Statistical and epistemological approaches of extreme event attribution

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Thèse de doctorat

Approches statistique et épistémologique de l'attribution d'événements extrêmes

Thèse de doctorat de l'Université Paris-Saclay
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“Un coup de dés jamais n’abolira le hasard.” – Stéphane Mallarmé [1]

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[1] “A throw of the dice never will abolish chance.” – Translated by A. S. Kline

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Summary

Extreme events are an expression of natural climate variability. Since anthropogenic emissions affect global climate, it is natural to wonder whether recent observed extreme events are a manifestation of anthropogenic climate change. This thesis aims at contributing to the understanding of the influence of anthropogenic climate change on observed extreme events, while assessing whether and how this scientific information – and more generally, the science of extreme event attribution (EEA) – could be useful for society. I propose statistical tools to achieve the former, while relying on qualitative interviews for the latter.

The statistical part focuses on European heatwaves. I quantify the role played by the atmospheric circulation in the intensity of four recent heatwaves. This analysis is based on flow analogues, which identify days with a similar circulation pattern than the event of interest. I then disentangle the influence of climate change on the dynamical and non-dynamical processes leading to heatwaves. I calculate trends in the occurrence of circulation patterns leading to high temperatures and trends in temperature for a fixed circulation pattern, applied to the 2003 Western Europe and 2010 Russia heatwaves. I find that the significance of the results depend on the event of interest, highlighting the value of calculating trends for very specific types of circulation.

The epistemological part evaluates the potential social uses of extreme event attribution. I assess how it could inform international climate negotiations, more specifically loss and damage, in response to a number of claims from scientists going in this direction. I find that the only potential role EEA could play to boost the loss and damage agenda would be to raise awareness for policy makers, aside from the negotiation process itself. I also evaluate how the different motivations stated by EEA scientists in interviews fare compared to the existing evidence on social use of this type of scientific information. I show that the social relevance of EEA results is ambiguous, and that there is a lack of empirical data to better understand how different non-scientific stakeholders react and appropriate EEA information.

Résumé

Les événements extrêmes sont l'expression de la variabilité climatique naturelle. Puisque les émissions anthropiques affectent le climat mondial, il est naturel de se demander si les événements extrêmes observés récemment sont une manifestation du changement climatique. Cette thèse se propose de contribuer à la compréhension de l'influence du changement climatique anthropique sur les événements extrêmes observés, tout en évaluant si et comment cette information scientifique – et plus généralement, l'attribution d'événements extrêmes (AEE) – pourrait être utile à la société. Je propose des outils statistiques et j'utilise un ensemble d'entretiens qualitatifs pour répondre à ces questions.

La partie statistique s'applique aux vagues de chaleur européennes. Je quantifie le rôle joué par la circulation atmosphérique dans l'intensité de quatre vagues de chaleur récente. Cette analyse s'appuie sur des analogues de circulations, qui identifient des jours ayant une circulation similaire à celle de l'événement étudié. Ensuite, je dissocie l'influence du changement climatique sur les processus dynamiques et non dynamiques menant aux vagues de chaleur. Je calcule des tendances sur l'occurrence de circulations favorisant les fortes chaleurs et sur la température pour une circulation fixée, pour les vagues de chaleur de 2003 en Europe de l'Ouest et de 2010 en Russie. Je trouve que la significativité des résultats dépend de l'événement étudié, ce qui montre l'intérêt de calculer des tendances pour des types de circulation atmosphérique précis.

La partie épistémologique analyse les utilisations sociales potentielles de l'AEE. Je mesure comment elle pourrait informer les négociations internationales sur le climat, en particulier les pertes et préjudices, en réponse à des arguments de scientifiques dans ce sens. Je trouve que le seul rôle que l'AEE puisse jouer pour renforcer les pertes et préjudices est un rôle de sensibilisation des politiques, en marge du processus de négociations. Je compare également les motivations avancées par les scientifiques dans les entretiens avec les résultats existants sur l'utilité sociale de ce type d'information scientifique. Je montre que la pertinence sociale des résultats d'AEE est ambiguë, et qu'il y a un manque de données empiriques pour mieux comprendre comment différents acteurs s'approprient et réagissent à cette information.

Contents

Introduction

2017 – Hurricane season: Category 4 Hurricanes Harvey, Irma, and Maria, left a trail of destruction in Caribbean and along the United States coast. They are three of the five costliest hurricanes in the United States[2]. July 2018 – Northern Hemisphere summer: records of temperature are broken in many countries[3]. Scandinavia experiences temperatures above 30°C next to the polar circle, with anomalies compared to the average seasonal temperatures locally rising above 15°C . 51.3°C were recorded in Ouargla (Algeria) on July 5th, the highest temperature ever recorded for the whole African continent (since the start of reliable observations). In Japan, the thermometer rose higher than ever on the archipelago on July 23rd with 41.1°C in Kugayama. Other absolute records have been broken in Los Angeles (USA), Montreal (Canada), Bakou (Azerbaidjan), Tbilissi (Georgia), Erevan (Armenia), Kaboul (Afghanistan), Wonsan (North Korea) and in many other cities. I could continue the list of extreme events that happened around the world in the last twelve months for a few pages.

At the same time, climate scientists have detected a significant change in several climate variables (Bindoff et al., 2013a). The most famous example of this change is the global mean temperature. Since 1880, it has risen by a trend of 0.07°C by decade[4]. We are more and more certain that this change is attributable to the anthropogenic greenhouse gases emissions, which started to accumulate in the atmosphere since the start of the industrial revolution (Bindoff et al., 2013a). We talk about *anthropogenic* climate change.

Extreme events have always happened and are a feature of natural climate variability. However, since the background climate is changing, it is legitimate to ask ourselves whether observed extreme events are a manifestation of this changing climate superimposed to natural variability. As Robert A. Heinlein puts it “climate is what you expect, weather is what you get”[5]. In a changing climate, what can we expect to get? and could we expect what we got? The goal of this PhD is to (partly) address the following question:

How can we treat the question of the influence of anthropogenic climate change on observed extreme weather events?

Chapter 2 answers a part of this question through a review of the scientific literature on extreme event attribution, which is the part of climate science dealing with the influence of

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[2] https://eu.usatoday.com/story/weather/2018/01/30/2017-s-three-monster-hurricanes-harvey-irma-and-maria-among-five-costliest-ever/1078930001/

[3] http://www.meteofrance.fr/actualites/64599542-chaleur-des-records-dans-le-monde-entier

[4] Source: NOAA https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

[5] This quote comes from Heinlein’s novel *Time Enough for Love*. A complete explanation of its origin is presented on this site: https://quoteinvestigator.com/2012/06/24/climate-vs-weather/

anthropogenic climate change on observed extreme weather events. In the rest of the PhD, I interpret the *How can we treat* in two different manners, in order to give two different perspectives on this issue. The title of this PhD manuscript highlights this dual approach, which is the main originality of this thesis. It is difficult to accurately name scientific disciplines my work relates to because both climate science and social science are very interdisciplinary in nature. Calling the two approaches statistical and epistemological may be slightly incorrect and clumsy. However, those two disciplines describe both approaches as accurately as possible in one word.

The first perspective is rooted in climatology, and more specifically in statistical climatology. In chapters 3, 4 and 5, I propose methodologies to help to disentangle the processes leading to an extreme event. Temperature has the advantage of having the most reliable observation-based dataset. It is also the most studied variable in the literature, and detection and attribution studies have been most successful for temperature. It was hence easier to build new statistical tools to analyze extremes of temperature than other types of extremes. The methodologies proposed in the PhD are applied to European heatwaves, but in theory, they could be applied to other types of extreme weather events. The second perspective is rooted in social science, and more specifically in epistemology. Its goal is to understand the potential social uses of scientific results regarding the influence of anthropogenic climate change on observed extreme weather events. In order to do so, I analyze how the science of extreme event attribution is perceived by non scientific stakeholders through the case study of the international negotiations on loss and damage (Chapter 6). Then, I examine the social and scientific motivations stated by climate scientists to conduct extreme event attribution studies. I evaluate the evidence to support the social motivations in the social science literature (Chapter 7). Finally, I discuss which scientific directions can be deduced from this social science perspective. Before that, chapter 1 explains the motivation behind the multi-disciplinary approach.

Chapter 1

Motivating the multi-disciplinary nature of this work

I am a climate scientist by training. However, I had experience in social sciences before the start of my PhD, and I tried to educate myself as best as I could during the last three years (with the invaluable help of a few social scientists). This introductory chapter is an attempt to explain the background that led to this PhD topic, and to the choice of its double disciplinary outlook. I explore how climate, climate change, and extreme weather events are three scientific topics that engage different epistemic communities. I first give a few landmarks on the construction of climate as a scientific topic. Then, I discuss anthropogenic climate change and how it changed climate science. Lastly, I discuss how climate change influence extreme weather events, and the different questions this relationship poses for different scientific disciplines. This chapter is far too short to give a complete overview of the construction of these three scientific topics. Its goal is not to be exhaustive, as these three topics could be PhD topics in themselves. It simply gives a few reasons why the study of the influence of climate change on extreme events is a scientific object of interest for a wide variety of disciplines.

1.1 History of climate science

Climate is both the result of very complex physical processes and a determinant external factor for human societies. It is hence only natural that it is a scientific object of interest for both physical and social sciences. Staszak (1995) describes the birth of concepts and epistemological approaches, which he pinpoints as still relevant for today's geography, but which I also consider relevant for climate science. In *Meteorologica*, Aristotle proposes theories to explain what he calls *meteors*, which are ephemeral phenomena, like rain, floods, earthquakes, or thunder (Aristotle). In *Airs, waters and places*, Hippocrates studies the relationship between men and "milieu", including climate characteristics like the temperature, and the seasonal cycle (see Figure 6 of Staszak (1995))(Hippocrates). Epistemologically speaking, Aristotle adopts a physical science approach, while Hippocrates is closer to human sciences[1]. These different approaches are still relevant to understand how climate science developed itself.

With the development of navigation and the exploration of the world, scientists started to have access to new observational data. In 1686, Edmond Halley published *An Historical*

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[1] Note that Hippocrates died fourteen years before the birth of Aristotle

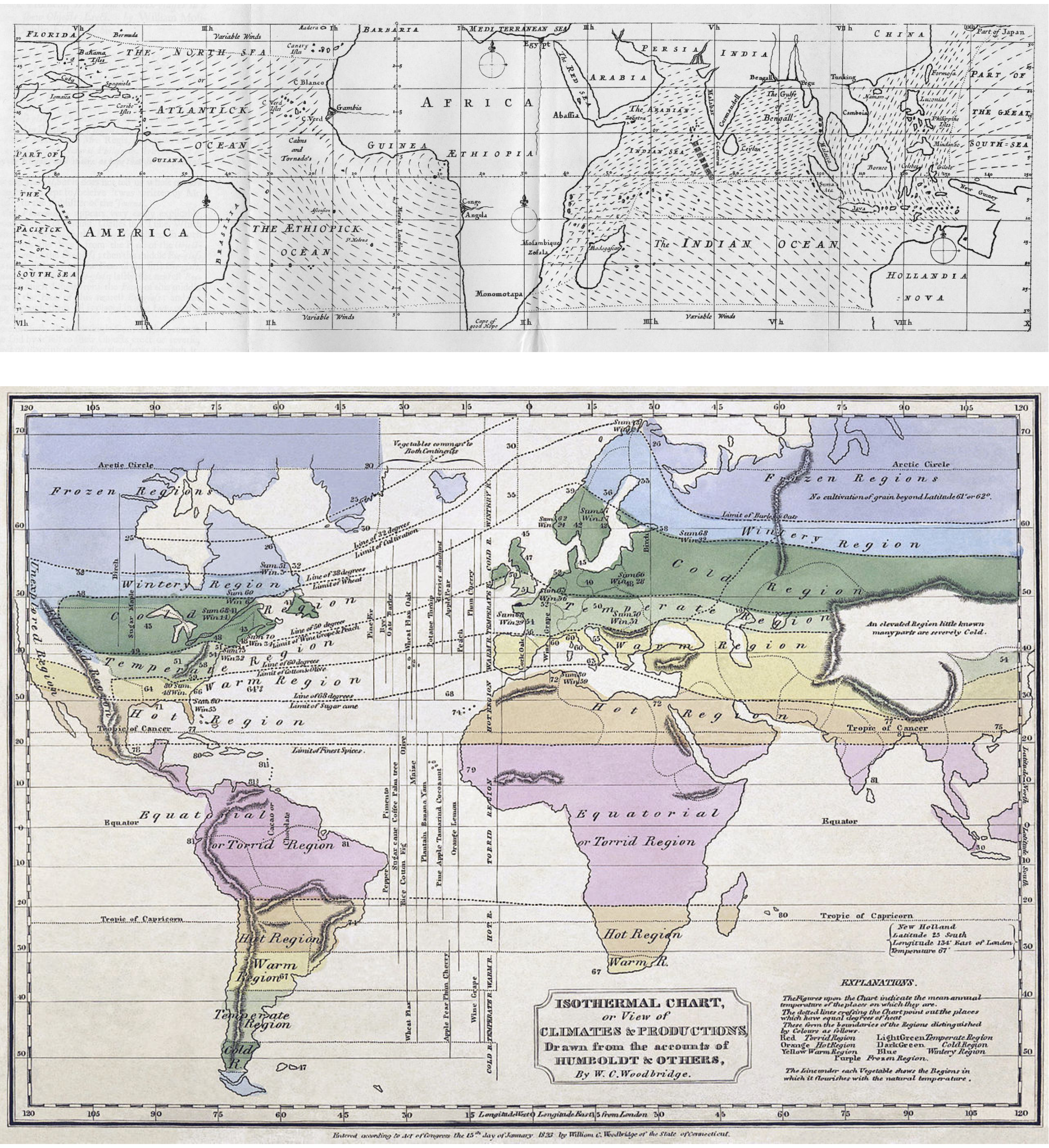

Figure 1.1 – Early climate maps. Above, Halley's charts of the trade winds from his book *Philosophical Transactions*(1686). Below, an isothermal chart drawn in 1823 by William Channing Woodbridge, based on Alexander von Humboldt's work.

Account of the Trade Winds, and Monsoons, Observable in the Seas between and near the Tropicks, with an Attempt to Assign the Phisical Cause of the Said Wind (Halley, 1753), which contains the first world map of the winds over the oceans, displayed in Figure 1.1[2]. Benjamin Franklin published the first chart of the Gulf Stream in 1770. Alexander van Humboldt described different types of climates around the world, associated with different kinds of plants. Figure 1.1 shows a map drawn in 1823 by one of his contemporaries, William Chan-

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[2] Thrower (1969) draws a thorougher picture of Halley's cartographic activities

ning Woodbridge, based on Humboldt's work. Many classifications of the Earth's climates have been proposed since then, including the Köppen classification (Köppen, 1931). Classifications of climates represent a vision of a plurality of climates, which are determined through the average[3] of meteorological conditions in different places.

In parallel of this description of the climates of the Earth, scientists developed theories to explain what they observed. The understanding of the physics behind the properties of climate spans through different space and time scales. There are theories to explain a specific phenomenon. For example, in 1735, George Hadley proposed a mechanism linked to the Earth's rotation to explain the existence of trade winds. Other theories apply to the global climate state. In 1824, Joseph Fourier discovered the greenhouse effect (Fourier, 1824). While the sun energy goes through the atmosphere in the visible spectrum (through the sun light), the Earth emits this energy in the infrared, and the atmosphere blocks part of this infrared radiation, making the Earth's climate warmer than it would be without the atmosphere. At the beginning of the 19th century, geologists started to suspect the existence of ice ages, and that climate was not constant in time (Agassiz, 1837). This called for an explanation of these changes. John Tyndall (Tyndall, 1861), Svante Arrhenius (Arrhenius, 1896) and Thomas Chamberlin (Chamberlin, 1897) proposed an atmospheric theory, linking the past changes in temperature to past changes in atmospheric components. These components called greenhouse gases, in particular carbon dioxide, are responsible for the greenhouse effect proposed by Joseph Fourier. In the 1920s, Milutin Milankovitch proposed an astronomical theory of climate changes based on calculations of cycles in the Earth's eccentricity, obliquity and precession (Milankovitch, 1920).

This brief history does not seek to be exhaustive. Entire books (e.g. Edwards (2010)) and PhD theses (e.g. Guillemot (2007)) have been written on parts of climate science history. I want to highlight that since the end of the 17th century, climatology has developed in two different directions: one which could be related to geography and the other to physics[4]. On the one side, we have the observation and description of different climates (in plural form), versus on the other side, the understanding of the climate (in the singular) as a physical object. Of course, the separation between both disciplines is a bit artificial. One of the reasons for that is that science has not always been as compartmentalized as it is now. Hadley's theory of trade winds was based on Halley's theory of trade winds. Milankovitch received support from Köppen. Another reason is that geography is divided between physical and human geography. As I am by no account a geographer, I will not dive in these subtleties here and keep to the simple distinction between physics and geography, which should suffice to serve the purpose of this introduction. Another (controversial) contribution to early climate science that does not fit in this division is Montesquieu's theory of climates in *Spirit of the Laws* (1748), in which he postulates that climate is the main explanation of the nature of men and societies[5]. Montesquieu's theory is a successor to Hippocrates'. I divided the contribution of the scientists I listed above mainly based on the difference between the history of climatology told by geographer Claude Kergomard during a seminar on geographical climatology at the EHESS (École des Hautes Études en Sciences Sociales) and on the history of climatology I learned through my studies in physical climatology. The epistemological difference between a vision of a plurality of climates versus a global climate revealed itself to be important with the

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[3] According to Julius van Hann climatology aims at determining the means and other statistical properties of all relevant atmospheric variables (Hann, 1883).

[4] researchers in both domains call themselves climatologists!

[5] Shackleton (1955) details the birth of this theory

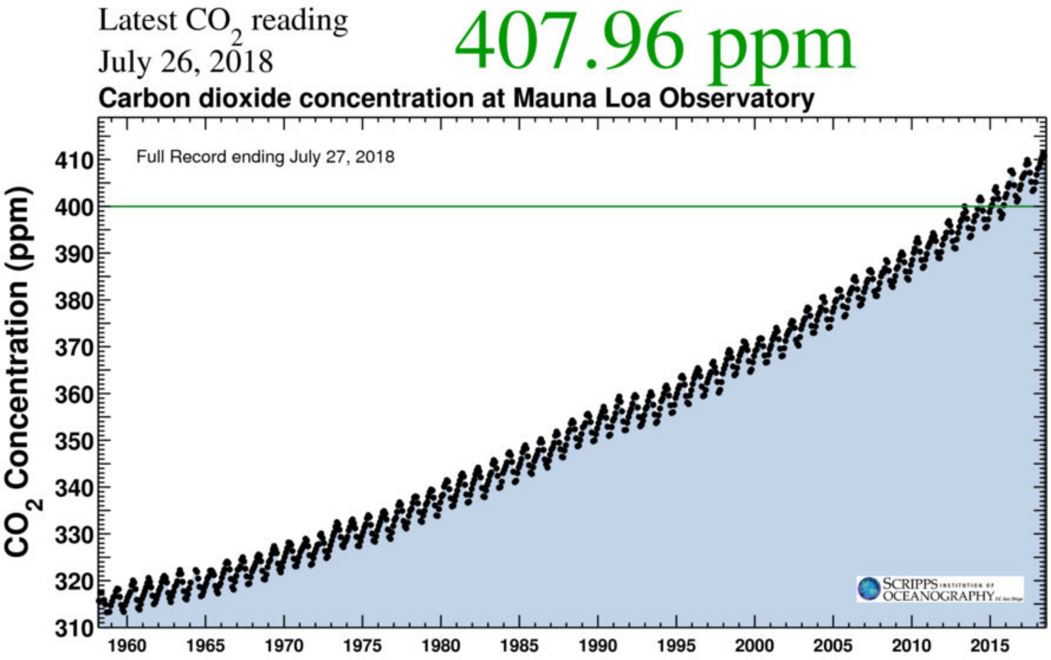

Figure 1.2 – Evolution of atmospheric concentration of CO$_2$ at Mauna Loa Observatory in Hawaii from 1958 to 2018, downloaded from the SCRIPPS website (`https://scripps.ucsd.edu/programs/keelingcurve/`) on July 29th 2018.

discovery of anthropogenic climate change and the epistemic revolution this discovery brought.

1.2 Anthropogenic climate change: a game changer

In *An Essay on the geography of plants* 1805, Alexander von Humboldt writes: “By cutting down the forests, agricultural people have lowered the humidity of the earth climate; marshes were drained and useful plants diffused gradually over the plains previously occupied by cryptograms, which make farming impossible.” (Buttimer, 2012). Since the end of the eighteenth century, the theory that men could modify local climate through land use was seen as a source of both concerns and opportunities[6]. At the time, the scientific literature to back up this theory was close to inexistent, which did not stop policy makers to consider it very seriously (Locher and Fressoz, 2012). These theories lost momentum in the second half of the 19th century, for reasons detailed in Locher and Fressoz (2012).

Anthropogenic climate change became a scientific topic of interest in the second half of the 20th century (Weart, 1997). Two technological advances brought the topic on the table. First, the development of observational networks and new technologies to observe diverse variables all around the planet, in the ocean, and in the atmosphere, led to better understanding of the climate. In 1957, Charles Keeling started to measure the level of atmospheric CO$_2$ in a station in Antarctica[7]. A few months later he added another measuring site in Mauna Loa (Hawaii).

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[6] Montesquieu’s theory of climates was part of this movement.

[7] Weart(1997) describes the historical background that led to Keeling’s experiments. See also *Fixing climate*,

Less than three years later, these first measurements already showed that the concentration of carbon dioxide (CO_2) was rising (Keeling, 1960). The Keeling curve kept rising every year since then, in accordance with rising CO_2 emissions (Figure 1.2). This observation was a cause for concern in light of the greenhouse effect. Since the 1970s, satellites give access to a mass of new data, allowing to monitor the evolution of many climate variables. In 1987, Genthon et al. (1987) published the results of the analysis of the Vostok ice cores showing the correlation between the evolution of temperature and CO_2 levels in the last 150 000 years, reinforcing the greenhouse effect theory.

The other major evolution of climate science came from the apparition of computers. They made possible computations that were out of reach until then. The informatics revolution was applied to meteorology before climatology. The physical equations derived from fluid dynamics and thermodynamics that regulate the atmosphere were known since the seminal work of Vilhelm Bjerknes (Friedman, 1989). However, solving these equations would require an enormous computing power. According to Richardson (1922), 64 000 people would have to solve differential equation to produce a weather forecast in real time (and this estimation was very optimistic (see Lynch (2006)'s analysis of Richardson's work)). The Hungarian-American scientist John von Neumann is the first to have the idea to use computers to overcome this limit. This led to the development of the first weather forecast model operational for the entire United States that Jules Charney and his team developed in Princeton. Following this first success, the same team developed the first general circulation model (GCM). This model was able to reproduce the main characteristics of global atmospheric circulation. In the 1970s, weather forecast models extended so that they became global, and GCMs started to include more and more components. The atmospheric part of GCMs is based on the same equations than weather forecast models. This atmospheric part is coupled with other components of the climate system, which play an important role on longer time scales, like the ocean and the vegetation. GCMs soon became tools to evaluate the possibility of climate change, leading to a report led by Charney commissioned by the American Academy of Science (Charney et al., 1979). This report estimates "the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ± 1.5°C". Indeed, GCMs offered the opportunity to explore multiple potential futures, which no other parts of climatology was able to do (Demeritt, 2001)[8].

The nature of climate change, and the way science apprehends it changed the epistemological approach to climate science in two major ways. First, it reinforced the vision of climate as a global object. Keeling's curve represents the evolution of CO_2 as a global variable (CO_2 distributes quickly in the atmosphere), which is the cause of climate change. Demeritt (2001) notes that this perception of greenhouse gases ignores the social differences between the sources of emissions (not discriminating emissions related to different types of activities). Furthermore, GCMs are by definition global. They allow the study of variables like the global mean temperature, which would have no sense in traditional climatology (Aykut and Dahan, 2015). The development of GCMs also had impacts for other practices of climatology, which struggled to get access to funding. For example, Martin-Nielsen (2015) tells the progressive marginalization of Hubert H. Lamb's research from U.K. climate research following the apparition of GCMs. The physical vision of a singular climate has overtaken the geographical

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written by Wallace Broecker and Robert Kunzig (Broecker and Kunzig, 2008).

[8] This paragraph is partly based on the first chapter of *Gouverner le climat* published in 2015 by Stefan Aykut and Amy Dahan (Aykut and Dahan, 2015)

vision of a plurality of climates.

Second, a climate change could have major impacts for human societies. Reciprocally, the way of living of human societies can have an impact on climate change: anthropogenic climate change could be avoided with a lower consumption of fossil fuels. It led to a change in scientific practices: "important trends in the [...] history of climate change analysis were a shift from scientific-curiosity-driven towards issue-driven research, an increased demand for assessment of the risks of climate change, and an increased demand for analysis of the policy meaning of the knowledge and theories about the human influence on climate"(van der Sluijs (1997) p.18). Climate change was not anymore only a scientific problem. It was also a social and political problem. This multi-dimensional nature turned climate change into a scientific and political co-construction (Dahan, 2010). This co-construction is best seen through the concomitant history of the Intergovernmental Panel on Climate Change (IPCC) and the United Nations Framework Convention on Climate Change (UNFCCC). The first one was founded in 1988 to assemble the scientific knowledge available on climate change (seeAgrawala (1997, 1998a,b) on the IPCC creation). It released its first assessment report in 1990, which motivated the creation of the UNFCCC in 1992 at the Rio Earth Summit. Since then, the IPCC is charged with the regular release of assessment reports on climate science, which are "policy relevant" but not "policy prescriptive" reports. Behind this facade of "Science speaks truth to power" (Merton, 1973), the connexions between climate change science and climate change policy through these two arenas are much more complex. Hulme and Mahony (2010) sum it up as follows: "One thing that nearly all commentators and critics agree on about the IPCC is that it has had a significant influence on climate change knowledge, on public discourse about climate change and on climate policy development."

1.3 From global climate to local impacts

One can argue that through the global framing of climate change it proposes, climate science has participated to create a politically unsolvable problem, which led to the failure to reach an international agreement to deal with climate change at the 15th conference of Parties (COP) of the UNFCCC in Copenhagen (Aykut and Dahan, 2014, 2015; Prins et al., 2010; Sarewitz, 2011). There were already critics of the scientific framing of climate change as a global problem defended, among others, by the IPCC and of its consequences for the political climate regime before COP15 (Carolan, 2008; Demeritt, 2001; Pielke Jr, 2007).

I started my PhD a few months before COP21, and the subsequent Paris agreement, in a different political and scientific context than the global framing of climate change that was mainstream at the time of COP15. Following the failure of Copenhagen, climate politics have stopped looking for a global top-down solution to climate change. They have shifted towards local-based solutions, through a bottom-up process in which each country decides of the form and of the level of its contribution. This shift to local impacts is concurrent with a change in demands to science. Wise et al. (2014) observed "a growing intensity of calls for more decision-oriented research [...]. as priorities have moved from estimating impacts and vulnerabilities in order to make the case for mitigation, to adaptation planning and action in a world that is looking less and less likely to stay within 2°C of global warming".

An answer to these calls can be found in the emergence of regional climate services, which aim at providing information on the local impacts of climate change to both scientific and non-scientific stakeholders (Hewitt et al., 2012; Vaughan and Dessai, 2014; Visbeck, 2007). For example, the European Union funds the Copernicus Climate Change service, launched in 2014, which, according to its website "will combine observations of the climate system with the latest science to develop authoritative, quality-assured information about the past, current and future states of the climate in Europe and worldwide." During this PhD, I participated to the European funded EUCLEIA (European climate and weather events: Interpretation and attribution) project. This project aimed at better understanding the possibilities of extreme event attribution, in order to provide the foundation for an operational attribution service[9]. One of the goals of its successor, EUPHEME (EUropean Prototype demonstrator for the Harmonization and Evaluation of Methodologies for attribution of extreme weather Events) is to provide a prototype attribution service website[10].

The emergence of climate services poses new questions for the relationship between science and society. How can we assess the relative contribution of climate services to the benefit of society? Vaughan and Dessai (2014) show that there is little knowledge on climate services effectiveness. They propose design elements for an evaluation framework. They suggest an analysis through four angles. What are the benefits of a climate service for its end users? Does the nature of the information (associated uncertainty, time of production, accessibility to a non scientific audience...) it can provide answer the recipient needs? How is it organized and which governance does it rely on? What is its economic value? In this context, and to help addressing these questions, I chose to adopt a *reflexive approach* of my research (and of the more general field of research surrounding it), by complementing the physical part of this PhD with an epistemological view on its potential usefulness for society. By reflexive approach, I mean a self-examination undertaken with the help of social science tools of the underlying values, principles, and motivations of a research field and of the socio-economic consequences of its results (see Anne Blanchard's PhD thesis for a discussion on reflexivity in relation with interdisciplinarity between human and natural science (Blanchard, 2011)).

1.4 Climate change and extreme weather events

The study of extreme events and of their evolution related to anthropogenic climate change is doubly interesting. First, extreme weather events cause a wide range of damages, as shown by these recent examples. Harvey, Irma and Maria respectively cost \$125, \$50 and \$90 billions[11]. The summer 2003 European heatwave has been associated with up to 70000 excess deaths across the continent, including around 500 attributed deaths for the sole city of Paris (Mitchell et al., 2016). The drought that plagued Afghanistan in the first half of 2018 has had major impacts on the country's agriculture, and forced farmers and their families to leave their home[12]. Droughts and heatwaves are also precursors of wildfires. One of these fires had dramatic consequences in Greece on July 23rd 2018, as it reached a densely populated coastal

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[9] More information is available on the EUCLEIA website `https://eucleia.eu/`

[10] More information is available on the EUPHEME website `http://eupheme.eu/`

[11] `https://www.washingtonpost.com/news/capital-weather-gang/wp/2018/01/30/harvey-irma-and-maria-now-in-the-top-5-costliest-hurricanes-on-record-noaa-says/`

[12] `https://reliefweb.int/report/afghanistan/thousands-affected-ongoing-drought-afghanistan`

area[13]. The authorities announced on July 29th that the death toll had reached 91. This was Europe's deadliest fire in a century[14]. A recent example of disaster loss related to floods is the collapse of a dam in Laos following heavy rains[15]. These impacts are not only caused by the meteorological hazard, they also depend on exposure and vulnerability (Lavell et al., 2012).

Second, extreme events raise public attention on the matter of climate change. Demeritt (2001) argues that "the 1988 heat wave and drought in North America were arguably as influential in fostering public concern as any of the more formal scientific advice". In France, the 2003 heatwave served as a wake up call for the danger of heat, and led French authorities to adopt adaptation policies (Fouillet et al., 2008; Salagnac, 2007). Hence, understanding the links between extreme weather events and climate change is both an interesting scientific problem and a social issue. What is the influence of anthropogenic climate change on extreme weather events? Can we detect changes in the current frequencies and intensities of these hazards, and on related impacts? What can we learn from models about their future potential evolutions? Before introducing my work, I succinctly present the state of knowledge on the influence of anthropogenic climate change on extreme events impacts.

Evaluating the influence of climate change on extreme events poses scientific challenges. Indeed, extreme events are by definition rare, which means that it is hard to evaluate how they evolve based on short datasets. In fact, it is already difficult to evaluate the intensity of an event of a 1-in-100 year return period in a stationary climate with a 50 year long observational dataset, which is longer than what we have for some variables (like soil moisture, which is a good variable to evaluate droughts). To overcome this difficulty, climatologists can rely on statistical tools like extreme value theory (Smith, 1990) and/or on climate models, which produce longer datasets. Zwiers et al. (2013) give a complete overview of the challenges and results of research dedicated to extreme events, their evolution, and how this evolution is (or is not) linked to anthropogenic climate change. Sillmann et al. (2013a) evaluate the ability of the CMIP5[16] models to reproduce observed temperature and precipitation indices. Sillmann et al. (2013b) provide an overview of these indices projections for the twenty-first century under several scenarios. Chapter 3 of the IPCC special report Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Seneviratne et al., 2012) proposes an overview of the results of research regarding both the historical evolution of extreme events and their projected change by the end of the twenty-first century based on climate models following different socio-economic scenarios (Seneviratne et al (2012)). Figure 1.3 summarizes the change in the uncertainties on the relationship between anthropogenic climate change and different types of extreme events through three IPCC assessment reports: the third assessment report (TAR, 2001), the fourth assessment report (AR4, 2007), and the SREX (2012). It shows that depending on the type of event, the level of uncertainty varies. The influence of climate change on temperature extremes and sea level extremes is more certain than on precipitation, droughts and tropical cyclones.

What about the evolution of impacts? Hazards are only one of three constitutive elements

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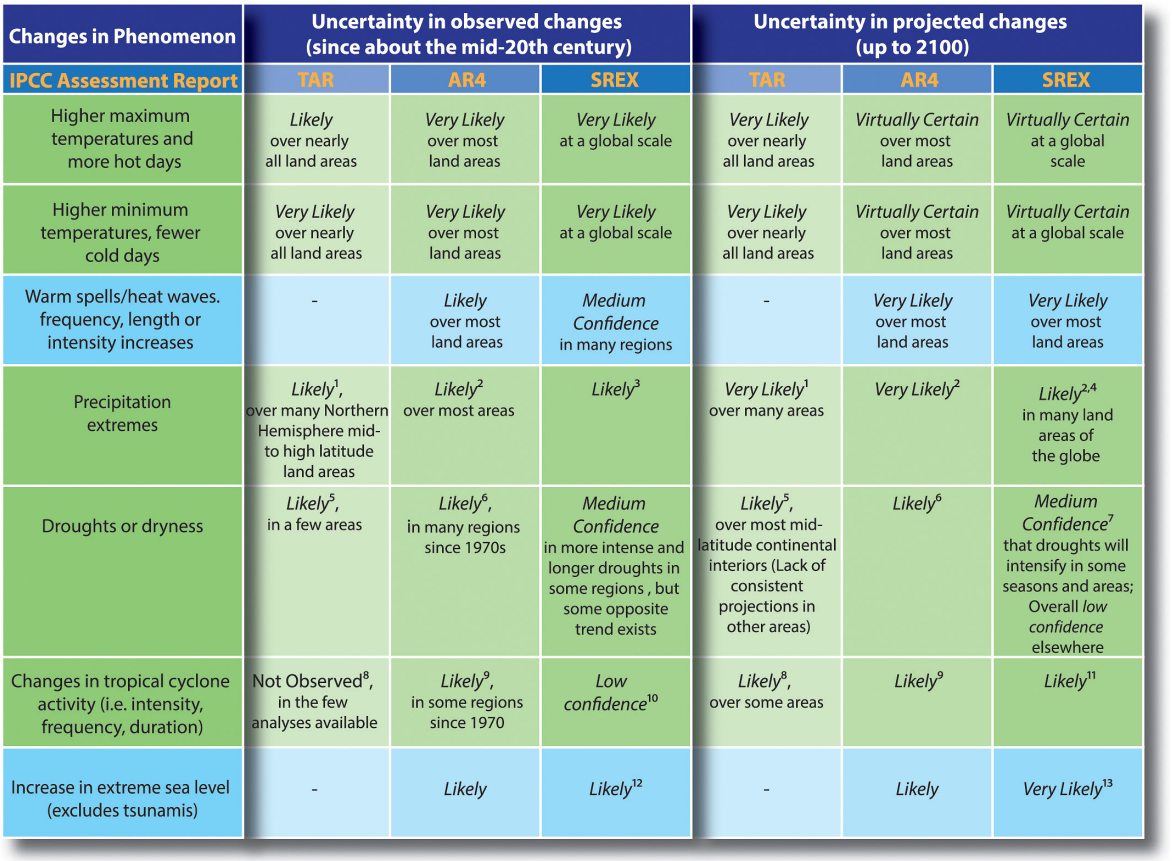
[13] `https://www.theguardian.com/world/2018/jul/24/greek-wildfires-dry-winter-and-strong-winds-led-to-tinderbox-conditions`

[14] `https://www.cbc.ca/news/world/greece-wildfire-village-grieves-death-toll-rises-day-six-1.4766270`

[15] `https://www.theguardian.com/world/2018/jul/24/laos-dam-collapse-hundreds-missing`

[16] The Coupled Model Intercomparison Project Phase 5 provides simulations of an ensemble of coupled models for several common experiments (for example for different future scenarios). See Taylor et al. (2012)



Changes in Phenomenon	Uncertainty in observed changes (since about the mid-20th century)			Uncertainty in projected changes (up to 2100)		
IPCC Assessment Report	TAR	AR4	SREX	TAR	AR4	SREX
Higher maximum temperatures and more hot days	*Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Higher minimum temperatures, fewer cold days	*Very Likely* over nearly all land areas	*Very Likely* over most land areas	*Very Likely* at a global scale	*Very Likely* over nearly all land areas	*Virtually Certain* over most land areas	*Virtually Certain* at a global scale
Warm spells/heat waves. frequency, length or intensity increases	-	*Likely* over most land areas	*Medium Confidence* in many regions	-	*Very Likely* over most land areas	*Very Likely* over most land areas
Precipitation extremes	*Likely*[1], over many Northern Hemisphere mid- to high latitude land areas	*Likely*[2] over most areas	*Likely*[3]	*Very Likely*[1] over many areas	*Very Likely*[2]	*Likely*[2,4] in many land areas of the globe
Droughts or dryness	*Likely*[5], in a few areas	*Likely*[6], in many regions since 1970s	*Medium Confidence* in more intense and longer droughts in some regions , but some opposite trend exists	*Likely*[5], over most mid-latitude continental interiors (Lack of consistent projections in other areas)	*Likely*[6]	*Medium Confidence*[7] that droughts will intensify in some seasons and areas; Overall *low confidence* elsewhere
Changes in tropical cyclone activity (i.e. intensity, frequency, duration)	Not Observed[8], in the few analyses available	*Likely*[9], in some regions since 1970	*Low confidence*[10]	*Likely*[8], over some areas	*Likely*[9]	*Likely*[11]
Increase in extreme sea level (excludes tsunamis)	-	*Likely*	*Likely*[12]	-	*Likely*	*Very Likely*[13]

Figure 1.3 – Recapitulative table of the uncertainty in observed and projected changes for different types of extreme weather events. Source: Introduction of the IPCC AR5.

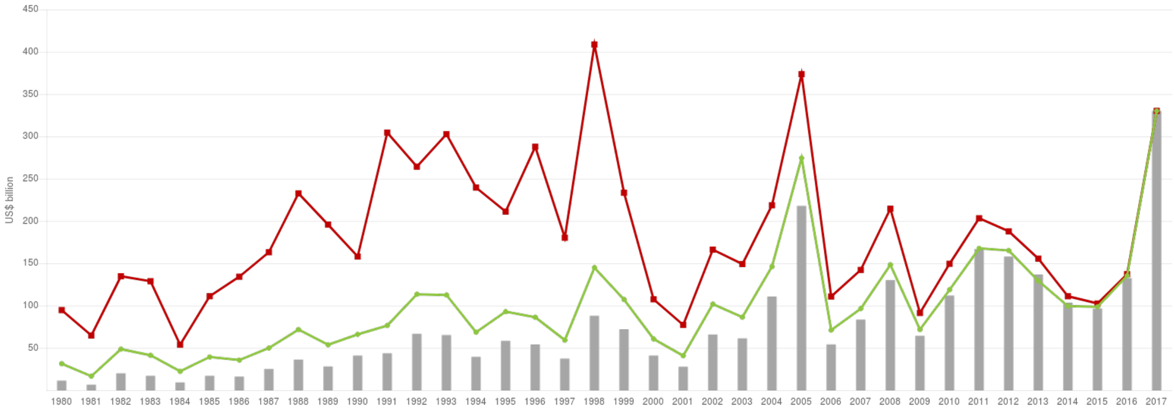


Figure 1.4 – Variations of worldwide losses related to extreme weather events (storms, floods, droughts, heatwaves, coldspells) between 1980 and 2017 in $US billions. The grey histograms are the nominal yearly losses. The green curve shows these losses adjusted for inflation between the year of occurrence and 2017. The red curve shows these losses normalized by GDP (Gross Domestic Product) between the year of occurrence and 2017. Figure created using the MunichRe Natcatservice available online: `http://natcatservice.munichre.com/`.

of disaster risks. Risk also depends on vulnerability and exposure (SREX, 2012, Chapter 4

(Handmer et al., 2012)). Impacts happen when extreme weather events occur in vulnerable, exposed zones. I coauthored a chapter of a CNRS book on adaptation to climate change with Pascal Yiou. In this chapter we discuss the potential inputs of extreme event attribution science to risk assessment. The English version of this chapter is provided in Appendix E. Figure 1.4 displays the evolution of worldwide economic losses between 1980 and 2017 provided by the reinsurance company MunichRe. If nominal losses clearly increase in this period, there is no clear evolution of losses normalized by GDP (which increased during this period). This lack of trend in normalized disaster losses is consistent with the literature, which has shown that trends in exposure and wealth are the main drivers of the increase in disaster losses (Bouwer, 2011; Visser et al., 2014). This does not mean that the observed increase in some extreme events (see Figure 1.3) does not play a role. The lack of trend in normalized disaster risks means that the trends of the the two remaining elements of risks, hazards and vulnerability, compensate each other. It is very hard to evaluate trends in vulnerability, and the trends on the most studied hazards (cyclones) are not clear for the historical period (Figure 1.3). For now, it is not possible to conclude to a role or to a lack of role of anthropogenic climate change in the evolution of disaster risk losses (Bouwer, 2011; Visser et al., 2014). “Losses from extreme weather may begin to show increases when changes in extreme weather events become more apparent” (Bouwer, 2011). There is hence a need for a better understanding of the influence of climate change on impacts. Sillmann et al. (2018) discuss the challenges to propose risk indicators to complete the already existing hazard indicators (Sillmann et al., 2013a,b).

The events studied in this PhD are European heatwaves (with the exception of a European drought in Chapter 5). Heatwaves[17] are part of the European natural variability in Europe. Their occurrence is related to specific dynamical conditions and to other physical processes like low soil moisture (e.g. Seneviratne et al. (2010), Quesada et al. (2012)). The top ten European heatwaves observed in the 1950-2014 period are detailed in Russo et al. (2015)[18]. Climate change adds a signal on the natural variability. There has been a large number of studies on both the general evolution of extreme European heat events (e.g. Bador et al. (2016); Christidis et al. (2015a); Russo et al. (2015); Seneviratne et al. (2016)) and on the role of climate change on specific observed European heatwaves (e.g. Beniston and Diaz (2004); Black et al. (2004); Hauser et al. (2017); Otto et al. (2012); Stott et al. (2004)). There is *medium confidence* that climate change has increased the probability, the intensity, the duration and the calendar period for European heatwaves, and *high confidence* in their projected increase for the twenty-first century (Seneviratne et al., 2012). The angle chosen in this PhD is to evaluate whether those changes are related to changes in dynamical and/or in non-dynamical processes.

Global dynamics are driven by the temperature gradient between the equator and the Poles, which generates an energy transfer. The warm air from the equator is conveyed towards the tropics (25°N–25°S) in the Hadley cells. In the extra-tropical regions, the difference of temperature between the tropics and the poles, combined with the systematic eastward deviation of winds related to the Coriolis force (caused by the Earth’s rotation) creates the jet stream, a strong eastward current (it can locally exceed $100 m.s^{-1}$). The fluctuations of the jet stream are responsible for daily variability in the extra-tropical regions. In the North

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[17] Note that there are many different definitions of heatwaves (e.g. Sillmann et al. (2013a)). The choice of the definition can have an influence on the results of studies. This point will be discussed in more details in Chapter 2. Also see the introduction of Sebastian Sippel’s PhD thesis (Sippel, 2017) on the definition of extreme events.

[18] The 2018 Scandinavian heatwave happening as I write these lines will probably be one of the biggest European heatwaves ever recorded.

Atlantic region, and specifically in Europe which is the region of interest in this PhD, the main mode of variability (which ensues from the jet stream fluctuations) is called the North Atlantic Oscillation[19].

1.5 Outline of the manuscript

In order to answer the question **How can we treat the influence of anthropogenic climate change on observed extreme weather events?**, this manuscript is organized as follows. Chapter 2 introduces the science of extreme event attribution. It examines how different scientists appropriate the question "was this event influenced by climate change?" This discussion is based on a literature review and interviews conducted with scientists working on extreme event attribution.

Chapters 3 to 5 introduce methodologies to better understand how the dynamic and non-dynamic components of European heatwaves have evolved and are projected to evolve. Chapter 3 proposes to quantify the influence of the atmospheric circulation on the intensity of recent heatwaves. Chapter 4 is dedicated to the question: "will the atmospheric conditions that led to specific heatwaves become more or less frequent in the future?" Chapter 5 explores how the temperatures observed for these atmospheric conditions evolve in a changing climate. These three chapters rely on statistical tools. Chapters 2 to 5 contain both a published article and further reflexions.

Chapters 6 and 7 discuss the potential uses of extreme event attribution. Chapter 6 studies a specific group of stakeholders that has been identified by a few scientists: negotiators involved in the climate international negotiations on loss and damage. Chapter 7 presents the scientific and social motivations stated by scientists to justify their practice of extreme event attribution. It examines how these perspectives fare when confronted to social science literature. These two chapters rely on interviews conducted with both scientists and negotiators.

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[19] This explanation is very simplified. Chapter 1 of Julien Cattiaux's PhD (Cattiaux, 2010) presents a much more detailed explanation of European dynamics.

Résumé

Contexte et problématique

Ce chapitre introductif s'attache à poser le contexte et la problématique de cette thèse, tout en défendant un regard multi-disciplinaire sur cette problématique. Elle s'intègre dans une dynamique scientifique de compréhension de la façon dont les événements extrêmes, témoins de la variabilité naturelle du climat, sont impactés par le changement climatique d'origine anthropique. Le but de cette thèse est de répondre à la question suivante :

Comment peut-on traiter l'influence du changement climatique d'origine anthropique sur des événements extrêmes observés ?

Le choix d'un regard multi-disciplinaire

Deux façons d'interpréter cette question sont explorées dans cette thèse. D'une part, je propose des outils statistiques permettant de mieux comprendre comment les processus dynamiques et non dynamiques menant à un événement sont affectés par le changement climatique. Les événements étudiés dans cette thèse sont essentiellement des canicules européennes. D'autre part, j'essaie de comprendre quels sont les usages sociaux potentiels des résultats scientifiques sur le rôle du changement climatique sur les événements extrêmes. J'adopte donc un regard réflexif ancré dans les sciences sociales sur ma pratique de climatologue ancrée dans les sciences physiques.

Plan de la thèse

Cette thèse s'organise en 6 chapitres, qui explorent 6 angles de la problématique :

- Qu'est-ce que l'attribution d'événements extrêmes et quelles sont les différentes manières de l'aborder ? (Chapitre 2)
- Comment quantifier la part de la circulation atmosphérique dans les anomalies de températures élevées observées pendant les canicules européennes ? (Chapitre 3)
- Le changement climatique affecte-t-il l'occurrence des types de circulation atmosphériques liés à de fortes canicules observées ? (Chapitre 4)
- A circulation fixée, quel rôle joue le changement climatique dans les températures caniculaires observées ? (Chapitre 5)
- L'attribution d'événements extrêmes peut-elle jouer un rôle dans les négociations climatiques dans le cadre des pertes et préjudices ? (Chapitre 6)
- Quelles sont les motivations avancées par les chercheurs pour justifier leur pratique de l'attribution d'événements extrêmes ? Quelle pourrait être l'utilité sociétale de cette science ? (Chapitre 7)

Chapter 2

Framing extreme event attribution

When an extreme meteorological event happens, the media tend to ask scientists why this specific event happened, and in particular if climate change caused it. As I write these lines, my PhD advisor is answering this type of questions applied to the end of June/beginning of July 2018 temperatures on French television (see also Stott and Walton (2013)). Before 2003, finding evidence of the role of anthropogenic climate change in the occurrence of a specific event was considered to be impossible (Allen, 2003). Extreme events have happened before anthropogenic climate change, and the cases for which we can say with certainty that the event could not have happened without anthropogenic climate change are scarce (there are a few exceptions to this rule as outlined by Knutson et al. (2018), Walsh et al. (2018), and Imada et al. (2018)). For example, Wetter and Pfister (2013) have found evidence that summer 1540 was likely warmer than summer 2003 in Europe. As the French poet Stéphane Mallarmé wrote in 1897: “A throw of the dice never will abolish chance.”[1].

A group of scientists have come back on that first stance by developing extreme event attribution (EEA). They translate the ill-posed (on Extreme Weather Events and Attribution, 2016) question “Was this event caused by climate change?” into questions like “Has the probability and/or intensity of this event changed because of climate change?” or “Did climate change affect the physical mechanisms leading to this event?” These different questions rely on different methodologies and give different elements to understand the role of climate change. The choice of framing can lead to different results, which calls for cautiousness in their interpretation, especially when communicated to the media (Otto et al., 2012). The goal of this section is to map the practices of the EEA community and to illustrate the variety of approaches to this challenge.

The article “Behind the veil of Extreme Event Attribution” presented in this chapter dissects the different ways to frame the attribution question in scientifically relevant ways. It was written following a number of articles discussing ways to frame EEA (e.g. on Extreme Weather Events and Attribution (2016); Otto et al. (2016); Shepherd (2016); Trenberth et al. (2015)). Its added value is the use of empirical data to describe the state of the EEA community and disentangle the different ways to frame an EEA case study. It relies on two corpora of interviews and a systematic analysis and classification of 105 case studies from five issues of the Bulletin of American Meteorological Society (BAMS) special reports explaining the extreme events of the year before. I conducted the nine interviews of one of the two corpora.

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[1] Translated by A. S. Kline from the original version: “Un coup de dés jamais n’abolira le hasard.”

The classification of the BAMS articles and the interview grids are presented in the tables of Appendices A, B and C. The list of references of the paper is blended into the general references of the manuscript (as will be the case for the papers presented in the following chapters).

2.1 Article published in *Climatic Change*: Behind the veil of Extreme Event Attribution

Aglaé JÉZÉQUEL[2] • Vivan DÉPOUES[345] • Hélène GUILLEMOT[6] • Mélodie TROLLIET[7] •
Jean-Paul VANDERLINDEN[5] • Pascal YIOU[1]
Received 22 November 2017 – Accepted 3 July 2018

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2.1.1 Abstract

Since (Allen, 2003)'s seminal article, the community of extreme event attribution (EEA) has grown to maturity. Several approaches have been developed: the main ones are the "risk-based approach" — estimating how the probability of event occurrence correlates with climate change — and the "storyline approach" — evaluating the influence of climate change on thermodynamic processes leading to the event. In this article, we map the ways to frame attribution used in a collection of 105 case studies from 5 BAMS (Bulletin of American Meteorological Society) special issues on extreme events. In order to do so, we propose to define EEA, based on two corpora of interviews conducted with researchers working in the field, as follows: EEA is the ensemble of scientific ways to interpret the question "was this event influenced by climate change?" and answer it. In order to break down the subtleties of EEA, we decompose this initial question into three main problems a researcher has to deal with when framing an EEA case study. First, one needs to define the event of interest. Then, one has to propose a way to link the extreme event with climate change, and the subsequent level of conditioning to parameters of interest. Finally, one has to determine how to represent climate change. We provide a complete classification of BAMS case studies according to those three problems.

2.1.2 Introduction

Extreme event attribution (EEA) is a relatively new field of climate science, dealing with the influence of climate change on individual weather events. It started with Allen (2003) after an episode of extreme precipitation that struck southern UK in January 2003. Since then, EEA has grown, and many methodologies have been developed (Stott et al., 2016). With the

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growth of the field, different ways to frame EEA have emerged (e.g. Shepherd, 2016; Stott et al., 2016). The question of framing has been the root of debates among the community (e.g. Mann et al., 2017; Otto et al., 2016; Stott et al., 2017; Trenberth et al., 2015).

The aim of this article is to confront theoretical considerations to data, and to discuss the framing of EEA based on case studies to describe and understand what the EEA community actually does. In order to do so, we draw on two sets of semi-structured interviews. The first one was conducted among ten researchers participating to the European project EUCLEIA (called hereafter the EUCLEIA corpus). The second one was done with nine researchers who did not participate in the first series of interviews (A2C2 corpus) and mostly (with one exception) did not participate to EUCLEIA. The corpora are named after the grants that funded the surveys (see Acknowledgements). Although they share common points, the questions posed to both corpora differ as they were done for different purposes. The EUCLEIA corpus was the first step towards the creation of a European EEA climate service. The A2C2 corpus aimed at investigating what EEA is, and why researchers engage in it. Both grids of questions are provided in the supplementary material. The questions may have varied a little in the flow of the interviews.

We also rely on five issues of the Bulletin of American Meteorological Society (BAMS) annual reports explaining the extremes of the previous year, from 2011 to 2015, which aim at attributing specific events (Herring et al., 2014, 2015, 2016a; Peterson et al., 2012, 2013). We do not analyse the latest BAMS issue (Herring et al., 2018). They provide a collection of 105 case studies covering a large spectrum of established methodologies. Those reports give an overview of relatively mature and longstanding methods.

We will first lay out the history and introduce the different framing approaches of EEA. We will then explain how we tackled the classification of the case studies and how it led us to propose a working definition, inferred from the ensemble of interviews. We then deduce from this definition an ensemble of questions compulsory to answer in order to frame a case study, and show how the BAMS case studies give a range of answers to those questions.

2.1.3 Framing EEA : an history

2.1.3.1 The beginning of EEA

Myles Allen was the first to explicitly frame EEA in a publication in *Nature* in 2003, titled “Liability of Climate Change”. He personally experienced the flooding of the Thames occurring in this period. He asked the question of the cause of this event. He subtitled his article: “Will it ever be possible to sue anyone for damaging the climate?” The approach proposed by Allen (2003) takes its roots in a liability perspective. The idea was to compensate the “negative equity” individuals will face when they are confronted to weather-related events linked to anthropogenic emissions. For example, if their house loses value because climate change increased the likelihood of flood, they could sue the biggest greenhouse gas emitters. The main road block he identified is the scientific challenge of calculating the change in probabilities. The proposed methodology is to compare the probability of occurrence of an event in both a factual world — the world as it is with anthropogenic climate change — and a counterfactual world — the world that would have been without climate change.

A year later, Stott et al. (2004) published the first implementation of this approach, applied to the European heatwave of 2003. They proposed an estimation of “how much human activities may have increased the risk of occurrence of such a heatwave”. This article uses the concept of fraction of attributable risk (FAR), where risk means probability of occurrence. The FAR is the ratio of the difference between the factual and counterfactual probabilities and the factual probability. A FAR value of 1 means that without anthropogenic climate change the event is impossible. A FAR value of 0 means that anthropogenic climate change had no influence on the event probability. A negative FAR means that the event became less likely with anthropogenic climate change.

This first attribution methodology has been refined in more recent articles, facing one of the main problems of attribution, which is the need to have large enough ensembles of simulations to adequately sample all possible weather states for a given time period. Pall et al. (2011) rely on very large ensembles of simulations of an atmospheric model for both factual and counterfactual worlds. Those large ensembles have since been used in many studies and there have been developments to use them for operational near real-time attribution systems(e.g. Haustein et al., 2016; Massey et al., 2015; Wolski et al., 2014). In the rest of the article, this approach will be referred as risk-based approach, following the nomenclature of Shepherd (2016).

2.1.3.2 Later developments of EEA

A few years later, other ways to put an extreme event in the perspective of anthropogenic climate change have emerged. For example, without explicitly calling it attribution, Perlwitz et al. (2009) showed how the unusual SST pattern of winter 2008 in the Pacific were responsible for the drop in North American temperatures, and that without anthropogenic emissions, the cold would have been stronger. Similarly, Cattiaux et al. (2010) showed that the cold European winter of 2009/2010 was caused by the atmospheric circulation, and that for the same atmospheric pattern, the temperatures would have been lower in the past.

In 2015, Trenberth et al. proposed to move the focus of EEA from the risk-based approach — i.e. the comparison of probabilities in the factual and counterfactual worlds — to what Shepherd (2016) calls the storyline approach, which seeks to describe how climate change influenced the physical processes leading to the event. Their reasoning is that for some events the signal-to-noise ratio is small due to the internal variability of the atmosphere, so that the risk-based approach usually cannot conclude to any change of probabilities due to climate change. It is especially the case for the events mainly driven by dynamics, that will not happen if not for an extreme atmospheric pattern, like extreme precipitations or storms. Furthermore, the influence of anthropogenic forcing on the dynamics is still widely debated in the climate community and the models are not yet up for this task in most cases (e.g. Barnes, 2013; Francis and Vavrus, 2012).

Trenberth et al. (2015) hence propose to evaluate the changes induced by anthropogenic emissions given a circulation pattern. Given the assumption that the influence of climate on dynamics is not detectable, one can then show how climate change influenced the event. The authors put this approach in the perspective of a world that is necessarily different because of climate change: a “new normal”. They point out that “all storms, without exception, are different” and argue that the failure to prove that climate change modified the probability of occurrence of an event does not mean that climate change did not play any role.

According to our interviews, one of the factors that led to the storyline approach is the political context in the US, and specifically the policy makers who do not believe in climate change: “the only way to get through to these [deniers] is through the general public. And so it’s important to communicate with the general public, and tell them that climate has changed and in fact there are tens of billions of dollars of damages that are caused by climate change every year.” In this context Trenberth et al. (2015) find it more important to highlight any way in which climate change had an effect than to calculate a ratio of probabilities. This means that the risk-based approach focuses on quantifying the role of anthropogenic climate change on the probabilities of the event, while the storyline approach aims at unveiling the qualitative ways in which anthropogenic climate change affects the processes leading to the event.

As the storyline approach is recent, its contours are still blurry and differ between scientists. Indeed, Otto (2017) proposes a third approach, that she calls the Boulder approach, since it was developed by a group of scientists working at the National Oceanic and Atmosphere Administration, in Colorado. She explains that the goal of this approach is to “disentangle different causal factors leading to the event without necessarily quantifying the influence of these causal factors on the likelihood of occurrence”. However Shepherd (2016) cites papers of this group as examples of storyline approach. Depending on the authors, the storyline approach includes only the circulation conditional framing (Otto, 2017) or is large enough to integrate any study that dissects the physical processes leading to an extreme and analyze how anthropogenic climate change influences those processes. For the rest of the article, we use the storyline approach in the general sense of Shepherd (2016), which includes Otto (2017)’s Boulder approach.

2.1.3.3 Debating the advantages of different framing approaches

Trenberth et al. (2015)’s paper criticizes the risk-based approach stating that it is “is severely challenged [. . .] when it comes to climate extremes that are strongly governed by atmospheric circulation, including local aspects of precipitation”, that it “is rather ineffectual in cases that are strongly governed by the changed circulation, with generally an inconclusive outcome” and that “even when a detectable anthropogenic influence is found in a model, the reliability of that finding cannot carry much weight”. On the other hand, the circulation conditional framing is not without its own critics. Otto et al. (2016) give several examples for which the dynamics are different in the factual and counterfactual worlds, which leads them to state that “limiting attribution studies to the thermodynamic response alone does not allow for an assessment of the actual risk of the event occurring as the large-scale dynamics can counteract or enhance the thermodynamics.”

Mann et al. (2017) go in the sense of Trenberth et al. (2015) and argue for the use of a Bayesian — rather than frequentist — statistical approach, which would account for information we already have on the physics of both the event and climate change. They mix this argument with ethical considerations on the choice of the null hypothesis (prove that climate change had an influence on the event versus prove that climate change had no influence on the event). Stott et al. (2017) however highlight that the choice of the null hypothesis is independent of the statistical framework and that there are as many biases in Bayesian as in frequentist framings. Curry (2011) also argues that there is no straightforward ethical choice of the null hypothesis in a climate change context (see also Allen (2011)'s response to Curry (2011)).

This debate is interwoven with a social concern on "which methodological approach would be more useful". Allen (2003) goes as far as arguing that the transposition of EEA to a sort of market-based mechanism could be the best solution to cope with the alarmingly slow pace of international climate negotiations. Trenberth et al. (2015) claim that their change of framing would "better serve societal needs" and would "provide a better basis for communication of climate change to the public". Otto et al. (2016) argue that "from the perspective of a stakeholder seeking information to inform disaster risk reduction strategies, it can be unhelpful to ask the question of how the probability has changed given the large-scale circumstances". A few studies explore who could be potential users of EEA (see James et al., 2014; Parker et al., 2017; Schwab et al., 2017; Sippel et al., 2015; Stott and Walton, 2013). In a second article, we will explore in depth the reasons why scientists work on EEA, based on our two corpora of interviews. For the rest of the present article, we will avoid considerations regarding the use of EEA.

Although a part of community engages in this debate, it is not the case of the whole community. We found almost no mention of it in our interviews. Moreover, a few articles have already proposed ways to combine both approaches (Shepherd, 2016; Vautard et al., 2016; Yiou et al., 2017). Stott et al. (2017) point out that "different approaches to event attribution may choose to occupy different places on the conditioning spectrum". Furthermore, authors like Pardeep Pall have engaged in both approaches (Pall et al., 2011, 2017).

2.1.4 The classification of the BAMS reports

This section explains how we approached the classification of the 105 case studies from the BAMS reports. We first tried to sort them between risk-based and storyline approach. This proved difficult because a lot of articles do not fall into either categories, or fall into both.

Stott et al. (2016) present a review of the different methods to do EEA. They distinguish them between coupled model methods, sea-surface temperature (SST) forced atmospheric model methods, analogue-based methods, empirical methods and broad-scale methods (they use the word "approaches" instead of "methods", but we changed it to "methods" in order to avoid a confusion with risk-based and storyline approaches).

We analyzed the genealogy of each article, in order to identify common methods. In supplementary table S4, we list all the case studies. We put an article in the genealogy column when the authors explicitly state their method is based on another article. The supplementary table S5.1 sums up our findings on this explicit genealogy of BAMS articles.

The coupled model methods are very diverse. We sorted them into different categories. For example, King et al. (2015); Lewis and Karoly (2013, 2014); Sun et al. (2014) have been cited several times by BAMS articles relying on the comparison of probabilities for different CMIP5 experiments for their analysis. Many other articles use this method without explicitly referring to a former article.

The most used method, also described as the SST forced method by Stott et al. (2016), stems from Pall et al. (2011), and has been refined by Massey et al. (2015), Schaller et al. (2014), Black et al. (2015) and Schaller et al. (2016). 21 BAMS articles cite at least one of those articles. This method is the one that fits best the risk-based approach. Five BAMS articles cite Christidis et al. (2013) which also use a large ensemble of an atmospheric model with different SST forcings for a part of their analysis.

Four articles (all from the same team) use the analogue method to perform a conditional attribution. They all cite Cattiaux et al. (2010) as the first article to study a specific event in the context of climate through the use of analogues. Articles with a method similar to what Stott et al. (2016) call empirical methods cite Van Oldenborgh et al. (2012), or do not reference a former article using this method (e.g. Siswanto et al., 2015). It is almost never the only method used in those articles (e.g. Sippel et al., 2016). The broad-scale methods (e.g. Min et al., 2011; Zwiers et al., 2011) are more detection and attribution of trends on extremes than EEA. We did not find references to those articles in BAMS case studies.

Four other methods are used in at least three different articles of the BAMS reports, which are not presented in Stott et al. (2016) and for which we hence give more details. Knutson et al. (2013b) question whether the models are able to reproduce the observed event with pre-industrial runs and with historical runs. They plot the evolution of the observed trend of the variable of interest (e.g. the mean spring temperature in the Eastern United States) with the starting year of the trend. They compare those observed trends with the ensemble of trends for both natural and anthropogenic forcings from CMIP5 models to see if the observed trends are consistent with climate variability alone. This method lies in between detection and attribution of trends and EEA. We found seven articles using this method in the BAMS.

The strategy of Arblaster et al. (2014) is to determine which parameters — among which climate change — are necessary to reproduce the observed anomaly — of temperature in this case. The coupling of a seasonal forecast system and of a multiple linear regression allows the authors to reconstitute the temperature and consider which physical processes were the most important predictors for the extreme event to happen. One of these predictors is the global mean temperature, the change of which has been attributed to climate change. The authors refer to this as a “multi-step attribution process”. 3 BAMS articles from the same team (including Arblaster et al. (2014)) use this method.

Guemas et al. (2013), Massonnet et al. (2015) and Fučkar et al. (2016) are case studies dealing with anomalies of sea ice extent. They rely on the reconstitution of anomalies with different initializations using a sea ice model. Murakami et al. (2015), Yang et al. (2015) and Zhang et al. (2016) examine tropical storms. They use forecast-oriented model simulations with different initializations to analyze the influence of climate change on those events.

Apart from the analogue method, the papers based on Christidis et al. (2013) also analyze the events with a circulation conditional framing. Those articles could fit in both a storyline and a risk-based approach. A few individual papers could also fit into a storyline framing (e.g. De Vries et al., 2013; Sweet et al., 2013). Hence, the storyline approach is less represented than the risk-based approach in the BAMS reports. This could be due to the fact that the storyline approach as proposed by Trenberth et al. (2015) emerged after a few of the BAMS reports were already published. The storyline approach lacks at the moment a widespread method like the one of Pall et al. (2011) is for the risk-based approach. This under-representation may also be related to the very short length of BAMS articles, which does not fit as well the storyline approach than the risk-based approach. This does not mean that no article use this kind of approach. Outside of the BAMS, Hoerling et al. (2013), Meredith et al. (2015), and Pall et al. (2017) are three examples of storyline approaches.

Only 49 out of 105 BAMS articles explicitly sort themselves as part of a type of method through a genealogical link to a published EEA article. We also failed to sort them between approaches. This suggests that the authors, and hence a significant fraction of EEA community, do not consider the choice of an approach or of a method to be defining elements of their analysis. We hence propose hereafter a way to describe all the potential framings of EEA, without relying on a sorting of different methods or approaches.

2.1.5 Defining EEA

We have found that sorting the case studies between methods excludes most of the BAMS articles. This means that trying to categorize the case studies into different approaches or methods does not suffice to give a proper overview of EEA. However, the framing of EEA has a clear impact on the results of any given case studies. Angélil et al. (2017) have shown how the results of all the BAMS articles from year 2011 to 2014 would differ using a different method (and data sources) than the one used by the original authors. Dole et al. (2011) and Rahmstorf and Coumou (2011) find apparently contradictory results regarding the attribution of the 2010 Russian heatwave due to different framings (Otto et al., 2012).

We propose hereafter to differentiate the ways to frame EEA based on several criteria. In order to do so, we first propose a definition EEA that captures all the different possible framings. We build it from the definitions of the relevant actors: the researchers working on EEA. We select the elements common to all of their definitions and we do not keep those which do not apply to every point of view in order to get the most consensual picture.

From both corpora of interviews we have asked 19 climatologists who have published papers on the subject to define EEA (question 2 in SM.1 and 3bis in SM.2). This sample of climatologists covers both approaches, and most (but not all) of the methods described in section 3. The most relevant excerpts of their interviews on that question are listed in the SM.3. Through the analysis of the lexical fields used in those answers we found a few elements that come back frequently when a researcher defines what is EEA. We have sorted them in the following categories:

1. the notion of causation,
2. the study of one specific extreme event,
3. the relationship with anthropogenic climate change and natural variability ,
4. the use of statistics,
5. the understanding of physical processes explaining the extreme,
6. the detection of a change.

The first three points seem to relate to almost all the answers. When they do not appear explicitly they are implied. EEA deals with what causes a specific extreme event, in relation with climate change. The fourth and fifth categories could be considered as references to the debate between risk-based and storyline approach we exposed in section 2, which seems to be ingrained in a part of the community. However, because we have shown that this debate is not essential to define EEA (in agreement with Shepherd (2016) and Stott et al. (2017)), we will not keep those elements as parts of our working definition of EEA.

The sixth category is probably an artifact related to the use of the word "detection" in the A2C2 corpus and not in the EUCLEIA corpus. We hence find it best not to consider it for our definition, since detection (in the sense of Hegerl et al. (2010)) is rarely a part of EEA studies.

Our working definition has to adopt the widest possible scope so as to include every acceptation of EEA and to discuss their differences. Building on the three first categories, we propose to define EEA as the ensemble of scientific ways to interpret the question "was this event influenced by climate change?" and answer it. We avoid references to causality, as advised in chapter 2 of on Extreme Weather Events and Attribution. We choose to refer to *climate change* and not *anthropogenic climate change*, as EEA could be applied to changes not related to anthropogenic activities (e.g. volcanic eruptions). Questions like "how the probability of an event is affected by climate change?", or "how climate change modified the physics of an event?" are different reformulations of the question "was this event influenced by climate change?" in a suitable way to make it possible to answer through a scientific study.

2.1.6 Framing EEA

We can use this definition to show all the possible framings of an EEA study. In order to do so, we decompose the original question "was this event influenced by climate change?" into three separate issues. First, how does one define the event to study? Second, what does one mean by "influenced by"? Third, how does one represent climate change? This partition and the variation of answers to those three questions allow us to give a better picture of the subtleties of EEA and to detail the choices one has to do to propose a methodology to study a given event.

2.1.6.1 The event

Class of events and singular event Before explaining the different ways to define the event to study, we go back to the question "what is the meaning of the word event?". There is a matter of whether we really consider a singular event or a class of event. In the first case, it would mean answering whether the exact event is influenced by climate change. In the second case, it would mean answering whether all the events within a class (e.g. all the heatwaves above a certain threshold of temperature for a given number of consecutive days) become more likely because of climate change. Harrington (2017) has shown how those two different choices can lead to different results.

The attribution of a singular event is contingent upon the idea that somehow, the causal chain leading to this event may be reproduced in whole or in part. The idea is to recreate the same event and to evaluate how this event fares with and without climate change. There are different ways to do that. For example, Hannart et al. (2016) use data assimilation that allows them to constrain the event to its observed trajectory in a model. Meredith et al. (2015) condition strictly the circulation of their model to the one observed during the very high precipitations they are interested in. Then, they run their model for 2 different levels of greenhouse gas (GHG) emissions and SST corresponding respectively to a factual and a counterfactual world. Arblaster et al. (2014) try to recreate the precise pattern of temperature anomaly observed during a heatwave by modeling several physical processes.

The attribution of a class of event is probabilistic. The goal is to evaluate if there is a change of the probability that any extreme event that shares its extreme feature with the event of interest happens due to climate change. This is mainly done by considering all the events above a certain threshold. Many studies use the observed extreme anomaly of the variable of interest as this threshold. Others choose a lower threshold, especially when the event is so extreme that it would be difficult to trust statistical tests too far in the tail of the distribution (as was done in Stott et al. (2004)). In that case, there is no need for the event to actually happen to do an EEA study. One just needs to choose a threshold, a duration and a region (Christidis et al., 2015b). A few methods rely on different ways to define a class of event, e.g. the ones based on analogues of circulation.

Choice of the event Apart from those general considerations on the meaning an “event”, before starting an EEA study one has to choose the event of interest. There are different reasons to consider an event to be interesting enough to study. It can be because of its impacts, its rarity, or both. We provide an overview of those motivations in supplementary Table S5.2.1. In the BAMS reports, out of 105 articles, 33 explain their interest in an event based solely on its rarity, 27 based solely on its impacts and 42 based on both. This does not mean that there are no other implicit reasons involved in the choice of a specific event. 11 articles advance different reasons (for a more comprehensive list of reasons, see the supplementary Table S4). For example, King et al. (2015) chose an event because it raised the media attention. We also stress that the impacts can go from very serious (e.g. “a tragic food crisis that led to famine conditions” in Funk (2012)) to rather harmless (e.g. the well-being of tennis players during the Australian Open (King et al., 2015)).

There is also the matter of the selection of the region where the event happened, which we summarize in supplementary Table S5.2.2. Most of the time, researchers study events happening in the region where they live. Out of the 105 case studies in the BAMS, 80 focus on the region of the first author’s laboratory. 69 study events happening in Annex I countries, as defined by the UNFCCC, 29 focus on non Annex I countries and the rest (7 out of 105) look at polar regions or the ocean. Hence there is a disproportion of case studies in favor of developed countries (this was also pinpointed by Stott et al. (2016) and Angélil et al. (2017)). This selection bias is exacerbated by the fact that climatologists are aware of the events happening in their own countries *because* they see them happening, while they might not pay attention to extreme events happening on the other side of the world otherwise than through media reports of their impacts.

Sometimes, local stakeholders play a part in motivating researchers to study a particular event. One of our interviewees told us that “policy makers [...] had questions about [an] event because they are of course concerned about whether or not the same kind of event might happen [again]". Regional projects also mainly finance studies about local events. For example, the EUCLEIA consortium produced 6 case studies about European extreme events (e.g. Hauser et al., 2017; Wilcox et al., 2017), and the French project Extremoscope financed research focused on extreme events affecting France (e.g. Ouzeau et al., 2016). A few stakeholders, like the Red Cross which worked with the World Weather Attribution project (Herring et al., 2016b) or UK's National Environment Research Council which funded the ACE (Attributing Impacts of External Climate Drivers on Extreme Weather) Africa project (e.g. see the acknowledgment of Bergaoui et al. (2015)), also support research studying developing countries, which do not have research infrastructures that can lead such studies.

This selection bias has societal impacts. Huggel et al. (2016) argue that the countries that would most benefit from EEA, especially in the context of loss and damage, are also those where there are no EEA case studies. The number of studies of extreme events happening in under-represented countries, which are also the most vulnerable, nonetheless keeps increasing with each BAMS issue (Stott et al., 2016).

Precise definition of the event Once an event is chosen, there are three choices left: the precise definition of the region affected, the time period to study, and the variable that will best represent the event. For the same event, different studies address those questions differently. For example in the BAMS report on 2013 extreme events, 3 articles deal with the Californian drought. Swain et al. (2014) consider a yearly event, Wang and Schubert (2014) focus on January and February, while Funk et al. (2014) study the winter season from November to February. Most of (if not all) the time, those choices are arbitrary, meaning that they do not arise from scientific considerations, but rather from political borders, or from regions defined in earlier articles that might not be relevant for the specific event of interest. Cattiaux and Ribes (2018) propose to optimize both of those choices by selecting the region and period for which the event has the lowest probability of occurrence. This could be a way to study the most extreme events, and to objectify the choice of a region and a time period.

2.1.6.2 Influence of climate change: level of conditioning

The second part of the decomposition of the question "was this event influenced by climate change ?" is to show all the different ways to analyze the role of climate change. In order to sort them, we follow on Extreme Weather Events and Attribution, which divides EEA between two types of methodologies: unconditional and conditional attribution. We have classified all the BAMS articles between different nuances of conditioning. We divided the articles into the following categories (see supplementary table S5.3 for an overview):

- Unconditional – 42
- Conditional to SST/SIC (sea ice cover) – 40
- Conditional to circulation – 9
- Conditional to El Niño/La Niña – 9
- Conditional to sea level rise – 2

- Effects of anthropogenic climate change on a precursor – 13
- Effect of other precursors than anthropogenic climate change –29

Attribution is *unconditional* when the study directly links anthropogenic climate change to an extreme observable, or its impacts. That can only happen in studies using either only observations or coupled models (CMIP5 or studies focused on a particular model) with a comparison between pre-industrial (or natural-forcings only) and historical runs. This does not mean that those studies are not conditional to the biases of the models they rely on. Examples of unconditional attribution in the BAMS are the papers of Lewis and Karoly (2014) or Knutson et al. (2013a).

Conditional attribution links anthropogenic climate change combined to a precursor to either an extreme observable, or its impacts. This precursor is an internal element of the climate system which played a role in the occurrence of the event. Many studies, especially the ones based on the most widely used method proposed by Pall et al. (2011) evaluate the influence of a thermodynamical precursor combined with GHG concentrations on an extreme observable (e.g. temperature or precipitation). A thermodynamical precursor is a precursor that is directly linked to the increase of temperature and for which the influence of climate change is already clear. Most of the time the thermodynamical precursor is the SST. Because of the computational costs of coupled models, the idea is to rely on atmospheric-only models, for which the SST is a boundary condition. They allow to better represent processes like dynamics or land-surface interactions which become more trustworthy at high resolutions.

According to Risser et al. (2017), the SST conditioning methods rely on three assumptions: (i) the effect of anthropogenic climate change does not depend on the state of the ocean, (ii) the ocean variability is not affected by anthropogenic climate change, and (iii) the effect of the atmosphere on the coupling between atmosphere and ocean is unimportant at the temporal scale of the event. The influence of SST conditioning, which is massively used in the EEA literature has not been enough documented to make the assumption that the probabilities calculated are equivalent to unconditional probabilities. Dong et al. (2017) show that this assumption is globally correct for temperature extremes but that the air-sea coupling significantly changes the results for precipitations and in certain regions for the circulation. Risser et al. (2017) also provide a methodology to evaluate the influence of the SST conditioning on EEA results. Other possible thermodynamical precursors are the global temperature (e.g. Hope et al., 2015) or sea level rise (e.g. Sweet et al., 2013).

Conditioning can also combine climate change to a precursor not clearly related to climate change through thermodynamics, i.e. a dynamical precursor. This type of conditional attribution is the one presented in Trenberth et al. (2015), which Shepherd (2016) called "storyline approach". The idea is that for events heavily conditioned by the dynamics, the climate change signal will be drowned in the internal variability. This does not mean that there is no effect of climate change. The question asked in this case would rather be "Given the change in atmospheric circulation that brought about the event, how did climate change alter its impacts?" (Trenberth et al., 2015) or "What is the best estimate of the contribution of climate change to the observed event?" (Shepherd, 2016).

There are examples of other types of conditioning dealing with other scales of internal variability. Nine BAMS articles study the influence of El Niño (or La Niña) on an event, combined with the influence of climate change on El Niño (e.g. King et al., 2013).

13 case studies focus on the role of climate change on a specific precursor of the event without attributing the event itself to climate change. For example, Funk (2012) calculate the Indian-Pacific warm pool (IPWP) enhancement by climate change. They rely on the literature to link the IPWP warming to droughts in Eastern Africa, which were their event of interest.

29 case studies also consider the impacts of other precursors than anthropogenic climate change. Most of these studies (22) are combined with a part discussing the role of climate change. The method of Arblaster et al. (2014) summarized in the third section gives an example of such an approach. The fact that seven BAMS studies analyze only the effect of other precursors than anthropogenic climate change shows that EEA can encompass attribution to climate change more generally than just anthropogenic climate change.

Lastly, Von Storch et al. (2014) and Feser et al. (2015) only detect changes without any attribution step so we could not sort them.

An interesting result of sorting BAMS studies into different levels of conditioning is that each issue of the BAMS increases the sampling of uses of different methods and the comparison of their results. Those studies are highlighted in boldface in the supplementary table S5.3. This is consistent with the recommendations of on Extreme Weather Events and Attribution (2016). The EUCLEIA project has also devoted one work package to multi-method case studies (e.g. Hauser et al., 2017; Wilcox et al., 2017).

2.1.6.3 Climate change: Definition of a counterfactual world

EEA usually relies on the comparison of a factual and a counterfactual world. The difference between these worlds is the key to calculate the role of climate change. Their definitions vary from one study to the other. To build a counterfactual world, one has to decide how far back to anthropogenic emissions one needs to go to represent a world without climate change. There are several ways to compare worlds with and without climate change. We have sorted the different ways to create a counterfactual world in the following categories (supplementary table S5.4 gives the detail of how we classified each BAMS article):

- Past/Historical – 24
- SST/SIC/GHG Preindustrial – 21
- SST/SIC/GHG Natural – 9
- SST/SIC/GHG Historical – 13
- Natural forcings only – 17
- Preindustrial – 22
- Not relevant – 15

The simplest way to proceed is to compare a past period to a most recent period, whether it is in observational datasets, or in the historical period of a climate model. This will not give a complete account of the effects of climate change, as the world of the past might already be affected by anthropogenic emissions. The main advantage (and disadvantage, given the length and availability of the observational datasets) of this technique is that it allows to rely on observations only (e.g. Van Oldenborgh et al., 2012). In this context, climate change accounts for both anthropogenic and natural forcings.

Other studies use pre-industrial runs from coupled models as counterfactual worlds. There is a thin line between a definition of the counterfactual based on the past and the counterfactual based on pre-industrial conditions. Sometimes the word pre-industrial is not explicitly stated but when the reference is a past climate of before 1900 we sorted it as pre-industrial (e.g. Barlow, 2015). This arbitrary choice can be challenged, as Hawkins et al. (2017) have shown that 1870 does not necessarily equal preindustrial. We however choose to keep it to make the classification simpler. An alternative option to pre-industrial for coupled models users is to use historical runs with natural forcings only, which are available for CMIP5 models. Five articles use both pre-industrial and natural counterfactual worlds.

For methods based on atmospheric models, the factual world is built using the observed SST as input. The tricky step is to create counterfactual SSTs (Schaller et al., 2016). There is an evolution from historical towards preindustrial through the BAMS issues. Otto (2017) also discusses the consequences of the differences between counterfactual worlds in the context of SST conditional attribution.

The use and comparison of several counterfactual worlds does not occur as frequently in the BAMS as the use of multiple levels of conditioning, although it does happen in the three latest issues studies here. However, there is a case for testing the influence of the choice of counterfactual on the results, since Hauser et al. (2017) have shown that it has an impact.

In the BAMS, the evaluation of contributions from differentiated external forcings, like GHG and aerosols, or land-use is rarely done. In contrast with the detection and attribution of trends, one of the interviewees states that “EEA is very very predominantly envisioned in an anthropogenic vs natural perspective, and only with this reading grid”. There are very few studies that differentiate the role of those anthropogenic forcings in the BAMS. As an exception to that rule, Wilcox et al. (2015) and Miao et al. (2016) make a distinction between aerosols and GHG emissions effects on the extreme event. We also point out that Pall et al. (2011) define their counterfactual by removing the GHG part of the anthropogenic forcing, not the aerosols.

We note that for a few articles, the explicit definition of a counterfactual world is not necessary. We sorted them as not relevant. Those articles use methodologies based on the reconstitution of an observed anomaly (e.g. Arblaster et al., 2014) or only do trend detection without any comparison to trends in a counterfactual world (e.g. Feser et al., 2015).

2.1.7 Conclusion

We have shown that the BAMS case studies use different types of methodologies, compare different datasets, and explore different conditionings in order to give a better picture of the diverse causes of an extreme event. We propose a definition of EEA that encompasses the different approaches used by the community described in section 2. EEA is the ensemble of scientific ways to interpret the question “was this event influenced by climate change ?” and answer it. It allows us to describe the differences between framings through three main axes: how does one define the event of interest? how does one analyze the role of climate change? what does one mean by a world without climate change? We have described the diversity of ways to answer these questions used in the BAMS and provide a complete classification in the supplementary material.

Although the BAMS issues are a very practical database due to the common strict guidelines, they also have limitations. Indeed, a few methods (especially those following the storyline approach) have not yet been used in the BAMS (e.g. Hoerling et al., 2013; Meredith et al., 2015; Pall et al., 2017) and may never be due to the limited space allowed for each case study. This entails that while the BAMS is informative of a large part of the work of EEA, it cannot be considered as an unbiased sample.

The next step of our unveiling of EEA will be to better understand its use, as it seems to be a point of contention between the different approaches we described in section 2. A few articles have already started to tackle this question (e.g. Hulme, 2014; Sippel et al., 2015). A second article will analyze in detail the two corpora of interviews to answer the question : “why do we do EEA?”

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2.2 Building a definition from interviews

We list below excerpts from the answers of interviewees who were asked what is their definition of EEA. Through the analyze of the lexical fields used in those answers we found a few elements which come back frequently when a researcher defines what is EEA. We highlighted the 6 categories we identified as follows:

1. **the notion of causation**
2. *the study of one specific extreme event*
3. the relationship with anthropogenic climate change and natural variability
4. ***the use of statistics***
5. **the understanding of physical processes explaining the extreme**
6. *the detection of a change*

Those excerpts were provided as supplementary material of the article.

2.2.1 EUCLEIA corpus

E1 "I mean that we have provided an **explanation of why** *that extreme event* happened"

E2 "There are two types of attribution [. . .] what is the probability of *that event* being of anthropogenic origin? what is the ***probability*** that *a certain event* is **due to** a climate forcing that could be natural [?]"

E3 "what we want to know is the **link** between *extreme events* that we witness and the anthropogenic made climate change."

E4 "the question of attribution is to **understand why** *this event* is occurring"

E5 "the job of attribution is to try to identify what are the relevant **causal** factors that influence the ***likelihood*** of *a particular event or a class of events* and as far as possible to quantify the relative importance of these different factors."

E6 "Attribution traditionally would be trying to distinguish whether it is **due** just to natural variations in the climate system, or in atmosphere or the atmosphere ocean or on the other hand how much is due to effects of human induced changes in the climate system. [. . .] I would say a part of the attribution is not only in the ***statistical*** sense whether is a trend or pure coincidence, but also whether we have the **physical storyline** of *an event*, which is more the **understanding of how** an event comes about."

E7 "to which extent human activity **causes** *such extremes events* or articulate extreme events [?]"

E8 "I can ask the question, whether when something happens now, if it is ***statistically*** coherent with the normal climate."

E9 "attributing an extreme event is determining **[what aspect] contributed** to *the event*"

E10 "what's **contributing** to the currents of *an extreme event*, and a different type of extreme event might have very different **causes**"

2.2.2 A2C2 corpus

A1 "It either means saying something about the *change* and ***risk*** that we are exposed to, **understand the circumstances** and that question might have been instigated by the occurrence of an extreme event or it means actually identifying the specific **causes** of *a specific event* that occurred."

A2 "Can we *isolate any change* in the ***frequency***, intensity of *an extreme event*, that is your expectations of simply what you would expect to occur by chance. And attribution is can we **attribute** this, such *detected* change to any external factor of the system."

A3 "to comment on an event [. . .] with the idea to say here is how man **contributed** to the ***probability of occurrence*** of some events, preferably extreme events 1"

A4 "Detection is determining whether a certain factor, a potential driver of change has actually driven *an observed change*. While attribution is determining the relative importance of various multiple drivers that might have an **effect** on that change."

A5 "I would rather talk about **causal** attribution, or of questions of **causality** in climate science."

A6 "For example if you take the ***centennial*** *flooding*, will it happen today as ***1-in-20 years*** event or will it take longer to happen?"

A7 "you sort of have these steps that you go through in your methodology."

A8 "you get questions from the media: what's the **cause** of this? Did it have a climate change component?"

A9 "Trying to assess the extent to which *an extreme event* was [. . .] **affected by** anthropogenic climate change."

2.3 A few comments on the methodology

The first goal of the series of interviews of climate scientists I conducted was to analyze the reasons why they engaged in EEA. I explore this angle in chapters 6 and 7 of this manuscript. I realized along the way of the analysis of the corpora of interviews that the question of how they engaged EEA was as important as the why. The material from both A2C2 corpus of interviews and the EUCLEIA corpus reflect a plurality of views regarding what is EEA (question 2 of the EUCLEIA corpus and 3 of the A2C2 corpus) and when and why they would consider an EEA exercise to be successful (question 4 of the EUCLEIA corpus and 7 of the A2C2 corpus). This was an occasion to document the different views on EEA, as objectively as possible, without taking position for or against different framings of EEA.

On the other hand, the growing number of EEA case studies and especially the articles published yearly in the BAMS reports gave access to sufficient data to make it possible to describe what was effectively done by the community by an empirical analysis. I chose to only classify the BAMS studies because they provide an homogeneous ensemble of articles. They present the advantage of being short enough to systematically analyze and sort them in a reasonable amount of time.

The interviews were done between June 2016 and January 2017, concurrently with and before the publication of a number of articles discussing the framing of EEA (in particular Angélil et al. (2017); Cattiaux and Ribes (2018); Harrington (2017); Lloyd and Oreskes (2018); Mann et al. (2017); on Extreme Weather Events and Attribution (2016); Otto et al. (2016); Shepherd (2016); Stott et al. (2016, 2017)). These articles were mostly theoretical discussions regarding the framing of EEA. Since at the time we designed the interview grid, questions surrounding the framing of EEA were only emerging, there are a few things I would do differently if I had to redo this work now. First, I would add a few questions, which were not there because I did not anticipate that describing the framing of EEA would be an essential part of the work. The classification of BAMS articles we propose in the article emerged progressively through different readings and sorting trials of the corpus of BAMS articles. This work could have been more effective if the questions asked to the interviewees helped to identify what they considered to be the essential steps of the framing of an EEA case study. At the time I conducted the first half of the interviews, I was not aware of the internal debates regarding risk-based and storyline approach. They became apparent to me through my participation to different workshops and conferences and through the reading of the articles mentioned above. Questioning the interviewees on their stance regarding this debate would have been valuable to determine whether it was fundamental or marginal for the ensemble of the community (although the analysis of the BAMS articles tends to confirm the latter).

Another essential step of building a corpus of interviews is the selection of participants. I chose participants working in different laboratories, with a focus on scientists not involved in EUCLEIA, since I already had access to the transcriptions of the interviews led for the EUCLEIA project. The sample of scientists interviewed covered a large part of the EEA community. Given the results of the BAMS classification, I missed a few teams. The corpus would be more complete if it included someone who used Knutson et al. (2013b)'s approach, someone from the (rather large) Australian EEA community, and, as stated in the article, someone from the Boulder group. The size of the sample was also determined by the time it took to conduct the interviews, and to analyze them. I discuss the homogeneity of the EEA scientists population and explain why we can rely on a relatively small sample of interviewees in chapter 6. The review of the paper (with four reviewers) helped to better reflect the views of the community.

Interviewing a sample of leading scientists in the field of EEA helped me greatly to structure my understanding of the topic. This is an innovative way to use semi-structured interviews, which are a social science tool, for a kind of review of a scientific topic. I am not aware of any other review using this methodology, which could be applied to other topics than EEA. This kind of interview-based approach, once refined, could be an original and informative way to review a scientific subject.

2.4 Conclusion

I highlighted three issues which help to structure the framing of an EEA study: the definition of the event, the way to evaluate the influence of climate change, and the definition of the counterfactual world. These questions apply to this PhD as follows. I study a class of events defined as events with an atmospheric circulation close to the one of the event of interest. The choice of the events of interest is motivated by geographical proximity and direct observation. The influence of anthropogenic climate change is evaluated twofold: I study the effects of anthropogenic climate change on a dynamical precursor, and the influence of anthropogenic climate conditional to this dynamical precursor. As I mainly propose methodologies based on trends, the definition of a counterfactual world is mostly not relevant (with the exception of the studies at the beginning of chapter 5 with a counterfactual world defined as a past period).

The diversity of framings and methods to perform EEA described in the article shows that EEA is an expanding scientific field. They also reflect different visions of what are the most relevant questions regarding the influence of (anthropogenic) climate change on individual events. Writing this article helped me to gain perspective on my own practice of EEA and in choosing a direction of research. As I never calculate a FAR or a risk ratio in this manuscript, one could argue that I do not perform EEA. I tend toward what could be considered as a storyline approach. First, I quantify the role of dynamics on European heatwaves for a constant climate (chapter 3). Second, I propose a methodology to evaluate the role of climate change on the dynamics leading to specific European heatwaves (chapter 4). Third, I present a way to calculate the role of climate change on high European temperatures for a fixed circulation (chapter 5).

Résumé

Contexte et objectifs

Ce chapitre se penche sur l'attribution d'événements extrêmes, une science jeune dont l'objectif est de déterminer si le changement climatique a joué un rôle sur des événements extrêmes précis ayant été observés. Il décrit les différentes méthodes et approches utilisées par la communauté scientifique pour évaluer ce potentiel rôle.

Méthodes

L'analyse présentée dans ce chapitre s'appuie sur trois sources de données : un ensemble d'interviews de scientifiques qui pratiquent l'attribution d'événements extrêmes, 105 études de cas d'événements extrêmes effectués pour des rapports spéciaux sur les événements extrêmes de l'année passée commandés par le BAMS (Bulletin of American Meteorological Society) et une revue plus générale de la littérature scientifique sur l'attribution d'événements extrêmes. Les interviews et la littérature permettent de comprendre ce qu'est l'attribution d'événements extrêmes et de poser une définition. La classification des études de cas selon plusieurs critères cartographie les différentes méthodes et mène à l'identification des éléments constitutifs nécessaires au cadrage de l'attribution d'un événement.

Résultats

L'attribution d'événements extrêmes est l'ensemble des façons scientifiques d'interpréter la question "cet événement a-t-il été influencé par le changement climatique" et d'y répondre. Trois sous-questions constitutives du cadrage de toute étude de cas découlent de cette question initiale. Premièrement, comment définir l'événement à étudier ? Il s'agit à la fois de choisir un événement et de le définir précisément. Deuxièmement, comment faire le lien entre cet événement et le changement climatique ? Les différentes méthodes utilisées dans la littérature peuvent être décomposées selon différents niveaux de conditionnement allant d'une attribution inconditionnelle du changement climatique sur la variable extrême observée, à une attribution conditionnelle à une autre variable, comme la circulation atmosphérique. Troisièmement, comment représenter le changement climatique ? La plupart des études de cas examinées reposent sur la comparaison d'un monde contrefactuel – le monde tel qu'il aurait été sans changement climatique – avec un monde factuel – le monde dans lequel nous vivons. La construction de ces deux mondes peut se faire de plusieurs manières. Ce chapitre contient les résultats de la classification des études de cas publiés dans le BAMS selon ces trois critères.

Chapter 3

Influence of circulation patterns on European heatwaves

I showed in the previous chapter that climate scientists have a tendency to study events happening in their own region. This finding applies to me too. I started this PhD in September 2015, just after a very hot summer in France, and more generally in central and Southern Europe. It was natural to start by studying the summer that just happened in front of my doorstep. For the rest of the PhD I sticked to European heatwaves that happened since 2003.

The main goal of this PhD (for the climate science part) is to disentangle the specific role of atmospheric circulation in the occurrence of heatwaves compared to other physical mechanisms in a changing climate. The first step in that direction was to evaluate the role of circulation for a fixed state of the climate. The fact that long-lasting blocking anticyclonic patterns are factors that enable summer European heatwaves has long been known (e.g. Yiou and Nogaj (2004), Cassou et al. (2005), Quesada et al. (2012)). The added value of the work presented hereafter is to quantify how much of the observed temperature anomaly could be explained only by the observed circulation pattern.

This led to the publication of the article presented hereafter, which proposes a methodology for this quantification applied to four European heatwaves (June 2003, August 2003, July 2006, and July 2015). For this purpose, we rely on flow analogues, which were already used by Pascal Yiou in several articles (e.g. Yiou et al. (2014), Yiou (2014)). We introduce the concept of *uchronic*[1] temperatures, i.e. temperatures that could have been for a given atmospheric circulation. I designed the computation of these uchronic temperature distributions and found that they depend on many different parameters, which are described in the paper. Sabine Radanovics wrote the castf90 program, which generates analogues, and I adapted it for the needs of the article. The rest of this chapter is dedicated to a few more details on the parameterization of analogues, which did not make the cut for the article and to a discussion regarding ways to evaluate their quality.

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[1] The word *uchronia* was coined in 1876 by Charles Renouvier. It is a neologism from *utopia* (no-place) replacing the Greek *topos* (place) with *chronos* (time). It refers to an alternate history that could have been but did not happen. For example, *The Man in the High Castle* written by Philip K. Dick in 1962 is a uchronic novel describing a world where Nazi Germany and Imperial Japan won World War 2.

3.1 Article published in *Climate Dynamics* : Role of circulation in European heatwaves using flow analogues

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3.1.1 Abstract

The intensity of European heatwaves is connected to specific synoptic atmospheric circulation. Given the relatively small number of observations, estimates of the connection between the circulation and temperature require ad hoc statistical methods. This can be achieved through the use of analogue methods, which allow to determine a distribution of temperature conditioned to the circulation.

The computation of analogues depends on a few parameters. In this article, we evaluate the influence of the variable representing the circulation, the size of the domain of computation, the length of the dataset, and the number of analogues on the reconstituted temperature anomalies. We tested the sensitivity of the reconstitution of temperature to these parameters for four emblematic recent heatwaves: June 2003, August 2003, July 2006 and July 2015. The paper provides general guidelines for the use of flow analogues to investigate European summer heatwaves. We found that Z500 is better suited than SLP to simulate temperature anomalies, and that rather small domains lead to better reconstitutions. The dataset length has an important influence on the uncertainty. We conclude by a set of recommendations for an optimal use of analogues to probe European heatwaves.

3.1.2 Introduction

There have been many studies showing that heatwaves are bound to become more intense and more frequent under climate change (Field and Intergovernmental Panel on Climate Change, 2012). The evolution of the probabilities of those events and of their properties, such as intensity, duration and extent, is a key question for adaptation due to their impacts, including on crop yields (Ciais et al., 2005) and human health (Fouillet et al., 2006; Peng et al., 2011). A first step is to understand the physical processes at play during heatwaves, such as the influence of soil moisture (Seneviratne et al., 2010), or SST (Feudale and Shukla, 2007). Yiou and Nogaj (2004) studied the relation between the atmospheric circulation and extreme events over the North Atlantic and Horton et al. (2015) linked the increase of heatwaves to the increase of the frequency of mainly anticyclonic weather types. In this paper, we aim at quantifying the role of the atmospheric circulation during spells of high temperatures, that occurred in major European heatwaves. In particular, we want to understand which proportion of the heatwave intensities can be explained solely based on the associated atmospheric circulation, in an effort to disentangle its contribution compared to other factors such as global warming or land surface feedbacks (Shepherd, 2015).

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Our methodology is based on flow analogues (e.g. Yiou et al., 2014). Historically, analogues were used in weather forecasting (e.g. Ben Daoud et al., 2016; Chardon et al., 2016; Duband, 1981; Lorenz, 1969; Toth, 1991b). They have been used in empirical downscaling (e.g. Chardon et al., 2014; Zorita and von Storch, 1999), circulation dependent bias correction (e.g. Djalalova et al., 2015; Hamill and Whitaker, 2006; Hamill et al., 2015; Turco et al., 2011), in combination with ensemble data assimilation (Tandeo et al., 2015), in probabilistic wind energy potential estimation (Vanvyve et al., 2015), and paleo climate reconstruction (Gómez-Navarro et al., 2014; Schenk and Zorita, 2012).

Here, the analogues are defined as days with an atmospheric circulation similar to the day of interest. The underlying assumption is that the circulation has an influence on more local climate variables such as temperature and that therefore the temperature in a specific region given a certain type of circulation has a more narrow distribution than the unconditioned temperature in the same region. To isolate the influence of certain types of circulation on the temperature, we compare the probability density functions of temperature anomalies reconstructed for both randomly picked days and days picked among analogues. The analogues depend on many parameters, including the size of the domain of computation, or the length of the dataset. The goal of this paper is to provide general guidelines to choose those parameters to get flow analogues adapted to the study of European summer heatwaves. Those guidelines are obtained from four emblematic cases of heatwaves. Our paper explores physical parameters on which the analogues are computed, and focuses on temperature reconstructions.

Section 2 details the methodology used in this study. Section 3 tests the sensitivity of several physical and statistical parameters on which the methodology is based. A part of this section is devoted to a qualitative evaluation of the uncertainty related to the limited size of the datasets. Section 4 focuses on the role played by the circulation in each of the chosen case studies. The results are discussed in Section 5 and conclusions appear in Section 6.

3.1.3 Methodology

3.1.3.1 Heatwave selection

We focus on heatwaves occurring during the summer months (June–July–August: JJA), knowing that the processes involved in the development of a heatwave vary from one season to the other. We chose heatwaves that stroke Europe since 2000: June and August 2003 (e.g. Beniston, 2004; Cassou et al., 2005; Fischer et al., 2007) in Western Europe (WE), July 2006 (Rebetez et al., 2009) in Northern Europe (NE), and July 2015 (Russo et al., 2015) in Southern Europe (SE). We chose to study June and August 2003 and not the whole summer for consistency in the length of the studied heatwaves. Furthermore, both heatwaves have been studied separately by Stéfanon et al. (2012). We use the NCEP reanalysis I dataset (Kalnay et al., 1996), which provides us with 68 years of data from 1948 to 2016. The advantage of this dataset is that it is updated near real time (with a three days delay), so that the methodology could give results already a few days after a given event. Longer datasets like ERA20C (Poli et al., 2016) or the NCEP 20th Century Reanalysis (Compo et al., 2011) are less frequently updated or do not include 2015, and were therefore not retained.

The peak temperatures occurred in different regions for each heatwave. These regions correspond to the black boxes in figure 3.1. They are centered on the region of highest temperature anomaly. The size of the boxes was defined such that the monthly temperature anomalies averaged over them are records (see figure 3.2). Hence we identify two heatwaves in 2003, in June and August, which is consistent with Stéfanon et al. (2012). Choosing a slightly larger box does not alter the results or the methodology.

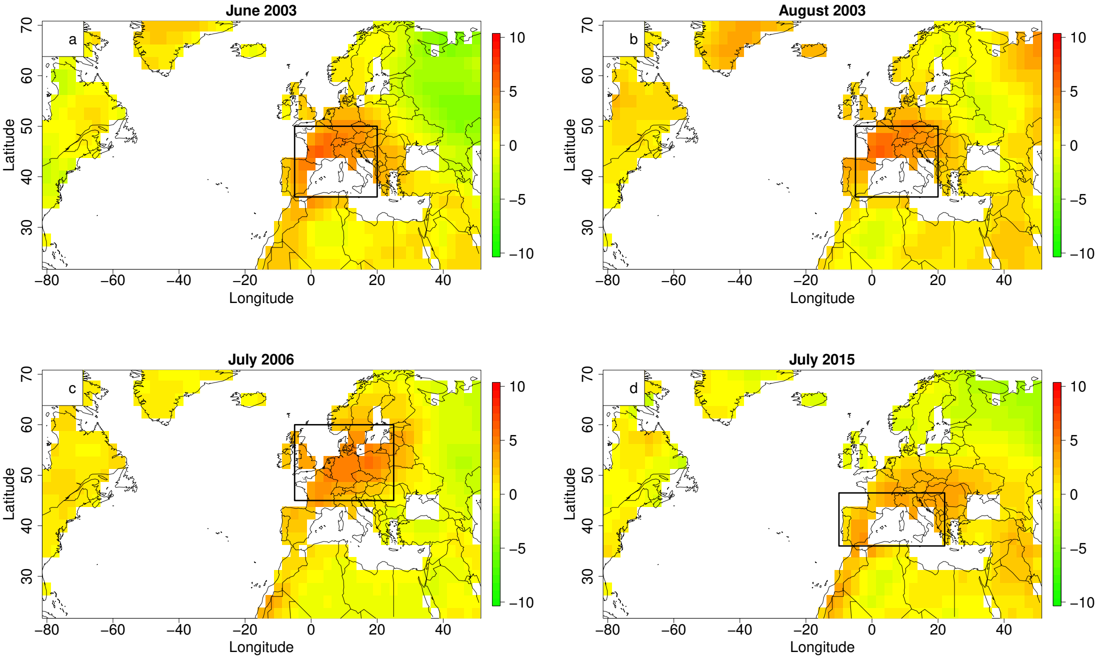

Figure 3.1 – Monthly mean temperature anomalies over land areas (NCEP dataset with reference to the 1948-2015 mean) for the four case studies (in °C). The black rectangles indicate the regions of interest for the rest of the study.

We observe a significant linear temperature trend ($p - value < 0.05$), related to climate change, for each month and region studied (red lines in figure 3.2): 0.23°C per decade for June (WE), 0.24°C for July (NE and SE) and 0.25°C for August(WE). For the rest of the study we calculate detrended temperatures using a non-linear trend, calculated with a cubic smoothing spline (green lines in figure 3.2). The reason is to extract the role of circulation in high temperature extremes, regardless of the state of the background climate, the evolution of which is non-linear.

3.1.3.2 Flow analogues

We used flow analogues to extract the contribution of circulation dynamics to the chosen heatwave events comparing their temperature anomalies to those of analogues. Analogues were defined as the N days with the most similar detrended sea level pressure (SLP) or geopotential height at 500 hPa (Z500) anomaly fields. The similarity was measured with the Euclidean distance between two maps (Yiou, 2014). We only considered the days within a 61 calendar days (30 days before and 30 days after) window centered on the day of interest because of the seasonal cycle of both circulation and temperature (Yiou et al., 2012). We further exclude the days coming from the same year as the event from the 1948–2015 data set, because

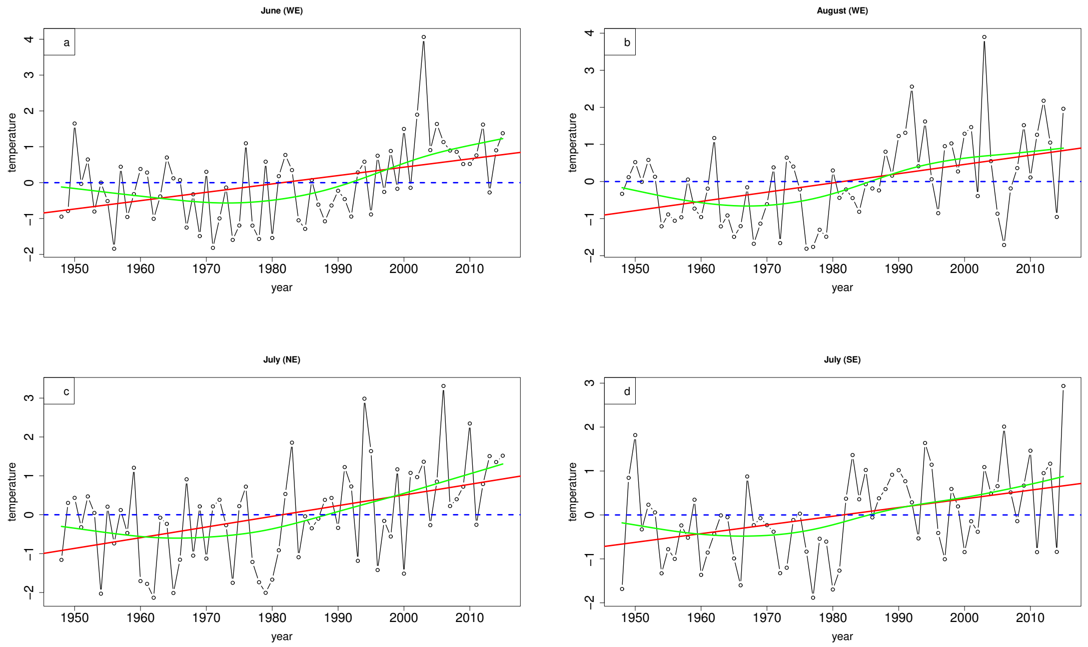

Figure 3.2 – Evolution of the monthly temperature anomalies averaged over the regions defined in figure 3.1. The red line corresponds to the linear trend, which is significant ($p - value < 0.05$) in all cases. The green line corresponds to a non linear trend calculated with a cubic smoothing spline.

of the persistence of the circulation. The program used to compute analogues CASTf90 is available online (`https://a2c2.lsce.ipsl.fr/index.php/licences/file/castf90?id=3`). Once the analogues were selected, we came back to the observable of interest (the detrended temperature anomalies) on those selected days. The whole process is summarized in figure 3.3.

3.1.3.3 Reconstruction of temperature distributions

Our goal is to reconstruct the probability distribution of detrended temperature anomalies conditional to the atmospheric circulation. For this, we consider a day i, with a temperature T_i and a circulation C_i with N analogues $C_i^1 \ldots, C_i^N$. The circulation analogues $\text{ana}_i^1 \ldots \text{ana}_i^N$ provide N copies of detrended temperature anomalies. Hence, we can recreate a sequence of daily temperature anomalies over a month by randomly picking one of the N best analogues for each day. The resulting monthly mean temperature anomaly is called *uchronic*, because it is a temperature anomaly that might have occurred for a given circulation pattern sequence. By reiterating this process, we recreated probability distributions of uchronic monthly detrended temperature anomalies conditional to the atmospheric circulation. We then compared this distribution to a distribution built from random days instead of analogues. In the rest of the article, we set the number of random iterations to 1000. This procedure is a simplified version of the stochastic weather generator of Yiou (2014), who also used weights based on the distances of the analogues. Table 3.1 illustrates this process for the July 2015 case.

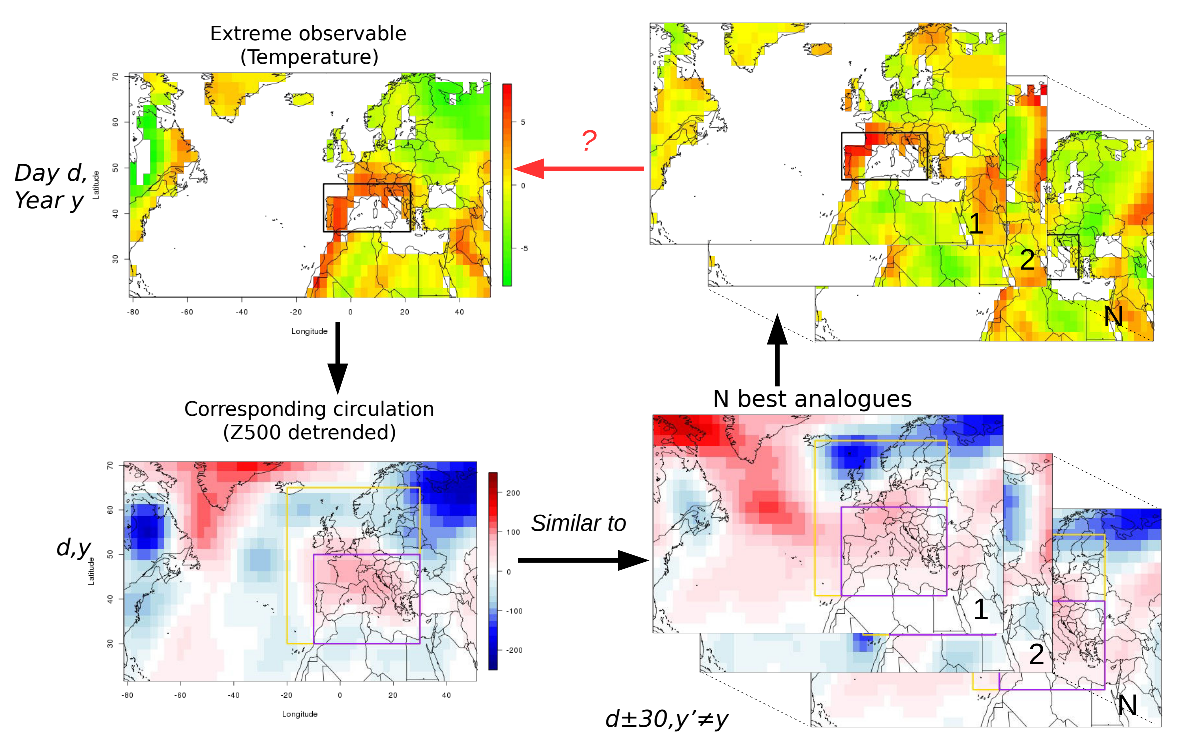

Figure 3.3 – A day with an extreme temperature anomaly (map on the top left) has a corresponding circulation, represented by the geopotential at 500 hPa (map on the bottom left). Flow analogues are days within the database which have a similar circulation to the day of interest (maps on the bottom right). The temperature anomalies of the analogues (maps on the top right) are then compared to the temperature anomalies of the day of interest (map on the top left).

3.1.4 Parameter sensitivity tests

The presented method depends on a few parameters. Their choice has an influence on both the results and their robustness. The following section explores the role of those parameters and how tuning them may give us further information on the relationship between circulation patterns and extreme temperature anomalies. We also want to know whether those parameters should depend on the specific event or not. This determines how general the approach can be and therefore its potential application to future events and other extra-tropical regions. In particular, we studied the role played by physical parameters: the variable on which the analogues are computed (SLP or Z500), the choice of the size of the domain on which the analogues are computed, and the length of the dataset, and a statistical parameter: the number N of analogues we kept.

Variable representing the circulation SLP (e.g. Cassou and Cattiaux, 2016; Della-Marta et al., 2007; Sutton and Hodson, 2005) and Z500 (e.g. Dole et al., 2011; Horton et al., 2015; Quesada et al., 2012) are the most commonly used variables to study the atmospheric circu-

Days of the event	Corresponding analogues	Randomly picked analogue
01/07/2015	$\text{ana}_1^1,\text{ana}_1^2,\ldots,\text{ana}_1^N$	ana_1^i
02/07/2015	$\text{ana}_2^1,\text{ana}_2^2,\ldots,\text{ana}_2^N$	ana_2^i
$\vdots$	$\vdots$	$\vdots$
31/07/2015	$\text{ana}_{31}^1,\text{ana}_{31}^2,\ldots,\text{ana}_{31}^N$	ana_{31}^i

Table 3.1 – Simulation of uchronic months using randomly picked analogues for July 2015.

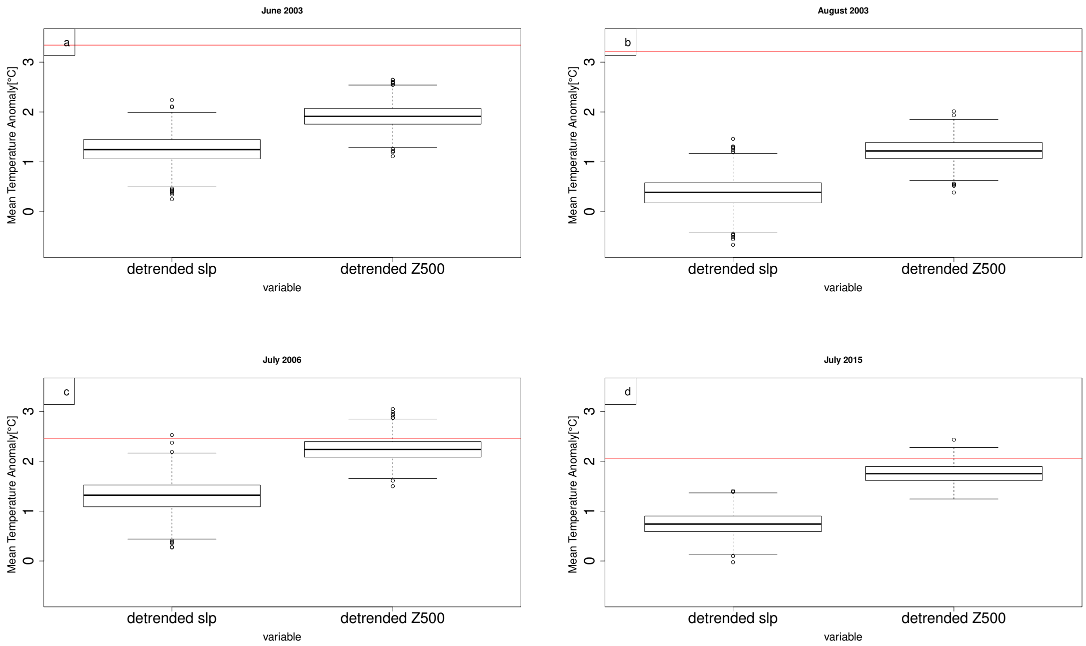

Figure 3.4 – The probability density of uchronic temperature anomalies from circulation analogues generated using detrended SLP (left boxplot of each subfigure) or detrended geopotential height at 500 hPa (right boxplot of each subfigure) for each case study: June 2003 (a), August 2003 (b), July 2007 (c), July 2015 (d). The red line represents the observed detrended temperature anomaly of the event. The three lines composing the boxplot are respectively from bottom to top, the 25th ($q25$), median ($q50$) and 75th quantiles ($q75$). The value of the upper whiskers is $min(1.5 \times (q75 - q25) + q50, max(\text{temperature anomaly}))$. The value of the lower whiskers is its conjugate.

lation. We calculated analogues using either the detrended SLP or the detrended Z500. The detrending was needed due to the dependence of Z500 on lower tropospheric temperatures, which are increasing due to anthropogenic climate change. We also detrended SLP since we found a small significant positive trend of mean monthly SLP over the North Atlantic domain for the 1948-2015 period.

The detrending of SLP and Z500 was done by computing a monthly spatial average of those fields. Then a non-linear trend was calculated with a cubic smoothing spline (Green and Silverman, 1994), in order to take into account the non linearity of climate change. This trend was removed to daily fields, which preserves the circulation patterns. We calculated the trends for both the North Atlantic region and the smaller regions on which the analogues are calculated. The differences between the trends for both regions were small. We did the detrending on the North Atlantic region in this study because the uncertainties on circulation patterns are amplified for smaller regions, especially as the NCEP reanalysis I grid is coarse (with a resolution of about 210km).

The uchronic detrended temperature anomalies for each event that were calculated using analogues of detrended SLP or detrended Z500 are shown in figure 3.4. The analogues computed using Z500 give uchronic temperature anomalies closer to the observed detrended temperature anomaly of the event than those computed using SLP. For the July 2015 case with an observed detrended temperature anomaly of 2.06℃ for example the mean of uchronic temperature anomalies calculated using SLP is 0.73℃ while the mean uchronic temperature anomaly calculated using Z500 is 1.76℃. The results are qualitatively similar for the other cases. The better performance of the Z500 analogues compared to the SLP analogues is probably related to the heat low process (e.g. Portela and Castro, 1996). Warm anomalies of surface temperature lead to convection. The elevation of warm air masses creates a local depression, which adds on top of an anticyclonic anomaly a cyclonic anomaly. This flattens the SLP patterns and blurs the signal, which does not happen with Z500. By using Z500 we also avoid any influence of the relief. Hence, we kept the detrended Z500 to compute the analogues for the rest of the study.

3.1.4.1 Size of the domain

The scale on which we compare circulation patterns plays a key role in the computation of the analogues. If the domain is too large, the system becomes too complicated, with too many degrees of freedom. The analogues could consequently only extract a low frequency signal, like the seasonal cycle. Van den Dool (1994) evaluates that it would take 10^{30} years of data to find two matching observed flows for analogues computed over the Northern Hemisphere. If we choose too small a domain, then we cannot study the role of the synoptic circulation. So, on the one hand, it is no use to calculate analogues on whole hemispheres, and on the other hand, we do not want to select domains which are smaller than the typical scale of extra-tropical cyclones (1000 km approximately). Radanovics et al. (2013) investigated automatic algorithms to adjust the domain size of the analogues for precipitation. Here, we prefer to select a domain that yields an a priori physical relevance to account for the most important features of the flow that affects high temperatures in Europe.

The ideal size of the domain reveals the scale at which the processes are relevant and may very well vary from one event to the other. This especially applies for studies on other types of events such as heavy precipitation, droughts or storms. We compared three different domains shown in figure 3.5 (right hand side):

- a large domain (the whole maps in figure 3.5), including the North Atlantic region, which corresponds to the domain usually used to calculate weather regimes (Michelangeli et al., 1995; Vautard, 1990),
- a medium domain (the golden rectangles in figure 3.5), centered on Europe, which is much smaller than the North Atlantic domain while being common to all events, and
- a small domain tailored for each event (the purple rectangles in figure 3.5), depending on the circulation pattern of the specific summer .

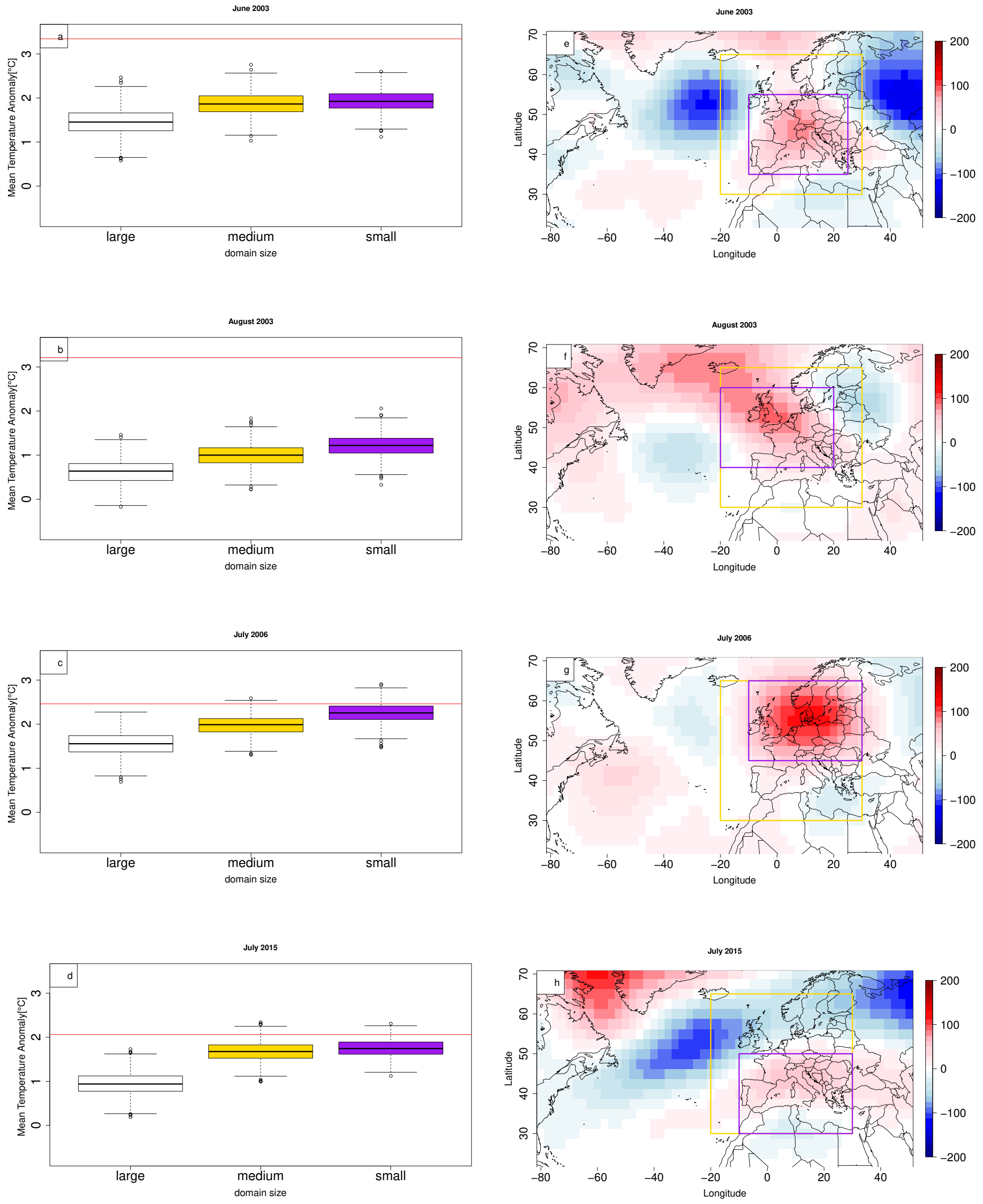

Figure 3.5 – Dependence of the probability density of uchronic detrended temperatures on the size of the domain. The maps on the right column represent the detrended Z500 monthly anomaly (m). The purple rectangles indicate the smallest zones of computation of flow analogues. The golden rectangles indicate the medium zone of computation of flow analogues. The large zone is the whole map. The boxplots of the left column display the distribution of the 1000 uchronic monthly detrended temperature constituted from randomly picked analogues. The color of the boxplot corresponds to the color of the rectangle delineating the region on which the analogues are computed. The red lines on the left hand side of the figure represent the observed detrended temperature of the case studies, from top to bottom : June 2003, August 2003, July 2006, July 2015.

The results are displayed on the left hand side of figure 3.5. The detrended temperature anomalies of the heatwaves of interest, shown by the red lines, are better reproduced using the smaller domains to calculate the circulation analogues for all four cases. This is because there are circulation patterns included in the North Atlantic domain which probably play no role in the establishment of a heatwave over Europe. For example in July 2015 we observe an important anticyclonic anomaly over Greenland. It adds a constraint on the analogues while supposedly playing no role on the lesser anticyclonic anomaly over the Northern Mediterranean region. The standard deviation of the uchronic detrended temperature anomalies also decreases with the size of the domain.

It is relevant to rely on standard domains for a first estimation of the role played by the circulation in the occurrence of a heatwave, for example by using the regions defined in Field and Intergovernmental Panel on Climate Change (2012). However, for a finer analysis focused on one specific heatwave, or a few given events, the choice of a tailored small domain gives better results. In the rest of the study, we hence kept the smaller domains.

3.1.4.2 Length of the dataset

The NCEP dataset contains 68 years. Although the recombination of analogues allows to recreate new events, the dataset is finite and hence does not cover the whole range of possible events. For example, if the circulation leading to a heatwave has a return period of more than the dataset length, there might not be similar circulation patterns in the dataset. In this situation, the computed analogues will not be a good proxy of the circulation of interest. Furthermore, even if there are close daily analogues to the daily circulation of the event, it might not account for other thermodynamical processes that may or may not happen simultaneously and lead to extreme temperatures. This shortcoming is called sampling uncertainty (on Extreme Weather Events and Attribution, 2016, Chap. 3), related to the fact that the past is one occurrence of many realizations which could have happened for a given state of the climate.

In order to get an order of magnitude of that uncertainty in the reconstruction of probability densities of temperature anomalies we used a 500 years long pre-industrial run from CMIP5 (Taylor et al., 2012). The model used is GFDL-ESM2M (Dunne et al., 2012, 2013). We chose this model because it was the model available on the IPSL data center with the longest run for both the temperature and the Z500. We selected one heatwave similar to July 2015, both in terms of temperature anomaly (compared to the detrended anomaly of July 2015) and circulation patterns (see figure 3.6). We assume that the internal variability of the model is similar to the internal variability of the reanalysis.

Analogues were computed for 60 different subsets of the 500 year dataset. The lengths of the subsets were 33, 68, 100 and 200 years (e.g. subsets of 68 consecutive years each, starting every 5 years of the data set). We then compared the means of the uchronic temperature anomaly distributions for the chosen July 2015-like month to one another for different subset lengths. The spread of the mean uchronic temperature anomalies calculated this way gives an estimation of the uncertainty related to the limited length of the dataset.

Figure 3.7 displays the results for subsets of 33, 68, 100 and 200 years. When the number of years of the subset decreases, the spread of the mean uchronic temperature anomalies increases, going up to approximately 0.71°C for the 33 years subsets, 0.62°C for 68 years, 0.36°C for 100 years, and 0.14°C for 200 years. This information is precious to determine in which

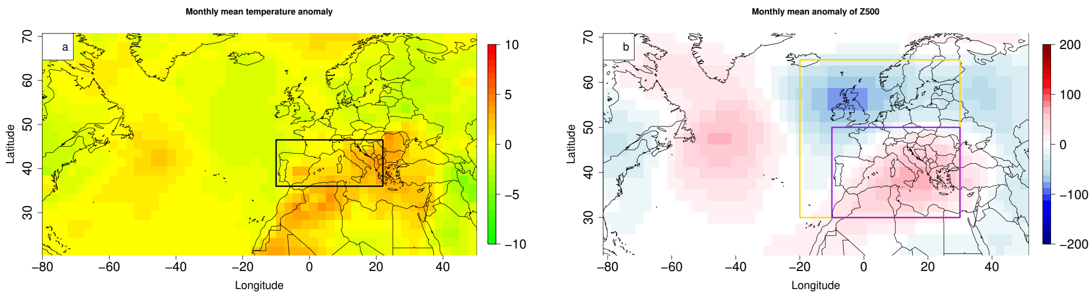

Figure 3.6 – Temperature anomaly (a) and Z500 anomaly (m) (b) of a July month from GFDL-ESM2M CMIP5 pre-industrial control run similar to July 2015.

measure smaller datasets are relevant for this methodology. It means for example that differences of up to 0.71°C in the mean uchronic temperatures calculated from 33 years long subsets can possibly occur due to internal variability without strictly needing additional forcing.

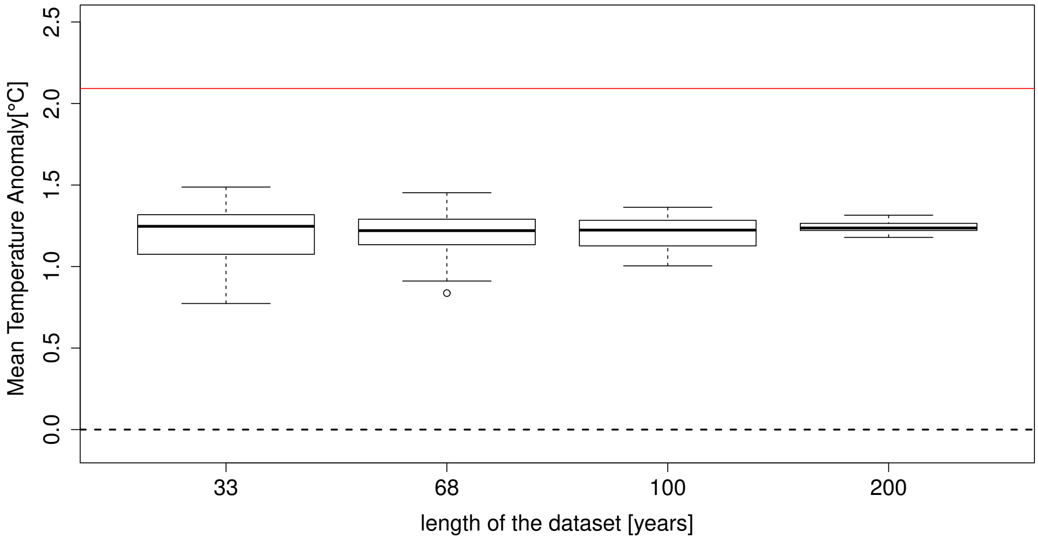

Figure 3.7 – Sensitivity to interdecadal variability depending on the length of the dataset. Distributions of the mean uchronic temperature anomalies for 60 different subsets of varying sizes (33, 68, 100, or 200 years) from a 500 years long pre-industrial control run (model GFDL-ESM2M) for the small domain of analogues computation.

The ability to find analogues close to the circulation of interest is related to both the size of the dataset and the size of the domain on which the analogues are computed (Van den Dool, 1994). It means that the analogues method will get more and more accurate as the reanalysis dataset extends in the years to come.

3.1.4.3 Number of analogues

For the reconstruction of events by recombination of analogues, we kept the N best analogues. The choice of N has an influence on both the uchronic detrended temperature anomalies and the statistical robustness of the study. The best uchronic detrended temperature anomalies are closer to the observed detrended temperature anomalies of the actual events for all case studies (see figure 3.8). We need to find a trade-off between having the best analogues which give results closer to both the observed circulation and detrended temperature anomaly, and having enough analogues to create a robust uchronic temperature anomaly distribution. The difference of mean uchronic temperature anomaly between keeping 5 and 30 analogues is of less than 0.2°C, so the sensitivity on this parameter is rather low. We kept 20 analogues for the rest of the study.

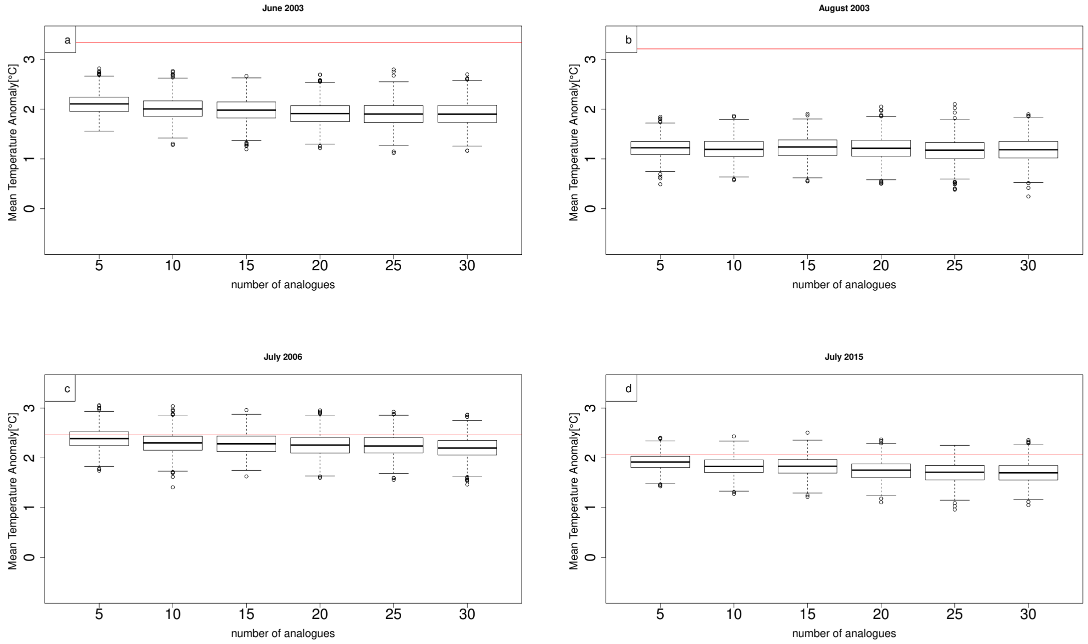

Figure 3.8 – Dependence of the probability density of uchronic temperature anomalies on the number of analogues retained. Difference between uchronic temperature anomaly distributions calculated using different numbers of analogues for each case study: June 2003 (a), August 2003 (b), July 2007 (c), July 2015 (d). The red line represents the observed detrended temperature anomaly of the event.

3.1.5 The role of circulation in heatwaves

With the parameters kept (Z500, small domains, 68 years reanalysis data, and 20 analogues) we simulated 1000 uchronic detrended monthly mean temperature anomalies for each of the four selected heatwave events (see the analogues boxplots in figure 3.9). The circulation contribution corresponds to the mean of the uchronic temperature anomaly distribution simulated using circulation analogues. The spread of the boxplots is due to the range of other processes which can, for a given circulation, lead to different temperature anomalies.

Event	Observed detrended temperature anomaly	Mean detrended uchronic temperature anomaly	Difference expressed as number of σ of the uchronic distribution
06/2003	3.3°C	1.9°C	6.1
08/2003	3.2°C	1.2°C	8.6
07/2006	2.5°C	2.3°C	0.9
07/2015	2.1°C	1.7°C	1.6

Table 3.2 – Observed detrended temperature anomaly compared to the mean detrended uchronic temperature anomaly for each case study.

In order to measure the contribution of the circulation we compared the distribution of uchronic detrended temperature anomalies with a control distribution built using random days (*Control-1* boxplots on figure 3.9). The control distribution is supposed to represent monthly detrended temperature anomalies for the given month and the given region without focusing on specific circulation patterns. However, the variability of random summers built that way is not realistic because the dependence between consecutive days is not accounted for. Analogues are by construction dependent from one another, because they are calculated using maps from consecutive (hence correlated) days, whereas randomly picked days are independent.

In order to create a more realistic distribution of temperature anomalies using random days, we also calculated detrended monthly mean temperature anomalies by using only one out of M days. M is a measure of the persistence of the circulation that is accounted for. We computed the autocorrelation of the detrended Z500 NCEP dataset for summer months (JJA) on each of the four small domains, for each grid point, with lags from 1 to 20 days (similar to Yiou et al. (2014)). For more than 10 days, the autocorrelations median tends to an asymptotic value of approximately 0.1. For three days, the median of the autocorrelation distribution is of approximately 0.65. For four days, it decreases to 0.45. Since the regions are small, the number of degrees of freedom is small too, which means that an autocorrelation of 0.45 is negligible. We hence arbitrarily decided to set M=3 (*Control-3* boxplots on figure 3.9). The circulation during heatwaves corresponds to a long-lasting blocking situation, hence the persistence is probably more than three days. This underestimation, combined with the limited length of the dataset explains why the studied events are all outside of the distributions calculated using random days subsampled every 3 days.

For every event, the circulation plays a significant role in the occurrence of the extreme. It only explains a part of it, more or less significant depending on the event. Indeed, it explains 38% of the anomaly for August 2003, 57% for June 2003, 81% for July 2015 and 92% for July 2006. Considering only the uchronic detrended temperature anomaly distribution, the observed heatwave is plausible given the large-scale trends and the circulation for both July 2006 and July 2015. Indeed the observed detrended temperature anomaly is within 2 σ of the uchronic detrended temperature anomaly distribution. The circulation together with the subtracted large-scale trend could explain the observed temperature anomaly. This is not the case for June and August 2003 where the observed detrended temperature anomaly is respectively 6.1 σ and 8.6 σ above the mean of the uchronic detrended temperature distribution (see table 3.2). The smaller standard deviation of the uchronic detrended temperature distribution compared to the random ones shows the effect of the analogues, that is to select a part of the distribution conditioned to the flow. Indeed the standard deviation of the uchronic detrended temperature anomaly distribution is approximately a third of the standard deviation of the temperature anomaly distribution using random days taking into account the persistence of the circulation (*Control-3*). Both standard deviations might be slightly underestimated due to persistence that was not accounted for. In the case of the uchronic temperature anomalies this can happen due to the random pick among the analogue days and for the *Control-3* due to situations with more than 3 days of persistence that are not accounted for.

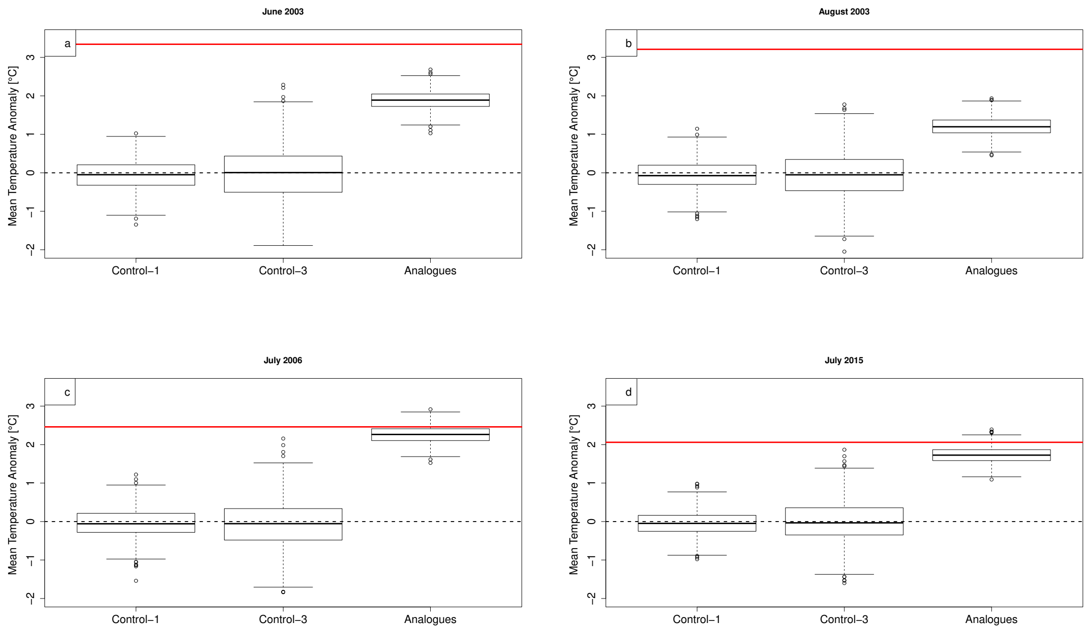

Figure 3.9 – Probability distributions of uchronic detrended monthly temperature anomalies simulated using random days (left boxplot of each subfigure), random days subsampled every three days to correct for serial dependence (middle boxplot of each subfigure) and analogues (right boxplot of each subfigure) for each case study: June 2003 (a), August 2003 (b), July 2007 (c), July 2015 (d). The red line represents the observed detrended temperature anomaly of the event.

In order to contextualize the four case studies, we reproduced the same kind of probability density function experiments for the same regions from 1948 to 2015 (figure 3.10). We calculated the uchronic detrended temperature anomaly distributions for the months of June from 1948 to 2015 on the regions (both the temperature and the circulation regions) defined for June 2003 (figure 3.10 a)). We did the same for the other three events. This type of contextualization can be interpreted as an estimation of how extreme an event really is, with respect to its atmospheric circulation.

The observed monthly mean detrended temperature anomaly falls between the 10th and 90th percentiles of the uchronic detrended temperature anomaly distribution for more than half of the years between 1948 and 2015. It falls between the 1st and 99th percentiles for more than two thirds of the years, even though the uchronic temperature anomaly distribution has a small spread compared to the total distribution. The years with observed detrended temperature anomalies out of interval between the 1st and 99th percentile correspond mostly to large detrended temperature anomalies with absolute value > 0.5°C. For less than a quarter of the years between 1948 and 2015 the mean of the uchronic detrended temperature anomaly distribution has a sign different from the observed detrended temperature anomaly. Those years correspond to low detrended temperature anomalies with absolute values < 0.5°C.

3.1.6 Discussion

The median of the uchronic temperature anomaly distribution is generally different from the observed temperature anomaly. In some cases, the observed detrended temperature anomaly (red line on figure 3.9) is not even in the uchronic temperature anomaly distribution. On figure 3.9 for June and August 2003, and for some of the years on figure 3.10, this is the case (indeed, the monthly detrended temperature anomalies for both months are higher than 3°C). This difference shows caveats in the methodology, and that some heatwave events cannot be explained only by their circulation.

Flow analogues are unable to reproduce the role played by the soil-moisture feedback. Indeed, the analogues do not take into account the history of the heatwave. Extreme heatwaves happen when the circulation causing the initial anomaly of temperature lasts more than a few days. As soil moisture becomes limited, the cooling of the atmosphere through evapotranspiration gets weaker, which exercises a positive feedback on the temperature. Seneviratne et al. (2010) isolates a dry and a wet regime, with a transition phase between both. The three temperature regions used here are prone to different evaporative regimes. In particular, the Northern Europe region is wetter than the other two. The role of soil moisture is thus less important (Seneviratne et al., 2006). On the other hand, several articles (Fischer et al., 2007; Stéfanon et al., 2012) showed the role of soil moisture in the exceptional temperature anomalies of summer 2003, especially for August. The analogues are picked without any condition on the previous days or soil moisture, and consequently they fail to reach the observed anomaly.

The main caveat of this methodology is the limited size of the dataset, which introduces an important sampling uncertainty, as seen in section 3.3, and also affects the quality of the analogues. As a result, the analogues might not be good enough to accurately reproduce the dynamical contribution. Indeed, an extreme temperature can be related to a rare circulation, the like of which might not be found in a short dataset. The distances between the analogues and the event, as well as their correlations, are indices to evaluate the relevance of the analogues in each case. A better definition of what is a good analogue will require further studies. Depending on the magnitude of the studied event, it might not be possible to reconstruct a comparable month by resampling the days in the dataset. This is the case for both June and August 2003, which have temperature anomalies about one degree Celsius above all the other years, despite the detrending. If the event is too rare, it will not be possible to reconstitute uchronic temperature anomalies close to the observed ones.

Another limitation relates to the coherence of the uchronic summers computed using analogues. Due to the persistence of the circulation, the analogues we picked for each day are correlated to one another. Indeed, analogues of following -and thus correlated- days are not independent. In our case, we picked the 20 best analogues for each day. For each event we hence have an ensemble of 20 times the number of days of the month analogues. A proof of the correlation between analogues of following days is that only half of the analogues in this ensemble are unique. However, the persistence is still underestimated compared to real sum-

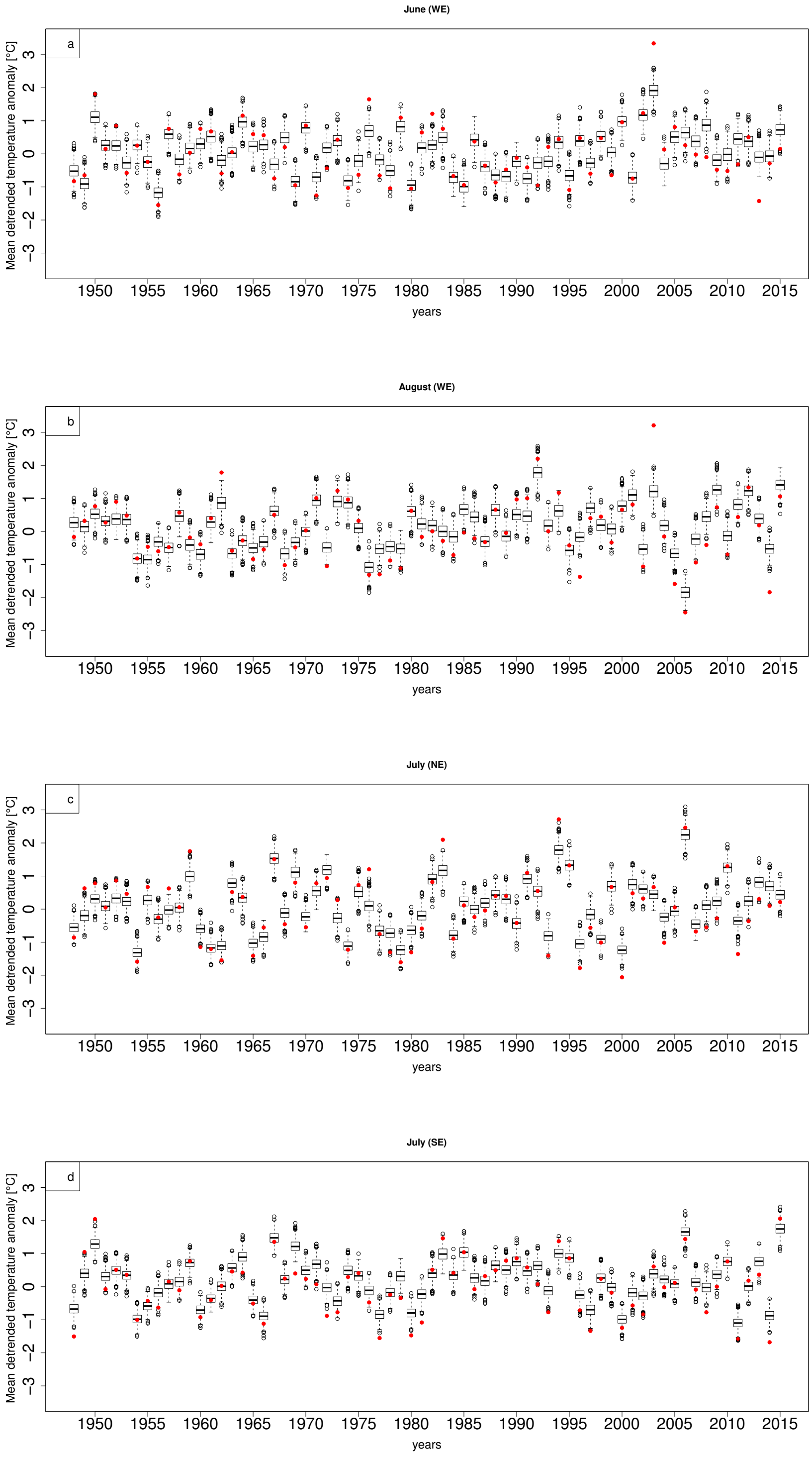

Figure 3.10 – Evolution of the detrended temperature distributions for all the months of June in Western Europe (a), August in Western Europe (b), July in Northern Europe (c) and July in Southern Europe (d). The regions are displayed in figure 3.1. The red dots correspond to the observed detrended temperature anomaly for each year.

mers. Consequently, the spread of the computed uchronic temperature anomaly distributions is underestimated.

Lastly, this article only considers one month-long heatwaves, while some events as short as three consecutive days can be considered as heatwaves (Russo et al., 2015). We have tested how the length of heatwaves affect the uncertainties of the method using a test similar to the one used in section 3.3, for events of different length (not shown here). The sampling uncertainty on the mean uchronic temperature anomaly decreases for longer events. It also seems that it can differ from one week-long event to the other. For a week-long events, the probability to only have days with poor analogues is higher than for longer events, especially if we deal with unusual events in terms of atmospheric circulation. Since the reasons behind those differences relate to the quality of analogues, we intend to treat this more thoroughly in further studies. However, we recommend to accompany any study using analogues as presented in this article with an evaluation of the sampling uncertainty to validate the relevance of the methodology. This evaluation could be based on pre-industrial runs similar to what is displayed here in section 3.3 or on large ensembles of simulations.

3.1.7 Conclusion

This paper proposes to quantify the role of the atmospheric circulation in the occurrence of an extreme monthly anomaly of temperature. The strength of our methodology is that it is easily adaptable to other regions, and to other events. The parameter sensitivity tests of section three provide general guidelines to choose flow analogues to investigate European summer heatwaves. It is best to use detrended Z500 as a proxy of circulation, and to compile the analogues on a small domain centered on the Z500 anomaly concomitant to the event. We also advise to use as long a dataset as possible.

The results on parameter sensitivities have potential implications for applications of the analogue method in a downscaling or reconstruction context as well. The questions of the predictor variable (or variables), that is the circulation proxy, is relevant in the downscaling context but may vary depending on the predictand variable. The question of domain size has been treated by several authors (e.g. Beck et al., 2015; Chardon et al., 2014; Radanovics et al., 2013) and the results are systematically in favor of relatively small domains, in line with our findings. Tests on archive lengths larger than typical reanalysis record lengths are rarely performed. The results are relevant since split-sample validation of downscaling methods is common practice and our results show that splitting the limited length reanalysis record leads to large uncertainties in the uchronic temperatures due to the limited sample size even using a relatively small domain.

The reconstitution of an ensemble of uchronic temperatures for a given circulation is a first step refine the approach of Cattiaux et al. (2010) to extreme event attribution. Indeed, looking at changes for a given circulation should reduce the signal to noise ratio of climate change versus natural variability (Trenberth et al., 2015) in what Shepherd (2016) calls a "storyline approach" to extreme events attribution. There are two ways to compare two worlds with and without climate change. The first one is to use climate simulations with and without anthropogenic forcing. The second one is to compare observations of recent years to observations from further back in time. It is then possible to detect a change between two periods or two simulations outputs. One has to keep in mind that detecting a difference of temperature is not enough to attribute the difference between the two to climate change, rather than to natural variability. Indeed, the internal variability between the two periods could be of the same order of magnitude than the difference caused by climate change. We have shown in section 3.3 that the longer the dataset, the more it reduces the impact of internal variability on the results.

Since among the tested parameters only the regions of the temperature anomaly and of the geopotential height field depend on the event, a diagnosis on heatwaves can be automatized and computed in less than a day once the data set is available.

3.1.8 Acknowledgments

NCEP Reanalysis data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at `http://www.esrl.noaa.gov/psd/`.
Program to compute analogues available online `https://a2c2.lsce.ipsl.fr/index.php/licences/file/castf90?id=3`. PY and SR are supported by the ERC Grant A2C2 (No. 338965).

3.2 Different ways to detrend Z500

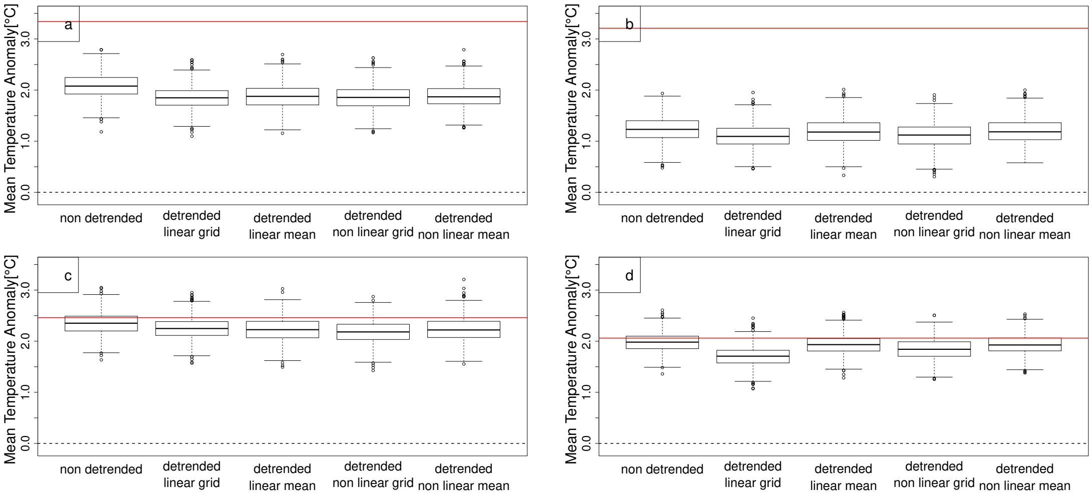

Figure 3.11 – The probability density of uchronic temperature anomalies from circulation analogues generated using non detrended Z500 (left boxplot of each subfigure) and four different ways to detrend Z500 for each case study: June 2003 (a), August 2003 (b), July 2007 (c), July 2015 (d). The red line represents the observed detrended temperature anomaly of the event.

The article explains the need for detrending Z500 fields. We used a cubic-smoothing spline to account for the non-linearity of climate change. We applied it to the spatial average of the Z500 field, in order not to dismantle the change of pattern related to the higher rate of climate change close to the poles. Figure 3.11 shows how this detrending operation affects the distribution of uchronic temperatures for the four events, compared to no detrending, and to other ways to detrend (linear, and by gridpoint). It appears that the way to detrend does not significantly change the result. The lack of difference between the detrending by gridpoint or of the mean is explained by the small size of the domain of analogue computation. This difference could grow for large domains for which the difference of warming between the southern and the northern gridpoints is large. The similarity between linear and non linear detrending is also intuitive, since the climate change between 1948 and 2015 is still limited. The difference between methods of detrending could grow with a longer time period, and a stronger change in climate, if we used longer datasets.

3.3 Length of the event

The heatwaves considered in the article are long lasting events affecting the monthly mean anomalies. However some strong heatwave events, with a shorter life cycle (7-10 days), might not be easily detected by considering monthly means anomalies based on calendar month. As stated in the article, we have tested how the length of heatwaves affect the uncertainties of the method using a test similar to the one used in section 3.1.4.2, for events of different lengths. We give a little more details on this part of the study which was not shown in the article to avoid overloading it.

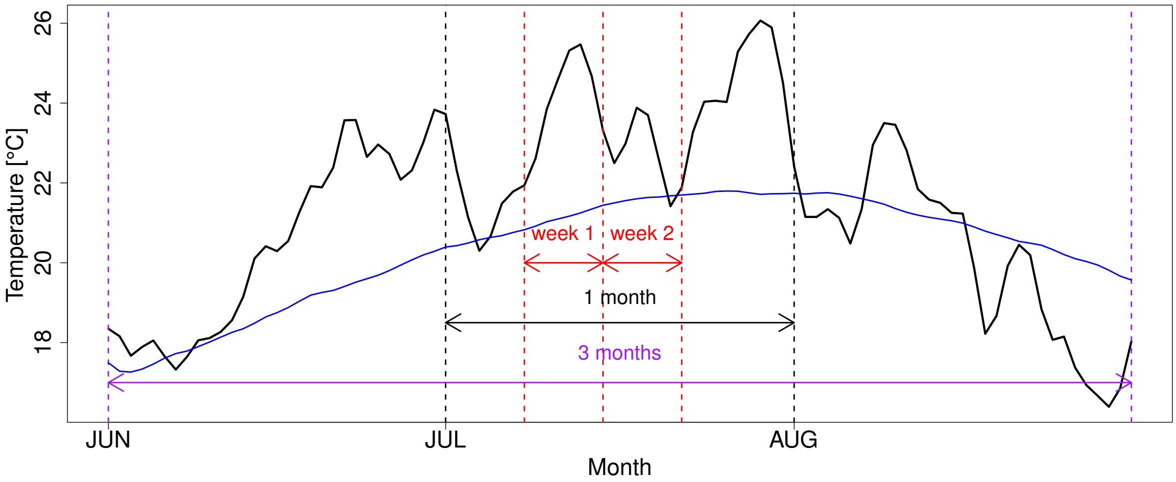

Figure 3.12 – Temperature series of a summer of the GFDL-ESM2M pre-industrial control run. The July month is similar both in temperature anomaly and circulation anomaly to July 2015 as shown in figure 6 of the article. The blue line corresponds to the mean daily temperature averaged for all the summers of the dataset.

In order to study the ability of the method for different event lengths, we used the GFDL-ESM2M pre-industrial run, as was done in section 3.1.4.2, while varying the length of the event. The events are defined in figure 3.12 ranging from a complete summer to two different weeks of the same month. It is possible to calculate the sampling uncertainties of each of these events for 68 years-long datasets. For this purpose, we compute the mean uchronic temperature anomalies for 60 different 68 years-long subsets of the GFDL-ESM2M pre-industrial control run. The range of mean uchronic temperature anomalies is an estimate of the sampling uncertainty. The results are displayed in figure 3.13 hereafter. The uncertainty is of 0.3°C for three months, 0.6°C for one month, 0.7°C for week 1 and 0.8°C for week 2.

We hence observe that the uncertainty on the mean uchronic temperature decreases for

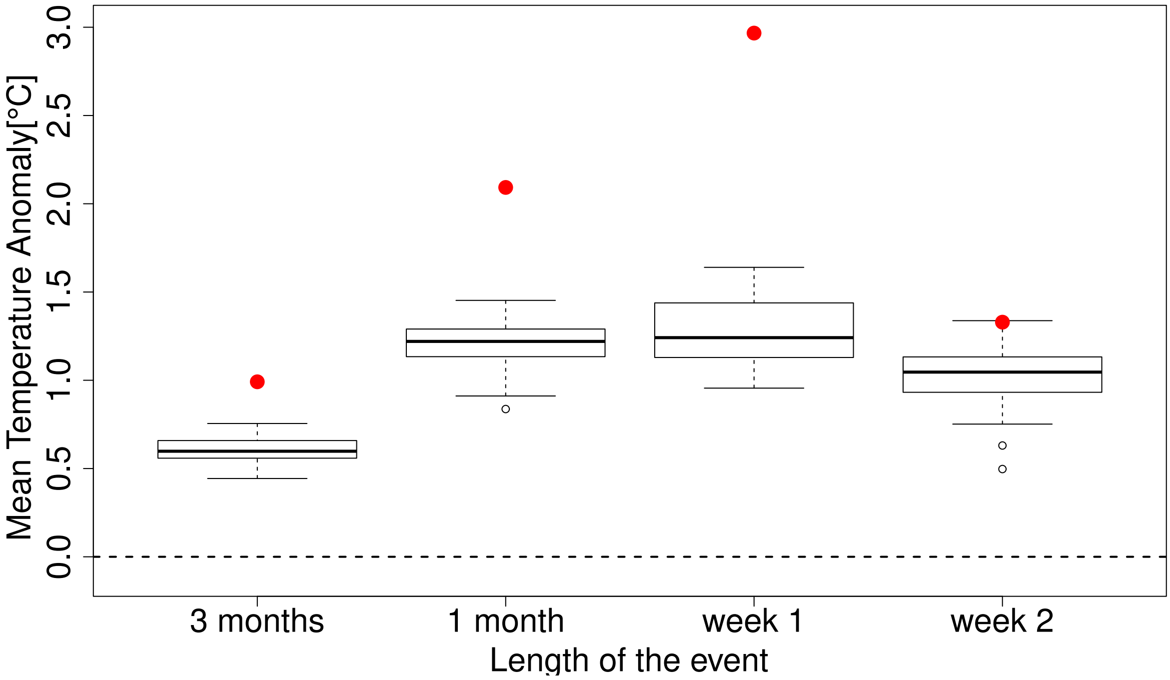

Figure 3.13 – Distributions of the mean uchronic temperature anomalies generated for 60 different subsets of 68 years from a 500 years-long pre-industrial control run (model GFDL-ESM2M) for the small domain of analogues computation. The boxplots correspond to different lengths of event : 3 months, 1 month, and two different one-week events from the same summer (cf figure 3.12 above). The red dots correspond to the temperature anomaly of each event.

longer events. For two different weeks with different temperature anomalies, the uncertainties vary. A more complete study would be needed to evaluate the range of uncertainties for a larger ensemble of weeks. It would be interesting to determine whether the uncertainties depend upon the rarity of the circulation of the event of interest. For example, the mean distance between the Z500 analogues and the weeks of interest is approximately 26.5m for week 1 and 28.5m for week 2. Therefore, the analogues in week 2 are poorer than in week 1. As stated in the article, the probability to have a large fraction of days with poor analogues is higher for a one week long events than for longer events. This leads us to questions on the quality of analogues, and to define what could be considered a good analogue.

3.4 Quality of analogues

One of the main problems I stumbled upon while working on this article and during the rest of my PhD was the *quality* of the analogues. How can we check that an analogue is good? What is a good analogue? Are the analogues good enough to perform an analysis (e.g. in order to calculate uchronic temperatures)? The analysis of uncertainties depending on the length of the dataset performed in section 3.1.4.2 gives an idea of the robustness of analogues for the computation of uchronic temperatures. It would be interesting to find a metric to get an idea whether an analogue is good or not, or if the day of interest presents a rare type of circulation. Although the following results are not mature enough to be presented in an article, I introduce in sections 3.4.1 to 3.4.3 three different options I started to explore during my PhD.

3.4.1 A qualitative check

The first approach is to qualitatively check whether the analogues look like the day(s) of interest. It is a simple comparison between two maps, where one can for example verify if the anticyclonic anomaly leading to a heatwave is correctly reproduced (in terms of both intensity and position) by the analogues. Here I give two examples of qualitative checks of the quality of the analogues. Those were published as supplementary materials of the articles presented in section 4.1 and 5.1.

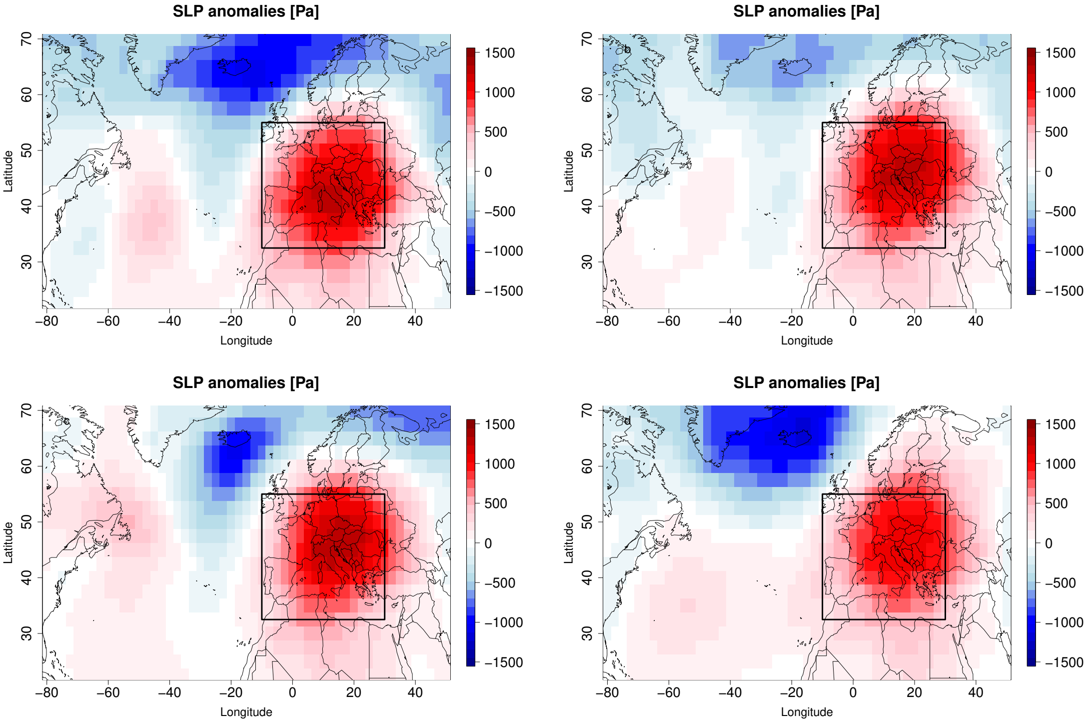

Figure 3.14 – SLP analogue composites (in Pa), as explained in text, for (a) NCEP reanalysis data, and 3 periods of CESM: (b) 1951–2000, (c) 2001–50, and (d) 2051–2100.

For the article presented in section 5.1, we used similar analogues to the ones presented in section 3.1. Figure 3.14 shows sea level pressure (SLP) composites for the following: (a) the 30th best daily analogues (i.e., the worst analogues of the 30 we keep when analogues are sorted by increasing distance) for each day of December 2015 using NCEP reanalysis data between 1949 and 2015; (b)–(d) three periods of the CESM (Community Earth System Model) (Kay et al., 2015) model: (b) 1951–2000, (c) 2001–50, and (d) 2051–2100. Panels (a)–(d) show that the analogues reproduce well the SLP anomaly in the black box in Figure 5.1, even though this is a record anomaly. The daily analogues allow us to reconstruct months with SLP anomalies that are close to the SLP pattern in December 2015.

For the article presented in section 4.1, we select analogues differently. In order to study the evolution of the observed daily circulation pattern Z^d, we created the class of analogue days $D(Z^d)$ regrouping all patterns with an Euclidean distance to Z^d below the 5th percentile

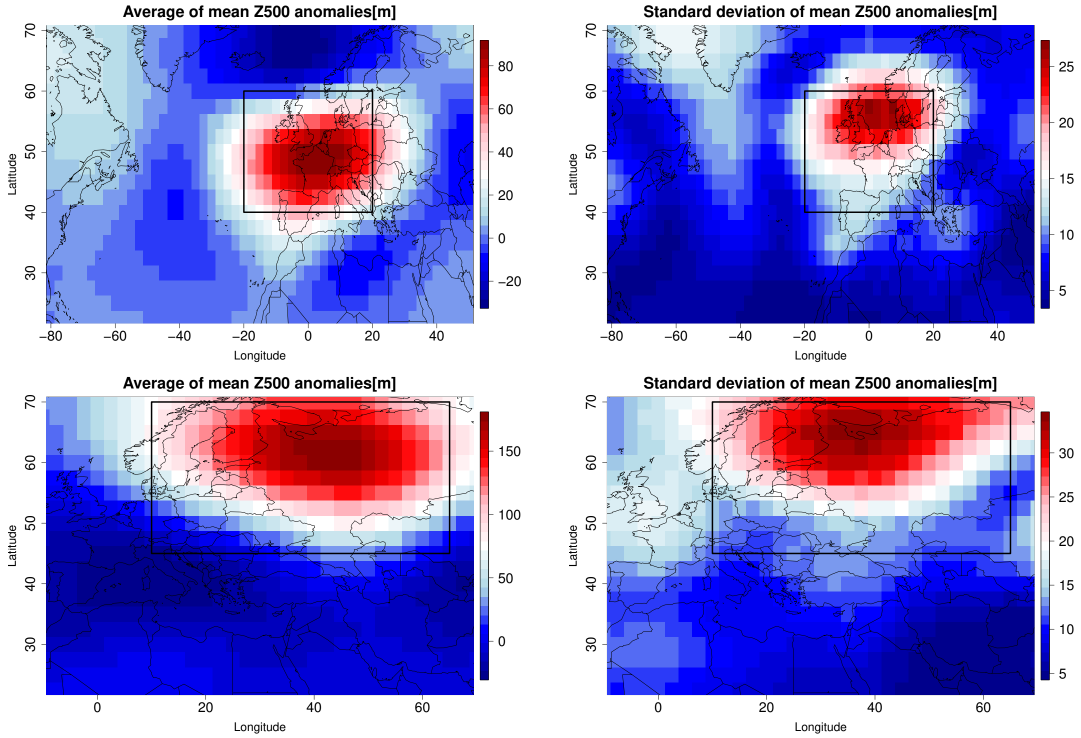

Figure 3.15 – Left column: Average over the CMIP5 ensemble of the means of the Z500 map of all the days within $D(Z^d)$ for August 13th 2003 (upper figure) and August 7th 2010 (lower figure). Right column: Standard deviation over the CMIP5 ensemble of the means of the Z500 map of all the days within $D(Z^d)$ for August 13th 2003 (upper figure) and August 7th 2010 (lower figure).

of those distances distribution. This means that we keep a lot more than 20 or 30 analogues. There is no guarantee that the days in $D(Z^d)$ accurately represent the blocking situations characteristic of both heatwaves. In figures 3.15 to 3.20 we displayed maps of days in $D(Z^d)$ for both August 13th 2003 and August 7th 2010. The zones of interest are the regions within the black rectangles on which the distances were calculated. We compared those maps to Figures 4.2e and 4.2f.

First, we checked whether the CMIP5 models (Taylor et al., 2012) and the CESM runs as a whole reproduced correctly the blocking situation. We calculated for each 18 CMIP5 model (respectively 30 CESM run) the mean Z500 map of all the days within $D(Z^d)$. We plotted in Figure 3.15 (respectively 3.16) the average and the standard deviation of those means for the CMIP5 ensemble (respectively the CESM ensemble).

Both ensembles reproduce correctly the position and size of the anticyclonic anomaly for the two case studies. However, they underestimate the intensity of the anomaly. This underestimation could be explained by the double average operation (average of analogues, and average between models).

We remove one of those averaging operations by showing these maps for each of the 18 CMIP5 models used in the article. Figure 3.17 and 3.18 show the average Z500 map of all the days within $D(Z^d)$ for each model used in the study.

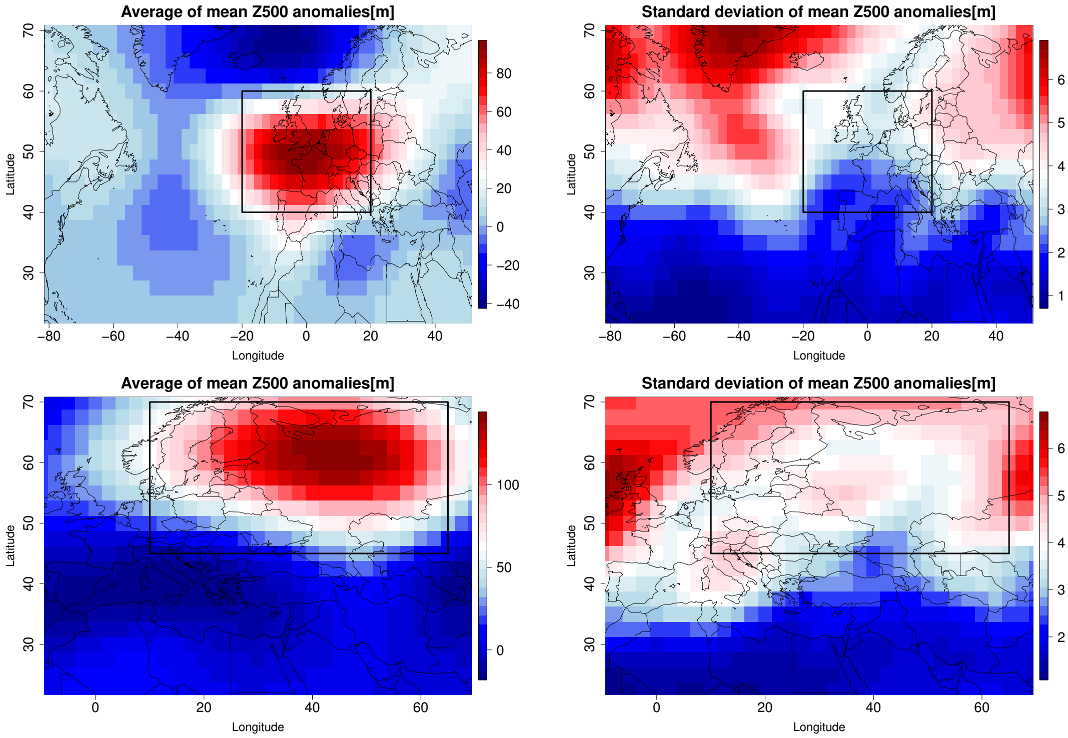

Figure 3.16 – Left column: Average over the CESM ensemble of the means of the Z500 map of all the analogues for August 13th 2003 (upper figure) and August 7th 2010 (lower figure). Right column: Standard deviation over the CESM ensemble of the means of the Z500 map of all the analogues for August 13th 2003 (upper figure) and August 7th 2010 (lower figure).

All the models reproduce well on average the position of the observed anticyclonic anomaly. However, they differ in their ability to reach its intensity. Apart from a few exceptions (none for August 13th 2003, bcc-csm1-l-m, CMCC-CM and CMCC-CMS for August 7th 2010), they fail to reach the observed intensity. This can be anticipated because the observed Z500 anomalies for both days are extreme, and we average over a fifth of the summer days of the considered time period. There are important differences between models (e.g. HadGEM2-CC and MPI-ESM-MR for 2003). This kind of map can help to evaluate which models are most trustworthy in terms of the quality of analogues. The models that are the worst at reproducing the observed intensity of Z500 based on analogues are not necessarily the same for the two different events and regions. For example, MIROC-ESM is one of the models with the highest reproduced anomaly for 2003 while having one the lowest for 2010. This type of model evaluation is hence case study dependent.

Another way to evaluate the analogues picked from the models is to consider whether the worst analogue selected for an analysis does still look like the observed day. Figures 3.19 and 3.20 represent the Z500 map of the day with the biggest distance to August 13th 2003 (3.19) and August 7th 2010 (3.20) in $D(Z^d)$ for each CMIP5 model used in this article. Those days are the furthest from the day of interest as defined with the Euclidean distance.

The quality of this worst analogue deteriorates compared to the means presented in figures 3.17 and 3.18. However, most of the models have worst analogues with anticyclonic anomalies in the region of interest, although the patterns can change depending on the model. For

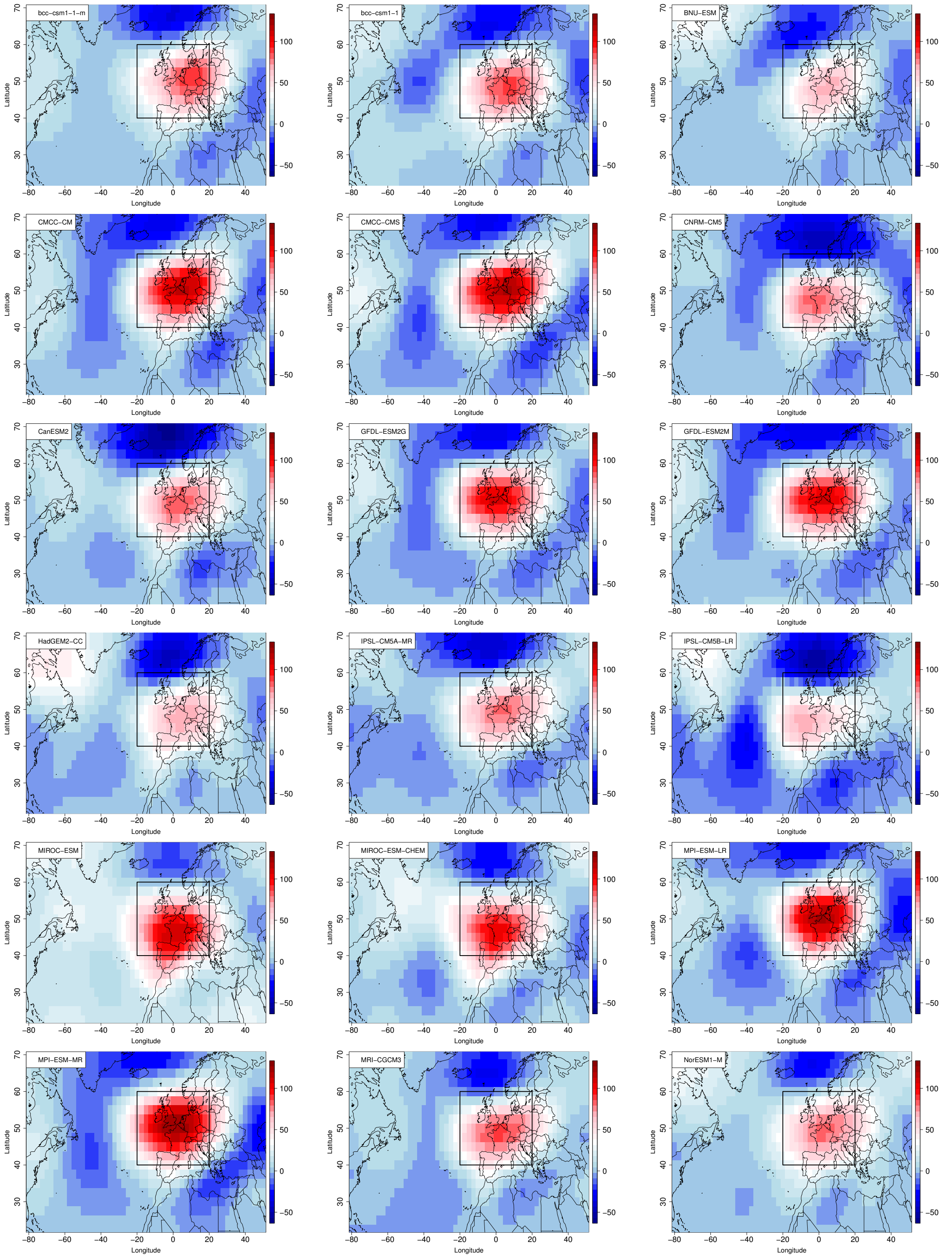

Figure 3.17 – Mean of the Z500 of all the days within $D(Z^d)$ for August 13th 2003 for each CMIP5 model used in this article.

example, in 2003, CMCC's worst analogue displays a too high anticyclonic anomaly, while MPI-EM-MR's presents both a cyclonic and an anticyclonic anomaly in the region of interest.

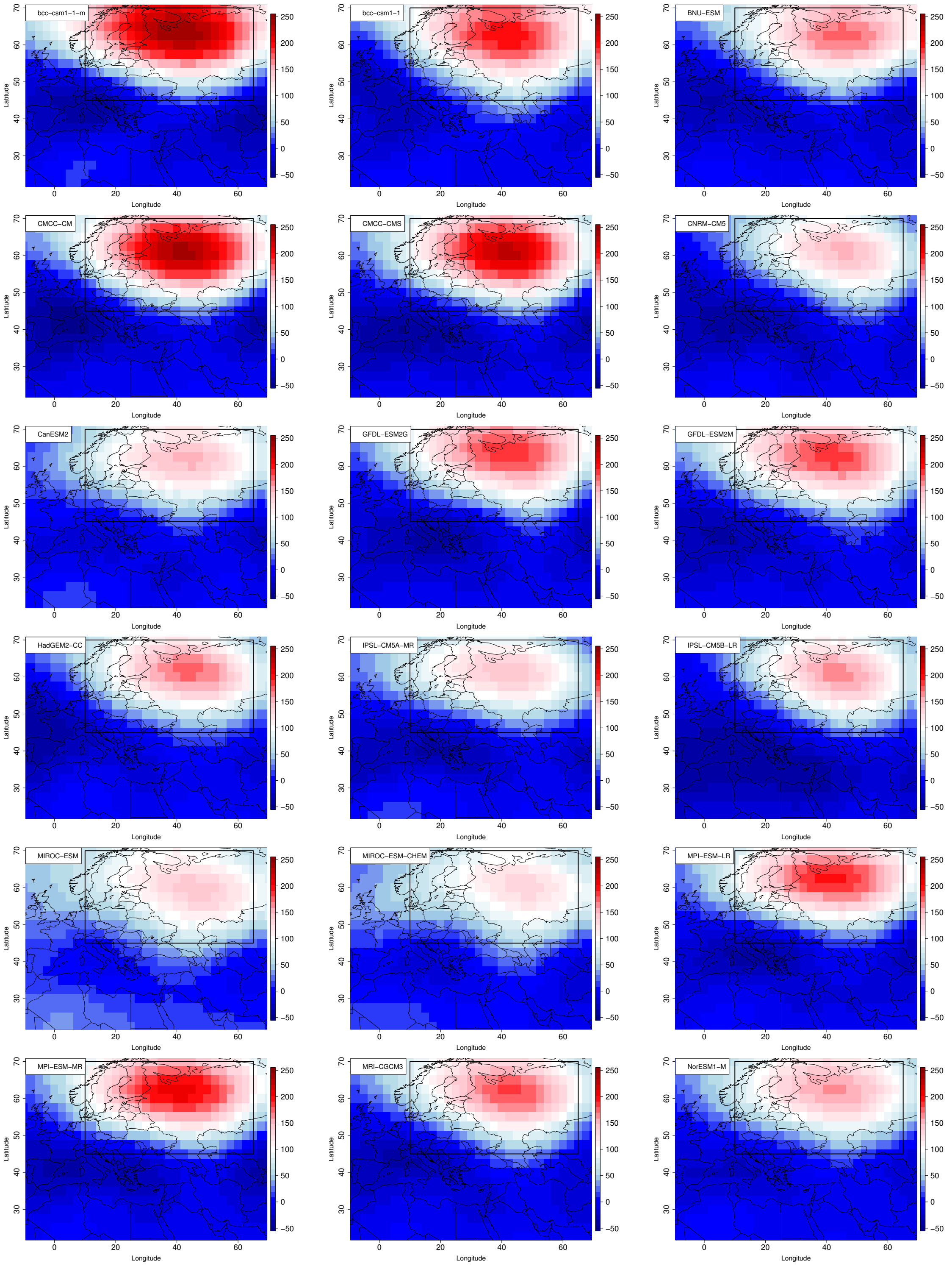

Figure 3.18 – Mean of the Z500 of all the days within $D(Z^d)$ for August 7th 2010 for each CMIP5 model used in this article

We made the arbitrary choice that these analogues are good enough for the study because they still have at least an anticyclonic structure in the region of interest.

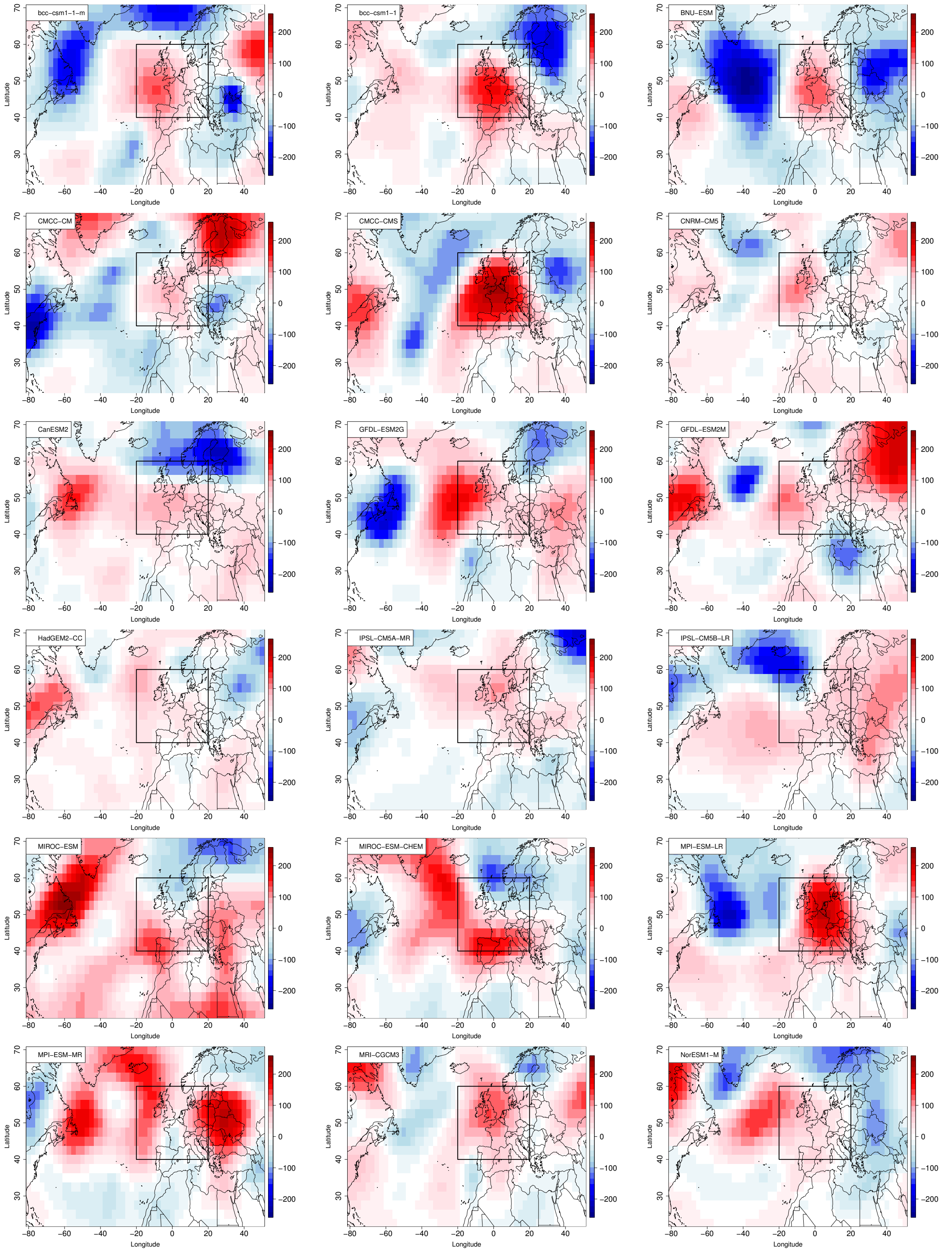

Figure 3.19 – Z500 of the day with the biggest distance to August 13th 2003 in $D(Z^d)$ for each CMIP5 model used in this article.

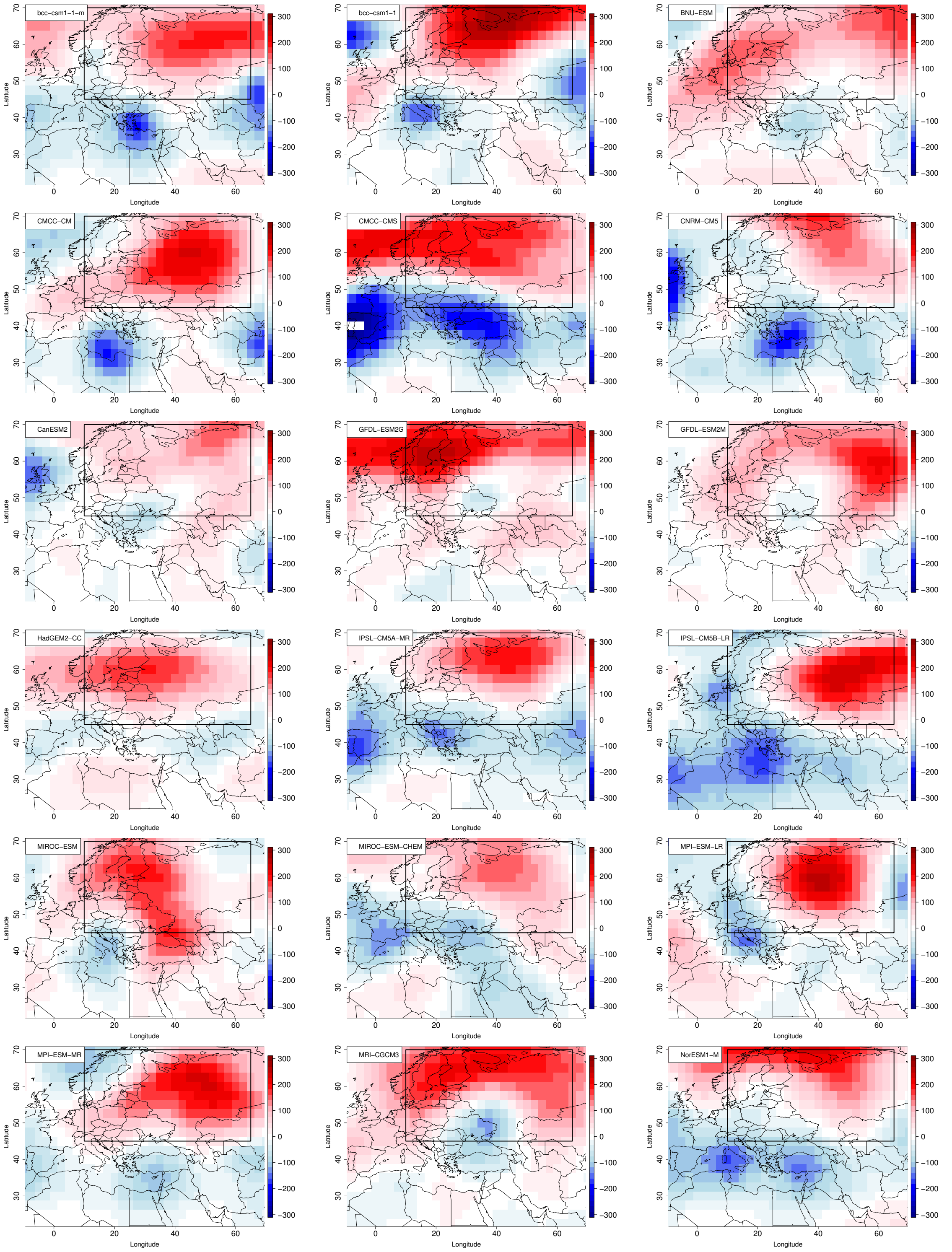

Figure 3.20 – Z500 of the day with the biggest distance to August 7th 2010 in $D(Z^d)$ for each CMIP5 model used in this article.

3.4.2 Quality relative to other analogues

This first approach of analogue quality has limitations, since it relies on the visual comparison of maps. In this section, I explore a way to build an analogue quality index. The general idea is to calculate the analogues and their distances for each day of the dataset and then to deduce the quality of an analogue by comparing its associated distance to the global analogue distance distribution. For example, in Yiou et al. (2017) (presented in Appendix E, as I am one of the co-authors) we ensured we selected analogues in the proximity to the observed circulation trajectory by only keeping those with a distance below a threshold. This threshold was defined as the median quantile of the distances of the 20 best daily January analogues. These analogues were calculated using the NCEP dataset between 1950 and 2014, excluding January 2014. The trajectories that are close to the observed trajectory are those whose average distance is lower than that threshold distance, scaled by an ad hoc "safety" factor of 1.5. This safety factor allows trajectories to escape the vicinity of the observed trajectory for one or two days.

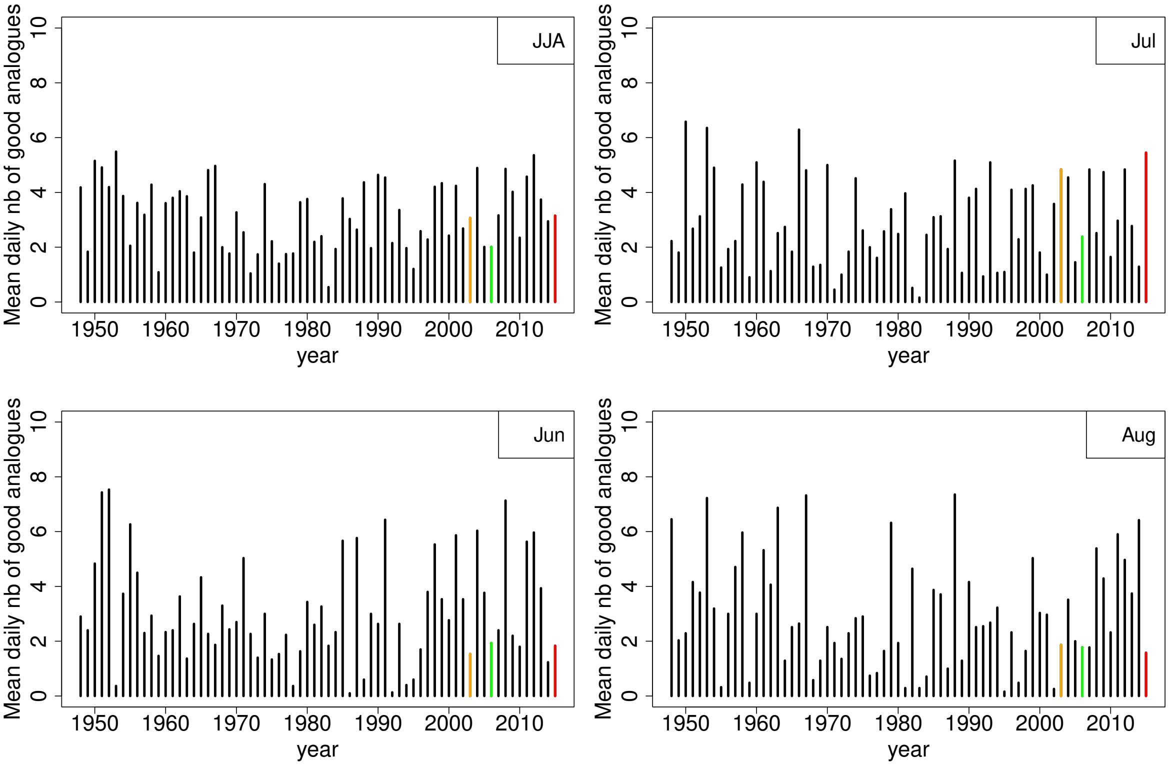

Figure 3.21 – Evolution of the yearly average average daily number of good analogues for summer (JJA), June, July and August. The good analogues are selected from the 20 best analogues calculated other the European region. The orange bar corresponds to 2003, the green one to 2006 and the red one to 2015.

To do that more systematically, we defined a good analogue, as an analogue whose distance is below the quantile 30 of the distance distribution and whose spatial rank correlation is above the quantile 70 of the correlation distribution. Yiou et al. (2018) defines good analogues in a similar fashion with stricter thresholds (quantile 25th for the distance and quantile 75th for the correlation). The spatial rank correlation is the Spearman correlation, which measures correlation between ranked variables. This choice makes the correlation estimate more robust to regional outliers. Although distance and correlation are related, they do not provide the same information. They are linked through a non-linear relationship, based on the covariance matrix. While the distance gives an information regarding the difference between two maps in terms of intensity and shape, the correlation filters the information on the shape of the atmospheric pattern.

I provide an example in figure 3.21 for summer (JJA) analogues (with quantiles defined only for the summer distributions). It displays the evolution of the yearly average daily number of good analogues between 1948 and 2015 in the European region (the medium domain shown in figure 3.5). We see that the number of good analogues depends on the year. This means that the circulation patterns observed in the years with few good analogues are rarer than for the years with a lot of good analogues. In particular, I highlighted in orange (2003), green (2006) and red (2015) the years of the events studied in the article of section 3.1. These years have a very low number of good analogues (except for July 2015), meaning that their circulation patterns were rare. This result sheds a new light on the events studied in the *Climate Dynamics* article, showing that June and August 2003 and July 2006 were not only extreme events in terms of temperature but also in terms of circulation.

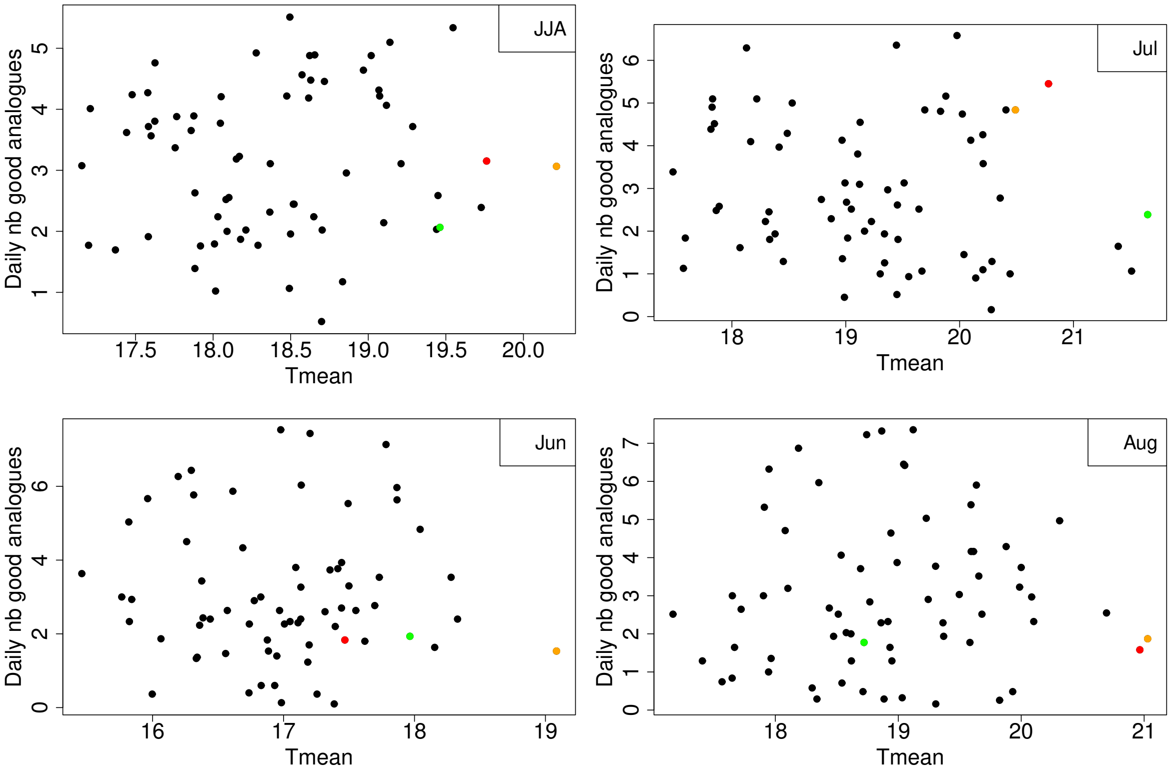

Figure 3.22 – Yearly average daily number of good analogues in function of the mean temperature for summer (JJA), June, July and August. The good analogues are selected from the 20 best analogues calculated other the European region. The orange bar corresponds to 2003, the green one to 2006 and the red one to 2015.

I plotted in figure 3.22 the yearly average daily number of good analogues in function of the mean temperature for the whole summer, and separately for the month of June, July and August in order to look for a possible correlation between temperature and rare circulations. It appears that there is no apparent link between these two variables. However, a more comprehensive look at daily values of temperature compared to the number of good analogues would be needed to further confirm this.

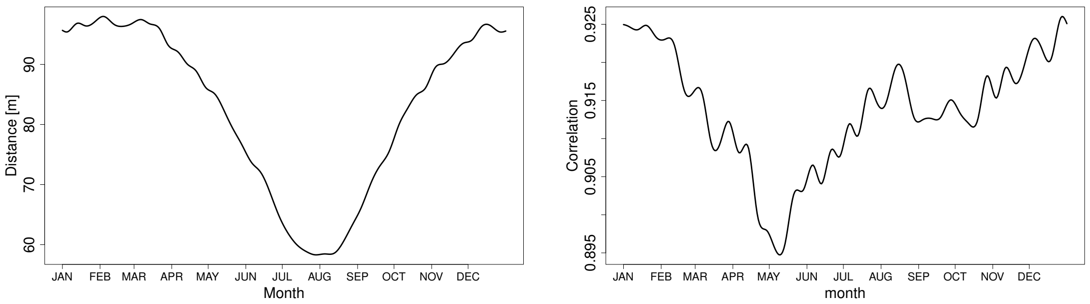

Figure 3.23 – Seasonal cycle of the distance and correlation of the 20 best daily analogues over the North Atlantic region between 1948 and 2015. It was computed using a cubic smoothing spline.

This proposed definition of good analogues is arbitrary, since it is based on arbitrary thresholds. There are a few technical parameters in the treatment of the distance and of the correlation. In particular, both the distance and the correlation have seasonal cycles, which are displayed in figure 3.23. Should a good analogue be defined based on its absolute distance and correlation, or on its deseasonalized distance and correlation? Not deseasonalizing means that the days from the months with the smallest mean distance and the highest mean correlation systematically have more analogues than for other months. For example, since there is a higher variability in winter compared to the other seasons, the good analogues should be rarer. Deseasonalizing means filtering the signal from the seasonal cycle to focus on good analogues season wise. Choosing whether or not to deseasonalize will hence answer different questions. The number of good analogues is also dependent on the chosen number of daily analogues. The main limit of this quality index is that it has no clear physical meaning, compared to the qualitative method where one can check whether the main features of the event of interest are conserved by the analogues.

With both the distance and the correlation deseasonalized, we can see the remaining signal regarding the relationship between daily analogue temperatures and distances or correlations. Figure 3.24 shows the difference between the distributions of temperatures depending on the distance and correlation of the 20 best NCEP analogues picked for every summer day between 1948 and 2015 over the North Atlantic region (the results are similar for the European region). We deduce that the lowest (highest) distances have a skewed distribution in direction of highest (respectively lowest) temperatures. This could be related to the fact that European summer warm days happen mostly for one type of circulation (anticyclonic blockings) while cold days can happen for many different types of circulation (see for example Quesada et al. (2012)). On the other hand, the lowest (highest) correlations correspond to more (less) extreme temperatures, with a larger (smaller) standard deviation. This means that we have less good analogues with our quality index for the extremely hot and cold days.

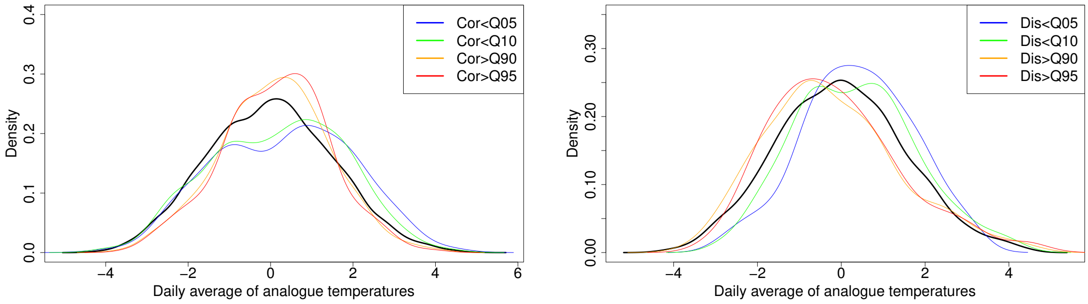

Figure 3.24 – Temperature distribution of the 20 best daily analogues over the North Atlantic region between 1948 and 2015 in black. On the left (right) panel, the red distribution includes only the analogues with a correlation (distance) over the 95th quantile of the correlation (distance) distribution. The orange distribution includes only the analogues with a correlation (distance) over the 90th quantile of the correlation (distance) distribution. The green distribution includes only the analogues with a correlation (distance) under the 10th quantile of the correlation (distance) distribution. The blue distribution includes only the analogues with a correlation (distance) under the 5th quantile of the correlation (distance) distribution.

3.4.3 Using different distances

The most classic distance used for analogue computation is the Euclidean distance, which has the advantage of being very cheap computation time wise. However, other distances have been used to calculate analogues. The Castf90 analogue program supports three different distances between two Z500 (or SLP) maps, which can be viewed as two vectors $A = (A_i)$ and $B = (B_i)$, $i \in \{1, \dots, n\}$ of same length n:

- the Euclidean distance defined as:

$$d(A,B) = \sqrt{\frac{\sum_{i=1}^{n}(A_i - B_i)^2}{n}}$$

- the Mahalanobis distance (Mahalanobis, 1936) defined as:

$$d(A,B) = \sqrt{(A-B)^T S^{-1} (A-B)}$$

  with S the covariance matrix

- the T–W distance based on the Teweles–Wobus index (Teweles and Wobus, 1954) is based on the comparison of North-South and East-West gradients G_A^{EW}, G_B^{EW}, G_A^{NS} and G_B^{NS} on each gridpoint:

$$d(A,B) = 100 \times \frac{\sum_{i=1}^{n} |G_{Ai}^{EW} - G_{Bi}^{EW}| + \sum_{i=1}^{n} |G_{Ai}^{NS} - G_{Bi}^{NS}|}{\sum_{i=1}^{n} max(|G_{Ai}^{EW}|, |G_{Bi}^{EW}|) + \sum_{i=1}^{n} max(|G_{Ai}^{NS}|, |G_{Bi}^{NS}|)}$$

The Mahalanobis distance differs from the Euclidean distance by taking into account the variance and the correlation of a time series. It lowers the weight of the principal component with the largest standard deviation. For example, on the North Atlantic domain, it will give a lower weight to the NAO signal, in order to also capture the other element of North Atlantic variability. The computation of the inverse of the covariance matrix becomes costly computation-wise for large regions and long datasets. Hence, unless one can prove that the Mahalanobis distance gives better results than the Euclidean distance, it is better to rely on the latter.

The T–W distance is based on the comparison of gradients. It was introduced in Teweles and Wobus (1954) as a measure of forecasting skill. Guilbaud and Obled (1998) have shown that the selection of analogues for precipitation forecast is improved when using the Teweles–Wobus index. More recently, this index has been used for analogue-based downscaling (e.g. Chardon et al. (2014, 2016); Radanovics et al. (2013)).

A few articles have compared the performance of different similarity measures for analogue selection. Toth (1991a) compares the quality of analogue forecast using nine different distance functions, including the Euclidean distance and Teweles–Wobus index. Teweles–Wobus is one of the worst measures in this case, while the Euclidean distance is one of the best. Matulla et al. (2008) compare four different metrics, including the Euclidean and Mahalanobis distances for the use of analogues for precipitation downscaling. They find that the optimal choice of similarity measure depends on the variable and on the region of interest. In their study, Mahalanobis performs poorly and the Euclidean distance does a satisfactory job. Here I show preliminary results comparing the uchronic temperature distributions obtained for the three different results. The selection of one of the measures would require much more work and was not in the scope of this PhD.

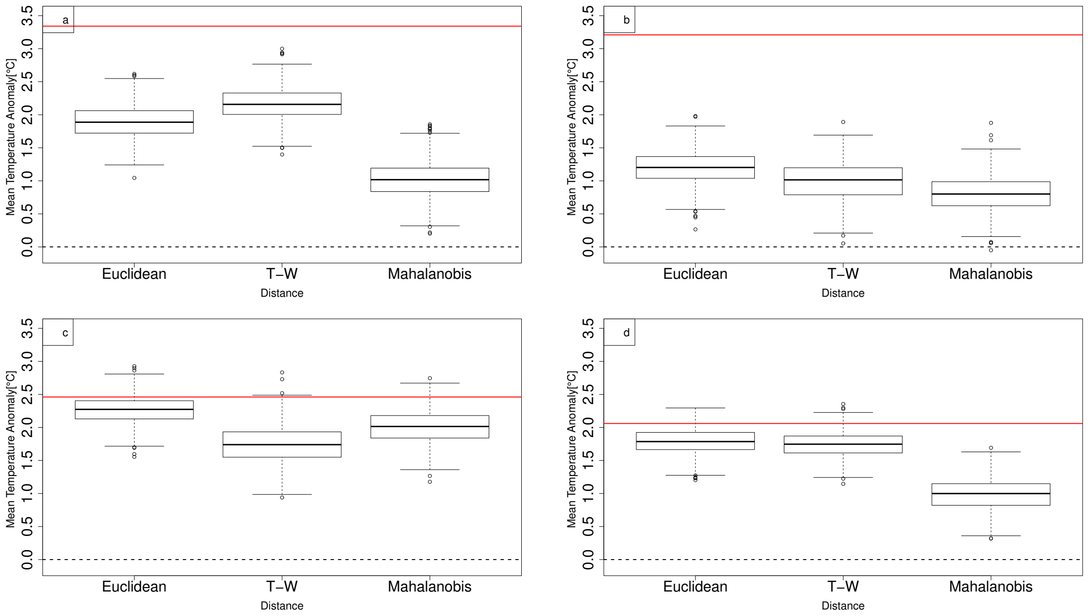

Figure 3.25 – The probability density of uchronic temperature anomalies from circulation analogues generated using different distances for each case study: June 2003 (a), August 2003 (b), July 2007 (c), July 2015 (d). The red line represents the observed detrended temperature anomaly of the event.

As an example of the importance of the choice of distance, I computed the uchronic temperature distributions for the four case studies presented in section 3.1 for the three different distances. We can see in figure 3.25 that although the choice of distance does not qualitatively affect the uchronic temperature distributions, it has a quantitative effect on them. Examples of differences induced by different distances are the differences between the uchronic temperatures computed using the Teweles–Wobus and Mahalanobis distances for both June 2003 and July 2015. More work needs to be done to better comprehend what explains those differences.

A good analogue could be defined as an analogue which is stable between distances. The use of more sophisticated distances to compute analogues is nascent. Yoann Robin presented promising results using the Wasserstein distance (Wasserstein, 1969), which emerge from optimal transport theory, in his PhD (Robin, 2018).

3.5 Summary and conclusions

Flow analogues are days with a circulation similar to the circulation of the day of interest. In practice, we calculate the distance between daily Z500 maps in a small region, and select the days with the smallest distance. The computation of analogues gives two main information. First, it gives us an idea of the rarity of the circulation of interest, depending on the quality of analogues, which we discussed above. Second, it gives us an ensemble of analogue days, which is a way to capture the influence of the Z500 pattern on other variables, such as temperature.

This chapter introduces the concept of *uchronic* temperatures, i.e. temperatures that could have been for the same circulation patterns. The computation of uchronic temperature distributions gives the range of expected temperatures for the observed circulation. Following the same methodology, I computed uchronic temperatures for December 2015 (Jézéquel et al., 2018) and uchronic precipitations for summer 2015 (Hauser et al., 2017) (see chapter 5). Sánchez-Benítez et al. (2018) used uchronic temperatures for their analysis of the early June 2017 European heatwave. Wilcox et al. (2017) computed uchronic precipitations for their analysis of the extreme European summer of 2012.

This first step helps to disentangle the role of dynamics from other processes explaining the occurrence of European heatwaves. The next step of this PhD is to assess how climate change influences the different processes leading to extreme heatwaves. The next chapter deals with the influence of climate change on the occurrence of circulation patterns observed during specific heatwaves.

Résumé

Contexte et objectifs

L’une des conditions nécessaires pour qu’une canicule se développe en Europe est la présence d’une situation atmosphérique propice à ce que la chaleur s’installe, le plus souvent un blocage anticyclonique empêchant l’air de circuler, ou une circulation faisant remonter l’air chaud du Sud vers le Nord. Ce chapitre cherche à quantifier la part de l’anomalie de température observée pendant une canicule attribuable à la circulation atmosphérique associée.

Méthodes

Les données principales utilisées dans ce chapitre sont les réanalyses NCEP, entre 1948 et 2015. L’utilisation d’analogues de circulation permet de déterminer un ensemble de jours ayant une circulation proche de celle observée pendant une canicule donnée. Afin de calculer les analogues d’un jour, on commence par calculer la distance euclidienne entre la carte de géopotentiel à 500hPa (Z500) observée ce jour-là et toutes les cartes de Z500 tirées de NCEP pour des jours calendaires proches (±30 jours calendaires). Les analogues sont les N jours pour lesquels cette distance est la plus faible (Figure 3.3). On peut reconstituer une *température uchronique* – température qui aurait pu avoir lieu pour la même circulation – en combinant les températures d’un analogue tiré au hasard pour chaque jour de la canicule. En réitérant ce calcul, on obtient une distribution de température uchronique. La moyenne de cette distribution est une approximation de la température attribuable à la circulation atmosphérique. L’obtention de cette distribution de températures uchroniques dépend d’un certain nombre de paramètres : le choix de la variable représentant la circulation, la taille du domaine sur lequel sont calculés les analogues, la longueur du jeu de données, le nombre d’analogues, et le choix de la distance. L’influence de ces paramètres est évaluée.

Résultats

Le calcul des températures uchroniques est appliqué à quatre vagues de chaleur européennes: Juin 2003 en Europe de l’Ouest, Août 2003 en Europe de l’Ouest, Juillet 2006 dans le Nord de l’Europe et Juillet 2015 dans le Sud de l’Europe. La circulation explique à différents niveaux les anomalies de températures observées pendant ces mois, entre 38% pour Août 2003 et 92% pour Juillet 2015 (Figure 3.9). Ce décalage peut s’expliquer par le rôle d’autres processus physiques, comme l’humidité du sol et/ou par la qualité des analogues qui dépend de la rareté de la circulation observée et de la longueur du jeu de données.

Par ailleurs, ce travail a été l’occasion de mieux comprendre le rôle joué par les différents paramètres testés et de proposer des recommandations pour de futures études s’appuyant sur les analogues de circulation. Le Z500 est plus approprié que la pression de surface pour calculer des températures uchroniques estivales. Le choix d’un petit domaine de calcul des analogues permet d’obtenir de meilleurs résultats. Enfin, les incertitudes augmentent lorsque la longueur du jeu de données diminue. Une évaluation de ces incertitudes est possible à partir de simulations de contrôle à climat constant.

Chapter 4

Influence of climate change on circulation patterns on European heatwaves

We saw in the previous chapter that atmospheric patterns partly explain the occurrence of heatwaves. In order to understand how the processes leading to European heatwaves are modified by anthropogenic climate change, I propose to consider separately the influence of climate change on the occurrence of circulation patterns leading to a given heatwave (in this chapter) and the influence of climate change on the intensity of heatwaves for a given circulation pattern (in the chapter 5). This decomposition could be considered as part of the *storyline* approach described by Shepherd (2016) and Trenberth et al. (2015). Yiou et al. (2017) (presented in Appendix E) proposes another way to decompose both parts of the role of climate change using analogues and the Bayes formula.

Jézéquel et al. (2017) have shown the need to rely on long datasets to be able to reproduce well the role of circulation in heatwaves. Since I wanted to find a signal related to climate change, in addition to reanalysis datasets, I used outputs from global circulation models (GCM), which simulate the evolution of a number of climate variables from 1950 to 2100 under different emissions scenarios.

In the following article, we propose a method to calculate dynamical trends for specific patterns related to extremely hot European days on a local scale. The novelty of this paper is to introduce a statistical methodology tailored to individual events. We search for significant changes in the frequency of an atmospheric pattern for smaller regions than what is usually the case in other studies on the evolution of circulation in mid-latitudes (e.g. Cattiaux et al. (2016); Deser et al. (2017); Peings et al. (2017)).

4.1 Article published in *Environmental Research Letters*: Trends of atmospheric circulation during singular hot days in Europe

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4.1.1 Abstract

The influence of climate change on mid-latitudes atmospheric circulation is still very uncertain. The large internal variability makes it difficult to extract any statistically significant signal regarding the evolution of the circulation. Here we propose a methodology to calculate dynamical trends tailored to the circulation of specific days by computing the evolution of the distances between the circulation of the day of interest and the other days of the time series. We compute these dynamical trends for two case studies of the hottest days recorded in two different European regions (corresponding to the heatwaves of summer 2003 and 2010). We use the NCEP reanalysis dataset, an ensemble of CMIP5 models, and a large ensemble of a single model (CESM), in order to account for different sources of uncertainty. While we find a positive trend for most models for 2003, we cannot conclude for 2010 since the models disagree on the trend estimates.

4.1.2 Introduction

Extreme event attribution (EEA) (Stott et al., 2016) aims at evaluating how the properties of a specific extreme climate event have been affected by anthropogenic forcings. Climate change may play a role on either — or both — the dynamics and the thermodynamics explaining the event. The influence of climate change on the thermodynamics of European heatwaves has been largely studied and proven for both specific events (e.g. Stott et al. (2004), Christidis et al. (2015b), Russo et al. (2015)) and types of events (e.g. heatwaves in Russo et al. (2014)). The evolution of the dynamics related to heatwaves is still a debated subject.

The atmospheric dynamics in the Northern Hemisphere mid-latitudes are driven by the vertical static stability (e.g. Lim and Simmonds (2009), Walland and Simmonds (1999)) and by the latitudinal temperature gradient. This gradient could be modified by climate change through two processes: the surface Arctic amplification (AA) and the upper-tropospheric tropical warming (Peings et al. (2017)). The evolution of those two factors is still very uncertain, with a wide range of responses across climate models (Zappa and Shepherd (2017)), and even across different members of a single model ensemble due to internal variability (Deser et al.

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(2017), Peings et al. (2017)).

Over Europe, the link between long-lasting anticyclonic circulation, called blockings (e.g. Ruti et al. (2014)), and high summer temperatures has been established (e.g. Jézéquel et al. (2017), Pfahl and Wernli (2012), Sousa et al. (2018)). Francis and Vavrus (2012) detected the emergence of a significant increase in the persistence of blockings over the recent years using a reanalysis dataset. They explain this emergence by a mechanism based on the AA. Coumou et al. (2015) found similar results focusing on summer and using satellite data. However, both Barnes (2013) and Screen and Simmonds (2013) argue that the results of Francis and Vavrus (2012) depend on the methodology they used and could be subject to ambiguous interpretations. Cattiaux et al. (2016) used global climate models (GCM) to extend the search of trends to the twenty-first century. They found no evidence of an increase of persistence of blockings. Those studies evaluate the evolution of the circulation on large scales, on either the whole Northern Hemisphere or the North Atlantic region. In contrast, we are interested in capturing trends related to specific heatwave events, and we hence focus on a much smaller scale.

Ruti et al. (2014) calculated summer trends of the blocking index defined by Tibaldi and Molteni (1990) over the Euro-Russian region using a reanalysis dataset and an atmospheric-only model for the 20th century. They found a statistically significant increase in the duration of blocking episodes for the second part of the century, which they attribute to climate change, using different forcings as inputs of their model. However, the 20th century might not be long enough to evaluate trends on blockings. Indeed, using a large ensemble from a single model representing internal variability, Peings et al. (2017) found a decrease in the blocking index over the 1920–2100 period for the North Atlantic region, which includes Ruti et al.'s Euro-Russian region. Those differences could be related to an inconsistency between different models or to different evaluations of the internal variability. This led us to use a set of different models and a large ensemble to account for both.

In the context of EEA, Trenberth et al. (2015) argued that due to the large internal variability of dynamical processes, it is best to focus only on thermodynamical processes for a fixed dynamical state in order to extract the signal related to climate change. A few attribution studies that condition the signal to the circulation follow this approach to extract thermodynamical signals hidden in a large internal variability (e.g., Cattiaux et al., 2010; Meredith et al., 2015). However, this does not allow to calculate the complete influence of climate change on the events of interest (Otto et al., 2016). Shepherd (2016) highlighted that it is possible to study the dynamic and thermodynamic contributions separately. Few papers have studied the influence of climate change on the dynamics applied to a singular event (Vautard et al., 2016; Yiou et al., 2017). Both of those articles calculate the dynamical difference between two worlds (with and without climate change). Here we focus on detecting whether there is an evolution between 1950 and 2100 in the occurrence of circulations related to a given day.

Jézéquel et al. (2018) proposed to calculate a trend on the number of close days to the observed flow of December 2015 in Western Europe using a single model ensemble. In the present article, we refine this approach to single day atmospheric circulation patterns. We detail the proper statical methodology to calculate dynamical trends with a focus on the calculation of the statistical confidence interval, of multi-model uncertainties, and of internal variability. We seek to detect changes in the occurrence of circulation patterns related to specific hot days. We leave the attribution of those changes to further studies. We first present the methodology to estimate trends of the circulation for a given daily event. We then apply this methodology to two case studies: the 2003 heatwave in Western Europe and the 2010 heatwave in Russia. These two heatwaves have been ranked first and second in Russo et al. (2015) list of top ten European heatwaves since 1950. We finally discuss those findings and potential larger applications of our methodology to other types of events.

4.1.3 Data and Methods

4.1.3.1 Datasets

In this study, we assume that the geopotential height at 500hPa (Z500) is a proxy for the extra-tropical atmospheric circulation. We focus on the summer season (June-July-August: JJA). We use daily averages of Z500 from three datasets over two European subregions: [20W–20E; 40N–60N], called Western Europe (WE) hereafter and [10E–68E; 45N–70N], called Russia (RU) hereafter.

The first dataset is the National Center for Environmental Prediction/National Center for Atmospheric Research, NCEP/NCAR, reanalysis I dataset (Kalnay et al., 1996) between 1950 and 2016. Its horizontal resolution is 2.5 by 2.5 degree. This dataset, called $\mathcal{A}_1$ hereafter, allows us to assess whether dynamical trends are detectable in a short dataset, which is as close as possible to the observations.

The second dataset is an ensemble of 18 models from the fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al. (2012), see model references and resolutions in the supplementary material) with easily accessible Z500 on the IPSL (Institut Pierre Simon Laplace) cluster. They cover the 1950–2100 period, with a historical simulation from 1950 to 2005 and RCP4.5 (Representative Concentration Pathway) and RCP8.5 scenarios from 2006 to 2100. This multi-model dataset is named $\mathcal{A}_2$.

The third dataset consists of 30 runs of the Community Earth System Model large ensemble (CESM-LENS) (Kay et al., 2015). The model horizontal resolution is 1 by 1 degree. It covers the 1950 – 2100 period with a historical simulation for the 1950 – 2005 period and the RCP8.5 scenario from 2006 to 2100. This ensemble dataset is named $\mathcal{A}_3$.

We use three types of data in order to compare reanalysis data with a single model ensemble (CESM-LENS) that reflects the internal variability of a climate model and a multi-model ensemble (CMIP5) that reflects the uncertainty due to the model formulation. This allows to estimate different components of the uncertainty (Section 4.1.3.3).

Historical runs over 1950–2005 are merged with RCP8.5 runs over the 2006–2016 period to allow the comparison with reanalysis data over the whole 1950–2016 period. The choice of RCP8.5 is (1) coherent with observations and (2) the only scenario available for CESM-LENS.

In this article, we focus on very hot days, which are related to anticyclonic blocking situations. We are therefore interested in finding close Z500 patterns to those types of circulation. The Z500 is however related to lower-tropospheric temperatures, so that a global surface warming implies a generalized Z500 increase. In order to focus on the dynamical signal and ensure that our method would not interpret a uniform Z500 rise as a change in circulation, we choose to remove this background thermal effect (contrarily to Horton et al. (2015)). This way, we aim at dealing with dynamical changes unrelated to thermodynamical trends. This is done by subtracting a spatially uniform Z500 trend, calculated on the mean seasonal (JJA) spatial average on the region of interest, using a cubic smoothing spline in time (similarly to Jézéquel et al. (2017)). By subtracting a uniform field, we do not alter the horizontal gradients of Z500 that depict the circulation. An alternative to using Z500 would have been to use SLP but in summer, the SLP field is affected by a heat low effect that blurs the dynamical signal (Jézéquel et al. (2017)).

4.1.3.2 Dynamical trend estimation

Our goal is to determine whether a given circulation pattern has become more or less frequent during a given period. We consider a Z500 reference pattern Z^d belonging to the dataset $\mathcal{A}_1$ that occurs on a day d. For all the days d' in the dataset $\mathcal{A}_k$, we compute the set of Euclidean distances between $Z^{d'} \in \mathcal{A}_k$ and the reference $Z^d \in \mathcal{A}_1$, defined as the root mean square of the differences between each grid point within the region of interest. For the reanalysis dataset, we exclude the days within the same year as the event of interest. We determine the xth quantile q_x of those distances for each separate dataset $\mathcal{A}_k$ (the value of q_x can hence differ depending on the dataset). The value of x can be chosen heuristically, e.g. the 5th quantile. From Z^d and q_x we define the class of days or patterns $D(Z^d)$ in the ensemble $\mathcal{A}_k$ that are similar to Z^d:

$$D(Z^d) = \{d' \in \mathcal{A}_k, \mathrm{dist}(Z^{d'}, Z^d) \leq q_x\}. \tag{4.1}$$

The class $D(Z^d)$ is shown for August 13th 2003 over the WE region for one model of $\mathcal{A}_2$ (MPI-ESM-MR) in Figure 4.1a (blue dots). Figures 3.15 to 3.20 show that even if the exact anomaly of Z500 is not captured by the days in $D(Z^d)$, they all display blocking patterns within the regions of interest. This means that the 5th percentile chosen to define $D(Z^d)$ is relevant to study the evolution of blocking patterns in those regions.

For each year y in $\mathcal{A}_k$, we count the number N_y of days in $D(Z^d)$ in order to study potential trends in N_y. This requires to properly model the evolution of this variable. The first step is to find a suitable distribution to describe it. The variable N_y is discrete and bounded. N_y can only take integer values between 0 and $N_{tot} = 92$ (the number of days in JJA). We display the evolution of N_y with time in Figure 1b for one model. As $Var(N_y)$ is 2.0 to 15.2 times larger than the expected value $E(N_y)$, we conclude that the distribution of N_y is systematically overdispersed with respect to a Poisson or to a binomial distribution (with parameter p), for which the variances would be respectively equal to $E(N_y)$ and $(1-p)E(N_y)$.

Once there is one day in $D(Z^d)$ in a given summer, there is a high chance that the following days will also be in $D(Z^d)$, because of the persistence of atmospheric circulation. Hence the odds of having another day in $D(Z^d)$ within a given year increase with the number of days already in $D(Z^d)$ within the summer. This explains why N_y is overdispersed. We chose to model the distribution as a beta-binomial distribution, which fits well bounded discrete distributions that are overdispersed, so that:

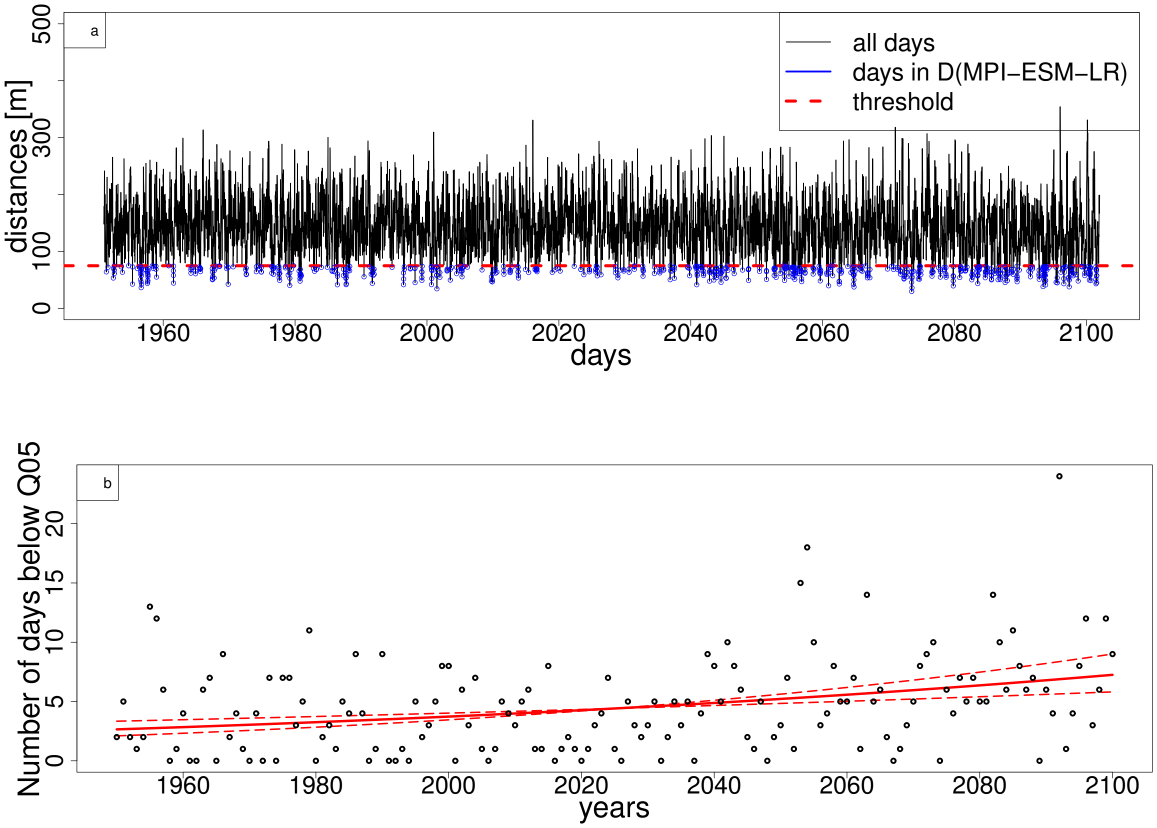


Figure 4.1 – Example for August 13th 2003 over the region [20W–20E;40N–60N] with the MPI-ESM-LR model and the RCP8.5 scenario. a) time series of daily Euclidean distances between $Z_{d'}$ and Z_d. The 5th percentile is represented by the red dotted line. The blue points are the days in $D(Z_d)$. b) Evolution of the number of days belonging to $D(Z^d)$, N_y. The black dots represent N_y. The red straight line is the modeled $E(N_y)$ using the glm, the dotted lines represent the confidence interval.

$$P(N_y = k) = \binom{N_{tot}}{k} \frac{B(k + \alpha, N_{tot} - k + \beta)}{B(\alpha, \beta)} \tag{4.2}$$

where B is the beta function (Whittaker and Watson, 1996), and α and β parameters which allow to account for possible overdispersion. We tested the goodness of fit of the beta-binomial distribution for each dataset using a Pearson χ^2 test. The p-values are all greater than the 0.05 significance level, meaning that we cannot reject the hypothesis that N_y follows a beta-binomial distribution.

The second step is to find a statistical model to describe the evolution of N_y with time. We used a generalized linear model (glm, see Eq. (4.4)) to determine the temporal trend of N_y (Nelder and Wedderburn, 1972). The glm is a generalization of the linear regression through the use of a link function g allowing the transformed mean to vary as a function of predictors. We transform the mean as $g(E(N_y/N_{tot}))$ where

$$g(u) = \log\left(u/(1-u)\right), \tag{4.3}$$

with $u \in [0,1]$ and $E(.)$ is the expected value. g is called the *logit* link function.

We used the R package VGAM (Yee, 2010), which includes the function vglm that fits a glm to beta-binomial distributions (Prentice, 1986).

For a year y in $\mathcal{A}_k$, we assume that

$$g(E(N_y/N_{tot})) = \alpha_N \ + \beta_N y, \tag{4.4}$$

where α_N and β_N are the regression coefficients.

The interpretation of regression coefficients is not straightforward, because the glm uses the logit link function, which produces a non-linear regression. We therefore present the results using fitted values of $E(N_y)$. We used the inverse link function $E(N_y) = N_{tot} \times g^{-1}(\alpha_N \ + \beta_N y)$ and the regression coefficients to obtain the fitted values of $E(N_y)$ for year y, which gives the solid red line in Figure 1b. We then calculated the difference between the fitted values of $E(N_y)$ between the end and the beginning of the time series, in order to analyze the evolution of $E(N_y)$.

This regression is a way to determine whether the days similar to Z^d get more (or less) likely with time. However, it does not discriminate whether any change detected is related to the fact that days close to Z^d happen more regularly every summer, or if they are more numerous within a given event. Decomposing those two parts of the signal is beyond the scope of the present article.

4.1.3.3 Uncertainties

In order to derive a confidence interval on the estimated trend, we first calculated a confidence interval for β_N – this is done assuming that $\hat{\beta}_N$ follows a Gaussian distribution. This confidence interval on β_N can then be translated into a confidence interval on the average number of days belonging to $D(Z^d)$, by calculating the fitted values of $E(N_y)$ corresponding to the upper (resp. lower) bound of β_N. We consider that the change is significant if the confidence interval on β_N does not include 0.

Besides the statistical uncertainty, the two ensemble datasets allow to evaluate the uncertainty due to internal variability in the case of CESM-LENS $\mathcal{A}_3$ and the multi-model uncertainty in the case of the CMIP5 ensemble $\mathcal{A}_2$.

The comparison of those three sources of uncertainties allows us to detect whether the circulation undergoes a significant evolution. It also weighs the sources of uncertainties and assesses the confidence in the methodology. We cannot attribute any detected evolution to climate change with this methodology, as we do not compare our results to those which could be obtained in a world without climate change.

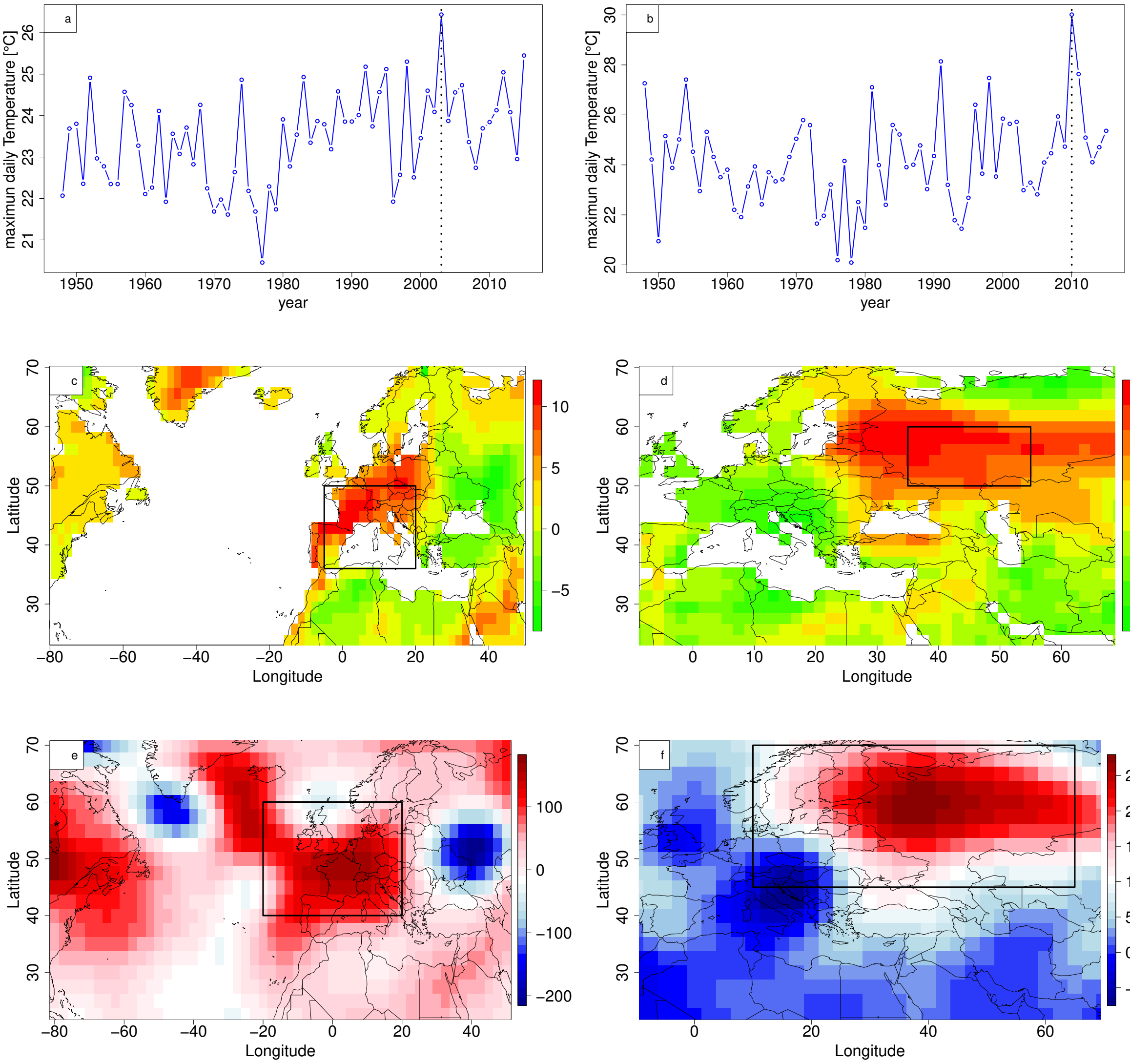


Figure 4.2 – Two case studies: August 13th 2003 and August 7th 2010 using the NCEP dataset. a (respectively b) Time series of the yearly hottest summer day in the black boxes of figure 2c (respectively 2d) of 2003 (respectively 2010). c (and d): temperature anomaly of August 13th 2003 (August 7th 2010). e (and f): detrended Z500 anomaly of August 13th 2003 (August 7th 2010).

4.1.4 Two case studies

We chose two epitomes of heatwaves of the 21st century, largely studied in the literature to apply our method: summer 2003 (e.g. Beniston (2004), Fischer et al. (2007), Stéfanon et al. (2012)) in the WE region and summer 2010 (e.g. Dole et al. (2011), Rahmstorf and Coumou (2011), Trenberth and Fasullo (2012), Otto et al. (2012), Hauser et al. (2016)) in the RU region. The thermodynamical component of climate change has been identified by those authors, but the dynamical contribution has not been as emphasized. We used those two cases as examples to apply our methodology to detect circulation trends.

The hottest day of the NCEP reanalyses in the WE region was recorded on August 13th 2003, and the hottest day in the RU region was recorded on August 7th 2010 (for both absolute value and summer seasonal anomalies), as shown in figures 4.2a and 4.2b. Figures 4.2c and 4.2d display the temperature anomalies for those days. The rectangles on those maps delimit the WE and RU regions (as defined in Jézéquel et al. (2017) and Barriopedro et al. (2011)). Figures 4.2e and 4.2f show the corresponding daily maps of Z500 anomalies. There is a strong similarity between the temperature and Z500 anomalies patterns for both days. This indicates a very hot air mass not just at the surface but through the entire lower troposphere. The rectangles on those maps are regions selected based on the position of the anticyclonic anomaly (as in Jézéquel et al. (2017)) to calculate the distances between the circulation of the day of interest and the circulation of the other summer days in the times series.

Figure 4.3 displays the results of Equations (2) to (4) with the 5th percentile. For the historical period, we get similar results for both 2003 and 2010. We detect no significant trend in NCEP for both events. This result is independent of the choice of reanalysis dataset (ERA20C and 20CR give similar results for 1950-2010). In the case of August 13th 2003, CanESM2 and 3 runs of CESM-LENS have significant positive trends, and one run of CESM-LENS has a significant negative trend from 1950 to 2016. The other models and runs display no significant trend. The bigger uncertainty comes from the internal variability assessed with CESM-LENS. This means that we cannot judge the quality of a model with respect to the simulation of dynamical trends by comparing it to the NCEP reanalysis, which is just one realization of what could have happened for the same background state of the climate. In the case of August 7th 2010, no model detects either a positive or a negative significant trend on the historical period. The statistical uncertainty is larger than for 2003. The multi-model uncertainty equals the internal variability. Using only reanalyses or historical runs of 67 years is not sufficient to detect any significant signal. This is coherent with the findings of Deser et al. (2017) who have shown that SLP trends over the North Atlantic region have different signs for different runs of CESM-LENS even over 50 years, although the focus of their study was the winter season. We get past the internal variability using 151 years (from 1950 to 2100) and RCP scenarios.

For the longer periods, the results differ between 2003 and 2010. For the former, 7 models detect a significant positive signal. For RCP 8.5, 10 models detect a significant positive signal. Out of the 30 runs of CESM-LENS, 29 detect significant positive difference between 1950 and 2100. With the exception of MIROC models, the models which detect a significant positive trend reproduce best the observed anomaly (Figure S5). Although the response differs from one model to another, there seems to be an agreement on a positive difference of approximately 5 days in 151 years. With the choice of the 5th percentile to define $D(Z^d)$, the mean number of days in $D(Z^d)$ for each summer is approximately 4 days. Therefore a difference of

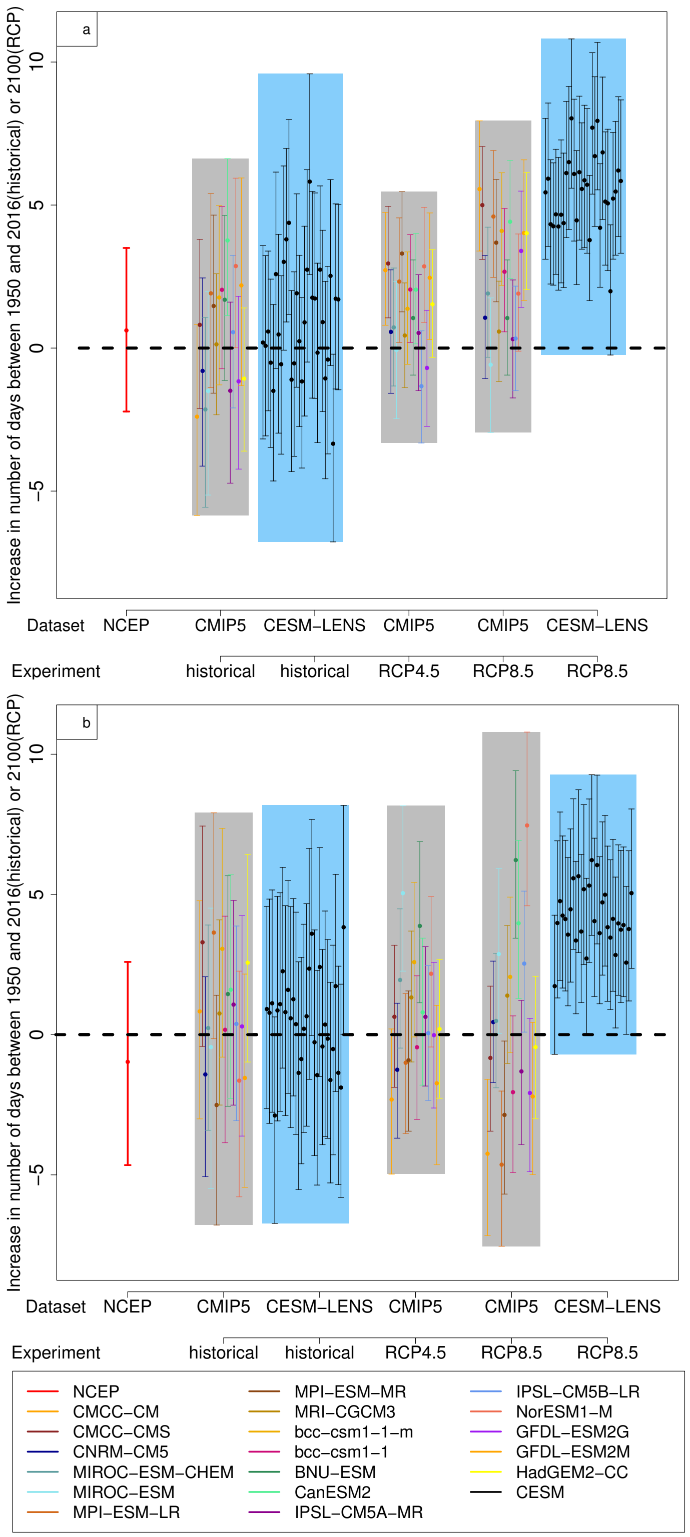


Figure 4.3 – Dynamical trends. Panels a and b display the modeled difference between the average number of days N_{end} and $N_{beginning}$ belonging to $D(Z^d)$ for NCEP (in red), CMIP5 (bars in gray shaded areas) and CESM (bars in blue shaded), for the historical, RCP4.5 and RCP8.5 experiments. Panel a is for August 13th 2003. Panel b is for August 7th 2010.

5 days is not negligible. The models do not agree for 2010. For RCP4.5, we find 2 models with a significant positive trend. For RCP8.5, we find 4 models with significant positive trends, 3 models with significant negative trends. Out of the 30 runs of CESM-LENS, 27 yield a significantly positive trend. The models hence disagree, which questions the robustness of trends found in studies where only one model is used. The models that find a significant positive trend (including CESM-LENS) are less able to reproduce the intensity of the observed Z500 anomaly (supplementary figures S4 and S6).

4.1.5 Discussion

Our methodology gives different results for the 2003 and 2010 events. While we find a positive signal with most models for 2003, the models do not show coherence for 2010. This is not surprising, as both events happened in two different regions, in which there is no reason for the dynamics to evolve in a similar way. We can see in Figures 4.2c and 4.2d that the atmospheric pattern in Western Europe in 2010 is almost the inverse of the 2003 pattern. However, we are more confident in the ability of the models to reproduce the 2003 pattern than the 2010 one because of the difference in intensity and extent of both blockings and the larger spread in Figure 4.3b compared to 4.3a. The trends are more pronounced in RCP8.5 than RCP4.5, which is an argument to attribute the significant changes in the weather pattern of one central day of the 2003 heatwave to climate change. If the models with significant positive trends are to be believed, and for the 2003 case these models are the ones simulating the most realistic patterns (see supplementary figures 3.17 and 3.19), this could mean longer and more frequent heatwaves similar to 2003 in Western Europe, without even taking into account the thermodynamical effect of climate change on temperature. This thermodynamical effect has been largely proven in the literature (e.g. Bador et al. (2017); Meehl and Tebaldi (2004)), and is stronger than the dynamical effect. We however stress that the Z500 anomaly is not a sufficient condition for a heatwave to develop (Boschat et al. (2016), Quesada et al. (2012)). Peings et al. (2017) find a decrease in the one-dimensional blocking index as defined by Tibaldi and Molteni (1990), which would indicate a lesser importance of the dynamics in the years to come, using the CESM-LENS dataset. There is no reason to expect the same results from both studies, since we focus on a specific dynamical event through the use of a two-dimensional Z500 field over a rather small region, while Peings et al. (2017) looked at circulations leading to heatwaves in general over a much larger region.

All the Z500 fields were detrended to remove from Z500 the thermodynamical influence of climate change. However, the shape of the modeled Z500 distribution can differ from the observed one. We tested 4 types of normalization: no normalization, a simple normalization (division by the standard deviation) on every grid-point, a simple normalization on the mean of the Z500 field and a quantile-mapping (e.g. Panofsky and Brier (1958), Déqué (2007), and Gudmundsson et al. (2012b)). We normalized using the 1950-2005 period which is common between historical runs and NCEP. Although the normalization changes results for a few individual models, it does not change the collective results of the ensemble of CMIP5 and CESM-LENS models (not shown here). Since the normalization does not fundamentally change our results, we use non normalized Z500 anomaly fields.

We also tested how the results change when we choose a different percentile to define $D(Z^d)$. We tested 4 percentiles: the 2nd, the 5th, the 10th and the 25th percentiles. The differences detected between the 1950 and 2100 values of N_y monotonically increase with the percentile. The results get more significant (further from 0 and in some cases become significant) for higher percentiles.

There are a few limitations to this methodology. We only considered daily events, which are not the heat events with the largest impacts. In the supplementary material, we calculated the dynamical trends for each day of both events (Figures 4.5 and 4.6). In terms of dynamical trends, we find that August 13th 2003 and August 8th 2010 are typical of the whole heatwaves. We also observe that for both cases RCP4.5 has less statistically significant models than RCP8.5 which could mean that the dynamical signal is enhanced with a stronger climate change. Another caveat is related to the internal variability of the dynamics. Given that 70 years are not enough for any signal to exceed the range of observed natural variability, we have to rely heavily on models that might not accurately reproduce some aspects of the dynamics of the atmosphere.

The biggest advantage of this methodology is that it is easy to implement and very cheap in computation time. It would be possible to do those calculations in a few minutes time each day for a region of interest, and hence give an idea of whether climate change might make dynamically driven events more or less likely in the future for very specific types of circulation. It could serve for other types of events than hot days, e.g. for atmospheric patterns leading to daily extreme precipitations. In further studies, we intend to use it more systematically to see if it helps us to identify types of circulation whose probabilities evolve according to an ensemble of models.

4.1.6 Acknowledgements

This work was supported by ERC Grant No. 338965-A2C2, by the French Ministry of Ecology, Sustainable Development and Energy, through the national climate change adaptation plan project EXTREMOSCOPE, and by the FP7 EUCLEIA project under Grant No. 607085. We thank five anonymous reviewers for their numerous constructive comments.

4.2 Choice of the reanalysis

As stated in the article, we checked that the choice of reanalysis did not influence the results. In order to do so, we compared NCEP with two other reanalysis datasets on the common period 1950-2010: 20CR (Compo et al., 2011) and ERA20C (Poli et al., 2016). The results of this comparison are displayed in Figure 4.4.

We can see that there is no major difference between those three reanalyses. We detect no significant trends. It could also be interesting to check results for longer time periods, since ERA20C starts in 1900 and 20CR starts in 1870. However, the confidence in the quality of the reanalysis decreases as we go back in time. As an example, Alvarez-Castro et al. (2018) have shown that the different members of 20CR are not consistent in their description of the dynamics of heatwaves before 1950. We have also found in the article that the signal gets clearer for a stronger climate change (from RCP4.5 to RCP8.5) so it is unlikely that we can capture a signal before 1950 for a very low level of anthropogenic emissions.

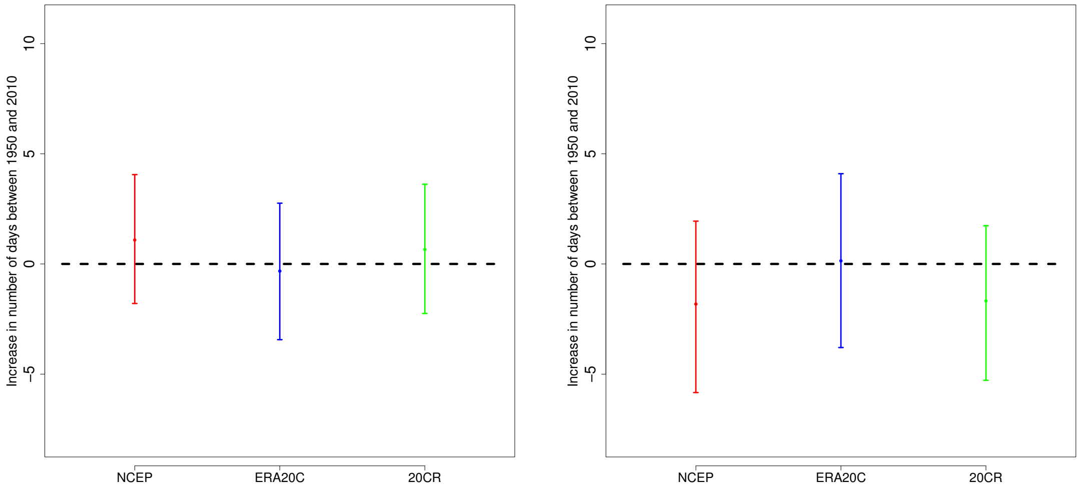
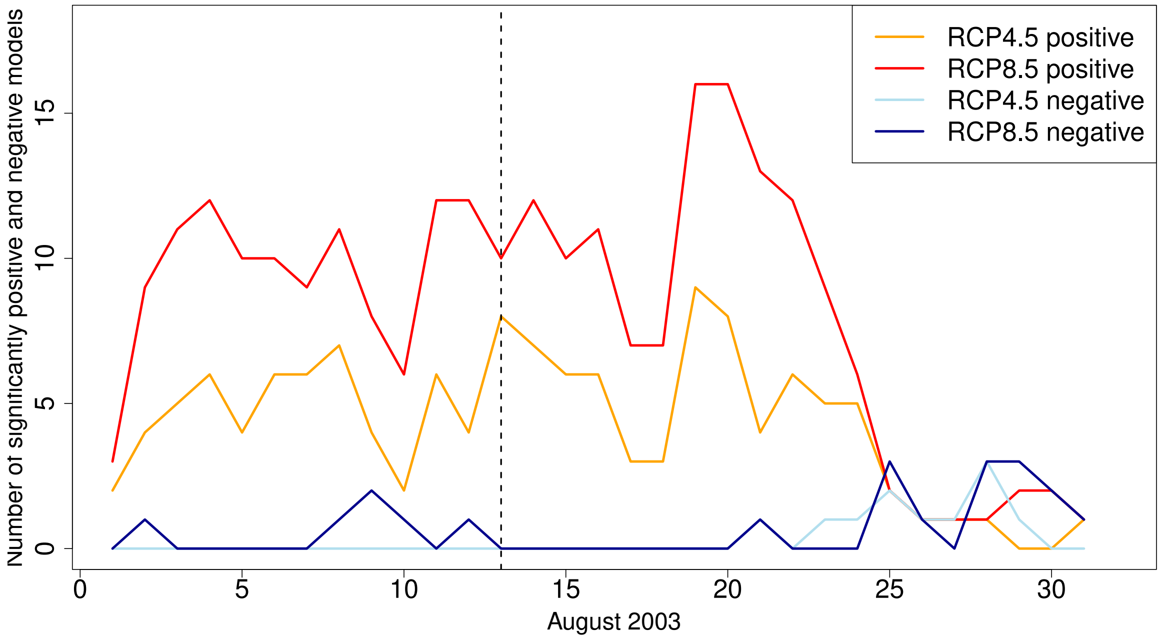


Figure 4.4 – Dynamical trends. Panels a and b display the modeled difference between the average number of days N_{end} and $N_{beginning}$ belonging to $D(Z^d)$ for NCEP (in red), ERA20C (in blue), and 20CR (in green) for the 1950–2010 period. The left panel is for August 13th 2003. The right panel is for August 7th 2010.

4.3 From one day to an event

The dynamical trends are calculated for single days. However, heatwaves last for several days. In particular, the two heatwaves we focus on last for several weeks. There were two heatwaves in Western Europe during summer 2003: one in June, and one in August (Stéfanon et al., 2012). In this article, we focus on the August 2003 heatwave. Its observed temperature anomaly (compared to the climatology of 1948–2016) over the WE region is positive from August 1st to August 30th. This anomaly is above one standard deviation of the calendar day temperature distribution between August 2nd and August 29th. For the 2010 heatwave, the observed temperature anomaly (compared to the climatology of 1948–2016) over the RU region is positive for the entire month of July, until August 20th. This anomaly is above one standard deviation of the calendar day temperature distribution between July 21st and August 16th.

In order to account for the durations of both heatwaves, we computed dynamical trends for each day of August 2003 and each day of July and August 2010. We plotted in Figure 4.5 (respectively 4.6) the evolution of the number of models and runs for which we find a statistically significant dynamical trend for 2003 (respectively 2010) over the 21st century. These figures are provided in the supplementary material of the article. As stated in the article, we deduce from them that August 13th 2003 and August 7th 2010 are typical of the whole heatwaves, and that the signal is stronger for RCP8.5 than RCP4.5, hinting at anthropogenic emissions as a possible cause of these significant trends.



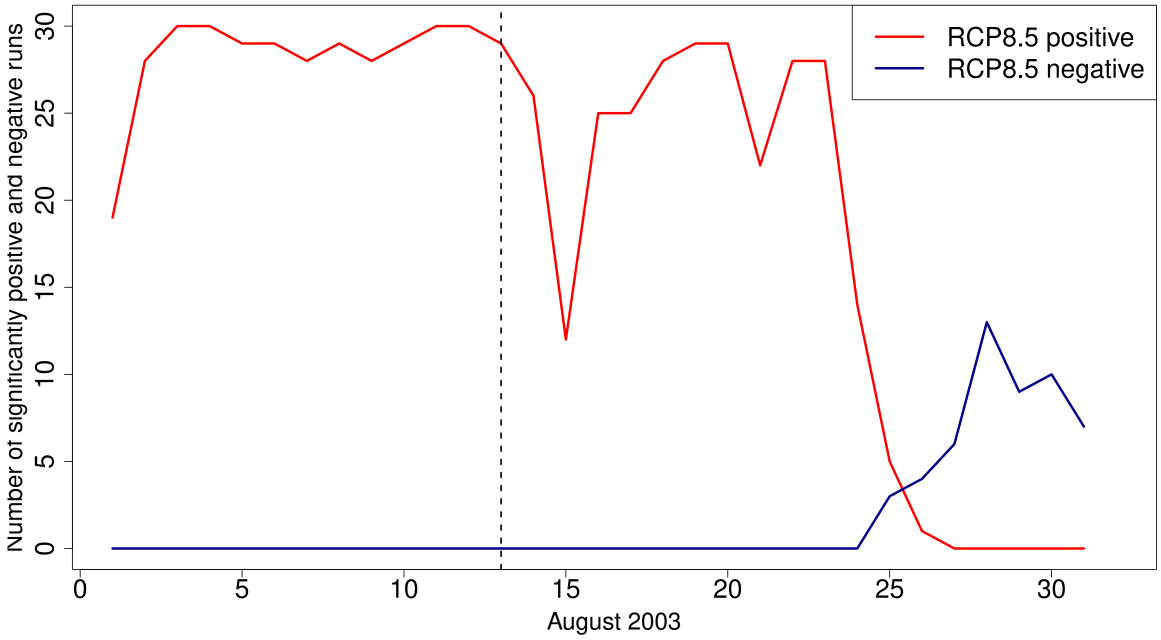
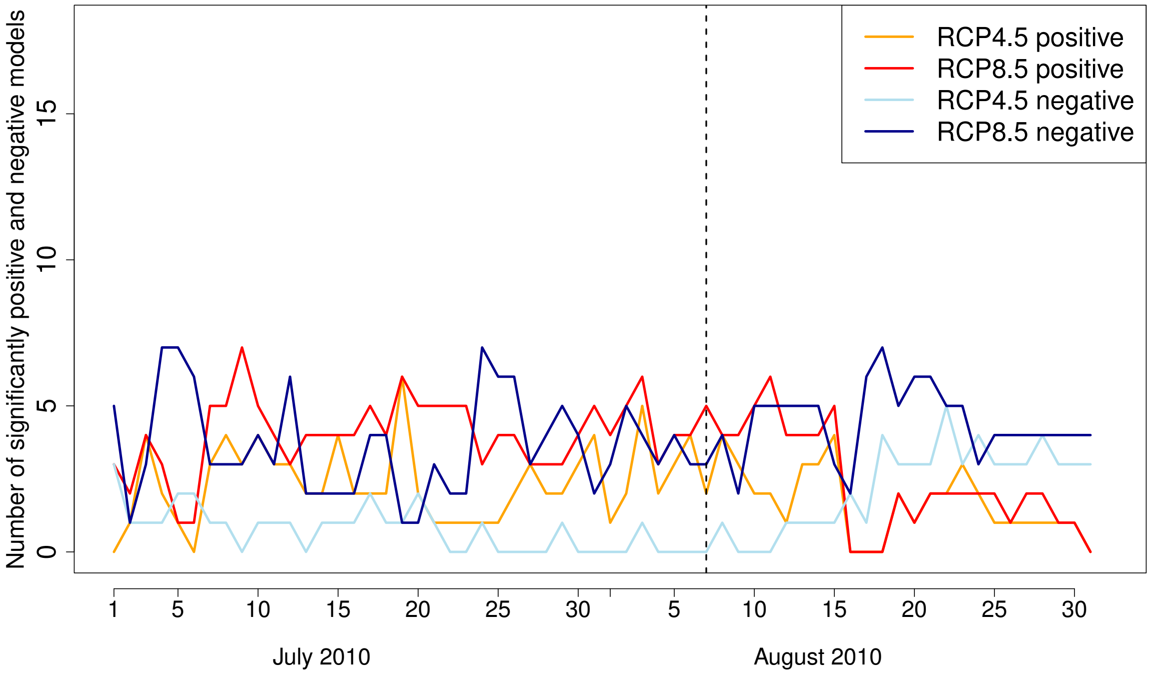


Figure 4.5 – Evolution of the number of CMIP5 models (upper figure) and CESM runs (lower figure) for which we find a statistically significant dynamical trend of August 2003 over the 21st century in the RCP4.5 and RCP8.5 scenarios. The dotted vertical line corresponds to August 13th, the hottest day of the heatwave studied in the main article. The red and orange lines correspond to positive trends. The blue and cyan lines correspond to negative trends.



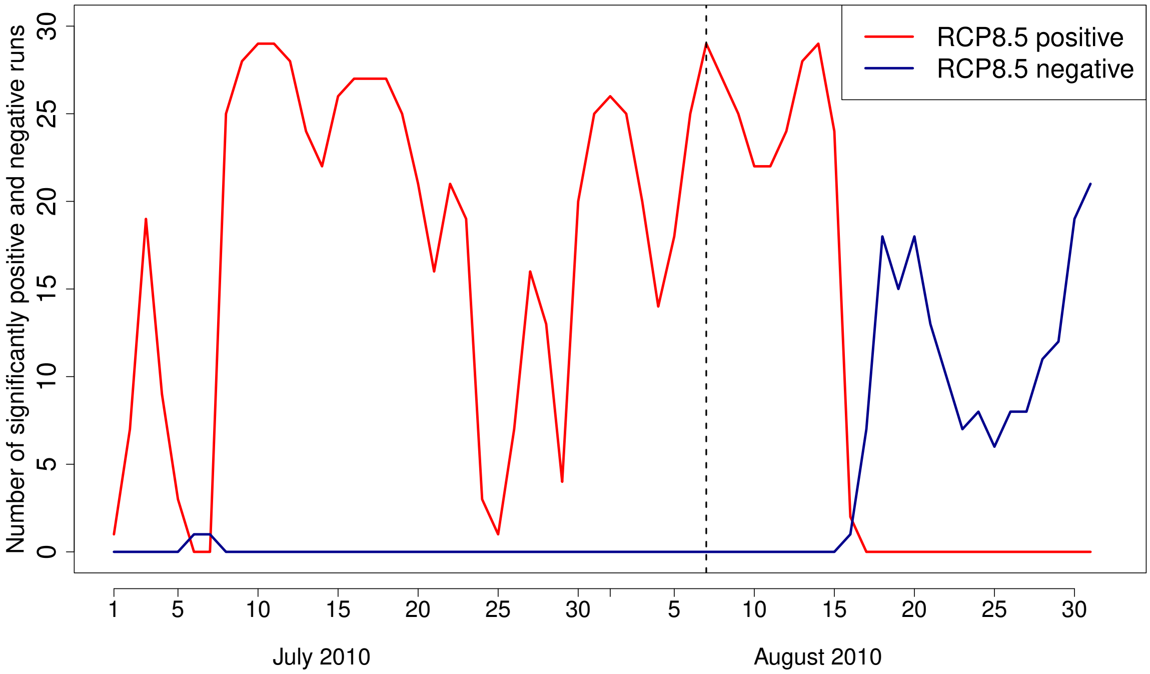


Figure 4.6 – Evolution of the number of CMIP5 models (upper figure) and CESM runs (lower figure) for which we find a statistically significant dynamical trend of July and August 2010 over the 21st century in the RCP4.5 and RCP8.5 scenarios. The dotted vertical line corresponds to August 7th, the hottest day of the heatwave studied in the main article. The red and orange lines correspond to positive trends. The blue and cyan lines correspond to negative trends.

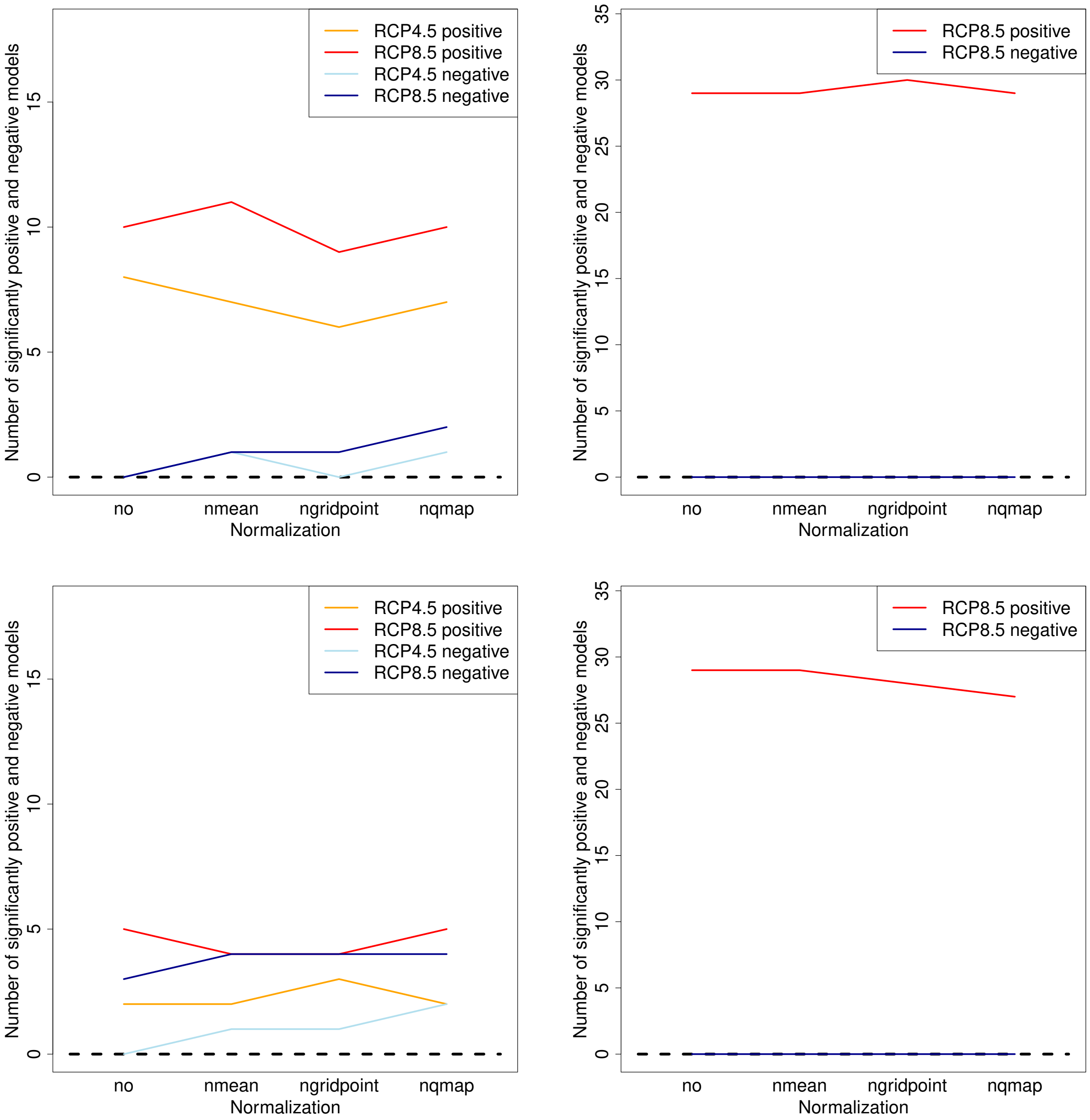


Figure 4.7 – Number of CMIP5 models (left panel) and CESM runs (right panel) for which we find a statistically significant dynamical trend over the 1950–2100 period in the RCP4.5 and RCP8.5 scenarios for a simple detrending (no) and 3 different normalizations (nmean, ngridpoint, and nqmap). The upper row corresponds to August 13th 2003 in Western Europe and the lower row to August 7th 2010 in Russia.

4.4 To correct the bias or not?

A large part of the work I did for this article was to test whether it was useful to correct biases in the Z500 time series. Indeed, the representation of circulation in models account for a large part of the uncertainty in climate change projections (Shepherd, 2014). The detrending of the Z500 fields is already a first bias correction, since all the means are set to 0 by this operation. Once this is done, there ought to be differences in the shape of the Z500 distribution depending on the model and run. Here the bias correction consists in a normalization of the models to a reference for a calibration period. In this case, the reference is the NCEP dataset and the calibration period is from 1950 to 2005 (the historical period for the CMIP5 models). The normalization is then applied for the rest of the time period. I tested three different ways to correct biases:

- a normalization (multiplication by the ratio of standard deviation $\frac{\sigma_{NCEP}}{\sigma_{model}}$) of the spatially averaged Z500 field (nmean in Figures 4.7,4.8 and 4.9),
- a normalization by gridpoint (ngridpoint),
- a quantile mapping (nqmap).

Figure 4.7 shows the number of CMIP5 models and CESM runs for each type of normalization, for which trends are significantly non zero. The results for the model ensemble are only marginally different. Indeed, the maximum difference between two different ways to bias correct is of two models in the CMIP5 ensemble and two runs in the CESM ensemble. For this reason we chose to keep the simplest bias correction, i.e. the simple detrending with no normalization. The ensemble results are similar for all methods of bias correction.

However, there can be differences in the dynamical trend value — or even sign — for a given model. Most of the models give almost the same result for each bias correction. We give the example of CMCC-CMS in figures 4.8 and 4.9. However, CNRM-CM5 gives very different results depending on the bias correction, as displayed in figures 4.8 and 4.9. This model is by far the model most sensitive to bias correction, as even the sign of the dynamical trend vary between no normalization and the nmean or nqmap bias correction. This would indicate that the standard deviation of CMCC-CM5 on the historical period differs compared to NCEP. The sensitivity to bias correction could be a possible way to evaluate how much one can trust a model.

The fact that it does not seem useful to bias correct further than a simple detrending at this point does not mean that we should exclude this possibility for future works. The number of studies in the literature dealing with the bias correction of fields associated with the atmospheric circulation is still very low compared to bias correction of temperature or precipitation (e.g. Christensen et al. (2008); Gudmundsson et al. (2012a); Maraun (2016)). One of the problems of bias correcting Z500 is that we are interested in patterns, which means that the variable of interest is necessarily multi-dimensional. For example, the ngridpoint bias correction could break down the spatial consistency of atmospheric patterns generated by the model. The recent development of multi-variate bias correction methods (e.g. Vrac (2018)) could pave the way for the bias correction of Z500 and/or SLP field and make the studies based on their evolution in models more robust.

4.5 Summary and conclusions

This chapter introduces a new methodology to calculate dynamical trends for specific daily circulation patterns at a local scale. This methodology was applied to two days corresponding to high temperature records: the hottest days of the 2003 heatwave in Western Europe and of the 2010 heatwave in Russia. Although we found no clear signal for 2010, approximately half the models of our ensemble detect a significant increase of the circulation pattern observed in

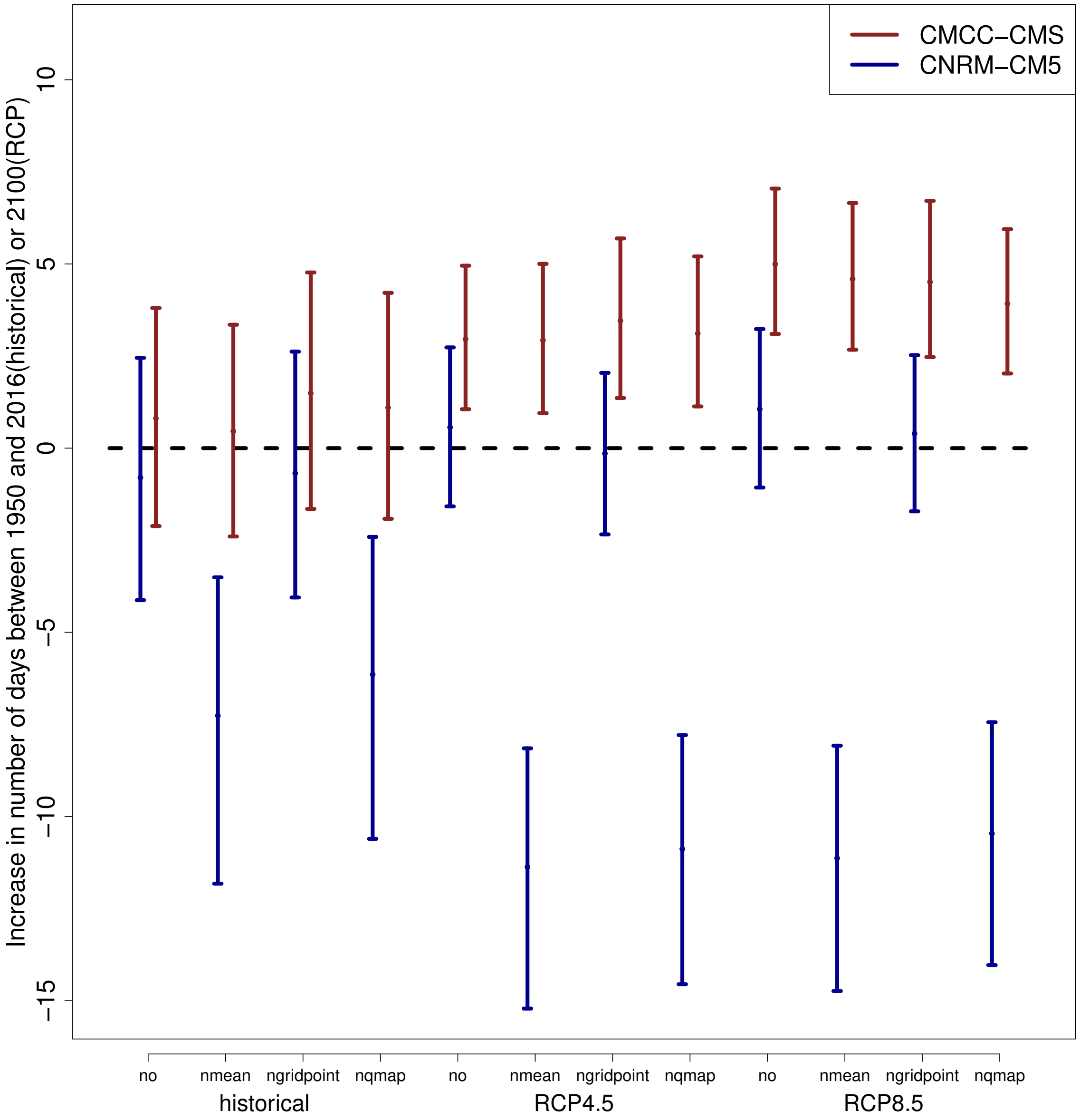


Figure 4.8 – Dynamical trends: modeled difference between the average number of days N_{end} and $N_{beginning}$ belonging to $D(Z^d)$ for CMCC-CMS (in brown), and CNRM-CM5 (in blue) for the historical, RCP4.5 and RCP8.5 experiments for August 13th 2003. Each experiment is displayed for a simple detrending (no) and 3 different normalizations (nmean, ngridpoint, and nqmap).

2003 for the 1950–2100 period.

An important feature of this study was to calculate dynamical trends for a large ensemble of datasets to evaluate the different sources of uncertainties on the result. We have not exploited the full possibilities of having an ensemble of models. For example, we only highlight statistically significant trends, although for 2003 there are also a number of models with non statistically significant positive trends, which go in the sense of the general result we found for this event. In fact, all the models display a positive trend for RCP8.5 except MIROC-ESM for which the trend is negative (not significantly). Being not statistically significant does not mean

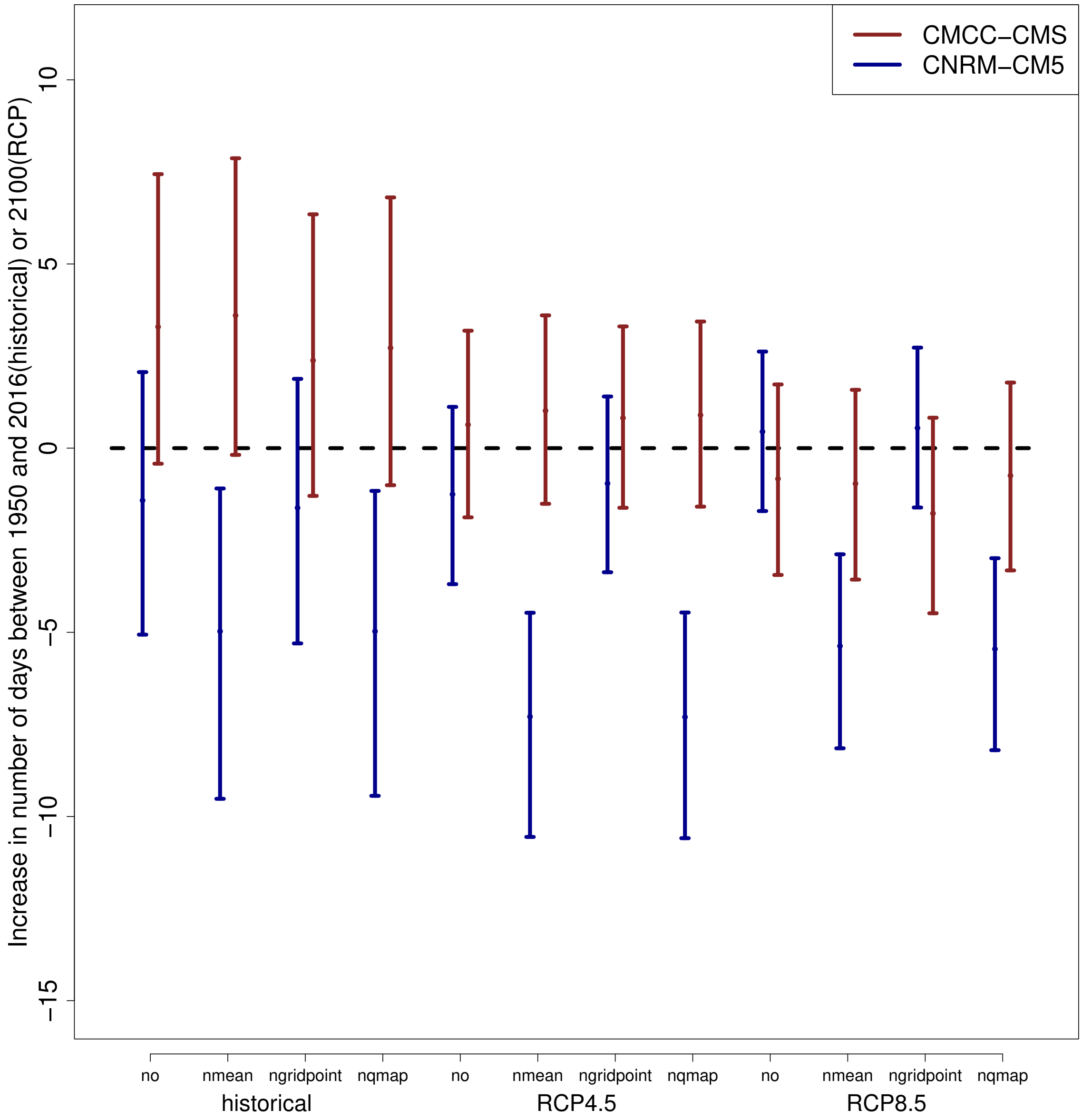


Figure 4.9 – Dynamical trends: modeled difference between the average number of days N_{end} and $N_{beginning}$ belonging to $D(Z^d)$ for CMCC-CMS (in brown), and CNRM-CM5 (in blue) for the historical, RCP4.5 and RCP8.5 experiments for August 7th 2010. Each experiment is displayed for a simple detrending (no) and 3 different normalizations (nmean, ngridpoint, and nqmap).

that these trends are meaningless. First, the significance depends of the level chosen for the test (here 5%) and the number of significant models could vary for a different level. Second, the non-significant results become interesting when there are multiple tests (like here with several different models). For example if we had two statistically significant positive trends, and 16 non-significant positive trends, we would still have a meaningful signal, against the hypothesis that there is negative trend. There is still work to do to propose a significance index based on the ensemble of results, rather than several significance indices for each model/run.

By calculating daily trends for each day of both heatwaves, we managed to generalize the results from one day to a whole event. The main perspective of this methodology is to calculate dynamical trends for all days of the reanalysis in a given region. This will allow us to identify which types of circulation pattern are affected by climate change. Another step would be to link these days with a changed frequency with other variables like precipitation or temperature, to see if circulation patterns leading to extremes become more or less likely, or at the contrary if non extreme days become rarer or more frequent. Finally, this analysis could be applied to different regions, in order to understand how the effects of climate change on circulation could differ at a local scale, possibly in relation with physical processes.

Résumé

Contexte et objectifs

La circulation atmosphérique explique en partie l'occurrence des canicules européennes (chapitre 3). L'influence du changement climatique sur la circulation atmosphérique dans les moyennes latitudes est un sujet de débat dans la communauté scientifique. Ce chapitre propose d'évaluer comment le changement climatique perturbe la probabilité d'occurrence de circulations atmosphériques similaires à celles observées lors de canicules historiques.

Méthodes et données

Ce chapitre présente le concept de *tendance dynamique*. On commence par calculer l'ensemble des distances entre les cartes de géopotentiel à 500 hPa (Z500) des jours estivaux (Juin-Juillet-Août) d'un jeu de données et la carte de Z500 associée à un jour de canicule. On sélectionne ensuite l'ensemble des jours en-dessous du cinquième quantile de la distribution de ces distances. Ce sont les analogues de circulation du jour d'intérêt. Enfin, on compte le nombre d'analogues par an. La tendance dynamique est calculée à l'aide d'un modèle linéaire généralisé adapté à la forme de la distribution du nombre annuel d'analogues (Figure 4.1).

Ces tendances dynamiques sont calculées pour plusieurs jeux de données : les réanalyses NCEP, un ensemble de modèles CMIP5 (18 modèles), et le grand ensemble du modèle CESM (30 membres). L'utilisation de modèles permet de calculer les tendances dynamiques pour une période prolongée, entre 1950 et 2100. Les différences entre modèles permettent d'évaluer l'incertitude liée au choix du modèle, tandis que les différences entre les membres d'un même modèle reflètent les incertitudes liées à la variabilité interne.

Résultats

Les tendances dynamiques sont calculées pour les deux vagues de chaleur les plus importantes de la période pour laquelle nous disposons de données : Août 2003 en Europe de l'Ouest et l'été 2010 en Russie (Figure 4.3). S'il est impossible de détecter une tendance significative pour la période historique ou dans le jeu de réanalyses à cause de la trop forte variabilité interne, plus de la moitié des modèles trouvent une tendance significative pour le cas de 2003. L'ensemble des modèles ne produisent pas de signal clair pour 2010. Ces résultats calculés pour le jour le plus chaud de chaque canicule restent sensiblement les mêmes pour l'ensemble des jours de chaque canicule.

Chapter 5

Influence of climate change on European heatwaves for a given circulation pattern

The previous chapter tackled the question of the influence of climate change on circulation patterns leading to European heatwaves. The present chapter deals with the influence of climate change on the intensity of European heatwaves for a fixed circulation pattern. Cattiaux et al. (2010) used analogues to show that the winter 2010 cold spell would have been even colder in the past for the same circulation pattern, implying that climate change made the cold spell warmer. I propose hereafter several analogue-based methodologies to complement this first type of qualitative approach.

The first idea I tested was to compute uchronic temperatures as introduced in chapter 3 for different subperiods, corresponding to different levels of climate change. This led to the publication of an article in the special report of the BAMS Explaining Events of 2016 from a Climate Perspective on the warm December 2015 in France. Since we showed in chapter 3 that we need long time series to constrain the uncertainties related to internal variability on the uchronic temperature distributions, we relied on a large ensemble of a single coupled climate model to get a long enough dataset. I applied a similar methodology for an article I coauthored on the 2015 Central European drought (see Appendix E), which I develop in this chapter.

I will introduce later two other ways to detect the influence of climate change on uchronic temperatures. Thermodynamical trends are trends on temperature for a given type of circulation. The residual trend is the remaining trend once the general trend (without fixed circulation) is subtracted from the thermodynamical trend. I discuss the meaning of both types of trends and calculate them for the same days of interest than the one studied in chapter 4: August 13th 2003 and August 7th 2010.

5.1 Article published in the *BAMS* special report *Explaining Events of 2016 from a Climate Perspective*: Analysis of the exceptionally warm December 2015 in France using flow analogues

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5.1.1 Abstract

December 2015 in France was an extreme of circulation and temperature. Both circulation and climate change partly explain the 4°C anomaly. We found no link between climate change and circulation.

5.1.2 The event

The December 2015 average temperature broke a record in France, with an anomaly of +4.1°C (Fig. 1a) with respect to the 1949-2015 climatology. The linear trend of average December temperature (in red in Fig. 1a) is not significant ($p\text{-value} > 0.05$), as regional temperature variability is high in winter. Such a positive temperature anomaly has impacts on the vegetation cycle (the French press covered this topic in the daily newspaper Le Monde[2]). It also affects local economies, e.g. tourism in ski resorts. The temperature anomaly was concomitant with a zonal atmospheric circulation over Western Europe (Fig. 1b), directing mild subtropical air masses towards France. We found that the mean monthly SLP (sea level pressure) anomaly over the black box of Fig.1b is also a record high for the NCEP reanalysis. Such a circulation type generally leads to warm temperatures overs France (Yiou and Nogaj, 2004).

In this paper we seek to address three questions: How much does the circulation anomaly explain the temperature anomaly during December 2015 in France? What is the influence of climate change on the occurrence of the circulation anomaly? How does the distribution of temperature conditional to the atmospheric circulation evolve with climate change? We hence perform a conditional attribution exercise (on Extreme Weather Events and Attribution (2016), p. 30), with a circulation that is fixed to the observation of December 2015. This estimates the thermodynamic contribution of climate change on the increase of temperature (Vautard et al., 2016; Yiou et al., 2017).

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[2] `http://abonnes.lemonde.fr/biodiversite/article/2015/12/30/la-nature-deboussolee-par-un-hiver-tres-doux_4839801_1652692.html?xtmc=temperature&xtcr=1`

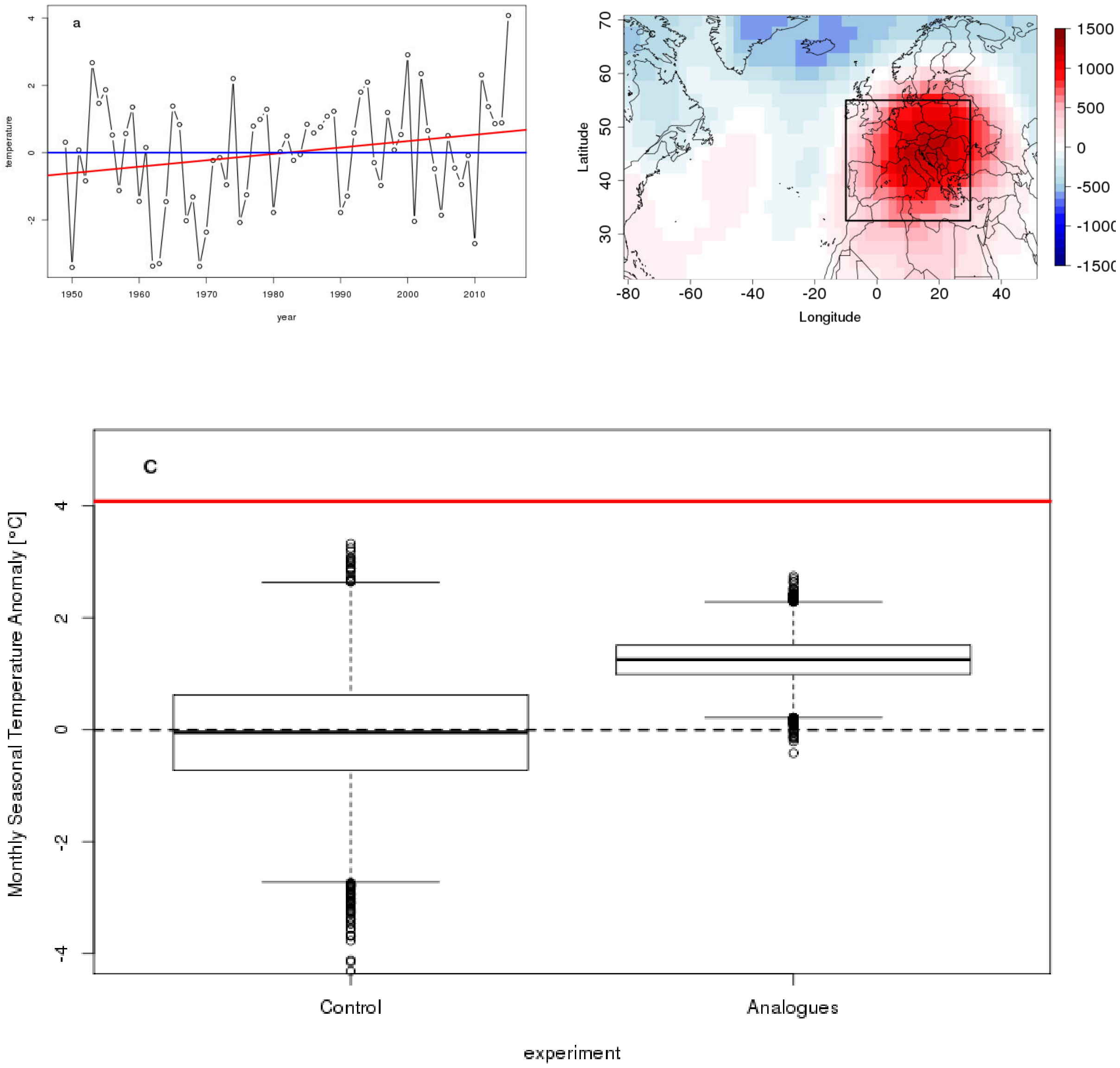

Figure 5.1 – Evolution of the French national temperature index for the month of December between 1949 and 2015. The red line is the (non significant) linear trend. (b) SLP anomalies for December 2015 relative to the 1949–2015 average of the NCEP Reanalysis I dataset (Kalnay et al. 1996). (c) Comparison of uchronic monthly seasonal anomalies of the national index distribution for randomly picked days (Control) and randomly picked analogues. The red line is the observed temperature anomaly (+4°C). The three lines composing the boxplots are respectively from bottom to top, the 25th (p25), median (p50) and 75th percentile (p75) of the uchronic temperature anomaly distribution. The value of the upper whiskers is $min(1.5(p75 \pm p25) + p50, max(temperatureanomaly))$. The value of the lower whiskers is its conjugate. The circles represent the values that are outside of the whiskers.

5.1.3 Flow analogues and the role of circulation

We evaluated the link between the SLP anomalies over the black box in Fig. 1b and temperature in France using the method of flow analogues (Yiou et al., 2017). We considered the French national temperature index supplied by Météo France (Soubeyroux et al., 2016). This daily index is computed as the average of 30 stations distributed over France and starts in 1949. We use temperature anomalies with respect to a daily seasonal cycle obtained by spline smoothing (cf. Yiou et al. (2008)). The circulation proxy is the SLP from the National Centers for Environmental Predictions (NCEP) reanalysis, between 1949 and 2015. For each day of December 2015 we identified the 30 best analogues of SLP (with a Euclidean distance) from 1949 to 2015 on the domain delimited by the black rectangle in Fig. 1b. Jézéquel et al. (2017) showed that the results on analogues are qualitatively insensitive to the number of analogues (between 5 and 30 analogues). We simulate daily sequences of SLP by randomly picking one of the 30 best analogues within the NCEP dataset for each day. The repetition of this random selection (with replacements) builds an ensemble of uchronic months. Those uchronic months reproduce the SLP anomaly of December 2015 (see Fig. S1a-d in Supplementary Material). We then compute monthly averages for December of the national temperature index. We hence obtain uchronic French seasonal anomalies of temperature for December. We iterated this process 104 times in order to produce uchronic probability distributions of monthly mean temperatures (see Jézéquel et al. (2017) for more details). This uchronic distribution of temperatures represents the ensemble of temperatures that could have been expected for the circulation observed in December 2015. We compared the uchronic distribution of temperature anomalies to a distribution built from randomly picked December days. In Fig. 1c, the Control experiment corresponds to a monthly average of the daily temperature anomalies from the 104 random samples without conditioning on the atmospheric circulation. In order to take into account the dependence between consecutive days in the Control distribution, we calculated the monthly means using only every third day (Jézéquel et al., 2017).

We find that the SLP partly explains the monthly temperature anomaly in France during December 2015 (Fig. 1c). The median of the uchronic temperature anomaly distribution is 1.3°C, i.e. $\sim$30% of the anomaly. The other $\sim$70% of the anomaly could be explained by other factors (e.g. snow cover feedback). This positive anomaly demonstrates the link between the synoptic situation and the anomaly of temperature in France, and justifies the choice of a conditional attribution approach.

5.1.4 Role of climate change

In order to estimate the role of climate change we rely on the CESM1 model large ensemble (Kay et al., 2015). We use 30 members for both surface temperature and SLP using historical runs between 1951 and 2005 and RCP8.5 between 2006 and 2100. We reconstitute the French national temperature index from the surface temperature using the coordinates of the 30 stations used to calculate the index. Kay et al. (2015) showed that CESM-LENS reproduces reasonably well features of the Northern Hemisphere atmospheric circulation. An analysis of the SLP distances between those observed during December 2015 and CESM simulations indicates that they are not statistically different from the NCEP reanalysis (Fig.S1e in the Supplementary material). We hence consider that this model does not yield biases that prevent its use for the purpose of this study.

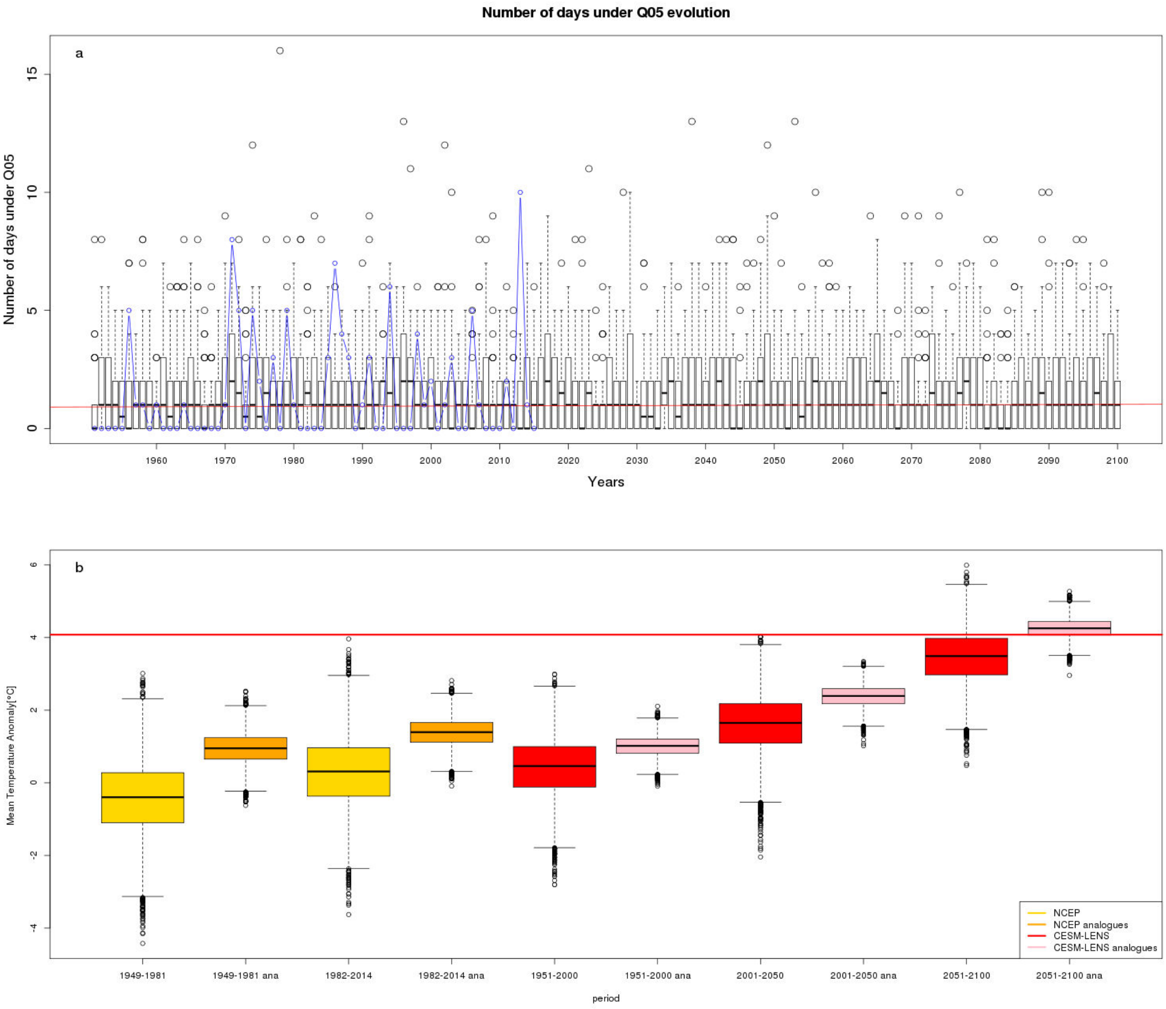

Figure 5.2 – (a) Number of days per year with SLP distances below the 5th percentile of the distribution of daily distances to the closest December 2015 day. The boxplots show the dispersion of CESM ensemble members. The blue lines-dots are the values for the NCEP reanalysis. The red line is the (non significant) linear trend of the median of the CESM ensemble members. (b) Boxplots of the distributions (respectively uchronic distributions) of anomalies of the national temperature index relative to the observed climatology of this index between 1948 and 2015, in yellow (orange) using NCEP and in red (pink) using CESM-LENS subsets.

We estimate the influence of climate change on the circulation pattern leading to December 2015 by computing the probability distributions of distances between SLP anomalies among all the December days in both NCEP and CESM and the closest day of December 2015 (Fig. 2a). We keep only the distances below the 5th percentile of the distribution, in order to focus on the days with SLP anomalies closest to those observed in December 2015. For each December, we count the number of days below this threshold for each ensemble member (NCEP and CESM). If the circulation that prevailed in December 2015 became more frequent with time, then a trend should be detected in this number of days. We detect no such trend. Therefore it is not possible to conclude there is an impact of climate change on the atmospheric circulation itself.

We then estimate the temperature anomaly for a similar event in terms of synoptic circulation without climate change, and in future climate change scenarios by computing analogues of circulation from different periods of observations and CESM simulations. We analyzed the uchronic temperature anomalies constructed with analogues of the December 2015 flows from two time periods of the NCEP dataset. We compared an early subset of 33 years (1949-1981) to a more recent one (1982-2014). The two gold boxplots in Fig. 2b represent those two experiments. We detected a difference of 0.4°C between the two distributions, in contrast with the monthly temperature trend for 1949-2015 displayed in Fig. 1c, which is not significant. However, it is not possible to attribute this difference of temperature to climate change, as it could also relate to interdecadal variability, especially for very small subsets of 33 years, whose length was imposed by the NCEP reanalysis length.

In order to study the relative influences of climate change and variability, we rely on CESM-LENS. We study three periods of 50 years: 1951-2000, 2001-2050, and 2051-2100. Using 30 members, we have 1500 years of data for each sub-period from which we can calculate the analogues (which correctly represent the observed SLP anomaly as displayed in the supplementary material Fig. S1a-d). This reduces the uncertainty related to the quality of the analogues we picked. The three pink boxplots in Fig. 2b represent the uchronic distributions for SLP analogues picked from CESM-LENS. The three red boxplots represent the control distributions for the same sub-periods. We observe that the December 2015 anomaly of temperature was never reached before 2000. It is still not reached for 2001-2050 under the RCP8.5 scenario. For the second half of the 21st century the temperature anomaly is expected to exceed 4°C for the same synoptic situation. The observed anomaly is still warmer than the median of the control distribution. A caveat of this study is that we only used one model, which could have biases especially in the future.

5.1.5 Conclusion

The month of December 2015 set a record temperature in France. The zonal circulation that prevailed over Western Europe during the whole month accounts for $\sim$30% or 1.3°C of the temperature anomaly. No trend was found in the atmospheric circulation patterns themselves (Fig. 2a). For this given circulation, our analysis shows that the observed temperature is never reached in the second half of the 20th century (Fig. 2b), and the model is unable to reach it even during the first half of the 21st century. However, the December temperature observed in 2015 is projected to be exceeded in the second half of the 21st century under the same synoptic situation. Cattiaux et al. (2010) found with a similar analysis that the cold winter of 2009/2010 would have been colder if not for climate change. Our analysis of December 2015 is a warm counterpart to that study. We find a 1.4°C difference between the median of the uchronic temperatures of the second half of the 20th century and the first half of the 21st century and an additional 1.9°C for the second half of the 21st century. We find approximately the same differences between Control distribution medians, which means that the trend conditional to the circulation equals the unconditional trend.

5.1.6 Acknowledgements

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5.2 Model evaluation

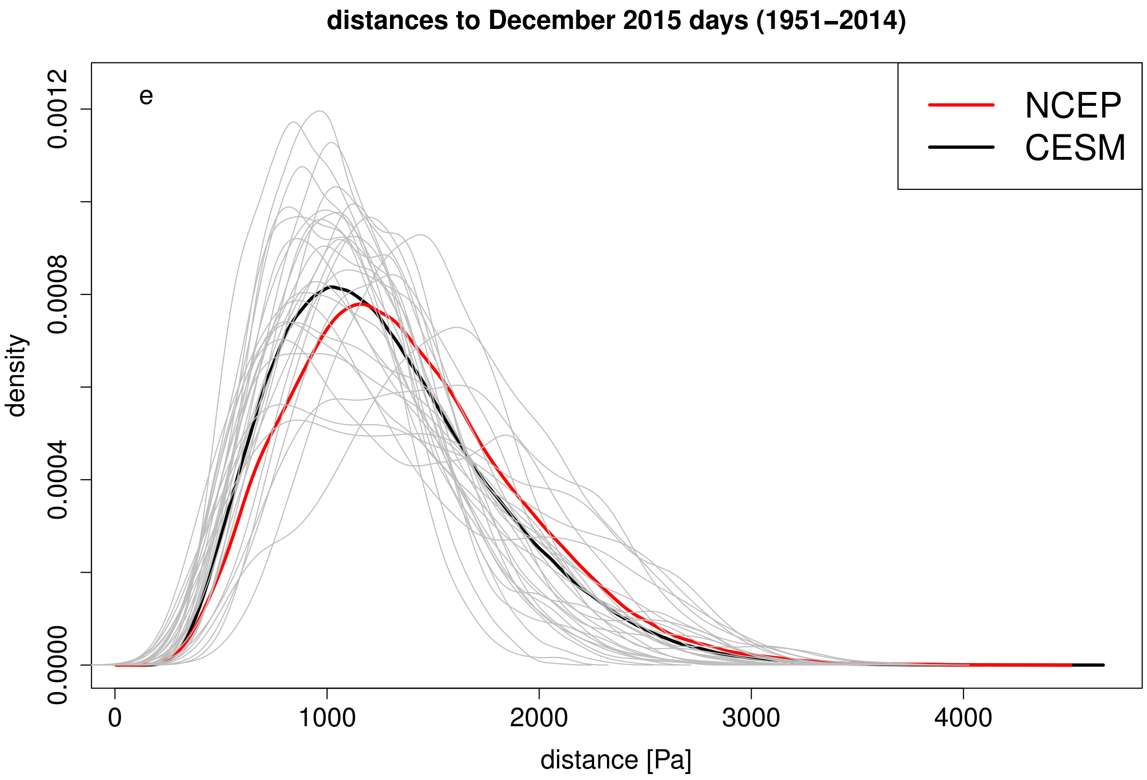

Figure 5.3 – Probability density function of daily distances of SLP anomalies (Pa) between 1951 to 2014 to NCEP SLP anomalies of Dec 2015. Distances between NCEP and Dec 2015 (red); between CESM and Dec 2015 (black); between each ensemble member and Dec 2015 (gray).

We have tested the adequacy of the CESM model to reproduce circulations similar to December 2015. In Figure 5.3 we plot the probability density function (PDF) of daily distances to the SLP of December 2015 from the NCEP dataset. Those distances are calculated for all the December days between 1951 and 2014 for both CESM and NCEP SLP. The black line represents the PDF for the CESM multimodel ensemble; the gray lines represent individual members. The red line represents the PDF for NCEP. The NCEP distance distribution remains within the spread of the individual members distributions, hence we cannot distinguish NCEP from CESM due to internal variability.

Another important variable for our study is the temperature. It seems that the CESM ensemble is unable to recreate as strong a temperature anomaly as the one observed in December 2015. This calls for further studies to understand why CESM has a bias in its representation of extremely high winter temperature in Western Europe. This bias does not necessarily mean that the model cannot reproduce how the shift of the distribution of temperature with climate change but it is an important caveat of our methodology.

5.3 Another example: the 2015 European drought

As part of my PhD, I participated to the European project EUCLEIA (EUropean CLimate and weather Events: Interpretation and Attribution). EUCLEIA meant to develop an operational event attribution system for Europe. One of the work packages aimed at attributing case studies of European extreme events with a multi-method approach. I participated to the case study on the 2015 drought in central Europe, which led to a publication by Hauser et al. (2017) (see Appendix E). The precipitation anomaly was the lowest in this region, since the beginning of observations.

We used a similar approach to the one developed in Jézéquel et al. (2018) for temperatures, applied here to precipitation. For each day of June–July–August(JJA) in 2015, we compute analogues of circulation from the detrended Z500 NCEP dataset, between 1950 and 2015. The daily analogues consist of the 30 closest days (using the Euclidean distance) within 30 calendar days of the day of interest. The circulation analogues were computed over a central European region (0°W to 30°W and 30°N to 60°N). This region was determined iteratively to obtain the cumulated precipitation anomaly distribution closest to the observed anomaly.

We then compute uchronic cumulative seasonal precipitation anomalies, to simulate precipitation during a summer that could have been, given the circulation of JJA 2015. We use the E–OBS dataset (Haylock et al., 2008) for precipitation. We iterate this process 1000 times to create a distribution of possible summer cumulative precipitation. This cumulative precipitation is spatially averaged over the Central European region defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (see Figure 3.1 p.123 of Seneviratne et al. (2012)). We can see in Figure 5.4 that the circulation explains approximately two third of the observed anomaly of precipitation.

To see if we pick a climate change signal for a fixed circulation pattern on the observational record, we select analogues of JJA 2015 in two sub-periods: 1951–1982 and 1983–2014. We detect no change in precipitation distribution between the two periods (Figure 5.4). This result does not prove that there is no change, since we only have very small subperiods, which means that internal variability could hide any influence of anthropogenic climate change. The ensemble of methods used in Hauser et al. (2017) lead to contradicting results regarding the influence of climate change on this specific event. This shows how the influence of the choice of methodology and of model can play a crucial part in the results, especially for events with low signal-to-noise ratios, like droughts.

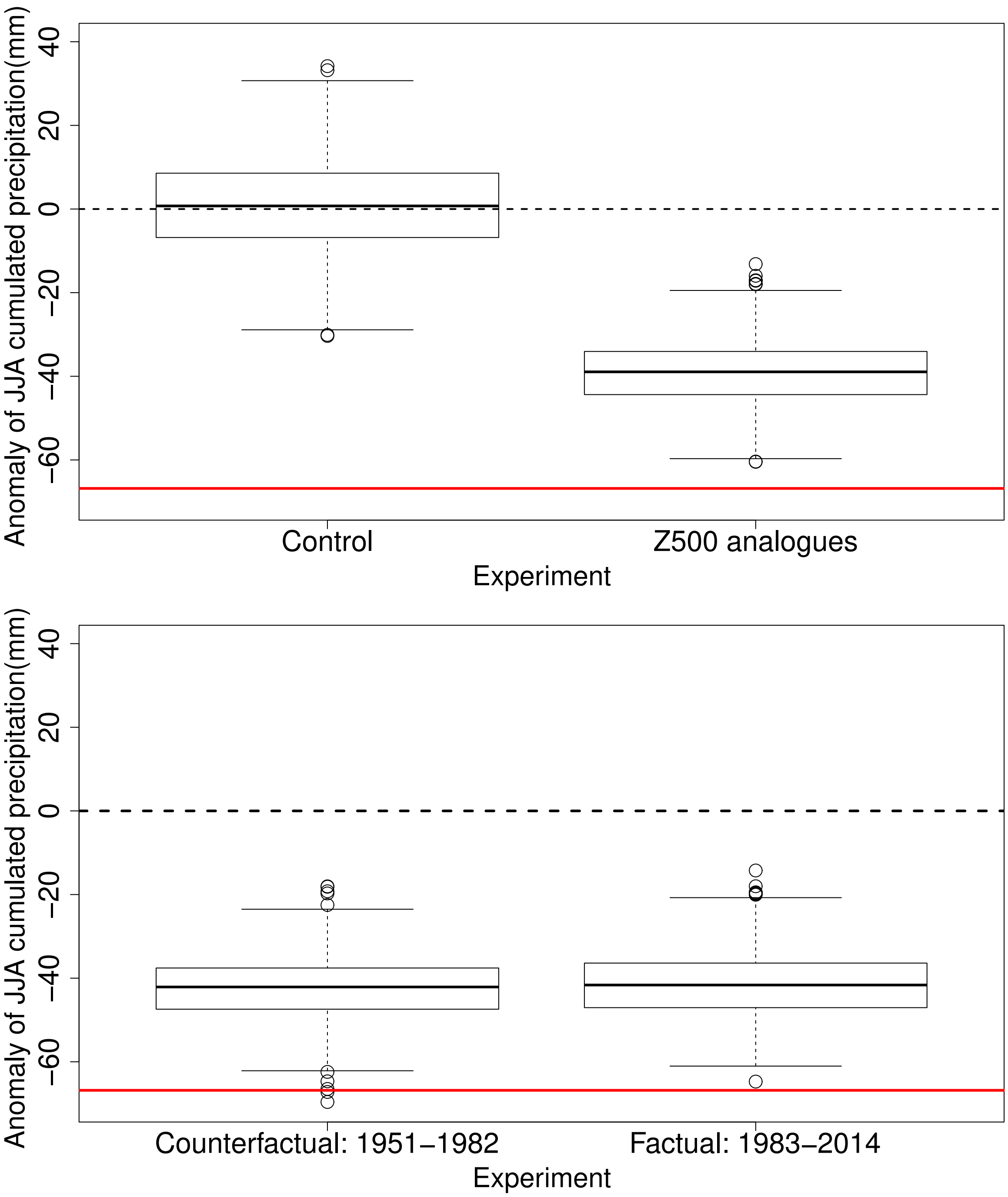

Figure 5.4 – Upper panel: comparison of uchronic monthly seasonal anomalies of the national index distribution for randomly picked days (Control) and randomly picked analogues. Lower panel: comparison of uchronic monthly seasonal anomalies of the national index distribution for randomly picked analogues in two subperiods: 1951–1982 and 1983–2014. The red line in both plots is the observed temperature anomaly (+4°C).

5.4 Thermodynamical trends

5.4.1 Concept and methodology

The results presented in this chapter have relied on the comparison of different subperiods representing different levels of anthropogenic climate change. This allows comparing a *counterfactual* world — defined as a past period — to a *factual* world — defined as a more recent, or even as a future period. However, emissions of greenhouse gases accumulate progressively in the atmosphere and climate changes continuously. Limiting ourselves to two subperiods means that we lose part of the information contained in the studied dataset. Here, I propose to study the evolution of thermodynamics for a fixed circulation state, by calculating *thermodynamical trends*, which complement the dynamical trends introduced in chapter 4.

The thermodynamical trends are computed for the circulation of a single day of interest. The two case studies chosen here are the same as for dynamical trends: 13th August 2003 in Western Europe and 7th August 2010 in Russia. The first step is to select analogue days in the same way as we did for dynamical trends. We define the analogues by all the days with a distance to the circulation of the day of interest below the 5th percentile of the distribution of summer days distances to the day of interest. The datasets used are also the same as for dynamical trends (NCEP, 18 models from CMIP5 and 30 runs from CESM).

From those analogue days, I deduced times series of deseasonalized daily temperatures. These temperatures are averaged over the WE region (-5°W to 20°W and 36°N to 50°N) defined by Jézéquel et al. (2017) for 2003 and over the part of Russia that suffered the most of the 2010 heatwave (35°W to 55°W and 50°N to 60°N) defined by Dole et al. (2011). The seasonal cycle was calculated with a cubic smoothing spline computed on the daily calendar day average for each dataset. The deseasonalization allows us to filter the difference in temperature between analogues picked for days at the beginning, in the middle or at the end of the summer. By doing this, we possibly ignore any possible changes of seasonality in the occurrence of analogues, which could have an influence on thermodynamical trends. A few studies hint at changes of the seasonality of atmospheric circulation over Europe (Cassou and Cattiaux, 2016; Vrac et al., 2014). A limit of this study in regards to seasonality is the systematic picking of analogues in JJA, while the calendar days which could correspond to summer are shifting because of climate change. For a first order approach of thermodynamical trends, I prefer to filter this signal through the temperature deseasonalization.

The thermodynamical trends are calculated using a simple linear regression of deseasonalized daily temperatures over time. I calculated the regression coefficient and a 95% confidence interval for each dataset and each experiment.

5.4.2 Results

Figure 5.5 displays the regression coefficients of thermodynamical trends in °C by decade for both August 13th 2003 and August 7th 2010. Most of the thermodynamical trends are significantly positive. For 2003, the NCEP thermodynamical trend is significantly positive. 15 out of 18 CMIP5 models and all the CESM runs are able to reproduce this result, although they tend to overestimate the value of the thermodynamical trend. The trends computed for CMCC-CM and bcc-csm1-1 are not significant, and significantly negative for MIROC-ESM.

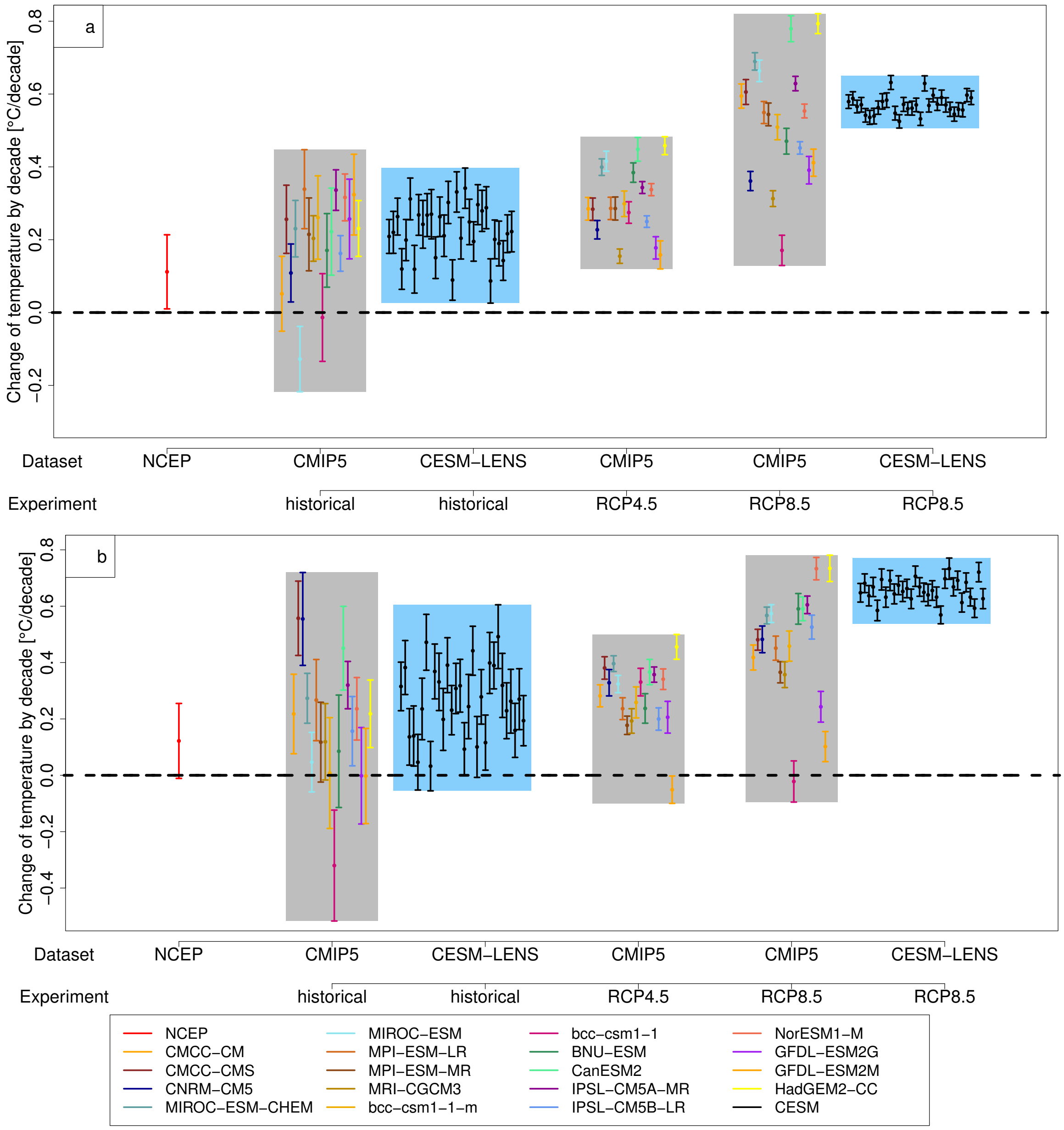

Figure 5.5 – Thermodynamical trends. Panels a and b display the regression coefficient of the analogue temperatures in function of time for NCEP (in red), CMIP5 (bars in gray shaded areas) and CESM (bars in blue shaded areas), for the historical, RCP4.5 and RCP8.5 experiments. Panel a is for August 13th 2003. Panel b is for August 7th 2010.

The NCEP thermodynamical trend for 2010 is not significant. However, it is very close to being significant and the difference between 2003 and 2010 thermodynamical trends in the reanalysis is very small. This shows that the significance criteria may not be the best to sort these trends and calls for more work to describe them better. A possible option would be to sort them by p-values. The spread of thermodynamical trends for both the CMIP5 and the CESM ensemble is larger than for 2003, possibly pointing to a larger role of internal variability in the RU region.

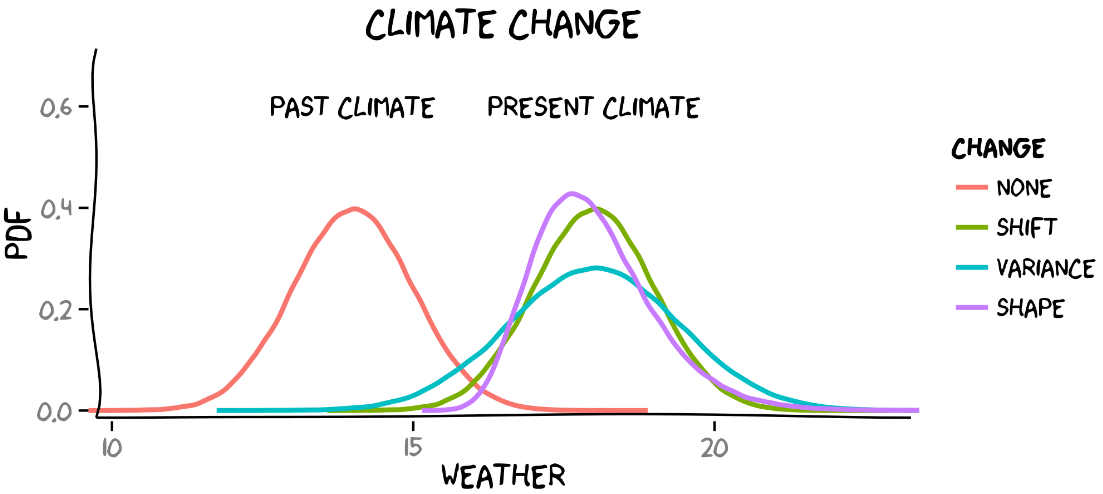

Figure 5.6 – Different possibilities of changes of temperature distribution due to anthropogenic emissions. Inspired from figure 1.8 of the IPCC AR5. Credits to Soulivanh Thao.

The confidence intervals of each model and the internal variability between CESM runs drop for the 1950–2100 period. For 2003, the trends are all significantly positive, approximately between 0.2 and 0.5°C by decade for RCP4.5 and between 0.2 and 0.8°C by decade for RCP8.5. All the trends increase between RCP4.5 and RCP8.5 except for bcc-csm1-1. For 2010, the trends are all significantly positive except for GFDL-ESM2M for RCP4.5 and bcc-csm1-1 for RCP8.5. They are between -0.1 and 0.5°C by decade for RCP4.5 and between -0.1 and 0.8°C by decade for RCP8.5.

5.4.3 Discussion

Since the thermodynamical trends are stronger than the dynamical trends, it is already possible to detect a significant trend with the historical period only. The internal variability between the different runs of CESM is twice smaller than the spread between different models. This allows the evaluation of models through a comparison with the reanalysis dataset. For example, MIROC-ESM for 2003 and bcc-csm1-1 for 2010 seem to be unreliable. There is a possibility that they do not reproduce well the evolution of the relationship between atmospheric circulation and temperature. This also raises the problem of bias correction of the temperature datasets. I did not have the time to test how different ways to bias correct temperatures influence the results during my PhD but it is a direction I would like to explore to calculate more robust thermodynamical trends.

5.5 Residual trends

5.5.1 Concept and methodology

The computation of thermodynamical trends gives us an idea of the evolution of temperature for a given circulation. It is intuitive to find positive thermodynamical trends as the signal-to-noise of the temperature elevation is high. However, it does not tell us if these trends are equivalent to the normal regional temperature trends, or if fixing the circulation has an influence. This relates to possible changes in the shape of the temperature distribution. We know that anthropogenic emissions have increased and are bound to continue to increase global and regional mean temperatures, but the change in variance and shape of the temperature distribution are less clear (e.g. Christidis et al. (2011); Fischer and Schär (2008); Fischer et al. (2012); Nogaj et al. (2006); Schär et al. (2004); Zwiers et al. (2011)). Figure 5.6 summarizes the different ways climate change could alter the temperature distribution. We have seen in chapter 3 that the uchronic distribution for a given circulation corresponds to a smaller part of the whole temperature distribution. What we want to understand here is whether the uchronic distribution stays at the same place in the future distribution as in the present distribution. In other words, does the circulation leading to extreme temperatures in the present lead to less, similarly or more extreme temperatures in the future?

In order to extract this information from thermodynamical trends we calculate *residual trends*. The residual trend is the remaining trend for a given circulation once the regional trend is withdrawn. We calculate regional trends for August 13th 2003 and August 7th 2010 on the WE and RU region from the series of mean summer temperatures over both regions. These trends are computed using a cubic smoothing spline. We subtract these trends from the daily analogue temperature series, and then we compute linear trends of detrended daily analogue temperatures in function of time.

5.5.2 Results

Figure 5.7 displays the regression coefficients of residual trends in °C by decade for both August 13th 2003 and August 7th 2010. For 2003, the NCEP residual trend is significantly negative. Five CMIP5 models are able to reproduce this result, with different values for the thermodynamical trend. The others have non significant trends for the historical period. The NCEP thermodynamical trend for 2010 is not significant. The spread of thermodynamical trends for both the CMIP5 and the CESM ensemble is larger than for 2003, with two (respectively seven) models detecting a significantly positive (negative) trend.

The confidence intervals of each model, the internal variability between CESM runs, and the model spread drop for the 1950–2100 period. For 2003, four (respectively eight) models detect a significant negative trend for RCP4.5 (RCP8.5) and one (two) models detect a significant negative trend with the rest being non significant. For 2010, five (respectively seven) models detect a significant negative trend for RCP4.5 (RCP8.5) and three (four) models detect a significant negative trend with the rest being non significant. Different runs from the CESM ensemble detect significant trends from opposite signs, hinting at a large role of internal variability in residual trends.

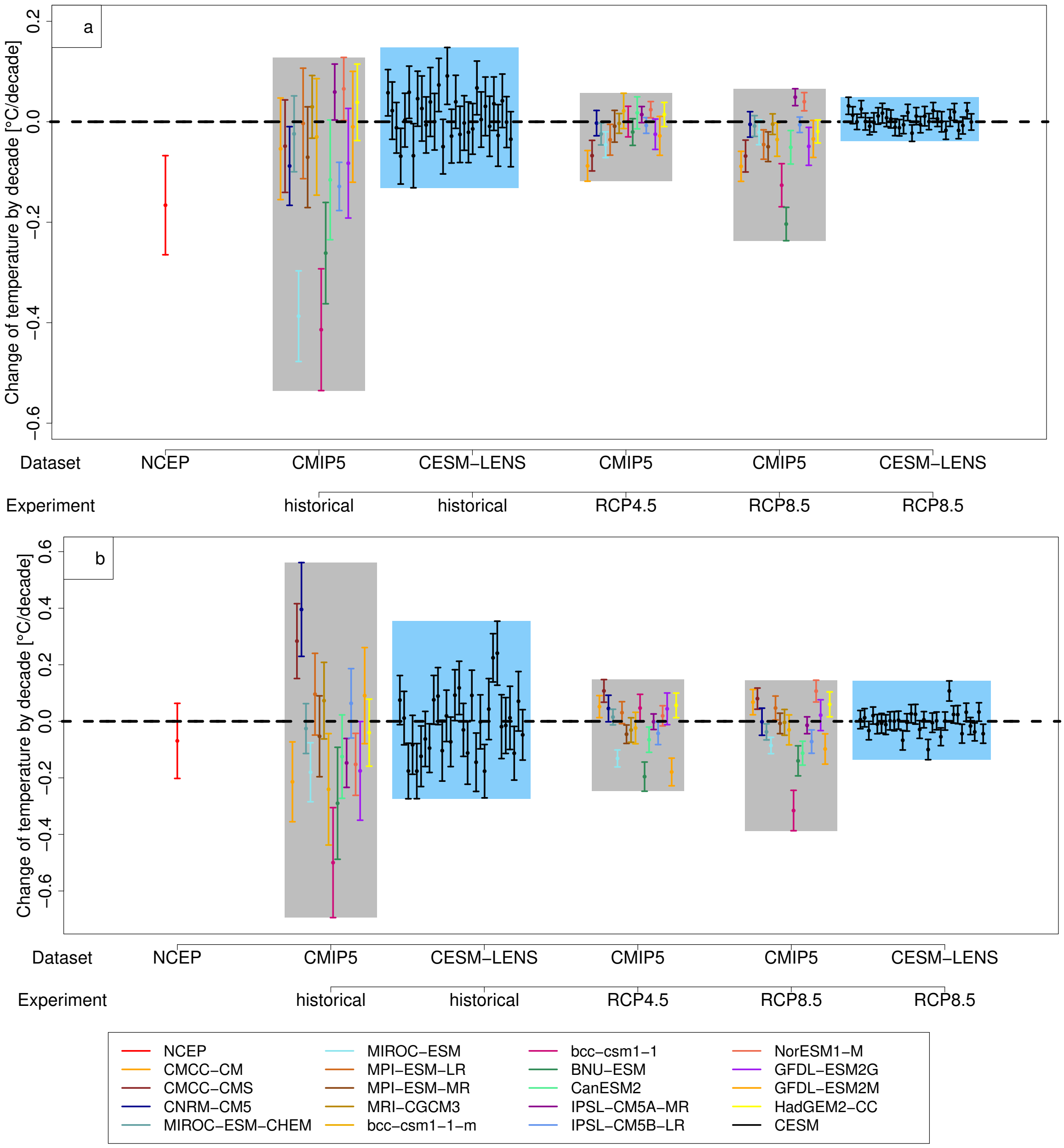

Figure 5.7 – Residual trends. Panels a and b display the regression coefficient of the detrended analogue temperatures in function of time for NCEP (in red), CMIP5 (bars in gray shaded areas) and CESM (bars in blue shaded), for the historical, RCP4.5 and RCP8.5 experiments. Panel a is for August 13th 2003. Panel b is for August 7th 2010.

5.5.3 Discussion

For the 2003 (and in a lesser extent 2010) circulation pattern and associated temperature, almost half the models, and perhaps most importantly the reanalysis detect a significantly negative residual trend. This implies that the rate of warming for the type of circulation related to both heatwaves is not necessarily the same than the regional rate of warming. In addition to the modeling of the change of the mean temperature with climate change, there are discussions regarding the evolution of the shape of its distribution. The fact that we found negative residual trends could indicate a decrease of the standard deviation of the distribution, or a change in the types of circulation leading to the most extreme heatwaves. A more complete study of residual trends applied to a large ensemble of circulation types could be a way to detect potential changes in distribution shapes and to understand what they correspond to.

5.6 Summary and conclusions

This chapter proposes several ways to evaluate the influence of climate change on a variable for a fixed circulation. A first approach is to compare the uchronic variable for two different periods with different levels of anthropogenic emissions. The second approach is to calculate thermodynamical trends, i.e. trends on the variable for an ensemble of days with a circulation pattern close to the circulation of the day of interest. As a second step, residual trends allow to compare the thermodynamical trends to general trends, calculated without constraints on the circulation.

To propose reliable thermodynamical and residual trends, there is still work left to do in two main directions: bias correction of temperatures, and evaluation of uncertainties, especially for residual trends. A possible alternative way to calculate these trends would be to rely on generalized additive models (GAM) (Hastie and Tibshirani, 1990). It is noteworthy that although thermodynamical trends are not very informative for variables clearly related to thermodynamics like the temperature, they could also be used on variables like precipitation, for which they could give valuable information. This distinction between types of variables is similar to the one done by Trenberth et al. (2015).

Résumé

Contexte et objectifs

Le chapitre 4 présente une méthodologie pour évaluer l'influence du changement climatique sur les types de circulation menant à des canicules. Pour compléter cette méthodologie, ce chapitre s'attache à évaluer l'influence du changement climatique sur l'intensité des canicules à circulation fixée.

Méthodes

Plusieurs méthodes sont introduites dans ce chapitre. La première consiste à calculer les températures uchroniques définies dans le chapitre 3 pour différentes sous-périodes d'un jeu de données. Dans un second temps, j'introduis le concept de *tendances thermodynamiques*. On calcule les analogues de la même manière que dans le chapitre 4, ce sont les jours dont la distance au jour d'intérêt est inférieure au cinquième quantile des distances au jour d'intérêt. Il est alors possible de calculer la tendance sur les températures de ces jours analogues à l'aide d'une simple régression linéaire. Enfin, les *tendances résiduelles* permettent de comparer la tendance observée sur la température estivale moyenne à celle observée à circulation fixée. Cette comparaison devrait permettre de mieux comprendre comment la distribution de température est amenée à évoluer sous l'influence du changement climatique. Les tendances résiduelles sont calculées à partir des températures des jours analogues auxquelles la tendance moyenne calculée avec l'ensemble des jours d'été a été retranchée.

Résultats

La comparaison de températures uchroniques a été appliquée au cas du mois de Décembre 2015, un record de chaleur pour ce mois en France. La température uchronique augmente avec le changement climatique, et selon le modèle CESM, l'anomalie de température observée devient même anormalement basse pour ce type de circulation dans la seconde moitié du 21ème siècle (Figure 5.2). En revanche, on ne détecte pas de changement de précipitations uchroniques dans les réanalyses entre deux sous-périodes de trente ans pour la circulation liée à la sécheresse de 2015 en Europe centrale (Figure 5.4).

Les tendances thermodynamiques et résiduelles ont été calculées pour les mêmes cas et les mêmes jeux de données que dans le chapitre 4. Les tendances thermodynamiques sont presque toutes significativement positives. L'incertitude liée au choix du modèle est élevée (Figure 5.5). Une partie des modèles (et dans le cas de 2003 les réanalyses) détectent une tendance résiduelle significativement négative, ce qui pourrait signifier que les températures extrêmes liées à ces deux types de circulation se réchauffent moins vite que la moyenne (Figure 5.7).

Chapter 6

Using Extreme Event Attribution. Case study: Loss and Damage

Since 1995, the United Nations Framework Convention on Climate Change (UNFCCC) organizes its Conference of Parties (COP) every year. COPs are a gathering of Parties. These Parties are member States, divided between Annex I countries[1] and non-Annex I countries[2]. Annex I countries "include the industrialized countries that were members of the OECD (Organisation for Economic Cooperation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States."[3]. Non-Annex I countries are "mostly developing countries"[3]. Aside from these Parties, who are allowed to negotiate, the COPs host observers. Observers are divided in nine constituencies: the business and industry non-governmental organizations (BINGO), the environmental non-governmental organizations (ENGO), the local government and municipal authorities (LGMA), the indigenous people organizations (IPO), the research and independent non-governmental organizations (RINGO), the trade union non-governmental organizations (TUNGO), farmers and agricultural non-governmental organizations (Farmers), women and gender non-governmental organizations (Women and Gender) and youth non-governmental organizations (YOUNGO)[4]. I started attending these meetings as a YOUNGO member, at intersessionals, which are smaller gatherings in between COPs. During my PhD, I attended COP21 as a YOUNGO member and COP22 as a RINGO member.

One of the role of the constituencies is to organize localized actions within the negotiation center, shedding light on what is at stake in the negotiation rooms. These types of action mainly serve media purposes. At the June intersessionals preceding COP21, one of the burning issues was the possible inclusion of a 1.5 °C target to reinforce the 2 °C target. In order to push for the inclusion of a 1.5 °C target, the ENGO and YOUNGO constituencies stood in front of the negotiation room with pictures showing the impacts of the latest big hurricanes and typhoons (e.g. Pam, Yolanda, Haiyan) and suggesting that the delegates should give their names to the next disaster (see Figure 6.1). The idea was to tell negotiators that if they did not manage to agree on a 1.5 °C target they would be guilty of these disasters and their impacts. It also implied these disasters were attributable to anthropogenic climate change, which was (and is

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[1] Full list of Annex I countries: https://tinyurl.com/ybp3udkd

[2] Full list of Annex I countries: https://tinyurl.com/y7bvd2c7

[3] https://unfccc.int/parties-observers

[4] A fun description of the roles of different participants at COPs: https://studentclimates.wordpress.com/2015/12/08/star-cop21-episode-4-a-new-cop/

still) at odds with the current state of knowledge.

Figure 6.1 – Picture of a YOUNGO action at Bonn intersessionals – June 10th 2015 – IISD Reporting Services

In a similar fashion, at COP19, Filipino head negotiator Yeb Saño delivered a poignant speech[5] to denounce the inaction at COPs while Philippines were devastated in the wake of super Typhoon Haiyan: “To anyone who continues to deny the reality that is climate change, I dare you to get off your ivory tower and away from the comfort of you armchair. [...] you may want to pay a visit to the Philippines right now.” He points out the role of anthropogenic climate change in the occurrence of this disaster: “We must stop calling events like these as natural disasters. [...] It is not natural when science already tells us that global warming will induce more intense storms.” Through the example of Haiyan, he is pushing specifically for the inclusion of loss and damage within the work of the Convention: “if we have failed to meet the objective of the Convention, we have to confront the issue of loss and damage. Loss and damage from climate change is a reality today across the world.”; “We call on this COP to pursue work [...] until the promise of the establishment of a loss and damage mechanism has been fulfilled”. These two examples show that in COPs, the attributability of extreme events matter less than the key messages some of the actors need to deliver.

Since Yeb Saño’s speech, loss and damage has gained traction. In this chapter, I present the history and loss and damage and its current state within the UNFCCC. I then discuss how a few climate scientists have pushed for the use of extreme event attribution (EEA) for loss and damage. The main part of this chapter is an analysis based on two corpora of interviews: one with climate scientists (the A2C2 corpus, which was also used in Chapter 2), and one with delegates (and their advisers). I present the perspectives of both stakeholder groups on the potential use of EEA for loss and damage.

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[5] http://www.climatechangenews.com/2013/11/11/its-time-to-stop-this-madness-philippines-plea-at-un-climate-talks/

6.1 Loss and damage

6.1.1 History

Loss and damage in the context of the UNFCCC is hard to comprehend because it does not have a commonly agreed upon definition. In order to draw its contours, I first explain how the topic of loss and damage gained traction in climate negotiations. I rely on Mace and Verheyen (2016), who track the advances of loss and damage through years of UNFCCC proposals and decisions, and on Vanhala and Hestbaek (2016), who detail the evolution of the framing of loss and damage through political shifts in different Parties positions.

The first mention of "loss and damage" goes back to the negotiations to establish the UNFCCC, in 1991. Vanuatu, on behalf of the newly formed Alliance of Small Island States (AOSIS) proposed to create an "International Insurance Pool" to "compensate the most vulnerable small island and low-lying coastal developing countries for loss and damage arising from sea level rise." (Vanuatu, 1991). This proposition did not become a part of the convention, although a trace of it remained through a reference to insurances (Mace and Verheyen, 2016). Loss and damage is historically an important subject for small islands states, which have been pushing for it since the very beginning of the convention.

The topic started to gain traction around COP13 (2007, Bali) and COP14 (2008, Poznan). The terms "loss and damage" in relation to climate change are included in the Bali action plan (paragraph 1.c.iii of CP.13 (2007)), and a workshop was organized at COP14, where AOSIS proposed a "Multi-Window Mechanism to address loss and damage" including "three inter-dependent components: an insurance component, a rehabilitation/compensatory component, and a risk-management component" (AOSIS, 2008), expanding the concepts related to loss and damage beyond insurance. At the same time, civil society took interest in the topic (Harmeling, 2008; Linnerooth-Bayer et al., 2008; MCII et al., 2008; Verheyen and Roderick, 2008). In particular, Verheyen and Roderick (2008) positioned loss and damage as an object "beyond adaptation". The inclusion or non-inclusion of loss and damage in adaptation remained contentious until the Paris agreement. From this point, countries from the Least Developed Countries (LDC) group started to join the efforts of AOSIS to advocate for the inclusion of a loss and damage mechanism within the UNFCCC, while developed countries kept rejecting it (Vanhala and Hestbaek, 2016). Vanhala and Hestbaek (2016) also identify 2008/2009 as a change of framing from an "insurance and risk transfer" or a "compensation and liability" frame to a "more ambiguous "loss and damage" frame".

Loss and damage became a high-profile issue at COP18 in Doha and COP19 in Warsaw. Parties agreed in Doha to "address loss and damage associated with the impacts of climate change in developing countries that are particularly vulnerable to the adverse effects of climate change" (CP.18, 2012). At COP19, Parties agreed on the establishment of the Warsaw international mechanism (WIM) to "address loss and damage associated with impacts of climate change, including extreme events and slow-onset events, in developing countries that are particularly vulnerable to the adverse effects of climate change" (CP.19, 2013). Although the existence of this mechanism was a huge step forward for defenders of loss and damage, "much remain[ed] to be decided on how the mechanism will function, how it will be financed, and what it actually requires states to do" (Vanhala and Hestbaek, 2016). The positions of different countries regarding loss and damage reflect their disagreements on what loss and damage should encompass. Indeed, loss and damage opens the door for compensation and liability, and the possibility to require finance from developed countries (Huq et al., 2013). This partly explains the lack of definition, which was the only way to advance in the negotiation process.

The Paris agreement and its accompanying decision reflect well the dividing lines between Annex I and non-Annex I countries regarding loss and damage. On the one hand, the inclusion of loss and damage in the Paris agreement in a paragraph separated from adaptation was considered a victory for developing countries (Article 8 of the agreement (2015)). On the other hand, developed countries, the US in particular, conditioned their acceptance of the agreement to the explicit exclusion of compensation and liability. As stated in paragraph 51 of the accompanying decision to the Paris agreement (CP.21, 2015), the conference of Parties : “agrees that Article 8 of the Agreement does not involve or provide a basis for any liability or compensation”.

6.1.2 Definition (or lack of)

Loss and damage gained traction in the negotiation through an ambiguous frame and a lack of clear definition (“The reason loss and damage was easy was that nobody knows what it means yet” (Vanhala and Hestbaek, 2016)). Boyd et al. (2017) investigate the different meanings of loss and damage through interviews with thirty-eight key stakeholders. They identify four perspectives. The *Adaptation and Mitigation perspective* considers loss and damage as all the impacts of anthropogenic climate change, which the Convention as a whole aims to avoid. In this perspective, there is no need for an additional loss and damage mechanism, as the goal of mitigation and adaption is precisely to avert and minimize loss and damage. The *Risk Management perspective* links loss and damage to ungoing efforts in disaster risk reduction (DRR). The *Limits to Adaptation perspective* presents loss and damage as the residual impacts of climate change which were not avoided through mitigation and go beyond the possibilities of adaptation. The *Existential perspective* is centered on the need to address the inevitable harm the most vulnerable populations already face because of climate change.

The type of loss and damage considered has also evolved from the first proposals from Vanuatu (Vanuatu, 1991), which only concerned “loss and damage arising from sea level rise” to “loss and damage associated with impacts of climate change, including extreme events and slow-onset events”(agreement, 2015; CP.19, 2013). This expansion of the limits of loss and damage is certainly related to the growing number of countries advocating for action on loss and damage, which are vulnerable to different types of impacts.

6.1.3 Link between Extreme Event Attribution and Loss and Damage

Depending on the chosen perspective, the attributability of weather-related impacts is not always necessary to deal with loss and damage (Warner and van der Geest, 2013). However, the UNFCCC intuitively should deal with impacts that can be related to climate change. Before loss and damage became a hot topic in the negotiations, Allen (2003), Allen and Lord (2004), and Allen et al. (2007) already discussed the potential of attribution of extreme events to allow wronged citizens to appeal for compensation and liability. In fact, the perceived social need to attribute extreme weather impacts to climate change was the motivation stated by Allen to start investigating the scientific possibilities to perform attribution for specific extreme events that caused a lot of damage. He considers this solution as “apolitical” (Allen, 2003), in stark contrast with the political battles led within the UNFCCC surrounding loss and damage. A big difference between the arguments of Allen (2003), Allen and Lord (2004), and (Allen et al., 2007) and UNFCCC loss and damage is that the former considers compensation of losses mainly from an Annex I country system, while the latter applies specifically to the most vulnerable (non Annex I) countries. Allen's view hence misses a part of the problem, especially because Annex I countries losses are often of economic nature, while non Annex I countries also deal with non-economic losses (e.g. loss of life, loss of culture). However, his view may lead to faster results, for several reasons: it is easier to attribute events in Annex I countries (Huggel et al., 2016; Mera et al., 2015), and Annex I countries victims have a better access to national and international law. We note that there are disagreements within the UNFCCC regarding the scale (national, regional, or global) at which loss and damage should be addressed (Vanhala and Hestbaek, 2016).

Hulme et al. (2011) alert against the potential use of weather event attribution for the allocation of adaptation funding (note that when this article was published, loss and damage was only emerging in negotiations and that the WIM did not exist). They highlight three main problems behind the idea that adaptation funding should go to the impacts which are directly related to anthropogenic climate change through attribution (a position that was defended by Pall et al. (2011) and Hoegh-Guldberg et al. (2011)). First, EEA relies on models to estimate changes of probability, which introduce large uncertainties and subjectivity in the results. Surminski and Lopez (2015) also raise the issue of the unreliability of models, which are the basis of FAR calculation. Second, EEA measures changes in hazards, not in risk. It hence ignores potential changes in risks related to changes in exposure or vulnerability, and is still far from dealing with the political, social and ethical components of impacts. In line with this point, Huggel et al. (2013, 2015) argue that for EEA to be relevant to international climate policy it has to expand from the evaluation of changes in hazards to changes in risks. Third, they argue that the allocation of funds through attributability frames adaptation in a compensatory way rather than on building capacity with respect to vulnerability.

With the establishment of loss and damage as a major topic in the run-up to the Paris agreement and afterwards, scientists started to highlight the issue of establishing a link between impacts and anthropogenic climate change. Following the adoption of the WIM, James et al. (2014) explain that "From a scientific perspective, [...] the first challenge in implementing the WIM would be to estimate where and when loss and damage can be attributed to anthropogenic climate change", which calls for detection and attribution and EEA information. They point out that this potential scientific input has been largely ignored in negotiations. They are concerned "that a body of scientific evidence is growing, which is highly relevant to the WIM, yet is seen as a distraction from the negotiations" and call for a better communication between scientists and policy makers (see also Parker et al. (2015)).

In parallel, with the growth of EEA as a scientific topic, a more general discussion on the motivation of scientists to do EEA and on who could be the potential users emerged. The use of EEA results as material to back up a liability case, possibly in the context of UNFCCC loss and damage is among the four motivations proposed by Hulme (2014). Stott and Walton (2013) do not mention loss and damage as a potential domain of application, while Sippel et al. (2015) do. What is interesting here is that both EEA and loss and damage have been growing concurrently, and that a part of the scientific community has established a link between both topics. The way EEA scientists apprehend loss and damage is one of the issues I explore in this chapter. I will discuss the other practical uses of EEA in chapter 7.

A few articles discuss the relevance of EEA for loss and damage. Some of them consider that EEA has an essential part to play. Thompson and Otto (2015) argue that EEA is a necessary scientific input to provide restorative justice, which would be a basis for "healthy long-term international relations." Beyond monetary compensation, it would be a way for big emitters to acknowledge their part in impacts suffered by the most vulnerable countries, and this acknowledgement would be a first step in the making of amends. According to Mace and Verheyen (2016), the role of attribution science is threefold: the attribution of emissions, the attribution of impacts to extreme events and EEA. They argue that the scientific establishment of a link between emissions and specific impacts put policy makers in a position where it is more advantageous for them to take action collectively in the UNFCCC than to risk being brought before a court of law. Verchick (2018) adopts a similar point of view. He values EEA on the ground of the "unavoidable moral duty to know what's going on". EEA results could provide "substantial leverage" to push for ambitious mitigation, adaptation and loss and damage policy.

Others are less enthusiastic (although not as critical as Hulme et al. (2011)). Wallimann-Helmer (2015) remarks that not all loss and damage result from climate change. Some are related to natural variability. The type of responsibility differs between these two cases. EEA could help to distinguish which impacts would fall under corrective liability or remedial responsibility. However, he also asserts that corrective liability (related to attributable events) should be a secondary concern in regards to remedial responsibilities because loss and damage approaches are prospective in nature, and because it would be inappropriate to subsidize only the attributable fraction of loss and damage. This makes the utility of EEA only secondary. Surminski and Lopez (2015) criticize the conception that EEA could support the compensation of loss and damage, which could "distract from the importance of recognizing risk in its totality", by focusing only on hazards. Boran and Heath (2016) argue that given the history and processes of the UNFCCC, the normative frame based on compensation and liability is bound to fail. They propose an alternative "risk-pooling logic", in which EEA would strengthen insurance mechanisms. Huggel et al. (2016) discuss the type of climate information needed to feed different normative principles of justice. They show that a compensation process, which would be based on attribution results, would not be feasible with the current level of confidence in scientific evidence. In particular, they reveal an injustice in the scientific potential to attribute events depending on the region and on the type of impacts. This injustice is caused by the uneven quality of observational records. The most vulnerable countries are also those for which attributability is the lowest. Lusk (2017) discusses the social utility of event attribution, and concludes that the best social fit for EEA would be loss and damage. He however points out that EEA is not the only way to address loss and damage and that there is no certainty that it will ever be used in the UNFCCC arena. Roberts and Pelling (2018) point out that although it could be useful, EEA should not be a pre-requisite as there are still a lot of scientific challenges to deal with on the way to operationalization, which should not hinder efficient and rapid loss and damage action. Support should be given foremost to the most vulnerable, rather than the most attributable.

Parker et al. (2017) are the first to analyze stakeholders perceptions of event attribution. They conducted interviews within a panel of 31 stakeholders involved in loss and damage, carried between November 2013 and July 2014. They focus on two questions: how much is known about probabilistic event attribution, and how probabilistic event attribution might inform loss and damage. They conclude that there is little awareness of EEA between stakeholders, and that their perspective on its potential use diverge. The 31 stakeholders interviewed by Parker et al. (2017) are a mix of NGOs, social scientists, governmental and intergovernmental organizations, climate scientists and private sector representatives. The lack of agreement they found may be related to this diversity. I hence investigated if and how EEA could feed the loss and damage negotiations through the combination of two corpora of interviews: one exclusively with EEA scientists, and one exclusively with loss and damage delegates and their advisors. This was also an opportunity to update the results of Parker et al. (2017) post Paris agreement. I present hereafter the analysis of these interviews. The interview grids are displayed in Appendix C.

6.2 Material and Methods

This study adopts a phenomenological approach to the study of the science policy interface. Its objective is thus to contribute to the "understanding [of] unique individuals and their meanings and interactions with others and the environment" (Lopez and Willis, 2004).

It is based on two corpora of semi-structured interviews from two different groups of individuals. The first corpus consists of nine climate scientists working on Extreme Event Attribution (EEA), and the second of twelve delegates and affiliates working on loss and damage. Saturation[6] has been used as the primary guiding principle for sample size (see Mason (2010)). Saturation has been verified through the repeated removal of each and every corpus individual from the corpora and checking that this procedure did not influence the results. The relatively small sample size may be explained by the relative homogeneity and small size of the target populations, the focused nature of our inquiry and the saliency of the issue at hand for the interviewee (for a description of the populations see below). As comparison points Creswell (1998) identifies minimum sample size of five for interview-based phenomenological studies while Morse (1994) identifies this minimum as being six.

6.2.1 Selection of interviewees

We targeted two populations from the general group of stakeholders involved in Loss and Damage, which was already studied by Parker et al. (2017) and Boyd et al. (2017). The first population consists of climate scientists working on EEA. The science of EEA originated in 2003 (Allen, 2003). The community expands regularly and now includes researchers from most of the Annex I countries and China. We can consider that our target population consists of scientists participating in the European project EUCLEIA (EUropean CLimate and weather Events: Interpretation and Attribution), and/or in the IDAG (International ad hoc Detection and Attribution Group), and/or who wrote an article about EEA, for example in one of the special issues of the BAMS (Bulletin of the American Meteorological Society) explaining the events of the previous year. Although this population is quite large (e.g. there are 132 articles in the six published yearly issues of the BAMS), it is homogeneous. Indeed, most groups working on EEA have coauthored articles with other groups. Their background is either in

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[6] A sample is saturated when adding new data (in this case, conducting other interviews) does not provide new information.

physics or statistics . They are mostly men.

For the first corpus, our sample consists of nine climate scientists. They were selected based on their publications and involvement in EEA research. They all came from different laboratories based in Europe, North and South America. An effort was made to cover different types of methodologies. Five of them were interviewed during the IMSC (International Meeting on Statistical Climatology, held in Canmore, Canada, in June 2016), two others were interviewed in person during other occasions and the last two via skype, between June 2016 and January 2017. The nine interviewees included eight men and one woman. Five have a background in physics and four in statistics. We chose to only interview holders of PhD with a permanent position as they are more likely to be in contact with stakeholders outside the world of research.

The second targeted population consists of people closely involved in the loss and damage negotiation process. The targeted group are the 20 members of the Warsaw Implementation Mechanism (WIM) executive committee (Excom) and/or the persons who participated to the closed to observers negotiations on loss and damage at COP19. This second group includes less than 50 persons, as not all delegations are present for the negotiations on loss and damage, which are still a rather small (but highly political) topic within the COP. This population is gender balanced and evenly distributed between Annex I and non-Annex I countries.

For the second corpus, our sample consists of twelve interviewees involved in the loss and damage negotiations. Eight of them were Parties delegates, including five members of the WIM Excom. Out of the twelve interviewees, three were Annex I countries delegates. Three others were advisers to delegates, all to non Annex I countries. Five interviewees were delegates from non-Annex I countries. The last one was a member of the United Nation Framework Convention of Climate Change (UNFCCC) secretariat. This corpus is hence imbalanced in favor of non-Annex I countries. This is related to a certain reluctance of Annex I countries delegates to participate to these interviews. We could only get European Annex I delegates. However, the Annex I countries delegates provided rather homogeneous answers, hence the sample of three seemed to be enough to characterize their position. The twelve interviewees included seven men and five women.

The first target of these interviews were members of the WIM Excom whom we contacted before COP22. Starting from the ones who accepted, we asked each interviewee to recommend others, following a snowball sampling technique. Seven interviews were conducted during the COP22 in Marrakesh in 2017, and five others were done via skype afterwards. Due to the political nature of the topic, a part of the persons we contacted were too suspicious to accept an interview (especially members of Annex I countries).

6.2.2 Interview procedure

We conducted semi-structured interviews. The chart of confidentiality follows the Chatham House rule, as agreed with the interviewees before the beginning of the interview. The climate scientists were asked to define extreme events, detection and attribution, and extreme event attribution, what was their personal contribution to EEA, how they came to work on it, why they were interested in it, what was their criteria to consider that an EEA exercise they engaged into was successful, whether they were in contact with potential users, if yes what were their expectations and if not why not, whether they considered EEA to be useful, and in what manner, and how they imagined the future of EEA. Two questions were specifically on loss and damage, whether they knew about it (if not, we explained), and which role they thought EEA could play regarding loss and damage.

The delegates and affiliates were asked what was their personal definition of loss and damage, what was the state of loss and damage during/after COP22, what was their role regarding loss and damage, how they would define extreme weather events and measure their impacts in the context of the PA, why did the WIM Excom define an action area about slow onset events and not about extreme weather events, how they imagined the implementation of loss and damage, what is the role of science in loss and damage, whether they work with scientists and about the future of loss and damage. Four questions were specifically on EEA. We asked them how an extreme weather event would be attributed to climate change in the context of loss and damage, what they thought of the attribution of individual extreme weather events, what would be their ideal contribution from climate science on the attribution of extreme weather events and how they would deal with the events for which the uncertainties are too high for science to attribute them to climate change.

The questions related to slow onset events vary a bit from one interview to the other because we specifically asked the members of the Excom why there was an action area about slow onset events and none about extreme weather events while we could not ask the same question to people who were not part of the process of defining those action areas. We asked them how they understood the place of both slow onset events and extreme weather events in the negotiations.

We chose not to directly ask the delegates whether they knew about EEA or not in order to gauge how they would interpret our questions, and whether they would bring up EEA results by themselves. We also wanted to give them latitude to describe the type of attribution science they would like without describing pre-existing methodologies.

All the interviews were recorded, with the consent of the interviewees, and later transcribed for the analysis. We only used a part of the questions of both corpora for the analysis presented in this chapter. The first corpus has also been used in (Jézéquel et al., 2018b). The questions of the second corpus regarding the definition of loss and damage have been explored by other researchers using their own corpus of interviews and we considered we had nothing new to add on that topic (Boyd et al., 2017).

6.2.3 Data Analysis

The interview transcripts were analyzed using a qualitative, iterative, inductive, phenomenological approach, in three steps. First, we identified nine themes covering the content of the interviews: the definition of extreme weather events by climate scientists, and by delegates, the definition of impacts by delegates, delegates knowledge of the influence of anthropogenic climate change on extreme weather events, delegates knowledge of EEA, the opinion of climate scientists on EEA for loss and damage, the one of delegates, delegates on the difference between slow onset events and extreme weather events, and delegates on uncertainties regarding the attribution of some extreme weather events to anthropogenic climate change. The second step was to select the excerpts of interviews related to each of those themes. The third step was to build the tables presented in Appendix D from those excerpts.

6.3 Results

6.3.1 Delegates knowledge of EEA and scientists knowledge of loss and damage

Two years before the 2015 Paris Agreement, stakeholders involved in loss and damage had various, and often incorrect knowledge of EEA (Parker et al., 2017). A year after the Paris Agreement, despite calls (James et al., 2014) and initiatives (Parker et al., 2016) from scientists for better communication towards stakeholders, our survey shows that the diagnostic stays the same. Table 6.1 summarizes the understanding of twelve delegates and affiliates on both the general influence of anthropogenic climate change on extreme events and EEA. Less than half of them had prior awareness of EEA. The understanding of both the challenges and the concepts associated with EEA vary from one interviewee to the other. The general understanding of how extreme weather events are affected and will be affected by climate change also differs from one delegate to the other. Most of them declare that climate change affects the severity and the frequency of extreme events, without discriminating between regions of the world and types of events. The Intergovernmental Panel on Climate Change (IPCC) establishes this variability in the influence of anthropogenic climate change on different types of events and in different regions in its last assessment report (Bindoff et al., 2013b) and specifically in its special report on extreme events (Seneviratne et al., 2012). This shows that those research findings have not been assimilated by all the negotiators.

	Influence of anthropogenic climate change (ACC) on extreme weather events (EWE)	Knowledge of extreme event attribution (EEA)
D1	ACC contributes to existing EWE, but does not induce totally new weather events.	– "Difficult to say that one event in its entirety is attributable to climate change." – Has not heard about EEA.
D2	ACC increases the severity, intensity and frequency of extreme events.	– It is possible to calculate the difference in magnitude or in probability caused by ACC for a specific EWE within a matter of days. – Has heard of EEA.
D3	ACC increases the unpredictability of EWE Explicit reference to IPCC.	– Impossible to attribute one event to ACC – Has heard about EEA. – EEA is "a way to say whether CC is 30% or 20%, it is very technical."
D4	ACC increases the frequency, and the intensity of EWE	Has not heard about EEA. Outside of field of expertise.
D5	ACC increases the frequency, the impacts and the	– Has not heard about EEA.

	magnitude of EWE. Explicit reference to IPCC.	– Attributing one storm to ACC is “impossible, non scientific even.”
D6	ACC explains the occurrence of extreme events like hurricanes. The refusal to link EWE to ACC comes from political reasons, not from science.	– Has not heard about EEA. – Does not understand the need for EEA because the science is “easy”.
D7	No specific statement.	– Has heard about EEA.
D8	ACC increases the frequency, and the severity of extreme events. ACC is not the only driver of EWE.	Refuses to answer the question. Outside of field of expertise
D9	The frequency, the severity and the location of current EWE are a result of ACC. ACC is not the only driver of EWE.	– Has heard about EEA. – There are other factors than ACC in EWE.
D10	No specific statement.	Refuses to answer the question. Outside of field of expertise
D11	The influence of ACC on EWE depends on the type of events and on the region studied. Explicit reference to IPCC.	– “it’s difficult to attribute just one event to climate change, scientifically.” – Has not heard about EEA.
D12	ACC increases the number of EWE. ACC is not the only driver of EWE.	– EEA is difficult because of “climate variability”. – Has heard about EEA. – Even if we cannot “fully” attribute, we may attribute a part of the event to ACC.

Table 6.1 – Delegates knowledge of the relationship between extreme weather events and anthropogenic climate change. Complete quotes supporting this table are available in the Appendix D(Table D.4 and D.5).

Conversely, only a minority of EEA scientists interviewed in this study had previously heard of loss and damage (Table 6.2). This indicates that a very small part of the EEA community actively researches how to integrate EEA results in loss and damage. Both topics are quite complex to comprehend for the other group. EEA is, as stated by one of the delegates, “very technical” (D3). Loss and damage is a political concept. It has been integrated in the negotiations without a clear definition (Boyd et al., 2017). This might not evolve in the future, since the blurriness associated with the topic is the result of a compromise between the positions of Annex I and non-Annex I countries (Vanhala and Hestbaek, 2016). The understanding gap between the EEA and the loss and damage communities makes it currently difficult for EEA to be integrated into the loss and damage negotiations. More communication between the two groups would be a necessary condition for EEA to be used in the context of climate negotiations (James et al., 2014).

Delegates also generally consider the knowledge on extreme weather events to be greater than that on slow onset events (see Table D.8). Slow onset events include “sea level rise, increasing temperatures, ocean acidification, glacial retreat and related impacts, salinization,

	Knew L&D	Which role do you think EEA could play regarding loss and damage(L&D) ?
C1	No	Maybe useful for liability but complicated: – acceptability of the science by a court. – failure to mitigate vs failure to adapt.
C2	Yes	Uncomfortable with the idea: – the science is not robust enough yet. – the robustness/attributability depends of the types of events and of the region: unfairness in attributability.
C3	No	Useful to determine what should be compensated. The way to implement is still mysterious.
C4	Yes	Confused: – would be necessary to evaluate what is related to climate change. – justice problem regarding the geographical distribution of attributability. – compensation and liability are explicitly removed from the Paris agreement.
C5	Yes	Useful to determine what should be compensated.
C6	No	Not convinced: – the real problem is to find ways to mitigate. – problem of reproducibility of the science with just one planet. – could slow decision making.
C7	Yes	Does not think it will play a major role for L&D. 2 possible other other options: – EEA for quantitative risk assessment (part of L&D and adaptation, has nothing to do with liability). – indirect influence on L&D through liability cases outside of the UNFCCC.
C8	No	Not convinced of the use of EEA for L&D: – uncertainty. – non-linearity of the impacts. – apportionment of the blame between emitters.
C9	No	Against the use of EEA for L&D: – all the money would go to the lawyers. – non-linearity of the impacts. – complexity of choosing between different ways to count. – international help should be based on resources, not on attributability.

Table 6.2 – Answers of the climate scientists regarding the possible use of EEA for L&D. Complete quotes supporting this table are available in the Appendix D (Table D.6).

land and forest degradation, loss of biodiversity and desertification." (CP.16, 2010) However, the scientific understanding of how climate change affects some extreme events is yet lower than for slow onset events (James et al., 2014). This discrepancy could be twofold. First, the IPCC released a special report on extreme events in 2012 (Seneviratne et al., 2012), which is interpreted by this "issue [is] fairly well covered" (D11). Second, although anthropogenic climate change may have an influence on extreme events, they have happened before. Stakeholders have historical experience dealing with them and there are already many ways to address their impacts. For example, D2 states that "the rapid onset events like floods, hurricanes, and event droughts, are well-known phenomena that occurred naturally before human-induced climate change.”

6.3.2 Potential uses for EEA in loss and damage

In order to better understand how EEA could be used in loss and damage, we interrogated the delegates on their vision of EEA in relation to loss and damage and the climate scientists on their vision of loss and damage in relation to EEA. Their answers are summarized in Tables 6.2 and 6.3. A significant part of the climate scientists are not convinced of the potential usefulness of EEA for loss and damage and a few delegates think that EEA could be ill-used and dangerous. Most of the delegates, especially those from non-Annex I countries, agree that EEA could be useful to some extent. They think that EEA could help to raise awareness among policy makers on the fact that the impacts of climate change are already being observed. EEA could also act as a basis to put pressure on Annex I countries to meet their responsibilities. It becomes more complicated upon devising how EEA could be part of a concrete loss and damage mechanism, directly linking an extreme weather event with some kind of international help. Our analysis of the interviews unveiled six serious hurdles of technical and ethical natures, which hinder a concrete use of EEA for loss and damage.

Climate scientists are sometimes uncomfortable with the use of their results given the current state of EEA, which is still a relatively new branch of climate science, and lacks robustness in some cases. For instance, subject C2 stated that he would be “uncomfortable [...] if you would use our current methodology to make any statements about it and describe dangerous events.” C8 is also uneasy about the inherent uncertainties of EEA results. This worry is related to the robustness of the current methodologies (Hulme et al., 2011). Indeed, to this day, there are examples of EEA case studies leading to quantitatively, and sometimes qualitatively, varying results about the same event, depending on the methodology and model used (Angélil et al., 2017; Hauser et al., 2017). If EEA results are to be included in a loss and damage mechanism, they would need to be robust, so that other EEA studies could not contradict them.

Another technical problem resides in the differences in our capacity to attribute different kinds of events in different regions (e.g. C2, C4 and C9). Some events are easier to attribute than others: it is simpler to get robust results for heat-related events than for precipitations, and attributing storms and hurricanes (on Extreme Weather Events and Attribution, 2016) is a still an unresolved challenge. Additionally, EEA studies in particular and climate sciences in general are more robust when they rely on long observational records. However, Annex I countries are generally better covered than non-Annex I countries. This is particularly true for African countries (Huggel et al., 2016). Therefore, the most vulnerable countries are also those for which scientists are less prone to attribute an extreme event to anthropogenic climate change. Although there are articles proposing to extend EEA to attributable extreme weather events in Annex I countries (Mera et al., 2015), the current UNFCCC mandate addresses loss and damage “in developing countries that are particularly vulnerable to the adverse effects of climate change” (CP.19, 2013).

Even if those technical challenges were dealt with and the science were able to calculate the attributable part of any extreme event impact, there would still be political hurdles in the attribution of responsibility. Interviewees from both corpora raised the problem of the

	Relevance of EEA for L&D
D1	EEA could be useful for awareness raising for mitigation. EEA could be dangerous: – if framed in the compensatory way (ethical problem of accepting that you cause impacts on other countries and get away with it with money). – problem of maladaptation vs lack of mitigation.
D2	EEA could be useful: – for understanding of the role of climate change on extreme events. – but it is a "second order problem".
D3	EEA could be dangerous: – it puts the light on climate change while there are other drivers of impacts.
D4	EEA could be useful: – to determine what is L&D. – to raise awareness among policy makers.
D5	EEA could be dangerous: – apportionment of responsibility between emitters is not easy. – only the mediatized events would be addressed. – paying only for the attributable part is morally wrong.
D6	Does not understand the need for EEA because the science is "easy".
D7	EEA has potential in a forward looking framing.
D8	EEA is useful to put pressure on big emitters to take their responsibilities towards vulnerable countries.
D9	EEA is useful to put pressure on big emitters to take their responsibilities towards vulnerable countries.
D10	EEA is useful because it is the only way to measure the contribution of anthropogenic climate change to an event.
D11	EEA is important to discriminate what part of the impacts is related to ACC and what comes from maladaptation.
D12	EEA is useful to raise awareness among policy makers.

Table 6.3 – Answers of the delegates regarding the possible use of EEA for L&D. Complete quotes supporting this table are available in Appendix D (Table D.7).

apportionment of responsibility based on emissions (C8 and D5). The apportionment of the emissions and their related responsibilities is not only an EEA problem but has been a constant issue since the beginning of the negotiations. There are different ways to calculate the contribution of a country to global emissions depending on the components of anthropogenic forcings (CO2 only, different greenhouse gases, land-use changes...), the start year of the emissions, the year the impacts of climate change are evaluated, whether one should account for emissions within a territory, or for consumption-based emissions, or for emissions per capita, or for the total emissions of a country, and the indicator of climate change (e.g. global mean surface temperature) (Skeie et al., 2017). Otto et al. (2017) propose a mechanism to apportion the attributable part of the impacts of an extreme event between emitters. They show that emission apportioning choices impact responsibility repartition. Without an agreement on how to apportion anthropogenic emissions responsibilities in the UNFCCC, it is doubtful that this problem will be solved in the context of a hypothetical loss and damage implementation mechanism based on EEA.

Ahead of this, there are also subjective choices to make in the framing of an EEA case study (Jézéquel et al., 2018b), which has led to a debate regarding the framing most useful to stakeholders (Lloyd and Oreskes, 2018). Different framing options lead to answering different questions regarding the influence of climate change on individual extreme events. The subjective choices scientists have to make depend on the objective of the study. It hence should be concerted with the relevant stakeholders, in order to answer their questions (Otto et al., 2016) (also see Table D.1). Loss and damage delegates, however, are probably not the stakeholders suited to the task. Indeed, one of the first subjective choice in an EEA study regards the precise definition (duration and region) of the studied event, which has a quantitative impact on the results (Cattiaux and Ribes, 2018). When asked how they would define extreme weather events and their impacts, delegates typically answered that this type of technical question was outside their field of expertise (see Appendix D Tables D.2 and D.3). This means that both communities consider that the choice and definition of the events of interest and of the relevant way to link these events to anthropogenic climate change should be done by the other community.

Another responsibility dilemma lies between the one who failed to mitigate and the one who failed to adapt (C1, D1, D3, D11). This relates in part to a point raised by Hulme et al. (2011) that EEA could only be useful if it attributed changes in impacts, not changes in hazards. Only a few EEA case studies tackle impacts (Mitchell et al., 2016; Schaller et al., 2016).There is still a long way before attributing the large variety of economic and non-economic losses. In particular, dealing with (possibly by quantifying) cultural and non-economic losses poses operational and ethical problems (Wrathall et al., 2013). This point is important because the observed increase in damages related to natural disasters has been shown to be due to an increase in exposure and vulnerability rather than an increase in hazards (Visser et al., 2014).

Delegates may point out that EEA could lead to a situation where the politicians would only pay for the attributable part of the event (e.g.: D5). This is especially troublesome when considering that impacts are not linear (C8 and C9): “a lot of these things involve a threshold [...] the straw that breaks the camel’s back, the non linearities become extraordinarily difficult to deal with.” (C9). This is illustrated by D2 when recounting the impacts of the Haiyan typhoon in 2013. “Philippines is well adapted to typhoons. [...] Haiyan came, they got the warning, they went to the shelters, they died in the shelters. Haiyan was a super typhoon. The shelters were not built to withstand a super typhoon.”

For all of these reasons, it is hard to believe that EEA may be part of a concrete legally-binding loss and damage mechanism within the UNFCCC. Apart from its ‘softer’ role in raising awareness, concrete uses of EEA could possibly happen outside of the climate negotiations. Delegates (as well as C7) identify the disaster risk reduction community as the relevant stakeholders regarding technical issues on natural disasters. Hence, this community has more chances to grasp the concept and limits of EEA and to integrate its results in their work. There have also been recent arguments for (Marjanac and Patton, 2018) and against (Lusk, 2017) the use of EEA for liability purposes in courts outside of the UNFCCC jurisdiction. Whether EEA will be needed in those contexts remains to be explored by scientists in a separate analysis of each stakeholder group’s needs (Sippel et al., 2015).

6.4 Discussion and conclusion

At first sight, the introduction of loss and damage “associated with the adverse effects of climate change, including extreme weather events” (agreement, 2015) calls for a tool to determine which extreme weather events are effectively related to climate change. However, despite the lobbying of a few scientists, EEA does not blend in negotiation texts. Six hurdles delegates and scientists associate with the use of EEA for loss and damage emerge from the analysis of the interviews I present here. The first two hurdles are technical: the lack of confidence in EEA results, and the lower attributability of events in the most vulnerable countries. Four other hurdles regard the attribution of responsibility that could ensue from EEA results. This could lead to politically complicated (possibly impossible) choices: the apportionment of responsibilities between emitters, the definition of the extreme events, the apportionment of responsibilities between the ones who failed to mitigate and the ones who failed to adapt, and the risk of only dealing with the attributable part of an event.

The relationship between EEA and loss and damage sheds light on the relationship between science and negotiations within the UNFCCC. For comparison sake, let’s take the example of the 2°C threshold, which is an example of co-construction between science an policy within the UNFCCC (Aykut and Dahan, 2011; Cointe et al., 2011; Randalls, 2010). At COP15 in Copenhagen, the choice of a long term goal was at stake. Two options were the 2°C threshold, which made it into the final decision, and a fixed amount of emissions. Cointe et al. (2011) analyze the reasons for the success of the 2°C threshold. One of the main point they develop is that “it is less accurate and less clearly measurable than concentrations, which affords it an ambiguity that is very useful in the negotiation process: we can point relatively precisely to the moment when 450ppm of atmospheric GHGs are to be expected, but much less precisely to the moment when the average global temperature will have risen 2°C above the pre-industrial baseline.” Flexibility and blurriness are essential for the political process. Policy is not rational, it thrives on “constructive ambiguity” (Geden, 2016). The example of EEA is representative of scientists’ lack of understanding of the type of scientific information to which the UNFCCC is porous. As Geden (2018) puts it : “climate researchers need to understand processes and incentives in policy making and politics to communicate effectively.”.

Despite the fact that EEA, as a very technical and precise science, is not adapted to the negotiation process, the fact that loss and damage is supposed to deal with events related to climate change remains legitimate. Aykut et al. (2017) introduced the concept of a *globalisation of the climate problem*, meaning “the inclusion of new issues and actors into the climate regime”. Through a compilation of articles on specific topics based on the ethnographic analysis of COP21, they show how climate change negotiations integrate other international policy topics, which are not necessarily directly linked to climate, like fossil-fuel regulation (Aykut and Castro, 2017), or security and migration (Maertens and Baillat, 2017). Loss and damage (at least the part on extreme weather events) includes disaster risk reduction issues in the COPs. The integration of disaster risk reduction within COPs presents two main advantages. It profits from the general momentum and media coverage of the climate arena, which is huge compared to traditional disaster risk reduction forums (e.g. the Sendai protocol, which is cited by a few of the interviewed delegates). It also opens the possibility of a shift of responsibilities in case of disasters. As D8 puts it: “One of the important things about the climate change convention and the international climate change regime is that there is a responsibility in the convention for Parties, for developed country parties, to finance adaptation and resilience building. Whereas in all of the other international arenas that are related the responsibility falls on the country itself.". Another interesting point is that the original loss and damage proposal only included loss and damage associated with sea level rise (Vanuatu, 1991). I do not have the material to treat this question, but it would be interesting to investigate when and how extreme weather events (and the associated disaster risk reduction issues) were included in the UNFCCC loss and damage. This could help to understand which groups are behind this inclusion of disaster risk reduction, within the UNFCCC.

The analysis presented in this chapter confronts the perspectives of two groups of stakeholders in regards to the potential inclusion of EEA results in a loss and damage process: EEA scientists and loss and damage delegates. It shows that for now, EEA results could only feed awareness raising, rather than the negotiation itself. Because of the limited time I had to complete this study, I chose to ignore a third major stakeholder group: the NGOs. This is an important limit of the results presented there. Indeed, this group plays an key part in the climate regime both within and without the UNFCCC arena (e.g. de Moor et al. (2017) on the role of climate activists and Morena (2017) on the role of philanthropies at COP21). The example I showed in Figure 6.1 shows they already attribute typhoons to anthropogenic climate change without the use of science. Interviews with NGO representatives would be needed to understand whether they would find EEA results useful, and for which purpose (e.g. awareness raising, lobbying) they could use it.

Résumé

Contexte et objectifs

Les pertes et préjudices (en anglais loss and damage) sont la partie des négociations climatiques censée gérer les impacts des événements extrêmes et des événements lents liés au changement climatique. Ce concept, nécessairement flou pour des raisons politiques, prend de plus en plus d'ampleur dans les COPs. Une partie de la communauté scientifique investie dans l'attribution d'événements extrêmes voit en les pertes et préjudices un domaine potentiel d'application. Ce chapitre explore si et comment l'attribution d'événements extrêmes pourrait effectivement être utile dans le cadre des pertes et préjudices.

Méthodes

Pour cela, je me suis appuyée sur trois jeux de données : une revue de la littérature existante sur ce sujet, un corpus d'interviews de scientifiques pratiquant l'attribution d'événements extrêmes, et un corpus d'interviews de négociateurs (ou de leurs conseillers) travaillant sur les pertes et préjudices. La confrontation de ces deux regards sur la question est la principale innovation proposée ici par rapport aux études déjà entreprises par d'autres équipes.

Résultats

Premièrement, il ressort de cette analyse que les négociateurs ont une compréhension basique et partiellement (voire fortement) erronée de l'état de la science sur l'influence du changement climatique sur les événements extrêmes. La majorité des scientifiques interviewés n'ont jamais (ou très peu) entendu parler des pertes et préjudices. Deuxièmement, la majorité des négociateurs pensent que l'attribution d'événements extrêmes pourrait servir à sensibiliser différents publics, dont les politiques, aux enjeux du changement climatique. En revanche, l'utilisation de résultats d'attribution d'événements extrêmes pour un mécanisme concret de pertes et préjudices semble peu probable, pour six raisons qui ressortent des entretiens. Les deux premières raisons sont techniques :

- le manque de confiance dans la robustesse des résultats d'attribution.
- il est plus difficile d'attribuer des événements dans les régions les plus vulnérables.

Les quatre autres posent des problèmes de choix politiques que les COPs ne sont pour l'instant pas parvenues à trancher :

- la répartition des responsabilités en fonction des émissions.
- le choix et la définition des événements à attribuer.
- la répartition de la responsabilité entre ceux qui ne sont pas parvenus à atténuer et à s'adapter.
- le risque de ne gérer que la partie attribuable des impacts d'un événement.

Chapter 7

Using Extreme Event Attribution: General outlook

In the previous chapter, we have seen that the potential use of EEA in the context of loss and damage is not straightforward. In fact, it is unlikely that EEA results could feed a loss and damage mechanism, which does not mean that these results have no value for an informal use. The present chapter provides a more general outlook on the uses of Extreme Event Attribution. While the previous chapter included an analysis of the perspective of a specific group of potentially interested stakeholders, this one is focused on the perspective of scientists and on their reasons to engage in EEA.

When Allen (2003) introduced the concept of event attribution, he had a clear motivation: to provide the basis for science-based liability. Based on EEA results, individuals faced with attributable losses could sue polluters to compensate their losses. The multiplication of law suits could then lead to make the economy more sensitive to the cost of climate change. In the words of Allen: “even the most impassioned eco-warrior has nothing on a homeowner faced with negative equity.” Allen and Lord (2004) develop this argument further, asking “who will pay for the damaging consequences of climate change” following the first event attribution of summer 2003 European heatwave by Stott et al. (2004). Allen et al. (2007) propose a review of the state of detection and attribution (including event attribution) and pose a few questions to the legal community to tailor attribution research for the needs of the court.

With the development of attribution science, scientists started to advance other social reasons to motivate their research. For example Pall et al. (2011) state that “the recently launched Adaptation Fund, intended to finance climate change adaptation activities in developing nations, operates under the auspices of the United Nations Framework Convention on Climate Change that specifically defines ‘climate change’ as due to greenhouse gas emissions. By demonstrating the contribution of such emissions to the risk of a damaging event, our approach could prove a useful tool for evidence-based climate change adaptation policy.” In doing so, they shift the potential use for EEA from liability to adaptation. Since then, a number of studies explore the different potential uses and users of EEA. Stott et al. (2013) discuss six reasons why EEA is relevant for different groups of stakeholders: development of extreme events science, dissemination of climate change impacts to the public, litigation[1],

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[1] Note that while liability is the legal responsibility of a person, litigation refers to the process of taking a case to a court of law so that a judgment can be made.

information for adaptation policy, attribution of the effects of potential geoengineering compared to climate change, and insurance. Stott and Walton (2013) present the results of a workshop organized between stakeholders and scientists. They identify possible interest from insurers, lawyers, charities, the media, government and private sector representatives. They state that "what became apparent is that there is a clear need for attribution science, but the need is not uniform either within or across sectors.". Sippel et al. (2015) conducted a series of interviews with a range of stakeholders to understand their perspectives on EEA. The panel of interviewees mostly showed interest for EEA results in their respective domains (e.g. for insurance, awareness raising, adaptation policy and loss and damage). However, as this was an explorative study, the number of interviewees and their diversity do not allow to generalize these results or to prove that EEA is useful for a specific domain. To do so would require case studies conducted with targeted groups of stakeholders. This was one of the goals of the EUCLEIA project. Work Package (WP) 4 of EUCLEIA aimed at "assessing detection and attribution through general public and stakeholder analysis". I will discuss in depth its results in this chapter.

In chapter 2, I introduced a debate in the EEA community regarding framing approaches, which is related to diverging opinions regarding the use of EEA. On the one hand, Trenberth et al. (2015) defend the *storyline approach* as a "better basis for communication of climate change to the public". On the other hand, Otto et al. (2016) criticize this approach in favor of the *risk-based approach* "from the perspective of a stakeholder seeking information to inform disaster risk reduction strategies." Their disagreement ensues from a different perception of the end users of EEA results. Indeed, Shepherd (2016) underlines that the two approaches to event attribution are not mutually exclusive, and that "the most useful level of conditioning will depend on the question being asked", and hence on the targeted stakeholders. Lloyd and Oreskes (2018) discuss the "extremely heated response"[2] to the storyline approach and make a link with the choice of null hypothesis. The risk-based approach intends to prove that anthropogenic climate change played a role, while the storyline approach puts the burden of proof on showing that anthropogenic climate change had no effect. The first approach is prone to type II errors – i.e. false negatives – while the second is prone to type I errors – i.e. false positives. In the same line of thought, Mann et al. (2017) argue that the ethical choice is to avoid false negatives, as the consequences of understating the impacts of climate change could lead to under-preparation to these impacts (in opposition to Stott et al. (2013)'s warning about the "danger of premature attribution"). Stott et al. (2017) qualify this claim by pointing out that depending on the targeted stakeholders and on the financial means they can grant to adaptation, the relevance of choosing one approach varies. To put it in the words of Lloyd and Oreskes (2018): "The relative risks and benefits of the two approaches – including both the risks of over-reaction and under-reaction – deserve a fuller, and more evidentially based discussion than they have to date received." It is hence important to understand why scientists engage in EEA. Lloyd and Oreskes (2018) observe that scientists defending the risk-based approach – and the same case is true for the other side – base their rhetoric on public needs, without presenting evidence to support these needs. Our goal in this chapter is to contextualize these

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[2] This identification of an "extremely heated response" may be considered as an overstatement, as Lloyd and Oreskes (2018) base their arguments on three papers (Eden et al., 2016; Otto et al., 2016; Stott et al., 2016) and on a few abstracts of interviews mostly in response to Trenberth (2011), which, while relevant to the debate on EEA practice, discusses attribution more generally. Indeed, in line with the argument of chapter 2, the prism of the debate between storyline and risk-based approach is not sufficient to describe the diversity of the EEA community.

theoretical debates on the social need for EEA and to assess the motivations of EEA scientists.

Hulme (2014) proposes four types of motivation to explain the reasons why scientists do EEA: scientific interest, evidence to boost adaptation policies, liability, and awareness raising. This chapter explores the motivations stated by the scientists interviewed in the EUCLEIA and A2C2 corpus used in chapter 2[3]. Their statements are analyzed in the light of the (sparse) existing literature on EEA uses and on the results of EUCLEIA WP4. We follow the sorting laid out in Hulme (2014) with a few modifications to depict the full range of statements from the interviews: scientific curiosity, climate change litigation, information for decision makers and awareness raising. These four motivations correspond to the first four motivations proposed by Stott et al. (2013). We did not keep the geoengineering evaluation motivation as it was not mentioned by any interviewee. The insurance motivation is included in the information for decision makers category, as we consider insurers as private sector decision makers. We explore these different motivations while keeping in mind three background questions:

- Is there an added value of EEA compared to general statements on extreme events evolution, which could, for example, be deduced from the IPCC reports (see Chapter 1)?
- Is EEA the only and most relevant scientific way to answer these motivations?
- Which EEA approach (following the storyline vs risk-based debate) would be more suitable for this motivation?

This leads me to discuss the emergence of a European attribution service, in parallel of the work done in this direction within the EUCLEIA and EUPHEME projects (see Chapter 1). Before concluding, I examine the potential and the possibility for forward-looking attribution.

7.1 Motivations to conduct EEA

7.1.1 Scientific curiosity

Hulme (2014) advances the motivation of scientific curiosity, as attribution of individual events "piques the scientific mind". It pushes the boundaries of climate models by asking them different questions, and encourages scientists to test original configurations of their models, like the weather@home experiment (Massey et al., 2015). Stott et al. (2013) highlight the challenges in understanding and modeling extreme events and how they are affected by anthropogenic climate change. The momentum related to EEA has led to more research on these topics, and hence participated to the improvement of extreme event science.

The scientific motivation to pursue EEA is not the main motivation – both in terms of time spent on it during the interview and in scientists evaluation of which EEA uses were most important – stated by scientists in the interviews. However, it is mentioned by almost all the scientists interviewed in the A2C2 corpus (except for A7), and it came up thrice in the EUCLEIA corpus. As the EUCLEIA corpus explored the scientists' perspectives on the building of a climate service, aimed at non-scientist stakeholders, the lack of reference to a

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[3] The interview grids are presented in Appendix C. The methodology is similar to the one detailed in chapters 2 and 6

A1	“From a scientific prospective it is maybe not as quite as useful. It sometimes feels a little bit like ambulance chasing” “That is what paparazzi do” “I think event attribution will come to that stage [where] first of all, we convince ourselves that we’ve been able to do it reliably and then secondly we convince ourselves, for a given kind of event, that we understand the processes that were involved in producing that kind of event. Then at that stage, the scientific value of undertaking this kind of research becomes lower. ”
A2	“I think it is useful to satisfy scientific curiosities. From a scientific point of view, it’s extremely interesting because it is difficult. [...] We only have now the observation, we only have now the methodologies, and we only [...] start to have the models. I don’t think they really are up to do the job yet, but we only started to have the models to basically answer to this question. So again, there is still a huge scientific challenge to move ahead, there are still many open questions there is still a lot of things to do, to check, to understand and to get there.”
A3	“As a researcher I was interested in it because I was under the impression that I could improve what was done [in terms of tools]”
A4	“I am more interested in generating understanding about our tools, methods, assumptions, and the kind of a general understanding of how the things are changing rather than specific results.” “it is useful [...] for generating understanding of the tools that we have at hand.”
A5	“What I find stimulating scientifically is to see opportunities to make progress in climate science [based on causal theory]. [...] This is something that has not been done, hence everything has to be done. I find it quite stimulating.”
A6	“There’s an interest in the development of mathematical models. I develop methodologies [...] for me, the users are climate scientists.”
A8	“[I am not interested in EEA] from a scientific stand point”
A9	“[I am interested in EEA] because it is a challenging question”
E4	“[I consider the development of an EEA service important to achieve] better understanding of what’s leading to a given event and also how this would happen in the future with greenhouse gazes.” “Scientists would be interested in the results of EUCLEIA”
E8	“I am satisfied here when I understand, I really understand the physical processes that generated these events and if I’m sure that I can reproduce this experiment.” “we’re building something that’s [...] very useful for other colleagues and other researchers”
E10	“I feel that my own interest remains on the research, on the natural sciences nature of the problem, instead of how to provide a service to the other, to the society.”

Table 7.1 – Statements of interviewed scientists on the scientific interest of EEA. The excerpts from participants A3, A5 and A6 are translated from French.

scientifically grounded motivation is not surprising. Table 7.1 displays the most relevant excerpts from interviews on this point. We found a discrepancy in the views of EEA as a scientific object. From two different interviews we get both “from a scientific perspective it is maybe not quite as useful” (A1) and “from a scientific point of view, it’s extremely interesting.” (A2)

A few interviewees raised concerns about the relevance of EEA as a research question (A1 and A8)[4]. It is interesting that those worries exist within a pool of climate scientists who have participated in EEA research[5]. For example, A1 fears that EEA is “a little bit like ambulance chasing” and that “that is what paparazzi do”. In the future, EEA might become more of a climate service and more of an engineer type of work. “Then at that stage, the scientific value of undertaking this kind of research becomes lower.”

We found nonetheless arguments to defend the scientific potential of EEA in the interviews. EEA interests scientists for three reasons. First, it is a “difficult” and “challenging” problem (A2 and A9). Second, it presents opportunities for the development of new methods (A3, A5, A6) and scientific knowledge (A2, A4, E4, E8, E10). Third, A4 makes a similar point to Stott et al. (2013) that EEA tests the ability of our models and tools in front of a complex problem. From this standpoint, the limitations of EEA are informative in themselves. A6, E4 and E8 also state that scientists are potential users of EEA results and of a possible service.

The points of view regarding the scientific interest of EEA differ. It is undeniable that the momentum created around this research question has led to improvements in statistical and physical tools used in climate science, as well as better understanding of the physical processes leading to specific extreme events. This benefit of EEA makes it relevant in comparison to other possible scientific endeavors regarding the evolution of extreme events with anthropogenic climate change. The diversity of approaches of EEA is an asset to develop the science of extreme events in several directions.

7.1.2 Climate change litigation

The potential to establish climate change liability was the initial motivation for EEA. Allen (2003) states that “the prospect of a class-action suit with up to six billion plaintiffs and an equal number of defendants may seem rather daunting, but if we can overcome these problems in end-to-end attribution, everything else is (at least conceptually) straightforward.” Stott et al. (2013) propose this motivation relying on arguments advanced by Allen et al. (2007), who defend an operational attribution system, which could simplify the judges task regarding an otherwise complex question. Hulme (2014) expresses concerns regarding the robustness of attribution statements and whether methodology and model-dependent results could “hold sway in courts”. This motivation is part of the larger context of emerging climate litigation (e.g. Adam (2011); Grossman (2003)). It also connects to the potential use of EEA for loss and damage to which chapter 6 is dedicated (see also Hulme (2014)).

Only five interviewees (A1,A4,A7,E1,E5) brought up liability as a potential motivation for EEA. Their statements are displayed in Table 7.2. All of them think that EEA may play a role in courts, although they are aware that it is not yet the case. A7 and E1 hint at a rise in interest from the legal community based on exchanges with stakeholders. However, A4 points out that a case can be concluded without EEA information and E5 raises concerns regarding

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[4] We could also consider that the fact that A7 only discusses social uses of EEA means that the research question is not very interesting from A7’s perspective.

[5] Note that climate scientists in general are not completely convinced by EEA. Bray and von Storch (2016)’s climate scientists survey shows that a part of the community is not even convinced it is possible to attribute an event to climate change (see Figure 77 of Bray and von Storch (2016)), and is not convinced of the robustness of existing EEA results (Figure 73)

A1	“[At some point], we would still want to continue to do [EEA] but more from a perspective of documenting the risks that we are exposed to or for finding legal liability for something that is happening to us.”
A4	“If you are thinking of legal cases and court, in domestic law, then I would say that detection and attribution is probably necessary. [...] I don’t think there are users of that, yet. [...] A primary reason [is] that any case so far has fallen short of even getting to the point where this question rises. There have been other circumstances when the case has been concluded, without getting to that point.”
A7	“I think it could potentially play an important role [...] in courts.” “Recently, I think lawyers are picking up on event attribution and they’re trying to explore whether and how it could be used in courts.” “I think it would make a difference if anywhere in the world there would be a successful court claim that some losses were due to anthropogenic climate change”
E1	“I think there is a potential use in terms of possible litigation, I mean I’ve been approached, and other have about his, and this may or may not be speculative but there are so many people by now who are considering whether or not it is possible to take cases to court against services and against an individual or a company for example, and they would seek to take it to court on the basis that their emissions caused damage and therefore they are interested in how they would do that and potentially they could use scientific information about the extent in which you could do this attribution of a damaging heatwave, for example, resulting in deaths or whatever it might be.”
E5	“One of the possible uses of attribution [...] is around apportioning blame, which might be an legal context [...] However, I think, you know it needs to be handled with great care in that kind of area, because it really has a long way to go before it’s sufficiently robust to provide sufficiently clear answers.”

Table 7.2 – Statements of interviewed scientists on the potential use of EEA in courts.

the current lack of robustness of EEA (similar to Hulme (2014)’s point).

Recently, two articles have discussed the use of EEA for litigation (Lusk, 2017; Marjanac and Patton, 2018). They come to opposite conclusions. On the one hand, Lusk (2017) argues that even if EEA solved the attribution problem it would not be sufficient to solve legal liability. He bases his argumentation on the *Comer vs Murphy Oil* case (2012), in which a group of Mississippi homeowners sued a group of oil and energy companies for damages related to Hurricane Katrina. The court did recognize the role of anthropogenic emissions in Katrina, without the help of EEA, although there is very limited scientific material to support this statement. However, “the court found the plaintiffs did not have a standing” for three reasons: untraceability of greenhouse gases – the mixing of gases in the atmosphere makes it impossible to relate the damages caused by Katrina to the specific emissions of the defendants – justiciability – the court found the topic to be political, meaning it should be addressed by legislative rather than legal action – and preemption – the court could not punish defendants for “actions at one point formally encouraged by other branches of the government”. This contradicts Allen (2003)’s statement that everything except EEA would be “straightforward”. On the other hand, Marjanac and Patton (2018)[6] argue that EEA could be an essential step in

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[6] Note that this article builds on a shorter commentary published previously by the same authors (Marjanac

the causal chain for climate change litigation. They claim that the type of scientific evidence from EEA could be accepted in courts by drawing analogy with similar types of evidence of causation, like results from epidemiology which have been used in health related cases. They show that both the US and the UK law have developed ways to "find exceptions to the traditional deterministic 'but for' test for causation in certain circumstances"[7].

Climate change litigation is steadily growing worldwide (see Figure 6 of Nachmany et al. (2017)). As of August 15th 2018, the US Climate Change Litigation Database includes 901 cases, and the non-US Climate Change Litigation Database 267 (`http://climatecasechart.com/about/`). The non-US cases accounting for loss and damage represent only eight percent of the total number of cases (see Figure 8 of Nachmany et al. (2017)). Climate change litigation is a growing, but still new legal topic, which still has a lot of challenges to tackle (Adam, 2011; Thornton and Covington, 2016; Torre-Schaub, 2018). In this context, the cases on loss and damage[8], for which EEA could be relevant represent only a minority. This does not mean that this type of cases has no potential to develop in the next few years, especially with the advances of science, and its ability to link damages to climate change (Marjanac and Patton, 2018; Nachmany and Setzer, 2018).

For this motivation, if the parallel with epidemiology is to be followed, the risk-based approach would be more adapted, since it provides risk-ratios which have been used in health-related cases (although not always correctly interpreted (Mcivor, 2013)). However, Marjanac and Patton (2018) base a large part of their arguments on a statement that advances in EEA will result in advances in *foreseeability*. In courts, proving foreseeability means that the defendants had access to information showing that climate change modified the risk of the event that engendered damages. If they did not take appropriate action to respond to this change of risk, leading to damages experienced by the plaintiffs, it could make a case for negligence claims. EEA puts more weight on ex-post science than on foreseeability. It uses the available science just after the event happened to calculate a risk ratio or a fraction of attributable risk. Observation datasets, models, and tools are constantly improving. Hence, EEA results could by definition not have been available to the defendant prior to the event that caused the damage. This does not mean that climate science cannot provide a basis for negligence claims, but this implies that EEA would not be the most relevant science for this specific purpose. More generally, there are still many hurdles on the way to climate change litigation. At this point, it is not clear if EEA could (and will) be used or not. Exchanges between legal experts and climate scientists will be necessary to define which type of scientifically-based evidence could stand in courts.

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et al., 2017)

[7] The 'but for' test would correspond to necessary causation, for which the damages suffered by the plaintiffs would not have occurred but for the defendants actions. Marjanac and Patton (2018) remarks that three case studies from the BAMS report on 2016 extreme events pass the 'but for' test (Imada et al., 2018; Knutson et al., 2018; Walsh et al., 2018). However, most EEA studies do not find a null probability of occurrence of the event in the counterfactual world. Marjanac and Patton (2018) hence discuss the possibility for climate change litigation for this majority of cases.

[8] Here loss and damage is disconnected from the UNFCCC loss an damage. It corresponds to "Lawsuits dealing with personal property damage or injury caused by climate change-related events." (Nachmany et al., 2017)

7.1.3 Information for decision-makers

Hulme (2014) and Stott et al. (2013) both state that a motivation for EEA would be to inform adaptation policy. Their perspectives on the relevance of this motivation diverge. Stott et al. (2013) make two points. First, they state that extreme events can be "harbinger[s] of the future". Attribution statements regarding the evolution of their probability could help decision makers to allocate funds for adaption (see also Hoegh-Guldberg et al. (2011)). Second, Stott et al. (2013) are concerned by possible cases of misattribution, which "could lead to poor adaptation decisions" (Stott and Walton, 2013), by adapting to events that will become rarer in the future (like cold spells). Hulme (2014)'s main point of contention is that behind this reasoning is the assumption that adaptation should be based on optimal decision-making[9]. Given the nature of climate change and the existing uncertainties on both climate variability and how it is affected by climate change, authors have been arguing for an approach focused on robust decision-making[10] (Dessai and Hulme, 2004; Dessai et al., 2009; Weaver et al., 2013). Hulme also argues that the allocation of adaptation fundings should be based on vulnerability to extreme weather events, rather that attributability (Hulme, 2014; Hulme et al., 2011). The stakeholders interviewed in Sippel et al. (2015) adopt a variety of perspectives on the potential of EEA for guiding the allocation of adaptation funds. Some of them think it will be useful, while others expect the process to be piloted by political moves rather than scientific evidence.

The participants to the interviews had many more comments and interest in the motivation to do EEA to inform decision making than for the two previous categories. The interviews show that scientists envision EEA as an input for decision making for wider applications than adaptation: they also discuss the use of EEA results to inform mitigation and insurance.

7.1.3.1 EEA to inform mitigation

Three interviewees expressed the view that EEA information could help to show the impacts of climate change and push policy makers to adopt ambitious emissions targets, in order to avoid further impacts. A1 states that "we need to quantify the risk as well so that we can make informed judgments about how much money we should spend in order to mitigate those risks.". E1 explains that "there's a political process ongoing which seeks to come to an international agreement by which countries would commit to action on reducing their emissions and, [...] as parts of this whole process, I would say that policy makers are interested in how do we relate what is now happening around the world in terms of extreme events, weather and climate events, to anthropogenic climate change." So does E4: "Governments [are potential users,] in terms maybe of the development of their strategies in terms of the reduction of emission, they would say OK if they do realize that certain events are possibly made more probable by greenhouse gases. Maybe they would be interested in this information, to say: "OK we want now to take a decision for future action to reduce the likelihood of such event"".

This reasoning of political pressure on governments is similar to some of the arguments exposed by negotiators in chapter 6. It is also consistent with the results of Bray and von Storch (2016)'s survey of climate scientists, revealing that most scientists agree that success-

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[9] Optimal decision making relies on scientific evidence to choose the decision which will minimize the losses. It is hence based on a predict then act decison framework.

[10] Robust-decision making "seek[s] to identify policy vulnerabilities under deep uncertainty about the future and propose strategies for minimizing regret in the event of broken assumptions" (Weaver et al., 2013)

ful EEA would help to demonstrate the urgency of reducing greenhouse gases (see Figure 75 of Bray and von Storch (2016)). They are even more convinced of this than of EEA's potential to support the design of adaptation strategies, although they are generally convinced of the latter point (see Figures 76 and 78 of Bray and von Storch (2016)). Whether EEA information could be effective in this case has yet to be proven. There are other scientific results calling for mitigation, and there is no evidence whether EEA has an added value or not. If it has an added value, it is not clear which approach of EEA would be most useful. More research should be done to investigate these questions. The frontier between the awareness raising and the information for decision makers motivations is blurry in this case.

7.1.3.2 EEA to inform insurance

Information for insurance
[For insurers and risk managers], what really matter is the risk and its evolution. It's really the risk figures, the probability of occurrence. (A5)
It might potentially play a large role in the risk assessment, in the quantitative risk assessment, but amongst other methods. (A7)
The insurance companies are very interested in [EEA] (E1)
The insurance sector wants to know the risk of failure of systems, or floods, or whatever, in the coming years. So what we need to know is basically what is the risk in the current time. So how this risk has changed from their chronological time series to today's weather. (E3)
There are some aspects of the insurance industry that need information about the longer term time scales and I certainly think attribution is relevant in that context. (E5)
The insurance companies I'm aware of, might not be willing now to look at such services. (E8)
Also insurance companies. It's basically for the stakeholders who have an interest in knowing if this kind of event is more frequent or something that we expect a few more of. (E9)
I guess, like, insurance company they would be interested in it, because it's one of the areas that they have to consider their cost and their loss. (E10)

Table 7.3 – Statements of interviewed scientists on the potential use of EEA to inform the insurance sector. The excerpt from participant A5 is translated from French.

Stott et al. (2013) make the point that EEA shows that insurers cannot base their risk calculation on a stationary hypothesis. This has been identified as a sector of application by a part of the interviewees, mostly from the EUCLEIA corpus (see Table 7.3). This difference between the corpora might be related to the fact that insurers were identified as potential stakeholders in the EUCLEIA project. It was discussed in general assemblies and workshops where the EUCLEIA members were present. It is noteworthy that E8 is the only one who doubts the potential interest of insurers for EEA: "the insurance companies I'm aware of might not be willing now to look at such services.". A study of insurers interest in EEA was conducted within the EUCLEIA project (EUCLEIA 4.3 report (von Storch et al., 2016)). In-depth interviews were conducted and analyzed for two groups of stakeholders: German insurers for EEA applied to Baltic sea storm surges, and French insurers for EEA applied to heatwaves in the Greater Paris area. The Baltic sea test case showed a general interest of the insurers in EEA nuanced by a number of "*'but's* like that EEA does not provide an added value to the existing information, other components of risk are more important, or that it is not applicable in existing business processes”. Another conclusion was that “despite the fact that most of the interviewees were certain that EEA is relevant, no one was convinced that the added value of EEA is currently large enough to pay for it.” The French test case revealed that the current French insurance sector operates in a rigid regulatory system. In this case, if EEA highlights the need to take into account the influence of climate change on certain types of events, it could lead to a change in insurers cultural practices. A case was also made to envision EEA on class of events, rather than single events (EUCLEIA 4.3 report (von Storch et al., 2016)). In the case of the insurance sector, it is clear that the change of probabilities of meteorological hazard matters (e.g. Reguly (2013); Warner et al. (2013)). What is less clear is whether EEA in either of its forms is the most relevant way to address the insurers needs. One of the issues is that EEA is tailored to very specific types of events. Another issue is that insurance is based on risks, not only on probabilities of hazards, which also rely on an evaluation of exposure and vulnerability (Sillmann et al., 2018). Lastly the proof of causation (or the calculation of the probability of occurrence of the event in a counterfactual world), is not especially relevant in the insurance context. A5 comments on that problem: “I think that insurers don’t care at all about the causal explanation. [...] what really matter is the risk, and its evolution.”. What seems most relevant for the insurance sector, while being the by-product of risk-based approach studies, would be the calculation of the current probability of occurrence of the event.

7.1.3.3 EEA to inform adaptation

The idea that EEA could inform and motivate adaptation is discussed by the majority of interviewees, and more specifically in the EUCLEIA corpus (see table 7.4). Only one interviewee (A2) explicitly states that he does not believe EEA could be useful in the context of adaptation. This conception of EEA use falls within a more general vision that extremes can be pacemakers of adaptation (Füssel, 2007; Moser and Boykoff, 2013; Travis, 2014). The point made by Stott et al. (2013) is that EEA information has potential to help decision makers discern which events are “harbingers of the future” and which are not. This could help avoiding some of the maladaptation practices described by Travis (2014), although not all of them. Indeed, Travis (2014) shows that the role of extreme events in triggering adaptation is still ambiguous, and highly dependent on the event and on the social and political environment in which it occurs: “the net effect of extremes on larger policy structures remains ambiguous in the literature, with the hint that even a strong signal does not necessarily ratchet policy adaptation.”

It is hard to find an argument specific to EEA – which would not apply more generally to the science of understanding the influence of climate change on extreme events – in the interviews to explain why and how EEA could help adaptation stakeholders. A few of the statements of usefulness are done without explanation (A9, E1, E5, E8, and E10). This does not mean that there is no reasoning behind their arguments, only that they did not feel the need to propose an explanation in the context of the interview. A1 and E6 highlight that the climate change related risks are “felt most strongly through impacts of extremes”. A5, E3, and E7 argue that understanding that extreme events are already changing because of climate change is a signal for the future of extreme events. These arguments can be applied to EEA, but they relate more generally to the development of science studying extreme events in the context of climate change. In fact, since EEA adopts an ex-post point of view on extreme

Information for adaptation
We work with stakeholders [...] their questions are very often about extremes and about what has caused extremes and whether or not they become more likely now than in the past and whether or not they will continue to happen in the future. [...] the people who are posing these questions come from governments, like provincial governments and other places and they are the people who are responsible for adapting to a changing climate and to managing the risks caused by changing climates and those risks are felt most strongly through impacts of extremes. (A1) • For the general public, one could argue it doesn't really matter what the reason is, for them, to be prepared, all that matters is whether the extreme change or not. • I don't think it is particularly useful information for adaptation plans, or something like that. (A2) It [EEA use] is to better manage risks, in particular to anticipate their evolution, to adapt to climate evolutions, in relation with adaptation policies. (A5) The potential users are the people having to make decisions about the future, some sort of investment, some resilience, a decision to move or something like that.(A9) • I think there's a potential for regional managers to understand [...] the current risks from extreme weather. • There are huge amounts of money at stake in terms of adapting to climate change. (E1) The use of attribution is at the base of adaptation. Because if we understand what what we are witnessing is due to, that it has strongly increased climate change then it will come again more frequently and then I have to do something, if I'm a user. (E3) The government is obviously concerned with adaptation to climate change, and industry is concerned with relatively long term investment with large expensive assets, I think they are gonna be interested in attribution results and services (E5) • I would say, private business, and why? Because extreme events affect their, the way they do their business and it's a starting point for them to develop their products, and their strategies, and it helps to have a tangible event, or an event attribution at hand because you can relate to it. • Policy makers, although they are primarily interested in developing policies for the future, being aware, specially in adaptation, in climate adaptation, not so much mitigation, but specially climate adaptation, that for adapting to climate change [...] you need to take climate change into account and it's already occurring. (E6) • The purpose of our work, and our message in the end should be to support adaptation to climate change. • It's mainly important to inform the public, to inform stakeholders and decision makers, and to give them a motivation, or maybe another motivation to do adaptation. • I think decision makers would be interested in our attribution information, because it may have an impact on their decisions if a certain extreme event was caused by human activity or if it was purely natural. Because if it was purely natural, well you can't do much about it, but if it was induced by human activity or at least supported by human activity then, then first you know that it will probably get worse in the future, because human activity continues to harm the climate, and secondly again it may help to make decisions for increasing adaptation. (E7) The first to be interested for me, are the public services, the cities or local governments, because they have to get the citizens prepared for future challenges, they have to make regulations. (E8) I guess mainly sectors [...] that need to have a long term planning, some industrial sector, like oil companies, when they need to have long term strategy on what to build, the energy sector, the insurance sector maybe. (E10)

Table 7.4 – Statements of interviewed scientists on the potential use of EEA to inform adaptation plans. The excerpt from participant A5 is translated from French.

events, the point has been made that it is not suited for adaptation, which is forward looking (Lusk, 2017; Thompson and Otto, 2015). Finally, E6 defends EEA because "it helps to have a tangible event", which shows that "it's already occurring". This point is also mentioned in

Sippel et al. (2015). One of their interviewees finds the focus of EEA on the current state of the climate valuable as it "would unambiguously highlight the relevance for addressing and reducing public health related risks now, not only in a somewhat distant future.". This argument can be related to EEA for awareness raising, which we will discuss later.

EUCLEIA dedicated a work task to "the understanding of user needs and the value of extreme event attribution for regional stakeholders". This research was based on in-depth interviews in two regions: the Baltic sea, which is subjected to storm surges, and the greater Paris area, with a focus on heatwaves. "Most stakeholders found that [EEA] would not change their own motivation or way of taking action. They told to be rather in need of information about vulnerability, potential impacts and promising adaptation options; such information was not perceived to be enhanced by EEA results." (EUCLEIA 4.2 report (von Storch et al., 2015)). The group of stakeholders interviewed for EUCLEIA rather found that EEA had potential for awareness raising of climate change. Another important result from EUCLEIA was that: "the assumption that EEA facilitates a more effective resource distribution, planning and implementation of climate adaptation could not be confirmed." (EUCLEIA 4.2 report (von Storch et al., 2015)). These results were also the object of an article (Schwab et al., 2017).

Two interviewees also present EEA results as a mean to increase the acceptability of possibly unpopular adaptation decisions. A1 states that: "from a policy maker perspective I think it has been a really useful thing to do. Very often, the message that climate is changing and that the risk to which the community is exposed is changing is only learned when an extreme event occurs and so the work that is done in the process of event attribution is what helps to help the users understand exactly what it is they are exposed to." A9 adds that "the expectation of the customers is that the people that they deal with understand why they made that choice, and don't question." They see EEA as a tool to justify decision makers actions in the eyes of their voters. This leads us to the last motivation to explain the success of EEA in the scientific community: the use of EEA for awareness raising.

7.1.4 Awareness raising

Hulme (2014) argues that frustration regarding the invisibility of climate change (Rudiak-Gould, 2013) is another reason that pushes scientists towards EEA. Stott et al. (2013) recommend rapid attribution in the wake of extreme events to inform the general public. Stott and Walton (2013) present similar arguments. Bray and von Storch (2016) reveal mixed feeling in the pool of scientists they surveyed regarding the ability of EEA results to make climate change visible and convince citizens of the reality of climate change. Our interviews give us an overview of the opinion of scientists engaging in EEA on its potential for awareness raising. This awareness raising seems to have two potential recipients: the media, and through them, the general public. As we have seen in the previous section, decision makers could also be considered a third category. The line between information for decision makers and awareness raising for said decision makers can get blurry.

Table 7.5 presents excerpts from the interviews relevant to awareness raising, divided in two parts: the demands they received from the media, and how they perceive the usefulness of EEA for the media and, through them, for the general public. Awareness raising is the motivation mentioned the most in the interviews, probably because it is the only one for which many

Demands from the media
My interest in event attribution [...] is [...] also because that is one of the pressing questions that the media asked for. (A2) The press asks us to comment papers, and events. (A3) Every now or then, I get a call from a journalist (A4) I've been in touch several times with medias on these topics. (A5) You get questions from the media: what's the cause of this? Did it have a climate change component? (A8) It is sort of the most current question on climate change. I would say that three quarters of the news stories that you hear about climate change are about extreme events.(A9) many climate scientist are being asked all the time about [...] these attribution questions by journalists (E1) My experience up to now has been that the media are very interested in this sort of information (E2) The journalists are the first to ask these questions. When we have some extreme weather they always ask the relation to climate change. (E3) The media would love [to have an attribution service] (E5) I think the media are immediately interested in it. (E9)
Perceived usefulness for the media and the general public
• I think the media are so interested, because [...] one degree warming doesn't sound like much but if it is actually implies that we get, what we really now have, much more heavy rainfalls or much more intense heat waves, and that is really something to worry about. • It is useful in, to basically have a case to communicate through media, what climate change really means, how it affect us. (A2) • The influence of climate change on the mean is not something that touch people that much, and especially it does not worry them. • The perception of problems induced by climate change will not be done on the basis of IPCC but when people are confronted to a severe extreme event [...] the awareness will come occasionally with these extremes. It allows to illustrate climate change. (A3) • [A usefulness] would be in terms of, for the general public, contextualizing future climate change, in terms of their experiences. • I think that study really brought across the idea that [summer 2003] is a summer that is 2.3 degrees warmer than usual, and that calibrated everything for them within their experiences. (A4) • I think a few climate skeptics may change their opinion because of well done causal attribution studies. • For the media and the general public, the usefulness of EEA is really the satisfaction to understand something. (A5) People make attribution statements without scientific evidence if we do not provide scientific evidence. I think overall it makes more sense to do it with the scientific evidence we have. (A7) The only way to get through to [politicians denying climate change] is through the general public. And so it's important to communicate with the general public, and tell them that climate has changed and in fact there are tens of billions of dollars of damages that are caused by climate change every year.(A8) There is some truth to that, that people respond to stories that resonate. (A9) I think we can do better than we're doing without the IPCC report, you know, it's not the best way of communicating the findings to the public. (E1) It's a climate understanding service, in the first place. (E3)

Table 7.5 – Statements of interviewed scientists on the demands from media and their perception of the usefulness of EEA for the media and the general public. The excerpts from participants A3, A5 and A6 are translated from French.

of the interviewees have been in contact with users: journalists (see the first part of Table 7.5).

That does not mean that all interviewees find the media to be the most relevant users. For example A6 states that "The media and all that, that's not very interesting to me" and A9 stresses that they are not the most interesting users in his opinion: "it is a user I suppose, but I am thinking not so much of the newspapers".

Most of the interviewees perceive EEA as a useful communication tool. It would help people to understand the links between climate and weather (A5,E3). There is also the idea that it is a different way to communicate climate change, implicitly or explicitly compared to more traditional ways to explain climate change, like the IPCC reports (A3, E1). EEA would be a way to make climate change visible, and to unveil its impacts. There is the idea that extreme events cause people to worry compared to figures on mean variables (A2, A3). EEA could hence make people realize the seriousness of climate change. Another argument for EEA as a tool of communication is that it would be a way to link climate change to people's experience, rather than to abstract scientific results (A2,A3,A4,A9). Two interviewees also bring up the the potential of EEA to change the opinion of climate contrarians (A5 and A8). Finally, A7 remarks that even without EEA, people make their own attribution statements: "people make attribution statements without scientific evidence if we do not provide scientific evidence. I think overall it makes more sense to do it with the scientific evidence we have." (see also (Leiserowitz et al., 2012)). Two examples of these non-scientific based attribution statements were presented to introduce chapter 6.

There are many questions surrounding the interest of media in EEA. There is no denying that it exists, since the majority of the interviewees mentioned the media as a user they interact with more or less frequently. It is more tricky to decipher which media circulate EEA results. For example, regional German and French media outlets cover extreme events like rainfall or storms without linking them to climate change, in contrast to national newspapers, which are more interested in EEA (EUCLEIA 4.4 report (Vanderlinden et al., 2016)). A8 highlights that the climate change angle is not always preferred by the media covering extreme events: "Most of the stories that get written just report on the event and they don't say anything about climate change or how this particular event may have been worse because of the human activities. [...] But there is a number of reports where climate change does get some mention." Another question is how much has EEA gained, and is gaining ground in diverse types of medias, including social media, with the increase in EEA studies (even since the EUCLEIA reports). It is extremely difficult to evaluate the actual weight of EEA in the media from a climate scientist point of view, especially when each extreme event triggers a number of calls by journalists. From the general point of view of the media, climate change news – including EEA – have to compete with a range of topics, like sports, politics, economy or entertainment. Even more complicated to evaluate than weight, efficiency of EEA stories in the public opinion should be assessed, in order to understand if they have the potential to change the opinion of individuals.

The EUCLEIA 4.4 report also highlights important points to make EEA results *relevant*, *trustworthy* and *understandable* for the general audience. The selection of events should be based on extreme damages, and at a regional scale. If possible EEA should study impacts and not only meteorological observables (relevance). EEA results should be presented alongside an explanation of the methodology that led to these results and with a physical explanation of the processes leading to the event (trustworthiness). The treatment of uncertainties and complex figures like the fraction of attributable risk is also tricky, as the participants to the EUCLEIA survey "demanded that information from EEA should be illustrated in an appropriate graphic format and be linked to pictures and storylines" (understandability). The gap between the present form of EEA results and the simplicity of the answers the media and the general public want is identified by a few interviewees: "They just want to have a binary answer : it is caused by the human influence or not [...] it is usually challenging to talk to them if the answer is no." (A2) and "I am under the impression that quantifying the change in probability of occurrence is not their first interest, what concerns them the most is whether there is an anthropogenic contribution or not." (A3). The difficulty to communicate EEA results was also raised in the EUCLEIA corpus to answer the question "What are the arguments you would expect from someone believing that extreme event attribution services are not needed or not desirable?" (see Appendix C). For example, E1 answers that "even if you find somebody who cares they wouldn't be able to understand the information and make useful sense, I think this would be another argument" and E8 states that "It may be almost impossible to get this message across, because we're not having a yes or no message, a zero or one message, but we're having something in between which is indeed hard to get across to people.". All these points should be taken into account when choosing which EEA approach to use for awareness raising. At the moment, we lack an empirical study to conclude in favor of one approach or the other. Confronting people with different ways to present EEA information through in-depth interviews and/or a survey would be a way to move forward on this topic. For example, Knoblauch et al. (2017) conducted a survey to test how people reacted to different ways to communicate risks of induced seismicity due to new technologies. They presented their sample with three different formats of written risk communication. They found that the respondents preferred having both qualitative and quantitative information, rather than only qualitative information.

Lastly, it is important to be realistic regarding the potential for EEA to raise awareness. Marquart-Pyatt et al. (2014) have shown the perception of climate change in the US is driven by political orientation, and that the influence of climate extremes is not discernible (at least at the time of their study). Konisky et al. (2016) find a "modest, but discernible" effect of extreme events on climate change awareness, but only for recent events, hinting at a short-term phenomenon. Bohr (2017) finds that temperature anomalies exacerbate political polarization on climate change, rather than change the initial opinion of the affected people. Hamilton et al. (2016) find similar results for floods. Marlon et al. (2018) argue that it is because of the subjectivity of the general public perception of climate change that experts and scientists need to step up and interpret weather events in regards of climate change. Events alone will not be sufficient to make climate change visible, maybe commented events could (again, this should be tested).

7.2 Building a climate service

What emerges from this panorama of perspectives of scientists regarding their motivations to undertake EEA studies is that first, there is a plurality of motivations and that individual scientists disagree regarding which one is most useful. Second, in the light of the EUCLEIA results, there is a lack of solid, empirical evidence to back up any of these motivations. In fact, the few empirical studies that have been conducted (the EUCLEIA reports, Schwab et al. (2017), chapter 6 of this manuscript) rather tend to find inconclusive results regarding the use of EEA for non scientific stakeholders. This does not mean that EEA cannot be useful, but simply that its usefulness is not straightforward, especially when it comes to social needs, and ought to be demonstrated for specific groups of stakeholders, which has not been done yet.

Such types of studies should be easier to do now that EEA has developed, and that there is a number of existing methodologies and approaches, which could be presented to stakeholders to test their relevance for different uses.

There is an incentive at the European level to implement an attribution service, through EUPHEME, the successor of the EUCLEIA project. One of EUPHEME's objectives is to "provide a user-oriented synthesis, disseminate consistent attribution assessments through a prototype attribution service website and demonstrate the potential of attribution products to a wide variety of stakeholders". At the same time, the European funded Copernicus climate change service[11] prepares the ground for an operational attribution service. Although the science may be mature enough for such a service[12], there is an apparent discrepancy between the funding of such an endeavor by the European Union and the lack of proof that it will be useful outside of the scientific community. EUPHEME's working group 1 aims at "establish[ing] a dialogue between users and scientists to develop a clear common understanding of event attribution and its uses including the full range of methodological uncertainties and potential implications for decision making". A legitimate question is whether there is a place for inconclusive results, similar to what happened in EUCLEIA, at this stage of the process. The concern about a potential lack of users is shared by some (a minority) of the interviewees. For example A6 states that: "[he does] not know if [an attribution service] would be really useful", and E5 declares that "[he is] not personally totally persuaded that an extreme event attribution service is a good idea" and that "it's not obvious to [him] that an operational attribution service is really what users need". More generally on climate services, which apply to the attribution service, E8 advances that "as long as we don't contact people, or don't make a survey, or a market study about this, [he] always hear[s] that we might be working on a very nice tool, or making a very nice whatever, which might not be useful to other stakeholders". What would happen to the emerging European attribution service if no user is found? Would climate scientists who have developed the science and lobbied for the creation of such a service be ready to accept negative results from social science? Climate services should not be implemented only because they are technically feasible, but also because they have proven their social usefulness (Dilling and Lemos, 2011; Hegger et al., 2012; Lemos et al., 2012; Lövbrand, 2011).

7.3 Forward-looking attribution

EEA is an *ex-post* science, meaning that it compares an event and what it would have been without climate change once the event is over. By construction, it does not look to what this event could be in the future. This ex-post framing is one of the limitations of EEA's potential uses, especially in regards to activities related to planning, like adaptation (Lusk, 2017; Thompson and Otto, 2015) or to prove foreseeability in a litigation context (Marjanac and Patton, 2018). This does not prevent a few interviewees to argue that understanding how climate change affects extreme events now is a sign of how it will continue to affect them in the future (e.g "We want to take lessons from events that occurred so we need to be able to apply those lessons to future events. I think the only way that we can do that is by understanding

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[11] `https://climate.copernicus.eu/`

[12] That point is debatable. For example, we get from the interviews: "I would say it's not mature enough, that we could provide services on these aspects. I think it's still in the research stages." (E10), or "it's going a little too fast in regards to the level of confidence we have at this point in datasets and in results."(A3).

the circumstances that accompanied the particular event."(A1); "If there is a climate change component to these events, that has implications for the future."(A8) ; "For stakeholders also this knowledge may be important, to know if it was caused by human influence, because then also stakeholders could expect this to get worse in the future." (E7) ; see also Stott et al. (2013)). However, a few interviewees also expressed unease in regards to the backward-looking framing of EEA. For example, E3 states that "what [states and local authority] want to know is not really if it's due to climate change, they want to know if this will come again. [...] That's also the difficulty I have in EUCLEIA is we look only at the past." E5 adds that "to make the service more useful it would have to have specific statements about the likelihood of similar events happening in the future." E9 adopts a similar reasoning: "I think the final product would be an assessment of if an event like this would become more likely in the future or not."

It is not true that all EEA studies are limited to only look at the event from an ex-post perspective. It is possible to use the same modeling and statistical tools to project the event in the future (Donhauser, 2017). In fact, the first EEA article (Stott et al., 2004) commented on what would be the probability of exceeding the 2003 summer European temperature by the 2040s and by the end of the century. One of the interviewees comments on the way the public appropriated this part of Stott et al. (2004): "the message that people took from that was that [...] they noticed that in 20 years, the 2003 event was not going to be all that rare. It was going to be a more or less average event. Then in 50 years time, it is actually going to be an unusually cool event. And I think it was looking toward the future, it made them realize this is an unusually hot year for us now, but it is not going to be in the future." Although most of the EEA articles do not include a forward looking attribution, there are examples. We found a few in the BAMS reports on extreme events of the previous year (see Appendix A). For example, Van Oldenborgh et al. (2012) put their results in perspective by calculating trends up to 2100 from models outputs. Sweet et al. (2013) evaluate the evolution of the annual maximum storm tide level for four different scenarios of sea level rise (see also Sweet et al. (2016)). Yoon et al. (2015) use the CESM large ensemble (Kay et al., 2015) to project the evolution of fire risks in the future. Jézéquel et al. (2018) also rely the CESM large ensemble to compare temperatures that could have been for a similar circulation in three sub-periods: 1951–2000 (the past), 2001–2050 (the present) and 2051–2100 (the future). Similarly, Vautard et al. (2018) use the EURO-CORDEX (Jacob et al., 2014) and the RACMO-EC-EARTH (Royal Netherlands Meteorological Institute Regional Atmospheric Climate Model, de Vries et al. (2014); Lenderink et al. (2014); van den Hurk et al. (2015)) ensembles to compare return periods in three sub-periods: 1971–2000 (the past), 2001–2030 (the present) and 2031–2060 (the future). Conducting these interviews and finding arguments for forward-looking attribution in several of them had a direct influence on the climate science side of my research. It is one of the reasons that led me to consider how observed events would evolve in the future in Chapters 4 and 5.

Forward-looking attribution poses new challenges, both from a science and a communication point of view. Every method relying on ensembles of regional or global models (like CORDEX, CESM or CMIP5) can easily be applied to the future. It is more tricky for methods based of very long simulations of SST-driven models for a counterfactual and a counterfactual world (e.g. Massey et al. (2015); Pall et al. (2011)), but not impossible. It would only require to run simulations for one or several future counterfactual worlds, worlds that represent realistic futures depending on different emissions pathways. It is more complicated than the normal counterfactual world, because we do not know the anthropogenic forcings of tomorrow, but it is possible to test different plausible scenarios, like what is done for other projection exercises. It would pose different communication challenges to explain the differences between scenarios, and how they impact the results. Apart from the potential to answer different social questions, forward looking attribution could also help to identify climate change related trends that are not strong enough to be significant on the historical period (see for example Chapter 4).

7.4 Summary and conclusions

We have seen in this chapter that climate scientists engaging in EEA make assumptions about how their results will be used. Their motivations can be classified into four main categories: scientific curiosity, climate litigation, information for decision makers and awareness raising. The problem I identify here is not that these assumptions are necessarily wrong, but rather that they lack empirical evidence at this point (except maybe for scientific curiosity for which scientists are both the providers and the users of EEA results).

EEA has fostered new methodologies, new models, and generally scientific improvement in the understanding of the influence of climate change on extreme events. It is at a point where it looks for potential users. It is important for scientists to keep an open mind on what EEA brings to the table, and on which opportunities they have to potentially develop tools imagined for EEA in directions fitting user needs. That could mean for example not to consider the potential of EEA only from an ex-post point of view.

Résumé

Contexte et objectifs

Dans le chapitre 2, j'ai introduit les différentes approches de l'attribution d'événements extrêmes, tout en soulignant que le choix entre ces approches était essentiellement motivé par des raisons d'utilité sociale. Dans ce chapitre, j'explore les différentes motivations avancées par les scientifiques pour pratiquer l'attribution d'événements extrêmes. Ces motivations sont analysées à la lumière des trois questions suivantes :

- L'attribution d'événements extrêmes a-t-elle une valeur ajoutée par rapport à des résulats scientifiques généraux sur l'influence du changement climatique sur les événements extrêmes ?
- L'attribution d'événements extrêmes est-elle le seul et le plus pertinent des moyens scientifiques de répondre à ces motivations ?
- Quelle approche de l'attribution d'événements extrêmes est la plus adaptée à chaque motivation ?

Méthodes

Pour cela, je me suis appuyée sur deux corpus d'interviews de scientifiques pratiquant l'attribution d'événements extrêmes (les mêmes que ceux utilisés dans le chapitre 2). J'ai trié les différentes motivations selon quatre catégories, déterminées à partir de Hulme (2014) et Stott et al. (2013) : la curiosité scientifique, le contentieux climatique, l'aide à la prise de décision, et la sensibilisation aux enjeux climatiques. J'ai confronté les extraits d'entretien aux quelques études existantes sur l'utilisation de l'attribution d'événements extrêmes, en particulier aux résultats du projet européen EUCLEIA.

Résultats

Il ressort de cette analyse que l'utilité sociale de l'attribution d'événements extrêmes n'a pas été démontrée, et qu'elle n'est pas évidente. L'essort de ce sujet scientifique et l'enthousiasme de la communauté se sont traduits par le développement de nouvelles méthodologies, de nouveaux modèles et plus généralement d'avancées dans la compréhension de l'influence du changement climatique d'origine anthropique sur les événements extrêmes. Des projets de services climatiques d'attribution sont en train d'être mis en place, et la question des utilisateurs devient donc essentielle. Il faudrait davantage d'études empiriques auprès des utilisateurs afin de répondre au mieux à leurs besoins.

Conclusion

Take home messages

The question I addressed in this PhD is: how can we treat the influence on anthropogenic climate change on observed extreme events? This conclusion summarizes the innovating achievements of my thesis. I first reviewed the science of extreme event attribution, which aims at unveiling this influence (or, in some case the lack of influence). I showed in Chapter 2 that there is a variety of ways to approach this question scientifically and I highlighted the different choices a researcher makes when he conducts an EEA case study: the choice and way to define the event of interest, the choice of the level of conditioning at which one looks for the influence of climate change and the choice and way to define a world without climate change to compare with the present world. In Chapter 7, I underlined how these different choices relate to different visions of the social utility of EEA.

In chapters 3 to 5, I proposed statistical tools to explore the influence of anthropogenic climate change on European heatwaves. More specifically, I aimed at disentangling the evolution of dynamical and non-dynamical processes leading to these events. In chapter 3, I built a methodology based on flow analogues to calculate the role of dynamics in high observed temperatures for a constant state of climate. *Uchronic temperatures* are the temperatures that could have been for similar circulation patterns. In chapter 4, I defined *dynamical trends*, which evaluate whether atmospheric patterns leading to observed extreme heatwaves have and will become more frequent under the influence of climate change. In chapter 5, I tested how uchronic temperatures change for different sub-periods with different levels of anthropogenic emissions. I enlarged this first approach of the influence of climate change on non-dynamical components of European heatwaves by introducing *thermodynamical trends* – trends of temperature for a fixed type of circulation – and *residual trends* – the difference between thermodynamical trends and simple seasonal trends of temperature in a given region.

Chapters 6 and 7 treat the initial question from a social science perspective, trying to understand how we can treat the problem in a socially relevant way. In chapter 6, I explored whether EEA results could feed climate negotiations in the context of the loss and damage agenda. My analysis was based on interviews of both EEA scientists and loss and damage delegates. I found that the only potential role EEA could play to boost loss and damage would be to raise awareness for policy makers, aside from the negotiation process itself. In chapter 7, I evaluated how the different motivations stated by EEA scientists in interviews fare compared with the existing evidence on social use of this type of scientific information. I showed that the social relevance of EEA results is ambiguous, and that there is a lack of empirical data to better understand how different non-scientific stakeholders react and appropriate EEA information. Finally, I asked whether we need the extreme events to have happened to highlight how anthropogenic climate change has modified and will continue to modify more and more the profile of extreme weather events.

The specificity of this PhD is to combine social and physical approaches to the same question. Interdisciplinary practices between social and physical sciences usually involve researchers from both sides collaborating on a given topic. It is unusual for one person to do both. Of course, doing both was only possible because I was integrated in both communities. At this point, I cannot prove here that there is an added value in the latter compared to the former. I can only highlight how both sides of my research enriched the other in my personal experience. It generally allowed me to take a step back on everyday research and to grasp the bigger picture within which my results fall. Chapter 2 emerged from the confrontation of the interviews I conducted and the literature I read for the physical part of my PhD. The first intention was only to analyze the motivations of researchers to get involved in EEA, but it became clear that a first step in that direction was to be able to map the different practices of EEA. Chapters 4 and 5 became more future oriented as I was finding in parallel that it may be more useful for society to present observed events not only in regards to what they could have been, but also what they could become. I also think that the analysis I presented in chapters 6 and 7 relies not only on social science but also on the understanding of EEA I have because I also engage in physical science. As this PhD comes to an end, after mostly doing multi-disciplinary work during three years, I start to see how both sides could join into interdisciplinary research. I sketch this interdisciplinary direction in the following perspectives.

Perspectives

I discussed specific perspectives in each chapter of the manuscript. I now explore a possible research direction that results from the ensemble of the work presented in this manuscript. Extreme event attribution aims at understanding the influence of anthropogenic climate change on past extreme events. A somewhat similar yet different question would be what the extreme events of the future might look like from scenarios of climate change.

EEA adds an element of connection to real events to the state of knowledge on the influence of climate change on extreme events. This connection matters, because the memory of past events plays a role in our ability to imagine future events, and hence to anticipate them (Schacter et al., 2007). However, EEA links extreme events to climate change in a reactive way, i.e. once the event is over. The impacts of climate change are doomed to grow in the years to come. It is not clear yet how every type of extreme events will evolve, but the trends are significant for a number of them, especially when we not only take into account the historical period but also projections (see the difference between uncertainty in observed and projected changes in Figure 1.3). Climate change poses questions on human societies management of extreme weather events because the past cannot be considered as representative of the future anymore. In this context, I showed in Chapter 7 that forward-looking attribution could be a way to project events of the past in the future. This would of course be complementary to the existing approaches, which give over types of inputs, but it may be a way to keep the connection to reality while projecting it in the future.

In the same line of thought, Hazeleger et al. (2015) argue for the construction of tales of future weather, or storylines, which could be a concrete basis to confront decision makers with unprecedented, yet foreseeable extreme events. They advocate for an interdisciplinary approach and for a co-construction with decision-makers of those storylines so that they are not only extremes from a meteorological point of view but also in terms of impacts. There are a few examples of such studies in the literature (e.g. Attema et al. (2014); Haarsma et al. (2013); Matthews et al. (2016, 2017); Prein et al. (2017)), although none of those I am aware of do so in an interdisciplinary or in a co-constructive way. They mostly stick to the meteorological part of the extreme. Matthews et al. (2017) go further than meteorological variables by basing their analysis on heat stress evolution, and by weighing it with population growth. They put it in the context of the conditions experienced during recent heatwaves in Indian cities. The reliance on past events reconstructed with plausible future anthropogenic forcing levels is not necessary to simulate future extreme events. For example, Bador et al. (2017) extract a future summer mega-heatwave from a regional climate model simulation. Ragone et al. (2018) rely on a large deviation algorithm to compute extreme heatwaves in a climate model. Those efforts are still quite recent and far from being as developed as extreme event attribution.

I had the opportunity during my PhD to test how a group of stakeholders would react to the tale of a future event. I participated in October 2017 to an experimental workshop with participants from SNCF (Société Nationale des Chemins de Fer), the French national state-owned railway organization. This workshop was organized by Vivian Dépoues, a PhD student working on SNCF adaptation policies to climate change (e.g. Dépoues (2017)). It was the occasion to open an alternative discussion space on adaptation to climate change within SNCF and to test how effective this opening could be. The focus of the workshop was on summer heatwaves. An article describing in details the objectives, the design, and the results of the workshop has been submitted and is reproduced in Appendix E. One of the elements we proposed to open the discussion in the workshop was the tale of a high-end but plausible future summer, sometimes between 2035 and 2065 in Languedoc Roussillon, a region in Southern France[13]. We built this tale together with Vivian Dépoues, based on his knowledge of SNCF, and my knowledge of the influence of climate change on heatwaves.

It begins with extremely dry winter and spring. The first heatwave happens at the end of May. Temperatures have not been below 25°C in Languedoc Roussillon for three nights in a row. It is Ascension Day, which means a lot of travelers use the train for the long weekend. Since it is the first time a heatwave occurs so soon, SNCF is not prepared. Not all AC have been revised yet, and the train that spreads weed killer on railways is scheduled for the week after. A regional train between Perpignan and Montpellier has to stop because of an outbreak of fire very early in the season. AC is failing on board. Passengers get down of the train in the middle of nowhere. Traffic is consequently stopped for hours. June is not too hot with cold air coming from the North. July is much worse. An atmospheric blocking settles over Western Europe. This heatwave lasts for a month and covers half of Europe. The exceptional duration of the heatwave takes it toll on bodies. Incidents multiply during July. We can imagine a number of sick leaves, which stretches thin SNCF staff. Passengers are tired because of the heat, causing incivilities on board. The spatial extent of the heatwave also means that we cannot count on reinforcements from other regions. Lastly, September comes, after a very dry summer. We can have a heatwave in Perpignan, and at the same time extreme precipitation in Montpellier neighborhood[14].

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[13] Languedoc Roussillon was the region of focus of Vivian's PhD.

[14] Extreme daily precipitation is common in Fall in this part of France. These episodes are also called "épisodes

This future summer was built to enhance possible changes in seasonality (Cassou and Cattiaux, 2016; Sánchez-Benítez et al., 2018; Vrac et al., 2014) and duration (e.g. Meehl and Tebaldi (2004)) of heatwaves. We also tested whether the possible juxtaposition of different extreme events (possibly enhanced by seasonality changes) would be meaningful for the participants of the workshop. We told this tale after presenting a more general outlook on results from climate science on heatwaves, and their evolution. The combination of those two types of scientific inputs led to a rich discussion on how SNCF could adapt to intensifying heatwaves, and more generally on the strategy of the company to deal with numerous changes in the years to come. We have no proof from this workshop that the use of a storyline had an influence on the following exchanges between participants. We would need other experiments to test the potential of storylines as a way of communicating the changes in natural variability induced by climate change.

Storylines would probably be most relevant if they were co-constructed and tailored with the targeted stakeholders in addition to the interdisciplinary approach we proposed for the workshop. Another element to test is whether there is a difference between the reception of qualitative storylines such as the one built for the workshop and quantitative storylines. These quantitative storylines could for example rely on regional modeling (Attema et al., 2014; Bador et al., 2017; Prein et al., 2017). Flow analogues used in this PhD could also be a way to build future heatwaves. This could be done by looking at analogues of past heatwaves in future projections, in a similar way to what is presented in chapter 5. Another possibility would be to use an analogue based weather generator (Yiou, 2014) with constraints to reach the highest possible temperature on a prescribed number of days with a realistic atmospheric circulation.

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cévennols" in French and "Mediterranean events". They can cause casualties and damages because of flash floods. Vautard et al. (2015) have shown that these events have very likely intensified since 1950.

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Appendix

Appendix A

Classification of the BAMS articles

The following table provides the complete classification of the 105 articles published in the BAMS special reports on extreme events of the previous year published in 2012, 2013, 2014, 2015 and 2016 (Herring et al., 2014, 2015, 2016a; Peterson et al., 2012, 2013). The case studies are sorted as they were in the BAMS issues. The table is organized in nine columns: the authors, the event studied, the reasons stated for the choice of the event, the precise definition of the event (period, region,...), the level of conditionality, the definition of the counterfactual world, the methodology, the explicitly stated genealogy (if any), and miscellaneous comments. Complete explanations of this sorting are provided in Chapter 2.

Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
van Oldenborgh et al.	Thailand floods	Impacts	July-September precipitations in the upper catchment of the Chao Phraya river	Unconditional + Effect of La Nina	Past	Calculation of trends in mean and variability	van Oldenborgh et al (2007)	Evaluation of the contribution of La Niña + Future
Funk	Drought in East Africa	Impacts	March-June and June-September precipitations in East African regions	Effect of CC on the Indian-Pacific warm pool (IPWP)	Past	Correlation between temperature and IPWP time series	-	-
Rupp et al	Texas drought	Rarity	Mean temperature and total precipitations for JJA and MAMJJA in Texas (thresholds)	Conditional to La Nina and to SST	SST/GHG/SIC historical	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	Double conditioning
Cattiaux and Yiou	Seasonal temperatures in Western Europe	Rarity	Similarity to the observed circulation	Conditional to the circulation	Past	Flow analogues	Cattiaux et al (2010)	-
Massey et al	Warm November and cold December in Central England (CE)	Occurence of such months in the last decades	Observed November and December temperatures in Central England (threshold) + fixed return time (100 yrs)	Conditional to SST	SST/GHG/SIC historical	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	-
Christidis and Stott	Cold winter of 2010/2011 in UK	Impacts and rarity	Observed December-January and December temperatures in Central England (thresholds)	Conditional to SST	SST/GHG/SIC preindustrial	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	-

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
B1	Rupp et al	Low precipitation in Central US in MAM, JJA, and MAMJJA	Impacts and rarity	Different return periods of low precipitations in Central US for MAM, JJA, and MAMJJA	Conditional to SST	SST/GHG/SIC natural	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	
B2	Diffenbaugh and Scherer	July 2012 US temperature	Impacts and rarity	Observed July temperature, Z500, and soil moisture (threshold)	Unconditional	Preindustrial	Comparison of probabilities for different CMIP5 experiments	-	Study of the impact of CC on several variables (T, Z500, soil moisture)
B3	Cattiaux and Yiou	US heatwaves of spring and summer	Impacts and rarity	Similarity to the observed circulation	Conditional to the circulation	Past	Flow analogues	Cattiaux et al (2010)	-
B4	Knutson et al	March-May warm anomaly over the Eastern US	Rarity	Observed MAM temperature anomaly in the Eastern US (threshold)	Unconditional	Preindustrial	Trend calculation for varying start years	Knutson et al (2013)	-
B5	Sweet et al	Hurricane Sandy inundation	Impacts	Tide level gauge (threshold/return period)	Conditional to sea level rise	Past	GEV + different sea level rise scenarios	-	Forward looking attribution
B6	Guemas et al	September Arctic sea ice minimum	Rarity + Failure of models to reproduce the observed anomaly	Sea ice extent loss (ability to reproduce)	Conditional to multiple precursors (sea ice memory, extreme storm, temperature)	Not relevant	Reconstitution of anomalies with different precursors using a sea ice model	-	No explicit evaluation of the influence of climate change (although some precursors are affected)

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
B7	Zhang and Knutson	September Arctic sea ice extent	Rarity	Sea ice extent (threshold)	Unconditional	Preindustrial	Trend calculation for varying start years	Knutson et al (2013)	
B8	De Vries et al	Non occurrence of the 11-city tour	Impacts	20cm ice thickness (threshold for the 11-city tour to occur)	Unconditional + Effect of snow cover	1.5°C colder to simulate « historic » climate → sorted as Past/historical	Ice growth model with different precursors	-	
B9	Dong et al	Extreme European summer (precipitation anomalies)	Impacts and rarity	Precipitation anomalies (ability to reproduce)	Conditional to the SST/SIC patterns + Effect of SST patterns on the circulation	SST/SIC historical	Atmospheric model with different SST and SIC conditions	Dong et al (2013)	The direct effect of radiative forcing (GHG + aerosols) is not taken into account. Only the SST pattern which results from both CC and internal variability
B10	Tett et al	Wet Northwestern summers	Recurrence of particularly wet summers rarity	Amount of 5-yrs average precipitation (ability to reproduce)	Conditional to SST	SIC historical	Atmospheric model with different SIC conditions	-	Evaluates the role of SIC only
B11	Sparrow et al	Summer 2012 UK high precipitation	Impacts and rarity	Observed JJA cumulated precipitation (threshold)	Conditional to SST	SST/SIC/GHG preindustrial	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	
B12	Yiou and	Wet North	High	Similarity to the	Conditional to the	Past	Flow analogues and	Cattiaux et al	

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
	Cattiaux	European summer precipitation	anomalies (not so rare)	observed circulation	circulation		weather regimes	(2010)	
B13	Trigo et al	Winter 2011/2012 drought in the Iberian Peninsula	Impacts and rarity	DJFM cumulated precipitation	Conditional to SST + Effects of other precursors (circulation)	SST/SIC/GHG historical	Large ensemble of an atmospheric model with different SST/GHG/SIC	Massey et al (2012)	
B14	Funk et al	Rainfall deficits in Eastern Kenya	Impacts	Standardized Precipitation index (threshold)	Conditional to ENSO (through SST patterns)	Not relevant (ENSO focused)	Global forecast ensembles driven by different SST conditions (ENSO-only vs full ocean)	Lott et al (2013)	
B15	Zhou et al	North China floods	Impacts + unusual precipitations in a drying trend	Observed precipitation anomaly (threshold)	Unconditional	Historical	Trend calculations		
B16	Imada et al	Heavy rainfall in Southwestern Japan	Impacts and rarity	Similarity to the observed circulation (PJ index)	Conditional to SST + Effects of CC on other precursors (circulation)	SST/SIC/GHG Preindustrial	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011)	
B17	King et al	2011-2012 rainfall over Southeast Australia	Impacts and rarity	Consecutive 5-day rainfall (threshold)	Conditional to La Niña + Effect of La Niña	Preindustrial	Comparison of probabilities for different CMIP5 experiments		
B18	Christidis et al	Heavy rainfall over Easter Australia in March 2012	Impacts	Several precipitation thresholds	Conditional to SST	SST/SIC/GHG natural	Large ensemble of an atmospheric model with different SST/GHG/SIC	Christidis et al (2013)	
B19	Dean et al	Two-day	Impacts and	Observed moisture	Effect of CC on a	Natural	Comparison of		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
		extreme rainfall in December 2011 in Golden Bay	rarity	flux and humidity (threshold)	precursor (circulation)	forcings only	probabilities for different CMIP5 experiments		
C1	Swain et al	California drought 2013/2014	Impacts and rarity	Observed mean yearly Z500 anomaly over the area of interest (threshold)	Effect of CC on a precursor (circulation)	Preindustrial	Comparison of probabilities for different CMIP5 experiments		
C2	Wang and Schubert	California drought in early 2013	Impacts and rarity	January and February cumulated precipitation	Effect of CC on a precursor (circulation, humidity), Effect of SST	SST/SIC/GHG historical	Comparison of probability density functions for different AMIP model time periods		
C3	Funk et al	California droughts of 2012/2013 and 2013/2014	Impacts and rarity	Observed California precipitation (ability to reproduce)	Effect of SST (including and excluding ENSO), Effect of CC on a precursor (SST), Conditional to SST	Detrended SST	Large ensemble of an atmospheric model with different SST + CMIP5 analysis		
C4	Hoerling et al	Northeast Colorado extreme rains	Impacts and rarity	Heavy 5-day September rainfall (high percentiles of the model distribution)	Conditional to SST	SST/SIC/GHG Preindustrial	Large ensemble of an atmospheric model with different SST/GHG/SIC		
C5	Knutson et al	US seasonal and annual mean precipitation extremes	Rarity	Second highest observed precipitation (threshold)	Unconditional	Preindustrial	Trend calculation for varying start years	Knutson et al (2013)	

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
C6	Edwards et al	Blizzard in Western South Dakota	Impacts and rarity	Daily snow water equivalent and precipitable water	Unconditional	Preindustrial	Comparison of intensities for different CMIP5 experiments		
C7	Knutson et al	Annual mean warm anomaly over Australia and Western Tropical Pacific	Rarity	Annual mean temperature (threshold)	Unconditional	Preindustrial and natural	Trend calculation for varying start years	Knutson et al (2013)	
C8	Lewis and Karoly	Annual and spring Australian temperature	Rarity	Anomaly of the second highest temperature record (threshold)	Unconditional	Preindustrial and natural	Comparison of probabilities for different CMIP5 experiments	Lewis and Karoly (2013)	
C9	Perkins et al	Hot Australian summer of 2012/2013	Impacts and rarity	Observed number of heatwaves and peak amplitude (threshold)	Unconditional	Preindustrial + historical	Comparison of probabilities for different CESM-LENS experiments	Lewis and Karoly (2013)	Heatwaves are defined using the excess heat factor definition
C10	Arblaster et al	Hot Australian September	Rarity	Observed temperature anomaly (ability to reproduce)	Effects of multiple precursors (including CC)	Not relevant here	Sensibility experiments with a seasonal forecast model		
C11	King et al	2013 Australia heat and drought	Impacts and rarity	Observed precipitation and second hottest year temperature (thresholds)	Unconditional	Preindustrial	Comparison of probabilities for different CMIP5 experiments		
C12	Harrington et al	Drought in New Zealand	Impacts and rarity	90th percentile of maximun three-month accumulation	Unconditional + effect of CC on a precursor	Natural forcing only	Comparison of intensities and number of days for		Most of the discussion does not

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
				of dry days + observed circulation index (threshold)	(circulation)		different CMIP5 experiments		consider events, but trends in means.
C13	Min et al	Summer 2013 Korean heatwave	Impacts and rarity	Observed SST anomaly and 60-year trend (threshold)	Effect of CC on a precursor (SST pattern)	Historical and natural forcings only	Comparison of probabilities for different CMIP5 experiments	Bindoff et al 2014	Distinction between natural, GHG, and all forcings
C14	Imada et al	Japanese heatwaves of 2013	Rarity	Observed temperature anomaly (threshold)	Conditional to SST	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al (2011), Shiogama et al (2013)	
C15	Zhou et al	Hot summer in Central Eastern China	Impacts and rarity + “great public interest”	Observed temperature anomaly (threshold)	Unconditional	Natural forcings only	Trend calculation for varying start years	Knutson et al (2013)	
C16	Singh et al	June severe precipitations in Northern India	Impacts and rarity	Observed cumulative rainfall (threshold)	Unconditional	Preindustrial	Comparison of probabilities for different CMIP5 experiments		
C17	Dong et al	Hot, dry summer in Western Europe	Rarity	Observed temperature anomaly (ability to reproduce)	Conditional to SST + Effect of otther precursors (SST pattern)	Historical SST/SIC/GHG	Atmospheric model with different SST and SIC conditions	Dong et al (2013)	
C18	Yiou and Cattiaux	Wet Southern European winter	Impacts and rarity	Similarity to the observed circulation	Conditional to the circulation	Not relevant here	Flow analogues	Yiou and Cattiaux (2013)	
C19	Schaller et al	Heavy precipitations in May-June in the upper	Rarity	Observed precipitation (threshold)	Conditional to SST/SIC/GHG	Preindustrial SST/SIC/GHG	GEV on observations + Large ensemble of an atmospheric model with different		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
		Danube and Elbe basins					SST/GHG/SIC		
C20	Añel et al	Extreme snow accumulation in the Pyrenees during winter and spring	Rarity, in regards to the opposing trend	95th percentile of accumulated snow (threshold)	Conditional to SST/SIC/GHG	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC		
C21	Van Storch et al	Violent storm Christian/Allan	Impacts	minimum core pressure of 970hPa or less	Not relevant	Not relevant	Trend calculation on a reanalysis dataset	van Oldenborgh et al (2012)	
C22	Christidis et al	UK cold spring of 2013	Impacts	Observed temperature anomaly (threshold)	Conditional to SST and to circulation (NAO index)	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Christidis et al (2013)	
D1	Yoon et al	Fire season in California	Impacts and rarity	Fire indices (KBDI, extreme fire risk area and number of days)	Unconditional	Preindustrial	Comparison of intensities for different CESM-LENS experiments		Forward looking attribution
D2	Wolter et al	Cold winter 2013-2014 in upper Midwest (US)	Impacts	Observed temperature anomaly (threshold)	Unconditional	Preindustrial	Comparison of probabilities for different CMIP5 and CESM-LENS experiments + non stationary GPD using observations		Forward looking attribution
D3	Trenary et al	Cold Eastern US winter	Impacts	observed temperature anomaly and number of cold days	Unconditional	Preindustrial	Comparison of trends for different CMIP5 experiments		
D4	Szeto et al	July flood on south eastern Canadian prairies	Impacts and rarity	Observed anomaly of May-June precipitation (as a precursor of floods)	Unconditional + Effect of other precursors (circulation, pond	Past/Historical	Trend analysis from observation and CMIP5		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
					drainage)				
D5	Yang et al	North America winter storm season	Rarity	Observed ETSI (Extra-tropical storm index) of 2013/2014 winter (threshold)	Unconditional + Effect of other precursors (tropical Pacific wind stress anomalies)	Preindustrial and past	Forecast-oriented model simulation with different initializations	Murakami et al (2015)	
D6	Wild et al	Storms over North Atlantic/UK	Rarity	Windstorm (with a detection algorithm)	Effect of other precursors (North American temperature, convective activity over the tropical west Pacific)	Not relevant	Correlation between different variables of reanalysis datasets		
D7	Otto et al	Water shortage in Southeast Brazil	Impacts	Observed precipitation (threshold)	Conditional to SST + Unconditional	Past + Preindustrial SST/SIC/GHG + Natural forcings only	Multimethod approach : non stationary GPD + Large ensemble of an atmospheric model with different SST/GHG/SIC + Comparison of probabilities for different CMIP5 experiments	Schaller et al (2014), Lewis and Karoly (2014) King et al (2015)	
D8	Hannart et al	Argentinian heatwave of December 2013	Impacts and rarity	Observed temperature (threshold)	Conditional to SST	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Schaller et al (2014)	Discussion on the choice of threshold and on the meaning of FAR
D9	Christidis	Winter	Impacts and	Observed	Effect of other	Natural	Comparison of	Christidis et	

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
	and Stott	2013/2014 rainfall in the UK	rarity	precipitation	precursors (circulation), Conditional to circulation	forcings only	probabilities for different CMIP5 experiments	al (2013)	
D10	Feser et al	Hurricane Gonzalo	Impacts + unusual trajectory	Extratropical transition of tropical cyclones	Not relevant here	Not relevant here	Nudging of a general circulation model trend calculation		
D11	Vautard et al	Fall 2014 precipitation in the Cevennes	Impacts	Observed precipitation anomalies (threshold)	Unconditional	Past	Non stationary GEV (Gumbel) on station observations		
D12	Kam et al	Record annual mean warmths	Rarity	observed annual temperature anomaly and second-rank thresholds	Unconditional	Preindustrial and natural forcings only	Trend calculation for varying start years	Knutson et al (2013)	
D13	Bergaoui et al	Drought in the Southern Levant region	Impacts	Observed anomaly of precipitation (threshold)	Conditional to SST	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Schaller et al (2014)	Explicit choice of a country with few EEA studies
D14	Barlow and Hoell	Drought in the middle East and central Southern Asia	Rarity	Precipitation anomalies (ability to reproduce)	Conditional to SST + Effect of other precursors (SST pattern)	Preindustrial SST/SIC/GHG	Atmospheric model simulations with different SST/GHG/SIC		
D15	Funk et al	Boreal Spring East African drought	Rarity	Observed evaporation and soil moisture anomalies (ability to reproduce)	Effect of CC on other precursors (precipitation, air temperature), Effect of other precursors (precipitation, air temperature)	Past	Comparison of intensities for different historical CMIP5 dates + Variable Infiltration Capacity model with different initializations		
D16	Marthews et	Drought in the	Impacts	Observed seasonal	Conditional to	Preindustrial	Large ensemble of an	Pall et al	

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
	al	horn of Africa		averaged rainfall (thresold)	SST	SST/SIC/GHG	atmospheric model with different SST/GHG/SIC	(2011), Otto et al (2015)	
D17	Wang et al	Deadly Himalayan snow storm of December 2014	Impacts and rarity	Tropical cyclone (several different characteristics)	Unconditional	Natural forcings only	Comparison of intensities for different CMIP5 experiments		Comparison GHG/aerosols/natural forcings only
D18	Min et al	Hot spring in Korea	Impacts and rarity	Temperature trends and observed temperature anomaly	Unconditional	Historical	Comparison of probabilities for different CMIP5 experiments		
D19	Weller et al	High SST	Rarity and occurrence without ENSO	Observed SST (threshold)	Unconditional	Preindustrial and natural forcings only	Comparison of probabilities for different CMIP5 experiments		Comparison with GHG/natural forcings only
D20	Wilcox et al	Summer in Northeast Asia	Rarity	Observed precipitation anomalies (ability to reproduce)	conditional to SST + Unconditional	Historical SST/SIE/GHG + Historical	Comparison of intensities for different atmospheric model experiments + Comparison of trends for different CMIP5 experiments		Comparison of All forcings/GHG only/AA only/SST only
D21	Song et al	Spring in Northern China	Impacts and rarity	Observed temperature anomaly corrected with urbanization effect (threshold)	Unconditional	Natural forcings only	Comparison of probabilities for different CMIP5 experiments	Sun et al (2014)	
D22	Murakami et al	Hawaiian hurricane season	Rarity	Observed yearly number of tropical cyclones (threshold)	Unconditional + Conditional to ENSO, PDO, IPO, and AMO	Preindustrial and past	Forecast-oriented model simulation with different initializations		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
D23	Yang et al	Tropical cyclones activity in the Western North Pacific in August 2014	Impacts and rarity	Tropical cyclones number	Effect of other precursors (circulation, ISO)	Not relevant	Correlations analysis with reanalysis (NCEP) and CMIP5		CMIP5 models are not able to correctly reproduce the observed trends on TC
D24	McBride et al	Dry spell in Singapore	Rarity	Observed length of dry spell	Unconditional, Effect of other precursors (ITCZ, MJO, ENSO)	Not relevant here – forward looking attribution	Analysis of CMIP5 and reanalysis datasets		forward looking attribution
D25	Siswanto et al	Jakarta flooding	Impacts	Observed precipitation anomaly (threshold)	Unconditional	Past	Non stationary GEV on observation		
D26	Rosier et al	Early July 2014 extreme rainfall in Northland (New Zealand)	Impacts and rarity	Observed precipitation anomaly (threshold)	Conditional to SST	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Schaller et al (2014), Black et al (2015)	
D27	King et al	Brisbane G20 heat event	Media attention	observed threshold of 2 different (hot and very hot) days	Conditional to SST	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Black et al (2015)	
D28	Black et al	Adelaide and Melbourne heatwaves	Impacts and rarity	Observed temperature (threshold)	Conditional to SST	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC		
D29	Hope et al	record high temperature in Australia in late Spring	Rarity	Observed temperature anomaly (ability to reproduce)	Effects of multiple precursors (including CC)	Historical SST/SIC/GHG	Sensibility experiments with a seasonal forecast model	Arblaster et al (2014)	
D30	Perkins and	Australian	Rarity	Observed	Unconditional	Preindustrial	Comparison of		

Num ber	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
	Gibson	May heatwave		temperature anomaly (threshold)			probabilities for different CESM-LENS experiments		
D31	Grose et al	Mean sea level pressure anomalies south of Australia	Impacts and rarity	Observed anomaly (threshold)	Conditional to SST	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Black et al (2015)	
D32	Massonnet et al	Antarctic sea ice extent	Rarity	Observed SIE (ability to reproduce)	Effects of other precursors (winds, near surface temperature, SIC)	Not relevant	Reconstitution of anomalies with different initializations using a sea ice model	Guemas et al (2013)	
E1	Kam et al	Record global and regional warmth	Rarity	Observed temperature and second highest temperature (thresholds)	Unconditional	Preindustrial and natural forcings only	Trend calculation for varying start years	Knutson et (2013,2014)	
E2	Wolter et al	3 US daily rainfall extremes	Impacts	Max 1-day precipitation and extreme wet days	Unconditional, Effect of other precursors (ENSO)	Not relevant	Correlation between observational variables/trends		
E3	Partain Jr et al	Alaska fire season	Rarity	Observed BUI (fire index) (threshold)	Unconditional	Preindustrial	Downscaled forecast model for two different periods with and without anthropogenic forcings (GHG and aerosols)		
E4	Fosu et al	Snowpack drought in Washington	Impacts	Correlation between precipitation and temperature over the	Effect of CC on precursors (NPI, correlation	Not relevant	Trends calculation on reanalysis and CESM-LENS		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
				Cascade mountains	between precipitation and temperature, temperature)				
E5	Sweet et al	Sunny day flood	Impacts and rarity + unusual to have a flood without precipitation	Observed water level (ability to reproduce)	Conditional to sea level rise	Not relevant – forward looking attribution	GEV + different sea level rise scenarios	Menendez and Woodworth (2010)	Forward looking attribution
E6	Trenary et al	US winter	Impacts and rarity	minimum mean JFM temperature + number of days below 10th percentile	Unconditional	Not relevant (trend calculation)	Non stationary GEV – trend calculation using reanalysis and CMIP5		
E7	Bellprat et al	Cold February over Northern America	Impacts and rarity	Observed temperature anomaly (ability to reproduce)	Effects of other precursors (SST, SIC, circulation)	Not relevant	Large ensemble of an atmospheric model with different surface boundary conditions and initializations of atmospheric conditions		
E8	Szeto et al	Drought in western Canada	Impacts and rarity	96th percentile of temperature and circulation index (threshold)	Effect of CC on precursors (temperature, circulation)	Natural forcings only	Comparison of probabilities for different CMIP5 experiments		
E9	Christidis et al	Winter sunshine in the UK	Impacts and rarity	Observed downward solar flux at the surface (threshold)	Conditional to SST and conditional to circulation	Natural forcings only (SST/SIC/GHG)	Large ensemble of an atmospheric model with different SST/GHG/SIC	Pall et al 2011, Christidis et al 2013, Christidis and Stott (2015)	

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
E10	Sippel et al	European heatwaves	Impacts	Observed heatwaves indices : seasonal maxima of 3-day mean temperature and seasonal maxima of 3-day daily maximum wet bulb temperature (thresholds)	Unconditional and conditional to SST	Past and preindustrial SST/SIC/GHG	Non stationary GEV + Large ensemble of an atmospheric model with different SST/GHG/SIC	van Oldenborgh et al. (2012) and Massey et al. (2015)	Comparison of several methodologies
E11	Dong et al	European summer heatwave	Rarity	Observed temperature anomalies (ability to reproduce)	Conditional to SST + Effect of other precursors (SST pattern)	Historical SST/SIC/GHG	Atmospheric model with different SST/SIC/GHG conditions		
E12	Lawal et al	Late onset of the wet season in Nigeria	Impacts	Start date → average monthly precipitation for April and May (thresholds)	Conditional to SST + Effect of other precursors (SST pattern)	Preindustrial SST/SIC/GHG	Large ensemble of two atmospheric models with different SST/GHG/SIC		Effect of/on soil moisture are also very briefly discussed but no results are shown.
E13	Mitchell	Egyptian heatwave	Impacts	Heat related health index : WBGT (threshold)	Conditional to SST	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Massey et al (2015), Schaller et al (2016)	
E14	Funk et al	Droughts in Ethiopia and Southern Africa	Impacts	June-September precipitation anomalies	Conditional to ENSO, Effect of CC on other precursors (ENSO)	Historical	Comparison of intensities for different historical CMIP5 dates + Variable Infiltration Capacity model with different initializations	Funk et al (2015)	
E15	Wehner et al	Heatwaves in	Impacts	observed temperature	Conditional to	Preindustrial	Non stationary GPD		

Num ber	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
		Pakistan and India		and heat index (threshold)	SST	SST/SIC/GHG	+ Large ensemble of an atmospheric model with different SST/GHG/SIC		
E16	Van Oldenborgh et al	Heavy precipitations of December 2015 in Chennai	Impacts	Observed precipitation anomaly (threshold)	Unconditional and conditional to SST	Past and preindustrial SST/SIC/GHG	Non stationary GEV and large ensemble of an atmospheric model with different SST/GHG/SIC	Vautard et al (2015), Massey et al (2015)	
E17	Burke et al	Extreme rainfall in Southeast China in May 2015	Impacts	Observed intensity and number of consecutive wet days (threshold)	Conditional to SST	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Christidis et al (2013)	
E18	Miao et al	Heat in Northwest China in July 2015	Rarity	Observed temperature anomaly (threshold)	Unconditional	Natural forcings only	Comparison of probabilities for different CMIP5 experiments	Zhou et al (2014) Sun et al (2014)	All and GHG forcings
E19	Sun et al	2015 extreme temperature events in Western China	Impacts and rarity	Observed temperature anomaly (threshold)	Unconditional	Natural forcings only	Comparison of probabilities for different CMIP5 experiments	Ribes et al (2013) Sun et al (2014)	
E20	Takahashi et al	persistent Japanese heatwave of early August	Impacts + unusual for an ENSO summer	Observed temperature anomaly (threshold)	Conditional to SST, Effect of other precursors (ENSO)	Natural forcings only SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC		
E21	King et al	Heat and drought in Indonesia	Impacts and rarity	Observed July-October average rainfall and temperature anomalies (thresholds)	Unconditional, Effect of other precursors (ENSO), Conditional to ENSO	Past and Natural forcings only	Comparison of probabilities for different CMIP5 experiments and in observation		

Number	Authors	Event	Choice of the event	Definition	Conditionality	Counterfactual	Methodology	Genealogy (if relevant)	Comment
E22	Black and Karoly	Southern Australia warmest october on record	Impacts and rarity	Observed temperature anomaly (threshold)	Conditional to SST, Effect of other precursors (ENSO)	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC	Black et al (2015, 2016)	
E23	Hope et al	record breaking heat in Australia in october 2015	Rarity	Observed temperature anomaly (threshold + ability to reproduce)	Conditional to SST, Effects of multiple precursors (including CC)	Preindustrial SST/SIC/GHG, Historical SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC, Sensibility experiments with a seasonal forecast model	Black et al (2015) Hope et al (2015) Arblaster et al (2014) Wang et al (2014)	
E24	Karoly et al	October 2015 record low rainfall in Tasmania	Impacts and rarity	Observed precipitation anomaly (threshold)	Conditional to SST, Effect of other precursors (ENSO), Conditional to ENSO	Preindustrial SST/SIC/GHG	Large ensemble of an atmospheric model with different SST/GHG/SIC, Comparison of probabilities for different CMIP5 experiments	Black et al (2015, 2016) Massey et al 2015	
E25	Zhang et al	extreme accumulated cyclone energy (ACE) in the Western North Pacific	Rarity	Observed accumulated cyclone energy (threshold)	Unconditional, Conditional to ENSO, PDO, IPO, and AMO	Historical	Forecast-oriented model simulation with different initializations	Murakami et al (2015)	
E26	Fuckar et al	record low sea ice extent (SIE) maximum in March 2015	Rarity	observed SIE (ability to reproduce)	Conditional to SIE + Effect of other precursors (circulation, initial SIE)	Historical (several dates) sea ice cover	Reconstitution of anomalies with different initializations using a sea ice model	Massonnet et al (2015)	

Appendix B

Summary tables of the BAMS classification

Annex 1 contains the complete classification of the BAMS papers. The tables presented hereafter summarize the results of the classification for a few criteria of analysis.

There are 5 summary tables. B.1 sorts the case studies by a genealogical criterion. B.2 gives an overview of the stated reasons to choose an event. B.3 details the regions of both the authors and the studied event. B.4 shows the repartition of the BAMS articles regarding the level of conditioning of the case study. B.5 shows the classification of the different counterfactual worlds.

When an article belongs to several categories, its name is in bold characters. Double and triple counting explain why the total can be higher than the total number of BAMS articles (105).

Genealogy	BAMS case studies	Methodology	Total
Pall et al. [2011],Massey et al. [2012,2015] and Schaller et al. [2014, 2016], Black et al [2015]	Rupp et al (2012), Massey et al (2012), Christidis and Stott (2012), Rupp et al (2013), Sparrow et al (2013), Trigo et al (2013), Imada et al (2013), Imada et al (2014), Otto et al (2015), Hannart et al (2015), Bergaoui et al (2015), Marthews et al (2015), Rosier et al (2015), King et al (2015), Grose et al (2015), Christidis et al (2016), Sippel et al (2016), Mitchell (2016), van Oldenborgh et al (2016), Black and Karoly (2016), Hope et al (2016)	Large ensemble of an atmospheric model with different SST/GHG/SIC	21
Christidis et al [2013]	Christidis et al (2013), Christidis et al (2014), Christidis and Stott (2015), Christidis et al (2016), Burke et al (2016)	Large ensemble of an atmospheric model with different SST/GHG/SIC - with an added conditioning to circulation	5
Knutson et al [2013]	Knutson et al (2013), Zhang and Knutson (2013), Knutson et al (2014a), Knutson et al (2014b), Zhou et al (2014), Kam et al (2015), Kam et al (2016)	Trend calculation for varying start years	7
Cattiaux et al [2010], Yiou and Cattiaux [2013]	Cattiaux and Yiou (2012), Cattiaux and Yiou (2013), Yiou and Cattiaux (2013), Yiou and Cattiaux (2014)	Flow analogues	4
Dong et al [2013]	Dong et al (2013), Dong et al (2014)	Atmospheric model with different SST and SIC conditions	2
Lewis and Karoly [2013, 2014], King et al [2015]	Lewis and Karoly (2014), Perkins et al (2014), Otto et al (2015)	Comparison of probabilities for different CMIP5 experiments	3
van Oldenborgh et al [2012]	Van Storch et al (2014), Sippel et al (2016)	Non stationary GEV (Generalized Extreme Value distribution)	2
Murakami et al [2015]	Yang et al (2015), Zhang et al (2016)	Forecast-oriented model simulation with different initializations	2
Sun et al [2014]	Song et al (2015), Miao et al (2016), Sun et al (2016)	Comparison of probabilities for different CMIP5 experiments	3
Arblaster et al [2014]	Hope et al (2015), Hope et al (2016)	Sensibility experiments with a seasonal forecast model	2
Guemas et al [2013], Massonet et al [2015]	Massonnet et al (2015), Fuckar et al (2016)	Reconstitution of anomalies with different initializations using a sea ice model	2

Table B.1 – This table lists the genealogy explicitly mentioned in more than one article. Only 51 out of 105 articles are sorted below (the others do not explicitly mention of genealogical link, or they mention an article which is not mentioned by any of the other articles)

Year	Rarity	Impacts	Both	Other
2011	Rupp et al (2012),Cattiaux and Yiou (2012)	van Oldenborgh et al (2012),Funk (2012)	Christidis and Stott (2012)	Massey et al (2012)

Year	Rarity	Impacts	Both	Other
2012	Knutson et al (2013), **Guemas et al (2013)**, Zhang and Knutson (2013), **Tett et al (2013)**	Sweet et al (2013), De Vries et al (2013), Funk et al (2013), **Zhou et al (2013)**, Christidis et al (2013)	Rupp et al (2013),Diffenbaugh and Scherer (2013),Cattiaux and Yiou (2013), Dong et al (2013), Sparrow et al (2013), Trigo et al (2013), Imada et al (2013), King et al (2013), Dean et al (2013)	**Guemas et al (2013)**, **Tett et al (2013)**, **Zhou et al (2013)**
2013	Knutson et al (2014a), Knutson et al (2014b) , Lewis and Karoly (2014), Arblaster et al (2014), Imada et al (2014), Dong et al (2014), Schaller et al (2014), **Añel et al (2014)**	Van Storch et al (2014), Christidis et al (2014)	Swain et al (2014), Wang and Schubert (2014), Funk et al (2014), Hoerling et al (2014), Edwards et al (2014), Perkins et al (2014), King et al (2014), Harrington et al (2014), Min et al (2014), **Zhou et al (2014)**, Singh et al (2014), Yiou and Cattiaux (2014)	**Zhou et al (2014)**, **Añel et al (2014)**
2014	Yang et al (2015), Wild et al (2015), Kam et al (2015), Barlow and Hoell (2015), Funk et al (2015), **Weller et al (2015)**, Wilcox et al (2015), Murakami et al (2015), McBride et al (2015), Hope et al (2015), Perkins and Gibson (2015), Massonnet et al (2015)	Wolter et al (2015), Trenary et al (2015), Otto et al (2015), **Feser et al (2015)**, Vautard et al (2015), Bergaoui et al (2015), Marthews et al (2015), Siswanto et al (2015)	Yoon et al (2015), Szeto et al (2015), Hannart et al (2015), Christidis and Stott (2015), Wang et al (2015), Min et al (2015), Song et al (2015), Yang et al (2015), Rosier et al (2015), Black et al (2015), Grose et al (2015)	**Feser et al (2015)**, **Weller et al (2015)**, King et al (2015)
2015	Kam et al (2016), Partain Jr et al (2016), Dong et al (2016), Miao et al (2016), Hope et al (2016), Zhang et al (2016), Fuckar et al (2016)	Wolter et al (2016), Fosu et al (2016), Sippel et al (2016), Lawal et al (2016), Mitchell (2016), Funk et al (2016), Wehner et al (2016), van Oldenborgh et al (2016), Burke et al (2016), **Takahashi et al (2016)**	**Sweet et al (2016)**, Trenary et al (2016), Bellprat et al (2016), Szeto et al (2016), Christidis et al (2016), Sun et al (2016), King et al (2016), Black and Karoly (2016), Karoly et al (2016)	**Sweet et al (2016)**, **Takahashi et al (2016)**
Total	33	27	42	11

Table B.2 – Stated reason(s) to choose the event

Year	Authors and events in the same region	Authors and events in different regions	Events in Annex I countries	Events in non Annex I countries	Poles	Ocean
2011	Rupp et al (2012),Cattiaux and Yiou (2012),Massey et al (2012),Christidis and Stott (2012)	van Oldenborgh et al (2012), Funk (2012)	Rupp et al (2012),Cattiaux and Yiou (2012),Massey et al (2012),Christidis and Stott (2012)	van Oldenborgh et al (2012), Funk (2012)		

Year	Authors and events in the same region	Authors and events in different regions	Events in Annex I countries	Events in non Annex I countries	Poles	Ocean
2012	Rupp et al (2013),Diffenbaugh and Scherer (2013), Knutson et al (2013),Sweet et al (2013), De Vries et al (2013), Dong et al (2013), Tett et al (2013), Sparrow et al (2013), Yiou and Cattiaux (2013), Trigo et al (2013), Zhou et al (2013), Imada et al (2013), King et al (2013), Christidis et al (2013), Dean et al (2013)	Cattiaux and Yiou (2013), Guemas et al (2013), Zhang and Knutson (2013), Funk et al (2013)	Rupp et al (2013),Diffenbaugh and Scherer (2013),Cattiaux and Yiou (2013), Knutson et al (2013), Sweet et al (2013), De Vries et al (2013), Dong et al (2013), Tett et al (2013), Sparrow et al (2013), Yiou and Cattiaux (2013), Trigo et al (2013), Imada et al (2013), King et al (2013), Christidis et al (2013), Dean et al (2013)	Funk et al (2013), Zhou et al (2013)	Guemas et al (2013), Zhang and Knutson (2013)	
2013	Swain et al (2014), Wang and Schubert (2014), Funk et al (2014), Hoerling et al (2014), Knutson et al (2014a), Edwards et al (2014), Knutson et al (2014b), Lewis and Karoly (2014), Perkins et al (2014), Arblaster et al (2014), King et al (2014), Harrington et al (2014), Min et al (2014), Imada et al (2014), Zhou et al (2014), Dong et al (2014), Yiou and Cattiaux (2014), Schaller et al (2014), Añel et al (2014), Van Storch et al (2014), Christidis et al (2014)	Singh et al (2014)	Swain et al (2014), Wang and Schubert (2014), Funk et al (2014), Hoerling et al (2014), Knutson et al (2014a), Edwards et al (2014), Knutson et al (2014b), Lewis and Karoly (2014), Perkins et al (2014), Arblaster et al (2014), King et al (2014), Harrington et al (2014), Imada et al (2014), Dong et al (2014), Yiou and Cattiaux (2014), Schaller et al (2014), Añel et al (2014), Van Storch et al (2014), Christidis et al (2014)	Min et al (2014), Zhou et al (2014), Singh et al (2014)		

Year	**Authors and events in the same region**	**Authors and events in different regions**	**Events in Annex I countries**	**Events in non Annex I countries**	**Poles**	**Ocean**
2014	Yoon et al (2015), Wolter et al (2015), Trenary et al (2015), Szeto et al (2015), Yang et al (2015), Wild et al (2015), Hannart et al (2015), Christidis and Stott (2015), Feser et al (2015), Vautard et al (2015), Kam et al (2015), Bergaoui et al (2015), Min et al (2015), Song et al (2015), Murakami et al (2015), McBride et al (2015), Siswanto et al (2015), Rosier et al (2015), King et al (2015), Black et al (2015), Hope et al (2015), Perkins and Gibson (2015), Grose et al (2015)	Otto et al (2015), Barlow and Hoell (2015), Funk et al (2015), Marthews et al (2015), Wang et al (2015), Weller et al (2015), Wilcox et al (2015), Yang et al (2015), Massonnet et al (2015)	Yoon et al (2015), Wolter et al (2015), Trenary et al (2015), Szeto et al (2015), Yang et al (2015), Wild et al (2015), Christidis and Stott (2015), Feser et al (2015), Vautard et al (2015), Kam et al (2015), Murakami et al (2015), Rosier et al (2015), King et al (2015), Black et al (2015), Hope et al (2015), Perkins and Gibson (2015), Grose et al (2015)	Otto et al (2015), Hannart et al (2015), Bergaoui et al (2015), Barlow and Hoell (2015), Funk et al (2015), Marthews et al (2015), Wang et al (2015), Min et al (2015), Wilcox et al (2015), Song et al (2015), McBride et al (2015), Siswanto et al (2015)	Massonnet et al (2015)	Weller et al (2015), Yang et al (2015)
2015	Kam et al (2016), Wolter et al (2016), Partain Jr et al (2016), Fosu et al (2016), Sweet et al (2016), Trenary et al (2016), Szeto et al (2016), Christidis et al (2016), Sippel et al (2016), Dong et al (2016), Lawal et al (2016), Miao et al (2016), Sun et al (2016), Takahashi et al (2016), Black and Karoly (2016), Hope et al (2016), Karoly et al (2016)	Bellprat et al (2016), Mitchell (2016), Funk et al (2016), Wehner et al (2016), van Oldenborgh et al (2016), Burke et al (2016), King et al (2016), Zhang et al (2016), Fuckar et al (2016)	Wolter et al (2016), Partain Jr et al (2016), Fosu et al (2016), Sweet et al (2016), Trenary et al (2016), Bellprat et al (2016), Szeto et al (2016), Christidis et al (2016), Sippel et al (2016), Dong et al (2016), Takahashi et al (2016), Black and Karoly (2016), Hope et al (2016), Karoly et al (2016)	Kam et al (2016), Lawal et al (2016), Mitchell (2016), Funk et al (2016), Wehner et al (2016), van Oldenborgh et al (2016), Burke et al (2016), Miao et al (2016), Sun et al (2016), King et al (2016)	Fuckar et al (2016)	Zhang et al (2016)
Total	80	25	69	29	4	3

Table B.3 – Regions and Authors.The UNFCCC (United Nations Framework Convention for Climate Change) website provides lists of Annex I and non Annex I countries.

Kam et al (2016) is about global warmth. We chose to sort it in the Annex II countries column because it also focuses on regional warmth in both Eastern Pacific and Southern India/Sri Lanka.

Year	Unconditional	Conditional to SST/SIC	Conditional to the circulation	Conditional to El Niño/La Niña	Conditional to sea level rise	Effects of anthropogenic climate change on a precursor	Effect of other precursors than anthropogenic climate change	Other
2011	**van Oldenborgh et al (2012)**	**Rupp et al (2012)**,Massey et al (2012),Christidis and Stott (2012)	Cattiaux and Yiou (2012)	**Rupp et al (2012)**		Funk (2012) (IPWP)	**van Oldenborgh et al (2012)** (El Niño/La Niña)	
2012	Diffenbaugh and Scherer (2013), Knutson et al (2013), Zhang and Knutson (2013), **De Vries et al (2013)**, Zhou et al (2013)	Rupp et al (2013), **Dong et al (2013)**, Tett et al (2013), Sparrow et al (2013), **Trigo et al (2013)**, **Imada et al (2013)**, Christidis et al (2013)	Cattiaux and Yiou (2013), Yiou and Cattiaux (2013)	Funk et al (2013), **King et al (2013)**	Sweet et al (2013)	Dong et al (2013) (circulation), **Imada et al (2013)** (circulation), Dean et al (2013) (circulation)	Guemas et al (2013) (sea ice memory, extreme storm, temperature), **De Vries et al (2013)** (Snow cover), **Dong et al (2013)** (internal variability/AMO), **Trigo et al (2013)**(circulation), **King et al (2013)**(El Niño/La Niña)	
2013	Knutson et al (2014a), Edwards et al (2014), Knutson et al (2014b), Lewis and Karoly (2014), Perkins et al (2014), King et al (2014), **Harrington et al (2014)**, Zhou et al (2014), Singh et al (2014)	**Funk et al (2014)**, Hoerling et al (2014), Imada et al (2014), **Dong et al (2014)**, Schaller et al (2014), Añel et al (2014), **Christidis et al (2014)**	Yiou and Cattiaux (2014), **Christidis et al (2014)**			Swain et al (2014) (circulation), **Wang and Schubert (2014)** (circulation, humidity), **Funk et al (2014)** (SST), **Harrington et al (2014)** (circulation), Min et al (2014) (SST)	**Wang and Schubert (2014)** (SST), **Funk et al (2014)** (SST (including and excluding El Niño)), Arblaster et al (2014) (multiple precursors including CC), **Dong et al (2014)** (SST pattern)	Van Storch et al (2014)

Year	**Unconditional**	**Conditional to SST/SIC**	**Conditional to the circulation**	**Conditional to El Niño/La Niña**	**Conditional to sea level rise**	**Effects of anthropogenic climate change on a precursor**	**Effect of other precursors than anthropogenic climate change**	**Other**
2014	Yoon et al (2015), Wolter et al (2015), Trenary et al (2015), **Szeto et al (2015)**, **Yang et al (2015)**, **Otto et al (2015)**, Vautard et al (2015), Kam et al (2015), Wang et al (2015), Min et al (2015), Weller et al (2015), **Wilcox et al (2015)**, Song et al (2015), **Murakami et al (2015)**, **McBride et al (2015)**, Siswanto et al (2015), Perkins and Gibson (2015)	**Otto et al (2015)**, Hannart et al (2015), Bergaoui et al (2015), **Barlow and Hoell (2015)**, Marthews et al (2015), **Wilcox et al (2015)**, Rosier et al (2015), King et al (2015), Black et al (2015), Grose et al (2015)	**Christidis and Stott (2015)**, **Murakami et al (2015)**	**Murakami et al (2015)**		Yang et al (2015) (tropical Pacific wind stress anomalies), **Funk et al (2015)** (precipitation, air temperature)	**Szeto et al (2015)** (circulation, pond drainage), Wild et al (2015) (North American temperature, convective activity over the tropical west Pacific), **Christidis and Stott (2015)** (circulation), **Barlow and Hoell (2015)** (SST pattern), **Funk et al (2015)** (precipitation, air temperature), **Yang et al (2015)** (circulation, ISO), **McBride et al (2015)** (ITCZ, MJO, El Niño), Hope et al (2015) (multiple precursors including CC), Massonnet et al (2015) (winds, near surface temperature, SIC)	Feser et al (2015)

Year	Unconditional	Conditional to SST/SIC	Conditional to the circulation	Conditional to El Niño/La Niña	Conditional to sea level rise	Effects of anthropogenic climate change on a precursor	Effect of other precursors than anthropogenic climate change	Other
2015	Kam et al (2016), **Wolter et al (2016)**, Partain Jr et al (2016), Trenary et al (2016), **Sippel et al (2016)**, **van Oldenborgh et al (2016)**, Miao et al (2016), Sun et al (2016), **King et al (2016)**, **Zhang et al (2016)**	**Christidis et al (2016)**, **Sippel et al (2016)**, **Dong et al (2016)**, **Lawal et al (2016)**, Mitchell (2016), Wehner et al (2016), **van Oldenborgh et al (2016)**, Burke et al (2016), **Takahashi et al (2016)**, **Black and Karoly (2016)**, **Hope et al (2016)**, **Karoly et al (2016)**, **Fuckar et al (2016)**	**Christidis et al (2016)**, **Zhang et al (2016)**	**Wolter et al (2016)**, **Funk et al (2016)**, **Black and Karoly (2016)**, **Karoly et al (2016)**, **Zhang et al (2016)**	Sweet et al (2016)	Fosu et al (2016) (NPI, correlation between precipitation and temperature, temperature) , Szeto et al (2016) (temperature, circulation)	Bellprat et al (2016) (SST, SIC, circulation), **Dong et al (2016)** (SST pattern), **Lawal et al (2016)** (SST pattern), **Funk et al (2016)** (El Niño) , **Takahashi et al (2016)** (El Niño), **King et al (2016) (El Niño)**, **Black and Karoly (2016)** (El Niño), **Hope et al (2016)** (multiple precursors including CC), **Karoly et al (2016)** (El Niño), **Fuckar et al (2016)** (circulation, initial SIC)	
Total	42	40	9	9	2	13	29	2

Table B.4 – Conditionality

The distinction between conditional to SST and conditional to El Niño is not trivial since the effect of El Niño should be included in the SST pattern. We put the study in the column conditional to El Niño/La Niña when the conditioning to El Niño is explicitly stated (e.g. for studies depending on the Niño index for the year) A few studies (Dong et al (2013), Dong et al (2014), Dong et al (2016)) consider SST pattern as a precursor without taking into account the role of CC on those SST patterns.

Double counting: 2 (2011), 4(2012), 5 (2013), 8 (2014), 11 (2015) - Triple counting : Dong et al (2013), Murakami et al (2015), Black and Karoly (2016), Karoly et al (2016), Zhang et al (2016)

Year	Past/Historical	SST/GHG/SIC preindustial	SST/GHG/SIC	SST/GHG/SIC historical	Natural forcings only	Preindustrial	Not relevant
2011	van Oldenborgh et al (2012), Funk (2012),Cattiaux and Yiou (2012)	Christidis and Stott (2012)		Rupp et al (2012),Massey et al (2012)			
2012	Cattiaux and Yiou (2013), Sweet et al (2013), De Vries et al (2013), Yiou and Cattiaux (2013), Zhou et al (2013)	Sparrow et al (2013), Imada et al (2013)	Rupp et al (2013), Christidis et al (2013)	Dong et al (2013) (SST and SIC only), Tett et al (2013) (SIC only), Trigo et al (2013) Dean et al (2013)	Diffenbaugh and Scherer (2013), Knutson et al (2013), Zhang and Knutson (2013), King et al (2013)	Guemas et al (2013), Funk et al (2013)	
2013	**Perkins et al (2014)**, **Min et al (2014)**	Hoerling et al (2014), Imada et al (2014), Schaller et al (2014), Añel et al (2014), Christidis et al (2014)		Wang and Schubert (2014), Funk et al (2014), Dong et al (2014)	Knutson et al (2014b), **Lewis and Karoly (2014)**, Harrington et al (2014), **Min et al (2014)**, Zhou et al (2014)	Swain et al (2014), **Knutson et al (2014a)**, Edwards et al (2014), **Knutson et al (2014b)**, **Lewis and Karoly (2014)**, **Perkins et al (2014)**, King et al (2014), Singh et al (2014)	Arblaster et al (2014), Yiou and Cattiaux (2014), Van Storch et al (2014)
2014	Szeto et al (2015), **Yang et al (2015)**, **Otto et al (2015)**, Vautard et al (2015), Funk et al (2015), Min et al (2015), **Wilcox et al (2015)**, **Murakami et al (2015)**, Siswanto et al (2015)	**Otto et al (2015)**, Hannart et al (2015), Bergaoui et al (2015), Barlow and Hoell (2015), Marthews et al (2015)	Rosier et al (2015), King et al (2015), Black et al (2015), Grose et al (2015)	**Wilcox et al (2015)**, Hope et al (2015)	**Otto et al (2015)**, Christidis and Stott (2015), **Kam et al (2015)**, Wang et al (2015), **Weller et al (2015)**, Song et al (2015)	Yoon et al (2015), Wolter et al (2015), Trenary et al (2015), **Yang et al (2015)**, **Kam et al (2015)**, **Weller et al (2015)**, **Murakami et al (2015)**, Perkins and Gibson (2015)	Wild et al (2015), Feser et al (2015), Yang et al (2015), McBride et al (2015), Massonnet et al (2015)

Year	Past/Historical	SST/GHG/SIC preindustial	SST/GHG/SIC	SST/GHG/SIC historical	Natural forcings only	Preindustrial	Not relevant
2015	**Sippel et al (2016)**, Funk et al (2016), **van Oldenborgh et al (2016)**, **King et al (2016)**, Zhang et al (2016)	**Sippel et al (2016)**, Lawal et al (2016), Mitchell (2016), Wehner et al (2016), **van Oldenborgh et al (2016)**, Black and Karoly (2016), **Hope et al (2016)**, Karoly et al (2016)	Christidis et al (2016), Burke et al (2016), Takahashi et al (2016)	Dong et al (2016), **Hope et al (2016)**, Fuckar et al (2016)	Kam et al (2016), Szeto et al (2016), Miao et al (2016), Sun et al (2016), **King et al (2016)**	Kam et al (2016), Partain Jr et al (2016)	Wolter et al (2016), Fosu et al (2016), Sweet et al (2016), Trenary et al (2016), Bellprat et al (2016)
Total	24	21	9	13	17	22	15

Table B.5 – Definition of the countefactual world

Funk et al (2014) corresponds to detrended SST. It is hence complicated to put it under the category SST/GHG/SIC preindustrial, natural or historical. We chose to put it in historical but it could be argued otherwise.

Double counting : 4 (2013), 5 (2014), 5 (2015) - Triple counting : Otto et al (2015)

Appendix C

Interview grids

C.1 EUCLEIA interview grid

CLARIFYING THE CONCEPTS.

I am starting with quite basic questions on the core concepts: EUCLEIA is about extreme event attribution; I need to clarify first these concepts with you.

1. How would you define an extreme event? Please focus solely on yourself.
2. Could you tell me, as if I was totally ignorant, what is meant, at least to you, by "extreme event attribution" within the context of EUCLEIA?

So EUCLEIA is about extreme event attribution, but with the goal of developing a "fully operational extreme event attribution service." I would also like to clarify the concept of "climate service".

3. 3*a*) What is, according to you, a "climate service"?
  3*b*) Where do you see this idea of "service" coming from?
  3*c*) How do you see it being developed within the field of attribution and extreme events?
  3*d*) What might be potential users of this kind of climate services?

WHAT DOES THE INTERVIEWEE THINK HER/HIMSELF

I will now ask you questions about extreme event attribution as a scientific endeavor, the focus will be on what YOU think:

4. When you engage into an extreme event attribution exercise, when and why do you consider that you have been successful?
5. 5*a*) I understand that the attribution of extreme events to climate change deals with attributing an extreme event to anthropogenic climate change, this in terms of intensity or in terms of probability of occurrence. Is this a correct way of understanding the concept? Could you explain this to me?
  5*b*) Where is your personal contribution situated?

We were talking about the science of attribution, and now lets switch to extreme event attribution as a service, meaning a science made for someone who is using it.

6. Why would YOU consider that the development of an extreme event attribution service is important?

   This question may seem far from you area of expertise. When envisioning the concept of service this may entail questions such as costs, payment, billing, etc... (the organization around providing a service and generating profit (value) from it) In short it may entail what we, in social sciences, call a business model.

7. With this frame in mind, what kind of business model would you envision for an attribution service? (a business model would includes all consideration associated with value creation (making money) when a service or a product is developed in order to be marketed)

   WHAT DOES THE INTERVIEWEE THINKS WHAT OTHERS THINK

   We are close to the end of the interview, I have three more questions, focusing on what you believe other people think:

8. In your opinion, and in order of priority, who do you believe would be interested in an extreme event attribution service and why would such a person (category of people) would be interested in it?
9. In your opinion what kind of product/service might be expected from an extreme event attribution service?
10. What are the arguments you would expect from someone believing that extreme event attribution services are NOT needed or not desirable.

CLOSING QUESTION AND STATEMENT

Are there things you would like to add? Questions or comments you would like me to convey to the investigators?

C.2 A2C2 interview grid

CLARIFYING THE CONCEPTS

1. To begin, could you present yourself, and tell how you became a climatologist?
2. Could you give me your definition of extreme events (EE)?
3. 3*a*) Could you give me your definition of detection and attribution (D&A)?
   3*b*) And your definition of D&A of EE?

   LINK BETWEEN THE INTERVIEWEE AND D&A OF EE

4. What is your personal contribution to D&A of EE?
5. How did you come to work on D&A of EE?
6. Why are you interested in D&A of EE?

7. When you engage into an extreme event attribution exercise, when and why do you consider that you have been successful?

   LINK WITH POTENTIAL USERS

8. Are you in contact with potential users of D&A?
9. If yes, what are their expectations regarding D&A of EE ? If no, why not?
10. 10*a*) Would you say that D&A of EE is useful?
    10*b*) If yes, in what manner?
11. Have you ever heard of loss and damage? (if no, explain) Which role do you think D&A of EE could play regarding loss and damage?
12. Finally, how do you imagine the future of D&A of EE?

CLOSING QUESTION AND STATEMENT

I have no more questions, do you have anything to add? Do you have any question for me?

C.3 Loss and damage (L&D) interview grid

CONTEXT

1. Could you present yourself? How did you become involved in the UNFCCC?

2. There are several definitions of L&D. What is yours?

3. What happened at COP22 regarding L&D?

4. What is your role regarding L&D?

5. In the Paris Agreement, loss and damage is, I quote, "associated with the adverse effects of climate change, including extreme weather events."

   5*a*) How would you define extreme weather events in this context?

   5*b*) How would you measure impacts?

6. One of the action area defined by the WIM Excom is about slow-onset events. Why isn't there one about extreme weather events?

   IMPLEMENTATION AND SCIENCE

7. How do you imagine the implementation of L&D?

8. 8*a*) What is the role of science in L&D?

   8*b*) Do you work with scientists?

9. How would an extreme weather event be attributed to climate change?

10. What do you think of extreme event attribution?

11. What would be your ideal contribution from climate science regarding the attribution of extreme events?

12. How would you deal with the events for which the uncertainties are too high for the sciences to attribute them to climate change?

OPENING

13. How do you imagine the future of L&D?

14. Do you want to add anything?

15. Do you have any questions for me?

Appendix D

Extreme event attribution for loss and damage: Tables with quotes

The following tables present the complete analysis of the interviews with quotes.

	Could you give me your definition of extreme events?	Quotes
C1	Impacts-driven definition	“In climate, we have a much less precise notion of extreme and it has more to do with impacts and how impacts are perceived than the actual magnitude of the event.”
C2	Rarity (statistical definition)	“My personal definition of an extreme event would be rare events, that is highly anomalous in terms of any weather variable. And which is often but not necessarily associated with strong socio-economical and ecological impacts.”
C3	Statistical definition. Notion of subjectivity in the definition	“qui se trouve sur le bord d’une distribution de probabilité” “la notion de probabilité, de seuil, elle varie, elle est pas du tout posée.”
C4	Rarity, notion of event (independently of extreme events)	“You know, I don’t think I have one. I mean I tend to think of them as events. Extreme ones would be ones that are, according to some measure, far away from normal.”
C5	Subjectivity. User(Impacts)-driven. Rarity (relative and subjective too)	“c’est pour souligner le fait qu’il y ait cette notion subjective de l’extrême, notamment par rapport aux préoccupations des utilisateurs quoi.” “ce qu’on retrouve systématiquement, c’est la notion de rareté.”
C6	Notion of record	“c’est un événement qui est plutôt un événement futur, et qui peut dépasser la plus grande valeur jamais observée”
C7	Statistical definition and, preferably, impact-driven definition	“I think there are two approaches. You could either look at it from the meteorological start point of view, and say yeah, it was a rare event, and it was in that sense extreme that it is was on the tail of the distribution. But, I think the more useful way, at least when you are aiming to do some public facing work to define extreme events, is to come from the impacts.”

C8	Definition based on duration and scale	"There are two kinds of extreme events. One of them are really weather events. And then, there are what we call climate events. And there are extremes of weather that occur all the time naturally. And there is an infinite variety to the weather."
C9	Definition based on impacts, on public interest	"extreme events is something that causes some sort of interest, massive impact" "something that people more or less care about I guess I would say, I guess that isn't just normal."

Table D.1 – Climate scientists definition of extreme events. Some interviewees were native French speakers, like the authors of this study. The interviews were hence conducted in French. We chose not to translate them in English in this verbatim table.

There are mainly 2 ways to define extreme events for climate scientists (Table D.1): statistical and impact-driven. The first one relates to an arbitrary threshold in a distribution. The second one is related to society, and its reaction to extreme events. There is a subjective part in the definition of the studied event. Indeed, the selection of the region, and of the duration of the event have consequences on the FAR calculation (Cattiaux and Ribes, 2018; Christiansen, 2015). Adding an evaluation of impacts further complicates the problem, as modelling impacts necessarily leads to other subjective choices. If EEA were to be used for L&D, then it would have to deal with impact-driven extremes (Huggel et al., 2015; Hulme et al., 2011; Surminski and Lopez, 2015). In fact, the definition of relevant events should be done in concertation with the end users, in order to correctly capture their perception of the impacts (C5). For this reason, we turned to delegates and asked them how they would define extreme events (Table D.2) and their impacts (Table D.3).

	Definitions of EE	Quotes
D1	Outside of field of expertise. Experts and scientists are the relevant people to define EE. There is no official definition in the UNFCCC.	"Quite honestly, I don't know." "We are entering the scientific world. What is a difference between a weather event and an extreme weather event?" "I think the disaster risk reduction community has a specific definition about it." "Under the convention, we have not defined this border, there's no specific definition in the negotiation context, there's no decision, there's no article that actually defines what an extreme weather event is."
D2	Lists types of events. Notion of return period.	"The extreme events, more generally, are extreme climatic events that we have seen over centuries, these are hurricanes, and typhoons, and cyclones, depending on which ocean you are talking about. Major rivers flood periodically, droughts occur periodically in mid continents." Notion of return period.
D3	Impacts-driven definition (NB: D3 works in disaster risk reduction)	"EWE is an event which overwhelms the capacity of a society to maintain the normal functions."

D4	Impacts driven (devastating natural disasters). Relationship with CC (unusual events).	"How you define extreme weather events on a purely non-scientific perspective, it's very much the devastating natural disasters that are happening more frequently." "So, sort of unusually high or strong cyclones or tornadoes that we've seen recently. Or out of season rainfall or drought, those are the extreme events."
D5	Impacts driven. Relationship with CC.	"Extreme weather events are impacts related to natural disasters that under this work stream then could under one way or another be related or attributed partly to CC"
D6	Definition of EE in opposition to slow-onset events (SOE)	"EE means something that comes suddenly."
D7	Impacts driven. Outside of field of expertise. Experts and scientists are the relevant people to define EE. There is no official definition in the UNFCCC	"There are a number of different definitions for a number of different extreme events." "why is that important?" "In our crowds, they're usually the large events that catch countries and communities off guard, they're not... yeah, floods that make the news." "At the moment, in our process, we don't have thresholds or definitions of what large or small events are. It's usually relying on what the met service says and relevant experts we're referring to."
D8	Defintion of EE in opposition to SOE	"I'll talk about extreme weather events, but I want to make sure we don't forget about slow-onset events." "EWE are something that the L&D work stream is addressing, especially through a comprehensive risk management convention."
D9	Lists types of events	Gives examples of EE: floods, droughts, hurricanes, heatwaves
D10	Lists types of events	"I can't remember, but there is a footnote in one of the past decisions coming from COP19, where there are examples of EE." Examples from his country
D11	Extreme events include both SOE and EE. Lists types of events.	"Well extreme weather events have to do with two types of events basically. We have slow-onset events that can be extreme.[...] Then you have, you know, the sudden onset-events such as hurricanes, heatwaves, and droughts that can also have extremely damaging effects"
D12	Lists types of events. Unusual/unexpected events	"I think that within the UNFCCC, we define those as the heatwaves, the loss and damage, the storms, etc" "EE to me are events that are extremes that are above the normal expected both in strength and frequency maybe"

Table D.2 – Delegates on the definition of extreme events

When asked to define extreme events, a part of the delegates list types of events, with no definition of what is extreme (Table D.2). Only D1 reflects on "What is a difference between a weather event and an extreme weather event?". There is a stark contrast with the climate scientists definitions. The delegates mostly do not seem aware of the wide variety of definitions of extreme events. There does not seem to be any definition of what is to be considered extreme within UNFCCC, nor any wish to establish one. For delegates, the relevant people to define extremes are experts. They rely on two communities of experts : disaster risk reduction practitioners, and met services. However, the choice of a definition of extreme events is subjective by nature. It can change the results of the study (at least quantitatively), which may have political consequences. The lack of awareness of these consequences in the delegates corpus calls for more communication from scientists regarding the limits of EEA. The difference between what delegates and scientists mean when they talk about extreme events is representative of the gap between both worlds, and the level at which they deal with climate change impacts (global versus local).

	Definitions of impacts	Quotes
D1	Outside of field of expertise. Numerous metrics. Quantitative and qualitative ways (possibly related to economic and non-economic losses).	"There's a quantitative way of measuring it, in numbers, and there's a qualitative way of measuring, which would be, I don't know, disruption of certain systems, economic systems or social systems, for so many days." "On the measurement, it's not really my domain to be quite honest, the exact measurement of an EE is not what we deal with." "There are so many ways of measuring it, depending on what you're trying to achieve and to communicate and to understand."
D2	Numerous metrics. 2 different types of impacts: economic and non-economic losses.	"Impacts are very easily measured. They are measured all the time." "The metrics vary." "A rich country doesn't lose human lives, it gets a lot of damage which is monetizable. A poor country loses lives, but in money terms, not much. So it depends on what metric you use, indicator you use to measure."
D3	Different types of impacts.	"Those are the three main impacts: life, health and critical infrastructure."
D4	Outside of field of expertise. Emphasis on non-economic losses (which are difficult to measure)	"That's the thing that I don't know. I don't know." "I think that there is some sort of hesitance in trying to answer that question because, especially if you want to talk about loss, or the non-economic impacts if you talk about this loss of cultural heritage. It's way more than just one weather event." "How do you quantify it? At what point do we say "Oh, that's L&D"? That's the difficulty." "it's that non-economic side that's very difficult to say that, to answer the question."
D5	Numerous metrics. Emphasis on non-economic losses (+ also frontier between economic and non-economic losses)	"That's a very interesting question, you can measure impacts in several ways." "it's very sensitive, it's nearly impossible and I think it's also maybe a bit perverse to start monetizing lives and biodiversity." Discussion on what qualifies as non-economic losses.
D6	Outside of field of expertise. Numerous metrics.	"Well, there are a lot of methodologies that we could use, even though we don't have operational decisions on this under the UNFCCC. At least, scientific people, they know about this."

D7	Outside of field of expertise (maybe not even relevant to the field). Numerous metrics. Emphasis on the scale of measures of impacts.	“It’s similar, we’re here in a political discussion.” “there are different types of definitions of what affects people at what level, but we’re much more sensitive than we might think” “those kinds of impacts are widespread, they’re low level, they’re typically not recorded, and they degrade human welfare in measurable ways.”
D8	Outside of field of expertise. Reflexion on economic and non-economic losses.	“That is a technical area that I don’t really have a huge amount of expertise in. I would leave that up to the risk managers and technicians in respect.” Reflexion on economic and non-economic impacts.
D9	Outside of field of expertise. Permanent vs non permanent. Relies on experts definitions (lists a few organizations).	“There’s that aspect to consider, you know the unavoidable, irreplaceable ones and of course the permanent ones versus those that can be avoided, reversed, repaired, temporary and not permanent.”
D10	Outside of field of expertise	“That’s a difficult question. [...] we still need to figure out how we do it”
D11	Needs more knowledge	“Well I think that’s where we have to get into a much more consistent way of reporting on that.”
D12	Outside of field of expertise. Reflexion on economic and non-economic losses	“That would depend on the expert in the area. I’m not an expert in the area.” “I would like to measure looking both at the non-economic losses and the losses and the ones that you can measure financially”

Table D.3 – Delegates on the definition of impacts

When asked to define impacts of extreme events, most of the delegates also stated that they are not the experts on this question and that it is something that should be decided outside of the UNFCCC area (Table D.3). They have a good understanding that there is a variety of ways to measure impacts. They seem to be more aware of the consequence of the choice of definition of impacts as some of the interviewees put forward a few political consequences of the choice of measure of impacts.The most frequent distinction between impacts measures revolve around economic and non-economic losses (D2, D4, D5, D8, D12). As of now, only a few EEA studies have attributed impacts. An example of economic loss attribution is Schaller et al. (2016), who attribute the change in the number of properties at risk of flooding around the River Thames during the 2014 southern England winter floods to climate change. An example of non-economic loss attribution is Mitchell et al. (2016), who attribute human mortality during the 2003 heatwave in Paris and London to anthropogenic climate change. There are a lot of other types of economic and non-economic losses, for which modelling methodologies are still to be built. Furthermore, it is difficult, especially in the case of non-economic losses to reduce impacts to a number (Wrathall et al., 2013).

	Influence of climate change on extreme events	Quotes
D1	Contributes to existing extreme events, no totally new weather events	“CC contributes to existing weather events, but is not actually at the origin of totally new weather events”

D2	Climate change increases the severity, intensity and frequency of extreme events	“The human-induced impact is to increase the severity, intensity and sometimes also the frequency of intense events, beyond the naturally occurring frequency. [...] So the one in twenty year has become a one in four year flood. That is human induced climate change. There is no other reason.” Gives a few examples of events (too frequent floods in Bangladesh, category 5 hurricane in the Atlantic, unprecedented flood in Louisiana)
D3	Climate change increases the unpredictability of extreme events. Refers to IPCC.	“The natural hazards as I said, will be more unpredictable, will be more extreme and then that will impact most of the events that will come in future. That is also part of the IPCC contribution AR5, that is the scientific background for our work.”
D4	Climate change increases the frequency, and the intensity of extreme events.	“the devastating natural disasters that are happening more frequently. So, sort of unusually high or strong cyclones or tornadoes that we’ve seen recently. Or out of season rainfall or drought, those are the extreme events. I think it’s about the frequency and their unusual strength that makes them related to L&D. That contributes to sort of identifying them as CC.”
D5	Climate change increases the frequency, the impacts and the magnitude of extreme events. Refers to IPCC.	“What you could say, and what the IPCC clearly says, is that the impacts and the magnitude, and the frequency of impacts will increase.”
D6	Climate change explains the occurrence of extreme events like hurricanes. The refusal to link extreme events to CC comes from political reasons, not from science.	“I think that all scientific people, they know the events. It is not beyond their capacity to analyze, but they could analyze this. It’s easy for scientific people to analyze, but it’s difficult for political people to implement.” “it depends on who is analyzing this. Hurricanes, it depends on how the scientific people do understand the linkage between hurricane events and L&D arising from the impacts of CC. If they are clearly analyzing the temperature increase, and then it will be easy for them to go through.” “it will be easy for them to come up with some proof, some data. But if they are dominated by some political issues, then it will be difficult for them to say “this is CC”.”
D7	No specific statement.	
D8	Climate change increases the frequency, and the severity of extreme events. CC is not the only driver of extreme events	“science is telling us those things will become worse, and will occur with more frequency because of climate change, science is telling us we’re gonna have bigger problems and that countries are gonna be severely affected by these bigger problems resulting from CC or exacerbated by CC”

D9	The frequency, the severity and the location of current EWE are a result of ACC. ACC is not the only driver of EWE.	“the science is loud and the science is clear. A lot of what is happening, the frequency of what is happening, in the places that it is happening and never used to happen before, the severity that is happening and didn’t happen before, people don’t believe... those who are believers see a lot of this as a result of CC.” “it’s very loud and clear: the frequency, the severity, the fact that it is happening in places where it didn’t happen before, and all of these things, makes a case for why it is about CC” “It does not mean that this is only CC.” “I think based on a lot of the work that has been happening, what I said early on in terms of frequency and severity and occurrence in places that didn’t happen before, that the linkages can be made to CC.”
D10	No specific statement.	
D11	The influence of climate change on extreme events depends on the type of events and on the region studied. Refers to IPCC.	“Extreme weather events was fairly well covered by the SREX report of the IPCC” “I wouldn’t lump all extreme events into one single bag. They vary very much from one region to the next, they vary very much whether you’re talking about drought, or cyclone, or flooding, or tide, you know, high tides and these kind of events that can obviously have extreme impacts, but are usually less frequent.”
D12	Climate change increases the number of extreme events. Climate change is not the only driver of extreme events.	“there are some events that would happen anyway, but then I think that climate change is going in such a way that there a more extremes or more whatever.”

Table D.4 – Delegates knowledge of the influence of climate change on extreme events

Globally (except for D11), the delegates’ knowledge about the role of anthropogenic climate change on extreme events is approximative (Table D.4). They believe that we know that climate change has an influence on extreme events, without discrimination of regions, or types of events. Some of them realize that climate change is not the unique driver of extreme events, others do not explicitly state that.A few of them back up their statements with references to the IPCC (D3,D5 and D11).The lack of understanding of the complexity of the relationship between climate change and extreme events, and of the difficulty to find any influence (or prove the lack of influence) of climate change on extreme events in many cases, testifies for the difficulty to both communicate and assimilate complex scientific messages. The fact that they think they know makes the possibility to change their views through communication more complicated. D6 considers that the link between climate change is easy to establish and that any reluctance to accept this link comes from political reasons. Although D6 is an outlier, his position reveals a general tendency from the delegates to consider that the science is easier to deal with than the politics (which is contrary to the position of (Allen, 2003)).

	Knowledge of EEA	Quotes

D1	Understanding of the challenges of EEA. Has not heard about EEA.	"I think it's difficult to say that one event in its entirety is attributable to CC." "CC contributes to existing weather events, but is not actually at the origin of totally new weather events."
D2	Understanding of the concept of EEA. Has heard of EEA.	"We are beginning to get closer and closer to getting credible scientists to be able to run the numbers and tell us whenever an event occurs within a matter of days of the event, the likelihood of that event, the magnitude that it had, because of elevated temperatures or human interference in the atmosphere in a percentage or probabilistic manner, that is fine. So essentially, the point is that without human-induced climate change, an event would have been category three, with human induced climate change it is category four or category five."
D3	Understanding of the challenge of EEA. Has heard about EEA. Approximative understanding of the concepts and methodologies of EEA.	"We had EE before the CC was there and we will have EE in the future, so we cannot attribute CC." "There is some interesting research going on with what they call the fraction of attribution of climate change to EE.[...] I think they call it Fractional attribution of CC, a way to say whether CC is 30% or 20%, it is very technical"
D4	Has not heard about EEA. Outside of field of expertise	"I would like to know more, I don't know much about it."
D5	Has not heard about EEA. Understanding of part of the challenges of EEA.	"IPCC has always clearly pointed out that it's extremely difficult if not impossible, non scientific even, to attribute one storm to CC" "I think it's not scientific to attribute one storm to CC."
D6	No understanding of challenges of EEA. Has not heard about EEA.	
D7	Has heard about EEA.	"It is an active area of research right now. Some groups in Oxford and other places are working on the attribution of extreme weather events."
D8	Refuses to answer the question. Outside of field of expertise	"I'm a lawyer so I can't really tell you about attribution."
D9	Has heard about EEA. Has a larger vision than just EEA including problem of apportionment of blame. Detection and Attribution for slow-onset events.	"People talk about the fact that you can't say for sure that this is CC that causes this, it's also the effect at the national level and that kind of things." "There are many persons who have actually been preparing papers on this. I've seen a couple of them where they are trying to make this issue of attribution a bit clearer."
D10	Refuses to answer the question. Outside of field of expertise.	"That's the question that needs to be asked to the technical people, the scientists."

D11	Good understanding of the challenge of EEA. Has not heard about EEA.	“when you have one EE, it’s an outlier in a lot of the analysis and it’s difficult to attribute just one event to CC, scientifically”
D12	Good understanding of the challenge of EEA. Has heard about EEA studies. Basic understanding of the concept of EEA.	“You can’t explain a weather even that would have happened, or identify the particular EE that would have happened, because we also know there is climate variability.” About 2003 European heatwave: “We attributed that.”“Is this attributable? Maybe not fully, but definitely there’s likely some attribution that can have ground.”

Table D.5 – Delegates knowledge of EEA

The delegates have different levels of understanding of why the attribution of a specific event to climate change might or might not be a challenge (Table D.5). The spectrum of answers goes from the idea that every event is attributable to climate change and that the people who do not acknowledge that do so for political reasons (D6) to saying that EEA is impossible and non scientific (D5). Out of the twelve delegates, five have already been confronted to EEA studies.

	Quotes of climate scientists on EEA for L&D
C1	“It comes into play in this kind of legal sense” “That would be the first step in a long legal battle and so we first have to accept [a FAR (Fraction of attributable risk)] in a court” “You would have to figure out what fraction [...] would have to be paid in a form of loss and damage and what fraction was the responsibility of the person who was damaged but they failed to adapt appropriately.” “It seems like a really complicated question actually.”
C2	“I wouldn’t be confident enough in our own results to be supportive that this, already at this stage, directly feeds on loss and damage.” “It will depend on the type of events, and maybe even the region of the events.” “I am thinking about the loss and damage, and what particularly the developing country may be affected by, which include droughts, tropical cyclones, potentially monsoon precipitations. All those are going to be extremely difficult. That is why I would be really uncomfortable if it was; if you would use our current methodology to make any statements about it and describe dangerous events.”
C3	“Je pense quand même qu’on s’attachera à compenser des pertes et des dommages causés par des événements qui sont eux mêmes causés par l’activité humaine. Faute de quoi, je vois pas trop pourquoi ça tomberait sous le sens du CC, sous la question du CC.” “Comment ça peut être fait, et comment la responsabilité sera partagée, ça pour moi c’est encore bien mystérieux.”

C4	“You can see reasons within the spirit of the UNFCCC: it’s impacts on climate change therefore, you should be showing that it is climate change that is affecting you. So that would be detection and atribution evidence..” “If you look seating in a courtroom I would say probably that detection and attribution is necessary.” “There is a major justice problem that emerges when you do that because the areas of the world for whom loss and damage is intended to be assessed; the loss and damages mechanisms is intended to assess, have generally not been monitored.” “In the Paris agreement, that is explicitly there, it is no liability and compensation. So what is it? It might be some sort of recognition of responsibility, what does that mean in terms of detection and attribution, the evidence must be required to gain funding for financing, I don’t know.”
C5	“Dans une situation où on dirait, [que] les pays industrialisés vont [...] abonder un fond qui va servir pour compenser les dommages dans les pays en développement, pour tant est qu’il soient affectés par des événements extrêmes causalement reliés au forçage anthropique [...] Eh bien dans ce cas là, évidemment, il faudra que dans le mécanisme à un moment donné il y ait un système d’expertise pour décider de ce qui doit être compensé de ce qui ne l’est pas” “Je pense qu’il y aura cette utilité-là, que tout le monde a dans le coin de la tête, en disant ouais un jour ou l’autre, tout le monde va vouloir nos expertises quoi. Enfin il y aura de gros enjeux économiques sur cette expertise-là.”
C6	“Je pense que ça peut aider un petit peu, mais je pense qu’il y a aussi un danger.” “La question c’est comment quelqu’un peut arrêter de fumer.” (i.e. comment est-ce qu’on peut arrêter d’émettre) “comme nous on a qu’une seule terre, et que les terres numériques ce n’est pas des terres sur lesquelles on peut vivre, ça fait peut-être que la question d’un point de vue philosophique est mal posée. [...] le corpus scientifique et philosophique de la statistique s’est toujours basé pour des expériences que l’on pouvait répéter plusieurs fois. Les décisions qui sont prises, c’est sur cette idée que l’on peut répéter l’expérience plusieurs fois.” “ça peut même ralentir la prise de décision”
C7	”I don’t think it will play a major role within the negotiations, within the UNFCCC” “It might potentially play a large role in the risk assessment, in the quantitative risk assessment, but amongst other methods. I hope it would play a larger role there.” “I think it could potentially play an important role outside the UNFCCC, in courts. And I am not sure about that [...] I think that might be one way where it could, outside the official loss and damage, be influencing loss and damage negotiations from there.”
C8	“This is very difficult because there is always some uncertainty, some wiggle room.” “There is so much non linearity in these things” “There are huge legal issues relating to any apportionment of blame, which is what the loss and damage aspects seem to have attached to it. And, because a lot of these things involve a threshold, you know the straw that breaks the camel’s back, the non linearities become extraordinarily difficult to deal with.” “And how do you apportion, I mean it’s all of humanity that’s burning CO2 and putting greenhouse gases into the atmosphere.”

C9	“Well it could, but I think it should not. I think this is not a helping knowledge [...] it would be liability basically [...] I think the problem with that argument is that, I mean there’s some basis for it for sure but I think first of all it would just give a huge amount of money to lawyers, without actually really solving much.” “The damages are a very nonlinear function. So it doesn’t partition in a linear way. And I think there would be just forever arguments about exactly, you know, about how you would evaluate that.” “There is already an international aid of course that is not predicated on liability. It is predicated on the fact that wealthy countries should help poor countries.” “I think it would lead to endless arguments, and it would be better just to keep it out of the tables, to say it is not a well-posed question, just to deal with the events impacts now.”

Table D.6 – Climate scientists on EEA for L&D. Quotes that helped to build table 6.2. Some interviewees were native French speakers, like the authors of this study. The interviews were hence conducted in French. We chose not to translate them in English in this verbatim table.

	Quotes of delegates on EEA for L&D
D1	“It is useful in terms that we should increase the pressure on mitigation.” “Some people consider it as just one way of trying to frame it in compensations that... so the... and I think that misses the point. [...] I think we’re not supposed to just do something which leads us into a dead end and then say “let’s see how we can pay for it”.It is definitely not a desirable state, that some countries produce impacts on other countries and then just say “okay, we’ll give you some money”.” “You can have two communities where they’re basically talking. We’re building in the coastal zone or we’re not building in the coastal zone. If the one that builds in the coastal zone is flooded, there will be a lot of L&D, but what does that really tell you? [...] You can’t do anything with that information, because “okay, you decided to be flooded, what do you want?” [...] you need to understand what the decision in the village was before you’re able to interpret the figures that you are getting.”
D2	“These are not natural events, they are human induced, the magnitude is because of human-induced climate change, but how much more we don’t know. Scientist have to tell us that.”
D3	“What predicts more the impacts is vulnerability, more than the hazard.” “I don’t think we should attribute CC to a single or particular event.” “Because an EE is not only climate, it’s several things, it has to do with poverty, with entitlement, with land-use planning, with many many things. If you start splitting up in different fractions, I am a bit reluctant there.”
D4	“If we say “this is what the indicators are. If it passes this, this, and this, it’s L&D”, then policy makers or countries can say “Oh sh** yeah, it’s happening”.”

D5	“How are you then, based on filtering out this much percent of the impact was related to CC, how are you then gonna divide and define the part related to CC to the responsibility of each party separately?” “You see, I’m not even sure whether, if it were possible, whether that would be of any help to proceed with the protection of people vulnerable to the impacts of CC.” “It could lead to a perverse situation where only the mediatisable, is that a word again I’m not sure ? the part that is being mediatised, could be addressed and then the rest would be left to those impacted to solve themselves.” “If you succeed in doing that and showing scientifically that these are fully attributed events and these aren’t, then you will always get politicians to say “we will only pay for those that are attributable, or we would only look for a solution for those that are 100% certain because of CC, and where it’s possible to say they are 100% certain because of CC and the others, well we don’t know so why should we take responsibility.” ”
D6	No relevant quote.
D7	“One of the things that captures my attention if it were more fully developed would be to understand how that science could contribute to understand potential scenarios of magnitude and frequencies of EE in the future related to weather.” “this body of science could offer scenarios that would help decision makers how to work [out...] what investment might make sense in which part of that continuum [between adaptation and contingency measures]”
D8	“If one is looking at liability, and compensation, attribution is very important to address the responsibility question.” “What it does is it just reinforces the call of many developing countries to deal with this in the CC agenda.” “If science could deliver that answer or that message, then you could cross that into a legal argument that calls for sustainable systematic approaches to deal with the types of impacts that poor and vulnerable countries are going to, well are facing.”
D9	“The work will have to continue with IPCC [...] to be able to make the connection a little bit stronger so that[...] the persons who are happy, some persons are happy to hide behind the facts and say “how can you prove that this EE or this slow-onset event is linked to CC, you can’t prove it and therefore, because you can’t prove it, [...] I have no responsibility for this and therefore I don’t have to help you in any way”...” “We’re counting on our scientific experts and persons out there to assist us in making stronger cases and that will allow us to get the necessary support and assistance in making progress.”
D10	“[The role of science in L&D] is extremely important because the attribution part can only be dealt by the science.”
D11	“Science is extremely important at this stage to get our numbers right, to start differentiating what is really attributable to climate forcing and changes in the climate, what is attributable to other processes.” “The other side of the coin of attribution is okay, if it is not attributable to CC, what is it attributable to?” “It’s always really easy to attribute everything to CC, but the reality is obviously different. You need to look... take a long hard look over time. We need to be able to tease out what is really attributable to CC from what is the background noise of development and poor development planning.”

D12	“I want scientists to be able to tell me, to quantify what has happened because of CC, what is the impacts of the losses and damage. [...] in these areas that have been clearly damaged because they are underlined by climate, in simple terms I can go on then to my policy makers: “this is what is contributed.””

Table D.7 – Delegates on EEA for L&D. Quotes that helped to build table 6.3.

As Tables D.6 and D.7 were the main basis for the Tables 6.2 and 6.3, I do not have anything to add about both of these tables.

	One of the action area defined by the committee is about “slow-onset events”(SOE). Why isn’t there one about extreme weather events?	Quotes
D1	We have more information on EE (in particular on how to address them from disaster risk reduction).	“In terms of time spent on the negotiations [...] we spend much more time with extreme weather events. Because this is where Parties decided that there’s the most information that already exists.” “There is already a lot of material that you can work on.”
D2	We have a better historical knowledge of EE than SOE (which are completely unprecedented).	“the rapid onset events like floods, hurricanes, and event droughts, are well-known phenomena that occurred naturally before human-induced climate change. But slow onset events, particularly sea level rise is a human induced element that hadn’t happened before.”
D3	EE are dealt with in the comprehensive risk management action area. SOE are less understood than EE.	“There is one about extreme weather events. There is one action area about comprehensive risk management.” “There are less research, there are less knowledge about the slow-onset events, because basically we have more knowledge, historical knowledge, of the extreme events. So I think that is why the input for slow-onset has a separate action area, it’s less understood.”
D4	There may be political reasons to avoid putting EE in the spotlight.	“Right now they’re taking less of an emphasis, only because it’s the more political science, in my opinion.” “I remember this from a conversation I had with a [Annex I country] negotiator last year [...] The [...] negotiator was saying “well, we just don’t want any or all the countries to say: oh look, this tornado happened, or oh look, we’ve seen changes in our environment, it’s because of climate change”.”

D5	EE are more visible. SOE are more difficult to monitor.	“Because I think extreme weather events speaks for itself” “Now slow-onset events are not only a lot more difficult to measure in terms of impacts and they’re a lot more difficult to monitor and therefore they get a lot less attention.” “Slow-onset events do need, I think, a separate work stream to draw the attention to the difficulty that is related to the attribution and the monitoring of these slow-onset events.”
D6	SOE are more difficult to grasp than EE.	”It’s very hard for [coastal communities] to understand”
D7	We already have UN institutions to address EE. There may be political reasons to keep the work on EE out of the convention (because the UNFCCC is legally binding).	“Part of it may be that there is another policy area under the ISDR that deals with disasters.” “the UN-ISDR has national platforms and they deal with a variety of hazards, and not just hazards relating to climate stressors and weather. [...] that process is not binding in the way that our convention is binding.” “Mixing in language from other processes, perhaps there was less appetite for doing so, for a variety of reasons, perhaps political.”
D8	EE are dealt with in the comprehensive risk management action area. We already have mechanisms to address EE. We don’t know how to address SOE.	“If you look at the work area work stream on comprehensive risk management, which there is one, that is the one that covers impacts from extreme weather events.” “there is less knowledge on how to address slow-onset events.” “not uncertainty that those impacts will eventually happen, but uncertainty or a lack of knowledge as to how to address this type of events.”
D9	EE are more visible. We know more about EE. We know more about how to address them. SOE are difficult to monitoring. EE are dealt with in other action areas (including comprehensive risk management).	“[EE are] receiving a lot of visibility” “slow-onset events are not receiving that kind of visibility, because it happens slowly and cumulatively over time, I used the phrase “like a thief in the night.”” “There is still a lot of information that is unknown about slow-onset events. The measures used for addressing them are harder to come up with than measures for addressing EE. And the ways to monitor those slow-onset events are also difficult, because it means you set your monitoring system that is supposed to be over a longer period of time, because of the fact that you are measuring slow changes” “it’s an area where more work is required in terms of building awareness, understanding how we measure it, understanding how we can address it, understanding how we can assist others in addressing it, raising the visibility of those areas” “It’s not like it’s lost, it’s just that we thought there was a need, and countries and sub-groups thought there was a need, for a special focus on slow-onset events, given all of the things that I mentioned before.” Also makes a point about EE being included in other action areas (like comprehensive risk management)

D10	Also surprised by the asymmetry. EE are dealt with in the comprehensive risk management action area.	"That was also my question as well. Because most of our countries feel... Let me give an example in my country [...], we feel the EE is one of the important events and it's similar to the other activities that are destructive." "One of the understanding was that it could fit somewhere in the comprehensive risk management, or something like that, the risk reduction maybe."
D11	We already know a lot thanks to the SREX. We already have mechanisms to address EE.	"Extreme weather events was fairly well covered by the SREX report of the IPCC" "I think this is an issue that's fairly well covered worldwide and has been addressed by the convention." "Where we did have a lot more work to do were on these issues of slow-onset events, so it's understandable that the Excom decided to put, you know, place the priority on that."
D12	EE are dealt with in the comprehensive risk management action area.	"There's a work stream about it: comprehensive risk management."

Table D.8 – Delegates on slow-onset events (SOE) and extreme events (EE)

The analysis of Table D.8 is fairly complete in section 6.3. Delegates generally consider we know a lot more about extreme events than about slow-onset events. This is confusing from a climate scientist point of view because we have more difficulty to understand how climate change affects some extreme events than slow-onset events. From a political point of view, slow-onset events pose new questions when it comes to dealing with them. In particular, a few countries risk losing their territories because of sea level rise, and there is a hole in international law regarding the status of the inhabitants of those sinking islands. Some delegates fear that the slow-onset events are forgotten in favor of extreme events. There has been a reversal in loss and damage main focus since the original proposal to include only loss and damage associated with sea level rise (Vanuatu, 1991). There is also a lack of scientific discussion regarding the use of detection and attribution of trends results, which would typically apply to sea-level rise, compared to discussions related to EEA. Of the literature introduced in section 6.1.3, only Huggel et al. (2013, 2015, 2016) discuss both detection and attribution of trends and EEA.

	How would you deal with the events for which the uncertainties are too high for science to attribute them to climate change?	Quotes
D1	Precautionary principle.	"How to deal with them? Mitigate them. Mitigation and mitigation and mitigation." "Even if just in case it would be linked to CC we could still avoid it."
D2	Need to address the impacts regardless of CC/no CC.	"The events are occurring. We need to deal with them."

D3	Precautionary principle.	“Have you heard about this? Precautionary principle ? You have to take it in order to avoid the impacts of EE.” “We will not accept loss of life, health, or the interruption of critical societal functions or critical infrastructures.” “We know that, from the economic side of things, that the introduction of prevention is cheaper than, you know, reparation.” “I don’t think we should use uncertainties as an excuse for not planning better.”
D4	Precautionary principle. Institute a status for events for which we don’t know.	“It goes back to precautionary principle and this recognized fact that we don’t know everything now and we have some strong indications as to how we should act.” “Even though you can’t that this particular event is L&D, there needs to be this recognized kind of gray area, where perhaps it would not lead to compensation, or money, or a dollar value, or a check from a rich country, not necessarily like that, but this gray area where you say that is probably L&D.”
D5	Need to address the impacts regardless of CC/no CC.	“I would, over time, hope that there is no need to single out CC at all and that a realistic approach can be found and that the right funds can be channeled.”
D6	No understanding of uncertainties. They are only related to politics, not to science.	“It is not beyond their capacity to analyze, but they could analyze this. It’s easy for scientific people to analyze, but it’s difficult for political people to implement.”
D7	Relies on the science of decision making under uncertainty	“There’s a whole science of decision making under uncertainty so I would hope for inputs from that body of scientists.”
D8	Need to address the impacts regardless of CC/no CC.	“At some point, even if you don’t know, even if science can’t tell you what’s happening, if it happens there has to be some way to address the impacts, regardless of whether science can tell you or not.”
D9	It is too soon to address this question. Need to address the impacts regardless of CC/no CC	“It’s difficult to sit down now, here, when we’ve only just finally got the PA last year, [...] to be able to sit here and say “this is what we’re gonna do about areas of uncertainty.” “There is uncertainty in some areas and there will be uncertainty, but as it is always said, are uncertainties in areas are reason to take no action while people die? I don’t think so.”
D10	Refuses to answer the question. Outside of field of expertise.	“That’s another difficult question, which is for the technical people I think.”

D11	Accept the possibilities of science. Uncertainty will not disappear. Geographical distribution of attributability.	“I think we have the false expectation that attribution somehow solves and eliminates uncertainty.” “Obviously, the issue of compensation for L&D looms its ugly head. The lawyers will be there waiting for the scientists to provide certainty where there is none.” “I don’t think uncertainty will be solved overnight and the attribution will have to be weak in some places and strong in others, where we have more certainty than others.”
D12	Precautionary principle.	“I come from a medical background, I’m used to aim on the side of pushing to save human lives. So I look at near everything, so if even if there is some slight possibility to save one or two human lives, I would look at that thing and say “that’s how” straight”

Table D.9 – Delegates on uncertainties regarding the attribution of some extreme events to climate change.

One of the questions I asked interviewees was ‘How would you deal with the events for which the uncertainties are too high for science to attribute them to climate change?’. The answers to that question were not used for the analysis of section 6.3. They are nonetheless informative. There is a consensus on the need to address loss and damage related to an extreme event regardless of our ability to attribute the event to climate change. The main difference is between people who understand the question in terms of mitigation or adaption. For the former, the idea is that if there is a risk of causing more extreme events, it is our duty to avoid this in virtue of the precautionary principle. The latter group adopt an ex-post perspective on catastrophe, highlighting the need to help impacted countries to recover. At this moment, this question is not yet on the negotiation agenda (D9). This illustrates how loss and damage exist within the context of the UNFCCC without a need to formally relate them to anthropogenic climate change.

Appendix E

Coauthored articles

During this PhD, I coauthored five articles, which are attached to this manuscript in the following order.

- *A statistical framework for conditional extreme event attribution* was published in Advances in Statistical Climatology, Meteorology and Oceanography.
- *Methods and Model Dependency of Extreme Event Attribution: The 2015 European Drought* was published in Earth's Future.
- *Crisis, disaster, risk and adaptation* is the english version of a chapter of *Adapting to Climate Change: A question for our societies* published by the CNRS Editions.
- *Revisiting dynamic and thermodynamic processes driving the January 2014 precipitation record in southern UK* is currently in revision in Scientific Reports.
- *An experimental workshop to question the implications of an increase in extreme weather events frequency on French railways system* has been submitted to Technological Forecasting & Social Change.

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A statistical framework for conditional extreme event attribution

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Abstract. The goal of the attribution of individual events is to estimate whether and to what extent the probability of an extreme climate event evolves when external conditions (e.g., due to anthropogenic forcings) change. Many types of climate extremes are linked to the variability of the large-scale atmospheric circulation. It is hence essential to decipher the roles of atmospheric variability and increasing mean temperature in the change of probabilities of extremes. It is also crucial to define a background state (or counterfactual) to which recent observations are compared. In this paper we present a statistical framework to determine the dynamical (linked to the atmospheric circulation) and thermodynamical (linked to slow forcings) contributions to the probability of extreme climate events. We illustrate this methodology on a record precipitation event that hit southern United Kingdom in January 2014. We compare possibilities for the creation of two states (or "worlds") in which probability change is determined. These two worlds are defined in a large ensemble of atmospheric model simulations (Weather@Home factual and counterfactual simulations) and separate periods (new: 1951–2014, and old: 1900–1950) in reanalyses and observations. We discuss how the atmospheric circulation conditioning can affect the interpretation of extreme event attribution. We eventually show the qualitative coherence of results between the choice of worlds (factual/counterfactual vs. new/old).

1 Introduction

Many extreme events that occur on a local scale are specific to large-scale atmospheric patterns (e.g., rainfall, windstorms, heatwaves in Europe, and phases of the North Atlantic Oscillation). If such links have been identified, changes in the probability of local extremes can be due to changes in the properties of the atmospheric circulation or changes in the link between the local variable and the circulation (which can remain unchanged). The first cause is sometimes qualified as "dynamic" because it refers to the motion of the atmosphere. The second cause is qualified as "thermodynamic" (or "non-dynamic"), because it implicitly assumes that the local variable is related to the local change of atmospheric physical properties (e.g., temperature, water content) in the absence of flow changes (Trenberth et al., 2015).

The extreme event attribution (EEA) consists of estimating if and how the probability of an extreme event depends on the climate forcings (National Academies of Sciences Engineering and Medicine, 2016). One of the outcomes is the assessment of whether anthropogenic forcings alter such probability. This type of study has been used for estimates of liability for extreme events that caused damages (Allen, 2003).

The first scientific challenge of EEA is to define two worlds to be compared. The EEA studies speak of a *factual* world when all climate forcings (natural and anthropogenic) are considered (Stott et al., 2004; Pall et al., 2011). This is presumably a world that "is", and in which an event is observed with probability p_1. The *counterfactual* world contains only natural forcings, and is a world that "might have been" without anthropogenic forcings. In such a world, the same class of extreme event would occur with probability

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p_0. Defining a counterfactual world is a difficult task because it is a possible but non-observed state of climate. Then, some studies define the fraction of attributable risk (FAR), which is the relative change of probability between the two worlds FAR $\equiv (p_1 - p_0)/p_1 = 1 - p_0/p_1$ (Stott et al., 2004). Other combinations of the p_0 and p_1 probabilities also provide pieces of valuable information (Hannart et al., 2016) in the framework of causality theory (Pearl, 2009). The FAR is interpreted in terms of a probability of *necessary* causation. A probability of *sufficient* causation is defined by $1 - \frac{1-p_1}{1-p_0}$.

An alternative approach to factual/counterfactual worlds can be proposed, as in van Haren et al. (2013): a "new" world in which we live, like the recent decades, and an "old" world in which our ancestors lived, like the beginning of the 20th century. We implicitly assume that these two worlds are different (at least from the environmental point of view). For instance, the anthropogenic forcings are likely to be stronger in the new world than in the old world. The main feature of this approach is that it can be based on observed data. It is difficult to decipher the natural and anthropogenic forcings between old and new. Moreover, the old world might not be free of anthropogenic forcings. It is just assumed that the old world is less affected than the new world by anthropogenic forcings. Therefore, such an observation-based approach can only provide qualitative information on EEA, from implicit hypotheses in the forcing changes, like "greenhouse gas forcing" is larger in the new world than in the old world.

Each of these two approaches can be summarized in terms of a *universe* containing two worlds (factual/counterfactual or new/old) in which probabilities of extreme events are determined.

A second challenge is to determine the dynamical and thermodynamical contributions to the change of probabilities of a class of events. We assume that extreme values of a climate variable are generally reached for given patterns of atmospheric circulation. The challenge is (i) to estimate the contribution of atmospheric variability in climate change, and (ii) to determine how the properties of a local climate variable would change if the atmospheric circulation is fixed to these patterns but forcings (natural vs. anthropogenic) are different. This is advocated by a "storyline" approach to describe a *class* of extreme events, by understanding the general synoptic conditions leading to the extremes (Trenberth et al., 2015; Shepherd, 2016). The storyline approach is designed to decompose the role of climate change in the dynamical and thermodynamical contributions. From a statistical point of view, this motivates the term "conditional attribution"; we investigate how the probability of a local extreme event that depends on a large-scale atmospheric circulation is affected by global climate change or the properties of the circulation itself. If we focus on precipitation extremes, the issue is to evaluate changes in atmospheric flows leading to high precipitation (the dynamical contribution) and changes in precipitation rates given a favorable atmospheric flow (the conditional thermodynamical contribution) (Trenberth et al., 2015). This requires one to define a metric to follow the atmospheric circulation conditioning. We propose two choices of such metrics and evaluate how they affect the interpretation of extreme event attribution.

The primary goal of this paper is to propose a statistical Bayesian framework to identify dynamical and thermodynamical contributions to a change of probability of a class of extreme events involving the atmospheric circulation. The Bayesian aspect emphasizes the role of atmospheric circulation trajectories that drive extreme events. For illustration purposes, we focus on the heavy precipitation event that occurred in Europe in January 2014, which has been investigated by many authors (Huntingford et al., 2014; Matthews et al., 2014; Christidis and Stott, 2015; Schaller et al., 2016). This event was a record precipitation in southern UK and Brittany (France). We test this statistical framework on a combination of two universes (factual/counterfactual and new/old) and two atmospheric circulation metrics. These four experiments allow for a focused discussion on the interpretation of extreme event attribution.

Section 2 details the datasets that are used to define two worlds. Section 3 explains the notation and methodology that is developed in the paper. Section 4 gives the results of the analyses from the two datasets. The results are discussed in Sect. 5 and conclusions appear in Sect. 6.

2 Data

This section explains the two universes that are considered in this study. The first one is based on a large ensemble of climate simulations. The second is based on reanalyses and observations.

2.1 Weather@Home

We used an ensemble of atmospheric model simulations from Weather@Home to test factual vs. counterfactual worlds. The Weather@Home data come from the "weather@home" citizen-science project (Massey et al., 2015). This project uses spare CPU time on volunteers' personal computers to run the regional climate model (RCM) HadRM3P nested in the HadAM3P atmospheric general circulation climate model (AGCM) (Massey et al., 2015) driven with prescribed sea surface temperatures (SSTs) and sea ice concentration (SIC). The RCM covers Europe and the eastern North Atlantic Ocean, at a spatial resolution of about 50 km. These simulations were used by Huntingford et al. (2014) and Schaller et al. (2016) to investigate the impact of climate change on the extreme precipitation of January 2014 in southern UK.

The factual world is made of ≈ 17 000 winters (December-January-February: DJF) simulated under observed 2013/2014 greenhouse gas (GHG) concentrations, SSTs and SICs. Initial conditions are perturbed slightly for each ensemble member on 1 December to give a different realization of the winter weather.

The counterfactual world is made of ≈117 000 simulations with different estimates of conditions that might have occurred in a world without past emissions of GHGs and other pollutants including sulfate aerosol precursors. The atmospheric composition is set to the pre-industrial, the maximum well-observed SIC is used (DJF 1986/1987) and estimated anthropogenic SST change patterns are removed from observed DJF 2013/2014 SSTs (Schaller et al., 2016). To account for the uncertainty in the estimates of a world without anthropogenic influence, 11 different patterns are calculated from climate model simulations of the Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al., 2012).

The circulation C is taken from the sea-level pressure (SLP) data of the RCM simulations. The climate variable R is the southern UK precipitation averaged over land grid points in 50–52° N, 6.5° W–2° E. Simulated R for the factual ensemble members with the wettest 1 % are comparable to observations of January 2014. The mean climate of the RCM has a wet (positive) bias of $+0.4\,\mathrm{mm\,day^{-1}}$ in January over southern UK (Schaller et al., 2016) but most RCM simulations for January 2014 show smaller anomalies than in the observations reported by Matthews et al. (2014), and show a weaker SLP pattern for the same precipitation anomaly. On average, the factual simulations reproduce a stronger jet stream, compared to the 1986–2011 climatology of January 2014 in the North Atlantic, suggesting some potential predictability for the enhanced jet stream of January 2014 (Schaller et al., 2016). The differences in SSTs, SICs and atmospheric composition between the two sets of simulations lead to an increase (from the counterfactual to factual) of up to $0.5\,\mathrm{mm\,day^{-1}}$ in the wettest 1 % ensemble members for January southern United Kingdom precipitation.

2.2 Reanalyses and observations

The comparison of old vs. new worlds was performed with two reanalysis datasets. We consider the circulation C from the SLP over the North Atlantic region (80° W–50° E; 25–70° N) for both reanalyses. The new world is made of the National Centers for Environmental Prediction (NCEP) reanalysis data for the winters (December to February) between 1951 and 2014 (Kalnay et al., 1996). The old world is made of the 20CR reanalysis dataset for the winters between 1900 and 1950 (Compo et al., 2011). The reason why both reanalyses need to be considered is that 20CR ends in 2011 and hence does not include the winter 2013/2014, in which we are interested, for the case study of Schaller et al. (2016). A few tests on the statistical properties of the circulation in both reanalyses were performed on their overlapping period (Schaller et al., 2016). It appears that in spite of using different climate models and with different resolutions, both reanalyses exhibit similar features. This means that the shift from the old world (with 20CR) to the new world (with NCEP) is rather smooth.

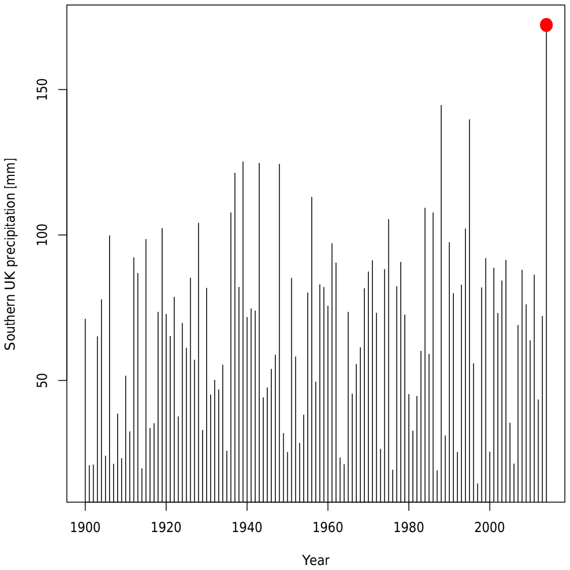

Figure 1. Time series of January cumulated observed precipitation in southern United Kingdom between 1900 and 2014 (in mm). The red dot indicates the value of R for January 2014.

The precipitation R is taken from daily precipitation observations from the UK Met Office (Matthews et al., 2014) between 1900 and 2014. The dataset consists of observations from 14 stations in the southern UK. These stations include Oxford, Rothamsted, Wisley, Bognor Regis, Cambridge, Eastbourne, East Malling, Goudhurst, Hampstead, Hampton, Larkhill, Otterbourne, Shanklin (Isle of White) and Woburn. The variable R is an average of daily values of these 14 stations. We verify that a record of January monthly precipitation was reached in 2014 (Fig. 1).

3 Methodology

3.1 Notations and rationale

We assume that a climate variable R (e.g., temperature, precipitation) and atmospheric circulation C (e.g., SLP, geopotential height at 500 hPa) are observed in a *universe* that contains two distinct *worlds* that we call $\mathcal{W}_0$ and $\mathcal{W}_1$. Here, R is a real variable and C is a two-dimensional field. For the first universe, $\mathcal{W}_1$ is the "factual" world and $\mathcal{W}_0$ is the "counterfactual" world. This universe is represented by the Weather@Home ensemble. In the second universe $\mathcal{W}_1$ is the new world and $\mathcal{W}_0$ is the old world. This universe is represented by the NCEP (1951 to 2014) and 20CR (1951 to 2014) reanalyses, and observed precipitation. We specify in the text the universes to which the worlds $\mathcal{W}_i$ belong, in order to avoid unnecessarily complicated notations.

We recall that the $\mathcal{W}_1$ worlds (in the two universes) are close to the one in which we live, either in terms of anthropogenic/natural climate forcings or in terms of temporal proximity (e.g., the last decades). The $\mathcal{W}_0$ worlds contain only natural climate forcings, or temporal remoteness (e.g., beginning of 20th century: 1900–1950 vs. recent decades: 1951–2014).

We define an extreme event (in either worlds and universes) when a reference threshold R_{ref} for R has been equalled or exceeded. A "class of events" includes the ensemble of weather types for which the threshold can be equalled or exceeded. In this paper, we assume that such an extreme event is reached during a spell of atmospheric circulation C_{ref} in the world $\mathcal{W}_1$.

The goal of extreme event attribution is to determine how the probability of an extreme event differs between $\mathcal{W}_1$ and $\mathcal{W}_0$. Achieving this goal is trivial if a rare event can occur in one of the worlds and cannot in the other. In practice, this does not happen for most extreme events that have occurred in the past decades, because there are often historical examples of such events (e.g., most European winter storms, European heatwaves). Thus, we assume that a given extreme or rare climate event has a probability of occurrence p_1 in $\mathcal{W}_1$, and p_0 in $\mathcal{W}_0$.

The probabilities p_1 and p_0 are defined by

$$p_i = \Pr(R_{(i)} > R_{\mathrm{ref}}), \tag{1}$$

where $R_{(i)}$ is the climate variable R in the $\mathcal{W}_i$ world, and $i \in \{0, 1\}$.

For obvious pragmatic reasons, we can assume that $p_1 > 0$, because we want to study an event that was observed in the real world. In addition, p_1 can be fixed to a quantile of the probability distribution of R in $\mathcal{W}_1$. Here we take $p_1 = 0.01$ to be consistent with (Schaller et al., 2016). This could be interpreted in a one-in-a-century event if the data have a yearly sampling. This defines a class of events (here high values of R). Therefore, there is no uncertainty in the determination of p_1. The uncertainty is shifted to the estimate of R_{ref} from $\mathcal{W}_1$ data (if $1/p_1$ is larger than the size of $\mathcal{W}_1$), and in p_0.

We want to estimate the ratio p_0/p_1, determine its uncertainty and investigate how it is controlled by physical factors. These physical factors include changes in the probability distribution of the circulation C between $\mathcal{W}_1$ and $\mathcal{W}_0$ and the changes in the probability distribution of R if C is similar in $\mathcal{W}_1$ and $\mathcal{W}_0$. We introduce the notion of vicinity of circulation trajectories, or the *neighborhood* $\mathcal{V}$ of an observed circulation C_{ref}. The trajectory neighborhood will be defined in two ways: from the distance to a known weather regime (Sect. 3.3.1), which is computed independently of the event itself, or from the distance to the observed trajectory of circulation (Sect. 3.3.2).

3.2 A conditional formulation of extreme event attribution

The probabilities $p_i (i \in \{0, 1\})$, which represent the marginal probability that the climate variable $R_{(i)}$ exceeds a threshold R_{ref} (unconditional on the circulation) in world $\mathcal{W}_i$, can be decomposed into a product of conditional probabilities involving the atmospheric circulation $C_{(i)} \in \mathcal{V}(C_{\mathrm{ref}})$ using rules of probability (Bayes' formula) as follows:

$$\begin{aligned} p_i \equiv \Pr(R_{(i)} > R_{\mathrm{ref}}) \quad &= \Pr(R_{(i)} > R_{\mathrm{ref}} | C_{(i)} \in \mathcal{V}(C_{\mathrm{ref}})) \\ &\quad \times \Pr(C_{(i)} \in \mathcal{V}(C_{\mathrm{ref}})) \\ &\quad / \Pr(C_{(i)} \in \mathcal{V}(C_{\mathrm{ref}}) | R_{(i)} > R_{\mathrm{ref}}). \end{aligned} \tag{2}$$

The three terms of the right-hand side of Eq. (2) can be computed from data in the two worlds $\mathcal{W}_i$.

The ratio $\rho = p_0/p_1$ is then decomposed into three terms that can yield physical interpretations. The first one is the thermodynamical change between the two worlds *for a given circulation*:

$$\rho^{\mathrm{the}} \equiv \frac{\Pr(R_{(0)} > R_{\mathrm{ref}} | C_{(0)} \in \mathcal{V}(C_{\mathrm{ref}}))}{\Pr(R_{(1)} > R_{\mathrm{ref}} | C_{(1)} \in \mathcal{V}(C_{\mathrm{ref}}))}. \tag{3}$$

In this term, the circulation is fixed to one that is close to C_{ref}, and changes of the probability of R are due to causes such as an increased temperature (increasing the water availability in the atmosphere, Peixoto and Oort, 1992). If the C_{ref} pattern is prone to high precipitation, this conditional term allows for a closer focus on the tail of the distribution of R.

The second term accounts for changes in the patterns of the atmospheric circulation and is hence called "circulation":

$$\rho^{\mathrm{circ}} \equiv \frac{\Pr(C_{(0)} \in \mathcal{V}(C_{\mathrm{ref}}))}{\Pr(C_{(1)} \in \mathcal{V}(C_{\mathrm{ref}}))}. \tag{4}$$

It is important to note that C_{ref} is the same in the numerator and denominator. The circulation term measures the change of likelihood of observing circulation sequences that look like C_{ref}.

The third term is a *reciprocity* condition for the circulation trajectory C:

$$\rho^{\mathrm{rec}} \equiv \frac{\Pr(C_{(1)} \in \mathcal{V}(C_{\mathrm{ref}}) | R_{(1)} > R_{\mathrm{ref}})}{\Pr(C_{(0)} \in \mathcal{V}(C_{\mathrm{ref}}) | R_{(0)} > R_{\mathrm{ref}})}. \tag{5}$$

This term determines the extent to which the circulation C_{ref} is necessary when $R > R_{\mathrm{ref}}$. For a fixed R_{ref} precipitation rate, it evaluates how likely a circulation such as C_{ref} is. This reciprocity term allows one to connect the risk-based approach of EEA, based on the study of ρ alone (Shepherd, 2016) to the "storyline approach" (Trenberth et al., 2015; National Academies of Sciences Engineering and Medicine, 2016), which involves the processes that drive the extreme precipitation.

The product $\rho^{\mathrm{dyn}} \equiv \rho^{\mathrm{circ}} \times \rho^{\mathrm{rec}}$ defines the *dynamical* contribution of the atmospheric change to the precipitation extreme conditional to a fixed thermodynamics. The reciprocity term explores the extent to which the circulation is close to the observed one when the cumulated precipitation is high. This multiplicative decomposition of probabilities can be compared with the "additive" decomposition of Shepherd (2016, Eq. 1), who also introduces a non-dynamical term. Our decomposition allows for the fact that the probability distribution of R and C could remain unchanged between $\mathcal{W}_0$ and $\mathcal{W}_1$, while the physical link between these variables evolve in compensating ways; the probability of having a high R when C is close to C_{ref} could decrease and the probability of having C close to C_{ref} when R is high could increase.

Sampling uncertainties on these three ratios can be determined by bootstrapping over the elements of $\mathcal{W}_i$.

The estimation procedure is the following:

1. determine p_1 (for example a century return period) and an empirical R_{ref} (for example from $\mathcal{W}_1$);
2. determine the neighborhood of C_{ref} (for example from the monthly frequency of a weather regime);
3. determine ρ^{the}, ρ^{circ}, ρ^{rec} and their sampling distribution for the two worlds, for example by bootstrapping over $\mathcal{W}_i$. The bootstrap is done by repeating random samples of seasons so that the intra-seasonal coherence is preserved.

We then assess whether ρ^{the}, ρ^{circ} and ρ^{rec} are significantly different from 1 by comparing their sampling distributions. We denote $\bar{\rho}$ the estimate of each ratio from all data. The 5th and 95th quantiles ($\hat{\rho}^{5\,\%}$ and $\hat{\rho}^{95\,\%}$, respectively) of the bootstrap simulations provide an interval of the sampling confidence interval $(\bar{\rho} - (\hat{\rho}^{95\,\%} - \bar{\rho}), \bar{\rho} - (\hat{\rho}^{5\,\%} - \bar{\rho}))$

We will illustrate this approach on the high precipitation event of the winter 2013/2014 in southern UK.

3.3 Circulation neighborhood

In this section, we propose two ways of defining the neighborhood of the circulation C_{ref}. This has an impact on the computation of the thermodynamical and dynamical terms of the decomposition of ρ.

3.3.1 Proximity based on weather regimes

High winter precipitation in Europe is generally associated with zonal atmospheric circulation. The circulation around the North Atlantic can be described by four weather regimes, which are quasi-stationary states of the atmosphere (Vautard et al., 1988; Kimoto and Ghil, 1993; Michelangeli et al., 1995). These weather regimes are obtained by a K means classification of anomalies of the winter SLP daily field from the NCEP reanalysis (Michelangeli et al., 1995; Yiou et al., 2008) on a reference period (1970–2000). The weather regime centroids are shown in Fig. 2.

The weather regimes of the 20CR reanalysis are the same as for NCEP, as well as the regime frequencies (Schaller et al., 2016, supplementary Fig. 7). After a removal of the mean, the SLP of Weather@Home simulations is projected onto these reference centroids to compute the weather regime frequencies. This is done to ensure the consistency of the interpretation of the regime frequencies.

The frequencies of the weather regimes are computed for each winter season (December-January-February). Very wet winters in the UK or northwestern France occur when the frequencies of zonal (ZO) or negative phase of the North Atlantic Oscillation (NAO−) weather regimes are high ($\geq 75\,\%$). This threshold duration roughly corresponds to the 97th quantile of frequency for the zonal (ZO) regime in Weather@Home simulations. This allows one to have a non-zero probability of $\Pr(C_{(i)} \in \mathcal{V}(C_{\mathrm{ref}})$ for the ZO regime in both reanalysis worlds.

The average frequency of the zonal weather regime is close to 25 % and the frequency reached 81 % in January 2014. The two other weather regimes (Scandinavian blocking and Atlantic Ridge) do not lead to very high precipitation rates in southern UK. The zonal weather regime favors warm temperatures in Europe, while NAO− favors cold temperatures (Yiou and Nogaj, 2004; Cattiaux et al., 2010).

The atmospheric trajectories can then be tracked by daily sequences of weather regimes. We summarize the information of a trajectory over a whole winter season (or a single winter month) by the frequencies of the four weather regimes. Hence, if C_{ref} was mainly zonal (as was the winter of 2013/2014), we will say that the circulation C is in the neighborhood of C_{ref} ($C \in \mathcal{V}(C_{\mathrm{ref}})$) if the frequency of the zonal weather regime exceeds 75 %. This definition obviously oversimplifies the notion of circulation neighborhood, but it gives an intuitive and qualitative understanding of the atmospheric circulation. This approach is also taken for consistency with the study of Schaller et al. (2016).

3.3.2 Proximity based on analogues of circulation

The computation of weather regimes provides an intuitive and physical interpretation of the atmospheric circulation patterns. But the atmospheric flow trajectories that are considered are, by construction, just closer to one of the weather regime centroids than the others, and not necessarily close to the circulation that prevailed during the event, which could be atypical in terms of weather regimes. Hence, we also explore the atmospheric circulation with *analogues*, which exploit explicitly a distance to a reference observed circulation pattern sequence.

If $C(d)$ is the SLP during some day d, the analogues of C are the days d_k in a different year, for which the Euclidean distance $d(C(d), C(d_k))$ is minimized. This defines analogues of circulation, based on SLP. Here we consider the North Atlantic sector (80° W–50° E; 25–70° N) to compute the distance between two SLP patterns, as in Yiou et al.

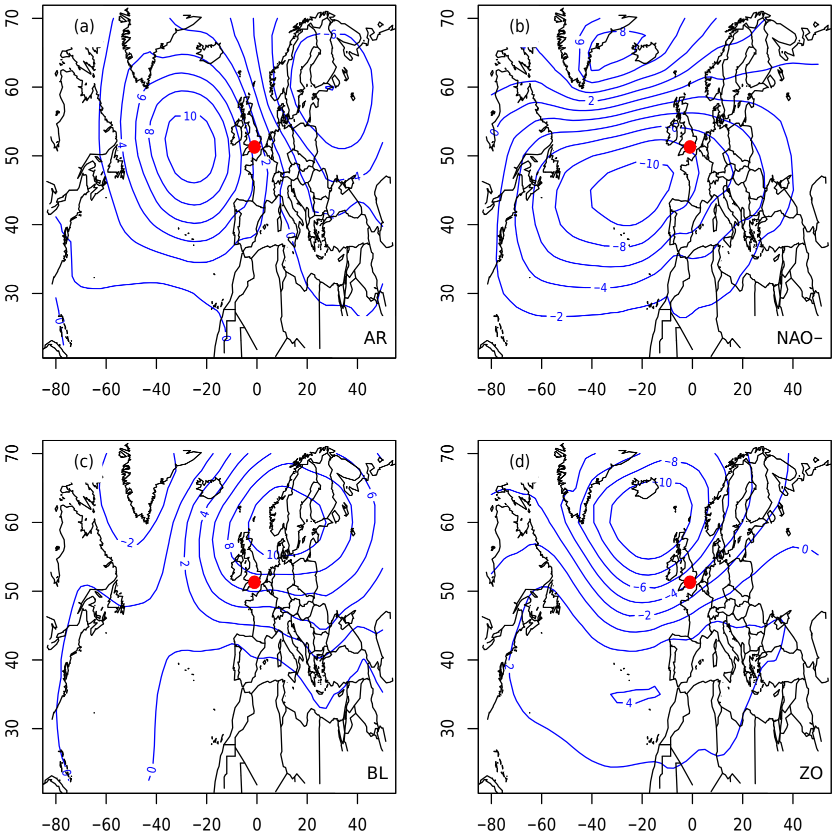

Figure 2. Four winter (DJF) weather regimes of the North Atlantic, computed from the SLP anomalies (in hPa) of NCEP reanalysis. **(a)** Atlantic Ridge (AR); **(b)** NAO−; **(c)** Scandinavian blocking (BLO); **(d)** zonal (ZO). The red circles indicate the region where high precipitation was observed.

(2013). We take the $K = 20$ best analogues of circulation for each day.

A justification to use analogues of circulation to describe the January 2014 atmospheric circulation comes from the fact that the SLP had a rather unusual pattern, which did not have all the characteristics of the zonal weather regime shown in Fig. 2. We illustrate this in Fig. 3 with the mean of analogues from $\mathcal{W}_0$ (1900–1950 in 20CR; Fig. 3c) and $\mathcal{W}_1$ (1950–2014 in NCEP; Fig. 3d). The mean SLP yields a rather steep gradient over UK and France. This steep SLP gradient is better reproduced in the analogue mean than in the ZO weather regime.

A heuristic way to define the neighborhood of the trajectory C_{ref} (e.g., a sequence of $C(d)$ with days in January 2014) is to compute the mean (over the days) of a quantile of the distances of the best analogues of K. This value can be modulated by a "safety" factor to ensure that there are enough trajectories around C_{ref} to construct statistics. This defines a neighboring "tube" around C_{ref} in the SLP phase space. This threshold is computed from the analogues of C_{ref} in January 2014 for the NCEP reanalyses (1950–2014, excluding January 2014) and gives a value of ≈ 12 hPa for a median quantile of the $K = 20$ best daily analogues and a safety factor of 1.5.

In addition to a definition of proximity, we use the dates of the best SLP analogues simulated reconstructions of climate variables. Here we focus on precipitation R. From a statistical perspective, the analogue precipitation is random "replicates" of the precipitation at the day conditioned by the atmospheric circulation. This allows for a determination of the probability distributions of precipitation (R) variability conditioned to the atmospheric circulation C.

Analogues of C and R provide a natural way of computing the probabilities in Eq. (2). We compute this estimate from the reanalysis datasets ($\mathcal{W}_0 =$ 20CR and $\mathcal{W}_1 =$ NCEP). By contrast, we test the null hypothesis H0 that circulation does not play a role in the high precipitation rate by computing the probability distribution of cumulated precipitation

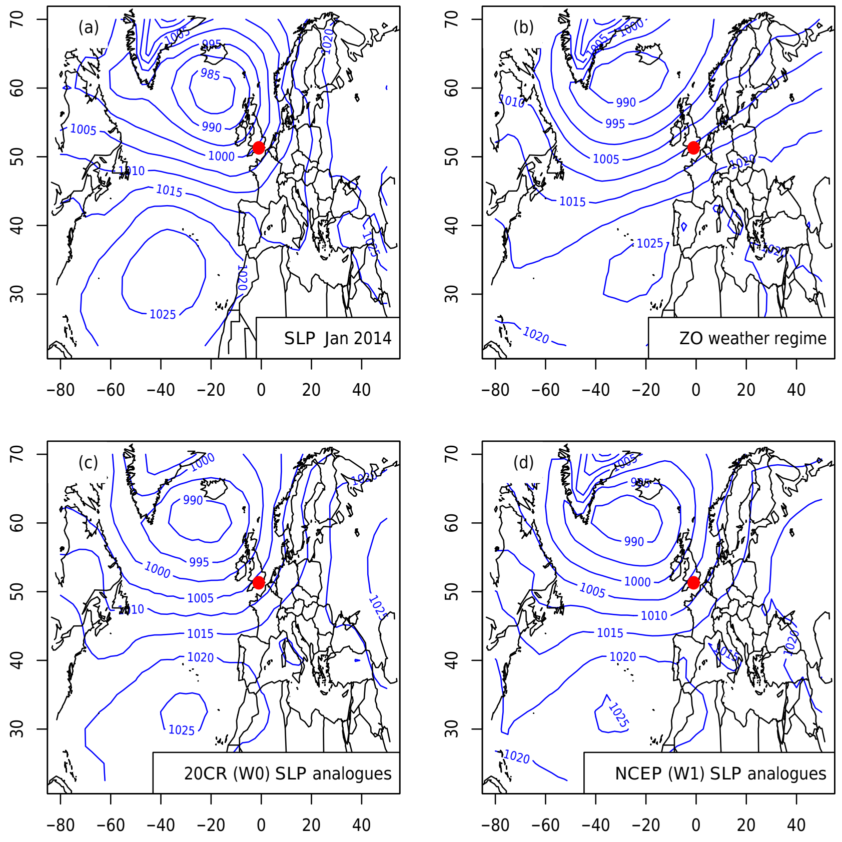

Figure 3. The mean SLP of January 2014 (in hPa) for **(a)** NCEP reanalysis **(b)** ZO weather regime computed from NCEP (Fig. 2d); **(c)** Mean of analogues in 20CR (1900–1950, $\mathcal{W}_0$); **(d)** Mean of analogues in NCEP (1950–2014, $\mathcal{W}_1$). The red circles indicate the region where high precipitation was observed.

in January when random days are drawn in $\mathcal{W}_0 = 20\text{CR}$ and $\mathcal{W}_1 = \text{NCEP}$. Hence, the null hypothesis H0 provides an estimate of the probability distribution of cumulated random precipitation for January months. We use a Kolmogorov–Smirnov test (von Storch and Zwiers, 2001, p. 81) to examine the difference between the H0 distribution and the circulation-dependent precipitation distribution. We decide to reject H0 at the 1 % level. When comparing the first and second (and third and fourth) box plots, Fig. 4 emphasizes the rejection of this null hypothesis because the distribution of analogue cumulated precipitation probabilities are significantly higher than for random days. In both cases (NCEP and 20CR), H0 is rejected with a level far below 1 %.

The ρ term is estimated by random resampling of daily R values in January and computing a monthly average. The probability distribution simulations of R in January 2014 for circulation analogues in $\mathcal{W}_0 = 20\text{CR}$ and $\mathcal{W}_1 = \text{NCEP}$ are shown in Fig. 4. For comparison purposes, mean precipitation taken from random days in the two worlds are also shown, to emphasize the role of the circulation in the high precipitation event in January. By comparing the second and fourth box plots, Fig. 4 shows a slight increase of the probability of having high precipitation in the new world with respect to the old world. The uncertainty on ρ can be estimated from these box plots.

The thermodynamical term is estimated from probabilities of R for analogues of C_{ref} in $\mathcal{W}_1$ and $\mathcal{W}_0$. The first step is to compute analogues of C_{ref} (the circulation in January 2014) in the two reanalysis datasets. For each day d of January 2014, we draw random circulation analogues in $\mathcal{W}_1$ and $\mathcal{W}_0$, and keep the sequence of their dates. Then we compute the sum of the analogue R for January 2014. By repeating this procedure, we obtain a Monte-Carlo estimate of the probability distributions of $R > R_{\text{ref}}$ conditional to C_{ref} for the old and new worlds. This procedure is similar to the static weather generator based on analogues described by Yiou (2014). This procedure allows one to estimate the probabil-

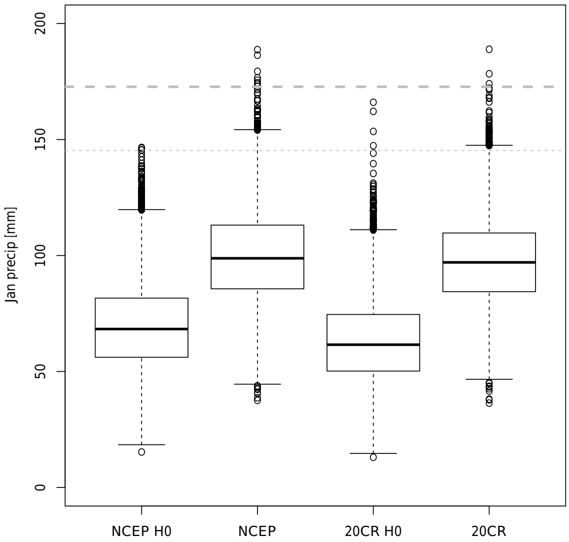

Figure 4. Box plots of cumulated precipitation simulations (in mm month^{-1}) from circulation analogues of January 2014 from 20CR (1900–1950) and NCEP (1951–2014). The NCEP H0 and 20CR H0 box plots of precipitation are taken from random days in January in 20CR and NCEP (rather than analogues). The horizontal thick dashed line is the observed value for January 2014. The horizontal thin dashed line is the 99th quantile of DJF monthly precipitation. The box plot lines indicate the 25th (q_{25}), median (q_{50}) and 75th (q_{75}) quantile (boxes). The upper whiskers classically indicate $\min(1.5 \times (q_{75} - q_{25}) + q_{50}, \max(R))$. The lower whiskers have a conjugate formula for low values.

ity distribution of ρ^{the}. In this study, we produce $N = 1000$ random samples of C and corresponding R.

The dynamical term ρ^{dyn} is obtained by dividing ρ by ρ^{the} (and using the Bayes formula). This procedure does not give an easy access to the circulation and reciprocity terms because it samples the vicinity of C_{ref}, not all the possible trajectories of SLP, including those which are not close to C_{ref}.

4 Results

4.1 Weather@Home

The daily SLP anomalies of the model simulations were classified onto the NCEP reanalysis weather regimes of Fig. 2. For each month, the four weather regime frequencies were computed.

For simplification we pooled all $\mathcal{W}_0$ simulations, unlike Schaller et al. (2016), who investigated each ensemble of counterfactual simulations separately. For each of the weather regimes (Atlantic Ridge: AR; zonal: ZO; NAO−; Scandinavian blocking: BLO), we determined the conditional probability distribution of January precipitation in southern UK when a weather regime frequency exceeds 75 % of the month. Figure 5 shows that only ZO and NAO− weather regimes reach the record values observed in January 2014, for $\mathcal{W}_0$ and $\mathcal{W}_1$. A dominant zonal weather regime obviously increases the probability of high precipitation in the winter, although extreme precipitation can also be reached with the NAO− pattern. A visual comparison of the two panels of Fig. 5 suggests that the probability of exceeding the 99th precipitation quantile in $\mathcal{W}_1$ slightly increases from $\mathcal{W}_0$ to $\mathcal{W}_1$, because the upper whiskers of the box plots increase. This visual impression is quantified by the analysis proposed in Sect. 3.2. The fact that precipitation can reach higher values in the counter factual world (Fig. 5b) is due to the fact that $\mathcal{W}_0$ contains approximately 7 times more simulations than $\mathcal{W}_1$.

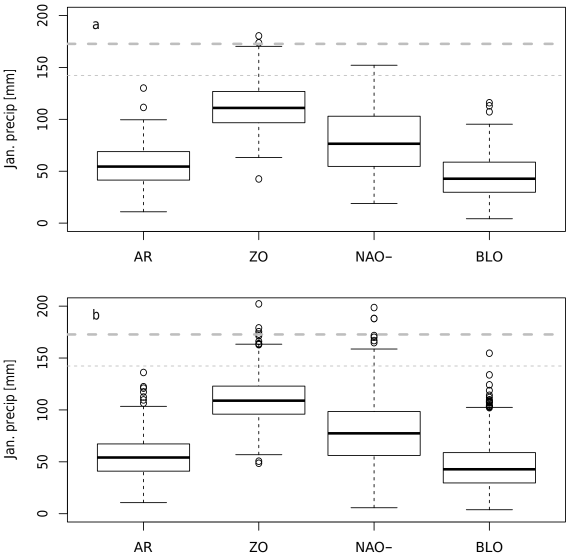

Figure 5. January precipitation probability distribution (box plots) conditional to winter weather regimes exceeding 75 % in Weather@Home simulations (**a**: $\mathcal{W}_1$ factual world; **b**: $\mathcal{W}_0$ counterfactual world). The thin dashed horizontal line is the 99 % quantile of the $\mathcal{W}_1$ (factual) Weather@Home simulations. The thick dashed horizontal line is the observed precipitation value for January 2014.

Figure 5 shows that the North Atlantic circulation patterns are discriminating for heavy precipitation in southern UK. Hence, we focus on the zonal and NAO− atmospheric patterns to compute the probability changes.

The difference of high precipitation distribution between $\mathcal{W}_0$ and $\mathcal{W}_0$ is determined by quantile–quantile plots for each weather regimes (Fig. 5). This quantile–quantile plot can only be obtained for a large ensemble such as Weather@Home, which effectively sample persisting atmospheric patterns and high precipitation. Such a diagram cannot be obtained for observations, which do not yield a sufficient number of data over the 20th century.

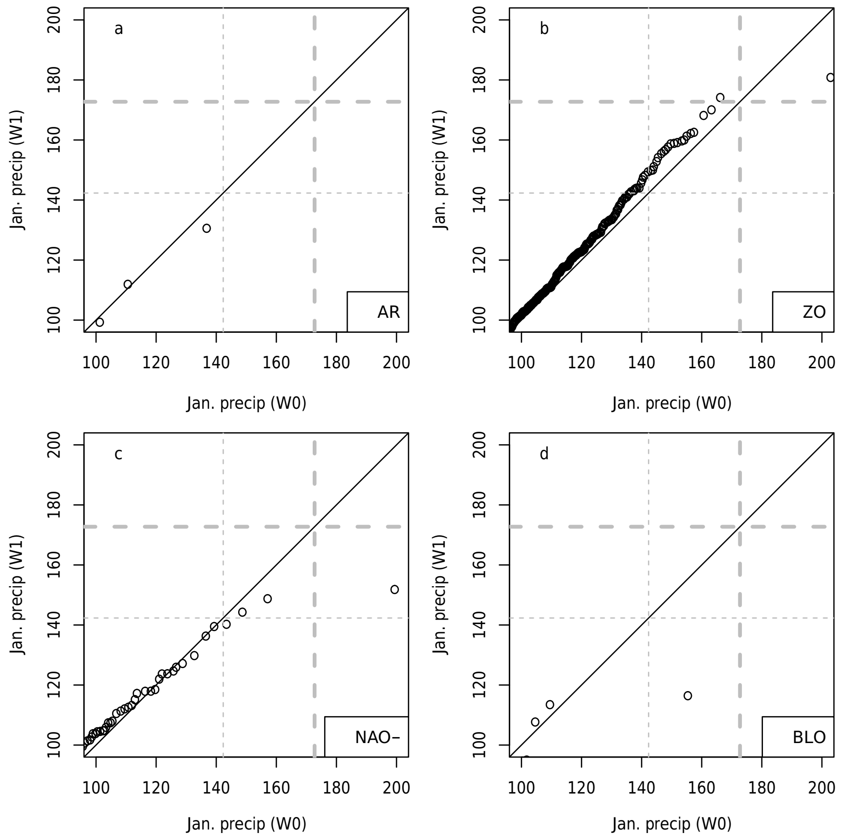

Figure 6. Quantile–quantile plots of January precipitation (in $\mathrm{mm\,month^{-1}}$) probability distributions between counterfactual ($\mathcal{W}_0$) and factual ($\mathcal{W}_1$) worlds in Weather@Home simulations, for each weather regime (**a**: Atlantic Ridge; **b**: zonal; **c**: NAO−; **d**: Scandinavian blocking). The continuous line is the first diagonal. The thick dashed lines indicate the observation in January 2014. The thin dashed line indicates the 99th quantile of observed January precipitation.

Figure 6b shows that $\mathcal{W}_1$ simulations are generally wetter than $\mathcal{W}_1$ for the zonal weather regime, apart from one extreme exception. The precipitation distributions are rather similar for the NAO− weather regime, albeit for an extreme value that far exceeds the observed record (Fig. 6c). The two weather regimes (Atlantic Ridge and Scandinavian blocking) hardly reach the value of the 99th quantile of observed precipitation. Figure 6 hence justifies a posteriori our methodology to compare the tails of the distributions of precipitation totals. The remainder of the paper focuses on the circulation patterns for which precipitation is likely to exceed the 99th quantile of observations.

The ρ ratios were computed from the ($\approx 17\,000$) factual and ($\approx 117\,000$) counterfactual Weather@Home simulations. Since p_1 is fixed to be 0.01 (for a return period of 1 century), the spread of ρ stems from the uncertainty on p_0 that is computed over the pooled counterfactual simulations (although, strictly speaking, R_{ref} uncertainty depends on the bootstrap sample from $\mathcal{W}_1$). The distribution of ρ is significantly different from 1, with a mean value $\bar{\rho} = 0.71$ (Fig. 7, "all" box plot). This indicates an increase of the probability of heavy precipitation in $\mathcal{W}_1$ with respect to $\mathcal{W}_0$, with a fraction of attributable risk (FAR $= 1 - p_0/p_1$) of 0.29. This probability ratio can be decomposed for the ZO and NAO− weather regimes. The estimates of ρ^{the}, ρ^{circ} and ρ^{rec} for the ZO and NAO− weather regimes are shown in Fig. 7. By construction, the products of the mean values recover the mean value of ρ (all box plot).

The three mean ratios ($\bar{\rho}^{\mathrm{the}}$, $\bar{\rho}^{\mathrm{circ}}$ and $\bar{\rho}^{\mathrm{rec}}$) are significantly different from 1 for the zonal regime ($\bar{\rho}^{\mathrm{the}} \approx 0.63$, $\bar{\rho}^{\mathrm{circ}} \approx 0.78$ and $\bar{\rho}^{\mathrm{rec}} \approx 1.45$). The $\rho^{\mathrm{the}} < 1$ is interpreted by an increase of precipitation from $\mathcal{W}_0$ to $\mathcal{W}_1$ given the same weather regime flow. $\rho^{\mathrm{circ}} < 1$ reflects an increase of the frequency of zonal patterns in $\mathcal{W}_1$ with respect to $\mathcal{W}_0$. $\rho^{\mathrm{rec}} > 1$ reflects that large precipitation amounts occur more often during episodes of zonal circulation.

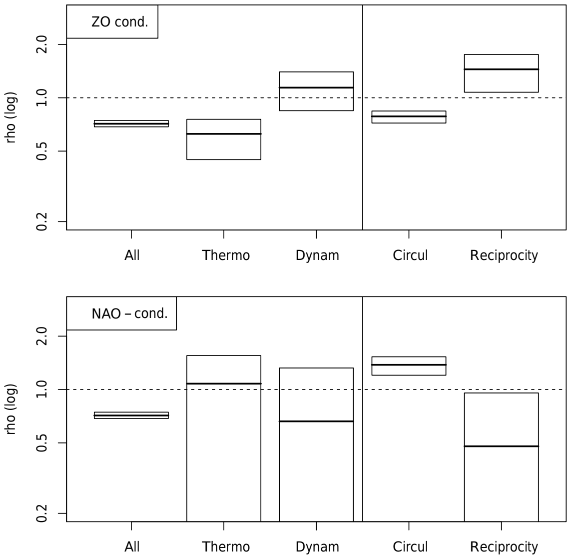

Figure 7. Changes in probability ratios from weather regimes in Weather@Home simulations. The probability ratios (vertical axes) are shown on a logarithmic scale. The horizonal dashed lines show the reference $\rho = 1$ line. The dynamical contribution is the product of the circulation and reciprocity contributions. The upper panel is the conditional probability ratios for the zonal regime. The lower panel is for the NAO− regime. The thick horizontal segment represents the estimated ratio $\bar{\rho}$ from all available data. The boxes represent the bootstrap confidence 90 % intervals $(\bar{\rho} - (\hat{\rho}^{95\,\%} - \bar{\rho}), \bar{\rho} - (\hat{\rho}^{5\,\%} - \bar{\rho}))$, where $\hat{\rho}^{5\,\%}$ and $\hat{\rho}^{95\,\%}$ are respectively the 5th and 95th quantiles of the bootstrap samples.

The NAO− yields a quite different picture, although it can lead to wet winters in southern UK (Fig. 5). The ρ^{the} ratio is not distinguishable from 1 and has a large variability. Therefore, it cannot be concluded that this weather regime has a significant thermodynamic contribution to changes of heavy precipitation rates. $\bar{\rho}^{\mathrm{circ}} > 1$ means that the mean January precipitation rate decreases for NAO− from $\mathcal{W}_0$ to $\mathcal{W}_1$. The reciprocity ratio $\bar{\rho}^{\mathrm{rec}}$ is lower than 1, meaning that NAO− is less likely during episodes of high precipitation. This means that the NAO− regime becomes less frequent and less rainy, in contradistinction to the zonal regime.

An analogue-like approach was used to estimate the ρ decomposition from the Weather@Home data. The distance between the January 2014 SLP in NCEP and each Weather@Home simulation was computed, as the average of daily SLP distances. Then the neighborhood of $C_{\mathrm{ref}} = C_{\mathrm{Jan.2014}}$ is defined when this average distance is lower than a threshold estimated from analogues of NCEP data. The value of the threshold is 1.5 times the average (over January 2014) of the median of the distances of the 20 best daily analogues. This leads to a threshold value of 12 hPa and defines the "circulation tube" of Sect. 3.3.2. In this way, the conditional probabilities (and their sampling distributions) can be estimated by bootstrapping. The sampling distribution of each probability ratio are shown in Fig. 8.

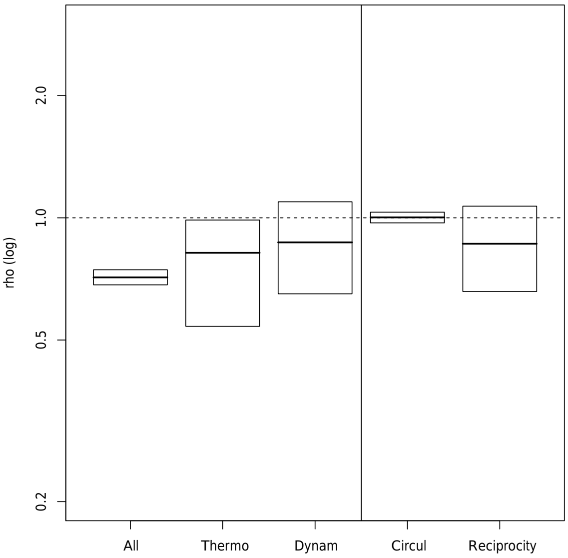

Figure 8. Changes in probability ratios from the analogue approach in Weather@Home simulations. The probability ratios (vertical axes) are shown on a logarithmic scale. The horizonal dashed lines show the reference $\rho = 1$ line. The dynamical contribution is the product of the circulation and reciprocity contributions. The boxes yield the same convention as in Fig. 7.

We see that the thermodynamical contribution is very similar to the one of the zonal circulation pattern in Fig. 7, but the dynamical contribution has an opposite sign. The circulation contribution is ≈ 1, indicating that the probability of having a circulation like the one of January 2014 does not change significantly, while the reciprocity term is lowered. Therefore, the frequency of a persisting zonal weather regime increases between the counterfactual and factual worlds, while probability of having a circulation history that is similar to 2014 remains stable. This apparent contradiction is explained by the fact that the circulation of January 2014, although zonal, was rather dissimilar to the usual zonal weather regime. Hence, by tightening the class of event from "high precipitation sum due to zonal weather regime" to "high precipitation sum due to a specific persisting circulation", we change the quantification of a dynamical contribution.

This emphasizes the need of a precise definition of the neighborhood of a circulation trajectory for the conditional attribution exercise. On the one hand, one looks at a persisting zonal circulation in a rather broad sense. On the other hand, one looks at a circulation trajectory that looks like the observation of January 2014, which yielded an atypical zonal pattern (van Oldenborgh et al., 2015).

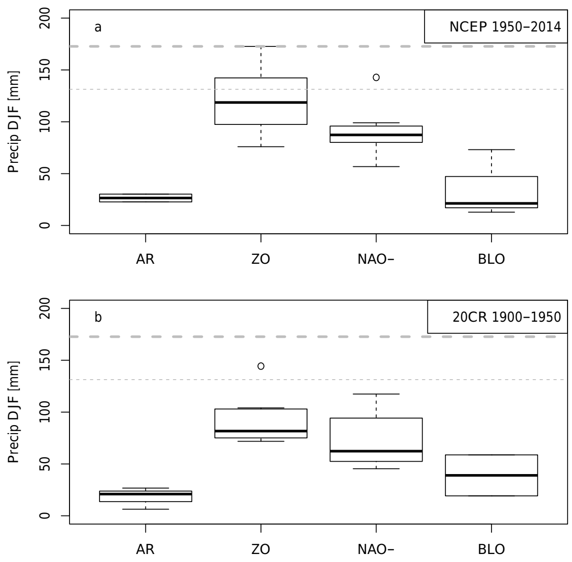

Figure 9. Cumulated southern UK January precipitation (in mm) probability distribution conditional to winter weather regimes exceeding 75 % in reanalyses (**a**: NCEP; **b**: 20CR). The thin dashed horizontal line is the 99 % quantile of $\mathcal{W}_1$ (NCEP). The thick dashed line is the precipitation amount in January 2014.

4.2 Reanalyses

The two reanalyses (20CR and NCEP) use different models, assimilation schemes and assimilated data. Schaller et al. (2016, supplementary information) showed that the weather regime classification in the overlapping period of the two reanalyses are very similar. We also verify that the analogues of January 2014 are qualitatively similar in the two reanalyses over the 1950–2011 period. For each day of January 2014, the 20 best analogues have between 12 and 18 days in common in the two reanalyses. The distances and spatial correlation yield probability distributions that cannot be distinguished by a Kolmogorov–Smirnov test (von Storch and Zwiers, 2001).

We set a high threshold of precipitation to the 99th quantile of January cumulated precipitation. Due to the rather low number of data points, we also considered the months of December and February during which high cumulated winter precipitation is likely. This choice can also be justified because the properties of the atmospheric circulation are baroclinic across the winter (Hoskins and James, 2014). We verify that high values of precipitation R can be obtained with more than one weather regime (namely, the zonal and NAO− regimes) in Fig. 9. This justifies that the decomposition of Eq. (2) is repeated for these two weather regimes, although it can be anticipated that this threshold cannot be exceeded for NAO− in $\mathcal{W}_0$ in the observations.

Again, the North Atlantic circulation patterns are discriminating for heavy precipitation in southern UK in the observation universe. Hence, we focus on the ZO and NAO− atmospheric patterns to compute the probability changes.

Similar estimates of ρ, ρ^{the}, ρ^{circ} and ρ^{rec} were computed from the NCEP ($\mathcal{W}_1$ from 1951 to 2015) and 20CR ($\mathcal{W}_0$ from 1900 to 1950) reanalyses (Figure 10). The mean ratio $\bar{\rho}$ is ≈ 0.82 ((0.36; 1.37) with a 90% confidence interval), indicating a FAR value of ≈ 0.18. The distribution of ρ is not significantly different from 1 (although the sampling distribution is skewed towards a lower value) due to the low number of observations, but its range is compatible with the Weather@Home estimate.

The three ratio distributions (ρ^{the}, ρ^{circ} and ρ^{rec}) were computed for the zonal and NAO− weather regimes (Fig. 10). The values cannot be determined for the thermodynamical and reciprocity terms because the precipitation threshold is not reached or exceeded in $\mathcal{W}_0$ during winters dominated by NAO−

The mean value is significantly different from 1 for the zonal regime ($\bar{\rho}^{\mathrm{the}} \approx 0.36$ (0.2, 0.71) for a 90 % confidence interval). They are not significantly different from 1 for the circulation and reciprocity terms $\bar{\rho}^{\mathrm{circ}} \approx 0.89$ (0.12, 1.34) and $\bar{\rho}^{\mathrm{rec}} \approx 2.5$ (0.2, 4)). This description is qualitatively similar to what was obtained with the Weather@Home analysis for the thermodynamical and dynamical terms, although the magnitudes differ, due to the differences between the two universes (factual vs. counterfactual, and new vs. old). The uncertainty increase is partly due to the limited lengths of the reanalysis datasets. The mean reciprocity ratio $\bar{\rho}^{\mathrm{rec}}$ is rather close to what was found in the Weather@Home analysis. It indicates an increase of zonal circulation when heavy precipitation occurs between the beginning of the 20th century and the present-day period.

The ρ ratio distributions for the NAO− regime are not very informative. The thermodynamic and reciprocity contributions cannot be estimated because the threshold of precipitation is never reached during a winter dominated by NAO− in the NCEP reanalysis, between 1951 and 2014, implying zero denominators in Eqs. (3), (5). A first interpretation is that the NAO− regime is so different in both worlds that the conditional precipitation change cannot be estimated (because $\Pr(R_{(1)} > R_{\mathrm{ref}} | C_{(1)} \in \mathcal{V}(C_{\mathrm{ref}})) = 0$ and $\Pr(C_{(1)} \in \mathcal{V}(C_{\mathrm{ref}}) | R_{(1)} > R_{\mathrm{ref}}) = 0$). This might be due to the low number of winters in the $\mathcal{W}_0$ world (i.e., 50 years).

The ratio distributions with the analysis of SLP analogues is shown in Fig. 11. The distribution of ρ^{the} yields a smaller variance than with the weather regime description due to the tighter constraint on the shape of the atmospheric trajectory. The dynamical term ρ^{dyn} is barely above 1 (contrary to the ZO weather regime in the same worlds), although not significantly.

This apparent contradiction is explained by the fact that the ZO weather regime becomes slightly more probable in $\mathcal{W}_1$ than in $\mathcal{W}_0$ (circulation term in Fig. 10), but the average

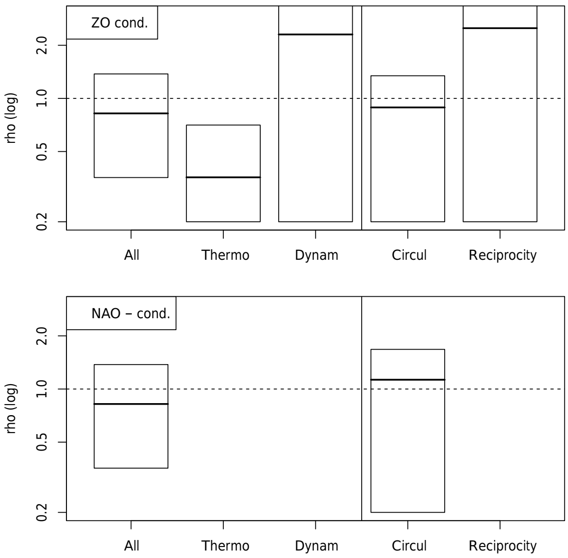

Figure 10. Changes in probability ratios in 20CR/NCEP reanalyses for the zonal and NAO− weather regimes. The probability ratios (vertical axes) are shown on a logarithmic scale. The horizontal dashed lines show the reference $\rho = 1$ line. The dynamical contribution is the product of the circulation and reciprocity contributions. The upper panel is the conditional probability ratios for the zonal regime. The lower panel is for the NAO− regime. There are no thermodynamical or reciprocity terms in the decomposition because high precipitation sums do not occur during persisting NAO− episodes in 1900–1950. The boxes yield the same convention as in Fig. 7.

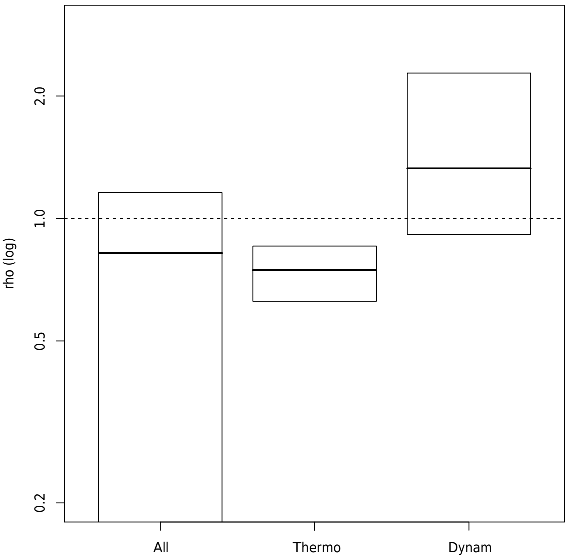

Figure 11. Changes in probabilities in 20CR/NCEP reanalyses conditional to the January 2014 SLP pattern, with circulation analogues. The boxes yield the same convention as in Fig. 7.

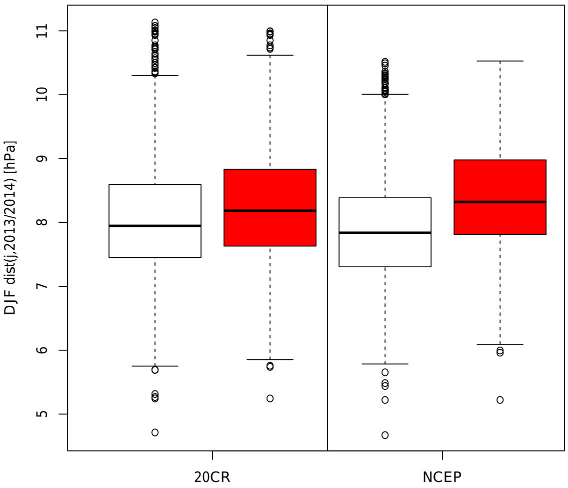

Figure 12. Distribution of mean distances (in hPa) between winter 2013/2014 and the 20 best analogues in NCEP and 20CR. The black box plot are for the whole winter (DJF) and the red box plot are for January 2014 only.

distance of SLP analogues of January 2014 slightly increases between $\mathcal{W}_0$ and $\mathcal{W}_1$ (Fig. 12). This reflects the fact that the January 2014 pattern is not a typical zonal pattern (as seen in Fig. 3) and that the thermodynamical term outbalances the dynamical term in the interpretation of $\rho < 1$.

The analogue method does not allow for an estimate of the circulation and reciprocity terms because we are only able to sample trajectories around January 2014, not all trajectories like in the Weather@Home experiments.

5 Discussion

We have performed analyses on two different world definitions (factual vs. counterfactual and new vs. old). There is no quantitative way of claiming that factual equals new and counterfactual equals old. It is only possible to argue qualitatively that the anthropogenic forcings were weaker in the old world than in the new world.

One of the caveats of attribution studies (including this one) is the uncertainty in the $\mathcal{W}_0$ world, which affects estimates of p_0. This problem exists in the counterfactual simulations of Weather@Home, which required the subtraction of an SST signal from 11 available CMIP5 simulations. Each of the individual counterfactual simulations show different behavior, although the ensemble yields a significant, albeit small, change with respect to $\mathcal{W}_1$, as shown by Schaller et al. (2016). The quality and quantity of the data that were used in the reanalysis experiments varies with time. This implies that the old world is more uncertain that the new world. The distributions of distances between analogues in Fig. 12 do not show large systematic biases in 20CR (1900–1950) with respect to NCEP (1951–2014). Using the whole ensemble of 20CR could allow for better estimates of weather regime frequency distributions in the $\mathcal{W}_0$ world, but the only precipitation data we used come from observations, which means that uncertainties in the ρ ratio are always large. Another possibility is to consider subperiods of 1900–1950, but the confidence for individual subperiods is bound to be very poor.

The analysis does not consider internal temporal variability in each world. The Weather@Home simulations do not have decadal variability, but reanalyses do. This was not taken into account here, but could be included by further dividing the two worlds (old vs. new) into subperiods (e.g., "high SST" vs. "low SST") in order to evaluate the feedback of natural SST variability on atmospheric circulation. This poses the problem of the length of available data onto which the statistics are built. This difficulty could be overcome by investigating ensembles of available simulations such as CMIP5 (Taylor et al., 2012) or CORDEX (Jacob et al., 2013).

The main assumption made in the Bayes decomposition is that the climate variable R is related to the atmospheric circulation field C, and that a storyline of C can explain an observed extreme of R. This ensures that the two conditional probabilities in Eq. (2) are non-zero so that the ratios are well defined.

In order to provide consistent results, it is necessary to have a correct representation of the atmospheric variability. This assumption is not trivial and required many verifications on the Hadley Center atmospheric model (Schaller et al., 2016). The circulation patterns that were simulated were validated over the North Atlantic region and Europe for the $\mathcal{W}_1$ factual world. The main difficulty is that there is no way to assess the validity of C in the $\mathcal{W}_0$ counterfactual world. This is where the assumption that $\mathcal{W}_1$ and $\mathcal{W}_0$ are close to each other is heuristically used in the estimate of the probability changes. Of course, this is not a strict proof of validation of the atmospheric circulation in $\mathcal{W}_0$.

When reanalysis data are used, the question of the atmospheric circulation validity and the R–C relation is tied to the quality of the data that are used in the assimilation scheme, for both worlds $\mathcal{W}_0$ and $\mathcal{W}_1$. The main caveat is that the early period of reanalyses are constrained by only a few observations (Compo et al., 2011). This means that the circulation reconstruction could yield wrong patterns (even for the members of the ensemble), with no possible validation test. The second caveat in this case is the length of datasets on which the probabilities are computed. Moreover, the observed climate (or its reanalysis) is one occurrence of many possible realizations that could have happened for a given climatic state. Therefore, this analysis should also be understood as being conditional to a dataset (either Weather@Home or the earlier part of the 20CR reanalysis), which is an uncertain representation of the world.

Our paper outlined an apparent discrepancy between weather regime and analogues of circulation to describe thermodynamical changes (and dynamical ones). Weather regimes offer a rather rough description of the atmospheric flow and the range of possible flows within a weather regime classification can be fairly large. The recent winter of 2015/2016 demands a finer description of the atmospheric circulation. Indeed, December 2015 had a mostly zonal weather regime (such as January 2014), with very mild temperatures in Europe, but southern UK and northwestern France were very dry (such as the rest of continental Europe), whereas northern UK experienced record precipitation and floods. The jet stream was slightly shifted (a few hundred kilometers) to the north, but the weather regime was still zonal, while having no resemblance to January 2014 (in terms of analogues). This questions the focus of extreme event attribution on regional climate precipitation alone, as already discussed by Trenberth et al. (2015), since the large-scale atmospheric circulation that drives the moisture transport can have shifts within the same weather regime and hit a region rather than its neighbors just by chance. This suggests an EEA analysis of the predictands of R (such as C), rather than R alone, with a focus on the dynamical terms.

Vautard et al. (2016) proposed an alternative method based on analogues to determine dynamical and thermodynamical components from the Weather@Home simulation data. It is interesting to notice that there is a consensus on the estimate of a thermodynamical term (i.e., with equal atmospheric circulation). Our finding emphasizes that a definition of a dynamical contribution is potentially ambiguous. We also emphasize that the approach of analogues can also be applied to daily Weather@Home data (Fig. 8). Vautard et al. (2016) investigated all possible patterns of atmospheric circulation on a monthly timescale, while this study focuses on January 2014, with a daily timescale.

The persistence of events and hence the timescale to be considered are major components to be considered. For instance, the probabilities of having a persistent zonal weather regime during a month and having a circulation that is similar to January 2014 have different distributions, and such distributions change in different ways between the two reanalysis datasets. Such a consideration is crucial for regional climate studies; as mentioned above, the example we chose in this paper is about precipitation in southern UK (and arguably northwestern France, which also had records of precipitation in January 2014). But case studies such as northern UK (in December 2015) or Wales in 2000 (Pall et al., 2011) would require separate analyses because the difference in atmospheric flows is different in a subtle but crucial way.

It is desirable to be systematic in the attribution of extreme events in continuous time, by examining all events. This pleads for analyses that can be performed quickly in order to estimate statistical diagnostics in a relatively short time. This can help guide the choice of costly experiments (in terms of computing power and memory management), such as Weather@Home, in order to refine estimates.

6 Conclusions

We have argued that the use of relatively short datasets (reanalyses) provides qualitatively similar information in terms of probability decomposition of the occurrence of a winter flood event. Such an analysis cannot replace Weather@Home simulations in order to quantify precisely the contribution of all factors. Therefore, the exercise with reanalyses is a detection rather than a thorough attribution, as defined by Bindoff et al. (2013). The attribution comes if the forcing changes are clearly identified in both periods, which is not done in this paper.

The names of terms (thermodynamical and dynamical) of the decomposition can be debated. It is important to note that changes in the properties of the atmospheric circulation C and the coupling between the local climate variables R and C play an important role in the definition of the extreme event.

The conditional part of the analysis is the most important point as it helps to explore the tail of the distribution of R. We emphasize that we analyze a high precipitation rate ($R > R_{\mathrm{ref}}$) conditional to a given circulation pattern C_{ref}. We had to make the analysis of the two types of weather regimes leading to high precipitation rates. The thermodynamical and dynamical contributions differed from one weather regime to the other. We also showed that the dynamical contribution to ρ depends on the way the neighborhood of the circulation trajectory is approximated (qualitative with weather regimes or quantitative with analogues). This points to the necessity of an a priori definition of the class events to be investigated, in order to obtain consistent results when following a storyline approach to extreme event attribution.

We emphasize that the paradigm of attribution of extreme events that we have explored can also be applied to other contexts, in particular extreme events of the last millennium as a response to solar and volcanic forcings (Schmidt et al., 2011, 2014; PAGES 2k-PMIP3 group, 2015). This can be done by exploring analogues of circulation of a given extreme event in remote periods (in model simulations) where natural forcings are well documented.

Data availability. NCEP reanalysis data can be obtained from the NOAA web site (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html). Weather@Home data can be obtained upon request (cpdn@oerc.ox.ac.uk). Southern UK precipitation data were obtained from the UK Met Office (Tim Legg, tim.legg@metoffice.gov.uk).

Competing interests. The authors declare that they have no conflict of interest.

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RESEARCH ARTICLE

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Methods and Model Dependency of Extreme Event Attribution: The 2015 European Drought

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Key Points:

- Multi-method event attribution of the 2015 European drought
- Contradicting evidence on the role of anthropogenic influence on the event
- Uncertainty in event attribution may be larger than previously thought

Supporting Information:

- Supporting Information S1

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Abstract Science on the role of anthropogenic influence on extreme weather events, such as heatwaves or droughts, has evolved rapidly in the past years. The approach of "event attribution" compares the occurrence-probability of an event in the present, factual climate with its probability in a hypothetical, counterfactual climate without human-induced climate change. Several methods can be used for event attribution, based on climate model simulations and observations, and usually researchers only assess a subset of methods and data sources. Here, we explore the role of methodological choices for the attribution of the 2015 meteorological summer drought in Europe. We present contradicting conclusions on the relevance of human influence as a function of the chosen data source and event attribution methodology. Assessments using the maximum number of models and counterfactual climates with pre-industrial greenhouse gas concentrations point to an enhanced drought risk in Europe. However, other evaluations show contradictory evidence. These results highlight the need for a multi-model and multi-method framework in event attribution research, especially for events with a low signal-to-noise ratio and high model dependency such as regional droughts.

1. Introduction

Event attribution is a quickly growing field (Herring et al., 2016; Stott et al., 2016; National Academies of Sciences, Engineering, and Medicine (NAS), 2016) with high visibility and potential key implications. It has, for instance, been suggested that evidence from event attribution research could be used in courts of law to obtain reparations following impacts of extreme weather events (Allen, 2003; Thompson & Otto, 2015; Stott et al., 2016). In event attribution, a change in the occurrence probability of an extreme event is quantified with the Risk Ratio (NAS, 2016), $\mathrm{RR} = p_\mathrm{f}/p_\mathrm{c}$, where p_f is the probability of the event in the factual climate including climate change, and p_c the probability of the same event in a counterfactual climate without anthropogenic climate change (Figure 1). This probabilistic framing is suited for events defined via the exceedance of a threshold of a weather variable, which always have some stochastic behavior. The observed event is thereby only used to define the threshold, and different meteorological situations could lead to events of the same magnitude. Although event attribution assessments are sensitive to methodological choices (Lewis & Karoly, 2013; Shiogama et al., 2013; Otto et al., 2015; Uhe et al., 2016), it is still common to rely on a limited number of models and methods (Sippel et al., 2016; Dong et al., 2016; Schaller et al., 2016; Mitchell et al., 2016). In this study, we analyze the role of methodological choices for the attribution of the 2015 European drought.

In the summer of 2015, Central Europe experienced a pronounced drought and heat wave. The event broke local temperature records (Dong et al., 2016; Sippel et al., 2016), and was characterized by very low precipitation (Orth et al., 2016), which resulted in significantly reduced surface water availability (Van Lanen et al., 2016; Laaha et al., 2016). While the extreme temperatures occurring during that event were shown to have a larger probability due to climate change (Dong et al., 2016; Sippel et al., 2016), the role of human influence on the meteorological drought (precipitation deficit) has not yet been assessed.

The use of general circulation models (GCMs) is central in event attribution studies. They allow the computation of large ensembles of the factual climate as well as of the counterfactual climate, for which

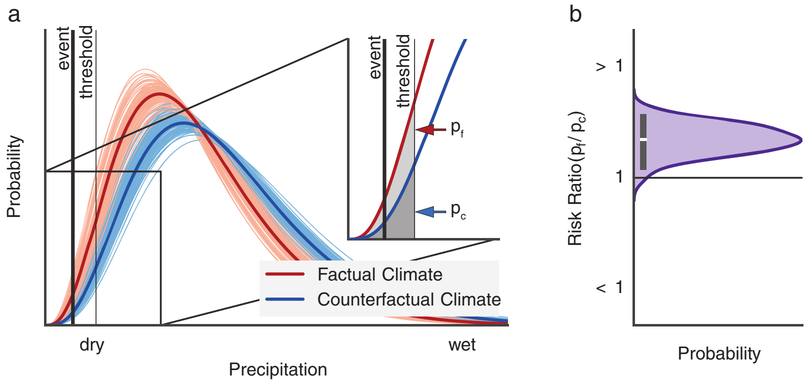

Figure 1. Probabilistic event attribution and the risk ratio. (a) Hypothetical Probability Density Functions (PDFs) of precipitation in the factual (red) and counterfactual (blue) climate. The thin, light lines indicate parameter uncertainty of the two PDFs. The magnitude of the investigated extreme event is indicated with the thick black line. To avoid a selection bias, we use the second largest event on the observational record as threshold, shown with the thin black line. (Inset) The parameters p_f and p_c are calculated as the gray area under the PDF. (b) PDF of the RR, taking the parameter uncertainty into account (magenta), 95% credibility interval (black bar), and best estimate (median, white line).

no observations exist. However, using GCMs also involves a number of methodological choices, potentially influencing the RRs obtained from them. In this study, we will assess the influence of the following choices on the RR: different counterfactual climates (as defined by different levels of anthropogenic forcing agents: greenhouse gases (GHGs) and aerosols), the selection of the climate model, the representation of sea surface temperatures (SSTs), and additionally the effect of using different datasets for observation-based RRs.

2. Factual and Counterfactual Climate

The factual climate (referred to as PRES, hereafter) should represent the “real”, current, climate conditions as accurately as possible. Here, it is estimated from simulations forced with boundary conditions (GHGs, aerosols, and potentially SSTs) representing observed, current-day values. The counterfactual climate, on the other hand, should represent a climate undisturbed by human influence. Four possibilities have been introduced in the scientific literature, which we will refer to as PAST, PAST_GHG, NAT, and piC, hereafter (Table 1). PAST consists of historical simulations forced with observed boundary conditions, but uses a time period from the middle of the 20th century, when the human imprint on climate was smaller. In this study, we use the 1960s as historical period, when the anthropogenic GHG forcing was about one-third of the current forcing. In contrast to anthropogenic GHG forcing, the anthropogenic aerosols load was not (quasi)monotonically increasing. In the 1960s, the European tropospheric sulfate load was much higher than in pre-industrial times, and also than nowadays (Figure S1, Supporting Information). Aerosols were found to influence precipitation globally and for certain regions (Wilcox et al., 2013; Polson et al., 2014). Therefore, RRs are subject to changes caused by direct and indirect aerosol effects which may not be appropriately attributed when using PAST only. Thus, we consider a second set of simulations including anthropogenic GHG emissons, but using constant, pre-industrial aerosol concentrations (GHG-only simulations). As these simulations still include anthropogenic GHG emissions, we also need to consider a historical period as counterfactual climate (PAST_GHG). Analyzing the difference between PAST and PAST_GHG allows us to compare the effect of aerosols on European precipitation. The next counterfactual climate, NAT, is forced by observed solar and volcanic boundary conditions, but GHG and aerosol concentrations are set to pre-industrial levels (i.e., historical natural simulations). The third counterfactual climate, piC, is obtained from pre-industrial control simulations. These are freely evolving simulations with GHG concentrations and anthropogenic aerosol emissions representative for the year 1850 but without historical natural forcing variations, notably volcanic eruptions.

Besides the choice of the counterfactual climate, the selection of the GCM (or GCMs) is also expected to influence the outcome of an attribution study. Furthermore, the degree of conditioning of the GCM will

Table 1.
Overview of Observation- and Model-Based Event Attribution Methods. SST_{OBS} Is an Observed SST (Sea Surface Temperature) Dataset and ΔSST is the Change in SSTs Due to Climate Change, Derived from Models in the Coupled Model Intercomparison Project (CMIP5)

Data basis	Name	Factual climate (p_f) (with climate change)	Counterfactual climate (p_c) (without climate change)
Models	PRES vs. PAST	Anthropogenic forcing simulation of present-day period with: (1) Interactive SSTs (2) Prescribed SST_{OBS}	Anthropogenic forcing simulation of past time period (1960s) with: (1) Interactive SSTs (2) Prescribed SST_{OBS}
	PRES vs. PAST_GHG	Anthropogenic forcing simulation of present-day period with: (1) Interactive SSTs (2) Prescribed SST_{OBS}	GHG-only forcing simulation of past time period (1960s) with: (1) Interactive SSTs (2) Prescribed SST_{OBS}[a]
	PRES vs. NAT	Anthropogenic forcing simulation of present-day period with: (1) Interactive SSTs (2) Prescribed SST_{OBS}	Natural forcing simulations of present-day period with: (1) Interactive SSTs (2) Prescribed $SST_{OBS} - \Delta SST$
	PRES vs. piC	Anthropogenic forcing simulation of present-day period with: (1) Interactive SSTs	Natural forcing simulation of pre-industrial time period with: (1) Interactive SSTs
Observations	Regression-based	Present	Past (e.g., 1960s)

[a] No simulations of this kind are used in this study.

influence the estimate of the RRs. Specifically, SSTs can either be interactively computed by the model or prescribed, for instance from observations. Thus, we will also contrast RRs from models with interactive and prescribed SSTs. An additional possibility is provided by simulations where regional climate models (RCMs) are used to dynamically downscale the generally coarse-resolution GCM output.

3. Methods and Data

3.1. Computation of Risk Ratios

As a result of diverse availablility of sample sizes, we use different methods to calculate RRs from models and observations. For the model-based RR, we assume that the precipitation data follows a gamma distribution (Stagge et al., 2015). We fit one gamma distribution to the simulated factual precipitation, and another to the counterfactual precipitation. From these two gamma distributions, we compute the probability that the precipitation amount will be below the chosen threshold, in the factual climate (p_f) and the counterfactual climate (p_c). We calculate uncertainties in a Bayesian setting and use a Markov Chain Monte Carlo (MCMC) sampler that is affine-transformation invariant (Goodman & Weare, 2010; Foreman-Mackey et al., 2013) to estimate the parameters of the gamma distributions. Starting from non-informative priors, the converged posterior distributions (50,000 non-independent samples) give an estimate of the parameter uncertainty.

For the observation-based event attribution, we follow a recent study (Gudmundsson & Seneviratne, 2016) and fit the precipitation data to a generalized linear model (GLM; McCullagh & Nelder, 1989) with global mean temperature as covariate, assuming a logarithmic link function and gamma distributed residuals. Global mean temperature from a global surface temperature dataset is smoothed with a LOWESS (locally weighted scatterplot smoothing) filter (Cleveland, 1979; using 5% of the data) to minimize the influence of the El Niño-Southern Oscillation (van Oldenborgh, 2007). For the factual climate (p_f), we insert the global mean temperature of 2015 into the GLM. For the counterfactual climate (p_c), we use the average temperature between 1960 and 1969. The same MCMC algorithm as for the model-based RR is used to calculate the posterior distribution. The return time of the event is calculated as the inverse of the probability of staying below precipitation of the event (p_f^{-1}).

3.2. Observation Data

To assess the uncertainty in observed precipitation, we consider four observational datasets: (1) the European Climate Assessment and Dataset (ECAD) E-OBS dataset (Haylock et al., 2008), (2) the National Oceanic and Atmospheric Administration's (NOAA) PREcipitation REConstruction over Land (PREC/L, Chen et al., 2002), (3) the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie & Arkin, 1997), and (4) the Climatic Research Unit (CRU) Time Series dataset (CRU TS, Harris et al., 2014). We employ the Goddard Institute for Space Studies (GISS) analysis of global surface temperature (GISTEMP, Hansen et al., 2010) as our global mean temperature dataset.

3.3. Model Data

For the model-based assessment of European drought risk, we use simulations from a total of 23 climate models. Three types of models are considered: GCMs which have interactive SSTs, GCMs with prescribed SSTs, and RCMs downscaling the output of GCMs.

Most of the considered models (19) have interactive SSTs and stem from the Coupled Model Intercomparison Project, Phase 5 (CMIP5; Taylor et al., 2012, Table S1). The factual climate (PRES) is estimated with simulations forced with the representative concentration pathway (RCP) 8.5 scenario (Meinshausen et al., 2011), because the historical simulations from CMIP5 end in 2005. RCP8.5 deviates slightly from the observations by now, however, the differences between the scenarios are not relevant until after 2030 (Kirtman et al., 2013). The modeled SSTs in the CMIP5 simulations do not correspond to the observed SSTs in the corresponding year, therefore we use a 20-year window around the event (2006–2025 for PRES). For PAST, we use historical simulations and select the years from 1951 to 1970. PAST_GHG is obtained from GHG-only simulations (also using 1951–1970), to assess the importance of aerosols for European precipitation within CMIP5. NAT is estimated from historical natural CMIP5 simulations. As these end in 2005, we select the years from 1986 to 2005. Finally, for piC, we use the last 200 years of the longest pre-industrial control simulation from each model, such that all GCMs contribute the same number of data points and the end point is closest to the starting point of the historical simulations to minimize the effects of model drift.

Two atmosphere-only models, namely HadGEM3-A and HadAM3P (as employed in the weather@home, w@h, volunteer-distributed modeling framework) (Massey et al., 2015) are used in our analysis (Text S1 and S2). Both models prescribe SSTs. They are forced with observed SSTs and sea ice at the lower boundary in order to simulate the factual climate. For the counterfactual climate, a climate change signal (ΔSST) is removed from the SST observations. ΔSST is derived from historical and historical-natural CMIP5 simulations. For HadGEM3-A, ΔSST is estimated from the multi-model mean, while for w@h 11 individual CMIP5 models are used (Schaller et al., 2016). Natural sea ice conditions are estimated by either using the maximum observed sea ice extent (for w@h, the winter of 1986/1987 as the employed dataset starts in 1985) or via the observed relationship between observed temperature and ice-coverage (HadGEM3-A). The last two of the 23 considered models are RCMs from the the Coordinated Downscaling Experiment over the European Domain (EURO-CORDEX, Jacob et al., 2014). Each RCM is forced with boundary conditions from historical and RCP8.5 simulations from five GCMs participating in CMIP5 (Text S3).

3.4. Post-processing

All observational and model data undergoes the same post-processing. We first calculate cumulative June-to-August (JJA) precipitation on land, area-averaged over the Central European region defined in the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX, Seneviratne et al., 2012) on the original grid of each dataset. All area-averaged data (models and observations) are then bias-corrected using a power transformation (Gudmundsson et al., 2012) to best match the cumulative density function of the E-OBS dataset for the period 1965–2013 (1985–2013 for the w@h simulations and 1971–2013 for the RCM simulations). This is done for every model individually, pooling all available ensemble members. The same bias correction is then applied to the counterfactual simulations.

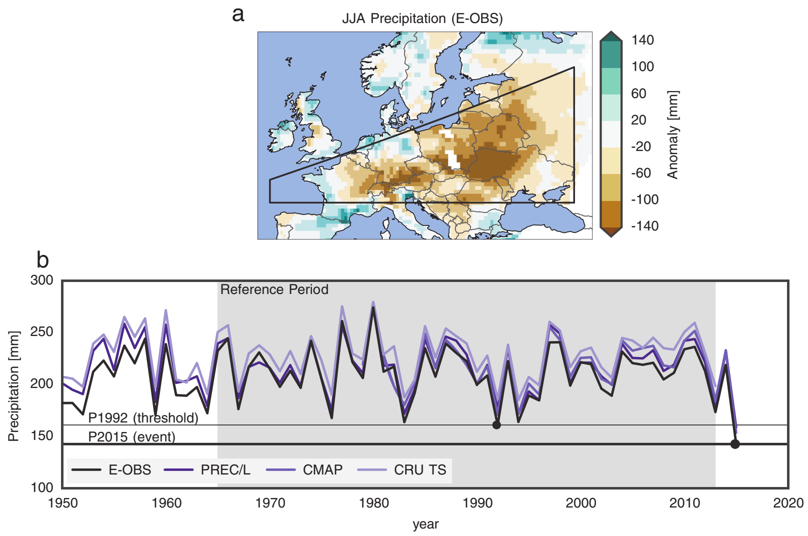

Figure 2. Precipitation in Central Europe. (a) Map of precipitation anomaly over Europe for the summer of 2015 (June-to-August (JJA), relative to 1965–2013). The black outline shows the study region. (b) Absolute precipitation over the study region for four observational datasets (see Section 3.2). The horizontal lines denote the lowest (P2015, thick line) and second lowest (P1992, thin line) observed precipitation in the E-OBS dataset. We use P1992 as threshold to compute p_f and p_c (see Figure 1). The gray shading indicates the reference period (1965–2013).

4. Results

The cumulative precipitation anomaly in Central Europe was very large in 2015, it was smaller than −140 mm in some regions (Figure 2a). Averaged over the target area, 2015 was the driest year on the observational record (Figure 2b and Orth et al., 2016). To assess the anthropogenic influence on this event, we estimate the probability of staying below a precipitation threshold in the factual (p_f) and counterfactual (p_c) climate. As threshold, we choose the largest observed event *before* 2015 (Figure 2b) to avoid a selection bias (Stott et al., 2004). Thus, we do not estimate the RR for the exact event, but for a class of events more severe than the driest summer before 2015.

We start our assessment with GCM simulations with interactive SSTs (i.e., a fully coupled ocean) obtained from CMIP5. Although the multi-model mean precipitation over Europe shows only a small bias (Flato et al., 2013), individual models exhibit considerable offsets (Figure S2), which we correct for (Section 3.4). The assumption of gamma-distributed data is visually assessed with quantile–quantile (QQ) plots of the historical simulations (Figure S3). The QQ plots give high confidence that the gamma distribution is appropriate to describe the used rainfall data. To derive a comprehensive attribution statement with several GCMs, it is common to pool individual models (Lewis & Karoly, 2013). In Figure 3a, we present two model pools based on all used CMIP5 members: (1) every ensemble member of each model (Table S1), and (2) one ensemble member of each model (to assign each model equal weight). Comparing the factual climate to the pre-industrial control simulations (PRES vs. piC) indicates a strong human contribution to the 2015 drought when considering all ensemble members, but not when considering one ensemble member per model. In contrast, an anthropogenic influence on European drought risk is uniformly suggested when using historical natural simulations as counterfactual climate (PRES vs. NAT). Note that, PRES and NAT do not share the same base period, and consequently their natural forcing differs, especially the volcanic aerosols. However, aligning the base period by using the years from 1986 to 2005 for PRES, changes the RRs only slightly (Figure S4a). Finally, with a historical period as counterfactual climate (PRES vs. PAST and PRES vs. PAST_GHG), the pooled CMIP5 ensembles indicate no human influence on precipitation. Additionally, we show a RR derived from 10 high-resolution RCM simulations, but only PRES versus PAST can be compared, as no simulations without anthropogenic forcing are available. The RCM-based assessment conforms to the CMIP5-derived RRs (PRES vs. PAST) and yields no detectable precipitation signal. Note that, however, PAST includes the high

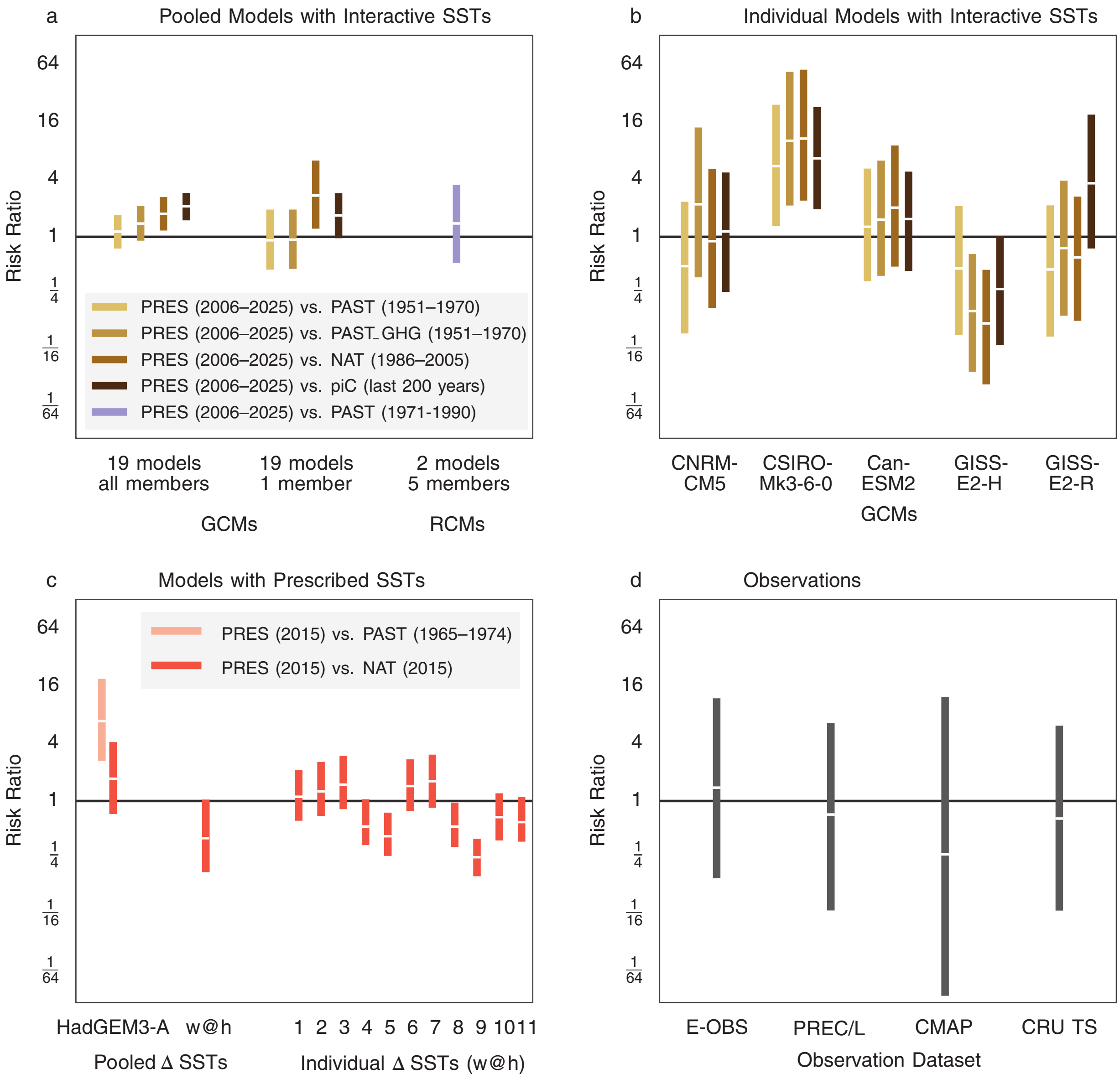

Figure 3. Risk ratios (RRs) for all model simulations, datasets, and counterfactual climates considered in this study. Bars show the best estimate (median) and 95% credibility interval of RR on a logarithmic axis. Dates in the legends indicate years used to estimate p_f and p_c, respectively. (a) Pooled general circulation models (GCMs) with interactive sea surface temperatures (SSTs) from the Coupled Model Intercomparison Project, Phase 5 (CMIP5), and regional climate models from the Coordinated Downscaling Experiment over the European Domain (EURO-CORDEX) for four counterfactual climates (Table 1). (b) Individual GCMs (from CMIP5) with five ensemble members each. (c) Model simulations with prescribed SSTs. On the left HadGEM3-A and the pooled w@h simulations. On the right all 11 w@h simulations forced with individual ΔSST patterns. (d) RRs for four observational datasets. See Table S2 to Table S4.

aerosol levels present during this time period (Figure S1). These comparisons show a first striking result. Namely, that the choice of the counterfactual climate used as a baseline can strongly affect the conclusions reached with respect to event attribution.

While the choice of counterfactual climate was found to be central to the result, we also expect that the results are dependent on the considered models. We assess the inter-model spread for the five GCMs with at least five ensemble members (Figure 3b). For PRES versus piC, only one out of the five models show significantly increased RRs. Using NAT as counterfactual climate yields RRs with a particularly large range. Three models suggest no change in drought risk, one (CSIRO-Mk3-6-0) indicates a doubling of the drought risk (lower uncertainty bound), while another (GISS-E2-H) suggests half the drought risk (upper uncertainty bound). PRES versus PAST_GHG yields similar RRs to PRES versus NAT. Finally, for PRES versus PAST the model results mostly conform to the multi-model RRs. Only CSIRO-Mk3-6-0 suggests an attributable increase in drought probability. Aligning the base period for PRES to the base period of NAT increases the RRs for all models, except CAN-ESM2 (Figure S4b). In essence, different subsets of CMIP5 models and counterfactual climates produce different attribution statements.

Next, we assess GCM simulations with prescribed SSTs (HadGEM3-A and w@h), where ocean temperatures are used as lower boundary condition. European summer precipitation is close to observations in Europe for HadGEM3-A (Figure S2), but w@h shows a large absolute bias and overestimates variability (Massey et al., 2015). Therefore, we also bias-corrected these simulations. Comparing PRES versus NAT for HadGEM3-A and the pooled w@h simulations yields a RR that is indistinguishable from one — no human influence is detectable (Figure 3c). The w@h simulations highlight the important role of different ΔSST patterns. Eight of them yield no significant change in drought risk, but the other three indicate a reduced drought probability. A comparison of w@h simulations under GHG-only, PRES, and NAT conditions (Figure S5) indicates that the anthropogenic increase in GHGs led to a drying, while the higher aerosol load caused a wetting. These changes are likely linked to the projected expansion of the extratropical zone of higher pressure which is particularly sensitive to rainfall changes over the Mediterranean region in summer in the current generation of GCMs, including HadGEM3-A and w@h. Thus, it may well be that the mostly-insignificant RRs are due to the compensating effect of GHGs and aerosols in these models. The w@h simulations only start in 1985, therefore we cannot compare PRES versus PAST. In HadGEM3-A, PRES versus PAST points to an increased drought risk and is highly significant. This could either be due to the different aerosol concentrations between the periods or because of negative precipitation trends in HadGEM3-A, which are in disagreement with observations (not shown).

Finally, we perform an observation-based event attribution analysis with four datasets (Figure 3d). Precipitation is regressed against smoothed global mean temperature, which is considered a proxy of climate change (van Oldenborgh, 2007; Otto et al., 2012; Gudmundsson & Seneviratne, 2016). The observation-based RRs have comparatively large confidence intervals, the RRs range from 0.01 to 13.4 (95% confidence interval), and none of the datasets indicate a change in Central European drought risk, in line with Gudmundsson and Seneviratne (2016). Using only global mean temperature in the regression analysis ignores potential aerosol effects, although they can influence regional-global precipitation (see discussion in Section 2). In fact, comparing the precipitation and the anthropogenic aerosol time series (Figure S1a and S1c), gives no indication of such a relationship operating in Europe, and a regression analysis confirms this. Years following large volcanic eruptions often have small precipitation amounts (Figure S1a and S1b), in line with earlier findings (e.g. Iles & Hegerl, 2015). This is not directly relevant for 2015, as no major volcanic eruption happened in the past few years. However, to rule out that the influence of the volcanoes could mask a trend in the regression, we re-computed the regression analysis, excluding years with high stratospheric aerosol concentrations, and still found no significant signal of global mean temperature or anthropogenic aerosols. Precipitation trends are not homogeneous in Central Europe — they tend to be positive in the east and negative in the west (not shown). However, even when splitting the region into a western and eastern part, no human influence is detected in the observations. The return time of the precipitation amount in 2015 is larger than 90 years (lower uncertainty bound at the 2.5th percentile). Results with an alternative observation-based methodology also show only a small precipitation difference between a recent and past time period, and are thus consistent with the regression-based assessment (Figure S6). This second method evaluates the thermodynamic effect of climate change (Analogue Method, Text S4).

5. Conclusions

The comprehensive assessment to attribute a human impact on the 2015 European summer drought presented in this study illustrates the complexity of the exercise. We find that the drought could be *more likely*, *less likely,* or *unaffected* by anthropogenic forcing, depending on the methodology and data source. Thus, we are not able to conclusively determine whether the 2015 drought was attributable to anthropogenic forcing. We note, however, that the RR with the largest signal-to-noise ratio, obtained by maximizing the number of considered models (whole CMIP5 ensemble) and using the largest forcing difference (through using pre-industrial GHG concentrations), suggests a detectable human influence on the likelihood of Central European droughts. This result should not be overstated though: the uncertainty of the multi-model assessment could be too small, as the individual models are not fully independent (Knutti et al., 2013). Additionally, great care has to be taken when interpreting results from pre-industrial control simulations, as natural forcings can be different from historical simulations (Taylor et al., 2012) and some models may have drift. We try to minimize the effect of model drift by using the last years of the pre-industrial control simulations. Note that RRs are indeed sensitive to the time period used from the pre-industrial control simulations (Figure S7). Using the mid-20th century as counterfactual climate (PRES vs. PAST and the observations), on the other hand, may underestimate the climate change signal, because one-third of the GHG forcing, and a large part of the anthropogenic aerosol forcing occurred before this period. When tested with CMIP5, however, the net effect was found to be negligible (Figure S8). The effect of aerosols on Central European precipitation was found to be small. Nonetheless, anthropogenic and volcanic aerosols can influence the climate (Chalmers et al., 2012; Wilcox et al., 2013; Iles & Hegerl, 2015), and its influence may need to be considered in extreme event attribution. Furthermore, our analysis reveals a strong model dependency, consistent with earlier findings for drought projections (Orlowsky & Seneviratne, 2013). Additionally, GCMs miss some observed precipitation trends, especially near coasts (van Haren et al., 2013). Finally, precipitation has a large interannual variability, which may mask existing trends (Orlowsky & Seneviratne, 2013). We restricted our analysis to meteorological droughts and would expect a stronger anthropogenic signal in other hydrological variables with a tighter link to temperature (e.g. soil moisture or precipitation minus evapotranspiration).

In this study, we highlight that any event attribution statement can—and will—critically depend on the researcher's decision regarding the framing of the attribution analysis, in particular with respect to the choice of model, counterfactual climate, and boundary conditions. This suggests that single-model assessments could overlook, or falsely detect signals, even when using a large number of ensemble members, an approach commonly applied in the literature (Otto et al., 2012; Sippel et al., 2016; Dong et al., 2016; Schaller et al., 2016; Mitchell et al., 2016). Our results also emphasize the difficulty of attributing drought events, even for an event as extreme as the 2015 drought, an aspect possibly underestimated in the research community (NAS, 2016) but in line with findings from other drought attribution studies (Shiogama et al., 2013; King et al., 2014; Kelley et al., 2015; Wilcox et al., 2015; Otto et al., 2015; Gudmundsson & Seneviratne, 2016). In the view of the consideration of event attribution in legal frameworks, it is thus crucial to assess human influence on climate extremes using multi-model and multi-method based event attribution.

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Crisis, disaster, risk and adaptation

Pascal Yiou and Aglaé Jézéquel

The history of the earth has been punctuated by environmental disasters and crises that have led to the disappearance of species and societies, as well as, on occasion, the emergence of new systems. Rather than dwelling on these geological and historical events, we will focus on today's climate change and its extreme events. Earth's habitable space is becoming more and more densely populated due to demographic expansion, which is perforce heightening the vulnerability of human societies to extreme phenomena, as reflected in the rapid rise in the cost of climatic and environmental events (MunichRe, 2016). The number of extreme climatic events in itself is on the rise as a result of climate change (IPCC, 2012) but without the same rapid growth. In this article, we focus on the interactions between scientists and society regarding the impact of extreme events in a changing climate.

A handful of definitions to aid understanding

The four nouns in the title of this article refer to related albeit complex notions. We define them precisely for reasons of consistency, and to enable a natural progression from one concept to the next. These definitions are specific to this paper.

A "crisis" is an extreme (climatic) event with serious consequences for an ecosystem or society. We can immediately exclude extreme events that do not have a socio-economic impact, such as a heat wave in an uninhabited area. The study of natural hazards falls within the scope of the earth sciences, including the atmosphere and ocean. Analysing a crisis requires an interaction with the social sciences and economic actors.

A "disaster", in the sense used by N. N. Taleb (2010), is a drastic change in the perception of an extreme event and a reassessment of the knowledge acquired in the face of the crisis. For example, the heat wave in Europe in the summer of 2003 was a crisis for several countries, challenging our understanding of the mechanisms of heat waves up to that point. Whereas a crisis may be managed, a disaster cannot be, and there are no (or no more) analogues for the latter. New knowledge may emerge from a climate disaster, as well as new forms of behaviour in the society facing the crisis. We will return below to examples of adaptation in the wake of a disaster.

The IPCC (IPCC, 2012) states that "risk" is a combination of climate hazard, vulnerability and a society's exposure. This definition may be linked to a policy's probability of failure (or risk of ruin) due to the emergence of a crisis in order to connect it to decision theory. For instance, the risk for a coastal development policy is the likelihood that a storm such as Cynthia (in 2010) will destroy all or some of the houses that are poorly protected. A priori, decisions are taken in the knowledge of risk, i.e. following an assessment of the probability of a crisis. The difficulty lies in the fact that these probabilities may evolve over time, either because of a changing natural hazard or because of increased vulnerability. Risk assessment, therefore, is largely about betting on future crises.

"Adaptation" is the series of measures taken to limit risks, manage crises and avoid disasters in a changing environment. Adaptation is based on projections of future risk, since we are keen to guard against events that may happen (Cooper and Pile, 2014). Adaptation measures range from constructing protective devices (such as dikes) to changing behaviours (e.g. avoid living in areas that are considered to be at risk of flooding).

These four closely-related concepts demonstrate how adaptation requires an awareness of the risk-crisis-disaster chain. This chain is illustrated in Figure 1.

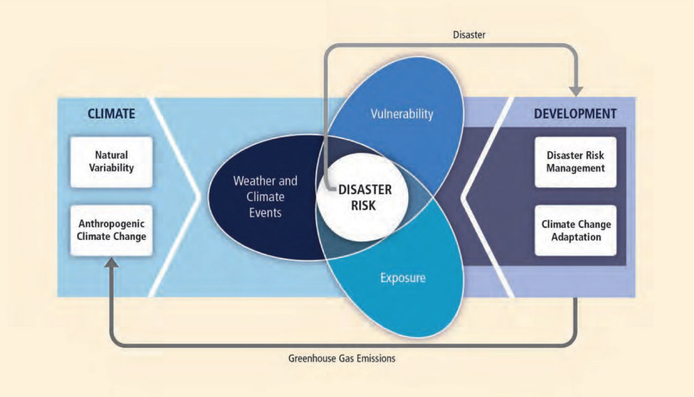

Figure 1. Description of climate risk and the relationship between climate change (blue colours) and society adaptation (orange). Adapted from Figure SPM.1 of the SREX report (IPCC, 2012).

Available tools

Climate science’s key contribution to risk assessment concerns hazard study. In particular, it looks at the evolution of these hazards in a changing climate. Extreme event attribution (EEA) is used to estimate changes in the probability of extreme events with the potential to trigger crises or disasters. The aim is to answer the following question: What is the probability that an event "similar to the one that has been observed" is linked to climate change? There is one main difficulty in this question: the rarity with which extreme events are observed, which means that counting them and estimating empirical probabilities are very uncertain tasks.

Pioneers working in the field of EEA (NAS, 2016) surmounted this problem by describing a factual world (the world in which we actually live) and a counterfactual world (where we would live if there was no climate change). This method involves comparing the probabilities of the same event occurring in each of the two worlds. Large sets of climate numerical simulations (tens of thousands) have traditionally been employed to estimate these probabilities in a world with current atmospheric levels of greenhouse gases, and with levels similar to those experienced at the beginning of the 20th century.

The EEA results still include a very significant degree of uncertainty, due especially to the natural variability of the climate, and they cannot be used as such in risk management policy (NAS, 2016). One potential strategy is to construct worst-case (but physically plausible) scenarios as a way of estimating the consequences for a potential policy or set of decisions. This is what happens in, for example, the energy sector to ensure that a country's power stations continue to provide a vital production minimum in response to an extreme heat wave that increases consumption and restricts output. These risk assessments vary according to the sector of activity, since climatic vulnerability thresholds are not the same from one industry to the next. Thermal extremes, for instance, may be expressed as indices of temperature intensity, duration of occurrence, geographic extent or seasonality depending on whether they affect the energy, health, transport or agriculture sectors. Selecting the most suitable indicator is one of the challenges faced by climate scientists and decision-makers.

Adaptation measures: the case of heat waves

We illustrate our argument with two heat waves, one that affected western Europe in 2003 and another that affected Russia in 2010. These two summer heat waves broke records for their duration, extent and cumulative intensity over a season. Both cases resulted in unprecedented numbers of deaths resulting from a heat wave in the modern era, together with significant environmental and economic consequences. The two events were linked to the exceptional persistence of anticyclonic atmospheric conditions and an abnormal drought prior to the heat wave. The twin events were not simply major climate crises of the 21st century but climatic disasters in two senses: they outstripped previously recorded heat waves and fell outside the norms of heat waves that have been experienced for several centuries. France found itself with problems regarding electricity production: the air temperature and the water temperature of the rivers were above the operating standards for the country's power stations. The disaster led to a re-evaluation of the standards of French power plants so that they could be adapted to handle this type of crisis. It also resulted in the creation of the French heat wave plan, an adaptation measure that proved to be effective during the July 2006 heat wave, where there were comparable temperatures but with less severe damage, especially in terms of fatalities.

In 2010, Russia and Ukraine experienced effects similar to the consequences of the 2003 heat wave in western Europe. The high temperatures were also accompanied by forest fires, which came close to areas contaminated by the 1987 Chernobyl accident. If these regions had caught fire in turn, it could have re-emitted radioactive dust into the atmosphere, creating the risk of a second nuclear incident. One adaptation measure in response to this climatic event would be to maintain forests as a way of restricting or preventing large-scale conflagrations, as was the case in 2010.

The challenge of adapting to the unknown

Most scientific studies are based on known events or events that have already been observed. In other words, risk is assessed in terms of past knowledge. We might know how to adapt to crises that have already taken place (and avoid other disasters of the same type) but the essence of a disaster is that it has not yet occurred. Anticipating new events is a challenge for science, especially in the context of climate change, while the IPCC predicts, for example, an increase in the duration, frequency and intensity of heat waves across the entire planet. Taking costly measures to adapt to disasters that may not occur (perhaps because of these measures) is sometimes a difficult decision to accept. The best that can be done at any given time in terms of risk assessment is to consider scenarios for future projections rather than relying on the past. Indeed, simply because an event has never happened in the past does not mean it will never happen in the future!

If we accept that risk adaptation can make use of scientific results, we realize that there is a very high degree of uncertainty about estimating probabilities. This uncertainty is linked to the natural variability of the climate; the heavy dependence of results on the climate model under consideration; and a range of technical assumptions that are sometimes difficult to detail to decision-makers who are not specialists. The worst-case scenarios (in accordance with the physical principles determined by scientists) are valuable for devising adaptation strategies based on the precautionary principle.

Climate scientists deliver their findings with the usual caution in order to avoid erroneous or false interpretations. One of the major difficulties in accepting adaptation strategies for climatic extremes is the rarity of the hazard, even if the consequences are significant. Although most of the EEA results show substantial increases in event probabilities, we are still in the field of rare events.

The other limitation is the national character of adaptation measures. Terrible heat waves hit the eastern United States in the 1980s, leading to federal adaptation plans in the country. But comparable strategies were only adopted in France after 2003, which did not prevent the 2010 disaster in Russia. It could be crucial to look at the crises that affect other countries since they may be precursors of our own disasters.

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Revisiting dynamic and thermodynamic processes driving the January 2014 precipitation record in southern UK

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Many attribution studies of extreme events have attempted to estimate the thermodynamic contribution (linked to thermal changes) and the dynamic contribution (linked to the atmospheric circulation). Those studies are based on statistical decompositions of atmospheric fields, and essentially focus on the horizontal motion of the atmosphere. This paper proposes a framework that decomposes those terms from first physical principles, which include the vertical atmospheric motion that has often been overlooked. The goal is to take into account the driving processes of the extreme event. We revisit a recent example of extreme precipitation that was extensively investigated through its relation with the atmospheric circulation. We find that although the horizontal motion plays a minor (but important) role, the vertical motion yields a dominating contribution to the event that is larger than the thermodynamic contribution. This analysis quantifies the processes leading to high winter precipitation rates, and can be extended for further attribution studies.

During the 2013/14 winter, southern UK has been affected by a spate of winter storms associated with a strengthening of the North Atlantic jet stream [1]. This exceptional situation resulted in heavy precipitation, with a precipitation record in southern UK (Fig.1a) [1, 2] and north western France in January. Such extreme events are projected to intensify in this region as a response to planetary climate change [3, 4], with important impacts on societies. Understanding the driving processes of those events and their sensitivity to anthropogenic warming is, therefore, crucial to anticipate the future risks of flooding over the UK.

A fruitful approach in climate event attribution consists in separating dynamic and thermodynamic contributions [5, 6, 7]. The thermodynamic processes are associated with the enhancement of the atmospheric water vapor content, following the Clausius-Clapeyron equation [8, 9, 10]. They are robust across climate models and result in a spatially homogeneous increase of precipitation [11]. The dynamic processes are related to the atmospheric circulation and remain highly uncertain at the regional scale [12, 13, 14, 11]. They considerably influence the ClausiusClapeyron scaling, strengthening for example, the daily heaviest precipitation [12, 13, 15, 14] and hourly precipitation extremes [16]. Therefore, considering the driving mechanisms separately is useful to deal with the highly uncertain dynamic changes and the robust thermodynamic changes in response to anthropogenic forcings.

Several studies attempted to quantify those individual contributions during the January 2014 heavy precipitation event. Schaller et al. [2] and Vautard et al. [17] concluded that a third of the increase in January precipitation can be attributed to changes in atmospheric dynamics and two thirds of the increase to thermodynamic changes. The two studies differ by the metric used to measure the effect of the circulation. Schaller et al. [2] used the daily mean sea-level pressure (SLP) at a specific point as a proxy of the circulation. This metric is a poor description of the atmospheric dynamics and accounts for only one local feature of the flow. Vautard et al. [17] applied a more general method based on flow analogues that are computed from monthly mean SLP over a regional domain (eastern north Atlantic ocean and Europe). However, this approach is sensitive to the way the similarity of the flows is approximated, either through weather regimes or flow analogues [17, 18]. In addition, flows are characterized by mean SLP patterns that only describe the low-level atmospheric circulation. Such characterization misses the developing vertical circulation that controls the initiation and strength of convection. Therefore the statistical approaches that have been used might provide a partial view of the atmospheric circulation and estimate only a part of the dynamic contribution to extreme events. In particular, an explicit representation of the atmospheric velocity in the available statistical diagnostics has been missing.

In this study, we propose an alternative framework to disentangle the dynamic and thermodynamic contributions. Changes in extreme precipitation are decomposed using a robust physical approach based on the atmospheric water budget (see Methods). This framework has been widely used in the tropics to relate local changes in precipitation to changes in atmospheric water vapor and circulation [e.g. 15, 19, 20]. This method is applied to January 2014 precipitation to understand the physical drivers of this extreme event. It also provides a physically-based quantification of dynamic and thermodynamic contributions that might be useful for extreme event attribution. The analysis is carried out using the ERA-Interim (ERAI) reanalysis [21], motivated by the horizontal resolution of this dataset (0.75°). The robustness of the results are tested using the NCEP reanalysis [22] (Supplementary Material).

The monthly-mean pattern of precipitation anomaly during January 2014 is better represented by ERAI (Fig.1b), as well as the daily variability. Both reanalyses, however, underestimate precipitation intensity. The monthly-mean water budget is computed to relate January 2014 precipitation anomalies to changes in the vertical moisture advection (ΔV_{adv}), the horizontal moisture advection (ΔH_{adv}) and surface evaporation (ΔE) (Methods section and Fig.1c,d,e).

January 2014 precipitation in southern UK is characterized by stronger than usual moisture vertical advection anomalies (larger than 2 mm/day on average for ERAI and NCEP) (Fig.1c,f and Supplementary Fig.1a). These positive anomalies moisten the troposphere by the vertical transport of moisture and sustain low-level moisture convergence. Abundant moisture in the atmospheric column and strong vertical motions resulted in heavy precipitation in southern UK. Horizontal moisture advection is small and negative at monthly time scale. Therefore it contributes to drying the troposphere and reducing precipitation intensity (Fig.1d,g). Surface evaporation is small over land and in particular, over southern UK (Fig.1e,f). Overall, January 2014 precipitation is dominated by moisture convergence associated with vertical motion. The dominance of this physical mechanism in inducing heavy precipitation has already been highlighted in previous studies [12, 13, 15, 11] using climate models.

At daily time-scale, vertical moisture advection is still the dominant process in generating intense precipitation (Fig. 2a), with a positive correlation of 0.8 between daily-mean P and V_{adv} in January 2014. Vertical advection moistens the troposphere through the vertical transport of moisture and is conducive to the development of convection at the same day of maximum vertical advection. This is the case for the heaviest rainy days of January 2014 (i.e. Jan. 1st, 4th, 18th, 24th and 31st), during which a minimum of 6 mm/day of V_{adv} was needed to induce precipitation rates ranging between 6 to 13 mm/day. In contrast to the vertical moisture advection, horizontal moisture advection has, in most cases, an asymmetric temporal structure relative to the heavy precipitation events. Positive moisture advection peaks 1 day before the maximum rainfall and becomes negative after the rainfall maximum (e.g. Jan. 24th). Thus it contributes to the moistening of the troposphere before the maximum precipitation and to its drying during the heavy rainfall events.

Our analysis decomposes the sequence of events that led to a high cumulated precipitation. The horizontal advection H_{adv} is a necessary precursor and the vertical advection V_{adv} is necessary and sufficient once enough moisture is available.

To identify the origin of the low-level moistening through horizontal moisture advection, monthly-mean 850hPa winds and the vertically-integrated moisture flux convergence are examined (Fig. 2b). Moisture convergence occurs over rainy regions, particularly over southern UK. Moisture divergence is localized over the North Atlantic, suggesting that this oceanic region is the primary source of moisture for the UK. Westerly winds over the North Atlantic were much stronger than normal during January 2014, favored by a persistent zonal circulation [2]. These winds contributed to advect moisture eastward towards the UK causing heavy precipitation and flooding. Moisture might also have been transported from the subtropical North Atlantic by south-easterly winds. January 2014 could therefore be connected to *atmospheric rivers*, which transport large flux of moisture from the subtropics to the mid-latitudes, leading to heavy precipitation and flooding over UK [23]. Back trajectory analyses are however needed to confirm the tropical origin of moisture during this event.

To further understand the mechanisms inducing heavy precipitation in southern UK, we focus on the dominant driver, i.e. the vertical moisture advection. V_{adv} anomalies are divided into thermodynamic and dynamic contributions (Methods section, Fig.3 and Supplementary Fig.1b). The thermodynamic component ($Thermo$) is associated with changes in water vapor that are largely dominated by the Clausius Clapeyron relation [8, 9]. The dynamic component (Dyn) is associated with changes in vertical velocity. Dyn and $Thermo$ compute the vertically-integrated dynamic and thermodynamic changes and include, therefore, the influence of temperature lapse-rates changes [24]. Dyn is the main contributor to the vertical transport of moisture and contributes to more than 90% of V_{adv} anomalies over southern UK (Fig.3a,c). $Thermo$ is very small (less than 1 mm/day in southern UK) and contributes only little to V_{adv} anomalies (Fig.3b,c).

In conclusion, the atmospheric circulation was a crucial element for January 2014 heavy precipitation. This extreme event was dynamically-induced by stronger vertical motions, which moistened the atmospheric column and promoted convection. Evaluating how anthropogenic climate change may alter the dynamic and thermodynamic contributions is essential to assess future projections of extreme precipitation. The *Dyn* and *Thermo* components are relevant metrics in that context. They yield a precise physical meaning at all vertical levels and at a regional scale. These metrics can be used in extreme event attribution studies (e.g. [2, 17, 18]) to provide a robust quantification of the role of the atmospheric circulation and water vapor in future changes in extreme precipitation. This approach can be applied consistently to reanalysis data or model simulations to analyze other wet winters. Our results do not necessarily contradict the existing event attribution papers: we find that the dominant factor for high precipitation is the vertical motion of the atmosphere. But long term changes in this advection mechanism can be very small, compared to changes in the thermodynamic term in the extra-tropics. They can even be of opposite sign [11]. Evaluating those changes in a precise way is needed to gain confidence on the physical drivers of precipitation extremes. This can be done with our Eq. (3), from long model simulations or reanalyses. Those results follow the so-called storyline approach advocated by Shepherd [7]. This helps constraining potential changes of those components if a baseline climatology is altered to estimate the components of low probability events.

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Methods

Moisture budget

Starting from the vertically-integrated water budget, regional precipitation at daily time-scale can be decomposed as:

$$\begin{aligned} P &= E - \left[\omega \cdot \frac{\partial q}{\partial p}\right] - [\mathbf{V} \cdot \nabla q] - \left[\frac{\partial q}{\partial t}\right] \\ &= E + V_{adv} + H_{adv} - dq. \end{aligned} \tag{1}$$

where E is evaporation, ω the vertical profile of vertical velocity, $\mathbf{V}$ the horizontal wind and q the vertical profile of specific humidity. Brackets refer to mass-weighted vertical integral. V_{adv}, H_{adv} and dq represent respectively the vertical moisture advection, the horizontal moisture advection and the time derivative of q.

The change in monthly-mean precipitation can be expressed as:

$$\Delta P = \Delta E + \Delta V_{adv} + \Delta H_{adv}. \tag{2}$$

Dynamic and thermodynamic contributions to precipitation changes

The vertical moisture advection is decomposed into a dynamic component (Dyn) related to vertical velocity changes and a thermodynamic component ($Thermo$) related to atmospheric water vapor changes that is largely dominated by Clausius Clapeyron equation:

$$\Delta V_{adv} = -\left[\Delta\omega \cdot \overline{\frac{\partial q}{\partial p}}\right] - \left[\overline{\omega} \cdot \Delta\frac{\partial q}{\partial p}\right] = Dyn + Thermo, \tag{3}$$

where the overbar indicates the 1981–2010 climatology mean.

Data availability

Era-interim data are available from the ECMWF Public datasets web interface (http://apps.ecmwf.int/datasets). NCEP data are available from the NOAA Public datasets web interface (http://www.esrl.noaa.gov/psd/thredds/dodsC/Datasets).

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Author contributions

B.O. designed the study, performed the analysis, produced the figures and wrote the paper. P.Y. provided advice in the study design and the interpretation of the results and contributed to the writing. A.J. discussed the results and edited the manuscript.

Additional Information

Competing Interests: The authors declare that they have no competing interests.

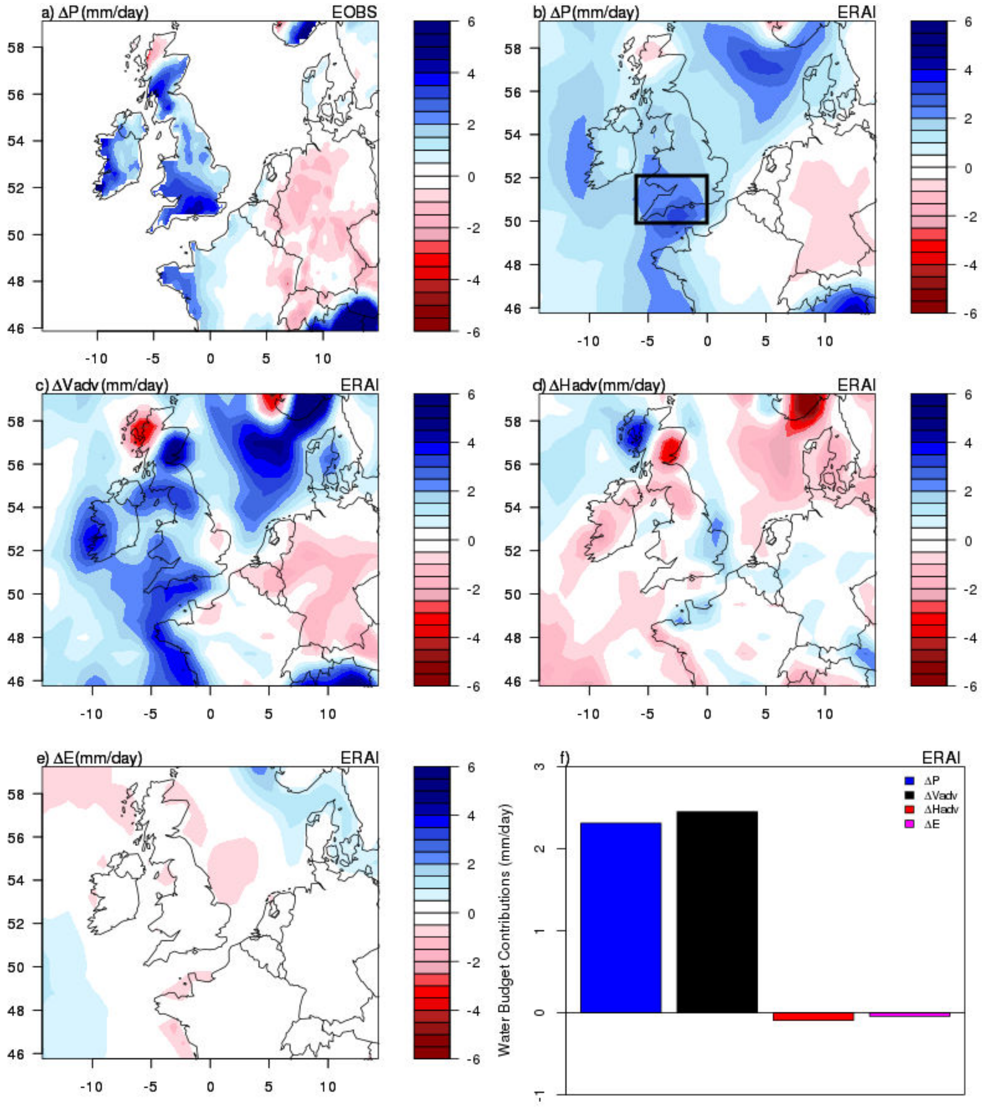

Figure 1: Monthly-mean anomalies for January 2014 of (a) EOBS [25] precipitation, (b) ERA-I precipitation, (c) Vertical moisture advection, (d) Horizontal moisture advection, (e) Surface evaporation, (f) the four water budget contributions averaged over southern UK (50-52° N,6.5° W-0°) as indicated by the black rectangle computed using ERA-I. Anomalies are relative to 1981-2010 climatology.

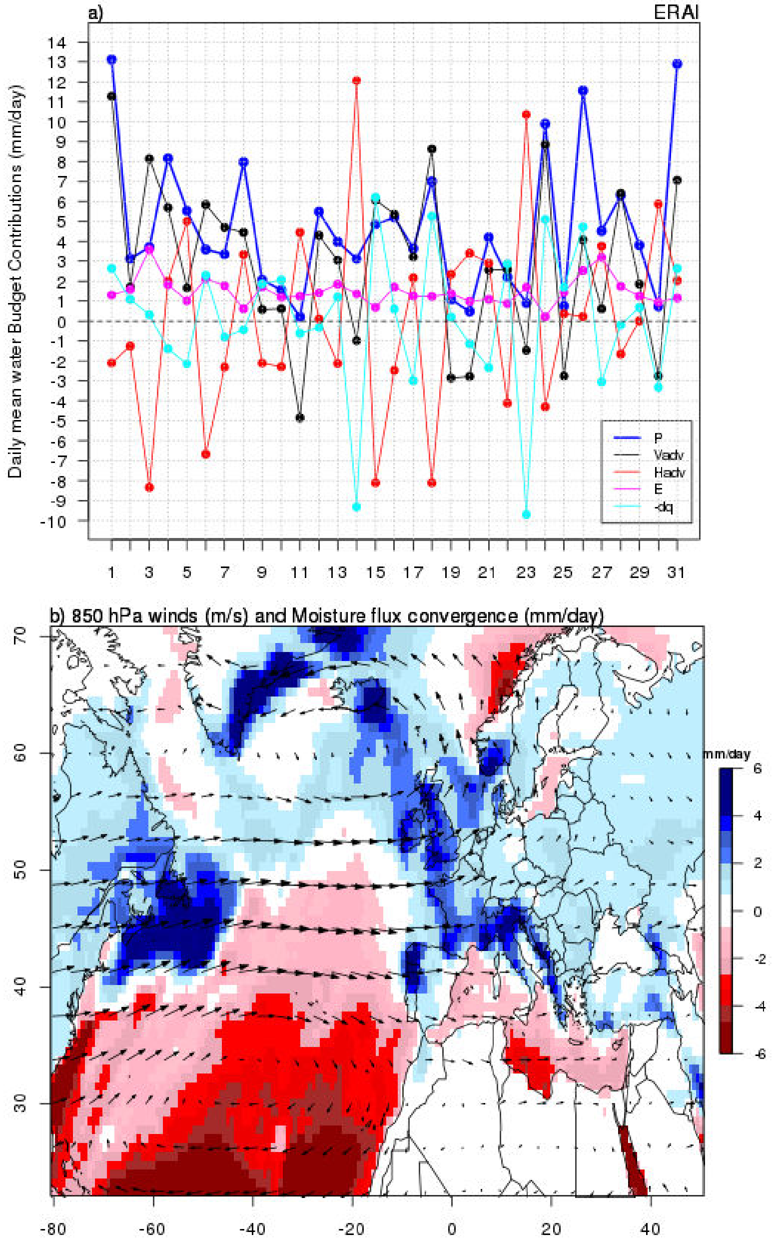

Figure 2: (a) Daily mean atmospheric water budget contributions for January 2014 averaged over southern UK, (b) Monthly-mean 850hPa horizontal winds and vertically-integrated moisture flux convergence for January 2014. Positive (negative) values correspond to areas of moisture flux divergence (convergence).

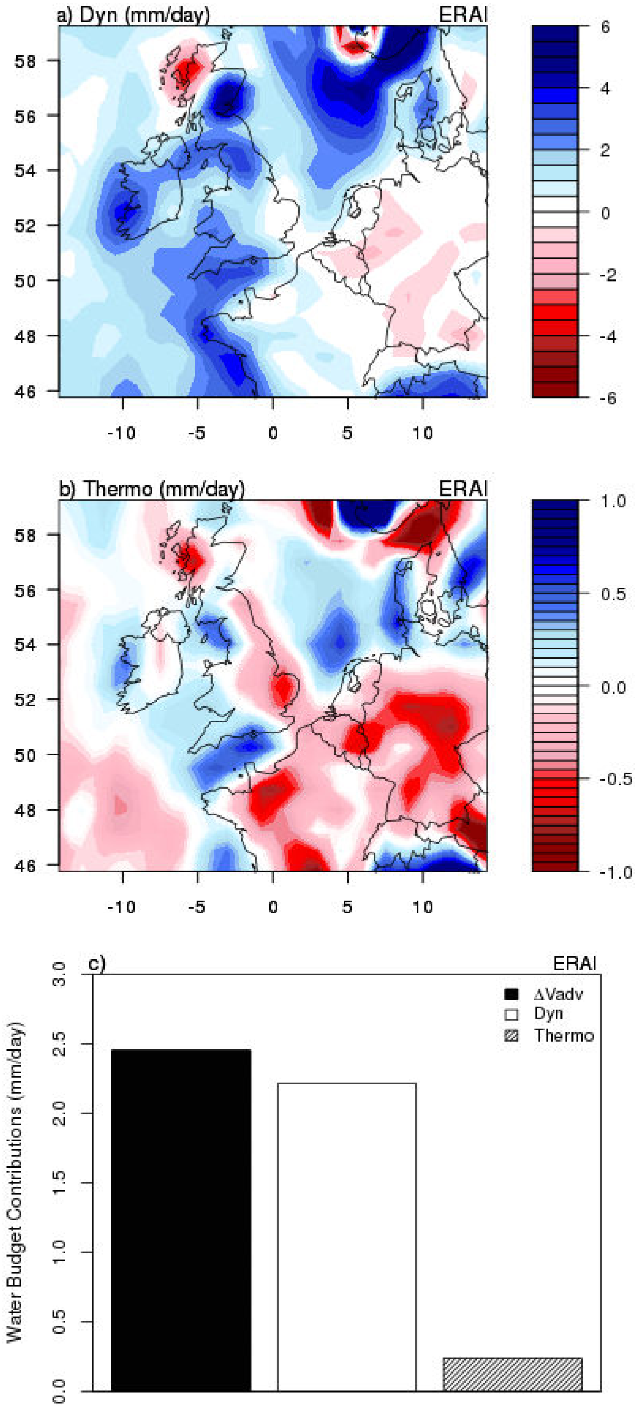

Figure 3: Monthly-mean anomalies of (a) dynamic and (b) thermodynamic contributions to precipitation anomaly during January 2014 derived from Eq. (3) using ERA-I, (c) As a, b but averaged over southern UK. Anomalies are relative to 1981-2010 climatology.

An experimental workshop to question the implications of an increase in extreme weather events frequency on the organization of French railways system

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An experimental workshop to question the implications of an increase in extreme weather events frequency on the organization of French railways system

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Abstract: Entangled in a complex socioeconomic environment, SNCF, the French national state-owned railway organization, is a good example of a company currently favoring reactive incremental adaptation to climate change over anticipated transformations. We designed and organized an experimental workshop to test how opening an exploratory space to discuss about the possible consequences of climate change may challenge this status-quo. Based on our previous work with SNCF, we decided to focus on increased climate variability in summer and extreme heat as potential disruptive characteristics of climate change. This article reports about this experiment and analyzes its outcomes, revealing that exploratory thinking can effectively raise original questions. Through the discussion, participants questioned management practices (e.g. vegetation management), but also management policies and guidelines (e.g. crisis management) and strategic investments. Moving from internal management concerns to social issues, they unveil critical governance challenges. At the end of the day, each institutional actor within the railway system - i.e. the infrastructure manager, mobility services providers, and traffic authorities - have to choose among several possible attitudes towards adaptation. Our discussions shows that these choices will especially depends on the overall market structure, which is different from one service to another and rapidly evolving. Collective adaption is therefore not self-evident and will only happen as the result of combined strategic decisions.

Keywords : railways, infrastructure planning, climate variability, exploratory, adaptation, governance

1. Introduction

This article presents the results of a research designed to investigate the consequences of an increased climate variability on the strategies of a major mobility company. The company is SNCF, the French national state-owned railway organization. It encompasses both the management of the network (SNCF Réseau) and the largest part of the operation of this network from regional transit to high-speed routes (SNCF Mobilités[1]).

During two years, we conducted a research in collaboration with SNCF to describe the effects of scientific discourses about climate change impacts on this organization. We studied its existing adaptation efforts: as institutional processes, autonomous initiatives (*exploration communities, innovation projects, etc.)* (Dépoues, 2017) and more decentralized reactions (Dépoues, Vanderlinden, & Venturini, 2017). Both at an institutional level and within management teams, SNCF is aware of climate change and understands its consequences. Nevertheless, this understanding does not appear to lead to any major transformational change. People working for SNCF draw a clear picture of their company as a sociotechnical system with many structural and conjectural constraints. Any technical or organizational innovation is thus necessarily the negotiated outcome of interactions among multiple legacies and various ongoing changes: "Our network is 150 years old [...] Everything has changed in 150 years [...] the climate has changed, but also the population, the means, the practice, etc."[2]

The company is entangled in a complex socio-economic environment with cross interactions with regulatory bodies, local authorities, other providers of public transportation and users. This creates a complex situation with internal (industrial processes, fixed-circulations schedules[3], etc.) and external (norms, political choices, etc.) constraints.

Railway in France is also a system at the crossroads facing major changes both on the supply (new technologies, connected services, rise of intermodal offers, markets liberalization and new entrants to the market, etc.) and on the demand sides (evolving mobility preferences, etc.). After years of underinvestment, strategic choices need to be done to renew the network and modernize the service. It is therefore SNCF top priorities[4] to improve dramatically its cost-performance, to succeed in its digital transformation, to develop its customer culture, and to improve its relationship with both users and transit authorities. Climate change comes as an additional concern among many

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[1] SNCF Réseau and SNCF Mobilité are two publicly-owned companies both placed under the control of a "holding" called SNCF.

[2] Quotes are parts of the workshop discussions (2018-10-30), translated into English.

[3] Ex. " an organization 2 years in advance for train paths, 6 months for schedules "

[4] Cf. http://www.sncf.com/fr/groupe (accessed 2018-2-2)

parameters of this rapidly changing environment. As a result, the company favors progressive adjustments, incremental and reactive adaptation.

Through anticipation and adaptive management, SNCF could better manage climate risks and take opportunities to offer an adapted and resilient mobility service. Yet, in line with our observations (Dépoues, 2017) and with the literature (Berkhout, 2012; Rotter, Hoffmann, Pechan, & Stecker, 2016; Surminski, 2013; WBCSD, 2014), a more transformative adaptation to climate change can only happen through a proactive uptake process (Rotter et al., 2016). Such a process requires dedicated deliberation spaces and times to clarify the relevant consequences of climate change in this particular context.

2. Research process: designing a workshop

To move further in this direction, we designed and organized an experimental workshop with SNCF in October 2017. This workshop intended to test how effective the opening of an alternative discussion space may be. It was designed to foster exchanges about the impacts of climate change for SNCF and the issues that could be raised, then to identify which discussions could emerge.

2.1 Workshops' objective and methods

Workshops and focus groups are common research devices to enable group interaction and reveal collective dynamics (Chambers, 2002). They provoke reactions between individual actors; make connections between issues. They make attitudes more apparent and create moments of reflexivity (Blanchard, 2011). Among researches on climate adaptation, workshops are frequently used to explore climate change consequences (Colombert, 2016; Corre, Dandin, L'Hôte, & Besson, 2015; Tissot et al., 2016)[5]; to facilitate the dialogue between scientists and decisions makers (Kane, Vanderlinden, Baztan, Touili, & Claus, 2014; Porter & Dessai, 2017) and even to co-design adaptation strategies (Haasnoot et al., 2013). Some of the workshops reported in the literature[6] are action-research devices; they intend to provoke changes in the system studied. They do so by intervening at particular moment to feed actual decision-making. For instance, (Malekpour et al., 2017) "put

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[5] Cf. http://www.gip-ecofor.org/doc/drupal/gicc/Lettre_GICC_numero21_1.pdf (accessed 2018-01-5)

[6] Bertrand et al. (2017) for instance created animation devices to build a common knowledge and overcome the "mismatch between supply and demand for climate knowledge". According to them, "the important thing is that people anticipate environmental situations and transform them into shared images and expectations that enable social action". Malekpour et al. (2016) proposed a model for "a diagnostic intervention in the ongoing process of strategic infrastructure planning, as a way of revealing context-specific impediments [...] tested in water infrastructure planning for one of the world's largest urban renewal areas in Melbourne, Australia" . Their goal is "enabling reflexivity within the ongoing planning process [...] about the development of processes and tools that support the widespread adoption and successful implementation of those solutions in the face of wide-ranging impediments". Similarly, Malekpour et al. (2017) tested a strategic planning intervention format as an alternative to predict-then-act approaches, to cope with uncertainties and complexities.

forward a planning intervention, which can be plugged into conventional planning processes". As such, we did not go so far: our workshop served a research purpose and aimed at producing original knowledge through interaction. However, the description we got of how climate change may question the system is an insight potentially very useful to shape and share visions for the future of rail in France.

If we were able to set up a successful workshop, it was because we prepared it through several months of fieldwork and interaction with SNCF teams. SNCF has been a key partner of this research allowing a privileged access to people working all across the organization and to internal working-groups on climate change. Thanks to this cooperation we could develop sustained relationships with several executives and have rolling discussions about how the organization deals with climate change. We met many of the participants before the workshop and we could count on their understanding of the research objectives and process. We also received a strong support from high-level executives in the company who helped us to select the participants and encouraged people to take part to the workshop. This allowed us to gather representatives from various SNCF activities ranging from infrastructure management to a variety of traffic services (Table 1).

Table 1: SNCF participants to the workshop

Representatives of*
SNCF Headquarter (n=4)**:** sustainability and climate officers, normalization and standards
SNCF Mobilités (n=3)**:** ● Intercités (classical national lines), regional sustainability manager, regional communication officer & digitalization project manager
SNCF Réseau (n=4)**:** ● Regional sustainability managers, Engeneering department - LNMP and Nîmes-Manduel projects (new High speed line and new railway station)

**Because of strong internal turnover within SNCF, many of the participants brought experiences coming from more than just one position. Nevertheless, participants regretted the absence of people directly involved in the maintenance.*

We decided to keep the workshop closed to external stakeholders to allow participants to express themselves freely, though this prevented us to debate questions involving external stakeholders. The workshop was held in SNCF buildings in the regional operations department of Montpellier, previously chosen for a detailed case study (Dépoues et al., 2017).

During four hours, it offered a space to engage in exploratory discussions on the consequences of climate change for SNCF activities. Following a research protocol agreed with participants, we recorded the whole workshop. Participants also received "participant's workbooks[7]" with specific questions and blank spaces to express their ideas and feedback (Blanchard & Vanderlinden, 2012). Nine participants returned their completed workbook. We analyzed the content of these workbooks and the complete transcript of the discussion according to a grounded-approach (Herpin, 2010; Lejeune, 2014), conducting a thematic analysis of our corpuses.

2.2. Workshop focus

Drawing on our previous interactions with SNCF staff and our knowledge of the company environment, we adjusted the proposed discussion framing and chose how and at which stage to introduce scientific inputs and raised different questions (Figure 1). Being able to include a climate-scientist in the research team was also a key ingredient of the experience.

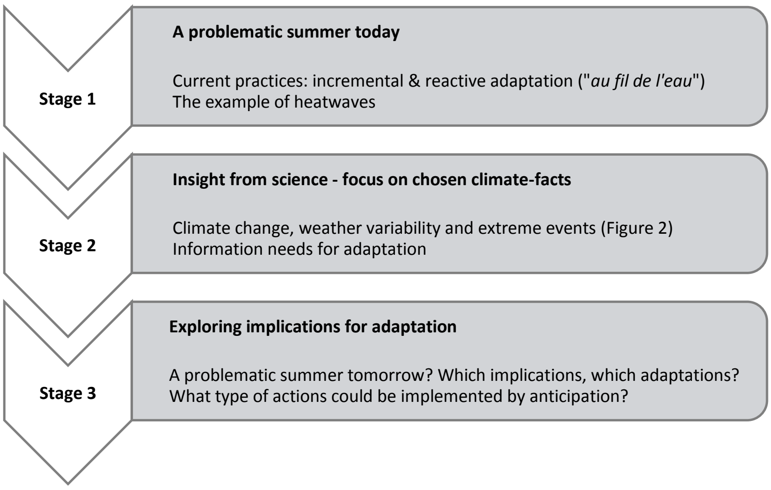

Figure 1: three stages of the workshop as it was built and items on the discussion agenda (Source: authors)

We hypothesized that some characteristics of climate change, might be major disruptive factors in spite of not always being immediately mentioned by the actors nor stressed in reference reports on climate change (Cattiaux, 2017a, 2017b; IPCC, 2014; Jouzel et al., 2014). Those characteristics are an increased climate variability, possible new extreme events and multiple uncertainties. We took the

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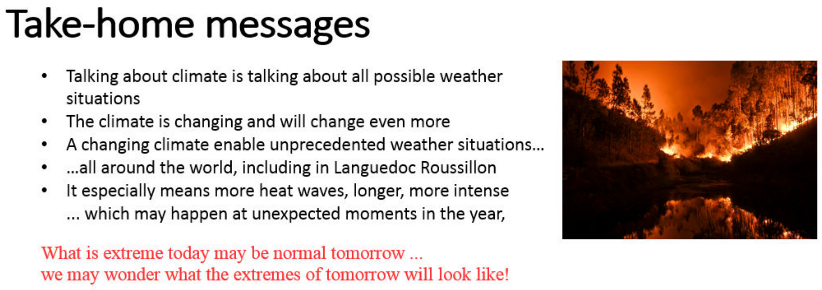
[7] Participant's workbook "is a methodological tool that optimizes the time we spend together. This optimization falls into two orders. First by formalizing break times, with writing breaks, we anchor our deliberations better in what each and every one of us brings. Secondly, the participant workbook enables us to collect some data in the form of your writings." (Blanchard & Vanderlinden, 2012).

apparent gap between how the company is adapting and those characteristics - recalled at the beginning of the session (Figure 2) – as the workshop starting point.



Take-home messages

- Talking about climate is talking about all possible weather situations
- The climate is changing and will change even more
- A changing climate enable unprecedented weather situations…
- …all around the world, including in Languedoc Roussillon
- It especially means more heat waves, longer, more intense … which may happen at unexpected moments in the year,

What is extreme today may be normal tomorrow …
we may wonder what the extremes of tomorrow will look like!

Figure 2: wrap-up slide on climate science presented during the workshop (Source: authors, translated)

Our goal was to draw all the consequences of this increased climate variability and uncertainty for the railway system: technical concerns but also non-technical, for instance consequences regarding the business model or the service delivered.

In a context of deep uncertainty, many authors suggest to favor exploratory approaches of adaptation rather than predict-then-act deterministic procedures (Dessai et al., 2009; Dittrich, Wreford, & Moran, 2016; Hallegatte, Shah, Brown, Lempert, & Gill, 2012). Formulating questions based on triggering issue, discovering alternative courses of action, testing current practices and planned actions against a variety of futures are among the first steps of such approaches. We subscribed to this type of frameworks. (Wardekker, de Jong, Knoop, & van der Sluijs, 2010) used "wildcards" (i.e. imaginable surprises) to stress test adaptation options for coastal-management. In a similar fashion, we intended to question the current representations and ways of doing. As Malekpour, de Haan, & Brown (2016), we explicitly raised the question "what could go wrong with current SNCF approach and strategy with regards to climate change?". We wanted the discussion to focus on the organization, its management practices, guidelines and its strategy more than available scientific information and uncertainties. The next sections report our findings.

3. Results

3.1 Questions raised by the focus on an increased climate variability, seasonal variation and extremes

We chose to discuss climate change with a seasonal approach, focusing on the current management of summer heatwaves and possible future hot seasons. This entry point drove the discussion towards the critical issue of increased inter-annual climate variability and seasonality (Cassou & Cattiaux, 2016; Fischer & Schär, 2009; Vrac, Vaittinada Ayar, & Yiou, 2014). Changes that were experienced by the workshop participants in the past did open conversations on the limits of current, well established, management practices. For instance, participants involved in the maintenance of the permanent way rose the issue of vegetation control along the tracks. Up to now, vegetation is managed through a centralized heavy process, relying on a national train operating all around the country to weed the tracks. This train has a very precise working-program planned up to three years in advance. This way of doing can only work if weeds lifecycle is foreseeable and stable enough. With an increase in variability, there may be early or late weed germination. Consequently, the train might miss the efficient treatment period. Alternative processes, maybe less centralized and more flexible, might therefore be implemented:

> "For two years we have not weeded at the right moments. [...] The leaves fall in December and there are droughts in February. [...] So, when we do a treatment in April it's useless. It would be necessary to do it after the rains of June whereas the national trains is planned for April-May, it is too early. […]. But we cannot program differently. With current industrial process of vegetation control with weeding trains set at the national level, we cannot fine-tune, we cannot do it case by case. Maybe we should work at the regional level to deal with it. The vegetation cannot be managed at the national level anymore with weather hazards and variations in seasonality we perceive, at least in Languedoc Roussillon. [...] It's been three years, that our regional train has to make a second pass because the first was useless. [...] We spread tons of glyphosate, it costs money and we are not very effective in Languedoc Roussillon at the moment."

This example shows, that sometimes, it is when focusing on variability more than trends that climate change really starts questioning current management processes.

Summer heatwaves are one of the extreme events with the most serious implications for SNCF activities. They have technical consequences – e.g. rails buckling implying to temporary reduce trains' speed (European Environment Agency, 2014; Ferranti, Chapman, Lee, Jaroszweski, & Lowe, 2017; Jaroszweski, Baker, Chapman, & Quinn, 2013). They also have more organizational and human consequences affecting both workers and users comfort and health. They are a potential source of perturbation and crisis. For instance, Dubost describes how, because of unbearable heat onboard during a short traffic interruption in a suburban train near the city of Paris, travelers got off the train causing a prolonged traffic interruption for safety reasons (Abramovici, 2011; Dubost, 2017). Discussing about the possible recurrence of situations that are currently considered as exceptional questioned the ability of current crisis management guidelines to withstand the test of time. Here are some of the questions risen during the workshop:

> "It is up to the company to decide if we must have trains running as scheduled despite exceptional conditions? At some point we must be able to answer no. When trains cannot circulate they cannot. I think we need to integrate this parameter in our operations. It's like that. This summer when it was

> 60°C in the US, planes did not take off. What do you want to do? Is it worth doing research to run engines at 60°C for only a couple of days or it is better not to take off for 3 days. These are all the questions we need to think about"
>
> "Even in the case of a weather alert we send out the trains - as long as it is only an alert, we send them out. But today we know that for some alerts, we should perhaps consider alternatives."
>
> "At least on secondary routes we can generalize replacement options. If we know we will be annoyed the whole summer because of heat, rather than waiting for the incident, we could anticipate and implement in advance an alternative bus transport."

Going in the same direction was the discussion about worst-case events. We did not want the debate to be limited only to imagine "most probable changes." Narratives of possible future weather situation can "provide complementary, more realistic and more physically consistent representations of what future weather might look like" (Hazeleger et al., 2015). Going in this direction, we proposed an example of high-end but plausible scenario built on the existing literature in climate science (Bador et al., 2017; Berry, Betts, Harrison, & Sanchez-Arcilla, 2017; Dubuisson, 2017; IPCC, 2014; Jouzel et al., 2014; Quesada, Vautard, Yiou, Hirschi, & Seneviratne, 2012; Stott, Stone, & Allen, 2004). This possible future was made of a succession of several subsequent extremes events in a summer sometimes between 2035 and 2050: a dry spring, an early but short heatwave in May, a longer even if not extreme heatwave from July to September when the Cévenol[8] season begins. We chose those events to be representative of various categories of climate evolution: changes in seasonality, changes in duration of heatwaves, and possible conjunction with disruptive climate events.

This exposé did not lead to a precise discussion on the responses to address to these particular cases. Participants more generally wondered what it could mean to cross these thresholds (ex. temperatures up to 50°C in summer becoming realistic (Bador et al., 2017)). It appeared very clearly that this could challenge some of the choices made today and particularly the viability of certain lines. This is particularly salient for lines exposed to climate hazard or dependent on seasonal flows (beach tourism in this region, ski elsewhere): "I wonder if in 2050-2100, the most structuring routes will be the same as today with this heat". In other words, climate change questions investment policies and strategic choices. In particular, contexts combining an enhanced climate vulnerability and evolving socioeconomic reality may lower the overall relevance of railroads.

> "-In case of heat, because of the risk of rails dilation you slow-down from 90 to 60 mph, but doing so, you disturb the whole traffic [...] -Such a deterioration of the performance questions the relevance of this mode of transport".

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[8] A "Cevennes storm" or "Mediterranean episode" is a particular type of rain which mainly affects the Cevennes region, in the south of France and often cause severe flooding. They result from hot, humid and unstable air coming from the Mediterranean, which can generate violent and sometimes stationary storms. They occur mainly in autumn, when the sea is the warmest and evaporation strong. http://www.meteofrance.fr/actualites/28475438-dossier-episode-mediterraneen (accessed 2018-2-2)

> "If tomorrow, every summer you cannot take the train for 10, 20 or 30 days because the rails, the catenary or the air conditioning ... it questions the durability of the rail system in general. Maybe there are modes of transportation currently developed that will be more adapted. Adaptation is perhaps just a question of survival of the rail system."
>
> "There are lines with few customers and very expensive to maintain: should we continue to operate them? We have the case with Intercités routes, for instance in Lozère, with a purely economic perspective, we should not circulate anymore. Maybe that's where we go for tomorrow, if in addition there is more problems because of the weather".

This discussion ranged from consequences of climate change to the railways installations themselves - which did not appear controversial - to more open-ended questions regarding management practices and policies or strategic investments. Moving from internal management concerns to social concerns, participants eventually reached issues that questioned current roles and opened up discussions on responsibilities and governance (Figure 3).

3.2 Discussing roles distribution, responsibility and governance

The responsibilities of the company were clear only for some of the issues that were raised. For instance, when it comes to vegetation control, there is no ambiguity regarding how to define and address the problem. Changing seasonal patterns becomes a source of inefficiency for those in charge of the maintenance of the network (namely SNCF Réseau and even more precisely the *M&T*[9] department for the maintenance planning and regional *Infrapôles* for the implementation). When detected, this inefficiency becomes a salient item on the company agenda. Consistency with its objectives, priorities and performance indicators is pursued. Making this inefficiency visible and measurable is therefore the main lever for climate adaptation. As Network Rail (SNCF Réseau counterparts in the UK, (Network Rail, 2017)) did, SNCF could implement an action plan to monitor the relationships between climatic conditions and maintenance operations. This may allow for the definition of targets to improve the management of these relationships. Emerging adaptation initiatives previously observed (Dépoues, 2017) already go in this direction. They combine new weather indicators in partnership with the national meteorological service and an improved monitoring of the network. Implementing the relevant changes, moving for instance towards decentralized weed-control, is then a classical challenge for change-management. This is also an R&D challenge with a major technical aspect consistent with SNCF innovation strategy (SNCF, 2017). New

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[9] "Maintenance operations, surveillance of railway installations, organization, work site supply chains, implementation of works … 24/7 Maintenance & Works staff ensure the maintenance and modernization of the railway network. […] To guarantee a high level of performance, innovation and safety, Maintenance & Works defines priority renewal projects, especially within the framework of the Network Modernisation Plan. It also organises maintenance actions tailored as closely as possible to railway needs": routine maintenance works, special maintenance works including renewal of the railway and grouped worked. https://www.sncf-reseau.fr/en/about/our-business/maintenance-works (accessed 2018-2-2)

IT solutions like smart-network monitoring offer new options for efficiency. Localized, predictive, agile maintenance based on sensor-data could effectively replace systematic centralized planning and could at least partially address this type of climate evolutions (““At the time leaves were falling in October ... it used to be like that. It is not the case anymore, so, […] we may set up different processes to deal with that, there are plenty of innovations we can use, digital, connected, there is plenty to do”).

For other issues, however, adaptation is not as straightforward. Responsibilities are not as clearly defined. For instance, when climate change challenges crisis management, it opens questions ranging from acceptability of preventive train cancellations to availability and systematization of alternative options (ex. buses) or messages sent to users[10]. Who is responsible for addressing these questions remains unclear, because of their multiple consequences in terms of service quality, efficiency, image of the company (we talked about SNCF perception in the media, especially in the new social media era[11]), but also in terms of public security. Mobility being a public service and railways being critical socio-economic infrastructures, such consequences go beyond SNCF itself. These questions involve many stakeholders both within SNCF and among public authorities. This part of the discussion on climate change impacts lead to a debate around costs, risks and responsibilities: “in the dialogue with traffic authorities, as soon as it comes to responsibilities and costs issues, discussions become like a ping pong game. Everyone is putting the responsibility on the others. We need to clarify who is in charge of what.”

SNCF Mobilités is often pointed as an easily identifiable culprit. It is on the front line, interacting on a daily basis with users of rails and directly blamed in case of disruption (“we are still the company that is quickly pointed out“; “in customers’ mind today, if we are forced to close a line, even because of a climate emergency, SNCF is still responsible”) . However, the company does not necessarily control all the levers to address the issue. As a mobility provider, it has first to deal with shorter time horizons: it operates with the existing infrastructure and in case of crisis has to follow SNCF Réseau instructions (SNCF, 2016)[12]. This situation will most likely be complexified by the opening of the rail

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[10] How to integrate this issue of adaptation into the information delivered to passengers? Is it a State responsibility or should it b delegated to SNCF? Are passengers ready to postpone their planned trips? “"A train-user book his ticket months in advance or even buy an annual transit pass. This means that from his perspective the trip is already promised, it is due. When there is an interruption it's intolerable because he perceived it as a broken contract”.

[11] “Customer's expectations are changing, becoming even more demanding and visible with social medias. In case of a crisis, cancelling a train may be very impacting for the company image. At the end of the day, whatever the initial cause, the message broadcasted is that “SNCF trains are not circulating”.”

[12] “SNCF Réseau is in charge, as Infrastructure Manager, of the management of operations related to the return to a nominal railway production on the National Rail Network” (translated from (SNCF, 2016)

transportation market: "In an opened-market, we just has to respond to the requirements of the authority in charge of the mobility policy[13]". SNCF Réseau, as a long-life assets manager, is more long-term oriented (CEDD, 2015) – and thus is a less visible potential "culprit". Yet, because of its natural monopoly on the infrastructure, it remains the unique and legitimate interlocutor for public authorities. Finally, public authorities have a duty to take care of public security[14]. They also enforce free-competition rules defined at the EU level for liberalized part of the service (freight, high-speed lines, international lines and soon regional traffic). Moreover, they design and financially support public mobility policies. Since the 2016 law[15], there are two important public levels of governance regarding railway transport: the national State and Regional councils[16]. The national State is the traffic authority for Intercités services, i.e. middle-distance trains operating classical lines[17]. Regional councils are the traffic authorities for regional trains (so-called TER).

Taking into account those heterogeneous contexts and constraints, discussion around roles and responsibilities is critical for designing and implementing an efficient adaptation strategy (Preston, Westaway, & Yuen, 2011): "a recent study shows that demarcations of responsibilities are often lacking in adaptation policy documents"[18]. As noticed in (European Environment Agency, 2014, p. 14), "the responsibility for adaptation action in the transport sector is often not clear. [...] in the event that adaptation related to transport would happen only spontaneously, conflicting and ineffective strategies could follow".

This rapid overview of actor's relationships shows that the conditions may exist for a constructive dialogue on climate adaptation, at least between public authorities and SNCF Réseau ("Being the unique manager of the Infrastructure, SNCF Réseau will perhaps remain as the good interlocutor. It is also responsible for what happens on its network"). Mobility providers for their part can choose to remain silent or to share information with the authorities. Among participants, both options were defended. SNCF Mobilités has the legitimacy of experience but the dialogue may become more difficult in a competitive setting:

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[13] As noted, it is already the case in urban areas "Keolis is not defining the mobility Policy of Bordeaux Metropolis, it just operates the service"

[14] Décret n° 2017-1071 du 24 mai 2017 relatif aux attributions du ministre d'Etat, ministre de la transition écologique et solidaire, cf. https://www.ecologique-solidaire.gouv.fr/direction-generale-des-infrastructures-des-transports-et-mer-dgitm (accessed 2018-02-05)

[15] Loi n°2015-991 du 7 août 2015 portant nouvelle organisation territoriale de la République (Loi NOTRe)

[16] Metropolitan France is divided into 13 administrative regions

[17] « Trains d'équilibre du territoire »

[18] Scholars proposed analytical framework to design comprehensive governance systems for adaptation. For instance (Huitema et al., 2016) provided a typology of options addressing the following dimensions problem choices, level choices, timing choices, choices concerning modes of governance and instruments, norms and principles choices and eventually implementation and enforcement choices.

> “We are still in a situation of monopoly, but soon we will not be the only ones on the market. If we raise this topic but our new competitors do not, our clients will think that there are people able to manage it more efficiently than we do. At the end of the day, which legitimacy will we have to talk about these issues more than any other?”
>
> “I still think that we must not remain totally silent. Precisely because of this new market situation. It would be too easy for traffic authorities to blame us for not alerting them. The new entrants encountering problems will explain that they are legacy of the past. As we know the risks we may gain from being irreproachable and transparent in the information we deliver to authorities."

3.3 A variety of potential adaptation postures

Throughout these discussions, participants did not hesitate to consider a wide spectrum of adaptation options. They went quite far in questioning the implications of climate change, behind the usual veil of institutional postures. Without any representatives of public authorities, we could not fully compare everyone’s viewpoints during the workshop. However, even within SNCF we note that adaptation strategies can be very different depending on the actor’s constraints and interests**:**

- From an asset manager perspective, adaptation means in the first place to improve the infrastructure – making it more robust or more resilient - to assure it will be able to cope with climate changes. The issue at stake is to make sure that railway as a mobility option will survive in the coming years.
- From a mobility-policy perspective, adaptation is about making the relevant investments and prioritize choices to assure durable and qualitative services to users. Favored routes and transport techniques are considered variables in this equation, sometimes as favored modes. This is consistent with ongoing evolutions that drive historical players such as SNCF Mobilités to redefine their identity from a railway company to mobility-services providers: “Our partners only consider the railway option. We have to say that SNCF is now an intermodal company. [...] There is a pedagogical aspect to make our customers understand that global warming can change how we can fulfill our mission. And our mission is not to operate railroads; it is to carry people, to offer mobility services. ”Their challenge is to meet policy-makers requirements in the most cost-efficient and satisfying way: “In some places, the most adapted train line may be a bus line […]”.
- From a commercial perspective (e.g. for TGV operating high-speed lines which are not subsidized as regional lines are) considering climate change means adapting the company value proposition[19] (managing risks and seizing opportunities) to keep or improve a

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[19] i.e. what it offers to its customers, the promise of benefits to be delivered to users.

> competitive advantage over other transport alternative. Adaptation therefore becomes part of an efficient marketing strategy wondering how customers' expectations will evolve regarding e.g. heat-comfort, top seasonal destinations or travel-priorities (will speed remain as important compared to reliability with more weather hazards especially for freight? (Dépoues, 2016)). As one participant said, "there are other companies entering the market both for travelers and freight, and [...] if Veolia trains are better air-conditioned, then more people will chose them, the comfort will become a criterion of competition"

This short description shows how, even within a "single" company such as SNCF Mobilités, several attitudes are possible and rational. Various economic configurations live together. Depending on the context, adaptation may be beneficial simultaneously, or not, to the interest of the state owned SNCF and to the interest of private operators[20]. It very strongly depends on the overall market structure, which is different from one service to another and rapidly evolving. For instance, regarding TER, the current liberalization phase makes any long-term planning very difficult. A participant testified: "I lived the opening of market for freight, in the beginning the competitors did not talk about societal problems, it is only about the economics, the price, how to manage costs, how to go faster. [...] Our competitors will be much more concentrated on market shares than on climate issues". However, with time, this type of configurations may evolve: - towards an oligopoly in which adaptation may become a collective problem addressed through sectoral agreements[21], or -towards monopolistic competition in which adaptation becomes part of a differentiation strategy (fostering adaptation as an innovation policy). The situation is already different for TGV or Fret SNCF (freight) which are commercial services engaged in an intermodal competition (against planes, coaches, trucks, etc.). In this context, adaptation can participate to the (re)definition of the benefits offered by SNCF to its customers: focusing for instance on user's comfort for TGV or reliability for the freight[22].

4 Conclusion

Railway services are part of a social contract and SNCF is a major actor of French mobility. It is a very well known organization with which users have an "affective" relationship (Opinion Way pour Trainline, 2018; Regniault, 2017). As a result, when we present climate change as a potential game-

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[20] about the public-private debate on adaptation see (Duit & Galaz, 2008; Klein, Juhola, & Landauer, 2017; Mees, Driessen, & Runhaar, 2012; Tompkins & Eakin, 2012).

[21] A participant who worked for the water industry before described this type of configuration between major companies in this sector.

[22] Conducting a foresight exercise, DHL, the German logistics company, for instance imagined a future in which vulnerability mitigation and resilience of transports becomes more important than speed and efficiency maximization because more numerous extreme weather events (DHL, 2012). Scenario 5: Global Resilience – Local Adaptation

changer, debates go far beyond technical adjustments or internal reorganization. Very quickly, they move towards bigger social questions regarding risk culture, mobility and travel expectations and habits (for work, for holidays[23]).

> "-Can we imagine to adapt daily transport plans? -It raises the question of working hours because people take the train too to go to work. -If tomorrow we have days with +8°C people will not work between 10:00 and 16:00, so there will be natural evolutions that will affect mobility-demand."
>
> "When you think that the school holidays begin on the same day for everyone and so you have 15 million people heading to the train stations, it's an aberration in terms of transport organization".

At the end of the day, there is no unequivocal adaptation response to these wicked problems (Rittel & Webber, 1973) but a plurality of possible attitudes. This included the acknowledgement that foreseeing change is not sufficient to act. Costs and technological challenges must be factored in, and sometimes prevent anticipatory adaptation. " Wait and see," is thus an option, thus accepting to suffer the consequences. For some key factors such as SNCF Mobilités or traffic authorities, many alternative strategic choices are still open-ended.

SNCF is facing a dual challenge: adapting its activities to maintain a viable service but also taking part to the adaptation of society more broadly. To what extent this is SNCF's responsibility is open for discussion and may depend on which branch of the company we are talking about. Nevertheless, one could defend that as the historic, national player SNCF may have a strategic interest to be proactive and contribute to the adaptation of the economy and society.

This discussion needs to keep going, involving more stakeholders. The original interaction experimented here was successful in giving flesh to theoretical questions about adaptation. What do we really want to adapt a mode of transportation, a mobility service, a company? For participants, this is not an abstract discussion anymore. As expressed in their workbooks, many participants in the room had this discussion together for the very first time (e.g. "I knew, 4 or 5 of the participants, I appreciated such occasions to meet and talk […] especially since SNCF Mobilités and SNCF Réseau are two different companies"; "What I appreciated was to get this transversal view thanks to the diversity of participants"). The workshop offered them a unique deliberative space to start thinking

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[23] For school holidays, France is divided in zones/regions made to handle the holiday rush better. A national schedule sets every year holiday's periods. These fixed dates are key determinant of train- passenger flows (what we call "grands departs"). For instance see, http://www.sncf.com/ressources/cp_27_-_grands_departs_2017.pdf

about this issue while providing a unique insight on the complexity of envisioning adaptation under deep and multi-source uncertainty.

Questioning management practices	**Questioning management guidelines**	**Questioning strategic choices**	**Questioning societal habits**
Ex. vegetation control	Ex. crisis management	Ex. investment décisions & prioritisations	Ex. work and holidays organization
→ New technologies, procedures changes (ex. decentralization of weeding)	→ New cancelling policy, substitution options, changes in users communication	→ Reconsidering routes viability, permanent mode switch, favoring strategic redundancies	→ Working and travelling differently, accepting to lower expectations (ex. losing in speed for security/reliability)
An internal issue			A societal issue
Clear roles and responsibility distribution.	Issues of public security + infrastructure availability: a discussion to set up between SNCF Réseau and public authorities?	-Mobility as a public service: designing mobility policies; role of regional and national traffic authorities (SNCF Mobilités – TER/Intercité: service-provider implementing public requirement) -Mobility as a commercial service, TGV or Fret: commercial services, adaptation as an added-value proposition	A broad societal issue in which SNCF might play a role, for instance doing pedagogy with train-users, participating in a collective dialogue on the necessary evolutions of the « contract » between users, authorities and mobility providers

Figure 3: synthetic mapping of adaptation issues as expressed during the workshop

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ÉCOLE DOCTORALE
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Titre : Approches statistique et épistémologique de l’attribution d’événements extrêmes

Mots clés : détection, attribution, événements extrêmes, changement climatique, statistiques, épistémologie

Résumé : Les événements extrêmes sont l’expression de la variabilité climatique naturelle. Puisque les émissions anthropiques affectent le climat mondial, il est naturel de se demander si les événements extrêmes observés récemment sont une manifestation du changement climatique. Cette thèse se propose de contribuer à la compréhension de l’influence du changement climatique anthropique sur les événements extrêmes observés, tout en évaluant si et comment cette information scientifique – et plus généralement, l’attribution d’événements extrêmes (AEE) – pourrait être utile à la société. Je propose des outils statistiques et j’utilise un ensemble d’entretiens qualitatifs pour répondre à ces questions.

La partie statistique s’applique aux vagues de chaleur européennes. Je quantifie le rôle joué par la circulation atmosphérique dans l’intensité de quatre vagues de chaleur récente. Cette analyse s’appuie sur des analogues de circulations, qui identifient des jours ayant une circulation similaire à celle de l’événement étudié. Ensuite, je dissocie l’influence du changement climatique sur les processus dynamiques et non dynamiques menant aux vagues de chaleur. Je calcule des tendances sur l’occurrence de circulations favorisant les fortes chaleurs et sur la température pour une circulation fixée, pour les vagues de chaleur de 2003 en Europe de l’Ouest et de 2010 en Russie. Je trouve que la significativité des résultats dépend de l’événement étudié, ce qui montre l’intérêt de calculer des tendances pour des types de circulation atmosphérique précis.

La partie épistémologique analyse les utilisations sociales potentielles de l’AEE. Je mesure comment elle pourrait informer les négociations internationales sur le climat, en particulier les pertes et préjudices, en réponse à des arguments de scientifiques dans ce sens. Je trouve que le seul rôle que l’AEE puisse jouer pour renforcer les pertes et préjudices est un rôle de sensibilisation des politiques, en marge du processus de négociations. Je compare également les motivations avancées par les scientifiques dans les entretiens avec les résultats existants sur l’utilité sociale de ce type d’information scientifique. Je montre que la pertinence sociale des résultats d’AEE est ambiguë, et qu’il y a un manque de données empiriques pour mieux comprendre comment différents acteurs s’approprient et réagissent à cette information.

Title : Statistical and epistemological approaches of extreme event attribution

Keywords : detection, attribution, extreme events, climate change, statistics, epistemology

Abstract : Extreme events are an expression of natural climate variability. Since anthropogenic emissions affect global climate, it is natural to wonder whether recent observed extreme events are a manifestation of anthropogenic climate change. This thesis aims at contributing to the understanding of the influence of anthropogenic climate change on observed extreme events, while assessing whether and how this scientific information – and more generally, the science of extreme event attribution (EEA) – could be useful for society. I propose statistical tools to achieve the former, while relying on qualitative interviews for the latter.

The statistical part focuses on European heatwaves. I quantify the role played by the atmospheric circulation in the intensity of four recent heatwaves. This analysis is based on flow analogues, which identify days with a similar circulation pattern than the event of interest. I then disentangle the influence of climate change on the dynamical and non-dynamical processes leading to heatwaves. I calculate trends in the occurrence of circulation patterns leading to high temperatures and trends in temperature for a fixed circulation pattern, applied to the 2003 Western Europe and 2010 Russia heatwaves. I find that the significance of the results depend on the event of interest, highlighting the value of calculating trends for very specific types of circulation.

The epistemological part evaluates the potential social uses of extreme event attribution. I assess how it could inform international climate negotiations, more specifically loss and damage, in response to a number of claims from scientists going in this direction. I find that the only potential role EEA could play to boost the loss and damage agenda would be to raise awareness for policy makers, aside from the negotiation process itself. I also evaluate how the different motivations stated by EEA scientists in interviews fare compared to the existing evidence on social use of this type of scientific information. I show that the social relevance of EEA results is ambiguous, and that there is a lack of empirical data to better understand how different non-scientific stakeholders react and appropriate EEA information.

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