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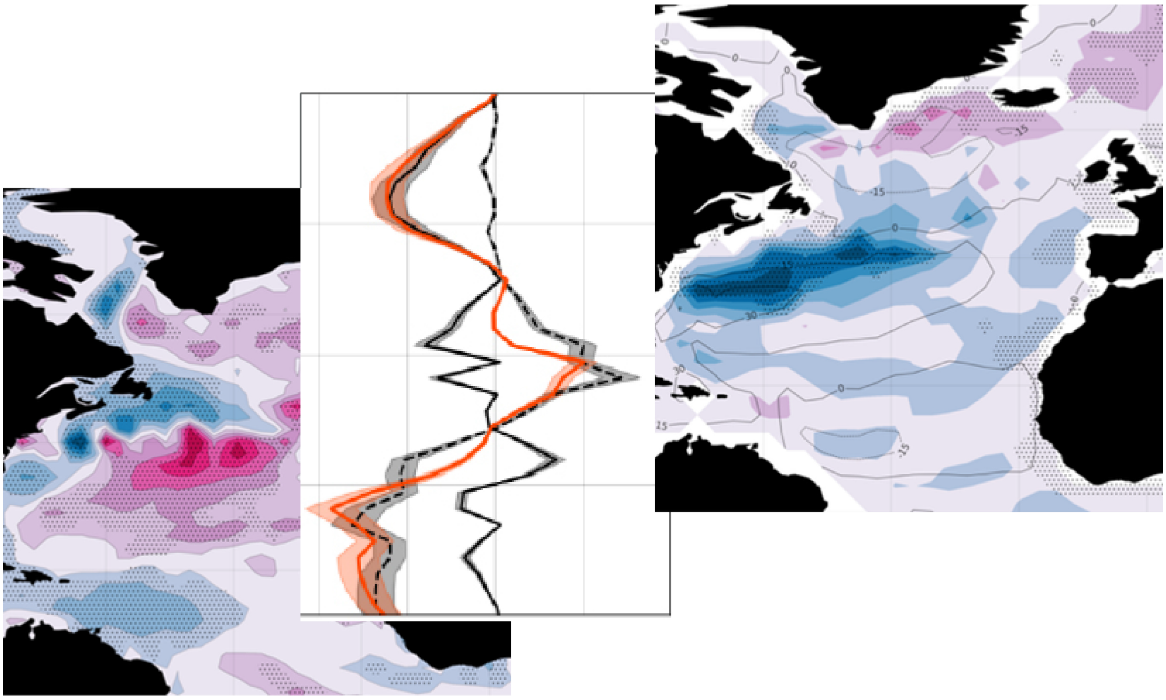
Sub-Decadal Variability of European Summer Heat Extremes



Lara Sophie Wallberg

Hamburg 2023

Berichte zur Erdsystemforschung
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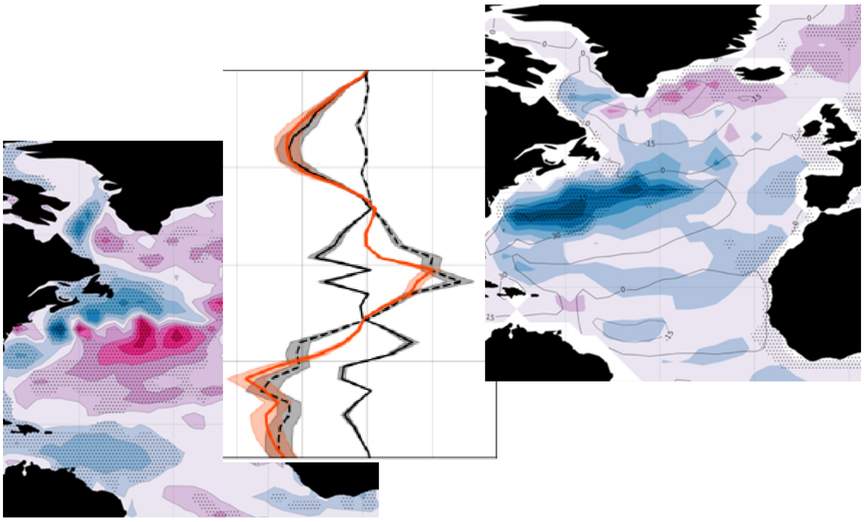
Sub-Decadal Variability of European Summer Heat Extremes



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Hamburg 2023

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ABSTRACT

In this dissertation, I study the variability of extremely warm European summers on sub-decadal time scales. Overall, Central European mean summer temperatures have increased significantly since the 1990s and are expected to further increase with rising greenhouse gas concentrations. However, these trends are accompanied by a large internal variability estimated to be of the same order of magnitude to many times larger than the temperature change we have seen in the last 30 years. The internal variability of European summer temperatures has already been linked to various mechanisms on seasonal to sub-and multi-decadal timescales. While local drivers such as atmospheric or surface conditions have been thoroughly investigated in terms of their impact on extreme events and variability, larger-scale drivers like oceanic influences, which can act over more extended time periods, are sparsely studied.

First, I aim to find a long-term mechanism linked to extremely warm European summers. I show that sub-decadal (5-10yr) variability is the dominant time scale for extremely warm European summers in the Max-Planck-Institute Grand Ensemble. I link the occurrence of these extremely warm summers to heat accumulation in the North Atlantic Ocean, where heat is redistributed several years prior to an extreme summer, thereby affecting ocean-atmosphere heat fluxes in the year of the extremely warm summer. This development is accompanied by a weakening and northward displacement of the jet stream, and an increased probability of atmospheric blocking over Scandinavia.

Second, I use this mechanism linking the accumulation and release of heat in the North Atlantic Ocean and extremely warm European summers to improve the prediction skill of exactly these extremely warm summers several years ahead. For that, I introduce an ensemble selection based on the accumulation of heat in the North Atlantic Ocean within the Max-Planck-Institute Earth-System-Model decadal prediction system. The predictive performance of this selected ensemble mean is tested against the full ensemble mean. This ensemble selection leads to an improvement in prediction skill of European summer temperatures.

Lastly, I underline the importance of my findings and prove their relevance with a real-life example: the heatwave in June 2023. In this case study, I clearly demonstrate now, by using the mechanism from the first study and the ensemble selection technique of the second study, this years extremely warm summer could have been better predicted three years ago.

Overall, the findings of this dissertation contribute to our understanding of sub-decadal processes driving extremely warm summers over Central Europe, with great potential to increase the prediction skill of these extremely warm summers, also in an operational setup.

ZUSAMMENFASSUNG

In dieser Dissertation untersuche ich die Variabilität von extrem warmen europäischen Sommern auf subdekadischen Zeitskalen. Insgesamt sind die Sommertemperaturen in Mitteleuropa seit den 1990er Jahren deutlich angestiegen und werden voraussichtlich mit steigenden Treibhausgaskonzentrationen weiter zunehmen. Diese Trends werden jedoch von einer großen internen Variabilität auf verschiedenen Zeitskalen überlagert, die in der gleichen Größenordnung bis um ein Vielfaches größer ist als die in den letzten 30 Jahren beobachtete Temperaturveränderung. Die interne Variabilität der europäischen Sommertemperaturen wurde bereits mit verschiedenen Mechanismen auf saisonalen bis subdekadischen Zeitskalen in Verbindung gebracht. Während lokale Treiber wie atmosphärische oder Oberflächenbedingungen hinsichtlich ihrer Auswirkungen auf Extremereignisse und Variabilität gründlich untersucht wurden, sind großräumigere Treiber wie ozeanische Einflüsse, die über längere Zeiträume wirken, nur wenig erforscht.

Zunächst versuche ich, einen langfristigen Mechanismus zu finden, der mit den extrem warmen europäischen Sommern zusammenhängt. Ich zeige, dass die subdekadische (5-10-jährige) Variabilität die dominierende Zeitskala für extrem warme europäische Sommer im Max-Planck-Institut Grand Ensemble ist. Ich bringe das Auftreten dieser Hitzeextreme mit der Wärmeakkumulation im Nordatlantik in Verbindung, wo die Wärme mehrere Jahre vor einem Extremereignis umverteilt wird und dadurch die Wärmeflüsse zwischen Ozean und Atmosphäre im Jahr des extrem warmen Sommers beeinflusst. Diese Entwicklung geht mit einer Abschwächung und Nordwärtsverschiebung des Jetstreams und einer erhöhten Wahrscheinlichkeit von atmosphärischen Blockings über Skandinavien einher.

Danach nutze ich diesen Mechanismus, der die Akkumulation und Freisetzung von Wärme im Nordatlantik mit extrem warmen europäischen Sommern verbindet, um die Vorhersagbarkeit genau dieser extrem warmen Sommer mehrere Jahre im Voraus zu verbessern. Zu diesem Zweck führe ich eine Ensemble-Auswahl ein, die auf der Wärmeakkumulation im Nordatlantik innerhalb des dekadischen Vorhersagesystems des Max-Planck-Instituts Erdsystemmodells basiert. Die Vorhersageleistung dieses ausgewählten Ensemble-Mittels wird gegen das gesamte Ensemble-Mittel getestet. Hierbei führt die Ensemble-Auswahl zu einer Verbesserung der Vorhersagefähigkeit der europäischen Sommertemperaturen.

Abschließend unterstreiche ich die Bedeutung meiner Ergebnisse und beweise ihre Relevanz anhand eines realen Beispiels: der Hitzewelle im Juni 2023. In dieser Fallstudie zeige ich deutlich, dass der extrem warme Sommer dieses Jahres mit Hilfe des Mechanismus aus der ersten Studie und der Ensemble-Auswahltechnik aus der zweiten Studie vor drei Jahren besser hätte vorhergesagt werden können.

Insgesamt tragen die Ergebnisse dieser Dissertation zu unserem Verständnis

der subdekadischen Prozesse, die extrem warme Sommer über Mitteleuropa antreiben, bei und haben damit das große Potenzial, die Vorhersagefähigkeit dieser extrem warmen Sommer zu verbessern, auch für den operationellen Einsatz.

PUBLICATIONS

This dissertation is based on the following two first-author publications which are included in the appendix:

APPENDIX A

Wallberg, L., Suarez-Gutierrez, L., Matei, D., and Müller, W. A.: Extremely Warm European Summers preceded by Sub-Decadal North Atlantic Heat Accumulation, EGUsphere [2023, preprint]
https://doi.org/10.5194/egusphere-2023-653

APPENDIX B

Wallberg, L., Suarez-Gutierrez, L., Matei, D., and Müller, W. A.: Improved Prediction Skill of Extremely Warm European Summers [to be submitted to GRL]

Furthermore I contributed to three further publications. The first-author publication is based on the results of my masters thesis, to the other two I contributed as co-author:

Wallberg, L., Rautenhaus, M., Ruggieri, P., Athanasiadis, P., Dobrynin, M., Mayer, B., and Baehr, J.: The Northern Hemisphere Winter Polar Jet Stream and its Connection to the Seasonal Prediction Skill of Weather Regimes over Europe [submitted to GRL, in review]

Olonscheck, D., Suarez-Gutierrez, L., Milinski, S., and 14 co-authors (including **Wallberg, L.**): The new Max Planck Institute Grand Ensemble with CMIP6 forcing and high-frequency model output, ESS Open Archive [2023, preprint] https://doi.org/10.22541/essoar.168319746.64037439/v1

Aranyossy, A., Brune, S., **Wallberg, L.**, Dobrynin, M., and Baehr, J.: Seasonal Predictability of wintertime North Atlantic cyclonic activity through the NAO and the eddy-driven jet stream [in preparation]

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"A good life depends on the strength of our relationships with family, friends, neighbours, colleagues and strangers."

— David Lammy

The preparation of this dissertation, but also the way to it, would not have been possible without the support of many different people.

My biggest thanks go to my supervisors, Wolfgang Müller, Laura Suarez-Gutierrez, and Daniela Matei. I would also like to thank you for your great support and guidance; in particular for the many long discussions, hundreds of iterations of proofreading, and for having always an open ear for all of my worries and problems. During my thesis, I have learned a lot from all of you. Especially I would like to thank Wolfgang for his endless motivation through all the challenges I encountered in this PhD journey.

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The last years had many memorable moments for me and you all played a part in it. Thanks for that!

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LIST OF ACRONYMS

ACC	Anomaly Correlation Coefficient
AMV	Atlantic Multi-Decadal Variability
CEU	Central Europe
ENSO	El-Niño Southern Oscillation
ERA5	ECMWF global reanalysis (fifth generation)
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, and August
LR	Low-Resolution
MPI	Max Planck Institute
MPI-ESM	Max Planck Institute Earth System Model
MPI-GE	Max Planck Institute Grand Ensemble
MSLP	Mean Sea Level Pressure
NAO	North Atlantic Oscillation
ORAS5	Ocean Reanalysis System 5
SAT	Surface Air Temperature
SST	Sea Surface Temperature
TAS	Temperature at Surface

UNIFYING ESSAY

Sub-Decadal Variability of European Summer Heat Extremes

Unifying Essay

"Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less."

— Marie Curie

1 INTRODUCTION

1.1 HEAT EXTREMES AND THEIR IMPACT ON SOCIETY

The increase of extreme heat events in frequency and intensity poses a grave threat to us and our planet. It is crucial to know when and why these events occur, as they can have significant impacts on health, environment, and society. Therefore, extremely warm summers pose a serious hazard that requires reliable forecasting and careful preparation.

Changes in heat extremes are shown and predicted to be a major impact of climate change. Both the frequency and intensity of heat waves have increased, which can be attributed to global warming (Schär et al., 2004; Seneviratne et al., 2006). In the European region, the frequency of heat waves has doubled since the pre-industrial era (Fischer and Knutti, 2015). Additionally, it is assumed that summers like the most extreme observed so far could occur every other year in a 2°C warmer world (Suarez-Gutierrez et al., 2018). By monitoring and analyzing such events, we can better assess the impacts of climate change and take targeted actions to combat and better adapt to it.

Extreme heat can lead to serious health problems and even death, especially for vulnerable populations such as the elderly, children, and people with pre-existing conditions (Mücke and Litvinovitch, 2020; Ebi et al., 2021). Heat stroke, heat cramps, and dehydration are just some of the possible consequences. With timely warnings, people can take appropriate precautions, such as avoiding excessive physical exertion, drinking adequate fluids, and seeking cooler environments to protect themselves and their loved ones.

Furthermore, knowledge of impending heat extremes allows for better planning and risk assessment. Government agencies, businesses, and organizations can prepare for the challenges that come along with extreme heat (Stillman, 2019; Heino et al., 2023). Infrastructure can be assessed and strengthened for potential damage from extreme heat. Buildings can be adapted to higher temperatures with better insulation, air conditioning systems, and shadowing opportunities (Kumar et al., 2021). Agriculture can adjust irrigation systems to grow robust, heat- and drought-resistant crops (Heino et al., 2023). In addition, water supplies can be better prepared for increased demand during an extremely warm summer. These preparation efforts can minimize potential damage and increase resilience to heat extremes.

For example, 2003 saw one of the most severe and devastating heat waves Europe has experienced since weather records began (Bono et al., 2004; Robine et al., 2008; García-Herrera et al., 2010). Between 30,000 and 70,000 people died during the heatwave, hospitals and medical facilities were overloaded, and shortages of medicines and medical staff occurred. The heatwave led to water shortages, especially in southern Europe, river levels dropped by up to 70 percent, and water rationing was imposed in large areas. The extreme temperatures and drought led to significant crop failures in many European countries, mainly affecting cereal, fruit, and vegetable crops. The crop failures had an impact on food prices and farmers suffered significant financial losses. Many European countries also had to deal with forest fires due to the drought in the summer of 2003; in southwestern Europe, for example, more than 8,000 km^2 of land were destroyed by forest fires. The total cost of fighting the fires amounted to several billion euros.

But not only the 2003 heatwave had a wide range of immediate and long-term impacts on society, economy, and environment in Europe; 1976 saw countless drought-related crop failures in the UK, the heatwave is considered the worst in British history (Murray, 1977). In 2010, Eastern Europe was affected by high mortality rates due to heat and heat-related forest fires, that together resulted in bad and persistent air quality levels (Shaposhnikov et al., 2014). In 2015, many southern European countries experienced heat waves, also resulting in forest fires, crop failures, severe health issues, and increased mortality (Russo et al., 2015). In 2018, Scandinavia experienced extreme drought levels which led to forest fires on an unprecedented scales (Bastos et al., 2020). In 2019, Europe was hit by another extreme heatwave, with new temperature records set in many Central European countries (Strauss et al., 2021).

These examples highlight the need to understand the underlying mechanisms of heat extremes. An improved understanding of the complex interplay between atmospheric and oceanic conditions, climate patterns, and human activities can enhance the predictability of such occurrences. This in turn can provide timely warnings, evidence-based decision-making, and rapid action.

1.2 DEFINITION AND DRIVERS OF HEAT EXTREMES

What are Heat Extremes?

Heat extremes are defined differently depending on context and discipline (Seneviratne et al., 2021). The meteorological definition of heat extremes refers to short, exceptional periods of significantly high temperatures that are above the normal temperatures for a given region and season. These events are usually referred to as heat waves and can last for several days or weeks. For meteorological heat extremes, specific atmospheric conditions and pressure systems that lead to such heat extremes are analyzed.

The climatological definition of heat extremes, on the other hand, looks at longer periods of temperatures that are statistically above normal climate conditions for a given region. This uses historical climate data to identify seasonal and long-term means and define heat extremes as deviations from the normal distribution of temperatures.

Together, these meteorological and climatological perspectives provide important information on heat extremes and enable a comprehensive understanding of these events. The meteorological perspective enables the observation and prediction of short-term heat extremes, while the climatological perspective reveals near-term climate trends and long-term changes in climate.

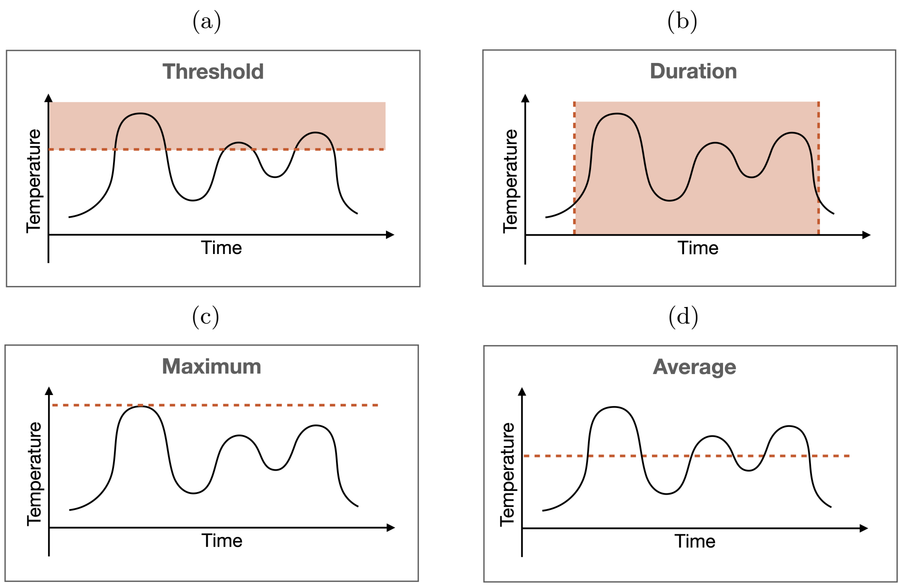

Figure 1.1: Characteristics of extreme heat. (a) Heat extreme defined by temperatures exceeding a certain threshold. (b) Heat extreme defined by certain duration of warm temperatures above a given threshold. (c) Heat extreme defined by maximum temperature in a certain period. (d) Heat extreme defined by high average temperatures during a certain period.

Extreme heat can be identified according to various characteristics, such as a temperature above a given threshold, the duration of high temperatures, the maximum temperature, and high average temperatures (Fig. 1.1). The threshold value for extreme heat defines the temperature that must be reached to be considered extreme (e.g. Fischer and Schär (2010), Fig. 1.1a). This value can vary depending on the region and climate. The threshold can be defined by a percentile, but also by an absolut value. For example, the German Weather Service (DWD) puts the absolute threshold for extreme heat in Europe at 35°C. In addition, the duration of the heat is another factor in determining whether it is an extreme (e.g. Meehl and Tebaldi (2004), Fig. 1.1b). A short rise in temperature over one or two days may be typical for some regions, but would possibly not be classified as extreme, while a longer period with high temperatures could have serious consequences. Heat can also be determined by the maximum temperature (e.g. Meehl and Tebaldi (2004), Fig. 1.1c), which is an indicator for the intensity and can be important for assessing its impact. A heatwave is additionally often defined as a sustained period of high average temperatures over several days or weeks (e.g. Robinson (2001), Fig. 1.1d). In summary, the exact definition of extreme heat can vary depending on the context, the objective of the analysis, and the region.

For the analyses in this dissertation, I use the threshold definition. Extremely warm summers are defined here as mean summer temperatures (JJA) in the region between 15°-35°E and 45°-60°N that fulfill two criteria: (1) Temperatures must exceed the 90th percentile of long-term mean summer temperatures. (2) Since I investigate extremely warm European summers on sub-decadal time scales (discussed in section 1.3), the temperatures must also occur in a positive sub-decadal phase with 5-10 year variability.

Possible Drivers and their Timescales

Heat extremes can be caused or amplified by multiple drivers occurring on different time scales, including sub-seasonal (e.g. Pyrina and Domeisen, 2022; Rousi et al., 2022), seasonal (e.g. Coumou and Robinson, 2013; Neddermann et al., 2019), sub-decadal (5-10yr) (e.g. Müller et al., 2020), decadal to multi-decadal (>10yr) (e.g. Ghosh et al., 2016; Borchert et al., 2019), but also centennial to millennial variations (e.g. Collins et al., 2013).

One of the main drivers for temperature variability on long time scales is the anthropogenic climate change, causing a shift towards a warmer mean state, which leads to rising global mean temperatures as well as more extreme temperatures (Fig. 1.2a). However, natural and regional climate variability also plays a role in creating heat extremes on a wide range of time scales (Schär et al., 2004; Fischer et al., 2012; Suarez-Gutierrez et al., 2020a). Here, an increase in temperature variability also lead to higher temperatures and to more extreme temperature events (Fig. 1.2b). The overall rise in temperature and increase in internal variability amplify each other and lead to much higher temperatures and more extreme temperature events (Fig. 1.2c).

(a)

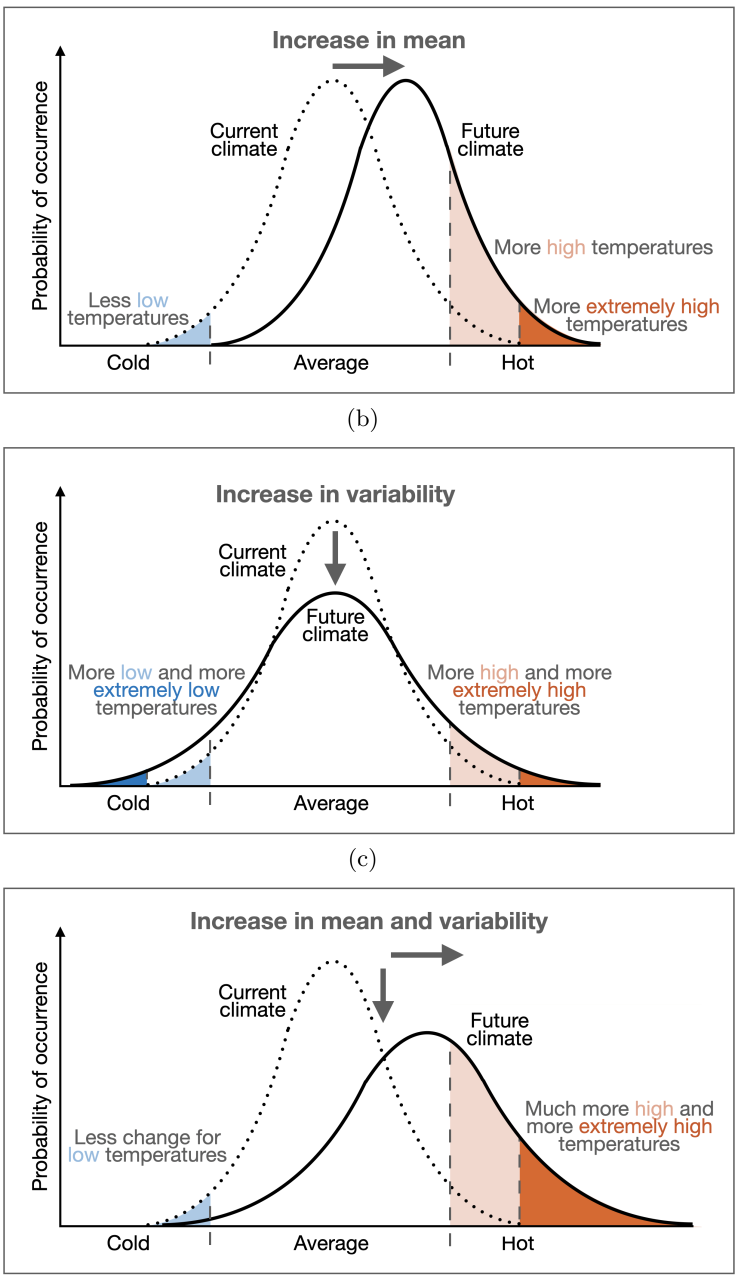

Figure 1.2: Increase in frequency and intensity of European summer heat extremes. (a) Increase in mean. (b) Increase in variability. (c) Increase in mean and variability. (Adapted from McMichael et al., 2001.)

On time scales of days to several weeks, the main drivers of extreme heat are soil moisture deficits and moisture-temperature feedbacks (Seneviratne et al., 2006; Fischer and Schär, 2008; Vogel et al., 2017; Suarez-Gutierrez et al., 2020a), diabatic heating, adiabatic compression and advection (Röthlisberger and Papritz, 2023), and large-scale atmospheric patterns such as atmospheric blocking and the North Atlantic Oscillation (Meehl and Tebaldi, 2004; Horton et al., 2015; Li et al., 2020; Suarez-Gutierrez et al., 2020a). However, these short-term drivers of extreme temperatures can be influenced and conditioned by mechanisms operating on longer time scales.

In the context of climate variability, mechanisms with long-term memory play a crucial role. On sub-decadal timescales, one such mechanism involves the heat inertia in the North Atlantic Ocean, which includes the ocean's ability to store heat and delay its eventual transfer and release. Some studies have examined various ocean-related quantities and processes, which consistently point to a so called forced damped oscillation: a positive feedback between the North Atlantic Ocean and the atmosphere, together with a delayed negative dynamical feedback of the North Atlantic Ocean (Czaja and Marshall, 2001; Eden and Greatbatch, 2003; Reintges et al., 2016; Martin et al., 2019). Moreover, this negative delayed feedback is linked to water mass redistributions in the North Atlantic Ocean on (sub-)decadal time scales. Additionally, studies have highlighted the far-reaching impact of ocean heat inertia on the variability of mean summer temperatures (e.g. Borchert et al., 2019).

Other long-term mechanisms, such as the Atlantic multi-decadal variability (AMV; Cassou et al., 2005; Hodson et al., 2010; Sutton and Dong, 2012; Ghosh et al., 2016; Gao et al., 2019; Qasmi et al., 2021; Ruprich-Robert et al., 2021) and the El-Nino Southern Oscillation (ENSO; Zhou and Wu, 2016; Luo and Lau, 2020; Martija-Díez et al., 2021; Maidens and Knight, 2023), also play significant roles in influencing extreme heat events. During positive phases of the AMV, surface temperatures in the North Atlantic are higher than the long-term average, this can lead to warm air masses being transported from the oceans towards Europe. In such cases, heat extremes may increase during the summer, as warm and dry conditions increase the likelihood of high temperatures. During positive phases of ENSO, so-called El-Niño, the sea surface temperature in the tropical Pacific is increased. This can lead to changes in the global jet stream and thus has an impact on atmospheric circulation. In Europe, this can lead to an increased likelihood of warmer summers, favouring heat extremes (e.g. Zhou and Wu, 2016; Martija-Díez et al., 2021). Thus, these longer-term patterns can have far-reaching effects on the climate system, affecting both extreme temperatures and their drivers over extended periods.

In summary, the emergence of heat extremes is a complex interplay of different factors on various timescales, from natural climate variability to human activities such as greenhouse gas emissions. Taking these different drivers into account is crucial for better long-term predictions of those heat extremes.

1.3 NEAR-TERM CLIMATE PREDICTIONS

From Weather to Climate Predictions
- The Importance of Sub-Decadal Time Scales

Weather forecasts have become an essential part of our everyday lives. They provide us with valuable information about short-term weather conditions and allow us to better plan our day. Weather forecasts are often direct deterministic forecasts because they attempt to predict future weather conditions based on physical laws and mathematical models. These forecasts are based on current observations and numerical weather models. Usually weather forecasts reach up to 14 days into the future (Palmer and Hagedorn, 2006; Fig. 1.3).

In contrast, climate projections deal with long-term climate trends and patterns that occur over longer periods of time. Here, the focus is not on the weather on a particular day, but on the development of climate statistics over years, seasons, decades, or even centuries. Thus, climate projections are also based on physical models, but more dependent on external boundary conditions than on the current observations at the start of the model run. Climate projections are crucial in understanding and preparing for the impacts of climate change (Palmer and Hagedorn, 2006; Fig. 1.3).

The response timescales of the climate system describe the speed at which the climate responds to external forcings (Meehl et al., 2021; Fig. 1.3). Some of these timescales are relatively short and are thus relevant for weather predictions, while others are very long and thus relevant for climate projections. For example, the land surface temperature and the troposphere respond quickly to changes in solar radiation or greenhouse gas concentrations, while the ocean temperature, especially in deep layers, and the ice mass changes can take decades or even centuries to show a full response.

Unlike climate projections, near-term climate predictions, such as on decadal time scales with 5-10 years lead time, include elements of classical weather forecasting (for example deterministic forecasts by initialized dynamical models) but on much longer time scales and thereby considering changes in the boundary conditions (e.g. external forcings, slower climate components, etc.). Decadal predictions close the gap between initial conditions and external forcing (Boer et al., 2016) and cover periods from a few up to ten years (Fig. 1.3). In the last two decades, decadal climate prediction has transformed from a groundbreaking pursuit led by a limited number of modeling groups to an established and widely embraced discipline within the scientific community (Smith et al., 2007; Keenlyside et al., 2008; Pohlmann et al., 2009). The MiKlip project (Mittelfristige Klimavorhersagen) established one of the first global decadal prediction systems under CMIP5 forcing, using the Max Planck Institute Earth System Model (MPI-ESM; Marotzke et al. (2016). This prediction system is also used by the German national weather service (DWD) for operational near-term climate predictions. Furthermore, other earth system models contributing to the Coupled Model Intercomparison Project phases 5 and 6 (CMIP5 and CMIP6) have been shown to be valuable for skillful decadal predictions (e.g. Doblas-Reyes et al., 2013; Delgado-Torres et al., 2022). Previous studies have examined the North Atlantic as one of the key regions for decadal climate predictions with striking prediction skill for various parameters, such as for the AMOC strength (Matei et al., 2012), the North Atlantic sea surface temperatures (Pohlmann et al., 2009; Kröger et al., 2012), and Atlantic tropical cyclones (Dunstone and Smith, 2010; Smith et al., 2010).

The understanding of the interaction between the atmosphere and the ocean is crucial for predictions on decadal time scales. Significant climatic variations can occur on these time scales, affecting agriculture, water availability, natural disasters, and other aspects of our lives. Forecasts on decadal time scales thus help to improve risk management in various sectors, support economic decisions and promote the well-being of society as a whole several years in advance. They enable us to understand and respond to short-term climatic changes, leading to better adaptive resilience to changing climate conditions in the long term. This requires complex climate models that can adequately capture these decadal time scales and sophisticated simulations that take into account both atmospheric and oceanic processes and the interactions between them.

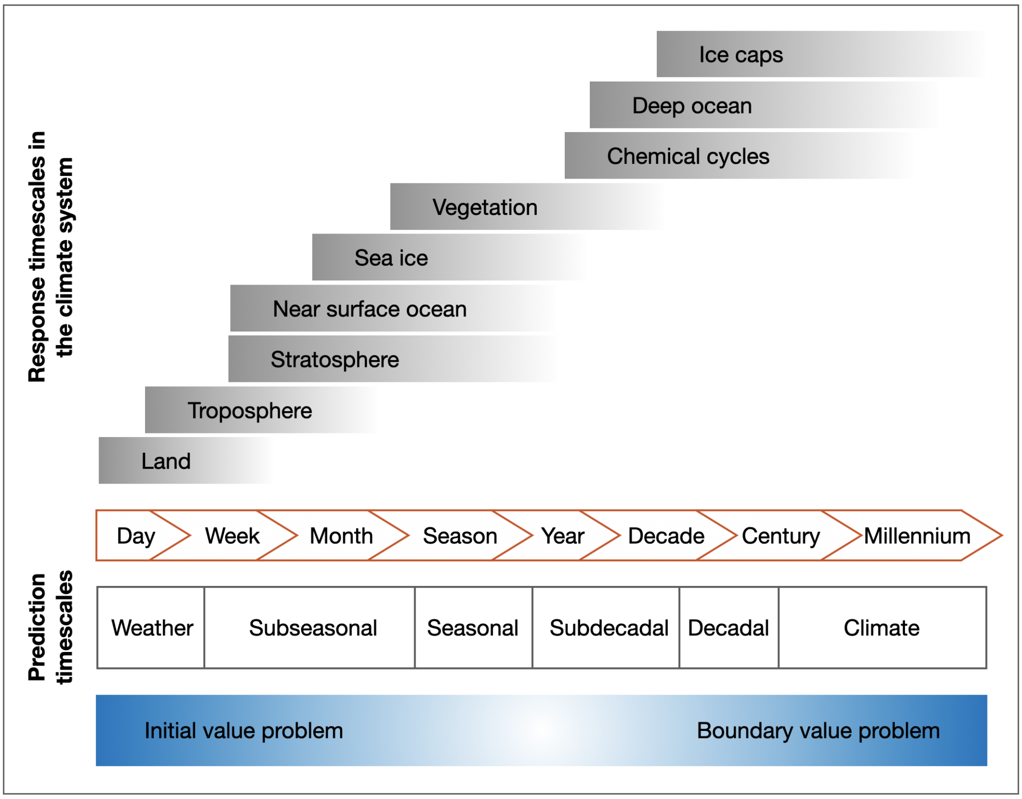

Figure 1.3: From weather to climate - Response time scales of the climate system and their prediction time scales. (Adapted from Meehl et al., 2021.)

Representation of Heat Extremes in Climate Models

Initialized climate prediction models require initial conditions about the coupled state of the climate (between ocean and atmosphere), and other relevant relevant parameters. However, due to measurement inaccuracies or missing data, these initial conditions can never be specified with complete accuracy. Since the atmosphere is a deterministic-chaotic system, small deviations in the initial conditions can lead to significant differences in the predictions (Lorenz, 1963).

To overcome these challenges, ensemble forecasts are often used for climate predictions (Gneiting and Raftery, 2005). This involves not only one single prediction, but several predictions with slightly varying initial conditions that are assumed to be equally likely (Fig. 1.4, orange lines). One possible method for evaluating ensemble members is by its ensemble mean, where the average overall individual predictions is considered (Fig. 1.4, blue line). However, with this method predictions usually become overconfident and therefore cannot represent the tails of the distribution, which means the extremes (Fig. 1.4, blue distribution).

An alternative option is to look at the ensemble members individually to better capture extreme events (Fig. 1.4, orange distribution). Since extreme events are rare, it is important to have a large enough number of ensemble members to achieve a large enough sample size. In fact, a large sample size is needed to increase the likelihood that certain members show an extreme.

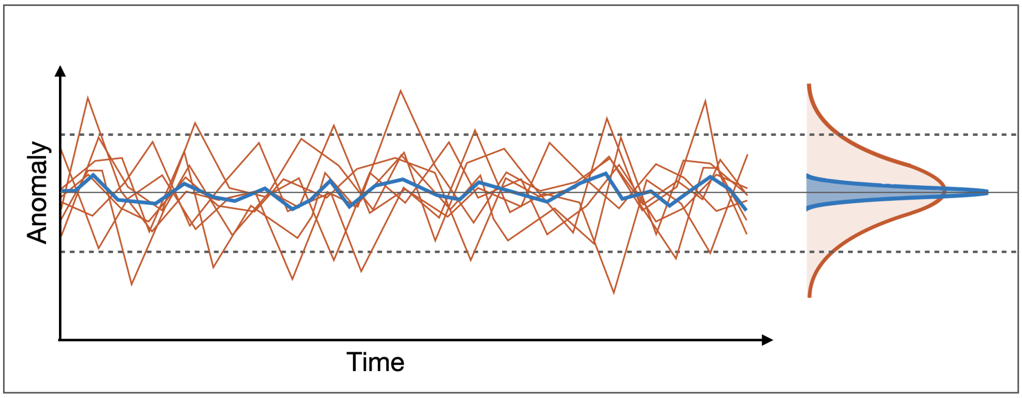

Figure 1.4: Illustration of an ensemble mean forecast (blue line) and forecasts of individual ensemble members (orange lines) and their associated probability distribution functions (PDFs).

One possibility to further increase the ensemble size is to use the ensemble members of several different models. These so-called "multi-model ensembles" potentially may allow for better understanding of the underlying mechanisms (Krishnamurti et al., 2000). However, the disadvantage is that inherent biases and different representations of the ocean-atmosphere mechanisms and interactions between the particular models are ignored, thereby decreasing the robustness of any drawn conclusions.

Another possibility is to select ensemble members based on specific criteria, such as their multiyear evolution or their ability to simulate specific atmospheric patterns. Selecting ensemble members this way is called "ensemble subsampling". This approach shows that also a decrease in ensemble members can lead to improvements in the representation of a certain process or to an improvement of prediction skill. Climate models underestimate the predictable signal (the actual representation of real-world processes in the model) compared to the unpredictable noise (internal variability) (signal-to-noise paradox; Scaife and Smith, 2018; Smith et al., 2020). Therefore, ensemble subsampling is, via the selection of ensemble members best representing the climate processes, a method of amplifying signal and reducing noise. Several studies, for example those of Dobrynin et al. (2018), Neddermann et al. (2019), and Carvalho-Oliveira et al. (2022) have already proved the power of a reduced ensemble for an improvement in prediction skill.

How does my research contribute?

As discussed in Section 1.2, the internal variability of European summer temperatures has already been linked to various mechanisms on seasonal to sub-and multi-decadal timescales. While local drivers such as atmospheric or surface conditions have been thoroughly investigated in terms of their impact on extreme events and variability, larger-scale drivers like the influence of the North Atlantic Ocean, which can act over more extended time periods, such as on sub-decadal timescales, are relatively understudied. Therefore, I analyze how extremely warm summers are affected by North Atlantic Ocean heat accumulation, as well as the influence of this driver on the prediction skill of European summer temperatures.

I investigate first whether the model can represent sub-decadal temperature variability and analyze the dominance of this time scale over Europe and its connection to European extreme temperatures. Additionally, I identify which processes in the North Atlantic Ocean lead to the occurrence of extremely warm summers. To address the research objectives, the following first two research questions have been formulated:

➜ **How is the sub-decadal variability of European summer heat extremes captured in the MPI-GE compared to observations? (Chapter 2 and Appendix A)**

➜ **Which mechanisms drive sub-decadal European summer temperatures and heat extremes? (Chapter 2 and Appendix A)**

To answer these research questions, I employ the 100-member Max-Planck-Institute Grand Ensemble (MPI-GE; Maher et al., 2019). With its extensive ensemble size and the wide time span it facilitates a comprehensive investigation and evaluation of the occurrence and intensity of rare events. The MPI-GE simulations were performed with MPI-ESM 1.1 in the low-resolution configuration (MPI-ESM-LR; Mauritsen et al., 2012; Giorgetta et al., 2013). This comprehensive, fully coupled climate model constitutes 100 simulations with distinct initial conditions, making it one of the most extensive ensembles of its kind. Here, I utilize monthly data averaged to seasonal summer means for June, July, and August (JJA) from 1950 to 2022. My used dataset comprises historical simulations from 1950 to 2005, as well as simulations under the RCP4.5 scenario up to 2022.

As discussed in Section 1.1, an improved understanding of the driving mechanisms of heat extremes might be used for better predictions of these extremely warm temperatures and thus would allow for timely warnings to protect and adapt human health, agriculture, and infrastructure for extreme weather. Thus, motivated by the results of Chapter 2, I turn to investigate if the accumulation of heat in the North Atlantic Ocean can be used to improve the prediction skill of extremely warm European summers, leading to my third research question:

➜ **Can the mechanisms driving sub-decadal variability be used to improve the forecast skill of European summer temperatures via selecting specific ensemble members? And if so, is such an ensemble selection operationally usable? (Chapter 3 and Appendix B)**

Based on the process identified in Chapter 2 and Appendix A, I introduce a specific ensemble selection and test the performance of this selected ensemble mean compared to the full ensemble mean. I then apply the ensemble selection, which is based on sub-decadal processes, to the occurrence of extremely warm summer days per year, thereby leaving the sub-decadal time-scales. In the end, I analyze the contribution of the introduced ensemble selection to the prediction skill of the extremely warm European June of 2023 within a case study.

To analyze the prediction skill of extremely warm summers, I employ an initialized decadal hindcast ensemble based on the coupled Max-Planck-Institute Earth-System-Model (decadal hindcast; Brune and Baehr, 2020) for this second part of my dissertation. To verify my results, I use global reanalysis data from ERA5 for atmospheric variables (Hersbach et al., 2018) and ORAS5 for oceanic variables (Zuo et al., 2019). Like MPI-GE, the decadal hindcast is also conducted using the low-resolution setup. For this hindcast ensemble, 80 ensemble members of hindcasts were initialized every 1st November between 1960 and 2019 from an assimilation experiment. Similar to the approach used in the first part, I rely on monthly data averaged to seasonal summer values for June, July, and August (JJA).

EXTREMELY WARM EUROPEAN SUMMERS PRECEDED BY NORTH ATLANTIC HEAT ACCUMULATION 2

"Insight must precede application."

— Max Planck

To quote Max Planck, *insight* and understanding of mechanisms *precedes* their possible *application*. In this first part of my dissertation, I therefore investigate how the previously mentioned forced damped oscillation in the North Atlantic Ocean acts on extremely warm European summers over longer periods (5-10 years) (Appendix A). To reliably capture the frequency and strength of such rare events as extremely warm summers, large samples are required. Hence, I use one of the largest ensembles of a comprehensive, fully coupled Earth system model currently available: the MPI-GE.

2.1 SUB-DECADAL VARIABILITY OF EXTREMELY WARM EUROPEAN SUMMERS

The first goal of this dissertation is to determine how the sub-decadal variability of extremely warm European summers is captured in MPI-GE compared to observations. Therefore, I use a cross-spectral analysis, based on a multi-taper method to analyze where the MPI-GE can represent which time scales well (Årthun et al., 2018). The multi-taper method is a spectral analytical technique used to assess the dominant time frequency of a time series. This is done by decomposing the data into a series of orthogonal tapers to calculate a set of spectral estimates. The dominant time frequency is then identified as the highest spectral peak or mode in the resulting spectrum. Here, I apply the multi-taper method to all 100 ensemble members and take the average over all spectra for each grid point to determine the dominant time scale.

I found that the sub-decadal time scale of 5-10 years is the dominant time scale of variability of European summer temperature including large parts of Central Europe, Eastern Europe, Scandinavia, and the Iberian Peninsula (Fig. 2.1a). However, the MPI-GE shows some limitations in the representation of decadal time scales (10-20 years) for which only a few grid points are dominant. For multi-decadal time scales (>20 years) even fewer grid points are dominant.

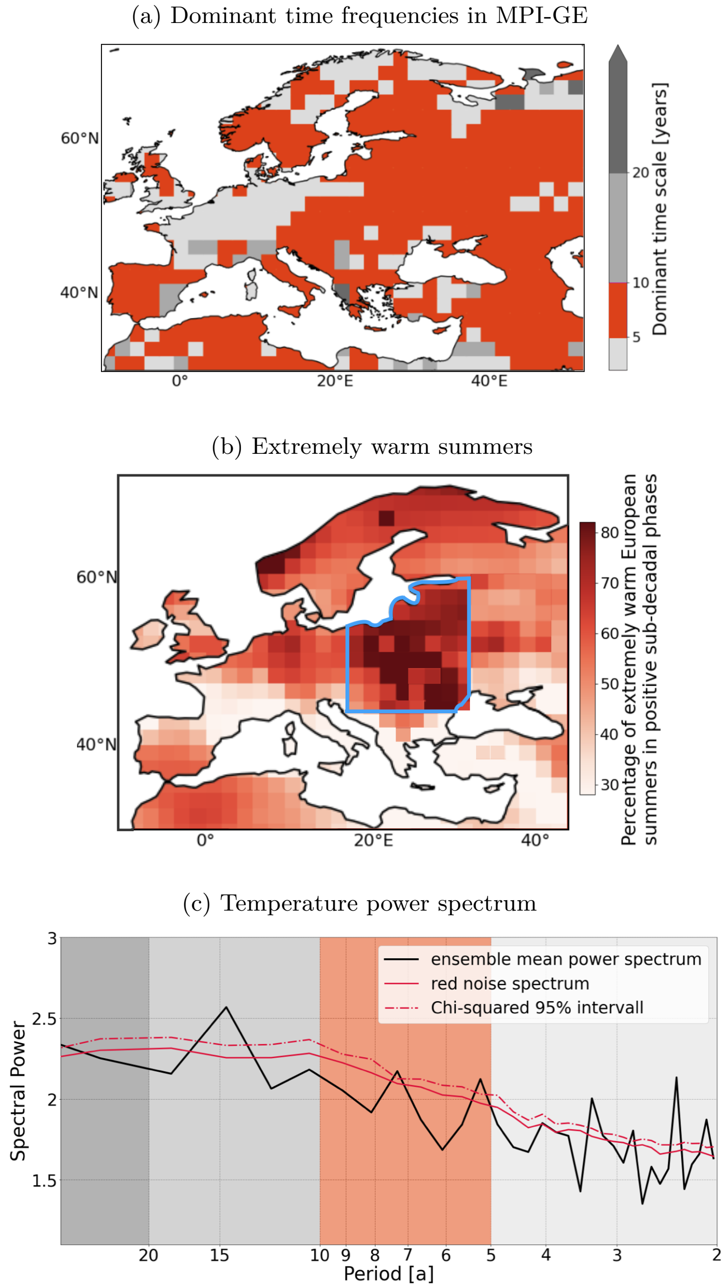

Figure 2.1: Heat extremes in MPI-GE. (a) Dominant time scales of European surface air temperature variability, (b) percentage of all extremely warm European summers occurring on sub-decadal time scales, and (c) Power spectrum of Central European surface air temperature in MPI-GE. Period 1950-2022. (Adapted from Appendix A Fig. A.1.)

Additionally, I set this result into perspective to sub-decadal warm phases of European summer temperatures. Therefore, I investigate where most extremely warm European summers (JJA T > 90th percentile) occur in a positive sub-decadal temperature phase ($T_{\text{5-10 year variability}}$ > 90th percentile). I find that extremely warm European summers tend to occur in 5-10 year phases of abnormally warm temperatures over large parts of Central and Eastern Europe (Fig. 2.1b).

The strongest correlation between the dominant sub-decadal pattern and the occurrence of extremely warm European summers is over Central Europe. This finding makes up my focus area for my further investigations within this first part of my dissertation, referred to as Central Europe (15°-35°E; 45°-60°N; Fig. 2.1b, blue box). A spectral analysis of surface air temperature for the spatial mean of this box shows that the temperature in this region is also mainly influenced by these sub-decadal time scales, which is consistent with the results in Fig. 2.1a (Fig. 2.1c). Similarly, there are two significant peaks within the sub-decadal time scales. In addition, there are further peaks in time periods of two to three years and about 15 years, indicating the possible involvement of other influencing factors and mechanisms on shorter as well as longer time scales

Overall, this first part of my analysis identifies 5-10 year sub-decadal variability as the dominant time scale of European summer temperatures, notably impacting Central Europe. This connection, which becomes particularly clear in connection with the occurrence of extremely warm summers, directs the dissertation's focal point.

2.2 MECHANISMS DRIVING SUB-DECADAL VARIABILITY AND THEIR INFLUENCE TO EXTREMELY WARM EUROPEAN SUMMERS

After demonstrating that sub-decadal timescales are the dominant source of variability over Central Europe, I want to find their driving mechanism. I start with my investigation for potential drivers in the North Atlantic region, since the North Atlantic Ocean has a profound impact on weather and climate over Europe (Cassou et al., 2005; Sutton and Dong, 2012) and since for sub-decadal processes the memory for several years is more likely to reside in the ocean than in in the atmosphere (Rhein et al., 2013). I analyze the behaviour of several variables that characterize the North Atlantic Ocean heat content variability during extremely warm European summers as well as several years prior to their occurrence to further understand the simultaneous occurrence and the drivers of sub-decadal variability and extremely warm European summers.

Here, I found that the North Atlantic Ocean heat accumulation prescribes the occurrence of extremely warm summers over Central Europe on sub-decadal timescales (Appendix A Fig. A.2 and Fig. A.3). In detail: Three years prior to extremely warm European summers ocean heat content starts to increase and accumulates heat along the North Atlantic current around 40°N (Fig. 2.2, first globe). Two to one year prior to extremely warm European summers this heat accumulation further intensifies and the North Atlantic current starts to shift northwards, resulting in warm suptropical water reaching higher latitudes. Here, high anomalies of the ocean heat transport, which affect the ocean heat content, lead to alterations in the temperature gradients between the ocean and atmosphere and affecting the ocean-atmosphere heat flux (Fig. 2.2, second and third globe). During extremely warm European summers this accumulated heat is released mainly through the subpolar gyre ocean heat transport to the atmosphere, leading to an increased ocean-atmosphere heat flux. The released heat causes then an above-average warming of the atmosphere reaching even high altitudes (Appendix A Fig. A.4a). This warming of the atmosphere leads via the jet stream displacement and enhanced atmospheric blocking conditions to extremely warm European summers (Fig. 2.2, fourth globe (Appendix A Fig. A.4b)).

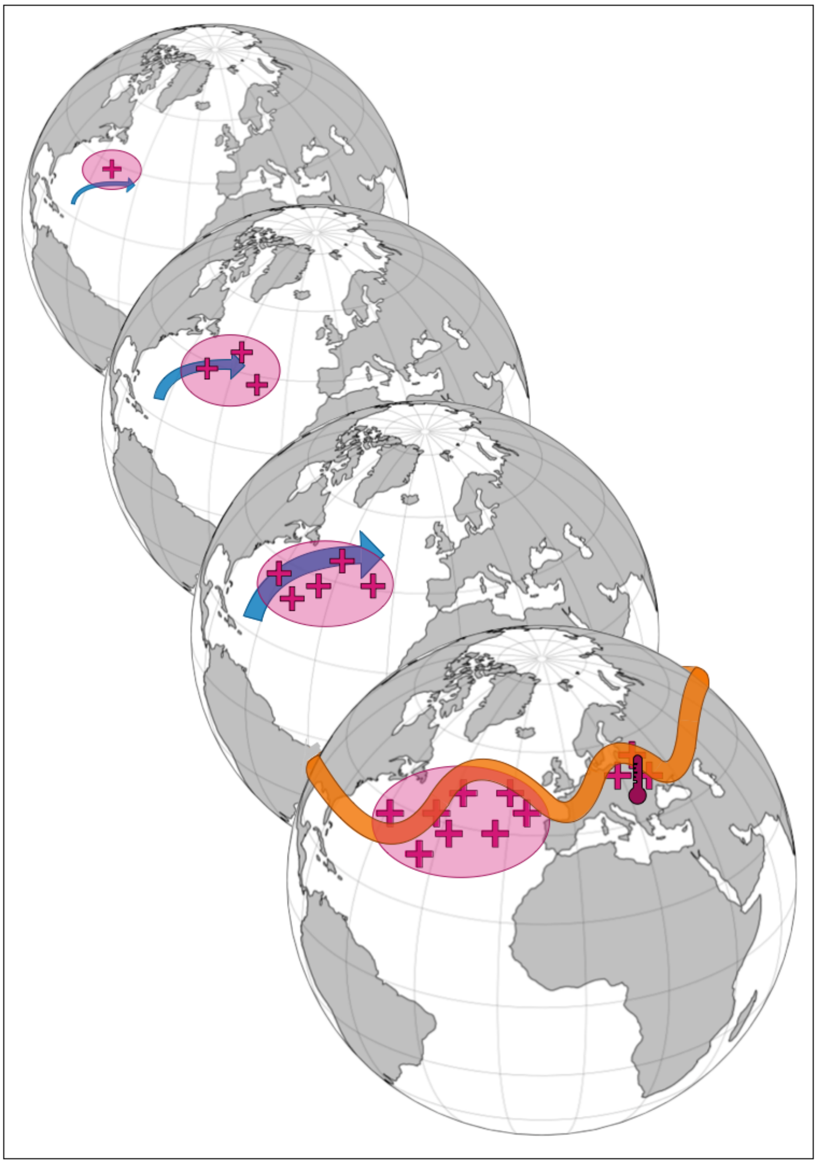

Figure 2.2: Schematic sketch illustrating the accumulation of heat in the North Atlantic Ocean. The blue arrows the increasing North Atlantic current, the pink crosses the increasing ocean heat content and accumulation of heat, and the orange belt the jet stream. The thermometer at lag 0 illustrates the extremely warm European summers. (Adapted from Appendix A Fig. A.5.)

IMPROVED PREDICTION SKILL OF EXTREMELY WARM EUROPEAN SUMMERS

3

"Prediction is very difficult, especially if it's about the future."

— Niels Bohr

In Chapter 2 (Appendix A) I found that the heat accumulation in the North Atlantic Ocean prescribes the occurrence of extremely warm summers over Central Europe on sub-decadal timescales. Now I use this finding to improve the prediction skill of extremely warm European summers with a decadal hindcast ensemble (Appendix B).

3.1 THE POWER OF ENSEMBLE SELECTION

Motivated by the previous results, I now develop a powerful tool for selecting ensemble members based on whether they capture sub-decadal processes in the North Atlantic coupled climate system to enhance the prediction skill of extremely warm European summers. In the following, I select only ensemble members that can correctly represent the previously found mechanism. In detail I choose those ensemble members that show a change in the anomalies of the barotropic stream function along the North Atlantic current, alternating from negative to positive anomalies over four years and show positive sea level pressure anomalies over Scandinavia (Fig. 3.1).

The initial condition is determined in year 0 via an assimilation; if this shows negative anomalies for the barotropic stream function, only the members that show a less negative barotropic stream function anomalies are selected for the prediction in the following year. For the prediction years 2 and 3, only those members are selected that show increasing positive anomalies of the barotropic stream function. In addition, positive mean sea level pressure anomalies over Scandinavia must be identified in prediction year 3. In this type of ensemble selection, ensemble members that do not reflect this mechanism are therefore discarded. For years in which less than 10 members are selected by this strict selection, the mean over the entire ensemble is used instead (full ensemble mean). Doing this for every year, I produce an ensemble selection, meaning fewer selected ensemble members, for some years (selected ensemble mean). This selection reflects the mechanism found in Appendix A.

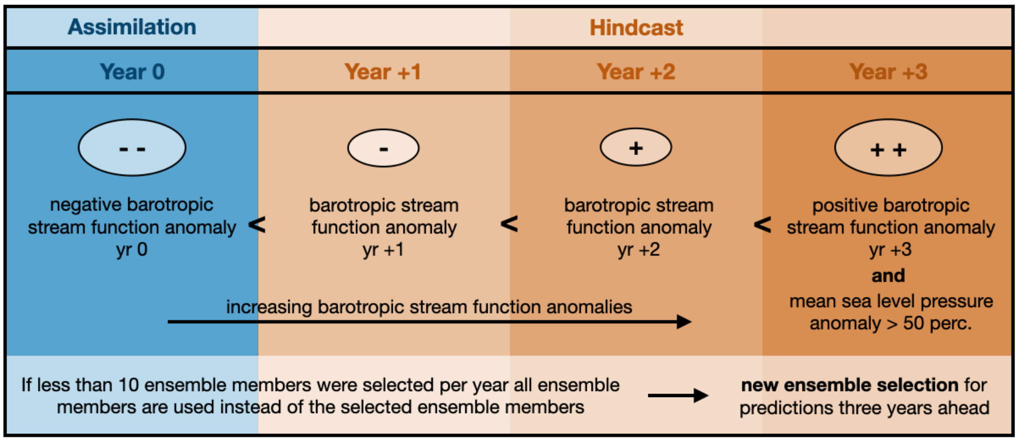

Figure 3.1: Ensemble selection and attached mechanism for Central European temperature predictions. (Prediction from November year 0 for summer year +3.) (Adapted from Appendix B Fig. B.2.)

Furthermore, I could verify the connection between oceanic anomalies and extremely warm summers by analyzing barotropic stream function anomalies at different time lags. The selected ensemble members exhibit patterns consistent with the described mechanism, highlighting the relevance of sub-decadal North Atlantic heat accumulation for the occurrence of extremely warm European summers (Appendix B Fig. B.4 and Fig. B.5).

Anomaly correlation coefficients (ACCs) for lead year +3 predictions of the surface air temperature between the full ensemble mean and ERA5 and between the selected ensemble mean and ERA5 provide information about the change in prediction skill through the ensemble selection (Appendix B Fig. B.3). Here, we find that the correlation coefficient over Central Europe increases significantly from the full to the selected ensemble mean (Fig. 3.2a). Furthermore, the spatial mean of Central European surface temperatures shows that the amplitudes of the selected ensemble mean are much closer to the high temperatures in ERA5 compared to the full ensemble mean (Fig. 3.2b). In total, the selected ensemble mean leads to an improvement of 9 phases (13 years) of sub-decadal temperature variations over Central Europe.

My results show that the new ensemble selection yields better representation and prediction skill of sub-decadal temperature variations over Central Europe, underscoring the effectiveness of the approach in forecasting extremely warm summers.

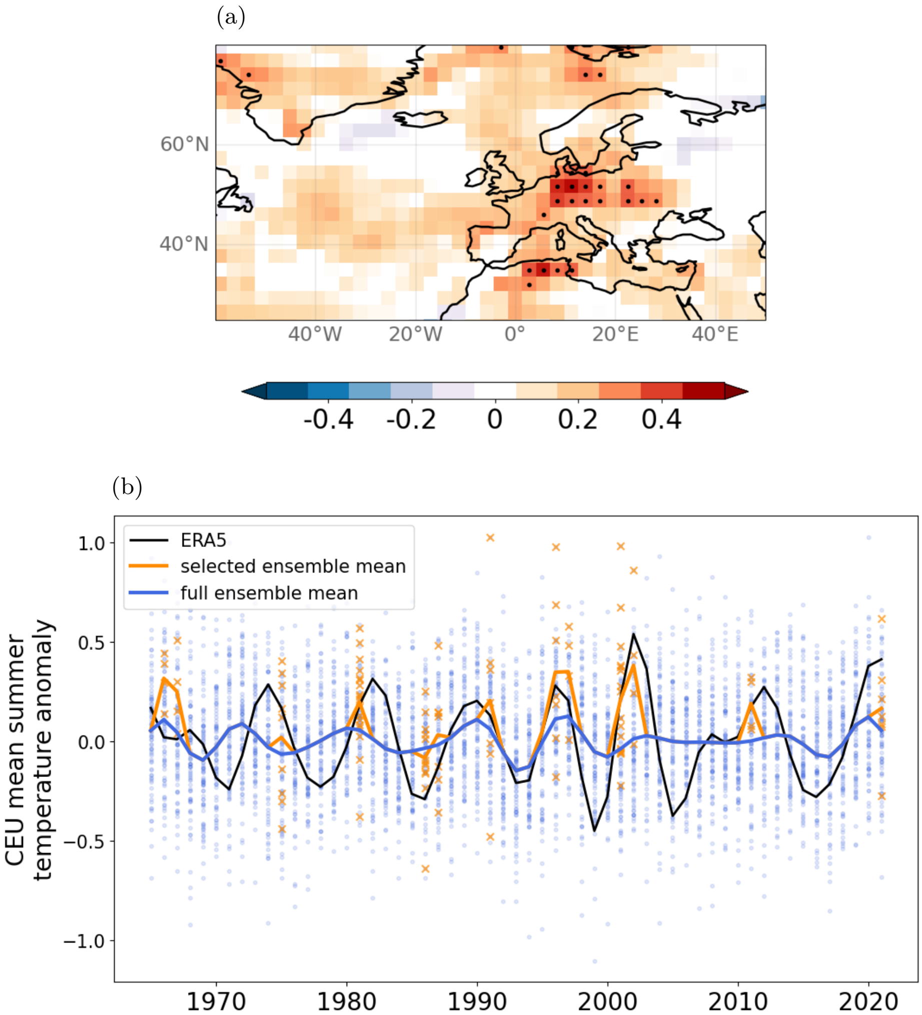

Figure 3.2: Representation of extremely warm European summers. (a) Anomaly correlation coefficient (ACC) of 5-10yr bandpass-filtered surface air temperature for lead year 3 showing the difference between the full ensemble mean and ERA5. Crosses represent significant changes at a 95% confidence level. (b) Anomaly of 5-10yr bandpass-filtered Central European summer surface air temperature for lead year +3 for ERA5 (black) and the hindcast ensemble mean (blue) and ensemble selection (orange). The single (selected) ensemble members are marked through dots (crosses).Period 1964-2021. (Adapted from Appendix B Fig. B.3.)

3.2 LEAVING THE SUB-DECADAL TIME SCALES

The results shown previously demonstrate that selecting ensemble members based on sub-decadal processes in the North Atlantic coupled climate system can increase the prediction skill of extremely warm European summers on sub-decadal time scales. I investigate now whether this ensemble member selection also improves the total number of correctly predicted hot summer days per summer, thereby applying the sub-decadal framework to individual years.

Here, hot summer days are considered to be days whose daily mean temperature exceeds 20°C (T>20°C). When comparing the number of these hot summer days between ERA5 and the full ensemble mean, I found that the full ensemble mean shows too little variability and thus cannot approximate the values of ERA5 (Fig. 3.3, blue bars). While the timing is correct for many years, the amplitude of the number of hot summer days is much too weak for the full ensemble mean. However, the selected ensemble mean can improve this amplitude for several years, so that in total the number of hot summer days is better represented compared to the full ensemble mean (Fig. 3.3, orange bars). Overall, there is an improvement in the prediction of the percentage of hot summer days in 15 years, only 3 years show an erroneous deterioration (the remaining 39 years show no change at all). This improvement in the prediction of the number of hot summer days is found in almost all years where both the corresponding positive sub-decadal temperature fluctuations and the extremes of the non-bandpass filtered temperature time series are in agreement (Fig. 3.3, time series). This analysis again shows that our ensemble selection identified ensemble members that are closer to the reanalysis than the full ensemble mean.

In summary, the ensemble selection approach shows improvements in predicting the total number of hot summer days and reproducing the amplitude and variability of these events compared to the ERA5 reanalysis. Ensemble selection performs better than the ensemble mean, suggesting that it is effective in capturing extreme heat events not only in the band-pass filtered, sub-decadal world.

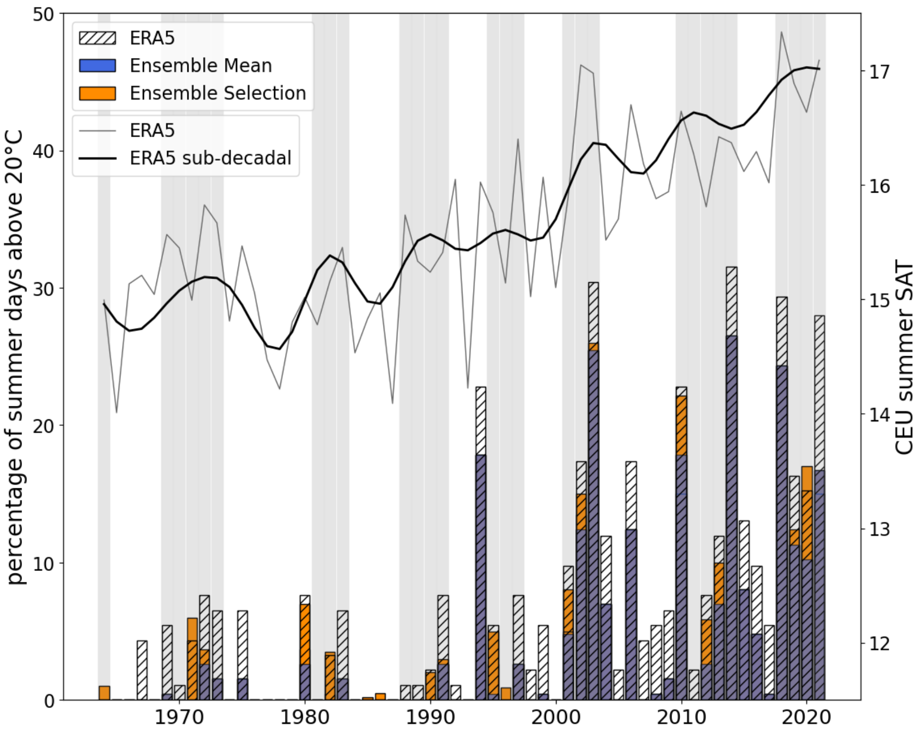

Figure 3.3: Extremes on non-sub-decadal time scales. a) Percentage of CEU summer days above 20°C for ERA5 (dashed bars), the full ensemble mean (blue bars), and the selected ensemble mean (orange bars) together with the ERA5 CEU temperature time series (grey) and the 5-10 year bandpass-filtered CEU temperature time series. The hindcast data are bias-corrected with ERA5 as reference. Grey shading of the background indicates positive bandpass-filtered phases within the detrended time series. Period 1964-2021. (Adapted from Appendix B Fig. B.6.)

4 CASE STUDY JUNE 2023

"Science is magic that works."

— Kurt Vonnegut

I now apply the identified mechanism (Chapter 2) and the resulting new ensemble selection (Chapter 3) to one of the most recent European heat waves, which caused the extremely warm June 2023. This case study is intended to answer the question of whether I could have predicted the above-average temperatures of June 2023 better at the beginning of my PhD three years ago with the knowledge that I have gathered in the context of this dissertation.

4.1 CONDITIONS IN JUNE 2023

In early summer 2023, sea surface temperatures (SSTs) in the Atlantic Ocean reached unprecedented levels. For instance, North Atlantic SST anomalies showed deviations of up to 5°C in June (Copernicus Climate Change Service (C3S); Fig. 4.1a). But not only the SST anomalies in the North Atlantic Ocean were particularly high, at the same time high surface temperature deviations occurred over Western- and Central Europe, as well as over southern Scandinavia. These anomalies were highest, with up to 4°C above the long-term average in France, the Netherlands, Belgium, and Germany (Fig. 4.1b).

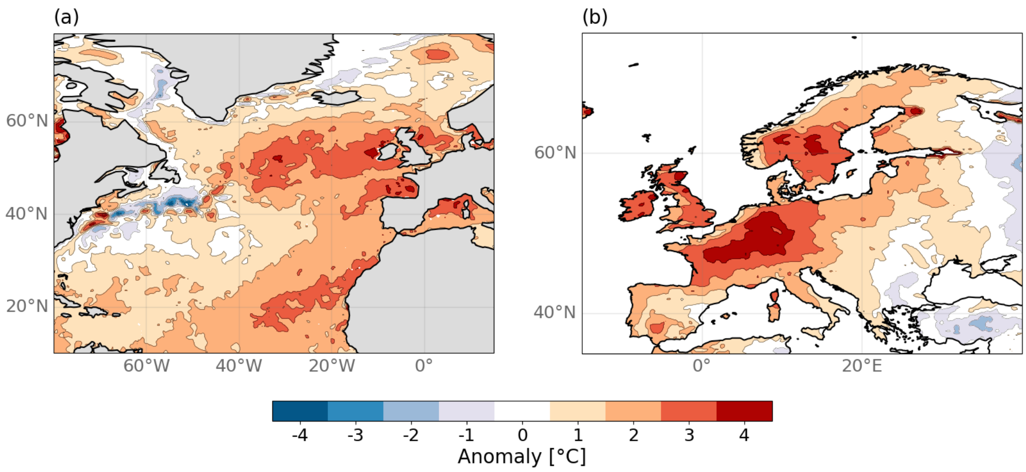

Figure 4.1: Case study (a) SST anomalies and (b) TAS anomalies for June 2023. ERA5.

4.2 THE YEARS BEFORE

This case study analyzes now how far these extreme SST anomalies are related to the mechanism found in Appendix A, i.e. how far an accumulation of heat in the North Atlantic precedes these SST anomalies and leads to the extremely warm European June 2023.

To investigate this question, I analyzed the heat content of the North Atlantic Ocean for up to 3 years prior to June 2023, meaning for the summers 2020, 2021, 2022, and 2023 itself. Here, I can indeed detect an accumulation of heat over time (Fig. 4.2a). As in my previous results, the accumulation of heat starts along the North Atlantic current around 40°N and then intensifies and extents also to higher latitudes (Fig. 4.2b). This result is not only found in ORAS5 and MPI-GE, but also in the selected ensemble members of the hindcast. In addition, the increased ocean-atmosphere heat flux and the positive SLP anomalies over Scandinavia associated with the mechanism can also be found in ERA5 for June 2023.

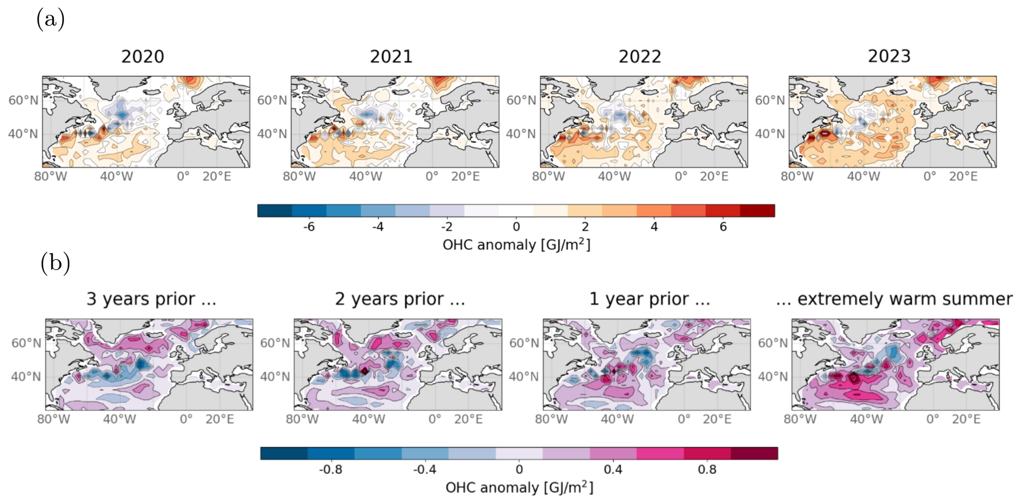

Figure 4.2: Heat accumulation. Ocean heat content anomalies for different lags prior (a) June 2023 in ERA5 and (b) extremely warm summers in general in MPI-GE for 1950-2022. ((b) adapted from Appendix A Fig. A.3.)

4.3 COULD WE HAVE KNOWN IT BETTER?

Having all of this in mind, the question arises whether the extremely warm summer of 2023 could have been better predicted already in 2020 with the help of the ensemble selection method presented previously.

The prediction of 2020 for the surface temperature of June 2023 shows little variability in the full ensemble mean, the temperature anomalies show a zonal structure with overall only small values (Fig. 4.3a). This suggests that the ensemble mean agreed that June 2023 would be a fairly unremarkable month in terms of temperature anomalies. Whereas the 2020 forecast for summer 2023 with the selected ensemble mean shows anomalies of over one degree over France and the Netherlands, indicating a shift towards positive temperature anomalies compared to the ensemble mean (Fig. 4.3b). Therefore, the anomalies of the selected ensemble mean show the same pattern as in ERA5 (see Fig. 4.1b). However, the intensity of the anomalies remains a quarter under the values found in ERA5.

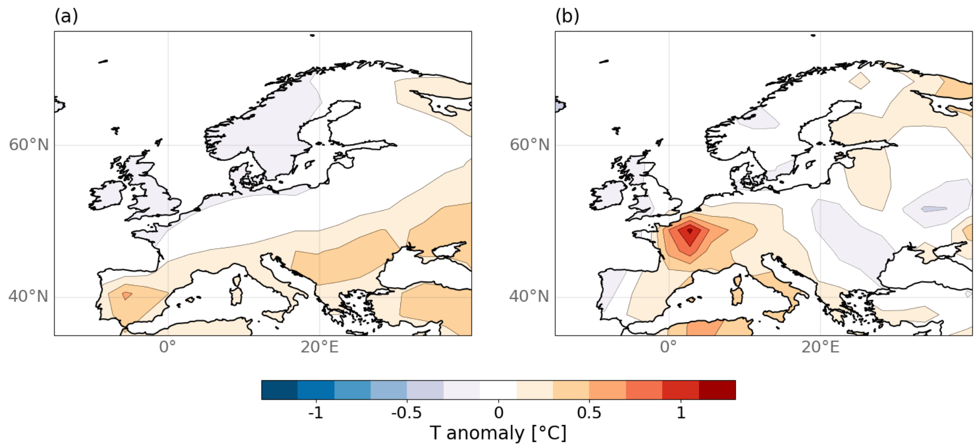

Figure 4.3: Predicted TAS anomalies for June 2023 (lead year +3) for (a) full ensemble mean and (b) selected ensemble mean. Decadal hindcast.

This case study shows that at least the extremely warm June of 2023 could have been better predicted three years ago with the selection of ensemble members presented in this dissertation. However, at the time of this case study, data was only available for June 2023, and the extension of this analysis to the entire summer (JJA) is still pending.

The results presented here underline once again the important role of heat accumulation in the North Atlantic for extremely warm summers; it shows impressively how our understanding of the interaction between ocean and atmosphere can have a direct impact on our daily life.

5 SUMMARY AND CONCLUSIONS

"The important thing is not to stop questioning."

— Albert Einstein

Overall, this dissertation presents a comprehensive analysis of the sub-decadal processes driving extremely warm summers over Central Europe in the context of the North Atlantic coupled climate system. To be more precise I want to provide short summarizing answers to my research questions:

How is the sub-decadal variability of European summer heat extremes captured in the MPI-ESM Grand Ensemble compared to observations?

The results reveal that sub-decadal timescales of 5-10 years are the dominant scale of variability in European mean summer temperatures in MPI-GE. Further, extremely warm summers tend to occur in 5-10 year phases of abnormally warm temperatures over Europe over large parts of Central and Eastern Europe. Here, the results highlight the influence of longer-term climate variability on the occurrence of extremely warm European summers. (Chapter 2.1)

Which mechanisms drive sub-decadal European summer temperatures and heat extremes?

Sub-decadal processes in the North Atlantic couled climate system drive the occurrence of extremely warm European summers over Europe. Ocean heat inertia causes a heat content accumulation, which precedes extremely warm European summers by several years. When the accumulated heat is released it influences atmospheric circulation patterns in a way favoring the occurrence of heat extremes over Europe. (Chapter 2.2)

Can the mechanisms driving sub-decadal variability be used to improve the forecast skill of European summer temperatures via selecting only specific ensemble members?

A ensemble selection method based on the mechanisms driving sub-decadal variability, triggering the accumulation of heat content in the North Atlantic, proves to be a powerful tool in improving the prediction skill of sub-decadal temperature variations and extremely warm European summers in MPI-ESM. The selected ensemble members show consistent patterns with the proposed mechanism, indicating again the relevance of sub-decadal North Atlantic heat accumulation in driving extremely warm European summers. The presented way to select the ensemble members is indeed operationally usable (Chapter 3). This result is further confirmed by a case study analyzing the extremely warm European summer of 2023. (Chapter 4)

My results show that positive anomalies of the ocean heat content, associated with the accumulation of heat in the North Atlantic, precede extremely warm European summers. This raises the question of whether a similar mechanism can be found for other seasons. Future work could, for example, investigate whether negative anomalies in the ocean heat content, associated with a heat reduction in the North Atlantic, lead to extremely cold winters.

This study provides a comprehensive understanding of the sub-decadal processes driving extremely warm summers in Europe. The ensemble selection approach offers improved prediction skill and is a valuable tool in forecasting extremely warm summers, suggesting a promising use of the mechanism for improved operational climate predictions. This potential application would need to be further elaborated. By considering the North Atlantic and climate variability, this dissertation offers valuable insights for decision-making and risk management, particularly in the context of increasing heat extremes due to overall rising global temperatures.

The presented work contributes to our understanding of the complex interplay between atmospheric and oceanic conditions. My findings enhance the prediction skill of extremely warm European summers and thus allow timely warnings, evidence-based decision-making, and rapid action. Therefore, I would like to end with the slightly modified words of Marie Curie from the beginning of this dissertation: ***Now where we understand more, we have to fear less.***

APPENDIX A & APPENDIX B

Sub-Decadal Variability of European Summer Heat Extremes

Appendix A

EXTREMELY WARM EUROPEAN SUMMERS PRECEDED BY SUB-DECADAL NORTH ATLANTIC HEAT ACCUMULATION

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Extremely Warm European Summers preceded by Sub-Decadal North Atlantic Heat Accumulation

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ABSTRACT

The internal variability of European summer temperatures has been linked to various mechanisms on seasonal to sub- and multi-decadal timescales. We find that sub-decadal time scales dominate summer temperature variability over large parts of the continent and determine a mechanisms controlling extremely warm summers on sub-decadal time scales. We show that the sub-decadal warm phases of bandpass-filtered European summer temperatures, hereinafter referred to as extremely warm European summers, are related to a strengthening of the North Atlantic ocean subtropical gyre, an increase of meridional heat transport, and an accumulation of ocean heat content in the North Atlantic several years prior to the extreme summer. This ocean warming affects the ocean-atmosphere heat fluxes, leading to a weakening and northward displacement of the jet stream and increased probability of occurrence of high pressure systems over Scandinavia. Thus, our findings link the occurrence of extremely warm European summers to the accumulation of heat in the North Atlantic Ocean, and provide the potential to improve the predictability of extremely warm summers several years ahead which is of great societal interest.

A.1 INTRODUCTION

Extremely warm European summers have an increasingly large societal impact. Extreme temperatures can lead to severe health problems and are thus associated with an increased mortality (Gasparrini et al., 2015; Vicedo-Cabrera et al., 2021). Furthermore, heat extremes can also lead to economic impacts, such as crop failure and water shortages (Ribeiro et al., 2020), along with political challenges, including climate-induced migration and the need for effective crisis management (Ceglar et al., 2019). European summers will become more extreme in a warming climate due to rising mean temperatures (Seneviratne et al., 2021) and also due to an increase in internal temperature variability (Schär et al., 2004; Fischer et al., 2012; Suarez-Gutierrez et al., 2020a). Moreover, when such extreme summers occur repeatedly year after year, they become even more threatening to the already vulnerable socioeconomic and ecological resilience of the region (Ruiter et al., 2020; Callahan and Mankin, 2022).

On time scales of days to several weeks, the main drivers of extreme heat are soil moisture deficits and moisture-temperature feedbacks (**Papritz23**; Seneviratne et al., 2006; Fischer and Schär, 2008; Vogel et al., 2017; Suarez-Gutierrez et al., 2020a) and large-scale atmospheric patterns such as atmospheric blocking and the North Atlantic Oscillation (Meehl and Tebaldi, 2004; Horton et al., 2015; Li et al., 2020; Suarez-Gutierrez et al., 2020a). However, these short-term drivers of extreme temperatures could be influenced and conditioned by mechanisms on longer time scales. Long memory mechanisms such as ocean heat inertia, i.e., the capacity to store heat and delay its transfer and release, have been found to influence mean summer temperature variability (Saeed et al., 2013; Ghosh et al., 2016; Borchert et al., 2019). Examples for these long-term mechanisms influencing European temperatures are the Atlantic multi-decadal variability (AMV; Boer et al., 2016; Gao et al., 2019; Qasmi et al., 2021; Ruprich-Robert et al., 2021) or the El-Nino Southern Oscillation (ENSO; Martija-Díez et al., 2021). The variability in the North Atlantic region has been shown to include a fully coupled atmosphere-ocean cycle with a period of about 7-10 years shown for different ocean-related quantities, such as ocean heat content and barotropic stream function (Reintges et al., 2016; Martin et al., 2019). In fact, these processes have a significant impact on European summer temperatures as demonstrated by Müller et al. (2020). However, the assessment of drivers for extreme temperatures on such long-term timescales is currently limited (Simpson et al., 2018; Wu et al., 2019), and their relevance for extreme summers remains uncertain (**Papritz23**). This research addresses this question and presents a comprehensive explanation for the occurrence of extremely warm European summers in sub-decadal warm phases, and their relation to the heat accumulation that occurs several years in advance.

Our investigation concentrates on the exceptionally warm European summers that occur in conjunction with positive sub-decadal temperature anomalies. To robustly capture the frequency and strength of such low-probability events, large sample sizes are needed. Here, we use one of the largest ensembles from a comprehensive, fully coupled Earth system model currently available, the Max-Planck-Institute Grand Ensemble with 100 ensemble members (MPI-GE; Maher et al., 2019). MPI-GE offers one of the most adequate representations of observed historical temperatures among single-model large climate models (Suarez-Gutierrez et al., 2021). MPI-GE is able to capture extreme summer temperatures (Suarez-Gutierrez et al., 2020b), including some of the most extreme European summer temperatures ever recorded (Suarez-Gutierrez et al., 2018; Suarez-Gutierrez et al., 2020a).

Using the MPI-GE, we examine the sub-decadal variability of extremely warm European summers and show how these summers are affected by North Atlantic Ocean heat content accumulation. We investigate whether the MPI-GE can represent sub-decadal temperature variability well, and identify where these time scales dominate over Europe and are linked to European extreme temperatures. Additionally, we identify which processes in the North Atlantic Ocean is responsible for the increase of the occurrence of extremely warm summers.

A.2 DATA AND METHODS

Model Description

We use simulations from the Max Planck Institute Grand Ensemble (MPI-GE; Maher et al., 2019). These simulations are performed with MPI-ESM1.1 in the low-resolution setup (MPI-ESM-LR; Mauritsen et al., 2012; Giorgetta et al., 2013). MPI-GE consists of 100 simulations with different initial conditions and is one of the largest ensembles of a single, comprehensive, fully-coupled climate model. In the atmosphere, the MPI-ESM-LR reaches up to 0.01 hPa (about 80 km) with 47 vertical levels and a horizontal resolution of 200km at the equator. In the ocean, the MPI-ESM-LR is formulated on a C grid and orthogonal curvilinear coordinates (Marsland et al., 2003). To circumvent grid singularities at the geographical North Pole, the northern grid pole is shifted to Greenland, leading to high resolution in the Arctic and the high-latitude sinking regions. In the ocean, the MPI-ESM-LR has 40 vertical levels and a horizontal resolution of about 1.5° on average and varies from a minimum of 12km close to Greenland to a maximum of 180km in the tropical Pacific. Here, We are using monthly data averaged to seasonal summer means over June, July, and August (JJA) from 1950 to 2022. This includes historical simulations from 1950 to 2005 and RCP4.5 scenario simulations until 2022. For time-lagged analyses up to three years prior to 1950 are analyzed.

ERA5 data including the backward extension until 1950 are used as an observational reference to validate the results of the multi-tapering with MPI-GE (Hersbach et al., 2018).

Analysis Methods

We linear detrended all of our data in order to exclude the influence of global warming and other external forcings. Furthermore, we use a 5-10 year bandpass filter to remove frequencies and noise outside the sub-decadal range. Therefore, we use a standard top-hat filter response function.
In order to investigate extremely warm European summers on sub-decadal timescales, hereafter referred to as extremely warm summers, we consider those JJA mean temperature anomalies in the region between 15°-35°E and 45°-60°N exceed their 90th percentile and additionally occur in a positive bandpass-filtered phase (pooled in time and ensemble (T>90th percentile and T*bandpass* >0), 557 summers in total).
We use a cross-spectral analysis, based on a multi-taper method to analyze if and where the MPI-GE and ERA5 can represent the sub-decadal time scales (Årthun et al., 2018). This multi-taper method is a spectral analysis technique to estimate the dominant time-frequency content of time series by decomposing the data into a set of orthogonal tapers and computing a set of spectral estimates. The dominant time-frequency is then identified as the highest spectral peak or mode in the resulting spectrum, which characterize the dominant oscillatory patterns and variability of the data over time. We perform the multi-tapering for all 100 ensemble members and take the mean over all spectra for each grid point to ascertain the dominant timescale, where the dominant timescale is given by the highest significant peak (e.g. Årthun et al., 2018; Ghil et al., 2002). The significance of spectral peaks is determined by comparison with a red noise spectrum with a 95% confidence interval.
The significance of our results is tested with a bootstrap algorithm in which a reference index is computed in each grid point for 1000 randomly composed arrays of the corresponding variable (random sampling with replacement). We calculate the p-value from our 1000 bootstraps and control for the false discovery rate (equation 3 in Wilks (2016)) with a chosen control level of $\alpha_{\mathrm{FDR}} = 0.1$.
We scale the band-pass filtered summer mean anomalies by the standard deviation of unfiltered summer (JJA) mean anomalies during extremely warm European summers to better illustrate the imprint of the sub-decadal proportion of various climate variables on the occurrence of extremely warm European summers. In detail, we first calculate anomalies of the variables with respect to their long-term averages. We then define their total summer mean variability (σ_t) as the standard deviation of the unfiltered summer mean anomaly (x') for years showing an extremely warm European summer (t_{extreme}):

$$\sigma_t = \sigma(x'(t_{\mathrm{extreme}}))$$

We then divide the bandpass-filtered anomaly ($\tilde{x'}$) by the total variability σ_t at the time of each heat extreme. Lastly, we average over all cases of extreme events (N) to obtain the scaled anomaly ($\widehat{x}$):

$$\widehat{x} = \frac{1}{N}\sum_{1}^{N}\frac{\tilde{x'}}{\sigma_t}$$

All calculations of the scaled anomaly are performed gridpoint-wise. The scaled anomaly simply illustrates the proportion that a sub-decadal mean change has on the occurrence of an extremely warm summers compared to the overall occurrence of extremely warm summers. The corresponding scaled anomalies are added to the respective figure captions.

A.3 RESULTS

Sub-Decadal Variability and Extremely Warm European Summers

We use bandpass-filtering and a cross-spectral analysis to identify the dominant time-frequencies of European summer temperatures for each grid point in MPI-GE and ERA5 from 1950 to 2020 (Fig. A.1a,b and Methods). Areas with dominant sub-decadal variations (5-10 year variations) are found in MPI-GE over Scandinavia, the British Isles, the Iberian Peninsula, Italy, and large parts of Central and Eastern Europe. ERA5 and MPI-GE show high agreement for areas with dominant sub-decadal variations especially over Eastern Europe (Fig. A.1a,b). MPI-GE reveals some limitations in the representation of multi-decadal time scales (>20 years), which are dominant in ERA5 in the northern and southernmost parts of the domain. On time scales between 10 and 20 years, only a few grid points are dominant. Even fewer dominant grid points are found on time scales greater than 20 years.

Analyzing the ratio between all heat extremes and those occurring in a positive bandpass filtered phase, Central Europe stands out as the area with the highest percentages (Fig. A.1c). Regions within the Iberian Peninsula, northern Scandinavia, and Russia also stand out with coinciding extremely warm summers and sub-decadal variability. In summary, sub-decadal timescales of 5-10 years are the dominant scale of variability in European mean summer temperatures, and extremely warm summers tend to occur in 5-10 year phases of abnormally warm temperatures over Europe over large parts of Central, Eastern and Southern Europe.

The overlap between a dominant sub-decadal variability and the occurrence of extremely warm European summers is strongest over Central Europe (Central

Europe is defined by 15°-35°E; 45°-60°N, Fig. A.1c, blue box). The temperature of this region is also dominated by the sub-decadal time scales overall (Fig. A.1d), as expected from Fig. A.1b, two significant peaks within the sub-decadal time scales can be found here as well. Other significant peaks could be found around two to three years and around 15 years, indicating the possible influence of other drivers and mechanisms. We investigate the behaviour of several variables that characterize the North Atlantic Ocean heat content variability during extremely warm European summers as well as several years prior their occurrence to further understand the simultaneous occurrence and the drivers of sub-decadal variability and extremely warm European summers.

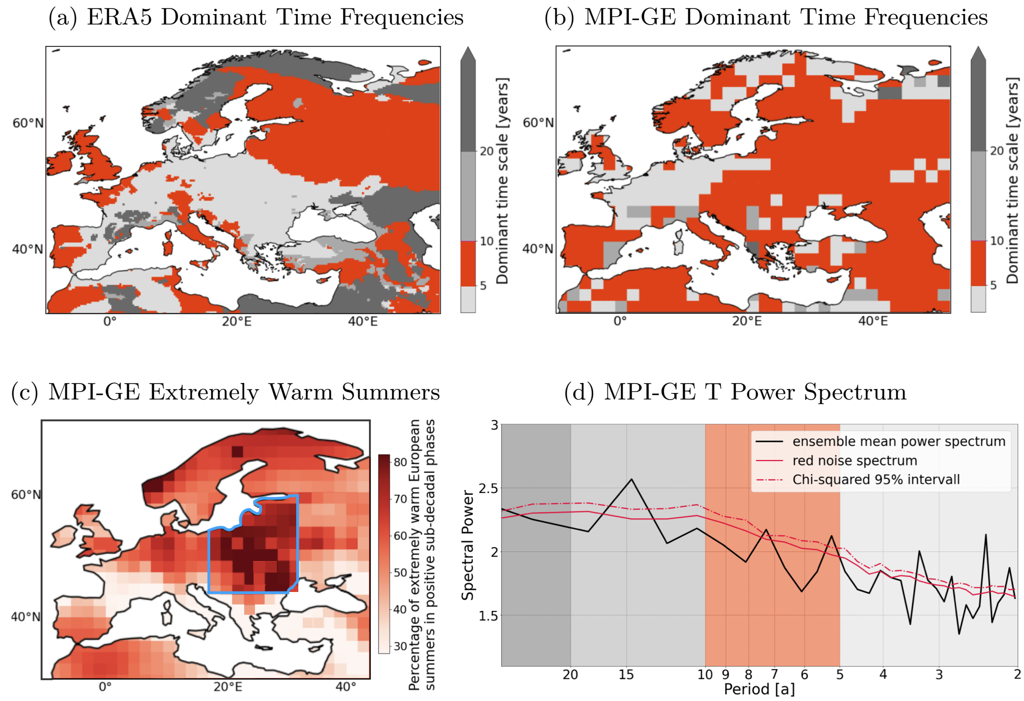

Figure A.1: Dominant time frequencies and their relation to extremely warm European summers. (a),(b) Cross-spectral analysis, performed using the multi-taper method, showing the dominant time scales of European surface air temperature variability in (a) ERA5 and (b) MPI-GE (see Methods). Color shading in years. (c) Percentage of all heat extremes (T>90th percentile) occurring in a positive bandpass filtered phase (T*bandpass* >0) per grid-point in MPI-GE. The blue box defines the region of interest for further analysis (Central Europe, ~15°-35°E; 45°-60°N). (d) Power spectrum of Central European (spatial mean of blue box) surface air temperature (black line) in MPI-GE (averaged over all ensemble member spectra). The significance is shown via a red-noise spectrum (solid red line) and the chi-squared 95% interval (dashed red line). The background is color-coded according to the time intervals in (a,b). Period 1950-2022.

The North Atlantic Ocean and Extremely Warm European Summers

We start with our investigation with the North Atlantic ocean-atmosphere latent and sensible heat fluxes for lags up to three years prior to an extreme summer, to examine the North Atlantic Ocean long-term variability could drive the sub-decadal variability in extremely warm European summers (Fig. A.2a).

At lag 0, when anomalies in the North Atlantic Ocean occur in the same year as the extreme summer, we find high anomalies, reaching up to 20% of the total variability, in the western part of the North Atlantic Ocean (30°-60°W; 25°-40°N), as well as in the north-eastern part of the North Atlantic Ocean (15°-25°W; 50°-70°N). These high positive anomalies in the North Atlantic Ocean, which indicate an above-average heat flux from the ocean to the atmosphere during extremely warm European summers and associated warming of the atmosphere, can be traced back several years prior to the extreme.

Although the global anomaly pattern suggests some relation to other long-term climate variability modes of the Pacific Ocean, such as the Pacific Decadal Oscillation and Tripolar Pacific Index (Fig. A.2b), further analysis shows that e.g. ENSO does not drive the pattern described here (Table A1). The fraction of extremely warm European summers during the different ENSO phases is consistently low for different lags. Whereas, the fraction of extremely warm European summers strongly relies on the state of the North Atlantic oceanic variables. This means that no specific ENSO phase (El-Nino, La-Nina, Neutral) can be concretely associated with extremely warm European summers on sub-decadal time scales. Whether this relationship is coincidental and caused by an extraneous process (Cane et al., 2017), or whether this response is indicating a dynamical relationship between processes in the North Atlantic Ocean and the occurrence of extremely warm European summers, is further investigated in the following.

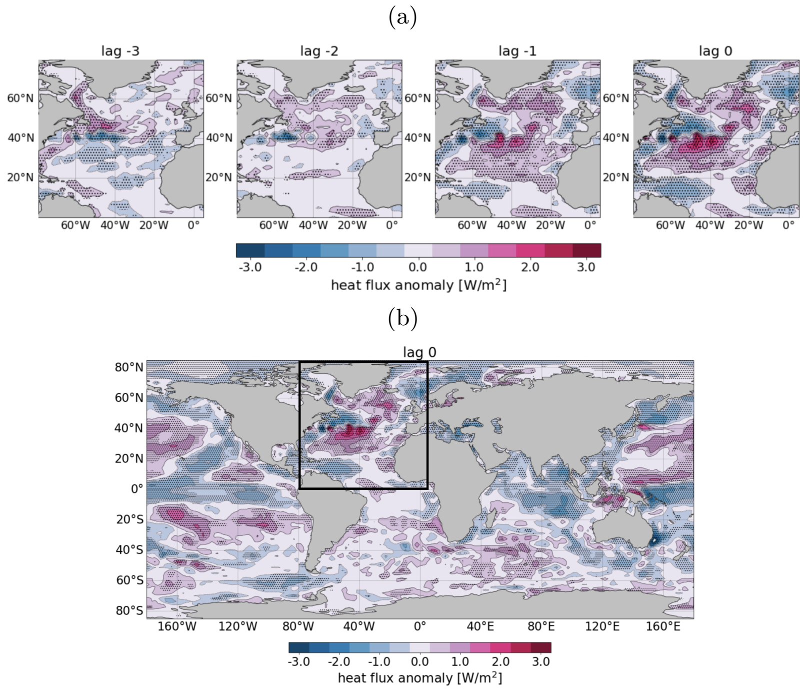

Figure A.2: Anomaly of 5-10 year bandpass-filtered Atlantic heat flux (latent + sensible) variability in MPI-GE for (a) different lags prior to extremely warm European summers and (b) lag 0 as a global map. Positive values indicate heat flux into the atmosphere. Values in Wm^{-2}, lags in years. Dots denote significance at a 95% confidence level. Period 1950-2022. For comparison the standard deviation of the year-to-year variation is of the order of $14\,Wm^{-2}$, which means that the highest values in the figure correspond to around 20% of the total variability.

Influence of North Atlantic Ocean Heat Accumulation on Extremely Warm European Summers

We test if the oceanic variability in the North Atlantic Ocean can influence atmospheric circulation patterns via heat accumulation and release. Therefore we evaluate the relationship between North Atlantic Ocean inertia and extremely warm European summers. First, we analyze the ocean heat content, which influences the temperature difference between the ocean and atmosphere and thus alters the rate of heat exchange and is therefore a driver for the ocean-atmosphere heat flux. Here, we investigate anomalies of the 0-700m averaged, 5-10 year bandpass-filtered ocean heat content (Fig. A.3a).

Starting around three years prior to extremely warm European summers, ocean heat content anomalies change from negative to positive all along the North Atlantic current, indicating an accumulation of heat in northern part of the subtropical gyre. For lag 0, these anomalies reach up to 25% of the total variability of the ocean heat content.

The ocean heat content is controlled by the meridional ocean heat transport, which describes the movement of heat energy from one region of the ocean to another and can lead to changes in the ocean heat content in different regions over time. Here, further insight into the dynamics of the North Atlantic Ocean subtropical and subpolar region is provided by the 5-10 year bandpass-filtered ocean heat transport and its decomposition into a gyre- and meridional circulation part (Fig. A.3b; calculated independently, see Ghosh et al. (2023)). The anomalies of the 5-10 year bandpass-filtered ocean heat transport reveals positive anomalies of the meridional heat transport around 20°N from two years prior to extremely warm summers onward. A substantial proportion of these positive anomalies of the meridional heat transport is not compensated by ocean heat transport changes at 40°N. Here, due to the increased net heat transport around 40°N, the ocean heat content in that region will increase, leading to the previously described accumulation of ocean heat content. The accumulated heat is released at lag 0, mainly through the gyre ocean heat transport around 65°N. Altering the temperature gradient between the ocean and the atmosphere, this heat release matches in turn with the positive ocean-atmosphere heat flux anomaly around 50-70°N (Fig. A.2).

The ocean heat transport is influenced by the direction and strength of the horizontal oceanic currents, characterized by the barotropic stream function. The barotropic stream function refers to the circulation of ocean currents at a certain depth, where the flow is primarily influenced by pressure gradients. Changes in the barotropic stream function can indicate shifts in the paths and intensity of ocean currents. As a result, the direction and strength of heat transport in the ocean may be affected. This, in turn, leads to changes in the distribution of ocean heat content across different regions. Thus, the barotropic stream function provides further knowledge about the paths of ocean currents (Fig. A.3c). Starting from three years prior to an extremely warm European summer, negative anomalies of the barotropic stream function occur in the northern part of the subtropical gyre, indicating a North Atlantic current weaker than its normal state, leading to a smaller horizontal volume transport and a southward shifted subpolar gyre boundary around three years prior to an extremely warm summer. The anomalies of the barotropic stream function change sign to positive values about one year prior to extremely warm summers, indicating strengthening of the North Atlantic current and associated greater horizontal volume transport. Moreover, the North Atlantic current shifts by a few degrees north compared to the mean state, indicating a volume transport into higher latitudes via the North Atlantic current. This increased northern horizontal volume transport together with the transition of the ocean heat content indicates the accumulation of heat along the northern branch of the subtropical gyre.

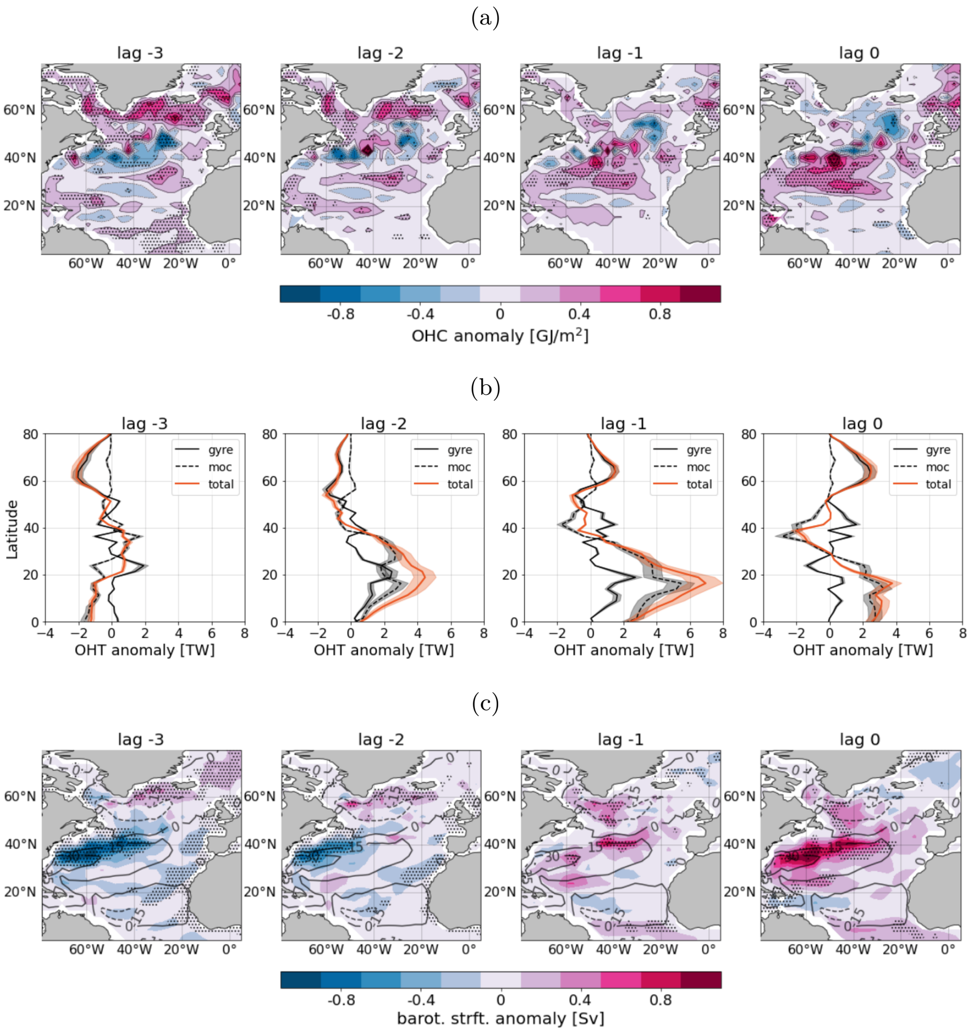

Figure A.3: Extremely warm European summers and their relation to ocean quantities. (a) Upper 700m ocean heat content. Anomaly of 5-10 year bandpass-filtered ocean heat content variability in MPI-GE for different lags prior to extremely warm European summers, values given in GJm^{-2}. For comparison the standard deviation of the year-to-year variation is of the order of $4.3\,\mathrm{GJm}^{-2}$, which means that the highest values in the figure correspond to around 25% of the total variability. (b) Ocean heat transport. Anomaly of 5-10 year bandpass-filtered ocean heat transport variability in MPI-GE for different lags prior to extremely warm European summers, values given in TW. For comparison the standard deviation of the year-to-year variation is of the order of 50 TW, which means that the highest values in the figure correspond to around 15% of the total variability. (c) Barotropic stream function. Anomaly of 5-10 year bandpass-filtered barotropic stream function variability in MPI-GE for different lags prior to extremely warm European summers, values given in Sv. Contour lines indicate the mean state of the barotropic stream function, values given in Sv. For comparison the standard deviation of the year-to-year variation is of the order of 8 Sv, which means that the highest values in the figure correspond to around 15% of the total variability. All lags are given in years. Dots (a, c) and shadings (b) denote significance at a 95% confidence level. Period 1950-2022.

Atmospheric Pathway leading to Extremely Warm European Summers

Three years prior to an extremely warm European summer, heat accumulates along the North Atlantic current. This heat is subsequently released into the atmosphere at lag 0. Here, we explain the atmospheric response bridging the ocean heat accumulation with the European summer climate.

The anomaly of the 5-10 year bandpass-filtered atmospheric temperature reveals positive temperature anomalies especially in higher latitudes around 50/60°N (Fig. A.4a). These temperature anomalies spatially fit to the previously located anomalies of the ocean heat content and resemble the heat accumulation shown in the previous section. Based on this dynamical linkage we conclude that the ocean is warming the atmosphere via the ocean-atmosphere heat flux rather than the atmosphere is cooling the ocean. Our conclusion is also supported by the positive sign of the heat flux anomaly, indicative of heat flux transfer from the ocean to the atmosphere. The transfer of heat from the ocean to the atmosphere is strong enough that its signal reaches up to 200 hPa altitude, with a peak in the range of 400-600 hPa. This warming of the tropospheric high latitudes provides a decrease of the meridional temperature gradient and results in a reduction of wind shear due to the thermal wind balance. This leads to a weakened jet stream in the years with extremely warm summers compared to years without extremely warm European summers. In addition, the average position of the jet stream is shifted northward during extremely warm European summers, this northward shift indicates the advance of subtropical air masses into higher latitudes (Fig. A.4; orange contour lines).

5-10 year bandpass-filtered sea level pressure anomalies, reveal a structure of a Scandinavian Blocking, which can be identified considering years with and without extremely warm summers (Fig. A.4b). The Scandinavian Blocking can drive heat extremes over Central Europe (Spensberger et al., 2020), and connects the sub-decadal North Atlantic Ocean heat accumulation leading via specific atmospheric conditions to extremely warm summers over Central Europe. Additionally, some studies show that the weakening of wind speeds during extremely warm European summers can increase the probability of atmospheric blocking (Woollings et al., 2018), which would in turn increase the likelihood of heat extremes (Kautz et al., 2022). Here, we showed that the long-term accumulation of heat in the North Atlantic Ocean lead to an above average ocean-atmosphere heat flux, which in turn can influence the atmospheric circulation and could further affect the occurrence of long-lasting high-pressure systems, favoring blocking.

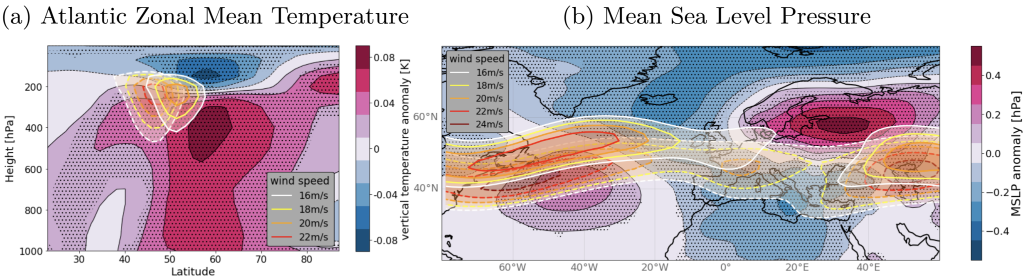

Figure A.4: Extremely warm European summers and their atmospheric pathway. (a) Anomaly of 5-10 year bandpass-filtered Atlantic zonal mean temperature variability in MPI-GE during extremely warm European summers (lag0), values given in K. For comparison the standard deviation of the year-to-year variation is of the order of 0.3 K, which means that the highest values in the figure correspond to around 30% of the total variability. (b) Anomaly of 5-10 year bandpass-filtered mean sea level pressure variability in MPI-GE during extremely warm European summers (lag0), values given in hPa. For comparison the standard deviation of the year-to-year variation is of the order of 3 hPa, which means that the highest values in the figure correspond to around 15% of the total variability. The orange contour lines indicate the mean position of the jet stream (given by the mean zonal wind speed over 200-300 hPa) averaged over years showing an extremely warm European summer (solid line) and years showing no extremely warm summer (dashed line), values given in m/s. Dots denote significance at a 95% confidence level. Period 1950-2022.

A.4 DISCUSSION AND CONCLUSION

The North Atlantic Ocean heat accumulation impacts the occurrence of extremely warm summers over Central Europe on sub-decadal timescales. Using MPI-GE, we show that starting several years prior, anomalies of the ocean heat transport and associated ocean heat content changes result in ocean-atmosphere heat flux anomalies leading to extremely warm European summers.

These positive anomalies of the ocean heat transport, as well as ocean heat content, lead to an intensification of the North Atlantic current and accumulation of heat content along the subtropical gyre. This accumulated heat content is released mainly through the ocean heat transport by the subpolar gyre to the atmosphere during extremely warm European summers. The released heat in turn leads to a displacement of the jet stream and enhanced atmospheric blocking conditions.

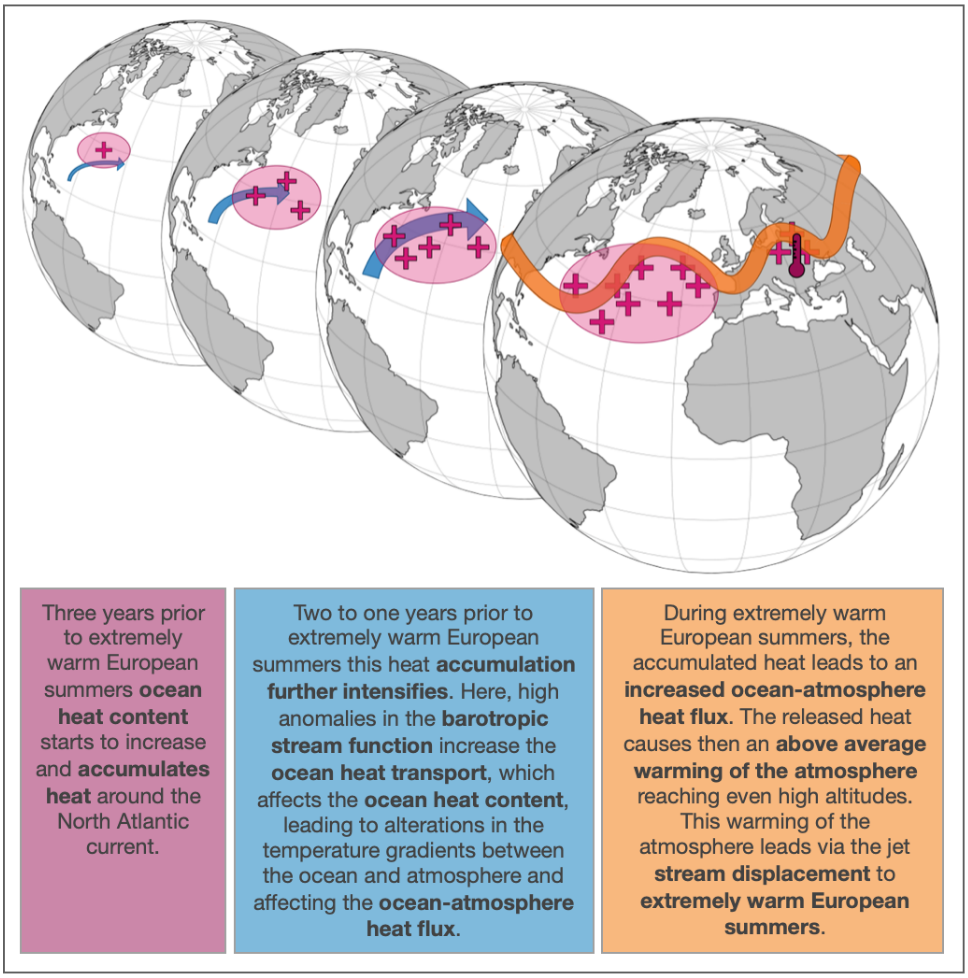

Figure A.5: Schematic sketch illustrating the described mechanism. The blue arrows illustrate the increasing North Atlantic current; the pink crosses indicate the increase of ocean heat content and accumulation of heat; and the orange belt illustrates the jet stream. The thermometer at lag 0 illustrates the extremely warm European summers.

Although we focus on three years prior to the extremely warm summers, there is evidence potentially linking this mechanism to a fully coupled atmosphere-ocean cycle in the North Atlantic Ocean evolving in a 7-10 year period. Such oscillating behavior has been identified in a number of quantities involving observed sea surface temperatures and Gulf Steam indices (Czaja and Marshall, 2001; McCarthy et al., 2018), or heat content and overturning stream functions (Martin et al., 2019), or for the North Atlantic Oscillation (NAO; Costa and Verdiere, 2002)). In fact, observations reveal that the European summer mean climate is ultimately connected to such a coupled atmosphere-ocean cycle (Müller et al., 2020). Comparable to our results, Martin et al. (2019) identified a similar atmosphere-ocean cycle using also the MPI-ESM in the low-resolution setup. Extending our analysis up to eight years prior to extremely warm summers is in line with their results, indicating the close relationship of the occurrence of extremely warm European summers with the sub-decadal North Atlantic atmosphere-ocean cycle (see Figures A1-A3).

We find that the coupled oscillation in the North Atlantic Ocean influences the occurrence of very hot summers in Europe on sub-decadal time scales. However, on this timescale other modes of oceanic variability, such as the North Atlantic Oscillation, El Niño-Southern Oscillation, or Pacific Decadal Oscillation may also be influential. Observed decadal teleconnections between the Pacific Ocean and North Atlantic Ocean have been shown e.g. in Müller et al. (2008). Global maps of heat flux during extremely warm European summers reveal negative anomalies within the tropical Pacific and patterns matching with the Pacific decadal variability (PDV; 90°-170°W/20°N), indicating an influence of other external drivers. However, a direct effect of PDV or ENSO on the sub-decadal occurrence of extremely warm European summers has not been found here. Additionally, our findings might also be impacted by other mechanisms that interact with each other and possibly lead to the occurrence of extreme events over Europe. For example the North Atlantic Oscillation (NAO) and the Atlantic multi-decadal variability (AMV) exert significant influence on the occurrence of extreme events over Europe (Scaife et al., 2008; Qasmi et al., 2021). The NAO plays a crucial role in shaping weather patterns, contributing to the development of heatwaves and droughts, while variations in the AMV can impact atmospheric circulation patterns, influencing the frequency and intensity of extreme events. Whether further climate modes have an impact on the proposed mechanism is beyond of the scope of this manuscript, and should be further explored.

Here, we focus on extremely warm European summers associated with the decadal atmosphere-ocean coupling in the North Atlantic Ocean. However, given that the coupled cycle appears over several years, we expect that there is not only an influence on the summertime, but also for other seasons and respective extreme conditions, and further variables relevant for heat extremes, such as the daily maximum temperature. Furthermore, the presented process of ocean heat distribution changes at multi-year lead times prior to an extreme event sets prospects to enhance the predictability of European climate and extremes. Multi-year prediction skill of European climate has been achieved on continental scale (Smith et al., 2020). However, an extension to predict extreme conditions has so far not fully been established (Borchert et al., 2019).

Moreover, the investigated sub-decadal extreme heat variability implies increased risk of heat-related socioeconomic and ecological impacts, in addition to year-to-year variability and rising temperatures due to increasing GHG concentrations. Due to the prominence of the sub-decadal variability and due to the severity of the impacts, a deeper understanding of the sub-decadal processes leading to such extremely warm summers is crucial for reducing the uncertainties in both attribution and prediction of high-impact events, which in turn facilitates preparedness and the efficiency of adaptation and mitigation efforts.

Lastly, this is a single model study which allows us to delve deeper into specific processes and model intricacies, which can contribute to model improvement and process understanding. Replicating this analysis for different climate models would be of great importance to sample potential model uncertainty in these results and help us gain further understanding of this mechanism.

Moreover, the investigated sub-decadal extreme heat variability implies increased risk of heat-related socioeconomic and ecological impacts, in addition to the year-to-year variability and rising temperatures due to increasing GHG concentrations. Due to the prominence of the sub-decadal variability and due to the severity of the impacts, a deeper understanding of the sub-decadal processes leading to such extremely warm summers is crucial for reducing the uncertainties in both attribution and prediction of high-impact events, which in turn facilitates preparedness and the efficiency of adaptation and mitigation efforts.

A.5 ADDITIONAL INFORMATION

Data Availability

Further simulation and download details for MPI-GE data can be found on our website (https://www.mpimet.mpg.de/en/grand-ensemble/). ERA5 data are available from the European Centre for Medium-Range Weather Forecasts (ECMWF) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5).

Barotropic Stream Function and Subpolar Gyre

The fact that no pronounced anomalies of the barotropic stream function can be found in the area of the subpolar gyre is probably related to the filter method we chose. The 5-10 year bandpass filter filters out all signals that occur on larger or smaller time scales. According to Nigam et al. (2018) the sub-polar gyre is subject to decadal variations of about 14 years and time scales which are not further relevant for our analysis.

Noise of the Ocean Heat Content

The fact that the anomalies in the ocean heat content occurs in a more patchy and noisy pattern can probably be explained by the fact that the ocean heat content is also influenced by the atmospheric variability. Since the barotropic stream function is less influenced by atmospheric variability, the signal is clearer here.

Link to fully coupled atmosphere-ocean cycle

Analyzing longer lags, in this case lag -7 to 0, prior to extremely warm European summers shows that the described mechanism can be seen as attached to a fully coupled atmosphere-ocean cycle evolving in a 7-10 year period (Figure A1-A3). Such oscillating behavior, without linkage to European summer climate, has been identified and described in previous studies (Czaja and Marshall, 2001; McCarthy et al., 2018; Martin et al., 2019). In Martin et al. (2019) a NAO-like wind-driven forcing steering dipolar ocean overturning anomalies are associated with a contraction and weakening of the sub-polar gyre (cf their figure 6). In the following years, the barotropic stream function reveals a poleward shift and a strengthening of the North Atlantic Current at the same time accumulates ocean heat content (cf. their figure 7). The barotropic stream function in MPI-GE prior to heat extremes similarly illustrates strengthening of the North Atlantic Current and accumulation of heat. For longer lags a phase reversal is apparent, similar to the oscillatory behavior of the coupling as described in Martin et al. (2019).

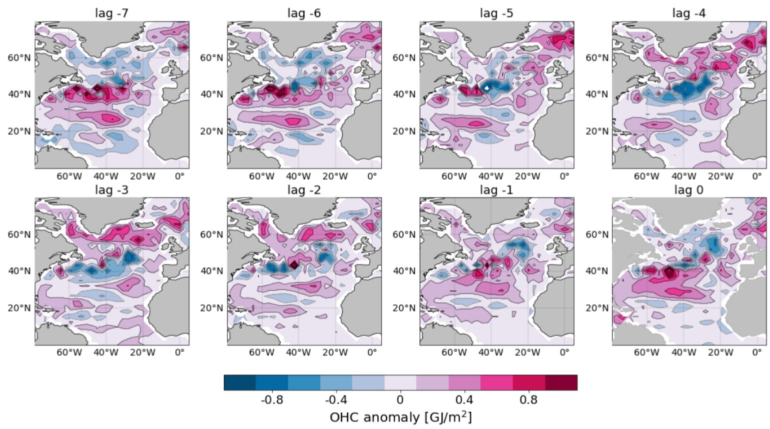

Figure A.6: Shift of the ocean heat content signal. Anomaly of 5-10 year bandpass-filtered ocean heat content (0-700m/30-60°W) variability in MPI-GE for different lags prior to heat extremes. Period 1950-2022.

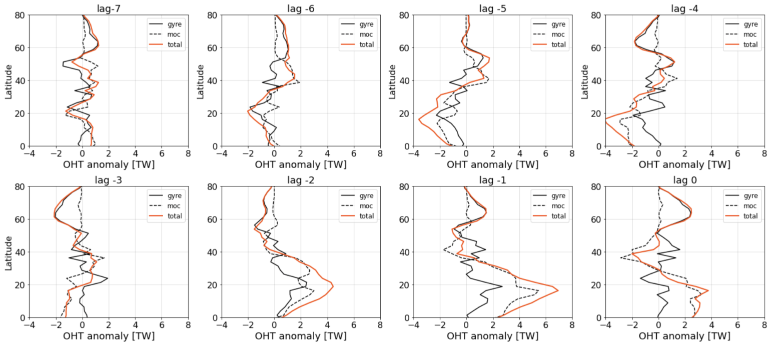

Figure A.7: Shift of the ocean heat transport signal. Anomaly of 5-10 year bandpass-filtered ocean heat transport variability in MPI-GE for different lags prior to heat extremes. Period 1950-2022.

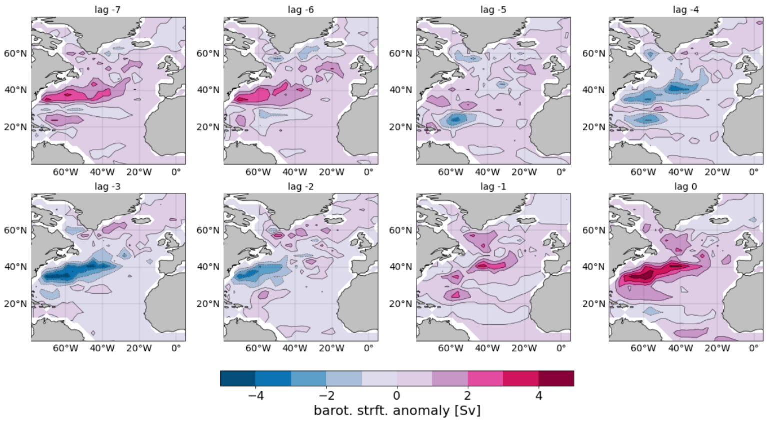

Figure A.8: Shift of the barotropic stream function signal. Anomaly of 5-10 year bandpass-filtered barotropic stream function variability in MPI-GE for different lags prior to heat extremes. Period 1950-2022.

Influence of the El Nino Southern Oscillation

Many studies have examined the influence of the El-Nino Southern Oscillation (ENSO) on European temperatures and also heat extremes (Martija-Díez et al., 2021). However, ENSO does not seem to play a dominant role for the mechanism studied here. On the one hand, the fraction of extremely warm European summers during the different ENSO phases (El-Nino, La-Nina, Neutral) is consistently low for different lags, so that no specific ENSO phase can be concretely linked to extremely warm European summers on sub-decadal time scales (Table A1). For this analysis, we defined ENSO phases by SSTs exceeding a threshold of ± one standard deviation in the Nino-3.4 region; however by checking other thresholds we verify that our conclusion is not threshold sensitive. Our statement that the extremely warm European summers are mainly driven by North Atlantic heat inertia and not ENSO is further supported by the proportion of extremely warm European summers during positive/negative anomalies of the barotropic stream function in the North Atlantic. Here, a clear correlation between both can be seen for different lags. While in lag 0 the extremely warm summers are mainly associated with positive anomalies of the barotropic stream function, these are in lag -4 mainly associated with negative anomalies of the barotropic stream function. Furthermore, for our study, no specific ENSO phase seem to be linked to specify anomalies of the barotropic stream function. In addition, the heat flux anomalies during extremely warm European summers show no typical ENSO pattern in the Nino-3.4 region (Fig. 2b). However, positive anomalies matching the North Pacific Index (NPI) could be found around 90°-170°W/20°N, indicating an influence of external drivers that, although beyond of the scope of this study, should be further explored.

Table A.1: Fraction of events that coincide with extremely warm European summers in MPI-GE. Period 1950-2022. The percentages are given by the ratio between the number of events (e.g. El-Nino events) during extremely warm European summers and the number of all occurring events.

	Fraction of events that coincide with an extremely warm European summer [%]		
	Lag -4	Lag -2	Lag 0
El-Nino events	9.1	8.3	7.5
neutral events	8.2	8.2	8.3
La-Nina events	7.2	7.7	8.0
positive barotropic stream function anomaly	4.5	7.1	13.2
negative barotropic stream function anomaly	11.7	9.2	3.0

Appendix B

IMPROVED PREDICTION SKILL OF EXTREMELY WARM EUROPEAN SUMMERS

Wallberg, L., Suarez-Gutierrez, L., Matei, D., and Müller, W. A.: Improved Prediction Skill of Extremely Warm European Summers [to be submitted to GRL]

Improved Prediction Skill of Extremely Warm European Summers

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- Sub-decadal North Atlantic Ocean heat accumulation seems to be related to the occurrence of extremely warm European summers in a decadal prediction system
- A new approach for reducing the ensemble size based on heat accumulation in the North Atlantic Ocean is presented
- This reduced ensemble increases the prediction skill of extremely warm European summers

ABSTRACT

The frequency of occurrence of extremely warm European summers, has increased dramatically in recent years and is expected to further increase with rising global temperatures. Reliable and skillful predictions years in advance of these high-impact events would be crucial to reduce potential societal, political, and economical impacts. We consider relevant processes highlighted in previous work showing that the accumulation of heat in the North Atlantic Ocean can precede extremely warm European summers on sub-decadal time scales. The accumulated heat is thus acting as a precursor for the occurrence of such extreme events. Building upon this understanding, we examine how the accumulation of heat in the North Atlantic Ocean can be used to increase the prediction skill of extremely warm summers. By introducing an ensemble selection based on this accumulation of heat, we find an improvement in prediction skill of Central European summer temperatures several years in advance.

PLAIN LANGUAGE SUMMARY

The occurrence of extremely warm summers in Europe has increased significantly in recent years, and this trend is expected to continue as global temperatures rise. These extreme heat events have significant impacts on society, politics, and the economy. It would be very helpful if we could predict these high-impact events reliably and accurately several years in advance to minimize their potential consequences.

In another study we found that the heat buildup in the North Atlantic Ocean plays a crucial role in predicting extremely warm European summers. We discovered that the accumulation of heat in the North Atlantic Ocean precedes these extreme events by several years. By using this storage of heat in the North Atlantic Ocean, we improve now the ability to predict extremely warm European summers.

B.1 INTRODUCTION

Extreme and record-breaking warm summers over Europe cause widespread damages and fatalities, as they severely impact infrastructure, agriculture, and health, with socio-economic losses regularly reaching billions of euros (Bastos et al., 2020; Ebi et al., 2021; Callahan and Mankin, 2022; Ballester et al., 2023). Thus, understanding and predicting these extreme events and extremely warm summers is of paramount importance.

The changing frequency of these extreme events has been linked to climate variability and climate change. For example, Fischer and Knutti (2015) found that climate change increased the likelihood of heat extremes over the European region, with the frequency of heatwaves doubling since the pre-industrial era. Further, Schär (2015) projected that, by the end of the century, the probability of extremely warm summers, which currently occur once every ten years, could occur almost every year in the absence of mitigation measures. Studies have hypothesized a mechanism that links variations in the AMOC or North Atlantic Ocean SSTs to changes in the ocean heat content, which result in atmospheric blocking patterns that favor heat waves over Europe (e.g. García-Serrano et al., 2015; Dong et al., 2016).

This mechanism has recently been further investigated by Wallberg et al. (2023), showing how extremely warm European summers are impacted by sub-decadal (5-10 year) North Atlantic Ocean heat accumulation. In detail, how positive anomalies of the ocean heat content, together with an above average as well as northward shifted horizontal North Atlantic current lead to an accumulation of heat

in the North Atlantic subtropical gyre on sub-decadal time scales. This heat is then released into the atmosphere up to three years later, leading to a jet stream displacement as well as blocking conditions over Europe and finally causing extremely warm European summers (mean JJA temperature > 90th percentile).
Recent advancements in initialized decadal prediction systems have significantly improved their performance, suggesting the potential for superior decadal-scale accuracy compared to climate projections (Smith et al., 2020). While climate projections provide a general trend, they lack the ability to precisely pinpoint specific years or phases when heat extremes will occur (Smith et al., 2020). This limitation underscores the need for initialized prediction systems, which excel at providing detailed forecasts, including timing information. Studies have emerged focusing on (hot) summer-predictions at a (sub-)decadal scale, offering novel insights and approaches (Dong et al., 2016; Borchert et al., 2019; Müller et al., 2020). These studies aim to enhance our understanding of hot summer events and their predictability beyond the traditional climate projection framework. Furthermore, the research conducted by Wallberg et al. (2023) demonstrates the important role of the previously described mechanism linking North Atlantic Ocean heat accumulation with the occurrence of extremely warm European summers.
This study now close up to results of Wallberg et al. (2023); We test whether this mechanism is also represented in a decadal prediction system. By using such a large ensemble of decadal hindcasts, we examine how sub-decadal North Atlantic Ocean heat accumulation can be used to increase the predictability of Central European summer surface air temperatures (10-30°E/45-55°N, sub-dec CEU SAT). We introduce an ensemble selection based on the findings of Wallberg et al. (2023), and test the performance of this selected ensemble mean compared to the full ensemble mean. We identify phases where this selection leads to an improvement in sub-dec CEU SAT prediction skill of European summer temperatures and analyze also where this improvement might come from. In the end we link our findings to the prediction of daily CEU SAT, meaning leaving the sub-decadal time scales behind.

B.2 DATA AND METHODS

MPI-ESM Decadal Hindcast

For the analyses we use an initialized decadal hindcast ensemble based on the coupled Max-Planck-Institute-Earth-System-Model in the low-resolution setup (MPI-ESM-LR; Mauritsen et al., 2019). In the atmosphere MPI-ESM-LR has a horizontal resolution of 1.875° at the equator on a Gaussian grid, reaching up to 0.01 hPa (about 80 km) with 47 vertical levels (Stevens et al., 2013). In the ocean MPI-ESM-LR has a horizontal resolution of 1.5° on a curvy linear grid with 40 vertical levels (Jungclaus et al., 2013). The hindcasts are forced by external radiative forcing corresponding to the historical CMIP6 forcing until 2014 and the SSP2–4.5 scenario from 2015 onwards. For the hindcast ensemble, 80 ensemble members are initialized on every 1st November between 1960 and 2019 from an assimilation experiment with 16 ensemble members and are run with 10-year lead-time. For this assimilation experiment, ensemble members were assimilated the observed oceanic and atmospheric state into the model from 1958 to 2019 by using atmospheric nudging and an oceanic ensemble Kalman filter (Brune and Baehr, 2020).

A recent study shows that extremely warm European summers are driven by subdecadal North Atlantic Ocean heat accumulation up to three years prior those summers (Wallberg et al., 2023). Therefore, we mainly analyze daily and monthly lead year 3 hindcast predictions for sub-dec CEU SAT from 1964 to 2021 (initialized from 1960 to 2018). We use the global reanalysis ERA5, including the backward extension until 1964, as an observational reference, covering the same time period as the hindcast and can thus assess the quality of the predictions (Hersbach et al., 2018). ERA5 data are regridded to the coarser MPI-ESM-LR grid. A comparison between the CEU SAT histograms for the hindcast and reanalysis shows some similarities. However, the distribution of ERA5 appears to be broader, indicating the lacking ability of the ensemble mean to represent extremes, in this case especially warm temperatures, as the right edge of the distribution (Fig. 1). In fact, this difference in the representation of extreme CEU SAT demonstrates the need of a subselection of ensemble members which might represent those extremes better.

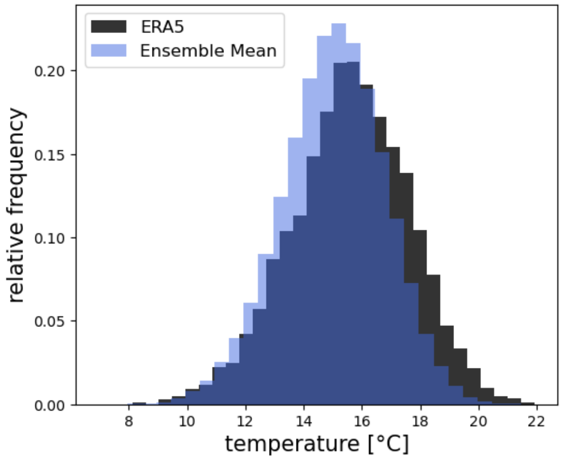

Figure B.1: Histogramm of sub-dec CEU SAT for the reanalysis (black) and the hindcast (blue). Period 1964-2021.

Bandpass-Filtering and Detrending

We use a 5-10 year bandpass filter to remove frequencies and noise outside the sub-decadal range. Therefore, we use a standard top-hat filter response function. This bandpass-filtering removes also long-term climate variations above 10 years like the global temperature increase within the recent years and is therefore a specific type of detrending. All non-bandpass-filtered data are not detrended to keep the influence of global warming and other external forcings.

Quantifying Prediction Skill and Significance

We quantify prediction skill in terms of anomaly correlation coefficients (ACCs), and calculate the spatial correlations between full ensemble mean/ selected ensemble mean anomalies and ERA5 anomalies. The anomalies are calculated with respect to climatology from 1985 to 2014.
The significance of the ACCs is tested with a bootstrap algorithm in which a reference index is computed in each grid point for 1000 randomly composed arrays (random sampling with replacement). A two-sided test defines grid points as significant at the 95% level for which at least 976 of the 1000 bootstraps are greater or smaller than the actual value.

Ensemble Selection

We use a specific ensemble selection to increase the prediction skill of CEU SAT. Here, the ensemble members were selected based on the mechanism described by Wallberg et al. (2023). There it has been shown that starting three years prior, anomalies of the ocean heat transport and associated ocean heat content accumulation result in ocean-atmosphere heat flux anomalies leading to extremely warm European summers. This connection between heat extremes and anomalies in the North Atlantic Ocean is also visible in barotropic stream function anomalies along the North Atlantic current (40-70°W/20-40°N) changing sign from negative to positive within three years prior to heat extremes and positive mean sea level pressure anomalies (25-50°E/55-65°N) occurring simultaneously with extremely warm European summers. Our ensemble member selection is based on these findings and features a more-step ensemble member selection. For this selection, we choose ensemble member that fulfill all of the following criteria:
Year 0: Only years showing a negative barotropic stream function anomaly in the assimilation are selected.
Year +1: For the previously chosen years we select ensemble members showing a barotropic stream function anomaly larger than the anomalies in year 0. This is to ensure that the sub-tropical gyre strength increases.
Year +2: Further, we select ensemble members only showing a barotropic stream function anomaly larger than in year +1.
Year +3: Finally, we select only the ensemble members showing a positive barotropic stream function larger than the anomalies in year +2, and additionally showing positive mean sea level pressure anomalies over Scandinavia (Scandinavian Blocking).
If during the selection process less than 10 member are selected, the selection mechanism fails and is reverted to the full ensemble mean. In all other cases we take the mean over the selected ensemble members. Doing this for every year, we receive an ensemble selection, meaning less selected ensemble members, for some years. The selection process is illustrated in Fig. B.2.

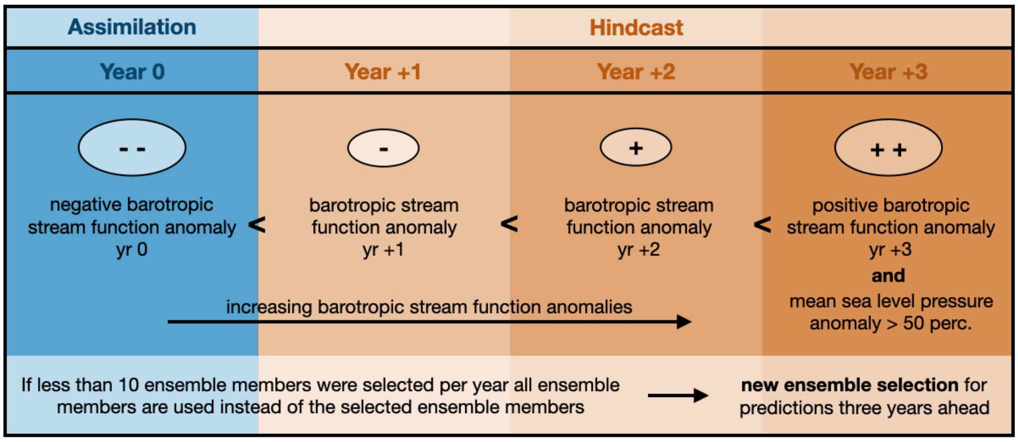

Figure B.2: Ensemble Selection and attached mechanism for CEU SAT predictions. (Prediction from November year xxxx for summer year xxxx +3.)

B.3 RESULTS

Prediction of Extremely Warm European Summers

We test the prediction skill of the selected ensemble mean compared to the full ensemble mean forsub-dec CEU SAT. Here, the full ensemble mean lacks the ability to represent the amplitude of sub-dec CEU SAT compared to ERA5 (Fig. B.3a). Overall, the full ensemble mean apperars to be too zonal and thus can not represent the extremes. However, the selected ensemble mean reveals a much higher variability of sub-dec CEU SAT than the full ensemble mean. The amplitudes of the selected ensemble mean are much closer to the high CEU SAT in ERA5 compared to the full ensemble mean. Also phases of high CEU SAT that are not captured by the full ensemble mean are now captured with the selected ensemble mean. In total, the selected ensemble mean leads to an improvement of 9 phases (13 years) of sub-dec CEU SAT variations over Central Europe. The correlation coefficient between the sub-dec CEU SAT time series for the selected ensemble mean and ERA5 is about 0.57. For comparison the correlation coefficient between the time series for the full ensemble mean and ERA5 is about 0.42. These improvements in sub-dec CEU SAT prediction skill are also visible in anomaly ACC maps (Fig. B.3b). The correlation coefficient increases up to 0.5 over Central Europe, between 10°E to 25°E and 45°N to 55°N from full to selected ensemble mean. Further improvements can be seen over the North Atlantic, Norwegian Sea, Western Europe, and North Africa.

In summary, our selected ensemble mean analysis improves the representation of sub-dec CEU SAT variations, increasing variability and correlation compared to ERA5. This selection also enhances the prediction skill of SAT, particularly over Central Europe.

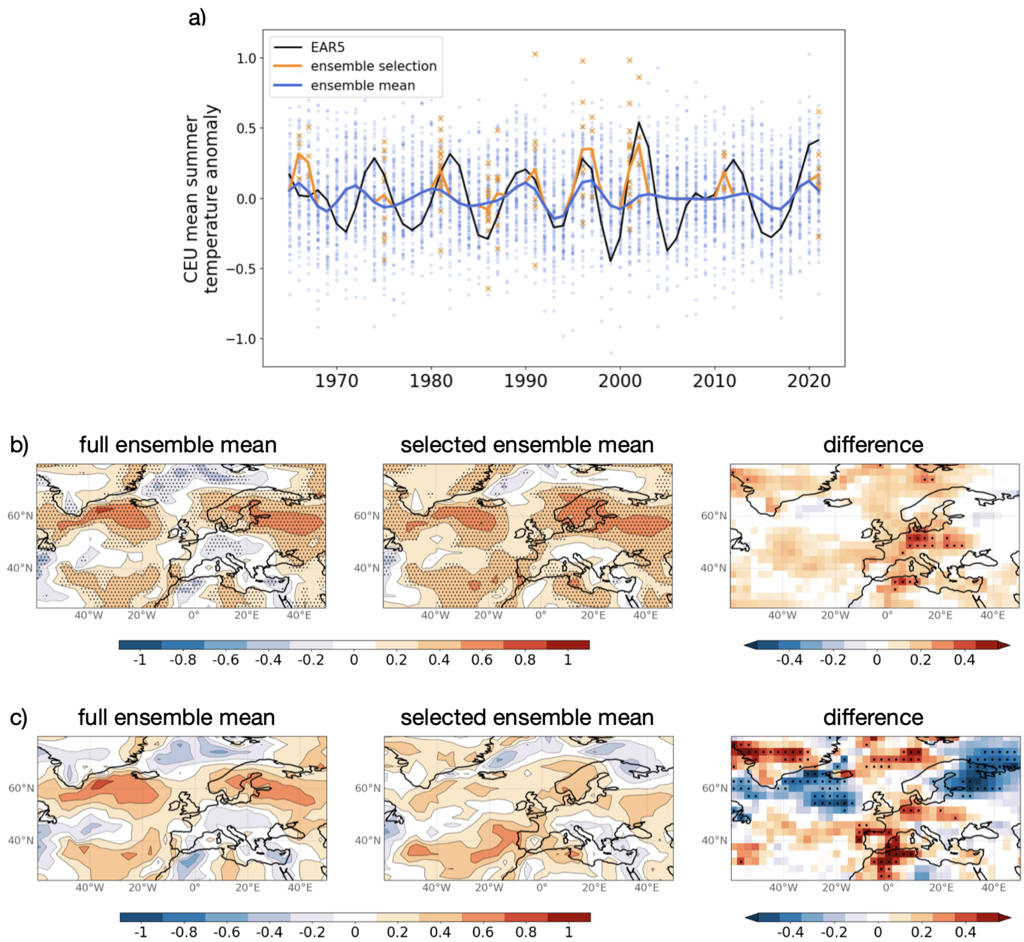

Figure B.3: Predictions of extremely warm European summers. (a) Anomaly of sub-dec CEU SAT for lead year 3 for ERA5 (black) and the hindcast ensemble mean (blue) and ensemble selection (orange). The single (selected) ensemble member are marked through dots (crosses). (b) ACCs of sub-dec CEU SAT for lead year 3 between ERA5 and the full ensemble mean (left), ERA5 and the selected ensemble mean (center), and their difference (right). Dots represent significance at a 95% confidence level. Period 1964-2021. (c) Same as (b), but this time only for the 13 years showing a difference compared to the full ensemble mean.

Link between Oceanic Circulation Anomalies and Heat Extremes

For a general verification of whether the hindcast can reproduce the afore mentioned mechanism at all, barotropic stream function anomalies will be checked for different lags as well as for different linkages between the oceanic anomalies and extremely warm summers.

We start with the selection of ensemble members based on the selection shown in Fig. B.2, which includes no knowledge when heat extremes occur and is therefore applicable in a real prediction system (Fig. B.4 upper row). This selection shows the by Wallberg et al. (2023) described transformation from negative to positive anomalies of the barotropic stream function prior to extremely warm European summers along the North Atlantic current, around 20-40°N. We verify this result with an idealized setup; We select ensemble member for different lags prior to extremely warm European summers. This "perfect test" thus includes knowledge when heat extremes occur and is therefore not applicable in a real prediction system (Fig. B.4 lower row). This selection shows a similar pattern of anomalies of the barotropic stream function found for the our ensemble selection. The broader spread of the selected ensemble mean compared to the perfect setup can be explained by the selection method, where we select ensemble member showing specific anomalies between 20-40°N, while the area in the perfect setup remains unspecified.

For both cases, the anomalies of the barotropic stream function show the same pattern as described by Wallberg et al. (2023) and therefore seem to be attached to the same mechanism.

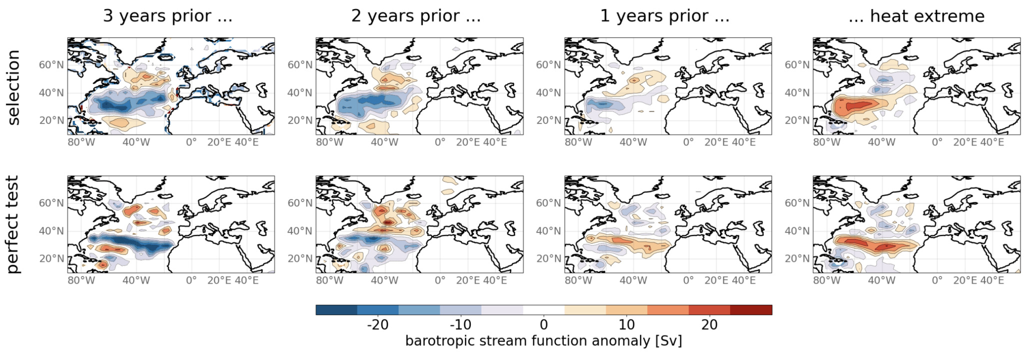

Figure B.4: Underlying mechanism. Anomalies of 5-10yr bandpass-filtered barotropic stream function for different lags prior extremely warm European summers for our ensemble selection (upper row) and a „perfect“ selection (including knowledge when heat extremes occur, lower row). Period 1964-2021.

The analysis of different combinations within the selection of ensemble members, based on different variables shows that only the selection of ensemble members that change from negative barotropic stream function anomalies to positive barotropic stream function anomalies and coincide with positive mean sea level pressure anomalies (- + +) leads to an increase in the prediction skill of sub-dec CEU SAT (Fig. B.5). All other combinations fail (barotropic stream function anomalies that turn from positive to negative and coincide with positive mean sea level pressure anomalies (+ - +), barotropic stream function anomalies that turn from negative to positive and coincide with negative mean sea level pressure anomalies (- + -), barotropic stream function anomalies that turn from positive to negative and coincide with negative mean sea level pressure anomalies (+ - -)(Fig. B.5). The spread of the selected ensemble members of these other combinations is in the full range of variability and could thus not lead to any improvement of sub-dec CEU SAT prediction skill.
In summary, the improvements in prediction skill of the sub-decadal CEU SAT variations are due to sub-decadal North Atlantic Ocean heat accumulation and thus confirm again the mechanism as described by Wallberg et al. (2023).

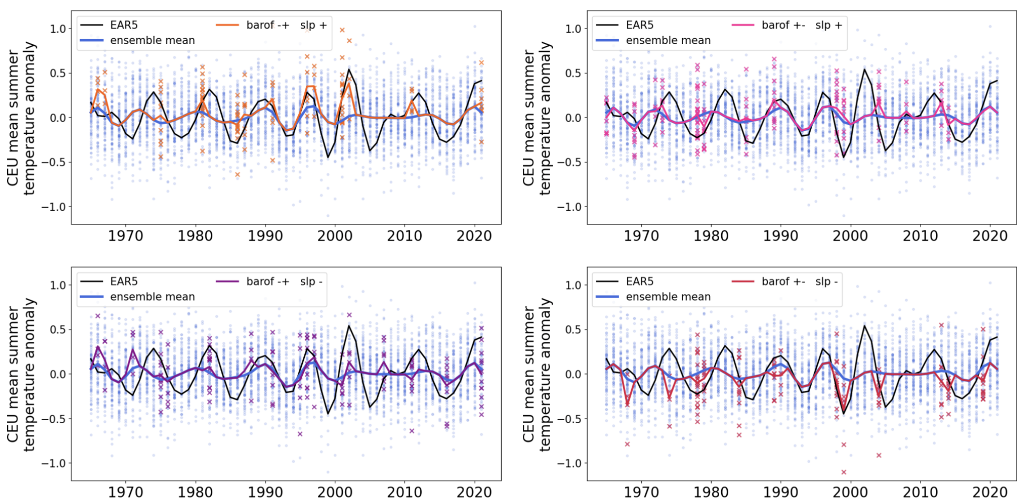

Figure B.5: Different ensemble member selections showing anomalies of sub-dec CEU SAT for lead year 3 for ERA5 (black) and the hindcast ensemble mean (blue) and ensemble selection (orange (same as Fig. 3a), pink, purple, red). The single (selected) ensemble member are marked through dots (crosses).

Link to non sub-decadal time scales

The results shown previously, demonstrate the influence of the accumulation of heat in the North Atlantic Ocean predicted CEU SAT by application of sub-decadal filtering. However, we want to investigate whether the ensemble member selection also improves also matters for the "real", non-sub-decadal-filtered world. Here, the distribution of the CEU SAT of the selected ensemble means corresponds much more to the ERA5 histogram shown above than to the full ensemble mean histogram (Fig. B.6a). Accordingly, the frequency of the extreme CEU SAT is better represented in the selected ensemble mean than in the full ensemble mean.

Furthermore, we want to analyze the total number of correctly predicted hot summer days per summer (again on non-sub-decadal time scales). Here, hot summer days are defined as those with a daily mean CEU SAT of more than 20°C (T>20°C). Comparing the occurrence of these hot summer days between ERA5 and the full ensemble mean reveals clear differences. The full ensemble mean shows low variability and cannot adequately represent the values observed in ERA5 (Fig. B.6b, blue bars). While the frequency matches quite well for many years between the full ensemble mean and ERA5, the amplitude of the number of hot summer days is significantly underestimated in the full ensemble mean. However, a promising trend emerges in the selected ensemble mean, which succeeds in increasing the amplitude of the number of hot summer days for several years. As a result, the total number of hot summer days is better represented compared to the full ensemble mean (Fig. B.6b, orange bars). This improvement in the prediction of the number of hot summer days is notable in 15 years, with only 3 years of unintended deterioration. The remaining 39 years show no change. These improvements in the prediction skill of hot summer days are consistent with both the corresponding positive sub-dec CEU SAT variations and the extreme CEU SAT values in the unfiltered temperature time series (Fig. B.6b, time series).

This analysis highlights that our ensemble selection approach seems to have identified ensemble members that are more similar to ERA5 than the full ensemble mean. In summary, the ensemble selection approach leads to a better prediction skill of the total number of hot summer days and effectively captures the amplitude and variability of these events compared to the reanalysis data. Thus, this provides a surplus in the prediction of heat extremes, on to of all other sources of internal variability and external drivers.

(a)

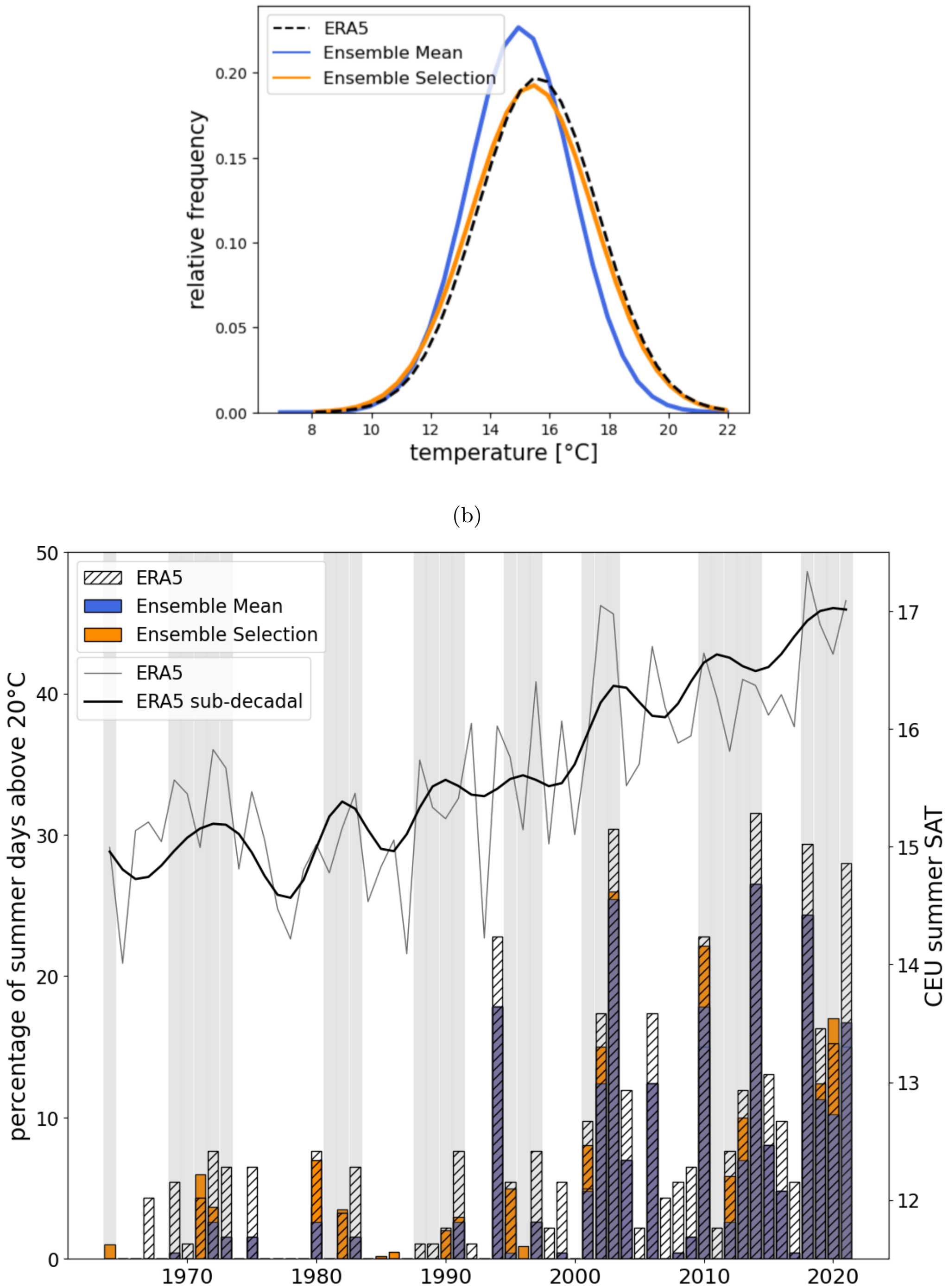

Figure B.6: Link to non-sub-decadal time scales. a) Histogram of sub-dec CEU SAT for ERA5 (black), the ensemble mean (blue), and the ensemble selection. (orange). b) Percentage of CEU SAT days above 20°C for ERA5 (dashed bars), the full ensemble mean (blue bars), and the selected ensemble mean (orange bars) together with the ERA5 CEU SAT time series (grey) and the sub-dec CEU SAT time series. The hindcast data are bias corrected with ERA5 as reference. Grey shading of the background indicates positive sub-decadal phases within the detrended time series. Period 1964-2021.

B.4 SUMMARY AND OUTLOOK

This study presents a powerful tool to select ensemble member based on sub-decadal processes in the North Atlantic coupled climate system in order to improve the prediction skill of extremely warm European summers, as well as CEU SAT overall. We show that the new ensemble selection based on specific anomalies of the barotropic stream function and mean sea level pressure leads to a better representation and prediction skill of sub-dec CEU SAT variations in a decadal prediction system. The correlation coefficient between the full ensemble mean/ selected ensemble mean and ERA5 increases from 0.42 to 0.57, indicating improved accuracy. The ensemble selection captures about nine phases (including 13 years) of sub-dec CEU SAT variations, resulting in ACCs of up to 0.5, demonstrating the efficacy of the approach in predicting heat extremes. The study further verifies the link between oceanic anomalies and heat extremes by analyzing barotropic stream function anomalies for different lags. The selected ensemble members exhibit patterns consistent with the mechanism described in previous research by Wallberg et al. (2023), indicating the relevance of sub-decadal North Atlantic Ocean heat accumulation. Additionally, the ensemble selection approach demonstrates improvements in predicting the total number of hot summer days and reproducing the amplitude and variability of these events compared to ERA5, indicating its effectiveness in capturing extreme heat events not only on sub-decadal time scales.

The study highlights the importance of considering the North Atlantic Ocean and climate variability in predicting extremely warm European summers. The findings suggest that sub-decadal North Atlantic Ocean heat accumulation plays a crucial role in driving these events. The improved prediction skill of CEU SAT obtained through the ensemble selection method offers valuable insights for mitigation and adaptation measures. Further research can explore the potential of this approach in long-term projections and its applicability to other regions affected by heat extremes. Overall, the study contributes to the comprehensive understanding and prediction of heat extremes and extremely warm summers, aiding in effective decision-making and reducing the impacts on human lives, the economy, and infrastructure.

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