CLINT

CLIMATE INTELLIGENCE

D4.1
Extreme Event Causation Analysis

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Author(s):	Eduardo Zorita, Niklas Luther, Elena Xoplaki, Jorge Pérez-Aracil
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LIST OF ACRONYMS

Abbreviations

AB: Advisory Board
CA: Consortium Agreement
CS: Climate Service
DDP: Deliverable Development Plan
DoA: Description of Action (Annex I of the Grant Agreement)
DM: Deliverable Manager
EE: Extreme Events
EC: European Commission
GA: Grant Agreement
GAs: General Assembly
MB: Management Board
Mx: Month number
PC: Project Coordinator
PI: Principal Investigator
PO: Project Officer
PR: Project Review
QC: Quality Control
QM: Quality Management
RP: Reporting Period
WP: Work Package

Report Specific

IPR: Intellectual Property Repository
C3S: Copernicus Climate Services
CAMS: Copernicus Atmosphere Monitoring Service
CEMS: Copernicus Emergency Management Service
CMIP: Climate Model Intercomparison Project
DRM: Disaster Risk Management
DRR: Disaster Risk Reduction
EOSC: European Open Science Cloud
WMO: World Meteorological Organisation

EXECUTIVE SUMMARY

This report reviews existing knowledge, data and models for physical causation analysis for different climate extremes, including concurrent extremes. It also includes results from the CLINT project regarding the analysis of climate model simulations from the CMIP6 repository targeting the causal links between sea-surface temperatures and some types of extreme events. We also include in the analysis a new simulation with a long, high-resolution regional atmospheric model for Europe covering the 20th and 21st centuries, which CLINT partners can use as a sort of long, highly resolved European reanalysis-like data set to pre-train machine learning models and analyse changes in extreme events.

The review of the existing literature identifies several causal factors for European climate extremes. For the winter season, the state of the polar vortex, including Sudden Stratospheric warming events, arises as one important factor. It is related to the North Atlantic Oscillation, precipitation anomalies in Southern Europe and cold spells in Northern Europe. However, the origins of the variability of the polar vortex are more uncertain. Similarly, the impact of sea-surface temperatures and sea-ice anomalies on atmospheric circulation and extreme events is still debated. This impact can be critical because of ongoing ocean warming and rapid changes in the cryosphere. Soil moisture appears as an important boundary condition for summer extreme temperatures and heat waves, but persistent atmospheric circulation forcing is necessary, which makes their prediction at seasonal and longer timescales challenging.

Concurrent extremes have recently been redefined in terms of compounded impacts, and therefore, they deviate from the purely physical definition of EE. In general, concurrent extremes are usually linked to persistent (over weeks) anomalous conditions. A paramount example is atmospheric blocking, which imprints temperature, causing HW (if occurring in summer), precipitation, and soil moisture (if occurring in the wet season). The interconnection within a concurrent event can occur across time and space, as catchment memory distributes the impact of the EE across different geographical and societal compartments at different times.

The analysis of the CMIP6 atmospheric simulations indicates that, in general, the impact of sea-surface temperatures is relatively weak, but it also shows that they offer some predictability for winter precipitation and summer temperature anomalies. A more focused analysis of the CLINT uses the case of the Iberian meteorological drought to show that sea-surface temperature anomalies in the Tropical Pacific are partly responsible for multiannual sequences of extreme dry winters in the Iberian Peninsula during the 20th century. El Niño-Southern Oscillation events in the Tropical Pacific also impact Lake Como precipitation, another CLINT use case.

1. INTRODUCTION

1.1 The role of climate simulations in causality analysis

Identifying causal relationships between Extreme Events (EE) and their physical drivers is relevant for supporting the results obtained from the data analysis based on machine learning (ML) algorithms. Since those ML algorithms are usually purely data-driven, they can reveal statistical links that are not necessarily physically consistent. As no controlled experiments can be conducted with the climate system, climate simulations play a central role in unambiguously identifying causes and effects. A combination of climate simulations and the results obtained from ML can provide a much more robust picture of the causal relationships and ensure better detection, prediction, and future projections of EE. The focus of WP4 within CLINT lies in combining the two lines of evidence provided by climate models and ML analysis to ascertain links between EE and their drivers, going beyond the pure identification of their mutual correlations. In this deliverable, we focus on the climate modelling part, with some indications about the implications for the ML causality analysis in CLINT. This AI-enhanced causality analysis will be summarised in Deliverable 4.2 later in the project.

This CLINT climate-model-based causality analysis includes data from free-running, fully coupled atmosphere-ocean-vegetation simulations. These simulations statistically mimic the behaviour of the climate system. The causal relationships between simulated EE and their drivers can be analysed by applying the same causality algorithms to observational data sets. The advantage is that the sample size can be expanded with the only limitation of computing power (e.g. climate simulations of several millennia are not unusual). In addition, to mimic laboratory experiments, we can carry out simulations with only part of the climate system allowed to vary freely (e.g., the atmosphere), and other parts of the system prescribed (e.g. sea-surface temperatures). It also allows us to distinguish between driver factors (the prescribed boundary conditions) and the driven variables (the model response to the drivers). Hence, the causality analysis is more straightforward than a fully coupled system. A disadvantage of these experiments is that, although climate models have attained high realism, they differ from the real world. Therefore, the conclusions derived from these numerical experiments must be considered carefully. This distinction makes using different climate models necessary to exclude possible artefacts arising in a single climate model. It also warns of the over-interpretation of causal relationships derived from the data obtained in a single simulation with a single climate model.

In the climatological context, causal relationships between EE and their drivers depend on the timescale and can broadly be classified as immediate and background causality. For instance, predicting heat waves (HWs) at seasonal time scales may be related to specific circulation patterns favouring warm air masses' advection to a particular region (immediate causality). However, due to anthropogenic climate change, Europe has witnessed a significant increase in average temperatures over the last century. HWs are becoming more frequent and intense due to the

mean temperature increase, and not necessarily due to changes in atmospheric circulation patterns that are the immediate cause of HWs (background causality). A combined situation in which the base temperature levels and the frequency or intensity of circulation patterns change with climate change is possible. The term causality, therefore, may bear a different meaning, depending on the context. When a HW is favoured by generally higher mean temperatures or a generally increased probability of a particular synoptic circulation pattern (background causality), causality is denoted attribution (to anthropogenic climate change), which is the focus of WP5 within CLINT.

1.2 Causality of compound events and concurrent EEs

The current definition of compound events (CE) involves their physical and societal impacts, i.e. it goes beyond the pure realm of climate dynamics. Under this definition, the analysis based on climate simulations is curtailed, as climate models often do not include all physical impacts (flooding) and certainly no societal impacts. However, climate simulations can provide valuable insights into the physical mechanisms and links between EE that may simultaneously occur and be physically connected. For instance, two EE, or two aspects of one EE taken in isolation, would not be considered exceptional and can, in conjunction, genuinely become a threatening EE regarding its impacts. The most apparent example is the connection between HW and droughts.

While many types of single extreme events have been associated with strong impacts on socio-economic sectors (e.g. Zampieri et al., 2017; Zscheischler and Fischer, 2020; Hao et al., 2022), the combination(s) of such events can further amplify these impacts in a non-linear manner as many systems have a degree of resilience to single extreme events but are unable to cope with multiple stressors (Leonard et al., 2014; Hao et al., 2018; Zscheischler et al., 2018; Zscheischler and Fischer, 2020; Zhang et al., 2021; Hao et al., 2022; Xoplaki et al., 2023). Ecosystems may not be directly adapted to the co-variability of temperature and precipitation, so bivariate anomalies can have significant impacts without temperature or precipitation being extreme in the univariate sense (Mahony and Cannon, 2018). An example from the food sector is the so-called false spring events. They occur when wet and warm conditions prevail in winter, triggering unusually early plant growth, which is then damaged by a frost event or severe drought the following spring, resulting in yield losses (Allstadt et al., 2015; Chamberlain et al., 2019). Wet and warm conditions in hot regions can also be particularly critical for human health, as the ability to release heat through evaporative cooling is impeded, disrupting the human body's thermoregulatory system (Davis et al., 2016; Russo et al., 2017). Both types of events are expected to occur even more frequently in the future due to climate change (Ault et al., 2013; IPCC, 2021).

The observation that high impacts may be caused by a combination of potentially non-extreme climate events fostered studying compound events (CEs). The Intergovernmental Panel on Climate Change (IPCC; Seneviratne et al., 2012) defines CEs as (1) two or more extreme EE occurring simultaneously or successively, (2) a combination of EE with underlying conditions that amplify the

impact of the events, or (3) a combination of EE that are not themselves extremes but lead to an EE or extreme impact when combined. Zscheischler et al. (2018) further defined CEs as combinations of multiple drivers, hazards and/or events that are individually not necessarily EE but that, in combination, often lead to disproportionate impacts on people and ecosystems (Seneviratne et al., 2012; Leonard et al., 2014; Caldeira et al., 2015). Considering that many socio-economic sectors are affected by weather and climate conditions, an appropriate risk assessment should be based on the multivariate nature of these types of events (Raymond et al., 2020), as the risk and associated return periods can be significantly underestimated if only a single event is studied (Wahl et al., 2015; Zscheischler and Seneviratne, 2017). As many compound events are closely linked to anthropogenic forcing (IPCC, 2021), studying and understanding them is becoming increasingly important.

1.3 Causality, Artificial Intelligence, and Climate Simulations

Artificial intelligence has recently gained popularity in climate science (e.g. Reichstein et al., 2019) due to the ability of algorithms to learn from data with highly complex, nonlinear relationships that can also be useful for detecting and predicting extreme events. Deep learning methods, in particular, have recently been employed to learn theoretically arbitrary nonlinear functions or relationships (Efron and Hastie, 2016; Goodfellow et al., 2016). However, many of these methods have been criticised as black boxes, particularly in climate, as they do not necessarily reflect the physical relationships (McGovern et al., 2019; Kashinath et al., 2021; Schultz et al., 2021), and the learned relationships may appear correct for the wrong reasons (Lazer et al., 2014; Lapushkin et al., 2019).

Causal methods enable the study of the interconnectivity of high-dimensional systems, such as climate, and provide an adequate way to identify causal relationships between climate variables that can be more robust than correlation- or regression-based techniques (Runge et al., 2019). One limitation in the causality and attribution of EE is the limited sample size in the observational record, as, by definition, EE are those that deviate from the 'norm' and are viewed as exceptional. Climate simulations may help provide a much larger sample size of 'modelled extremes'. Although climate models have biases, climate simulations can help identify which causal links are more likely in the real world. They also provide a test bed to assess the reliability of ML algorithms in controlled conditions. Deliverable 4.2 will go into deeper detail on ML-enhanced causality analyses and the interaction between simulations and ML.

2. DRIVERS OF EXTREMES AND COMPOUND EVENTS FROM THE PERSPECTIVE OF CLIMATE MODELLING

Table 1 includes potential candidates with a causal link to EE compiled from the published literature, and our research carried out in CLINT (e.g. Deliverable 3.1 EE detection). Note that here and elsewhere in this report, *drought* is constrained to denote only meteorological drought unless otherwise specified. The mechanisms that link these large-scale drivers to particular extremes are detailed below.

Table 1 - Potential causal predictors for CLINT EE and their mechanisms.

Potential Causal Predictor	Target	Mechanism
Extratropical sea-surface-temperature	Heatwaves	Advection of warm air masses
(West) Mediterranean sea-surface temperatures	Southern European heatwaves, summer drought	Advection of warm air masses
Tropical Atlantic sea-surface temperatures	Winter meteorological droughts	Impact on the winter North Atlantic Oscillation
Stratospheric Polar vortex	Winter meteorological droughts	Impact on the winter North Atlantic Oscillation
Arctic sea-ice cover	Winter Cold spells	Weakening of polar vortex
Planetary wave activity	Winter meteorological droughts	Impact on winter North Atlantic Oscillation
Atlantic Meridional Overturning Circulation	Tropical cyclones	Modification of the tropical meridional sea surface temperature gradient
North Atlantic Subpolar Gyre	Multiannual Central European meteorological droughts	Atmospheric blocking in response to cold North Atlantic surface
Spring soil moisture	Summer heatwaves	Modification of evaporative surface cooling

2.1 Oceanic predictors

The temperature of the ocean can have an impact on large-scale atmospheric circulation and evaporation from the ocean. This latter effect is well established, and higher SSTs should, in

principle, enhance moisture advection, particularly in coastal areas, leading to fewer droughts and localised flooding. The impact on the extratropical atmospheric circulation is more controversial since its internal variability is large, even with constant boundary conditions. Identifying a strong signal in the mean circulation in observations and simulations has been difficult. Nevertheless, any possible impact on EE would increase with the magnitude of SSTs. For example, it has been suggested that the 2003 European HW may have been associated with anomalously warm SSTs in the Indian Ocean and Mediterranean, influencing geopotential height and precipitation anomalies across Europe (Black and Sutton, 2006).

In long climate simulations, North Atlantic SSTs at mid-latitudes have been linked to HW (Duchez et al., 2016) and multi-decadal droughts over Europe (Ionita et al., 2021b). At these long-time scales, North Atlantic SSts are modulated by the Atlantic Meridional Overturning Circulation (AMOC), which transports warmer water masses from the tropics towards the polar latitudes. A more intense AMOC reduces the meridional temperature gradient in the North Atlantic basin. The AMOC index, usually defined as the maximum of the zonally averaged meridional stream function, is a potential causal predictor not only of European meteorological droughts in the continent and the frequency and intensity of hurricanes in the Atlantic basin, some of which may transition into extratropical storms. Whether or not the AMOC influences the number of storms or their intensity is still an open question. Although the observations do not suggest a clear statistical connection, ML algorithms could be more capable of identifying this link. A significant drawback is the short length of the observational record of the AMOC, which just covers a few decades. However, this limitation can be overcome when analysing climate model simulations.

Tropical Atlantic SSTs have also been shown to impact the North Atlantic Oscillation (NAO) state at seasonal time scales (Scaife et al., 2016). This result was obtained with one climate model but has yet to be confirmed using other models. Since tropical SSTs in the Pacific basin impact droughts and pluvials in the Western US, a similar link may also occur in the Atlantic basin. However, the Pacific basin is dominated by El Niño Southern Oscillation (ENSO), a powerful coupled mode of internal variability with global implications, whereas 'Atlantic ENSO' has a much more constrained spatial impact (Lübbecke et al., 2018). Tropical Atlantic SSTs should be considered a potential predictor of droughts and HWs due to their possible impact on the NAO.

The North Atlantic Subpolar Gyre (NASG) modulates the strength of the oceanic circulation in the subpolar region of the North Atlantic, which influences SSTs. A warmer NASG has been linked to colder and wetter summer temperatures in northern Europe and higher temperatures in the Mediterranean region (Hermanson et al., 2014). At longer timescales, climate change may also cause a weakening of the NASG and the AMOC (the so-called warming hole, Ghosh et al., 2023). The NASG should be included as a potential causal predictor of the intensity of HWs in Northern Europe.

The preliminary analysis conducted within CLINT has been based on the AMIP-type simulations of the CMIP6 project (MPI-ESM-2 with two different resolutions, CESM2 and EC-Eartth3). Observed SSTs drive these atmosphere-only simulations and cover, in general, the last decades of the 20th century - some models cover the period starting in 1950, others as late as 1979. Almost all models participating in CMIP6 provide an ensemble of AMIP simulations, where each simulation has been started with different initial atmospheric conditions. A strong impact of the SSTs on EE should be reflected in a simultaneous occurrence of those EE across all, or almost all, members of the same model ensemble.

2.2 Arctic sea-ice cover

Sea-ice cover strongly modulates the heat fluxes between the atmosphere and the ocean. An anomalous reduction of sea-ice cover in the autumn season in the Nordic Seas increases this upward heat flux and can potentially impact the atmospheric circulation. There has been a lively debate about the relevance of this mechanism for some cold spells (Barnes and Screen, 2015). There is a lively debate as to whether anthropogenically induced retreat of Arctic sea ice cover favours a wavier meridional flow in winter and, hence, a higher frequency of cold spells in some regions of the Northern Hemisphere, such as the Euro-Asian sector. Whereas some authors point to a clear physical link between autumn sea-ice cover and the breakdown of the boreal polar vortex in winter (Francis et al., 2012), modelling studies prescribing reduced sea-ice cover reflect minor responses in the atmospheric circulation, which would not be able to significantly impact air temperatures over the continent (Cohen et al., 2020). The question is still debated, but sea-ice cover should be regarded as a potential predictor of EE. Current consensus indicates that the influence of Arctic sea-ice cover changes on atmospheric circulation and EE is physically plausible but undetectable in the observational record, suggesting that the forcing is still weak compared to the internal variability or that other drivers mask the signal.

Note that cold spells are not the focus of CLINT and will not be explicitly considered in this deliverable. However, winter atmospheric circulation is related to meteorological episodes in Southern Europe (see next section). Hence, the impact of Arctic sea-ice cover anomalies on the recent drought periods experienced in this region cannot be ruled out.

2.3 Atmospheric circulation

Many types of EE are intrinsically triggered or at least modulated by the atmospheric circulation. For instance, persistent blocking highs, subtropical highs and atmospheric stagnation events are typically atmospheric patterns associated with warm and dry conditions (Zhang et al., 2021). High-pressure systems increase shortwave radiation and reduce moist air inflow underneath, thus favouring HW and meteorological drought conditions (Dong et al., 2018; Schumacher et al., 2019), while stagnation events prevent ventilation (movement of air masses) and deposition of atmospheric pollutants (Horton et al., 2014; Zou et al., 2020; Garrido-Pérez et al., 2018). For example, blocking can lead to a shift in storm tracks and meteorological drought conditions in

winter and high-pressure systems and HW episodes in summer (Kautz et al., 2022). In the Northern Hemisphere summer, warm and dry conditions can also be associated with amplified quasi-stationary Rossby wave patterns (e.g. Kornhuber et al., 2020), allowing CE to occur through the hemisphere, potentially yielding global impacts. In Europe, such conditions are associated with Rossby wave trains propagating from the United States (Ionita et al., 2021a) and to preferred stationary jet stream positions (Duchez et al., 2016) and double jets (e.g. Rousi et al., 2022).

Focusing on Europe, changes in the atmospheric circulation over the North Atlantic can impact the distribution of precipitation. For example, it is very well known that positive phases of the NAO favour drier conditions in southern Europe and the Mediterranean and wetter conditions in northern Europe, which is also reflected in drought indicators (Hao et al. 2019b; Vicente-Serrano et al., 2011). One of Southern Europe's most intense drought episodes occurred in 1991-1992. This multi-year drought was linked to a period of intensifying NAO that culminated in an unusually strong and persistent positive NAO phase. The origins of the multi-annual variability of the NAO remain obscure. Still, its understanding will undoubtedly be one of Europe's most valuable results for long-term drought prediction. Droughts and HW in Europe have also been shown to be connected to these types of phenomena in Australia (Toreti et al., 2019), with a large-scale mechanism being the Arctic Oscillation potentially modulating connections between the North Pacific Oscillation and the ENSO (Chen et al., 2013).

The NAO displays large internal variability at sub-seasonal and seasonal time scales, but some potentially skilful predictors have been identified. During the so-called Stratospheric Sudden Warming events (SSW) the state of the stratospheric polar vortex (e.g. Scaife et al., 2015, usually characterised by strong westerly winds in the lower and upper troposphere, breaks down. This signal propagates downward to tropospheric levels and can persist for a few weeks, giving rise to cold weather outbreaks in northern Europe and wet winters in Southern Europe - a typical negative NAO pattern. A quantitative prediction of this chain of events is possible with current numerical weather prediction models. SSWs represent one of the primary sources of subseasonal-to-seasonal predictability in the northern winter extratropics (e.g. Domeisen et al., 2022), but the uncertainty at these rather long lead times remains large. Moreover, the skill is realised only when SSWs are already included in the initial conditions of the S2S forecast system (Merryfield et al., 2020;). Current challenges are thus to anticipate the SSW and its associated impacts ML methods could contribute to reducing those uncertainties in the otherwise well-established causal chain of events.

In this sense, a key driver of the stratospheric polar vortex in general, and SSW in particular, is the activity of vertically propagating planetary waves (PW) of wavenumber 1, 2 and 3. These tropospheric waves originate near the surface and propagate vertically up to the stratosphere, where they break, weakening the polar vortex (e.g. Matsuno 1971). Strong enough PW can reverse the stratospheric westerlies, giving rise to SSW events (Domeisen et al., 2020), although SSW can also occur without tropospheric forcing (de la Cámara et al., 2019) Therefore, the PW activity in

the late autumn or early winter represents an additional predictor of the subsequent state of the NAO due to its influence on the polar vortex and SSW.

Another large-scale driver of HW and droughts is the Scandinavian teleconnection pattern, which can result in reduced precipitation over northeastern Europe during its positive phase (Bueh and Nakamura 2007). Another important mode of variability linked to European EE is the Eastern Mediterranean Pattern (EMP): This mode of variability over the eastern Mediterranean Sea has been linked to variations in temperature, precipitation, and cyclone activity over southern and eastern Europe regions. Positive phases of the EMP are associated with warmer and drier conditions, while negative phases are associated with cooler and wetter conditions. This link is primarily simultaneous at monthly time scales, and as such, the index does not provide direct predictability of droughts or HWs. However, the induced precipitation anomalies impact soil moisture, which can be a relevant causal predictor of a HW (see next section). The EMP is only partly related to the NAO due to its spatial fingerprint, which partially overlaps with the NAO dipole (Hatzaki et al., 2007).

The East Atlantic or East Atlantic/Western Russia (EA/WR) pattern has also been linked to variations in temperature and precipitation in Europe. In principle, it has a different circulation pattern from the NAO, and as for the EMP, its role in modulating soil moisture in the subsequent seasons needs to be considered.

Atmospheric circulation anomalies in remote regions can also influence European EE (see also Section 2.5). For example, in addition to ENSO, the enhanced predictability of the 2015-2016 winter by the Met Office extended prediction system was attributed to the state of the polar night vortex and the Quasi-Biennial Oscillation (QBO), which is a natural quasi-oscillation in the direction of tropical lower stratospheric winds. Therefore, these three predictors (ENSO, polar night index, and QBO) should also be considered by the ML prediction algorithms targeting winter droughts in Southern Europe.

An important class of CE is combinations of wet and warm conditions, which can induce false spring events relevant to agriculture and health through humid HW (see section 1.2). Wet and warm conditions can occur due to irrigated agricultural land in warm and humid regions, where the moistening effect of irrigation dominates, leading to increased wet bulb temperatures (Xue and Eltahir, 2015; Raymond et al., 2021). Other studies have linked such conditions to moist advection of warm air that may originate from tropical areas (Katsafados et al., 2014; Freychet et al., 2017; Russo et al., 2017). However, recent reviews (Raymond et al., 2021; Zhang et al., 2021) conclude that the drivers still need to be better understood.

2.4 Soil moisture

As mentioned in the previous section, atmospheric circulation patterns may not be predictable on subseasonal-to-seasonal time scales. However, if they display a strong anomaly in one season,

mostly spring, they can influence the soil's state and evolution in the following seasons, promoting summer soil moisture deficits and land-atmosphere feedback (Miralles et al., 2019). The state of the land surface, including soil moisture, vegetation cover, and surface albedo, can impact the energy and water balance in the atmosphere.

Soil moisture deficits reduce evapotranspiration, resulting in sensible local heat (Barriopedro et al., 2023; Domeisen et al., 2023). Furthermore, decreased evapotranspiration leads to drier air, reducing cloud cover and increasing shortwave radiation (Seneviratne et al., 2010). In transitional regions, soil moisture plays a role in the self-reinforcement of droughts. It can affect the atmospheric evaporative demand (AED), defined as the maximum amount of evapotranspiration from land surfaces if not limited by water (IPCC, 2021). During droughts, the low relative humidity, high air temperature and reduced cloudiness result in increased AED, which triggers soil evaporation and plant water consumption through transpiration (Miralles et al., 2019). Furthermore, plants tend to close stomata under increased water vapour deficit to avoid water loss, further reducing evapotranspiration and contributing to dry conditions (Massmann et al., 2019). When combined with strong winds, these dry conditions can set the stage for flash droughts (Otkin et al., 2018; Zscheichler et al., 2020; Pendergrass et al., 2020). Increased AED can intensify agricultural and environmental droughts by further stressing crops (Willems et al., 2013; Allen et al., 2015; Stocker et al., 2018; Liu et al., 2020) and increasing crop water use in irrigated areas (García-Garizábal et al., 2014), thus also contributing to hydrological droughts (Vicente-Serrano et al., 2017). In turn, AED is strongly influenced by air temperature. In particular, HWs cause AED increases in summer, which can thus aggravate droughts, as reported for the 2021-2022 European drought (Garrido-Pérez et al., 2024). Therefore, meteorological droughts and HW tend to intensify each other, accelerating the resulting impacts on socio-economic sectors such as agriculture (Lesk et al., 2016; Zampieri et al., 2017; Toreti et al., 2019b), As a consequence, soil moisture is considered an important modulator of many of the considered EE within CLINT.

This reinforcing cycle can also be present on longer timescales: For example, suppose a region experiences a persistent high-pressure pattern and dry weather conditions during spring. This can reduce soil moisture and increase the likelihood of HW the following summer. A prominent example was the HW in Western Europe in the summers of 2003 and 2010 (Seneviratne et al., 2010; Fischer et al.,2007; García-Herrera et al., 2019; Barriopedro et al., 2011; van Garderen et al., 2021). A dry spring left the soils in a water deficit, curtailing their evaporative cooling in summer. A very stable high-pressure situation during summer led to two of the strongest European HW in recent decades (Barriopedro et al., 2011). This mechanism has been used to retrospectively predict European HWs with some success (Domeisen et al., 2023).

Soil moisture may also feed back onto the atmospheric circulation if these soil moisture anomalies reinforce the circulation pattern anomalies that gave rise to soil moisture anomalies in the first place. One example is the state of soil moisture during the autumn months. Dry soil conditions in

the autumn can reduce the moisture available for vegetation and groundwater recharge during winter, increasing the likelihood of winter drought (Vicente-Serrano et al., 2011).

While the discussion above demonstrates that the climate can affect soil moisture, human intervention may also influence it. For instance, land cover changes (e.g. deforestation; Lejeune et al., 2018) and agricultural management (e.g. irrigation Thiery et al., 2020) can affect the characteristics of HW. For example, irrigation enhances evapotranspiration, which can cool the surface in the short term (Teuling et al., 2010; Lejeune et al., 2018). Long-term cooling can also be induced by certain forest types or trees, such as deciduous trees, due to their higher albedo and stomatal conductance (Schwaab et al., 2020).

2.5 Atmosphere-ocean coupled modes of natural variability

Internal climate variability can impact the likelihood and intensity of many EE. Much of these internal variations can be explained by atmosphere-ocean coupled modes of variability. For instance, hot and dry conditions are favoured during the positive phase of ENSO, as shown, for example, in South Africa (Hao et al., 2019a), South America (Cai et al., 2020) and the USA (Hoerling et al., 2013). ENSO and the Indian Ocean Dipole (IOD) have also been shown to influence such events in Australia (Reddy et al., 2022). The positive phase of the IOD could also promote warm and dry conditions in Europe (Saji and Yamagat 2003). Still, the discussion of the physical links remains open (Steptoe et al., 2018). In addition, the major modes of variability in European climate (e.g. NAO) favour extreme winter precipitation in central and northern Europe and but hinder extreme precipitation in southern Europe (Hao et al., 2019b). However, these connections can be strongly influenced by multidecadal variability and the state of other large-scale climate drivers (Willems, 2013).

Often, the associations of these teleconnections with droughts and HW have been studied individually, but they may be strengthened if the modes of variability are in phase. For example, it has been shown that when the Pacific Decadal Oscillation (PDO) and ENSO are in phase, drought events appear to be enhanced in many regions of the world (Ngyuen et al., 2021 and that positive phases of IOD and ENSO favour large-scale severe droughts across the Australian continent (Steptoe et al., 2018). Furthermore, some authors suggest that the effect of ENSO may be more visible in Europe when the NAO is weak and the PDO is in a positive phase (Zanchettin et al., 2008).

Some studies indicated that the relationships between the climate modes of variability and the EE can be non-stationary, meaning their dependence can vary over time (Steptoe et al., 2018). For example, Lopez-Parages et al. (2015) discuss that the links between ENSO and precipitation anomalies in the Euro-Mediterranean area are non-stationary as they depend on changes in the zonal mean upper-level flow, which then affects the propagation of air from the tropics to the extratropics. Furthermore, besides long-term trends, the global warming signal also affects the variability of many climate modes contributing to EE (Horton et al., 2015). It could explain some of these observed non-stationarities.

Focussing on the winter ENSO signal in Europe, the primary causal mechanism is the generation of Rossby waves by ENSO-induced precipitation precipitation anomalies in the Tropical Pacific, which propagate over the Northern Hemisphere, disturbing the usual circulation patterns (López-Parages and Rodriguez-Fonseca, 2012). The impact of ENSO was partly responsible for a successful hindcast (post-hoc) prediction of the European winter in 2015-2016 by the Met Office extended prediction system.

2.6 Anthropogenic forcings

As global temperatures rise, many types of EE are expected to increase in frequency and severity, so human forcing can be considered a single driver (IPCC, 2021). For warm and dry events, their frequency is expected to increase (Zscheischler and Seneviratne, 2017; Alizadeh et al., 2020; Vogel et al., 2020; Meng et al., 2022). The main driver of this phenomenon is the enhancement of HW due to rising global temperatures, which implies that hot and dry conditions will become more frequent in the future (IPCC, 2021). For example, record-breaking summers such as the summer of 2018 in central Europe could become the norm by the mid-21st century (Toreti et al., 2019a) and could not have occurred without human influence (Vogel et al., 2019).

Humid HW are also projected to become more frequent (Russo et al., 2017; Meng et al., 2022; Barriopedro et al., 2023), which can be critical for human health in some regions. Indeed, it is discussed that by 2100, the 6-hour wet bulb temperature in tropical and subtropical areas may rise above 30 °C and possibly even exceed 35 °C, which is considered a critical threshold for human survival (Pal and Eltahir, 2016).

For tropical cyclones, identifying trends remains a challenge due to the temporal length and quality of the data, and the IPCC (2021) concluded that confidence in long-term trends is generally low due to these issues.

3. IMPACT OF SEA-SURFACE TEMPERATURES ON MEAN SEASONAL CLIMATE USING SIMULATIONS FROM THE ATMOSPHERIC MODEL INTERCOMPARISON PROJECT

As reviewed in section 2.1, SSTs are considered one of the most obvious external drivers of atmospheric circulation and, therefore, possibly also of EE caused by anomalous weather patterns. Before embarking on a series of sensitivity experiments with coupled and regional climate models, WP4 of CLINT analysed the simulations with atmosphere-only global models available in the Climate Model Intercomparison Project version 6 (CMIP6, Eyring et al., 2016). These are the so-called AMIP-type simulations (Atmospheric Model Intercomparison Project). Almost all models participating in CMIP6 provide an ensemble of AMIP simulations, where each simulation has been started with different initial atmospheric conditions. These atmospheric simulations share the observed SST and sea-ice cover as common boundary conditions. The AMIP simulations considered here also share external forcings, including the concentration of greenhouse gases and volcanic eruptions. The greenhouse gas concentrations are responsible for most observed and simulated temperature trends but cannot drive interannual or decadal variability of the atmospheric circulation. If we do not consider volcanic eruptions, any correlation of interannual climate variability (or any other measure of synchronous behaviour) present in the set of simulations can be attributed to the effect of the commonly prescribed SST.

Similarly, a robust (physically based) impact of SST on EE should be reflected in a simultaneous occurrence of EE across all, or almost all, members of the same model ensemble. Therefore, identifying commonalities in the time evolution of the simulated atmospheric circulation and the occurrence of EE across all or most simulations can provide hints about the causal role of observed SSTs. Should atmospheric anomalies or EE occur simultaneously across simulations, they could be used as predictors for those types of EE. These results can guide the more complex sensitivity simulations and ML analysis with coupled climate models foreseen later in the project.

An advantage of this analysis is that it automatically includes any temporal lag between SSTs and the target variable, as the temporal lag should also be the same for all ensemble members. However, a drawback is that more than this analysis is needed to identify the optimal regions, areas, or temporal lags that should be used later in an ML-enhanced prediction scheme. This analysis should thus be considered as a first-step screening of the impacts of SSTs from the climate model perspective.

Following this idea, we selected four climate models from the CMIP6 repository: MPI-ESM-2-LR, MPI-ESM-2-HR, CESM and EC-Earth (Table 2). A full analysis will include all climate simulations in the AMIP category. Here, the analysis is restricted, as a first step, to models with a high spatial resolution among the CMIP6 models (needed to represent EE as realistically as possible), and the availability of several simulations with the same model (i.e. an ensemble with members-only

differing in their initial conditions). The relatively high spatial resolution is about 1 geographical degree, corresponding to about 70 km at mid-latitudes. This is still a coarse resolution to represent some of the EE in the focus of CLINT, which should be kept in mind.

Nevertheless, the climate models produce their own EE- generally tamer than the observed ones - but still realistic enough to explore the impact of large-scale drivers. To address issues derived from the limited spatial resolution, we have also completed one regional simulation for 1900-2010 with the regional atmospheric model Consortium for small-scale modelling-CLimate Model (CCLM, Steger et al., 2020) over the Euro-Cordex domain (Vautard et al., 2021)), driven at the boundaries by the ERA20C reanalysis (Poli et al.,2016). This simulation will be the focus of Section 6.

The second criterion for selecting these four CMIP6 models is the availability of an ensemble of simulations started with different initial conditions. Analysing those ensembles will allow us to filter internal variability. At the same time, using a multi-model ensemble allows us to detect robust signals, addressing the structural differences between different models that could, in theory, blur the identification of the impacts of SSTs. The ensemble size varies among the four climate models, ranging between 3 for both MPI-ESM model versions and 10 for CESM2. The period covered by the simulations also varies across models, with CESM2 providing the longest simulations (Table 2). All simulations cover the last decades of the 20th century (since 1979), but some models start in 1950.

Table 2. Some technical characteristics of the AMIP simulation ensembles used in the analysis of SST causality of EE.

Model	Average Spatial resolution latitude x longitude, degrees	Number of ensembles	Period
MPI-ESM-2-LR	1.875 x 1.875	3	1979-2014
MPI-ESM-2-HR	1.875 x 1.875	3	1979-2014
EC-Earth-3	0.70 x 0.70	6	1979-2017 (here truncated at 2014)
CESM2	0.937 x 1.25	10	1950-2014

The analysis was focused first on the seasonal mean atmospheric circulation of the Northern Hemisphere, including the winter (December to February) sea-level pressure, winter and summer (June to August) precipitation, and summer temperature as target variables. This choice of variables was dictated by the interest in the Mediterranean and Central European droughts, which usually occur during winter and summer, respectively. Anomalies in atmospheric circulation partially drive both phenomena and HW (Barriopedro et al., 2023).

An SST strong impact on EE drivers should be reflected in simultaneous variations of those driving variables (atmospheric circulation, precipitation and air temperature) across the same model ensemble members as a measure of synchronous evolution. The commonality metric across simulations for any given variable was defined as the linear correlation at the grid-cell level between all possible pairs of simulations. For instance, focusing on the climate model MPI-ESM-2-LR, which provides three simulations, the following maps display the mean of the grid-cell correlation between simulations 1 and 2, 2 and 3 and 1 and 3, similarly for all other three models.

The results obtained in 2023 indicate that SSTs modulate the atmospheric circulation in tropical regions. However, their imprint on mid-latitudes is rather small and restricted to some coastal areas, as illustrated in Figures 3.1-3.3, in the following subsections.

3.1 Sea-level pressure

All four models display a very similar spatial pattern of commonality for boreal winter sea-level pressure (Figure 3.1), with large values in the Tropical Atlantic (the simulations are global, but here, only the Atlantic-European-African sector is displayed). It should be noted that this analysis captures any SST impact independently of any lagged response of the atmospheric circulation to SST, as this potential lag should be the same across all simulations of an ensemble. This confirms the impact of tropical SST on the tropical atmospheric circulation but sheds clear doubts on the impact of SST on the seasonal mean of the atmospheric circulation over Europe.

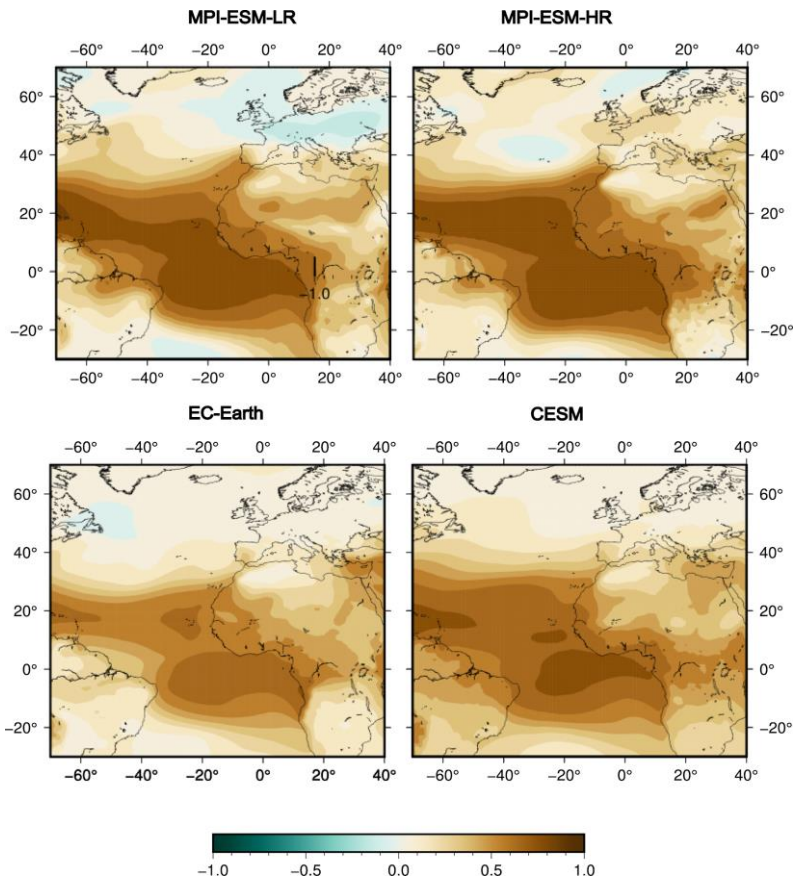

Figure 3.1: The commonality of winter sea-level-pressure interannual variations simulated at each model grid cell in an ensemble of AMIP (atmosphere-only) simulations conducted with one climate model. The boundary conditions are, for all simulations, the observed sea-surface temperatures in the period 1979-2017. A number of 1 indicates perfect synchrony, -1 is perfect anti-synchrony.

3.2 Precipitation

Concerning precipitation (Figure 3.2), the four models generally display a stronger temporal coherence among the ensemble members in winter than in summer and over the oceans than over land areas. Still, there is little synchronisation between SST and winter precipitation over Europe. There is some divergence among the four models, with the MPI-ESM-2-LR model displaying the strongest commonality. For precipitation, in which the issue of model resolution becomes more important than SLP, the two models with higher spatial resolution (MPI-ESM-2-HR and CESM2) show generally weaker commonality. Therefore, although there is some impact of SST on precipitation that could be exploited for prediction, especially in the coastal areas, this impact is small in general.

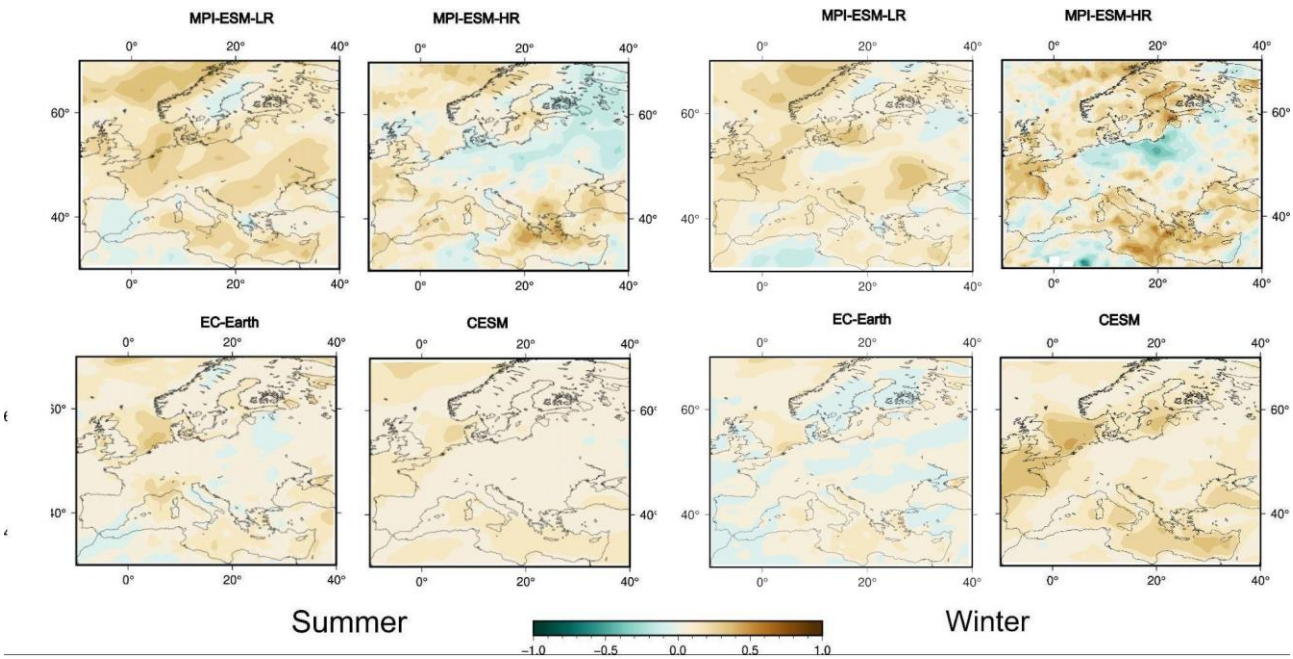

Figure 3.2 Measure of the commonality of the summer and winter precipitation interannual variations simulated at each model grid-cell in an ensemble of AMIP simulations, each conducted with one climate model. The boundary conditions are, for all simulations, the observed SST. A number of 1 indicates perfect synchrony, -1 is perfect anti-synchrony.

3.3 Air temperature

Figure 3.3 shows the commonality of summer temperatures. As expected, the commonality is very high over the ocean since the ocean surface temperatures are the same in all simulations. Air temperature over the oceans can deviate very little from those prescribed values, which are the same in all simulations. Consequently, all ensemble members produce a similar evolution of near-surface air temperature over oceanic areas. The analysis, however, also provides interesting insights since the temperature commonality is generally small over the land areas. Again, the model MPI-ESM-2-LR indicates a stronger impact of SSTs on air temperature in the other models, except in Central Europe.

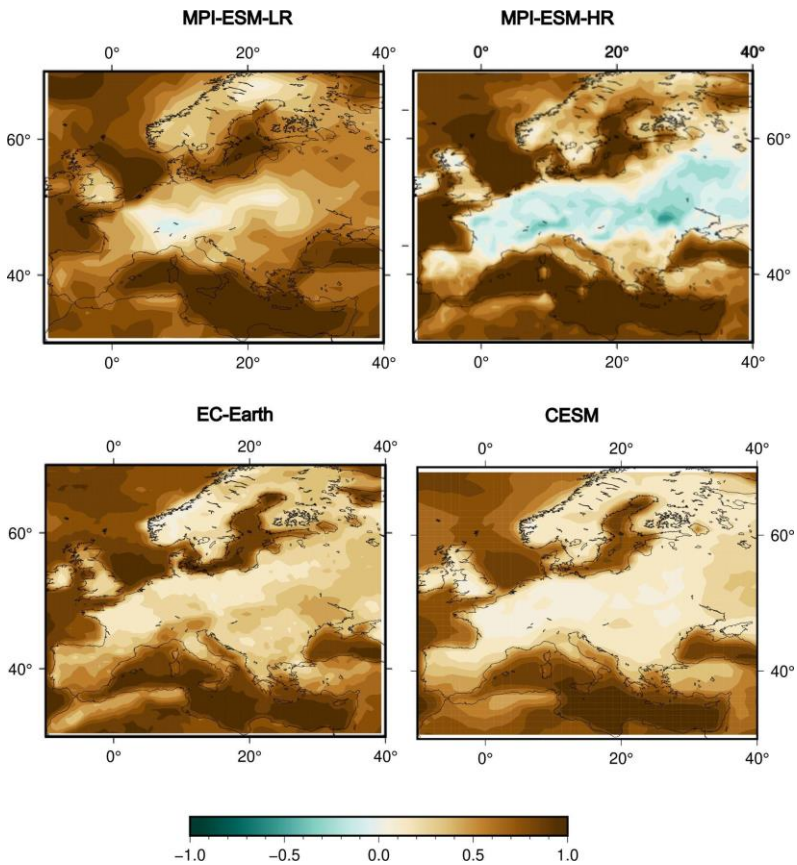

Figure 3.3 Measure of the commonality of the summer temperature interannual variations simulated at each model grid-cell in an ensemble of AMIP simulations conducted with one climate model. The boundary conditions are, for all simulations, the observed SST A number of 1 indicates perfect synchrony, -1 is perfect anti-synchrony.

In summary, the signal of SST on the variations of mean seasonal values of SLP and precipitation in Europe is, from the models' perspective, weak and mainly restricted to the tropical regions (SLP) or the ocean regions (precipitation). The impact on seasonal air mean temperature is very strong over the oceans and, in most models, is also restricted to the coastal continental areas.

4. IMPACT OF SEA-SURFACE TEMPERATURES ON EXTREME SEASONS

The previous analysis was based on simulated monthly means (whilst a similar analysis of the seasonal means delivers similar results). However, the focus of CLINT lies on EE's predictability and causality. In this section, we modify the analysis of commonality among members of the simulations to focus on extreme seasons rather than the mean seasonal climate. For this purpose, we restrict the calculations to trimmed correlations. Essentially, only values outside a predefined percentile of the deviations from the seasonal mean are considered for the calculations of trimmed correlations. However, trimming the sample size to focus on extremes can considerably reduce the sample size. If the predefined quantile thresholds are, for instance, 10% and 90%, only values below the 10% quantile or above the 90% quantile are considered to calculate the correlation. The remaining 80% of the data in each series are disregarded.

Since the extreme values in each series will not co-occur, the adequate sample size is (much) smaller. In the severe case where no values outside the quantile threshold co-occur any pair of simulations, this sample size will be zero. This would also indicate no synchrony of extremes in the ensemble. This situation does not occur in the present analysis, but a more sophisticated measure of synchroneity of extremes will be developed later in the CLINT project.

Therefore, a compromise had to be struck between the chosen quantile thresholds and the available sample size. For the available AMIP-type simulations, which may typically cover 50 years (for some models, this period is shorter) and focusing only on a three-month season, 20% of the sample size amounts to 30 instances to calculate correlations. Focusing only on the quantile range <5%,>95% would imply a sample size of just 15 cases. Therefore, this type of analysis cannot focus on the very extreme seasons, say below the 1% or above the 99% quantiles.

Another limitation is that the analysis cannot target sub-seasonal EE, like short HW, which would not strongly modify the seasonal mean. However, as SSTs vary slowly, their impact on sub-seasonal EE is likely probabilistic and not deterministic by, for instance, increasing the chances of HW occurrence rather than causing an EE at a specific date.

In the previous section's figures, we include the trimmed commonality maps for the same target variables and discuss the differences in the seasonal mean commonality. Here, we consider the quantile ranges (0-15%) for the lows and (85%-100%) for the highs extremes to retain a meaningful sample size.

4.1 Air temperature

We start with summer temperatures in Europe. Figure 4-1 shows the commonality of extremely low and high temperatures in the four model ensembles as before: MPI-ESM-2-LR, MPI-ESM-2-HR, EC-Earth-3, and CESM2.

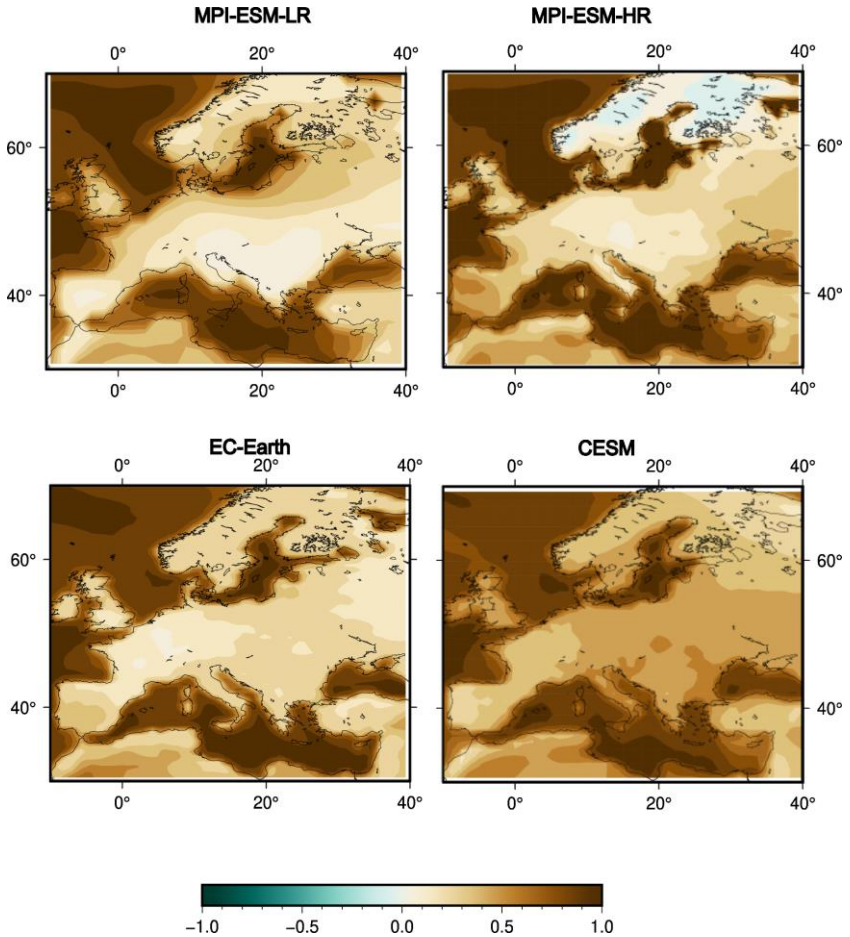

Figure 4.1: Commonality of extreme (smaller than 15% or higher than 85% quantiles) summer (June-August) monthly mean air temperatures across each model ensemble, calculated as trimmed correlations among all pairs in an ensemble.

Figure 4.1 indicates that the commonality varies across models but is generally similar to that obtained for the whole range of monthly temperatures. There is a slight tendency for this commonality to be larger than in the entire sample, for instance, for the model with the highest spatial resolution CESM2, for which the synchronous variation covers large areas of Central Europe. The results suggest that SST may be used as a predictor of HW in a statistical or ML model, although the temporal lag would need to be investigated by other methods. In general, however, the strongest commonalities are found closer to coastal areas, reflecting again the influence of the prescribed SSTs driving the simulations.

4.2 Precipitation

The commonality of extremely low or high winter precipitation - the other type of seasonal scale EE considered in CLINT is shown in Figure 4-2.

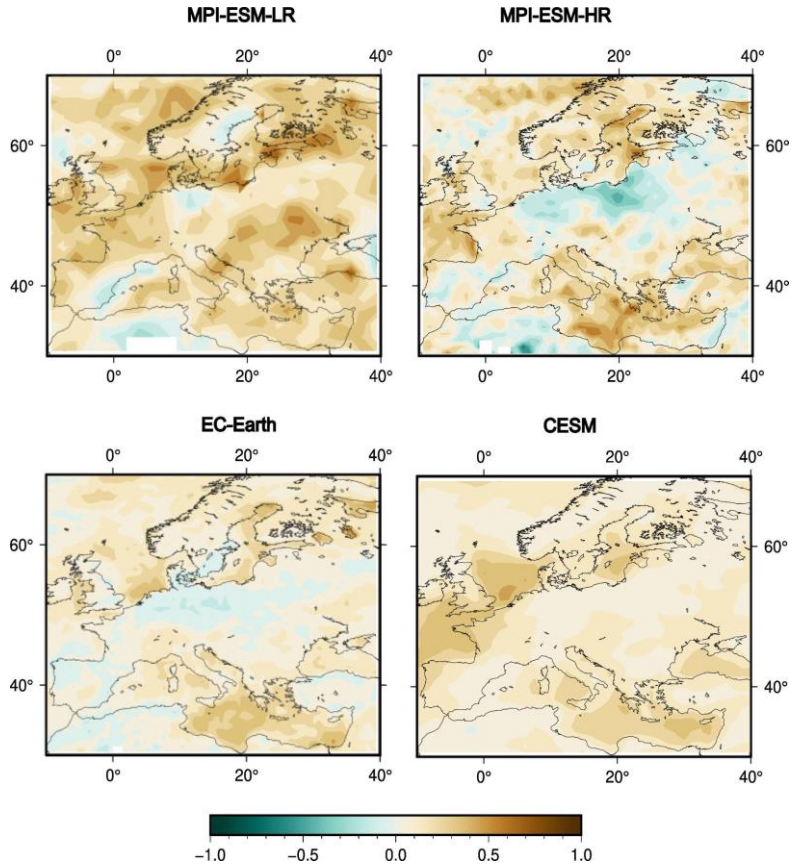

Figure 4.2: Commonality of extreme (smaller than 15% or higher than 85% quantiles) winter precipitation across each model ensemble, calculated as trimmed correlations among all pairs in an ensemble.

The ensembles indicate some degree of commonality for hydrological extreme winters. Again, there are agreements and disagreements among the models, with the high-resolution MPI-ESM-2-LR model diverging more strongly from the other three. The level of agreement is generally higher close to coastal areas and tends to diminish in continental inland regions.

In summary, the results for hydrological and thermodynamical extremes are consistent with those obtained using the whole range of the target variables. From the models' perspective, a different impact of SSTs during extreme seasons is distinguishable from the non-extreme seasons. For both, the signal of the SSTs on extreme summer temperature and winter precipitation is moderate, although certainly present, as the correlations across members of the simulation ensembles tend to be almost always positive.

Although the method used here is based on simple linear correlations, it does not imply that the link between SSTs and the target variables needs to be linear. It only assumes that the impact of SST is similar in all ensemble members, which is a very reasonable assumption, taking into account that the only difference between the ensemble members is the initial conditions.

5. METEOROLOGICAL DROUGHT OVER THE IBERIAN PENINSULA

The previous section concluded that the impact of SST on European seasonal extremes is weak. However, the possibility remains that SSTs influence specific strong events, i.e. those that have occurred once or only a few times in a relatively short period of analysis and, therefore, would have little impact on the commonality measure used in the previous section. This section aims to identify the impact of SST on specific but rare drought events in the Iberian Peninsula. This analysis aims to provide one of the CLINT use cases (the Duero basin precipitation).

5.1 A persistent period of dry Iberian winters

The time series of the winter mean precipitation in the Iberian Peninsula simulated by the four model ensembles are displayed in Figure 5.1. All ensemble members of the two models, MPI-ESM-2-HR and CESM2, show negative precipitation anomalies in the winters 2000-2003, also observed in the 20CR reanalysis (Compo et al., 2011). Other reanalysis products analysed also show a similar decrease in precipitation (not shown).

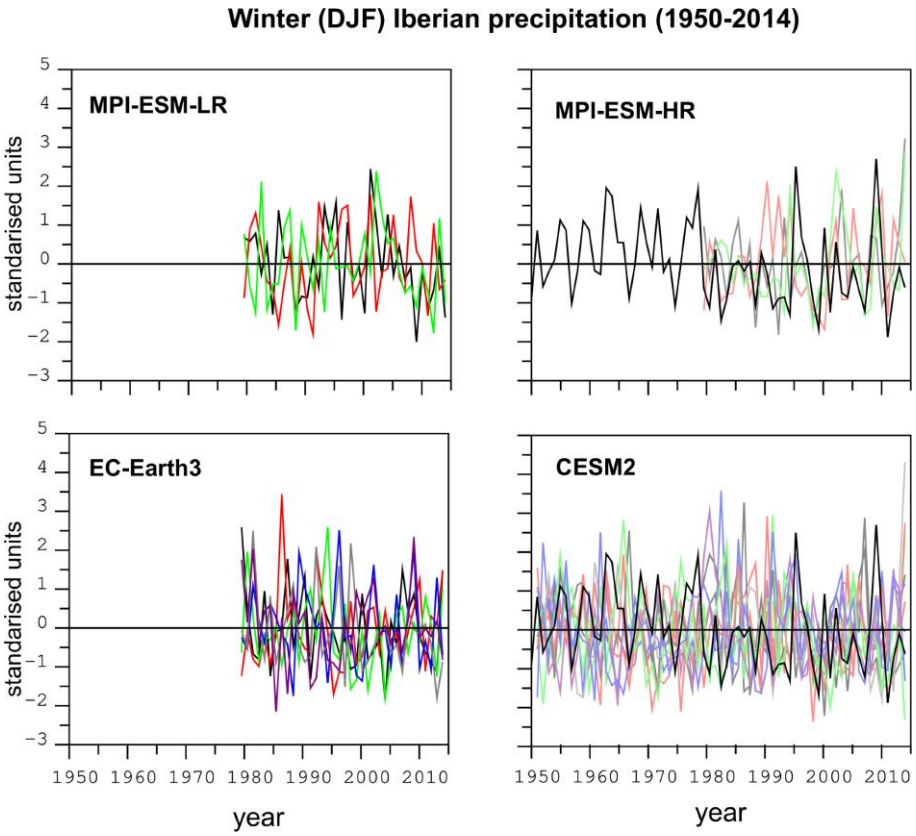

Figure 5.1 Time series of winter (December-February) precipitation averaged over the Iberian Peninsula as simulated by four global atmospheric models 8coloured lines), in standardized units. Two models (MPI-ESM2-HR and CESM2) display a series of dry winters of 2000-2003 that is matched by the 20CR reanalysis (black).

Similarly, the 2000-2003 winters represented one of the driest periods since the middle of the 20th century in both the 20CR reanalysis and the two model simulations Other simulated winters are even drier in the simulations but do not consistently appear across all ensemble members. Here, we characterise the large-scale patterns that are common in the two ensembles. A more detailed analysis will still be carried out with very long (1000 years) preindustrial control simulations (PI-Control) from the CMIP6. A preliminary analysis indicates that about 20 such events appear in MPI-ESM2-HR PI-Control simulation, which will be a suitable dataset for establishing causality with ML algorithms.

A more detailed version of the two models for the period 1990-2005 is displayed in Figure 5.2. The multiannual sequence of dry winters in the Iberian Peninsula is simulated by each ensemble member, suggesting that the prescribed SSTs may be partly responsible for this drought.

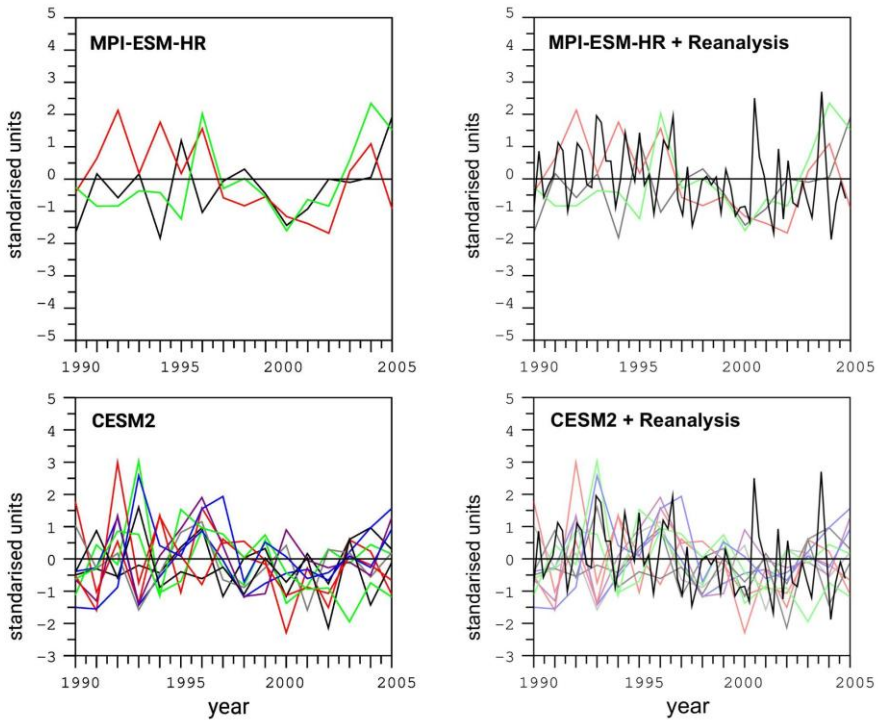

Figure 5.2: The same as Figure 5.1, but for the shorter period 1990-2005.

5.2 Large-scale climate patterns simultaneous with the 2000-2003 Iberian drought

Figures 5.3 and 5.4 show the Euro-Atlantic SLP anomalies and the global SSTs for the winters of 2000-2003, respectively. The SLP patterns simulated by the two models, MPI-ESM-2-HR and CESM2, display similar characteristics, although they are not identical. Both models show a cell of higher pressures over western Europe and the eastern Atlantic. The atmospheric circulation patterns resemble those associated with severe droughts over the Iberian Peninsula (e.g. García-Herrera et al., 2019). They are thus physically consistent with the simulated drying in those winters.

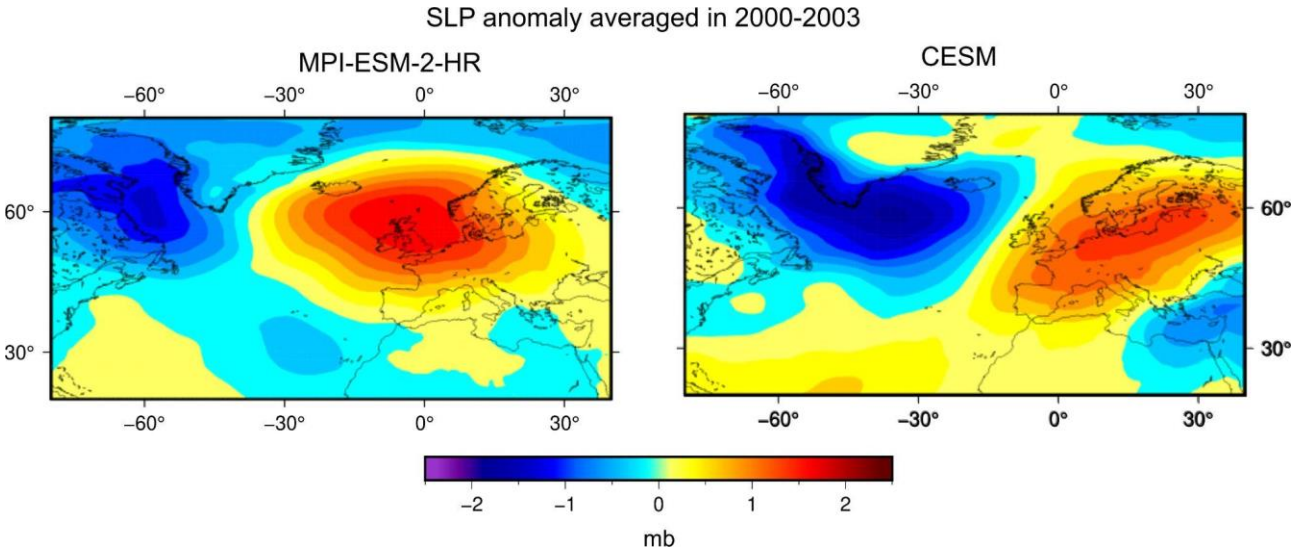

Figure 5.3: Patterns of SLP anomalies averaged for the winters 2000-2003 in the CMIP6 AMIP simulations in the MPI-ESM-2-HR and CESM2 ensembles.

It is also relevant to investigate which pattern of global SST anomalies also appeared during those winters. The SST anomalies averaged over 2000-2003 for the winter and autumn (September-November) seasons preceding the drought in Iberia are shown in Figure 5.4. The rationale for investigating the autumn SSTs is to explore possible predictability or persistence that may help identify the physical processes behind the SLP pattern. Note that the SSTs are prescribed in both ensembles; therefore, the SST patterns are identical.

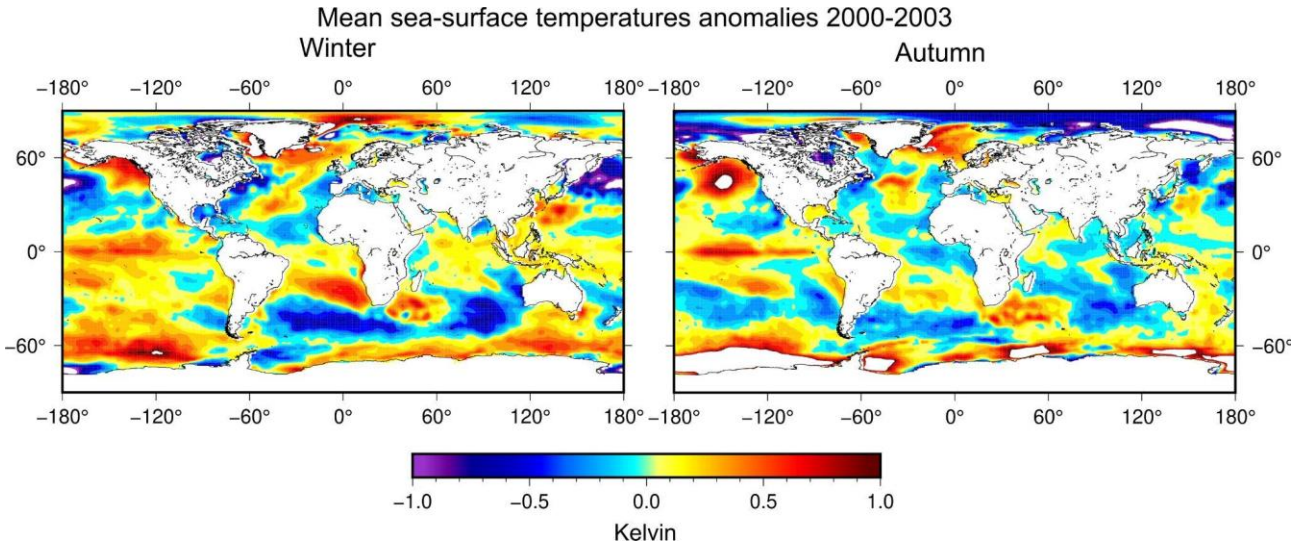

Figure 5.4: The observed global SST anomaly pattern averaged over the winters and autumns of 2000-2003.

The global SST pattern during the dry Iberian winters is reminiscent of an El Niño event, with the tropical Pacific being warmer than average. However, other areas in the North Atlantic also display

warm anomalies that could be conducive to higher SLP over Southwestern Europe. To elucidate which regions is causally related to the high SLP, dedicated experiments with prescribed SSTs are necessary (they will be carried out within CLINT). In parallel, similar events in the coupled PI-Control simulations will also be analysed with causal ML algorithms, as exemplified in Figure 5.5, by a simple composite analysis.

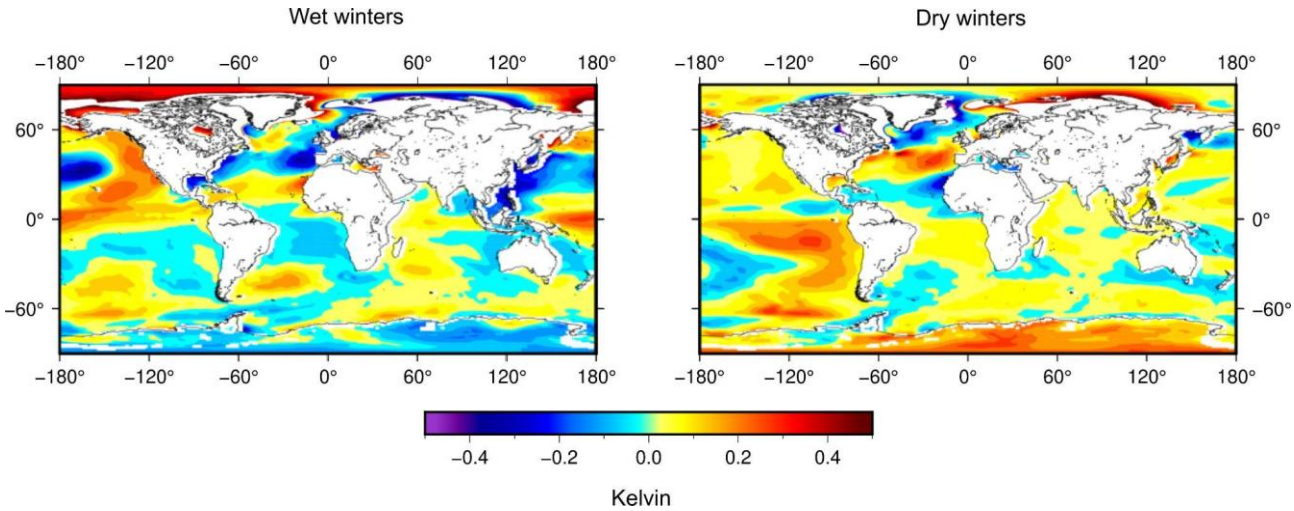

Figure 5.5: Composite analysis of global SSTs for persistent dry and wet winters in the Iberian Peninsula, simulated in a 1000-year-long PI-Control simulation with the CESM2 global coupled model.

Figure 5.5 displays the global SST patterns associated with multiannual sequences of extremely dry and wet winters in the Iberian Peninsula as simulated in the PI-Control simulation with the CESM2 model. There are about 20 dry events in the 1000-year-long simulation. These dry, persistent winter periods are accompanied by a warmer Tropical Pacific and warmer North Atlantic at mid-latitudes, roughly in agreement with the pattern observed during the 2000-2003 winters. There are some discrepancies, though. For instance, the pool of warmer waters in the North Atlantic appears displaced in the coupled simulations with respect to observations. Comparing the SST patterns for dry and persistent wet winters now, it can be seen that only these two areas - the tropical Pacific and the North and Tropical Atlantic - mirror each other, suggesting a causal relationship with persistent Iberian hydroclimate anomalies. The influence of the North Atlantic is more difficult to disentangle, as its SST anomalies could have been the result, not the cause, of the high SLP via temperature advection. This could be elucidated using Granger causality to the simulated SLP and SST time series. In summary, long preindustrial control simulations also point to warm Tropical Pacific SST as a causal predictor of recurrent dry winters in the Iberian Peninsula.

Besides the 2000-2003 drought, the Iberian Peninsula has experienced reduced precipitation in other periods in the 20th century that are not covered by the CMIP6-AMIP simulation. Within CLINT, we have completed a regional atmospheric simulation at a very high spatial resolution over the Euro-Cordex domain, driven by the ERA20C reanalysis (Poli et al., 2016). This simulation helps further investigate the link between SST and Iberian precipitation and the structure of those

persistent drought events. These data can also serve as a long pre-training data set, akin to observations, for ML algorithms. Results from this simulation are presented in the next section.

In summary, the winter precipitation record in the Iberian Peninsula displays a series of persistent dry winters around 2000 that is synchronous with two of the AMIP atmospheric simulation ensembles analysed here (CESM2 and MPI-ESM-2-HR). The other two model ensembles do not reproduce this event. The simulated patterns of atmospheric circulation anomalies are consistent in the two ensembles with winter droughts in this region, and the patterns of SST anomalies hint at the role of the warm Tropical Pacific and warmer North Atlantic. Long preindustrial control simulations with the coupled models CESM2 and MPI-ESM-2-HR include several similar events of persistent dry winters in the Iberian Peninsula and simulate warm SSTs in the Tropical Pacific.

6. A LONG HIGH-RESOLUTION REGIONAL ATMOSPHERIC SIMULATION OVER EUROPE: APPLICATION TO TWO CLINT USE CASES

The available observational records are usually short (observations) or may have very high spatial resolution (reanalysis), which may hamper the assessment of variability and change of EE and their driving factors. It also poses a limitation to train ML algorithms. For these reasons, we have conducted a relatively long (1900-2010) simulation in CLINT with the regional atmospheric model CCLM (Steger et al., 2020) with a high spatial resolution (10 km) over the Euro-Cordex domain (Vautard et al., 2021). The German Weather Service also uses this model for their operational weather predictions. This simulation (Table 3) has been driven at its boundaries by the ERA20C reanalysis (Poli et al., 2016). Therefore, the simulated temporal sequence is synchronised with the observed climate trajectory and can be considered a high-resolution reanalysis for Europe. The time resolution of the available data is hourly, so short-lived EE, such as flash flooding, can be analysed. Selected variables are available on the CLINT data-sharing facility at the DKRZ in Hamburg.

Table 3. Some technical characteristics of the regional high-resolution atmospheric simulation.

Model	Average Spatial resolution	Number of simulations	Period	Boundary conditions	Domain
Community Climate Limited Area Model (CCLM)	~10x10 km Curvilinear coordinates	1	1900-2010	ERA20C and observed SST and ice-cover	Euro-Cordex

6.1 Past persistent drought in the Iberian Peninsula

To illustrate the type of analysis this simulation allows, we consider the case of persistent droughts in the Iberian Peninsula, which was the focus of the previous section. Figure 6-1 shows the winter (December-February) series of precipitation anomalies over the Iberian Peninsula simulated by the CCLM run compared with the extended 20CR reanalysis (version 2c). The interannual variability simulated by the model is about half that of the reanalysis, likely due to the different sub-grid schemes used in CCLM and the 20CR models. This difference needs to be analysed further and compared to other data sets, but it is not relevant in this section. The temporal coherence between both time series is high, with a correlation coefficient of 0.76. The simulated precipitation series displays two multiannual periods with extremely low precipitation, one starting in 1904 and one beginning in 1919. Together with the period around 2000 analysed in section 5, they make the two driest series of winters in this region.

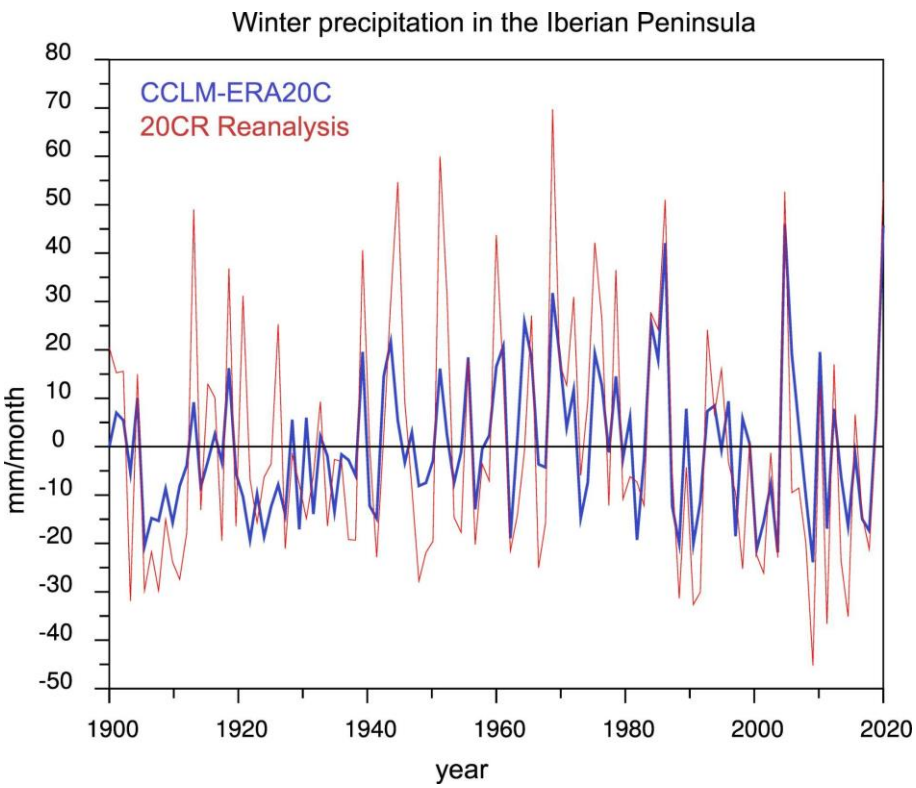

Figure 6.1:. Time series of winter (December-February) precipitation anomalies in the Iberian Peninsula from the 20CR reanalysis and simulated by the CCLM regional simulation driven by ERA20C.

Figure 6.2 shows the observed mean SSTs (from the HadISST data set, Reiner et al., 2003) averaged over the winters in each period. We can see in this figure that, in partial agreement with the results presented in the previous section, the global SST anomaly pattern is characterised by a warm Tropical Pacific, whereas SSTs remain colder than normal elsewhere. The latter may reflect the long-term warming effect through the 20th and 21st centuries since the SST anomalies are expressed relative to the long-term mean of the period covered by the CCLM simulation).

The Tropical Pacific patterns, however, support the idea that ENSO may be an important driver for persistent winter droughts in the Iberian Peninsula and that the warm SSTs in the North Atlantic shown in Figure 5.4 for the 2000 event may not be a robust predictor.

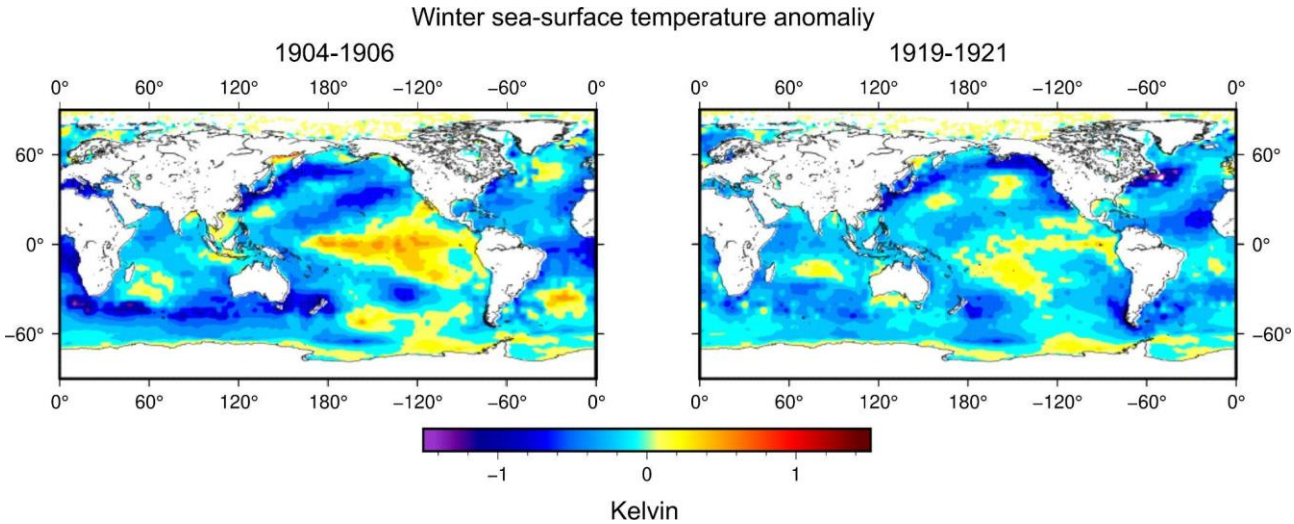

Figure 6.2: Patterns of observed winter SST (December-February) anomalies from the HadISST data set averaged in 1904-1906 and 1919-1921t. The anomalies are calculated using the period 1900-2010 as reference.

The atmospheric circulation patterns during those winter periods were also physically consistent with dry winters over the Iberian Peninsula (Figure 6.3), characterised by higher surface pressure over the mid-latitude North Atlantic. The relative strength of the SLP patterns in these two periods even agrees with that of the SST patterns, again suggesting that the Tropical Pacific is driving the atmospheric circulation towards more intense NAO states and, therefore, dry winters in the Iberian Peninsula.

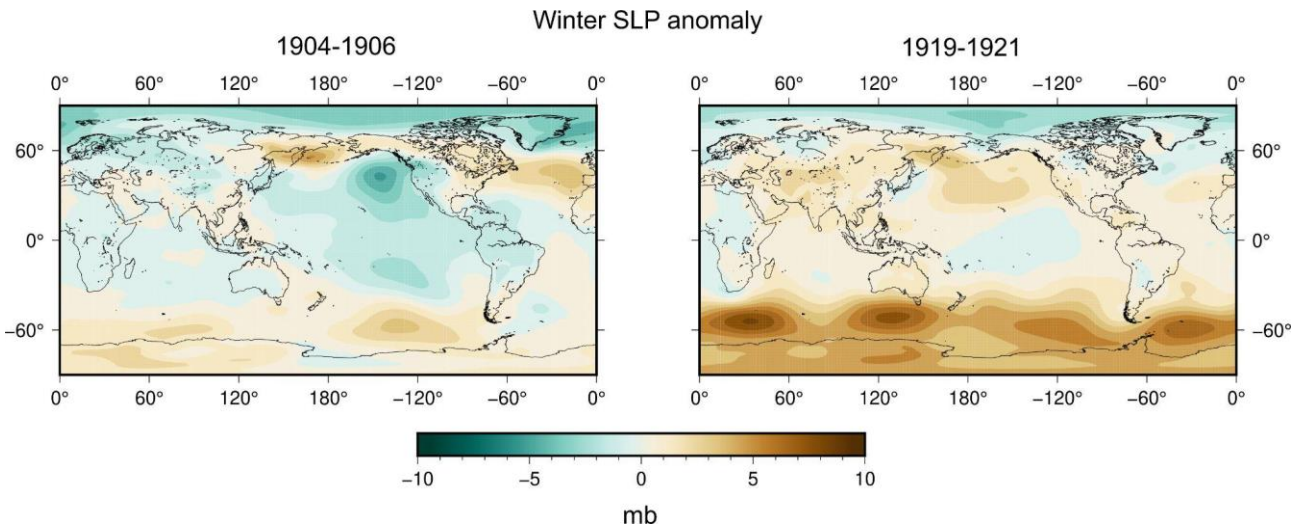

Figure 6.3: As Figure 6.2, but for the winter SLP anomaly pattern derived from the 20CR(v2c) reanalysis.

The high spatial resolution of the simulated data allows a closer inspection of the patterns of reduced precipitation in the Iberian Peninsula during these two events (Figure 6.4). Consistent with Figures 6.2 and 6.3, the simulated precipitation deficits are stronger during the first event of 1906 than during the second event in 1919. Both precipitation patterns have a similar spatial shape,

with stronger reductions in Western Iberia, including the Duero basin. Locally, the severe precipitation reductions are below or below 50% of the climatological mean. There are spatial differences between the two events, both within and outside the Iberian Peninsula. Along the northern fringe of the Peninsula and over Northern Africa, the precipitation anomalies are opposite, highlighting the large case-to-case variability and the need for a high-resolution dataset.

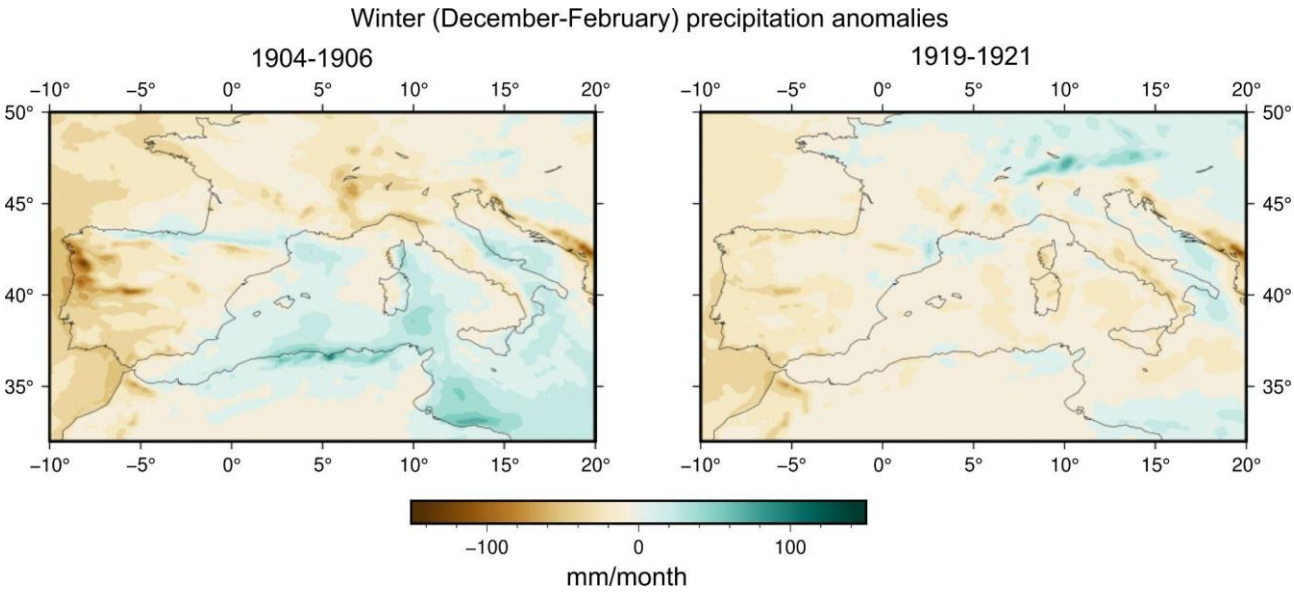

Figure 6.4. Precipitation anomalies (relative to the long-term mean of the whole simulation period 1900-2010) in Southwestern Europe for two winter periods of extremely low precipitation in the Iberian Peninsula (see Figure 6-1) simulated with the regional atmospheric model CCLM driven by the ERA20C reanalysis.

6.2 Impact of ENSO on Lake Como precipitation

The causal link between ENSO and precipitation in Southern Europe has been hinted at several times in the literature by CLINT project partners. Giuliani et al. (2019) identified an asymmetric connection between the state of ENSO in autumn and winter precipitation anomalies in Lake Como, with positive phases of ENSO driving lower precipitation in this region. Generally, previous studies on the ENSO impact on precipitation in Europe have found contradictory results, with some studies suggesting higher precipitation during positive ENSO phases but others finding the opposite (Brönnimann, 2007). Other studies found a time-scale dependency and period sensitivity to the connection between ENSO and precipitation in Western Europe (Brönnimann et al., 2007). Yet others find the opposite response between mild and extreme ENSO events (King et al., 2021).

Here, we further explore this connection in the high-resolution CCLM simulation. Aligning with the study of Gulliani et al. (2109), Figure 6.5 shows the late winter precipitation (January-March) averaged over the five strongest El Niño and La Niña events between 1950 and 2010, measured by the value of the autumn (October-December) Multivariate ENSO Index (MEI; Wolter and Timling, 1998). Therefore, this picture also conveys the possible predictive skill of the MEI on Southern European precipitation.

The precipitation composite patterns confirm the asymmetric character of the link between ENSO and European precipitation. The strongest El-Niño events in autumn are accompanied by drier winters in the Western Iberian Peninsula, as was found in the previous section 6.1. Also, they are linked to drier winters along the Alps. The five strongest La-Niña autumns also display drier winters in the Alps but wetter winters in Transalpine Italy (actually, this is the only region in Southern Europe land areas with a wet signal).

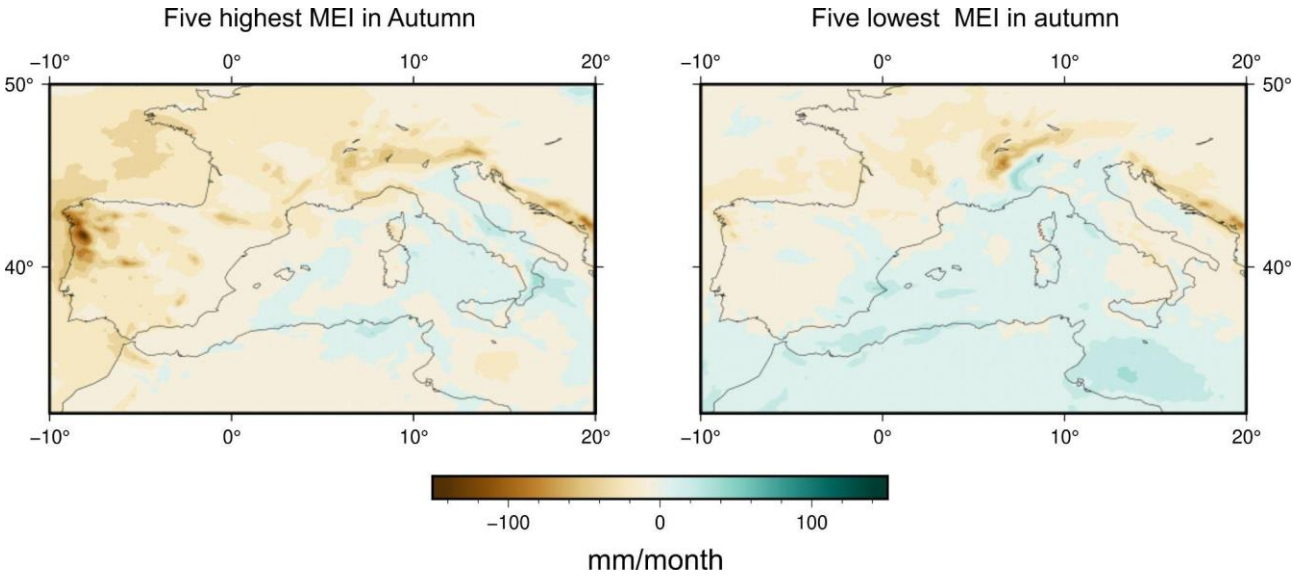

Figure 6.5: Average precipitation in the winters (January-March) with the five highest (El Niño, left panel) and the five lowest (La Niña, right panel) values of the Multivariate ENSO Index in the previous autumn (October-December). Period 1950-2010. Precipitation is simulated by the high-resolution regional atmospheric model CCLM driven by ERA20C reanalysis.

In summary, the analysis of longer periods than those usually considered in shorter reanalysis data unveils severe drought events in the Iberian Peninsula in 1906 and 1919, which may be casually linked to a warm Tropical Pacific, as it was probably the case for the more recent event in the year 2000. The high-resolution regional simulation with the atmospheric model CCLM displays a broadly similar spatial structure of dryness over the Iberia but also clear differences in detail outside the Peninsula, in Northern Africa and the Western Mediterranean. In these two winter periods, the Lake Como region also observes this spatial heterogeneity and asymmetry in the response to Tropical Pacific forcing. This implies that, although the causal link can likely be attributed to the SSTs in the remote region of the Tropical Pacific, each event may convey a different fingerprint. ML prediction algorithms would, therefore, need long, high-resolution precipitation records to provide predictions at local and regional scales. Still, they can also help to understand why this response is heterogeneous across neighbouring regions and why the response to a given driver is asymmetric and spatially heterogeneous.

7. CONCLUSIONS

Our review summarises the large-scale drivers of climatic EE and compound events assessed from the existing literature. Generally, the atmospheric circulation over the North Atlantic - the North Atlantic Oscillation and the boreal Polar Vortex - has an immediate influence on the frequency and intensity of different types of EE and compound events, particularly heat waves and droughts. Soil moisture resulting from the surface water balance in the previous seasons also contributes to the severity of summer HW. In turn, other boundary conditions, such as sea-surface temperatures and sea-ice extent, may influence the North Atlantic atmospheric circulation. The impact of sea-ice extent is still debated: it may exist, but it is arguably weak. Previous studies have identified a clear influence of North Atlantic and Tropical Pacific SST on hydroclimate conditions over Europe. Nevertheless, not all studies agree on the form in which this influence takes place, and sometimes even the sign of the sea-surface temperatures associated with dry conditions is debated.

Assessing physical causal links with sea-surface temperatures is critical for detecting, predicting, and attributing extreme events, which is the main objective of WP3-5 within CLINT. A multi-model ensemble with atmospheric-only models of the CMIP6 project has been set up in CLINT as part of WP4 to address this question. Analysing the ensembles of simulations with atmospheric-only models within the CMIP6 project, driven by the same observed sea-surface temperature variations, reveals a weak signal in both mean seasonal climate and extreme seasons over Europe. However, only a persistent series of winters in the Iberian Peninsula, which occur only a few times in a century, can likely be attributed to sea-surface-temperatures, probably in the Tropical Pacific. This is supported by an asymmetric stratification of dry and wet winters in the Iberian Peninsula and the Lake Como basin according to positive or negative ENSO state in the previous autumn. However, the spatial precipitation signal of ENSO varies rapidly across space, particularly in areas of complex topography, and hence, a very detailed analysis is necessary. One regional simulation of this kind has already been carried out within WP4, which can be used as a high-resolution reanalysis-like dataset of the 20th century to train ML models.

Regarding the mechanism behind compound extremes, they can be divided into the following sub-categories: atmospheric circulation patterns, land-atmosphere interactions, ocean dynamics and coupled ocean-atmosphere patterns, and the climate change signal due to anthropogenic forcing. These drivers can improve the detection and prediction experiments by explicitly including the physical nature of extreme events rather than requiring the underlying AI model to learn the process by itself (Schultz et al., 2021). For instance, ML- algorithms can be made more effective by splitting the prediction algorithm into two steps: first, an initial image recognition algorithm can identify emerging known large-scale circulation drivers, such as persistent anticyclones or specific teleconnection patterns. In the second step, a prediction the ML- algorithm generates a prediction based on the phase of those identified atmospheric patterns. Such pre-filtering could enhance the derived forecast's physical consistency and performance by partitioning the data into (physically)

adequate subsets. Physical laws can also be implemented directly into the optimisation problem of the training process, for example, by imposing constraints on the loss function (Kashinath et al., 2021).

Furthermore, variables related to land-atmosphere feedback are helpful for drought and heatwave prediction, as they modulate underlying processes associated with the severity of EE and can potentially connect meteorological, ecological and hydrological droughts. Finally, anthropogenic forcing imposes non-stationarities on many extreme events, mainly their frequency and magnitude. However, such non-stationarities are only sometimes exploited by machine learning models, as many of these algorithms assume that the training and test distributions agree (Sugiyama and Kawanabe, 2012). Therefore, incorporating techniques that account for this climate non-stationarity could improve the model's performance, especially for experiments targeting long time horizons.

8. BIBLIOGRAPHY

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