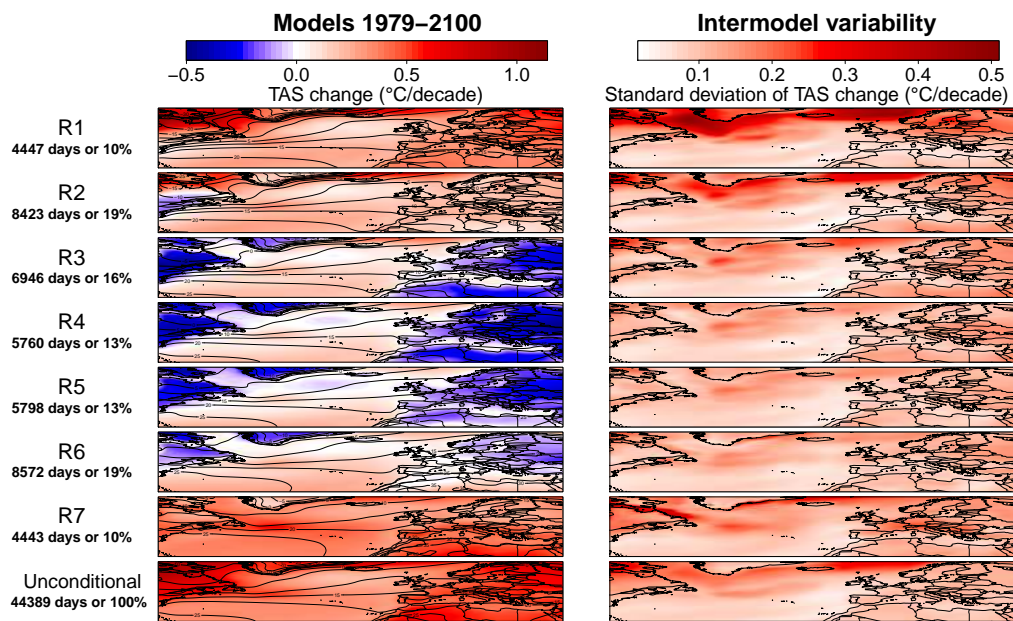


FIGURE S23 As in Fig. S22 but for TAS conditionally to the regimes.

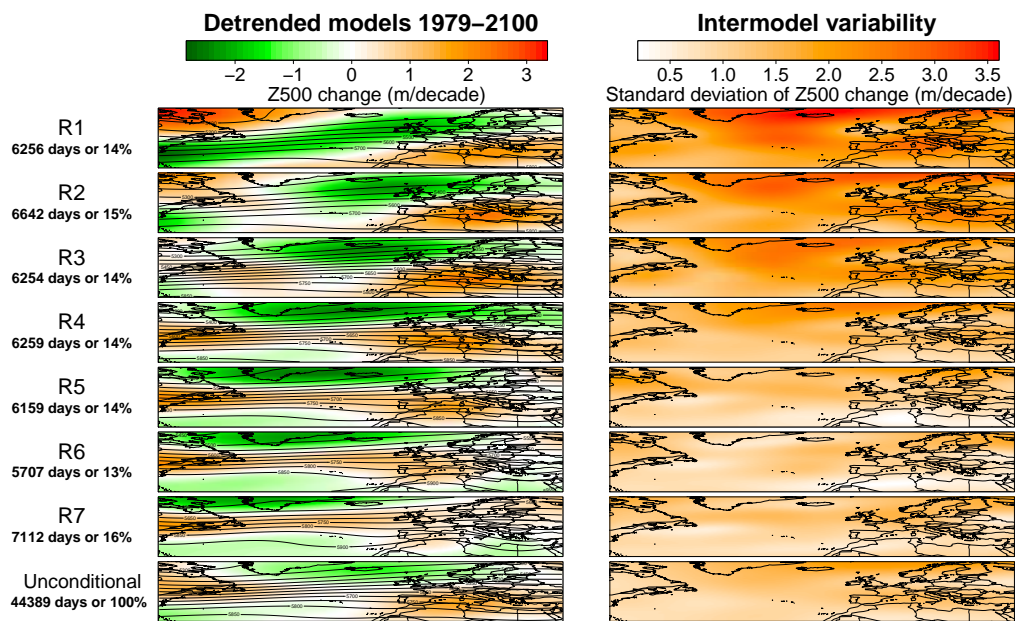


FIGURE S24 As in Fig. S22 but after detrending the data from climate models.

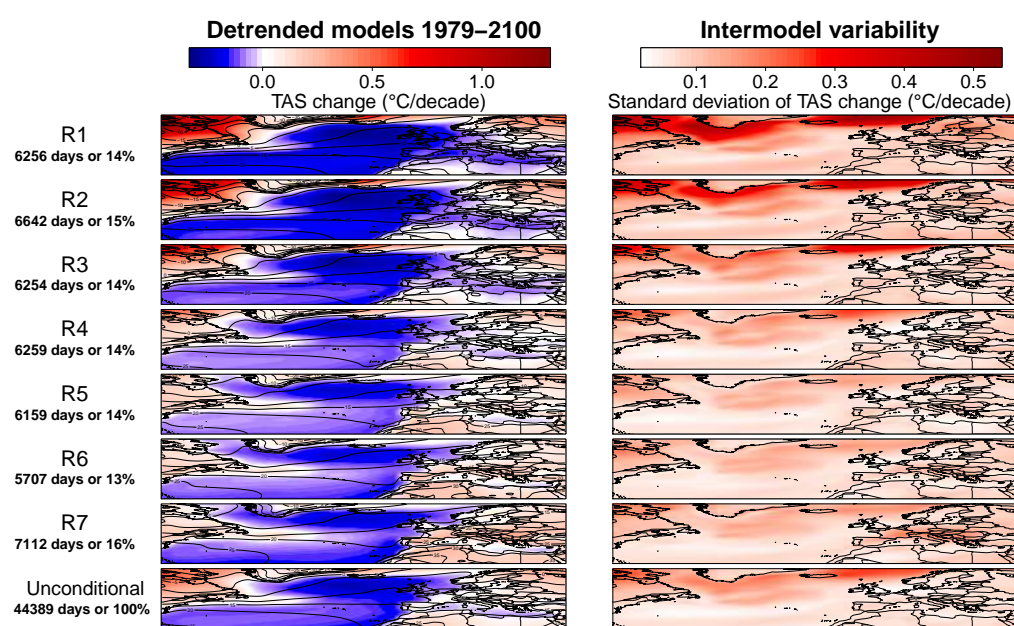


FIGURE S25 As in Fig. S24 but for TAS.

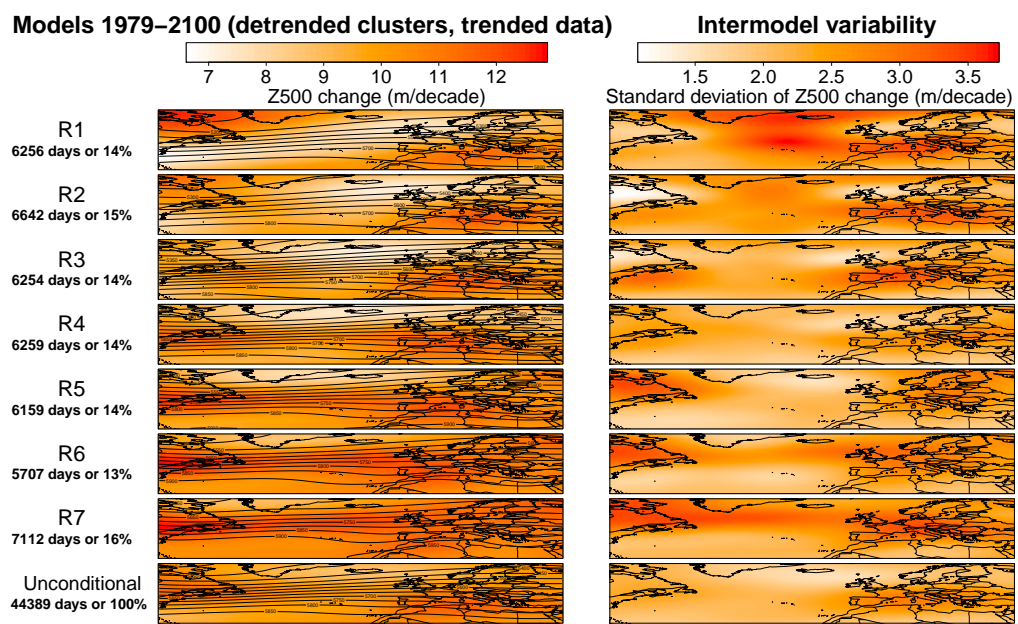


FIGURE S26 Regime composite maps calculated on Z500, conditionally to the clusters defined on detrended Z500.

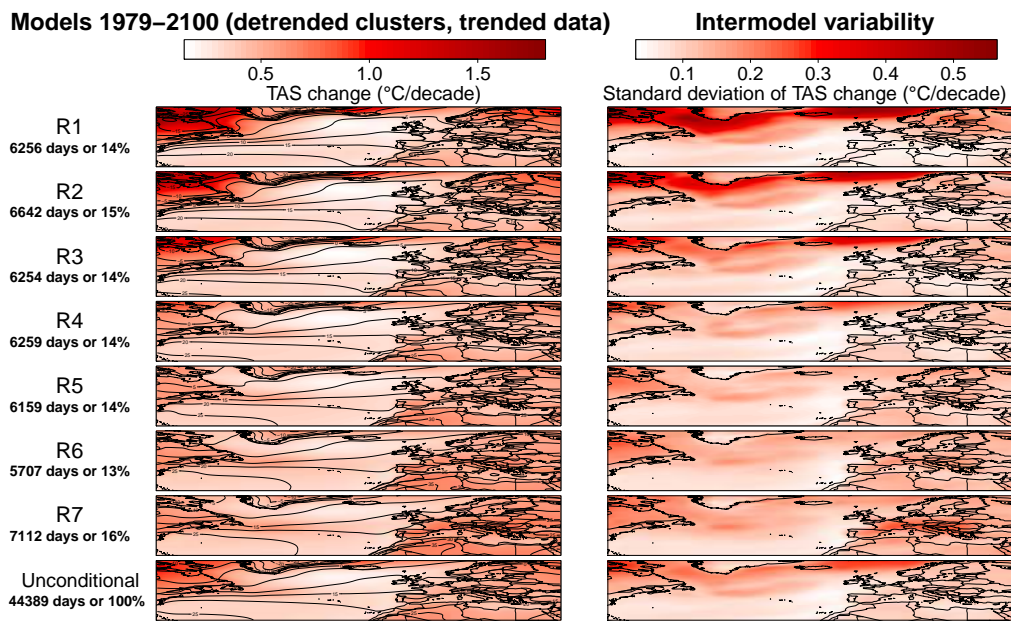


FIGURE S27 Regime composite maps calculated on TAS, conditionally to the clusters defined on detrended Z500.

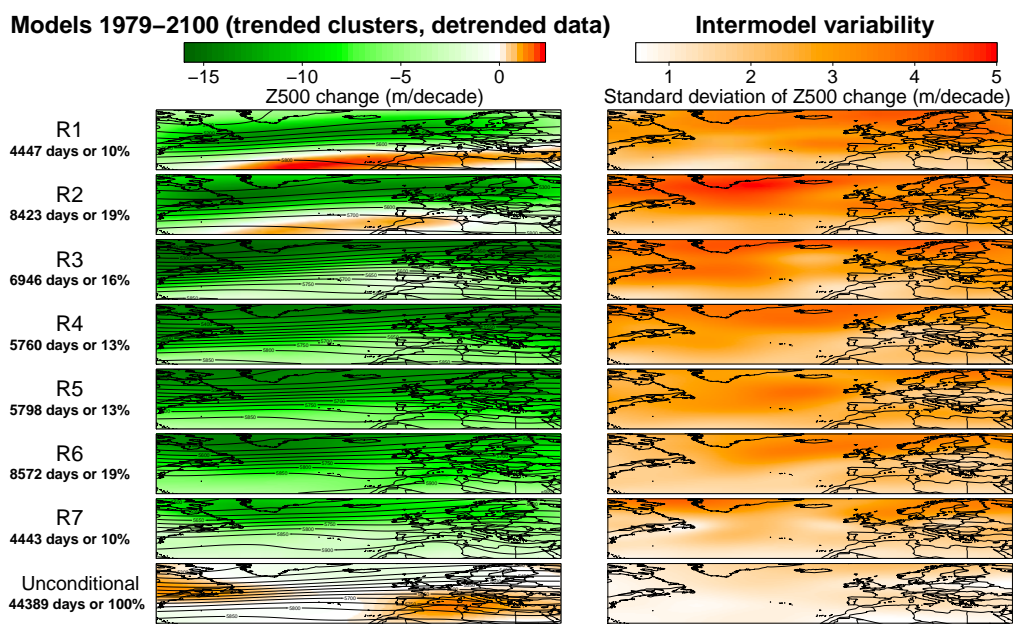


FIGURE S28 Regime composite maps calculated on detrended Z500, conditionally to the clusters defined on Z500.

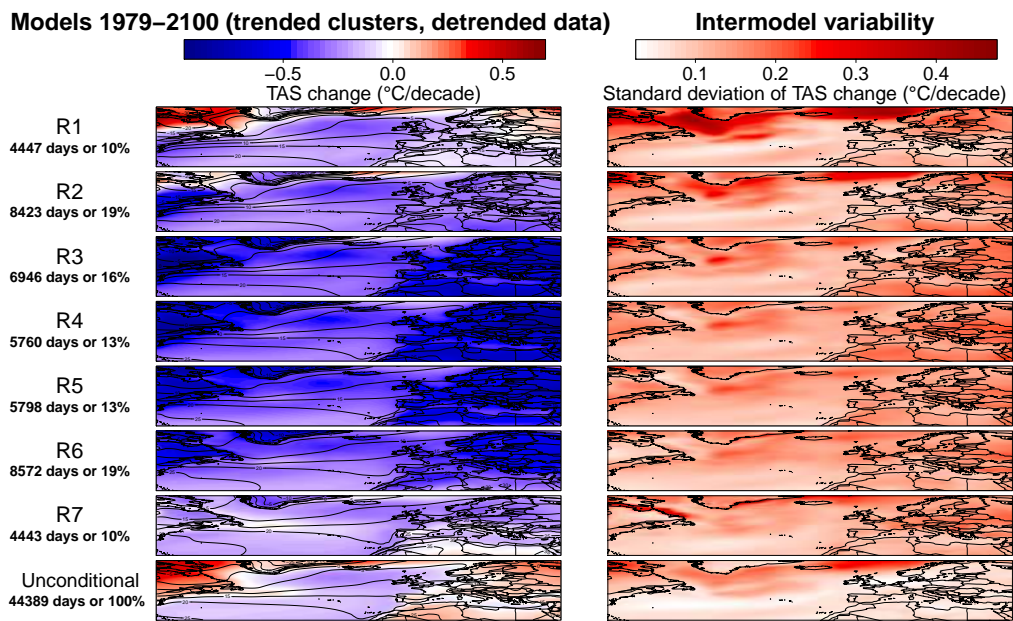


FIGURE S29 Regime composite maps calculated on detrended TAS, conditionally to the clusters defined on Z500.

A.3 Supplement of study on climate analogs

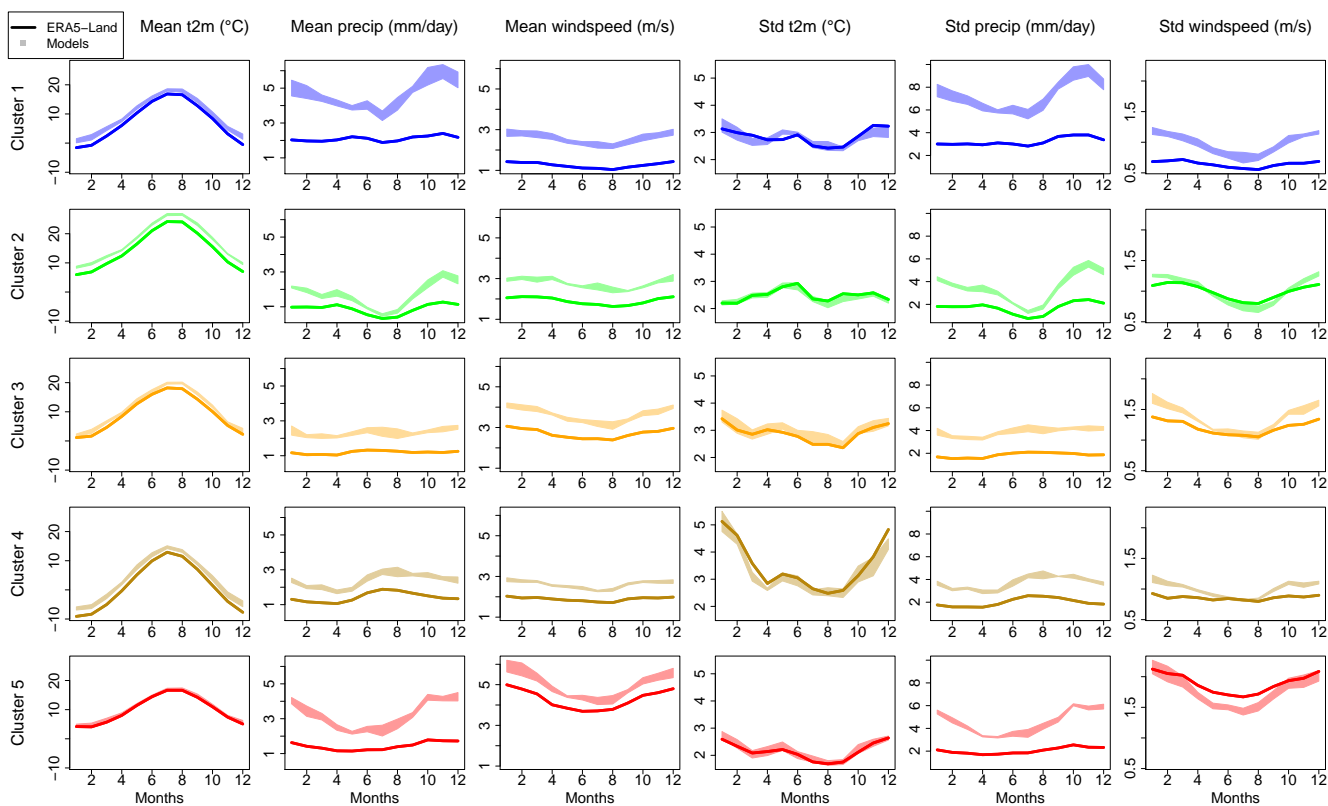


Figure A.1: Cluster properties with K-means ($k=5$) on ERA5-Land (1981-2020) and the five models (1971-2100). Each row (and color) corresponds to a cluster and each column to a monthly statistic of meteorological variable. The clusters from ERA5-Land are shown in solid line, and from the models in shaded envelope.

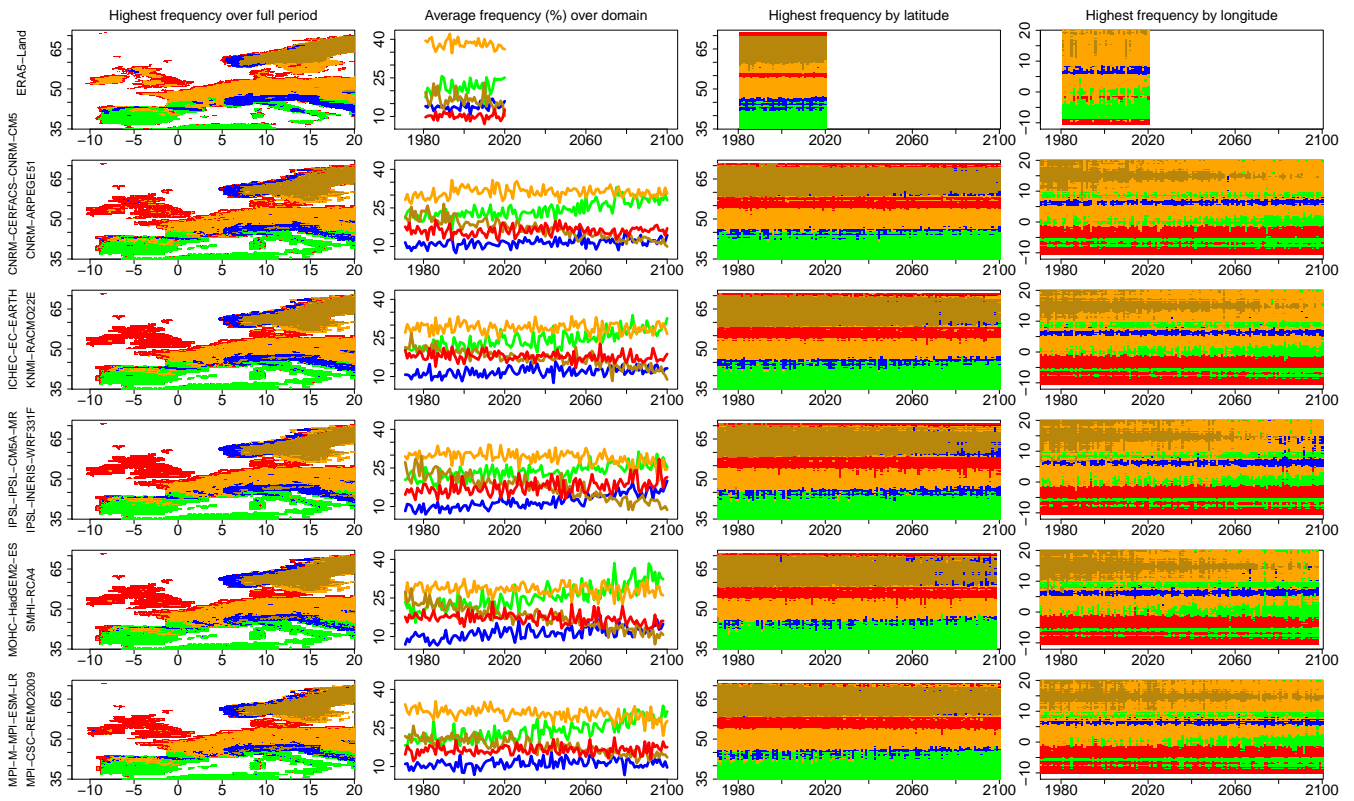


Figure A.2: Cluster evolution with K-means ($k=5$) on ERA5-Land (1981-2020) and the five models (1971-2100). First column: dominant cluster per location over the full period. Second column: annual cluster frequency over the full domain. Third column: annual dominant cluster per latitude. Fourth column: annual dominant cluster per longitude. The first row corresponds to the clusters from ERA5-Land, and each successive row to the clusters from a model. Each cluster corresponds to a color as defined in Figure A.1.

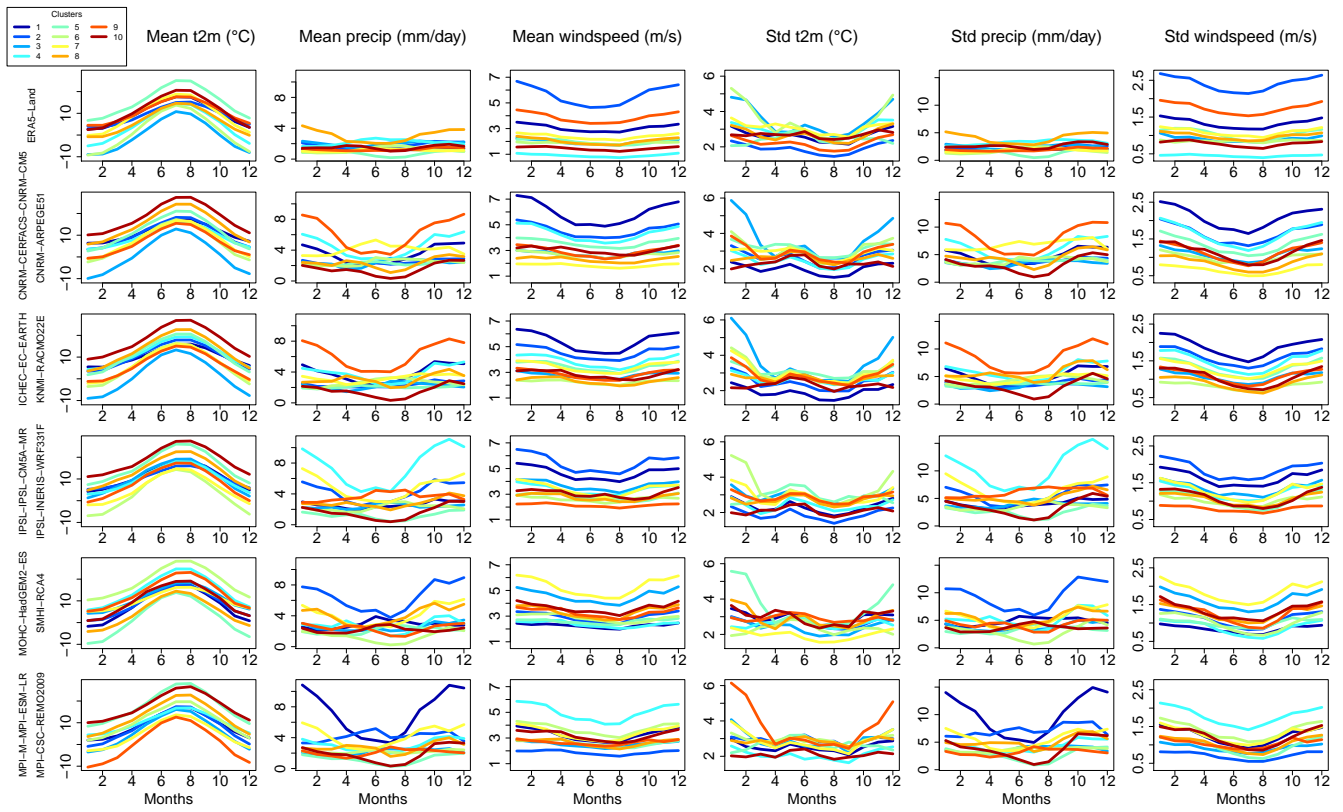


Figure A.3: Similarly to Figure A.1, but for 10 clusters. Each row corresponds to one dataset.

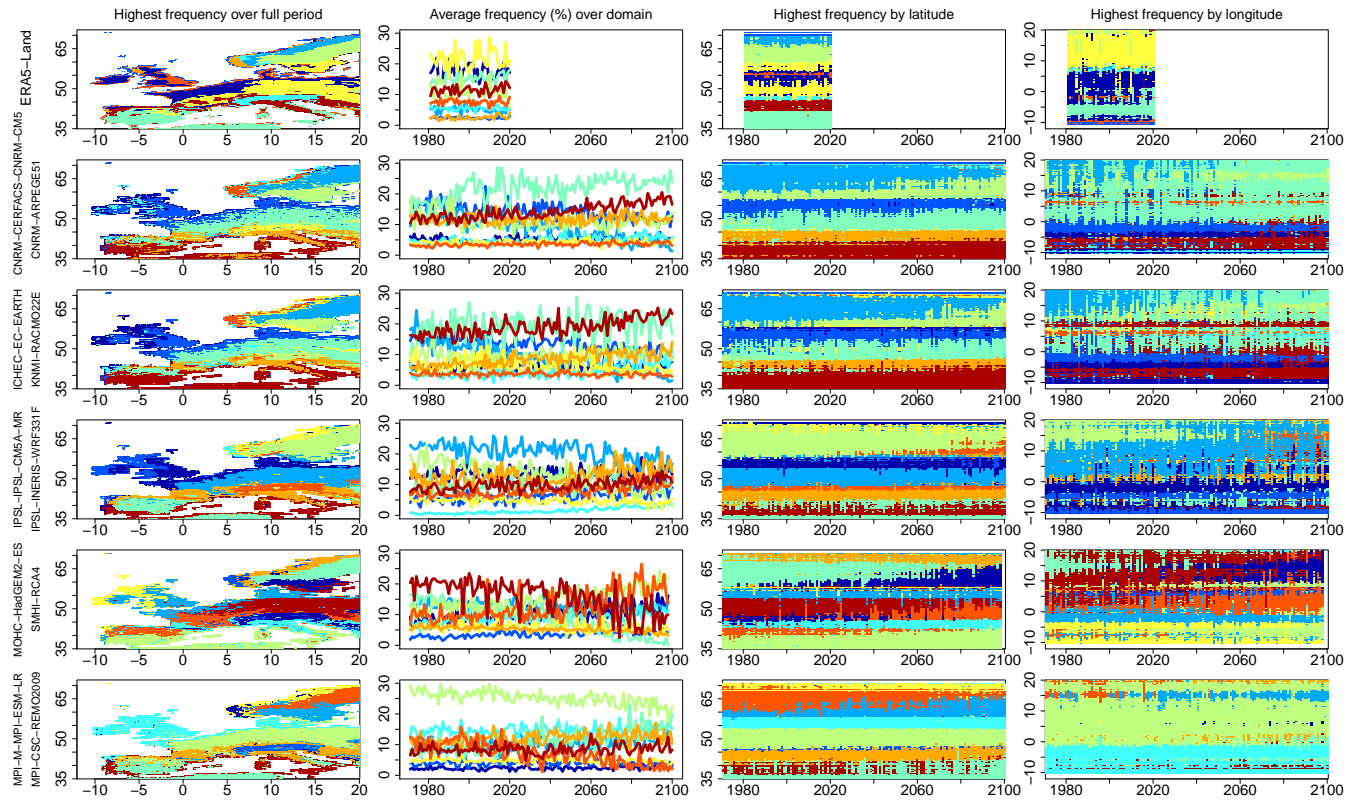


Figure A.4: Same as in Figure A.2, but for 10 clusters. Each cluster corresponds to a color as defined in Figure A.3.

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Titre : Changement climatique en Europe : co-développement de services climatiques locaux et approches de classification non-supervisée

Mots clés : Changement climatique, territoire, adaptation, services climatiques, statistiques, circulation atmosphérique

Résumé : Le changement climatique a diverses conséquences sur la société, mais les changements futurs sont incertains et un gouffre subsiste entre les connaissances scientifiques et l'action sociétale (atténuation, adaptation). L'écart en adaptation a été comblé en partie par l'essor récent des services climatiques, mais leur utilisation à l'échelle locale est liée à de nombreux obstacles. La France est un exemple de manque d'adaptation climatique au niveau territorial, et cette thèse se concentre sur le Golfe du Morbihan comme cas d'étude. Ma recherche vise premièrement à identifier le rôle local du changement climatique, deuxièmement à soutenir le développement local de l'adaptation, et troisièmement à explorer le changement climatique futur avec des approches de classification (non-supervisée).

Pour identifier le rôle local du changement climatique, j'ai analysé la littérature (grise et académique) et engagé des entretiens de terrain avec différents acteurs. Le territoire est particulier : contraste littoral-intérieur (économie, démographie), vie socio-économique organisée saisonnièrement, dépendance et conflit entre agriculture et tourisme. Le rôle local du changement climatique est complexe, impactant des activités emblématiques (ostréiculture, production de sel), se superposant à des problématiques existantes (déséquilibre socio-économique, conflit d'usage des terres), et affectant négativement l'agriculture mais positivement le tourisme. Les expériences locales sont généralement conformes aux connaissances scientifiques, mais certains éléments sont rares dans les perceptions locales.

Pour soutenir l'adaptation locale, j'ai participé à l'expérimentation de différentes activités de prospective (atelier de scénario, exposition art-science, conférence-débat) avec des acteurs locaux, basées sur un inventaire des services climatiques et sur des outils créatifs d'art-design (par exemple, des cartes à jouer). Les principaux résultats sont deux scénarios à long terme et de multiples actions à court

terme. Les deux scénarios représentent des visions divergentes du territoire : occupation continue de la côte malgré l'augmentation des risques côtiers, ou retrait de la côte et densification des zones urbaines à l'intérieur des terres. Les scénarios dépendent de l'urbanisation et de l'aménagement du territoire, de l'autonomie alimentaire et énergétique, et de l'équilibre démographique. Le thème de l'autonomie alimentaire et énergétique concentre les points de vue contradictoires entre les habitants.

Plusieurs thèmes climatiques locaux sont liés à la circulation atmosphérique, mais ses changements futurs sont très incertains. Pour étudier la saisonnalité future de la circulation, je classe des champs de hauteur géopotentielle durant toute l'année, à partir d'une réanalyse et plusieurs modèles climatiques. Les modèles climatiques, malgré leurs biais, reproduisent une évolution de la saisonnalité de la circulation qui est similaire à la réanalyse. Au cours des dernières décennies, les conditions hivernales ont diminué tandis que les conditions estivales ont augmenté, et ces changements se renforcent dans le futur. Néanmoins, la saisonnalité de la circulation reste similaire par rapport à l'augmentation moyenne du géopotentiel. J'ai par ailleurs développé une perspective de nouvelle approche pour étudier l'évolution locale de la saisonnalité météorologique, basée sur la classification de multiples variables (température, précipitations, vitesse du vent).

En plus des effets du changement climatique à venir, le Golfe du Morbihan va probablement accueillir de nouvelles populations, et une stratégie collective active d'adaptation est nécessaire. Plusieurs pistes ont été évoquées dans mes recherches pour répondre aux besoins locaux en matière d'adaptation climatique, notamment des perspectives inspirées des services climatiques existants dans d'autres pays. Les résultats de cette thèse mettent en évidence les dimensions physiques et sociales du changement climatique.

Title: European climate change: co-development of local climate services and clustering approaches

Keywords: Climate change, territory, adaptation, climate services, statistics, atmospheric circulation

Abstract: Climate change has various impacts on society, but future changes are uncertain and a wide gap remains between the scientific knowledge and societal action (mitigation, adaptation). The gap in climate adaptation was partly addressed by the recent growth of climate services, but their local usability is associated to many barriers. France is an example of lacking climate adaptation at territorial level, and this thesis focuses on the Gulf of Morbihan as a case study. My research aims first to identify the role of climate change in the territory, second to support the local development of adaptation planning, and third to explore future climate change through the angle of clustering approaches.

To identify the local role of climate change, I analyze the literature (grey and academic) and engage in field interviews with various stakeholders. Particular features of the territory emerge: the coastal-inland contrast (economy, demography), the socioeconomic life organized seasonally, and the dependence and conflict between agriculture and tourism. The local role of climate change is complex, impacting emblematic activities (oyster farming, salt production), overlapping with existing issues (socioeconomic imbalance, land-use conflict), and affecting agriculture negatively (warmer and drier summers) but tourism positively (longer summer weather). The local experiences are generally consistent with scientific knowledge (ongoing changes, link to climate change), although some elements are scarce in local perceptions (heatwaves).

To assist local adaptation, I participated to the experimentation of different foresight activities (scenario workshop, art-science exhibition, conference-debate) with local stakeholders, based on an assessment of climate services and on creative art-design tools (e.g. poker design cards). The main outcomes are two long-term scenarios, multiple short-term actions and several hinge points on which the scenarios depend. The two scenarios represent divergent vi-

sions of the territory: continued occupation of the coast despite increasing risks, or withdrawal from the coast and densification of urban areas inland. The scenarios depend on the issue development of urbanization and spatial planning, food and energy autonomy, and demographic balance. The theme of food and energy autonomy concentrates conflicting views between inhabitants, highlighting fears and desires about long-term territorial choices.

My investigation of the territory highlighted several climatic themes (e.g. seasonality of weather conditions) that are linked to atmospheric circulation, but future circulation changes are highly uncertain. To investigate the future seasonality of atmospheric circulation, I classify year-round patterns of geopotential height at 500 hPa (Z500) from a reanalysis and several climate models. Despite their biases, climate models reproduce similar evolution of circulation seasonality as the reanalysis. During the last decades, winter conditions have decreased while summer conditions have increased, and these changes strengthen under future climate change. Yet circulation seasonality remains similar relatively to the increase in average Z500, and the same happens for surface temperatures associated to the circulation patterns. I additionally developed the perspective of a new approach to study the local evolution of weather seasonality, based on the classification of multiple variables (temperature, precipitation, windspeed).

In addition to the effects from future climate change, the Gulf of Morbihan will probably welcome new populations, and an active collective strategy of adaptation is required. Several routes have been featured in my research to address the local needs in climate adaptation, including perspectives inspired from existing climate services in other countries. The findings from this thesis highlight the physical and social dimensions of climate change.

