SCALABILITY OF PROJECTED PATTERNS OF EXTREME WEATHER EVENTS OVER EUROPE USING REGIONAL CLIMATE MODEL PROJECTIONS

by

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ABSTRACT

SCALABILITY OF PROJECTED PATTERNS OF EXTREME WEATHER EVENTS OVER EUROPE USING REGIONAL CLIMATE MODEL PROJECTIONS

Climate change leads to significant increases in the frequency and severity of extreme weather events. Combating climate change and developing adaptation strategies is of great importance for a sustainable future. The effects of climate change need to be understood and addressed, and climate models are used for this end. However, due to differences in climate models and systematic errors in model calculations, different techniques such as “pattern scaling” are also used. The study used a pattern scaling approach, extracted from different global climate models, to examine how changes in temperature extremes and total precipitation in the EURO-CORDEX region respond to increases in global temperatures using certain extreme weather indices. According to the results, the yearly minimum value of daily minimum temperature (TNn) increases more than the yearly maximum value of daily maximum temperature (TXx) for Europe. The multi-model mean of the changes in scaled patterns of extreme temperatures emerges early, around 2020, even before it becomes robust. Additionally, the total annual precipitation amount (PRCPTOT) in the northern regions increases by up to 6-9% compared to the reference period, while decreases of up to 12-15% can be observed in North Africa. Finally, using the ERA5 dataset, the change in patterns of four extreme temperature indices was examined to determine whether end-of-century scaled patterns could be detected for the conditions that were observed. The observed patterns of change closely resemble the end-of-century scaled patterns identified by the GCM-RCM sample, indicating that end-century patterns are already emerging in some parts of the domain.

ÖZET

AVRUPA’DAKİ AŞIRI HAVA OLAYLARININ BÖLGESEL İKLİM MODELLERİ KULLANILARAK ÖNGÖRÜLEN DEĞİŞİKLİĞİNİN ÖLÇEKLENEBİLİRLİĞİ

İklim değişikliği, ekstrem hava olaylarının sıklığında ve şiddetinde önemli artışlara yol açmaktadır. İklim değişikliği ile mücadele ve uyum stratejileri geliştirmek, sürdürülebilir bir gelecek için büyük önem taşımaktadır. İklim değişikliğinin etkileri anlaşılmalı ve ele alınmalıdır; bu amaçla iklim modelleri kullanılmaktadır. Ancak, iklim modellerindeki farklılıklar ve model hesaplamalarındaki sistematik hatalar nedeniyle, örüntü ölçekleme (pattern scaling) gibi farklı teknikler de kullanılmaktadır. Çalışma, belirli aşırı hava durumu endeksleri ve örüntü ölçekleme yöntemiyle, farklı küresel iklim modellerinden elde edilen EURO-CORDEX bölgesindeki sıcaklık aşırılıkları ve toplam yağış değişimlerinin, küresel sıcaklık artışlarına tepkisini incelemiştir. Sonuçlara göre, Avrupa’da günlük minimum sıcaklıkların aylık minimum değeri (TNn), günlük maximum sıcaklıkların aylık maximum değerinden (TXx) daha fazla artmaktadır. Ölçeklenmiş aşırı sıcaklık örüntülerindeki değişikliklerin çoklu model ortalaması, henüz sağlam hale gelmeden önce, 2020 civarında, ortaya çıkmaktadır. Ayrıca, kuzey bölgelerde yıllık toplam yağış miktarı (PRCPTOT) referans döneme kıyasla %6-9 oranında artarken, Kuzey Afrika’da %12-15 oranında bir azalma gözlemlenmektedir. Son olarak, ERA5 veri seti kullanılarak, gözlemlenen koşullar için yüzyılın sonu ölçeklenmiş örüntülerinin tespit edilip edilemeyeceğini belirlemek amacıyla dört aşırı sıcaklık endeksindeki örüntü değişiklikleri incelendi. Gözlemlenen değişim örüntüleri, GCM-RCM örneklemi tarafından belirlenen yüzyıl sonu ölçeklenmiş örüntülerine yakından benzemekte olup, bu durum yüzyıl sonu örüntülerinin bazı bölgelerde şimdiden ortaya çıkmaya başladığını göstermektedir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

RR_{ij}	The daily wet day (≥ 1 mm) precipitation amount on day i, in period j
$\frac{S}{N}$	Signal-to-noise ratio
$< SP >$	Multi-model mean of all members for scaled patterns
$TN_{n_{kj}}$	Yearly minimum value of daily minimum temperature in month k, period j
$TN_{x_{kj}}$	Yearly maximum value of daily minimum temperature in month k, period j
$TX_{n_{kj}}$	Yearly minimum value of daily maximum temperature in month k, period j
$TX_{x_{kj}}$	Yearly maximum value of daily maximum temperature in month k, period j
σ_{SP}	Inter-member standard deviation of the change in scaled patterns

LIST OF ACRONYMS/ABBREVIATIONS

CO_2	Carbon Dioxide
CORDEX	Coordinated Regional Climate Downscaling Experiment
ENSO	El Niño-Southern Oscillation
ERA5	Fifth Generation ECMWF Atmospheric Reanalysis
ETCCDI	the Expert Team on Climate Change Detection and Indices
GCM	Global Climate Model *or* General Circulation Model
IPCC	Intergovernmental Panel on Climate Change
MENA	Middle East and North Africa
PRCPTOT	The Annual Total Precipitation on Wet Days
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
Rx1day	Maximum 1-Day Precipitation
S/N	Signal-to-noise Ratio
tasmax	Daily Maximum Near-Surface Air Temperature
tasmin	Daily Minimum Near-Surface Air Temperature
TN	Minimum Temperature
TNn	The Yearly Minimum Value of Daily Minimum Temperature
TNx	The Yearly Maximum Value of Daily Minimum Temperature
TX	Maximum Temperature
TXn	The Yearly Minimum Value of Daily Maximum Temperature
TXx	The Yearly Maximum Value of Daily Maximum Temperature
UAE	United Arab Emirates
UNFCCC	The United Nations Framework Convention on Climate Change
WHO	World Health Organization

1. INTRODUCTION

The phrase "climate change" refers to changes to the Earth's climate system that are brought about by both natural and man-made processes and result in long-term, irreversible shifts in climatic conditions. Significant variations in temperature, precipitation, wind patterns, and other climate factors are among these shifts. Even if climate change has happened naturally over hundreds of millions of years in the past, human activity is primarily responsible for the acceleration that has been seen in the recent century. The accumulation of greenhouse gasses released into the atmosphere as a result of the use of fossil fuels, deforestation, and various industrial operations is an example of human activities. Natural processes include phenomena such as volcanic eruptions, variations in solar activity, and changes in ocean circulation. Increasing fossil fuel use, deforestation and industrial activities, especially since the industrial revolution, have increased the release of greenhouse gasses into the atmosphere, which has led to global warming.

The increased frequency and intensity of extreme weather events is one of the most evident effects of climate change. Weather occurrences classified as extremes are those that are uncommon in general but when they do occur, they result in considerable loss and destruction. Extreme precipitation and temperatures can also contribute to extreme weather events. Droughts, intense storms, heatwaves, and heavy rains are some of these occurrences. Extremely high temperatures that persist for several days or weeks are known as heatwaves. The frequency and intensity of heatwaves have risen due to climate change. Significant health concerns may result from this situation, particularly for vulnerable populations like the elderly, young children, and people with chronic illnesses. Heatwaves also raise the demand for energy, strain electrical networks, and have a detrimental impact on agricultural output, endangering food security. Droughts are characterized as prolonged periods of water scarcity and in certain areas, the frequency and intensity of drought events have risen due to climate change. Droughts have a detrimental impact on ecosystems, water supplies, and agricultural productivity. Droughts can also cause migration, reduced water supplies, and higher food costs. They can lead to significant financial losses, particularly in nations that depend on agriculture. On the contrary, in certain areas, the frequency of extreme precipitation events has increased because of climate change. Landslides, urban floods, and river flooding can all result from heavy rains. These occurrences cause fatalities, damage to buildings and other structures, and harm to farmland. Floods are more likely to happen, especially in places with poor infrastructure and in urban areas. Climate change may lead to an increase in the frequency and intensity of severe storms, including hurricanes, typhoons, and tropical cyclones, similar to other climate extremes. Strong winds, abundant rainfall, and sudden rises in sea level (storm surge) can cause significant destruction in the infrastructure systems during these storms. Storms of this type have a devastating effect on coastal communities' inhabitants, infrastructure, and ecosystems. Depending on the geographic location, extreme weather events can have different regional effects. For instance, tropical locations are more likely to have violent storms and heavy rainfall, but mid-latitude areas may experience more heatwaves and droughts. Due to these regional variations, local factors must be taken into account while developing solutions to counteract climate change.

To comprehend and anticipate the effects of climate change, climate models are utilized. Simulations of the elements of the climate system and their interactions are conducted through mathematical representations known as climate models. These models use computer simulations to depict physical, chemical, and biological processes in the climate system and incorporate a variety of climate components, such as the atmosphere, seas, land surface, and glaciers. Regional climate models (RCMs) take into account the climate of a specific region in more detail, whereas global climate models (GCMs) mimic the large-scale dynamics of the climate system. Climate models are used to forecast future weather patterns, create plans and policies related to climate change, and evaluate shifts in the frequency and intensity of extreme weather events. These projections make an effort to forecast future variations in temperature, precipitation, sea level, and other climate parameters under various scenarios of greenhouse gas emissions. The knowledge offered by climate models shapes our understanding of the implications of climate change and the tactics we develop to mitigate these effects. As a result, actions like building climate-resistant infrastructure are possible. However, obtaining relevant information regarding climate change is challenging due to variations in climate models and systematic errors in model calculations. The pattern scaling technique, developed against these conditions and the subject of this study, accurately predicts temperature and precipitation patterns under increasing greenhouse gas concentrations, with increasing intensity of change per degree of global warming.

The response of changing extreme temperatures and precipitation to the rising levels of global warming was investigated in this study. To this aim, future increases in extreme temperatures were analyzed, taking into account global warming levels of 1^oC, 2^oC, and 3^oC, respectively, using daily minimum and maximum temperatures as well as precipitation calculated from regional climate projections. Using the annual mean of global mean temperature change of the GCM-RCM models, a scale was applied. The study employed the pattern scaling approach inferred from different global climate models to examine how changes in extreme temperatures and total precipitation respond to increases in the global temperatures. Additionally, the emergence of scaled patterns in the minimum and the maximum temperatures and precipitation in certain extreme weather indices, the annual maximum of daily maximum temperature (TXx), the annual minimum of daily minimum temperature (TNn), the annual minimum of daily maximum temperature (TXn), the annual maximum of daily minimum temperature (TNx) and annual total precipitation on rainy days (PRCPTOT) were determined. The study also examined the development of scaled patterns of precipitation and extreme temperature. To this end, examining whether the scalability of change in extreme temperatures applies equally to mean climatic state variables was one of the primary goals of the study. In order to investigate the variations of four extreme temperature indices in observations between the dataset's first 20 years and its latest 20 years (the ERA5 dataset) which spans the years 1981 to 2020 was also studied. Scaling extreme temperature and precipitation patterns in the EURO-CORDEX area was the main focus of the study.

2. THEORY

2.1. Climate Change

Climate change refers to the long-term changes of the Earth's climate system brought about by human-made or natural processes. These modifications can involve variations in air movements, temperature, precipitation, and sea level (IPCC, 2021). Climate change is seen as a complex phenomenon with significant global and regional impacts. These changes profoundly affect our planet's climate systems, disrupt natural balances and lead to significant socio-economic and environmental consequences for human societies. On a global scale, climate change is characterized by rising levels of average atmospheric temperatures. Increasing greenhouse gas emissions contribute to this increase, particularly through the release of greenhouse gasses such as carbon dioxide, methane, and nitrogen oxides into the atmosphere. As a result, the average global temperature rises, which raises sea levels, causes the polar ice caps to melt, and increases the frequency of extreme weather events (Nunes, 2023). These effects also lead to other consequences. For example, sea level rise increases the risk of erosion in coastal areas and threatens islands and coastlines, causing millions of people to be displaced. Simultaneously, factors associated with climate change, such as increasing temperatures and drought, reduce agricultural productivity and threaten food security. While this situation poses a serious threat to agriculture-based economies, it may cause food prices to increase and weaken the livelihoods of societies. Climate change also affects water resources and threatens water security by causing increased water stress and decreased freshwater resources in some regions.

Throughout Earth's history, climate change has been a natural occurrence, with changes in temperature and weather patterns, shown in Figure 2.1, resulting from a variety of circumstances like volcanic activity and changes in solar radiation. However, what makes the current climate crisis different from the past events is its unprecedented speed and intensity of change, and this speed and intensity is largely attributable to human activities. Anthropogenic factors, particularly the release of greenhouse gas emissions from the burning of fossil fuels, have significantly increased the rate of global warming and continue to do so because fossil fuels are still in use. This rapid change is increasing the severity and frequency of extreme weather events, disrupting ecosystems, and threatening the stability of communities around the world. Recognizing the role of anthropogenic impacts in the process of the exacerbation of climate change underlines the urgency of mitigation and adaptation actions to reduce emissions, transition to sustainable practices and mitigate impacts on both current and future generations.

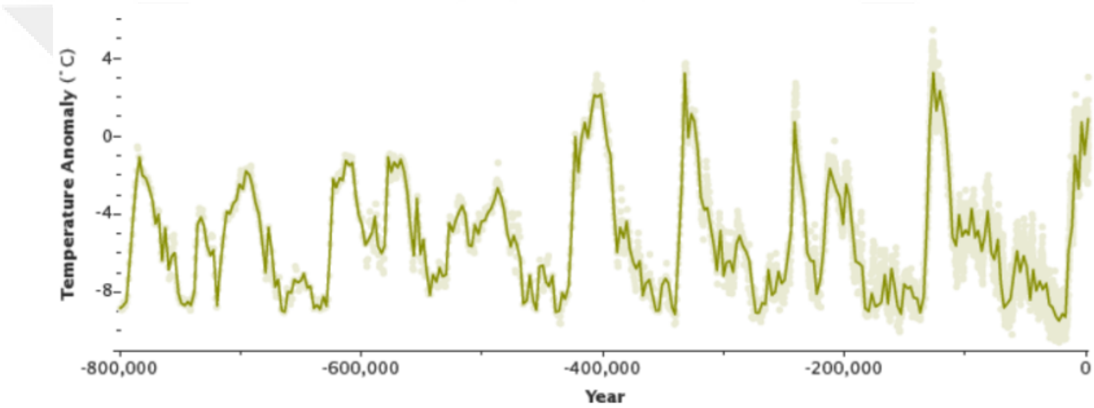


Figure 2.1. Temperature anomaly through 800,000 years of Earth's history (Simmon, 2010).

Even if the release of greenhouse gas emissions suddenly stops, the persistent effects of existing emissions already in the atmosphere will continue to have an important impact on global temperatures in the coming centuries (IPCC, 2013). It is because some greenhouse gasses are long-lived, especially carbon dioxide, which can remain in the atmosphere for hundreds of years. As a result, even if urgent action is taken to reduce emissions, Earth's climate system will continue to respond to already existing high concentrations of greenhouse gasses, leading to continued warming and associated impacts such as increasing frequency of catastrophic weather events, shifting patterns of precipitation, and rising sea levels. This situation shows that it is critically important not only to reduce emissions, but also to implement adaptation strategies to address the inevitable consequences of climate change and protect the health and welfare of present and future generations. Limiting global warming at

1.5^oC is the aim established by the Paris Agreement (UNFCCC, 2015), calling on countries to limit greenhouse gas emissions to prevent the most severe impacts. According to the IPCC (2023), there is a six-year window to halve global net carbon emissions required to achieve this target, but this is becoming increasingly difficult to achieve. Despite efforts to limit warming, the persistent effects of climate change are expected to persist for many years, even centuries (Nicholls *et al.*, 2018), underscoring the need for sustainable action and adaptation measures.

2.2. The Impacts of Climate Change

2.2.1. Global Impacts of Climate Change

Climate change is a global problem with far-reaching impacts on various aspects of Earth systems and societies. One of the most apparent consequences of this is the rise in global temperatures, resulting in heatwaves, melting glaciers, and changing weather patterns (IPCC, 2021). This warming trend also contributes to rising sea levels because of the melting of ice sheets and glaciers, posing a serious risk to coastal cities across the globe because of rising rates of erosion, floods, and saltwater intrusion. In addition, the frequency and severity of extreme weather events like hurricanes, droughts, floods, and wildfires are both increased by climate change. These incidents result in fatalities and property damage, and disruption of communities and economies on a global scale. Changes in precipitation patterns further complicate the problem as some regions experience more frequent and intense precipitation events, while others face increased risk of drought, affecting agriculture, water resources and ecosystems. Loss of biodiversity is another critical consequence of climate change. Changes in temperature and habitats disrupt ecosystems, lead to changes in species distributions, and increase the risk of extinction for several plants and animals. Agriculture and food security are also deeply affected as climate change affects crop yields, water availability, and the spread of pests and diseases, posing risks to global food production and food security (IPCC, 2022).

The health impacts of climate change are also significant and widespread. Rising temperatures and changing weather conditions impact human health and well-being globally by contributing to heat-related diseases, respiratory problems, vector-borne diseases, and food- and water-borne diseases. Climate change causes significant economic and social losses due to material damage, loss of livelihoods, impacts on sectors such as agriculture, transportation, industry or tourism, and disruptions in supply chains. Additionally, it exacerbates social injustices, which disproportionately impact vulnerable populations including the elderly, the impoverished, and disadvantaged communities. Tackling climate change requires urgent and coordinated global action to reduce greenhouse gas emissions, adapt to ongoing impacts, and build resilience in communities and ecosystems. By implementing sustainable solutions, the catastrophic impacts of climate change can be reduced, and it is possible to build a more resilient and sustainable future for all (WHO, 2016).

2.2.2. Regional Impacts of Climate Change

Climate change affects all regions in the world. For example, ice sheets at the poles are melting, causing sea levels to rise. On the other hand, while extreme weather events such as extreme precipitation are becoming more common in some regions, more extreme heatwaves and droughts are experienced in some regions. The nature and extent of climate change impacts vary across different regions, and these impacts may differ according to geographical context and unique features such as hydrology, semi-arid regions or deltas (Kilroy, 2015).

Regionally, climate change affects different geographical regions in different ways. Regional implications of climate change can vary dramatically throughout different parts of the world due to the interaction between local geographic, environmental, and socioeconomic elements with global climatic patterns. While several global phenomena, such as increasing temperatures, higher sea levels, and changing precipitation patterns, are observed worldwide, their consequences might vary in severity depending on regional attributes. For example, coastal locations are particularly susceptible to the adverse effects of rising sea levels and storm surges (Roy *et al.*, 2023). As a consequence, these areas are more prone to floods and coastal erosion, making them more vulnerable. Inland locations may have more frequent and severe droughts or floods (Durodola, 2019), which can have an impact on water supplies, agriculture, and ecosystems. Mountainous areas may exhibit high vulnerability to changes in snowmelt (Knight, 2022), which can have an impact on water resources. Fluctuations in temperature and precipitation can also impact the geographical range of species and ecosystems, hence influencing biodiversity and the protection of ecosystem services (Bellard *et al.*, 2012; Pecl *et al.*, 2017). The capacity of a region to adapt to and minimize the effects of climate change is further influenced by socioeconomic factors, including access to resources, infrastructure, and governance. Thus, while certain global effects are generally noticed, their appearance and intensity may vary depending on the region, emphasizing the significance of adopting region-specific strategies for climate resilience and adaptation.

Climate change will have widely varying impacts in different regions. However, areas where inhabitants heavily rely on the climate and where there is a decline in favorable climatic circumstances will be the most severely impacted (Samson *et al.*, 2011). For example, the Middle East and North Africa (MENA) region is highly affected by climate change. Increasingly worsening conditions of extreme heat, drought and aridity lead to high levels of vulnerability across sectors and social dimensions, with the agricultural sector being particularly vulnerable against the impacts of climate change.

Climate change has significantly affected Europe's climate and continues to do so. Due to climate change, the potential for future warming and extreme events requires adaptation measures. Impacts of climate change in Europe may include positive effects on forest growth and wood production in northern and western Europe. However, negative impacts from increased drought and disturbance risks may occur in southern and eastern Europe (Lindner *et al.*, 2010). Climate change may have impacts on Europe such as more frequent and severe extreme weather events, changing water and food systems, and increased spread of infectious diseases through changes in environmental suitability (Romanello *et al.*, 2021). Due to global warming, impacts from extreme climate conditions such as heatwaves, droughts and coastal flooding could increase by up to 10 times current damages for Europe by 2100. The most affected will be southern and southeastern European countries (Forzieri *et al.*, 2016). Climate change may have impacts on several critical sectors for Europe. It will negatively impact the agricultural sector in Europe as increasing extreme events and trade patterns may lead to reduced agricultural incomes (Jacobs *et al.*, 2019). The effects of climate change may have an impact on European foreign policy objectives, affecting political stability, migration, food security, and livelihoods in areas with strong linkages to Europe, similar to MENA countries (Detges and Foong, 2022). Climate change brought about by global warming may have positive effects for Europe. Positive impacts of climate change for Europe may include favored summer tourism in some parts of Western Europe and reduced electricity demand in most regions (Jacob *et al.*, 2018). Climate change may also have positive effects on Mediterranean ecosystem services, and these effects may include “reduced hillslope erosion, sediment yield, sediment concentration, or flood discharge” (Eekhout *et al.*, 2020).

2.3. Climate Models

Among the most important issues facing the world community today is climate change. Understanding and predicting the potential direct and indirect impacts of climate change is crucial for developing effective strategies for adaptation and mitigation. To this end, extensive research over the past 25 years has focused on future studies and model projections of climate conditions. Numerous research centers and scientists worldwide are engaged in both individual and collaborative efforts to study climate projections. These modeling studies are essential for predicting past and future climate scenarios. Climate models employ quantitative methods to analyze the relationships among various components of the climate system, including the atmosphere, lithosphere, biosphere, hydrosphere, and cryosphere. By utilizing observable and measurable data, these models can simulate the complex interactions within the climate system. They account for the energy balance between the Sun's shortwave radiation and the Earth's longwave radiation. Any imbalance in this energy exchange leads to changes in temperature, highlighting the critical role of climate models in understanding these dynamics. These models not only provide insights into historical climate conditions but also enable predictions about future climate changes. The comprehensive nature of climate modeling, which integrates multiple components and their interactions, is vital for developing robust climate projections. As a result, these studies are invaluable for informing policy decisions and guiding efforts to mitigate and adapt to the changing climate.

2.3.1. General Climate Models (GCM)

General climate models (GCMs), also known as global circulation models, represent the pinnacle of sophistication in climate modeling. These advanced models evaluate atmospheric and oceanic dynamics on a global scale, incorporating the intricate interactions between the atmosphere and oceans. To achieve this, GCMs divide the world into a series of horizontal and vertical grid cells, enabling the extraction of climate data for any specific location on Earth. Through the use of multiple simulation experiments and a variety of greenhouse gas emission scenarios, GCMs are employed to project future climatic conditions. These models simulate how the climate system reacts to emissions of greenhouse gasses, sulfate aerosols, and other climate-influencing human activities. Due to the early models' relative simplicity, one significant drawback of early GCMs was their inability to precisely resolve small-scale features (IPCC, 2007). But throughout time, improvements in computational capacity have greatly increased the horizontal resolution of these models, making it possible to produce meteorological products that are progressively more precise. By incorporating new elements into the models, like more accurate beginning condition representations, the improved processing power has helped to lower the level of uncertainty in the projections. A study by Hausfather *et al.* (2020) analyzed 17 projections from 14 models produced between 1970 and 2007, demonstrating that these models accurately predicted the observed global surface warming. This accuracy underscores the value of GCMs in understanding and predicting climate dynamics. As computational capabilities continue to improve, GCMs become ever more powerful tools in the quest to understand and mitigate the impacts of climate change, providing crucial data to inform policy and adaptation strategies.

2.3.2. Regional Climate Models (RCM)

Due to their coarse resolution, while useful, GCMs with different grid sizes are not appropriate for high-resolution studies of regional climatic variability. GCMs can cover the whole planet, which necessitates a coarser grid size, resulting in lower resolution output and long simulation times due to their complexity. Current GCMs typically have a resolution of about 150 km. While this is an advancement over previous models, higher resolution data is necessary for regional and local studies.In areas with complicated topography or climate conditions, GCMs are unable to provide the precise regional climate data needed by researchers, stakeholders, and decision-makers (Leung, Qian, and Bian, 2003).

To address this limitation, Regional Climate Models (RCMs) are used to dynamically downscale the output from GCMs to higher resolutions, shown in Figure 2.2, typically ranging from 10 to 50 km. This process, known as dynamic downscaling, involves using the global model's results as input for the regional models, which then produce more relevant and detailed datasets for specific regions (Giorgi and Gutowski, 2015). RCMs, like GCMs, utilize complex mathematical equations but are specifically designed to simulate climate processes for targeted regions. For impact assessment studies pertaining to phenomena like the consequences of climate change on water resources, agriculture, and urban planning, this high-resolution data is essential.

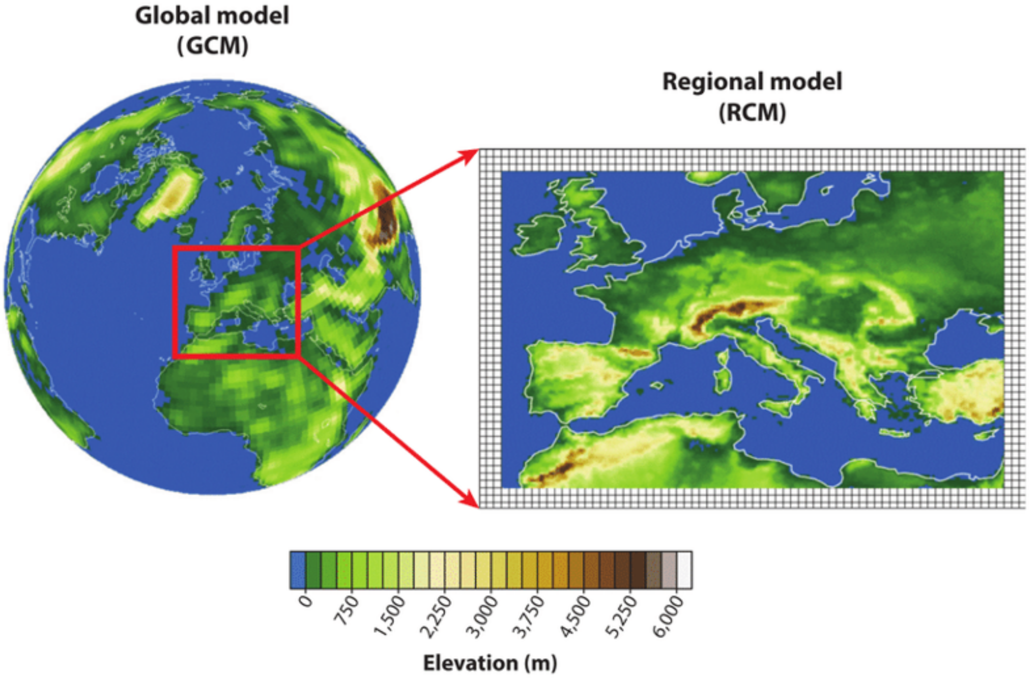


Figure 2.2. The notion of dynamical downscaling (Giorgi and Gutowski, 2015).

To conduct these impact assessments effectively, regional climate modeling techniques must be employed to provide climate data at higher resolutions. For example, models with a resolution of 10 to 50 kilometers are required to assess how climate change affects complex phenomena like crop yield and hydrological systems. RCMs use the output from GCMs as input and incorporate detailed topographical features, land-sea distributions, and surface characteristics to generate more authentic and finely resolved climate outputs. The rapid advancement of computing technology now allows modern RCMs to operate at resolutions of 10 km or higher. Even with known climate parameters and the ability to make projections for as little as ten years, predicting regional climate change remains challenging due to inherent uncertainties. Nonetheless, these high-resolution studies are very helpful in determining how much carbon dioxide may be in the atmosphere at any one time to reach a given level of surface warming. When more detailed resolutions are used, which account for land-sea distributions, vegetation, and surface topography, RCMs perform more accurately in simulating climate features (Arritt and Rummukainen, 2011).

Regional and global models may show different results in projections regarding climate change. For example, in a study examining surface solar radiation, projections of surface solar radiation show significant differences between regional and global models. Global models show an increase in surface solar radiation for Europe from 2006 to 2100, while regional models show a decrease in surface solar radiation (Bartók *et al.*, 2017). One study evaluated the differences in summertime climate change projections for Europe using regional climate models (RCM, the EURO-Coordinated Regional Downscaling Experiment) and their forcing global climate models (GCM, the Coupled Model Intercomparison Project Phase 5). It indicates that the global and regional predictions range significantly on large scales. For example, RCMs predict a 1.5-2 ^oC cooler summer warming and a much smaller 5% decrease in precipitation over a large region of Europe by the end of the 21st century, while GCMs predict a 20% decrease in precipitation (Boé *et al.*, 2020). Another study projects that summer precipitation will decrease in southern Europe and increase in northern Europe due to climate change, while individual models show inconsistent changes in precipitation (Matte *et al.*, 2019). The EURO-CORDEX regional climate model ensemble shows general agreement with observations and reanalyses but systematic deviations in temperature, precipitation and dynamic variables. Regional climate change in Europe generally scales with global temperature, except for very extreme precipitation and maximum temperatures, but the model scaling approach is robust for most variables and areas (Christensen *et al.*, 2015).

In the context of Regional Climate Models (RCMs), the CORDEX is plays for providing high resolution climate data worldwide. A coordinated effort called CORDEX uses RCMs to create regional climate predictions with grid resolutions ranging from 10 km to 50 km. This coordinated global effort seeks to improve our understanding of regional climate variability and change, essential for impact assessments and policy-making processes.

2.3.3. Representative Concentration Pathways (RCP)

The capacity of climate models to forecast future climatic conditions is their most important feature. As a result, it is crucial to forecast how greenhouse gas emissions-which are the main cause of the current climate change-will change over time, how much their concentrations in the atmosphere will rise, and how much the Earth will warm as a result. Assumptions concerning modifications to the physical, social, and economic factors influencing climate change must be made in order to predict and forecast future climatic scenarios. In order to produce reliable predictions of future developments, climate research takes into account a variety of elements, including changes in technology, land and energy use, and the emissions of air pollutants and greenhouse gasses. Socioeconomic and emissions scenarios are used to achieve this goal. These inputs are essential to climate model research and serve as the foundation for assessing possible effects on the climate, methods for mitigating such effects, and related costs (van Vuuren *et al.*, 2011).

These evaluations and assumptions are documented in RCPs for a variety of possible scenarios involving greenhouse gas concentrations. They provide a range of future forecasts, from low to high greenhouse gas emissions, from optimistic to pessimistic. Using these RCP scenarios, global models predict future climate conditions for various regions around the world. RCPs are not precise forecasts or policy suggestions, but rather offer a wide range of climate outcomes (Moss *et al.*, 2010; van Vuuren *et al.*, 2011). To support research into the effects of climate change and possible policy solutions, they offer varying amounts of greenhouse gasses and paths for their emissions. Numerous presumptions on population growth, economic expansion, technological advancement, and environmental and social sustainability are included in RCP scenarios. Potential future climatic changes are simulated using the parameters of each scenario. RCPs indicate greenhouse gas concentrations that will increase total radiative forcing-a measure of changes in the energy balance in the atmosphere due to shifts in atmospheric constituents like carbon dioxide-by specified amounts by 2100 relative to pre-industrial levels. The difference between solar radiation entering the atmosphere and radiation leaving it at the top is known as radiative forcing. The targets in RCPs are denoted as RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, reflecting different levels of radiative forcing (van Vuuren *et al.*, 2011). These pathways result in various potential increases in global average temperatures during the 21st century. For instance, RCP2.6, RCP4.5, RCP6.0, and RCP8.5 assume 2100 CO2-equivalent concentrations of nearly 490, 650, 850, and 1370 ppm, respectively (Moss *et al.*, 2010).

In this study, RCP8.5 was used, a scenario where greenhouse gas emissions continue to rise unabated, leading to an average global temperature increase of 4.3 ^oC by 2100 (van Vuuren *et al.*, 2011). The majority of recent studies on the effects of projected climate change has been on RCP8.5. This scenario with high emissions serves as an example of what can happen if society does not act as a whole to cut greenhouse gas emissions. RCP8.5 is especially helpful for short- and medium-term policy planning as well as for evaluating physical climate hazards. The total cumulative CO2 emissions recorded in the past are very similar to the emissions that correspond to RCP8.5. RCP8.5, which keeps CO2 emission levels at a reasonable pace even by 2100, is thought to be the most suitable scenario for the mid-century era given existing policies and stated intentions (Schwalm *et al.*, 2020).

2.4. Extreme Weather Events

An extreme weather or climate event is generally defined as “the occurrence of the value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values” (Seneviratne *et al.*, 2012). Extreme weather events are unusual, non-climatic and unseasonal severe weather conditions experienced in a particular location. Severe weather events that are rare or rarely encountered in the recorded weather history of a place are included in this category. Due to the impact of climate change, more extreme weather events have been observed in recent years. For a weather and climate event to be considered extreme, some important meteorological variable must lie near the upper or lower ends of the observed range of values according to the statistical distribution or reach a stage above an existing high threshold value. Weather or climate events that have a large negative impact on ecosystems or society are also considered extreme, although they are not statistically defined as "rare" (Türkeş and Erlat, 2017).

Climate change is typically linked to changes in average temperature and precipitation. However, it is emphasized that the majority of the social and economic consequences related to climate change will result from changes in the frequency and severity of extreme events (Karl *et al.*, 2008). The increase in the frequency of rainstorms is an expected consequence of the warming of the climate and this trend is observed. As the total amount of precipitation decreases, it is predicted that there will be more droughts in some regions and more frequent heavy precipitation in other regions. In some regions, there may be no change in the total amount of precipitation, but events such as precipitation falling less frequently and more intensely and flash floods may occur. These extreme climate events are expected to occur more commonly because of global warming, and the effects of global warming may place additional pressure on critical infrastructures, which are often designed to be long-lived. According to research illustrating how the effects of climate change may affect Europe's essential energy, transportation, industrial, and social infrastructures by 2100, damages from the phenomenon alone might quadruple by the 2020s and multiply by six by the middle of the century. Furthermore, research indicates that by the end of the century, the damage, which is presently estimated to cost €3.4 billion annually, might increase by more than ten times (Forzieri *et al.*, 2018). The same study's findings indicate that there will be a notable rise in the damage caused by heatwaves, droughts in Southern Europe, and coastal flooding; but, there will also be an increase in the danger of inland floods, storms, and forest fires throughout Europe. Due to their greater vulnerability, countries in southern and southeast Europe will probably need to incur larger adaptation expenses (Forzieri *et al.*, 2018).

Extreme weather events caused by climate change may bring different effects. Climate change has the potential to trigger socioeconomic and energy system disruptions by intensifying extreme weather events. Human-induced climate change increases the likelihood of extreme weather events such as floods, droughts and heatwaves, and these extreme events can potentially influence, for example, rebuilding and insurance pricing decisions (Stott, 2016). Extreme weather events and climate change significantly impact health and social care systems and require adaptation measures and strategic planning to increase resilience (Curtis *et al.*, 2017). Climate change increases the likelihood and intensity of extreme temperatures, heavy precipitation, drought, wildfires, and tropical cyclones, causing tens of thousands of deaths and billions of dollars in damage (Clarke *et al.*, 2022), and causing significant human diseases and adversely affecting mental health and well-being of the societies (Ebi *et al.*, 2021). Climate change also contributes to an increase in the frequency and intensity of daily extreme temperatures and an intensification of daily extreme precipitation (Stott, 2016).

On average, changes in climate extremes can be attributed to the escalation of global temperatures, increased levels of water vapor in the atmosphere, and changes in atmospheric circulation. Rising temperatures have a direct effect on heatwaves and lead to an increase in the amount of moisture present in the atmosphere, which in turn causes intense precipitation occurrences. The expansion of subtropical deserts originating from the equator leads to the enlargement of regions experiencing sinking and dry conditions, resulting in the expansion of land areas that are vulnerable to drought (Seidel *et al.*, 2008). The enlargement of this subtropical circulation pattern additionally enhances the transport of heat from the tropics to the Arctic, propelling mid-latitude storm tracks along with their precipitation to higher latitudes.

Climate change cannot be definitively linked to any short-term occurrence. The historical record has numerous instances of extraordinary occurrences that took place in the distant past, and it is evident that these events transpired independently of any climate alteration. There is empirical evidence of a rising occurrence and intensity of these events over time, which aligns with the predicted effects of global warming. Studies in climate physics suggest that this trend will persist in the future as the Earth continues to warm (IPCC, 2021). Therefore, it is appropriate to use a probabilistic risk management approach to analyze the connection between climate change and extreme weather events. The field of climate research focused on attributing extreme weather events has been growing, with a significant amount of literature available on the topic. The commonly employed method, frequently known as the risk-based approach (also referred as the probability-based approach) provides statements such as "human-induced climate change will result in a twofold increase in the likelihood of this type of event" or "human-induced climate change will lead to a 15% amplification in the intensity of this event." In these studies, the probability distributions of the index characterizing the event are estimated in both the current and hypothetical climates. Then, the probabilities and intensities for a given magnitude or probability of occurrence (e.g., 1 in a 100-year event) are compared.

2.4.1. Temperature Extremes

Climate extreme indices are fundamental diagnostic measures utilized to describe various aspects of geophysical systems, such as circulation patterns. They monitor and quantify phenomena such as droughts, El Niño-Southern Oscillation (ENSO) events, wind patterns, internal climate variability modes, and extreme events such as wildfires and heatwaves. These indices are essential tools in climate monitoring and prediction, providing valuable insights into the state and behavior of the climate system over time. The climate index overview page provides a comprehensive summary of the principles and methodologies underlying these indices. It serves as a foundational resource, outlining the philosophy and rationale behind the development and application of climate indices in scientific research and operational forecasting. By distilling complex climatic processes into accessible metrics, climate indices facilitate a deeper understanding of environmental changes and their implications for society and ecosystems. By using them methodically, we can better evaluate climatic variability and change, which helps policymakers prepare for and lessen the effects of climate change on the planet. Climate change-related extreme indices concentrate on relative thresholds that characterize characteristics in the tails of meteorological variable distributions (Zhang *et al.*, 2011).

The IPCC (2007) has noted a growing confidence that “certain extreme weather events will become more frequent, widespread, and intense during the 21st century.” This projection has led to an increased demand for information services focused on weather and climate extremes. Ensuring that living standards and economic growth are sustainable hinges on our ability to manage the risks posed by these extreme events. Addressing many practical challenges requires an understanding of the behavior of extreme values. Specifically, the infrastructures, public services, and other essential facilities that provide us with food, water, energy, health services, shelter, and transportation are highly sensitive to significant variations in meteorological conditions. Climate indices are useful instruments for calculating the variability of the climate and spotting related patterns.

Extreme temperatures that come with climate change are temperatures that are much more extreme than previous weather conditions. The frequency and severity of extreme weather events, particularly daily extreme temperatures, are increasing due to climate change (Ummenhofer and Meehl, 2017). Climate change brought about by human-induced global warming increases the likelihood of extremely hot seasonal temperatures and reduces the likelihood of extremely cold seasonal temperatures in several parts of the world (Stott *et al.*, 2016).

An additional warming of 0.5^oC could cause a strong change in minimum summer temperature indices in more than 70% of Europe. There may be a 60% increase on tropical nights and a 50% decrease on frosty days (Dosio and Fischer, 2017). Global warming of 2^oC would lead to significantly larger changes in the probabilities of extreme events, such as an increased likelihood of extreme heat occurring on average every 20 years (Kharin *et al.*, 2018). Warm spell duration, or the number of days contributing to “warm spells” in which the maximum temperature (TX) stays above the climatological 90th percentile, increases by 80, 65, and 62 days annually at 2.0^oC global warming. At this point, the frequency of cold nights and cold days decreases while the frequency of hot nights and hot days increases by 8-9 days (Nkemelang *et al.*, 2018). Events caused by extreme temperatures brought about by climate change include storms, floods, forest fires, and droughts. For example, climate change increases temperature variability in poor countries, making them much more vulnerable to extreme events such as heatwaves (Bathiany *et al.*, 2018).

How extreme temperatures arise is an issue that needs to be mentioned. Greenhouse gas forcing is the most important factor causing increased extreme temperatures (IPCC, 2021). Variations in large-scale patterns and modes of variability, soil moisture, evaporation, temperature, snow or ice, albedo, temperature, and local and regional forcings are some of the feedbacks that lead to variations in temperature extremes at regional scales. It leads to heterogeneity and related uncertainties in regional changes. Temperature extremes occur in part because of the changes in atmospheric circulation patterns, particularly anticyclonic circulations and northerly flow (Horton *et al.*, 2015). For example, extreme temperatures in Europe are mainly caused by the advection of cold air masses from the Arctic and Russia, with transport characterized by adiabatic compression and increased radiation and surface heat fluxes (Bieli *et al.*, 2015).

Since the IPCC's 2012 and 2014 reports, there have been many regional-scale studies examining trends in extreme temperatures using different measurements based on daily temperatures (Dunn *et al.*, 2020). For example, the Expert Team on Climate Change Detection and Indices (ETCCDI) is one of them. The ETCCDI indices stand out as a vital collection of fundamental climate indicators that are used to track the occurrence of extreme precipitation and temperature events. The ETCCDI is a working group supported by the UN whose goal is to find and disseminate best practices for describing climate variability and climate change. The ETCCDI indices are comprised of 27 distinct indices, all derived from daily observations of temperature and precipitation. In addition to a subset that is calculated on a seasonal and monthly basis to provide additional in-depth insights, these indices offer annual values for thorough study. Observation data show a decrease in the intensity and frequency of extreme cold and an increase in the intensity and frequency of extreme heat (IPCC, 2021). Depending on the region, temporal and spatial dimensions, and metrics considered, different trends in temperature extremes are seen at different magnitudes. Globally, between 1950 and now, there have been more warm days and nights, fewer cold days and nights, and more extreme temperatures-both the coldest and the hottest-than ever before (IPCC, 2021). For example, the mean temperature warming over land is approximately 45% higher than global warming, and the warming of land mean TXx is similar to the mean temperature warming over land. The warming of land mean TNn is even higher, with a warming of approximately 3^oC since 1960. When regional examples were examined, high warming was observed in TXx in Europe and northwestern South America and in TNn in the Arctic (IPCC, 2021). Extremes linked to daily minimum temperatures are changing more quickly globally and in the majority of land regions than extremes linked to daily maximum temperatures (Dunn *et al.*, 2020). Since 1950, the frequency of heatwave days, the average severity of heatwaves worldwide, and their duration have all increased dramatically (Perkins, 2015). Significant increases have been documented in Europe and Australia (IPCC, 2021). Regional variations of these can be seen in North America, Europe, Asia, and Australasia. In Europe, records of rising maximum temperatures and a rise in heatwave frequency have been made. In Central and Southern Europe, there has been an increase in both the frequency and the amplitude of high maximum temperatures (IPCC, 2021). In northern Europe, there has been a noticeable rise in the frequency of winter overheating incidents (IPCC, 2021). Cold periods in winter are decreasing in Europe (Brunner *et al.*, 2018; van Oldenborgh *et al.*, 2019). The likelihood of cold spells is twice as high as it would be in the absence of climate change (Christiansen *et al.* 2018).

According to projected forecasts, over the present century, there will likely be significant increases in the intensity and frequency of extreme heat events as well as decreases in the intensity and frequency of cold extremes worldwide (IPCC, 2021). The majority of land regions are expected to see an increase in the length, frequency, or intensity of hot periods or heatwaves, as well as an increase in the number of hot days and nights. Furthermore, the magnitude of extreme temperatures on land is predicted to rise more sharply than the average world temperature (IPCC, 2021). In certain mid-latitude and semi-arid regions, the highest increase in temperature on the hottest days is predicted to be roughly 1.5 to 2 times the pace of global warming. The highest temperature increase on the coldest days may be in the Arctic regions, at a rate of approximately three times that of global warming (IPCC, 2021). However, all these assessments depend on the spatial and temporal scales of the relevant extreme.

2.4.2. Precipitation Extremes

Excessive precipitation can affect the environment and society by causing floods and droughts. Precipitation extremes are linked to temperature, with heavy rain events increasing during warm periods and decreasing during cold periods (Allan and Soden, 2008). Precipitation extremes represent heavy precipitation and are affected by global warming, with 7% more extreme events than the expected number globally over the last decade, showing increasing trends in frequency and magnitude under global warming (Papalexiou and Montanari, 2019). Whether on a global or regional scale, climate change causes changes in the frequency, intensity, spatial distribution, length and timing of extreme weather and climate events. Precipitation showed high spatial and temporal variability on a global scale in the period 1900-2012, and increasing trends in precipitation amounts were observed on a regional scale (Türkeş and Erlat, 2017). While significant increasing trends are observed in the precipitation amounts recorded in the eastern parts of North and South America, Northern Europe and the central regions and north of Asia, significant aridification or decreasing trends are observed in the Sahel, the Mediterranean Basin including Türkiye (IPCC, 2021). Additionally, significant increases in heavy precipitation events (such as extremely high and extremely low precipitation) have been observed in several parts of the world and in Türkiye (Türkeş, 2012, 2014).

Extremes of precipitation are influenced by both kinetic and thermodynamic factors. A rise in severe precipitation is also a result of warming-induced thermodynamic changes. The impact of dynamic factor changes brought about by global warming on intense precipitation is more intricate and challenging to quantify. In addition to variations in greenhouse gas concentrations, other forcings can also impact precipitation extremes. These consist of urbanization, changes in land use and cover, and aerosol changes (IPCC, 2021). According to the IPCC's 2012 and 2014 reports, more places are experiencing an increase in heavy precipitation occurrences on land than a decrease. It should be highlighted, nevertheless, that these analyses showed large regional and seasonal variances, and trends in a number of places were not statistically significant. Extreme precipitation is becoming increasingly intense at global and continental scales (IPCC, 2021). For example, the average annual maximum precipitation amount in a day (one of the ETCCDI indices; Rx1day) has been increasing significantly over land and in humid and dry regions of the world since the middle of the last century (Dunn *et al.*, 2020). Average daily precipitation intensities have also been increasing since the middle of the last century in most land regions. For example, the probability of precipitation exceeding 50 mm per day increased during the period 1961-2018 (Benestad *et al.*, 2019).

Throughout the 1950s, Europe has experienced an increase in both the frequency and intensity of extreme precipitation (IPCC, 2021). There can be large differences between studies, regions and seasons. For example, it is stated that extremes related to extreme precipitation are more common in summer and winter and are not seen in other seasons (Helama *et al.*, 2018). Regionally, an increase is observed in Central Europe (Volosciuk *et al.*, 2016; Zeder and Fischer, 2020). The Eastern Mediterranean is experiencing modest rises, whereas the Western Mediterranean is experiencing decreases (IPCC, 2021). In summary, most land regions have seen an increase in the frequency and severity of heavy rainfall globally. In North America, Europe, and Asia, there has been a continental increase in the amount of heavy rainfall. However, the number of studies and available data are limited.

With increasing global warming, heavy precipitation may become more frequent and intense. For instance, extremely unusual (once per ten years) heavy precipitation events will become more regular and intense globally than they have been recently, if global warming levels reach $4^{o}C$ over the pre-industrial era (before the 1900s). Globally, the concentration of heavy precipitation will rise in proportion to the rate of increase in the maximum amount of moisture that the atmosphere can contain as it warms, by about 7% for every 1^oC of warming. At a 4^oC warming level, very unusual events like the 10- and 50-year events will increase roughly 2- and 3-fold in the future due to an increase in the frequency of heavy precipitation events. The degree of regional warming, as well as modifications to air circulation and storm dynamics, may all have an impact on the severity of extreme precipitation events at the regional scale. This could result in variations in the rate of extreme precipitation changes depending on the region (IPCC, 2021).

Extreme precipitation is expected to rise across Europe with global warming of 2^oC and higher. While not guaranteed, an increase at lower warming levels is probable (IPCC, 2021). For every 1^oC increase in global warming, it is predicted that the most extreme precipitation events currently recorded in Europe will quadruple (Myhre *et al.*, 2019). In northern Europe, there will likely be more extreme precipitation in the summer and winter (IPCC, 2021). In the southern Mediterranean region of Europe, for example, there are regional variations in terms of precipitation levels, which either rise or fall (IPCC, 2021). However, an increase is predicted in parts such as the Alps region and Northern Europe (IPCC, 2021). A further increase is expected for the winter season (Fischer *et al.*, 2015). Over 80% of Northern Europe's land area is expected to see a significant increase in extreme precipitation if global temperatures rise by 3^oC (Donnelly *et al.*, 2017; Cardell *et al.*, 2020).

3. DATA AND METHODOLOGY

3.1. Domain: Euro-Cordex

Climatic conditions can be characterized on various scales, encompassing global to local levels. The geographic distribution of contemporary climate is shaped by numerous factors, including latitude, proximity to oceans and other large bodies of water, and the presence of mountain ranges. Additionally, dominant wind patterns and ocean currents play significant roles in influencing climate. This complex interplay of factors is systematically represented in global classification schemes such as the Köppen-Geiger system. According to Peel, Finlayson, and McMahon (2007) and Türkeş (2022), this system categorizes climates into 25 distinct types based on criteria such as temperature, precipitation, and prevailing flora. The world's climates are divided into five main groups according to the Köppen-Geiger classification system, with each group represented by a different letter: A for tropical climates, B for desert climates, C for temperate temperatures, D for cold climates, and E for polar climates. These groups help in understanding and comparing the diverse climatic zones across the globe, providing a structured framework for climatological studies and applications.

The EURO-CORDEX domain, shown in Figure 3.1, encompasses the geographical region of Europe, providing high-resolution regional climate projections essential for regional climate studies and impact assessments (Jacob *et al.*, 2014). According to this classification system, the regions on the EURO-CORDEX examined in this study fall into the (B), (C) and (D) climate class, also known as the arid, temperate and continental climate zones, respectively. The arid climate group is seen in steppe and desert areas, and in the regions where it is seen, evaporation is more than precipitation. While the annual precipitation in the steppes is between 100-700 mm, in the deserts it is between 50-350 mm (Peel *et al.*, 2007). Specifically, in the temperate climate group, the average temperature of the coldest month ranges from above 0^oC to below 18^oC, while the average temperature of the warmest month is higher than

10^oC. This classification generally exhibits humid climate characteristics, where the seasonal variation in temperature is less extreme compared to other climate classes. This moderate temperature range results in a climate that is neither extremely cold nor extremely hot, allowing for a diverse range of flora and fauna. Within the temperate climate class, there are several subtypes, each with distinct seasonal patterns and characteristics. The focus of this thesis is on one such subtype, the Mediterranean climate, which is prevalent in certain parts of Europe. The Mediterranean climate, particularly known for its dry and very hot summers, is characterized by a stark seasonal contrast. Summers are typically long, hot, and dry, while winters are mild to cool with moderate rainfall. This climatic pattern is essential for understanding regional agricultural practices, natural vegetation, and overall ecosystem dynamics in these areas (Türkeş, 2022). In the Mediterranean regions of Europe, such as parts of Southern Spain, Italy, and Greece, the unique climatic conditions significantly influence local culture, lifestyle, and economy. The dry summer months necessitate specific agricultural strategies, such as the cultivation of drought-resistant crops like olives, grapes, and certain grains. Additionally, the climate impacts water resource management, urban planning, and tourism, which is a major economic driver in these regions. The Mediterranean climate's influence extends beyond mere temperature and precipitation patterns. It shapes the biodiversity and the natural landscape, fostering distinct ecosystems that are home to various endemic species. Understanding this climate is crucial for devising sustainable environmental policies and practices that can mitigate the adverse effects of climate change. Overall, the temperate (C) climate class, with its various subtypes including the Mediterranean climate, plays a pivotal role in shaping the environmental, economic, and cultural fabric of the European regions studied in this thesis. The emphasis on the Mediterranean climate, with its characteristic dry and very hot summers, provides a focused lens through which to examine broader climatic and environmental issues in Europe (Türkeş, 2022). Winters are severe in cold forest climates of class (D), continental climate zone. The warmest month's average temperature is over 10^oC, while the coldest month's average temperature is below -3^oC. The climates in this zone are characterized by the soil remaining covered with snow and freezing for months (Türkeş, 2022).

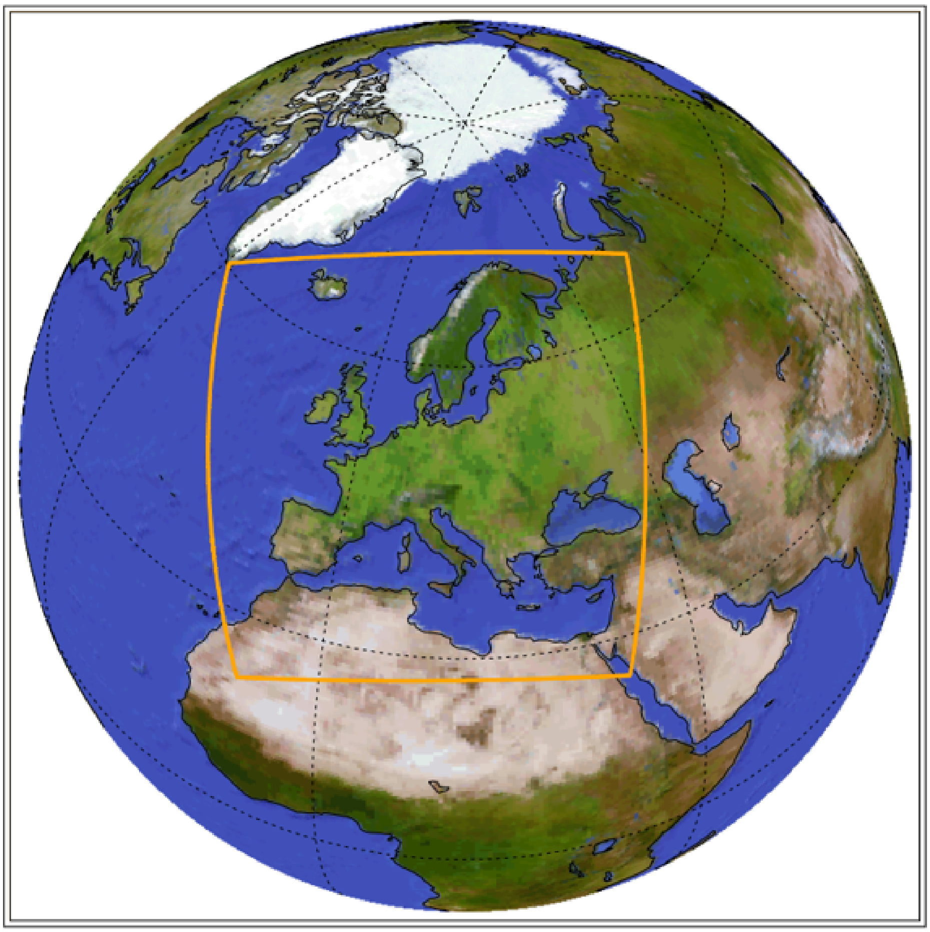
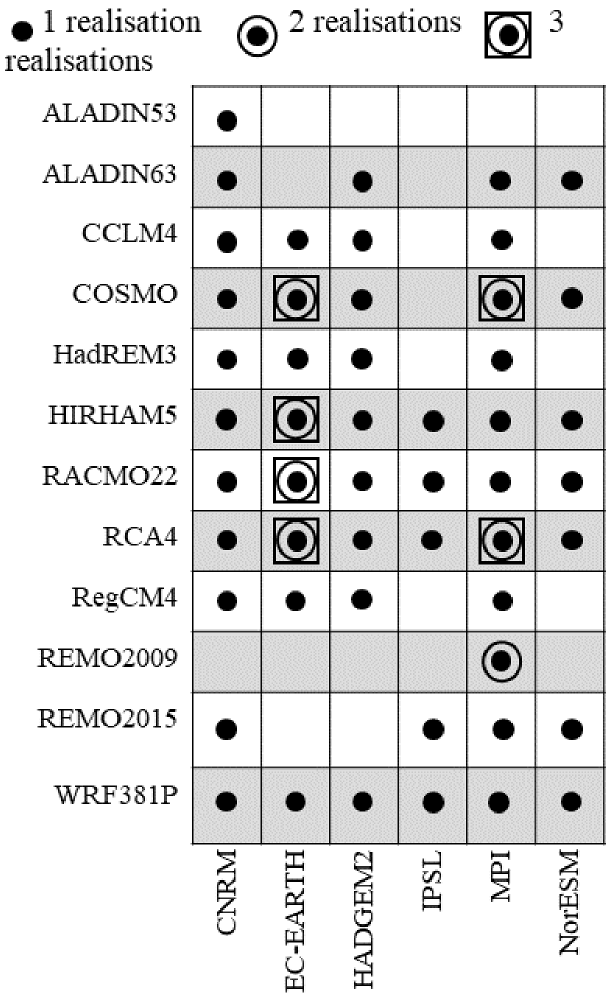


Figure 3.1. EURO-CORDEX domain map showing the spatial extent of the regional climate models (WCRP Cordex, n.d.).

3.2. Datasets

To analyze the potential impacts of climate change in accordance with the RCP8.5 scenario, daily maximum (Tasmax) and minimum (Tasmin) temperatures and precipitation (PR) from the EURO-CORDEX dataset, with a fine resolution of 0.11° grid mesh, were utilized as detailed by Jacob *et al.* (2014). The RCP8.5 scenario represents a high radiative forcing pathway, predicting that radiative forcing will reach 8.5 W/m^2 by 2100 due to ongoing increases in greenhouse gas emissions (van Vuuren *et al.*, 2011). In this scenario, projected changes in extreme temperature indices for the period 2080-2099 were compared to the baseline period of 1985-2004 by examining the multi-model mean from 64 regional climate simulations, providing a robust basis for understanding potential future climate conditions (Rockel, Will, and Hense, 2008; Colin, Déqué, Radu, and Somot, 2010; Baldauf *et al.*, 2011; Herrmann *et al.*, 2011; Kupiainen *et al.*, 2011; Samuelsson *et al.*, 2011; Giorgi *et al.*, 2012; Jacob *et al.*, 2012; van Meijgaard *et al.*, 2012). 64 different GCM-RCM EURO-CORDEX datasets were retrieved from the Earth System Grid Federation (ESGF) (Figure 3.2).



● 1 realisation ◉ 2 realisations ▣ 3
realisations

	CNRM	EC-EARTH	HADGEM2	IPSL	MPI	NorESM
ALADIN53	●					
ALADIN63	●		●		●	●
CCLM4	●	●	●		●	
COSMO	●	▣	●		▣	●
HadREM3	●	●	●		●	
HIRHAM5	●	▣	●	●	●	●
RACMO22	●	▣	●	●	●	●
RCA4	●	▣	●	●	▣	●
RegCM4	●	●	●		●	
REMO2009					◉	
REMO2015	●			●	●	●
WRF381P	●	●	●	●	●	●

Figure 3.2. The GCM-RCM matrix includes 64 simulations, with rows representing RCMs and columns representing GCMs..

The significance of using the RCP8.5 scenario lies in its representation of a "business-as-usual" pathway, which is critical for understanding the upper bounds of potential climate impacts if current emission trends continue. The high-resolution grid mesh of the EURO-CORDEX data allows for detailed regional analysis, essential for assessing localized impacts of climate change, particularly in capturing small-scale weather phenomena and extreme events that can significantly influence regional climate adaptation and mitigation strategies. Projections for the period 2080-2099 indicate substantial changes in extreme temperature indices, reflecting the impacts of continued global warming under the RCP8.5 scenario. By comparing these projections to the historical baseline of 1985-2004, trends and potential future risks associated with temperature extremes are identified. The comprehensive analysis of 64 regional climate simulations incorporates a range of models and scenarios to address uncertainties in future climate projections. The referenced studies provide a robust foundation for understanding the potential impacts of the RCP8.5 scenario, highlighting the importance of using multiple models to capture a range of possible future conditions (Rockel *et al.*, 2008).

High-resolution data is crucial for accurately representing regional climate dynamics (Colin *et al.*, 2010). Insights into model performance and reliability are provided by Baldauf *et al.* (2011), Herrmann *et al.* (2011), and Kupiainen *et al.* (2011), while the implications of extreme temperature changes for various sectors and regions are discussed by Samuelsson *et al.* (2011) and Giorgi *et al.* (2012). Contributions by Jacob *et al.* (2012) and Meijgaard van *et al.* (2012) enhance the understanding of model uncertainties and the importance of ensemble approaches in climate projections, offering perspectives on the broader impacts of climate change under high emission scenarios. This detailed analysis of the RCP8.5 scenario using EURO-CORDEX data underscores the potential for significant changes in extreme temperature indices by the end of the 21st century, highlighting the necessity of continued research and efficient techniques for both mitigation and adaptation to address the problems caused by climate change.

3.3. Methodology

3.3.1. Pattern Scaling

The pattern scaling technique accurately predicts temperature and precipitation patterns under increasing greenhouse gas concentrations, with increasing intensity of change per degree of global warming. Pattern scaling in climate change studies is used to estimate the forced change signal under increasing greenhouse gas concentrations (Tebaldi and Arblaster, 2014). It is an easy method to get climate projections that go beyond the results of using expensive global climate models (Herger *et al.*, 2015). Pattern scaling creates additional scenarios by scaling a spatial response pattern from a GCM according to a global warming projection from a simpler climate model. It explores spatial details of the climate system response without full simulation by GCMs (Lopez *et al.*, 2014). It enables interpolation beyond a limited set of available GCM simulations to evaluate alternative future emissions scenarios (Zelazowski *et al.*, 2018). Pattern scaling is a computationally efficient technique for generating global projections of future climate changes, including temperature and precipitation, across different emission scenarios (Xu and Lin, 2017).

The analysis focused on understanding the response of changes in extreme temperatures to global temperature increases, using the pattern scaling method deduced from various global climate models (GCMs). This method involved calculating the scaling as the division of the 20-year mean change in each temperature and precipitation index, relative to the baseline period of 1985-2004, by the global warming associated with the corresponding GCM in the GCM-RCM matrix (Matte *et al.*, 2019) (Figure 3.2). The scaling approach used here is based on linear scaling, which assumes a direct, proportional relationship between regional changes and global warming. The first step in this analysis was to compute the 20-year running means of regional changes in each index, using simulations from regional climate models throughout the century. These running means were compared to the reference period to capture the changes over time. For each 20-year running mean, the regional change signal was then divided by the respective 20-year mean global temperature change derived from the relevant GCM. This approach enabled a detailed examination of how regional changes in extreme temperatures correspond to global temperature increases. To illustrate, consider the output from the WRF381P regional model driven by the CNRM-CM5 global climate model. In this case, the scaling parameter was calculated using the global temperature output from the CNRM-CM5 model. By employing this method, researchers were able to investigate the correlation between changes in extreme temperatures and global temperature increases. This involved examining how changes in regional extremes are scaled relative to changes in global mean temperatures, thus providing insights into the sensitivity of regional climates to global warming. The methodology began with the identification of changes in extreme temperature indices over 20-year periods, relative to the baseline period of 1985-2004. These indices include metrics such as maximum and minimum daily temperatures, heatwave frequencies, etc. By calculating running means, researchers smoothed out short-term variability to focus on long-term trends. This long-term perspective is crucial for understanding the persistent effects of climate change on extreme temperatures. Next, these 20-year regional changes were normalized by the corresponding 20-year global mean temperature changes. This normalization process, or scaling, allowed the researchers to compare different regions and models on a consistent basis. The underlying assumption of linear scaling implies that for every unit of global warming, there is a proportional change in regional extreme temperatures. This linear relationship simplifies the complex dynamics of climate change, making it easier to predict regional impacts based on global temperature projections. These parameters helped quantify how much regional temperature extremes would change per degree of global temperature increase. This specific case study demonstrated the practical application of the scaling method, offering a clear example of how regional and global climate models can be integrated to assess climate change impacts. By employing this scaling method, the study aimed to establish a robust correlation between regional extreme temperature changes and global temperature increases. This correlation is vital for developing accurate regional climate projections, which are essential for local adaptation and mitigation strategies.

Understanding the scaling of extreme temperature changes helps policymakers and planners prepare for future climate scenarios, ensuring that infrastructure, public health systems, and natural resources are resilient to anticipated changes. Moreover, the analysis emphasized the importance of using a variety of climate models to account for the wide range of potential future conditions. The inclusion of various GCMs and RCMs allowed for a comprehensive assessment of uncertainties and variabilities in climate projections. Each model combination provided unique insights into how different regions might respond to global warming, emphasizing the need for tailored approaches in climate policy. In conclusion, the scaling method provided a systematic way to investigate the response of regional extreme temperature changes to global temperature increases. By dividing the 20-year mean regional changes by the corresponding global mean temperature changes, researchers were able to quantify the relationship between regional and global climate dynamics. This approach provided a more comprehensive insight into the possible effects of climate change on extreme temperatures, supporting more informed decision-making for climate adaptation and mitigation. The case study involving the WRF381P regional model and the CNRM-CM5 global climate model exemplified the practical application of this method, reinforcing its value in climate science.

3.3.2. Level of Global Warming

To thoroughly analyze temperature changes over time and assess the impact of global warming, the 20-year averages for each General Circulation Model (GCM) within each GCM-Regional Climate Model (RCM) pair (GCM-RCM pair) were first examined. The years in which global warming reached 1^oC, 2^oC, and 3^oC relative to the baseline period of 1985-2004 were identified. Subsequently, the 20-year average temperature changes for each individual member of the regional model projections were calculated for the years corresponding to the 1^oC, 2^oC, and 3^oC global warming levels. This method ensured that the analysis was based on clear, consistent comparisons and eliminated the potential for multiple shifts in the data. These regional averages were then normalized by dividing them by the analogous global mean warming levels, allowing for more effective comparisons of regional temperature changes relative to the global mean warming. This detailed and systematic approach provided a comprehensive understanding of the relationship between global and regional temperature changes over the specified periods, highlighting distinct impacts on different regions and offering insights into the variability and nuances of regional climate responses to global temperature increases.

3.3.3. Signal-to-noise Ratio (S/N)

A signal-to-noise ratio (S/N) was introduced in the study for each variable, computed using the following formula:

$$\frac{S}{N} = \frac{< SP >}{\sigma_{SP}} \tag{3.1}$$

where $< SP >$ represents the multi-model mean of all members for scaled patterns and σ_{SP} denotes the inter-member standard deviation of the change in scaled patterns (Christensen *et al.*, 2019). The S/N ratio serves as a critical measure to demonstrate the reliability and consistency of the projected changes across different model simulations. By calculating the S/N ratio, researchers can identify areas where the signal (the projected change) is strong relative to the noise (the variability among different model projections). A high S/N ratio indicates that the projected change is robust and consistent across the models, suggesting greater confidence in the predictions for those regions. Conversely, a low S/N ratio implies that the projections are less reliable due to higher variability among the models, indicating greater uncertainty in those areas. In the figures accompanying this analysis, gray shading is employed to highlight areas where the S/N ratio is less than one, visually indicating regions where the projected changes are not robust, as the variability among the models exceeds the strength of the signal. These areas of low S/N ratio require careful consideration, as the high uncertainty means that the projected changes in these regions should be interpreted with caution. This method of using the S/N ratio to evaluate the robustness of climate projections is crucial for understanding and communicating the reliability of model outputs. By clearly indicating areas of high and low confidence, the analysis provides valuable insights for researchers and policymakers, helping to prioritize regions for further study and to develop more targeted adaptation and mitigation strategies. The introduction and application of the S/N ratio thus play a vital role in advancing the field of climate science by enhancing the interpretability and usefulness of complex model projections.

3.3.4. Extreme Indices

Specifically, there are 16 temperature-based indices that emphasize extreme variations in daily maximum temperature (TX) and daily minimum temperature (TN). These indices include measures of maximum and minimum values, occurrences exceeding fixed thresholds, and values based on percentile thresholds. In addition to temperature indices, there are 11 precipitation indices within the ETCCDI set. These indices concentrate on total precipitation accumulations, events surpassing specific rainfall thresholds, and maximum rainfall extremes. By utilizing these indices, researchers and policymakers can gain a deeper understanding of climate extremes, thereby enhancing their ability to develop effective strategies for climate adaptation and mitigation.

Extreme indices related to climate change may include temperature-based indices such as TXx, TXn, TNx, TNn, and precipitation-based indices such as PRCPTOT.

<u>3.3.4.1. The Yearly Maximum Value of Daily Maximum Temperature (TXx).</u> TX_x represents the highest daily maximum temperature observed in month k, period j. Thus, TX_x denotes the peak daily maximum temperature recorded each month. It is expressed with the following formula:

$$TX_{x_{kj}} = max(TX_{x_{kj}}). \tag{3.2}$$

<u>3.3.4.2. The Yearly Minimum Value of Daily Maximum Temperature (TXn).</u> TX_n denotes the lowest daily maximum temperature observed in month k, period j. Therefore, TX_n represents the minimum daily maximum temperature recorded each month. It is

expressed with the following formula:

$$TX_{n_{kj}} = min(TX_{n_{kj}}). \tag{3.3}$$

3.3.4.3. The Yearly Maximum Value of Daily Minimum Temperature (TNx). TN_x denotes the highest daily minimum temperature observed in month k, period j. Consequently, TN_x represents the maximum daily minimum temperature recorded each month. It is expressed with the following formula:

$$TN_{x_{kj}} = max(TN_{x_{kj}}). \tag{3.4}$$

3.3.4.4. The Yearly Minimum Value of Daily Minimum Temperature (TNn). TN_n represents the lowest daily minimum temperature observed in month k, period j. Therefore, TN_n denotes the minimum daily minimum temperature recorded each month. It is expressed with the following formula:

$$TN_{n_{kj}} = min(TN_{n_{kj}}). \tag{3.5}$$

3.3.4.5. The Annual Total Precipitation on Wet Days (PRCPTOT). RR_{ij} represents the daily wet day (≥ 1 mm) precipitation amount on day i, in period j. I signifies the total number of days within period j. It is expressed with the following formula:

$$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}. \tag{3.6}$$

4. RESULTS AND DISCUSSION

4.1. Simulated Change in Tasmax, and Tasmin

Scaled models of the Tasmax and Tasmin for 2080-2099 were compared with the period 1985-2004. Northern Scandinavia and Iceland, typically colder regions, show an increase in Tasmax (Figure 4.1a). This is significant as the warming could accelerate the melting of ice masses, leading to a decrease in albedo. This, in turn, can contribute to further warming, creating a feedback loop that may impact local ecosystems and climate patterns. Similarly, the increase in Tasmax in Mediterranean regions like Greece, Türkiye, the Iberian Peninsula, and Northwest Africa could exacerbate existing challenges such as heatwaves, droughts, and water scarcity (Figure 4.1a). On the other hand, an increase is projected for Tasmin in all but the Southern part of Scandinavia, in Eastern Europe, in the Southern and Eastern parts of Türkiye, and in the interior of Northwest Africa (Figure 4.1b). It may affect agricultural practices and natural ecosystems by altering the length of growing seasons and winter chilling periods. These spatial variations underscore the importance of region-specific climate adaptation strategies to mitigate the diverse impacts of global warming.

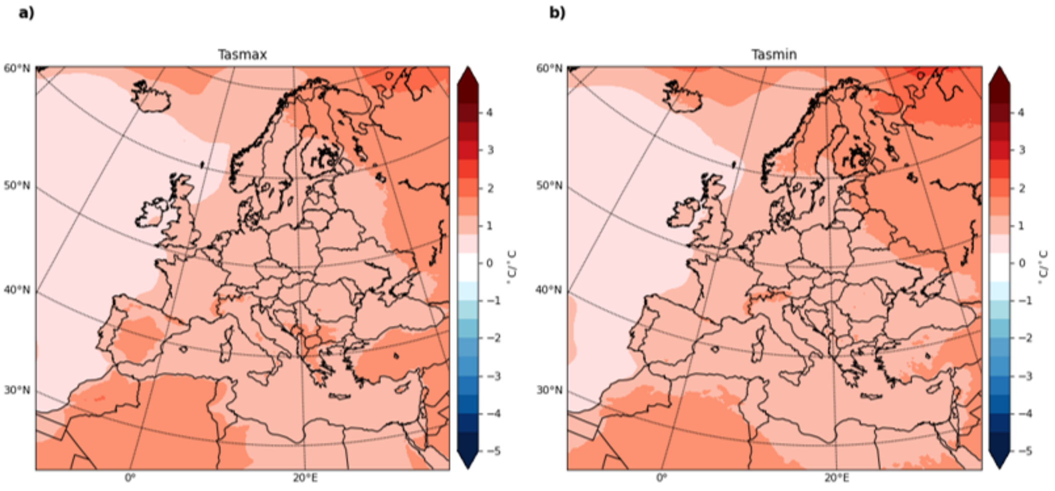


Figure 4.1. Change in scaled patterns of (a) Tasmax, and (b) Tasmin for the period 2080-2099 compared to 1985-2004.

4.2. Simulated Change in TXx, TXn, TNx, and TNn

Scaled patterns of the TXx, TXn, TNx and TNn indices for 2080-2099 were compared with the period 1985-2004. Figure 4.2 shows the ensemble mean and grayscale of the scaled changes in these four indices, demonstrating the robustness of the changes determined by the S/N ratio. The scaled patterns of the four indices at the end of the century show positive changes everywhere with a S/N ratio greater than unity, indicating robust changes and causing no gray shading in the reliable regions. The variation in the scaled patterns of TXx and TNx exhibits similar spatial trends, with greater increases in the Mediterranean Basin and Central Europe and smaller increases in Northern Europe, since the annual maximum of daily maximum and minimum temperatures most likely occurs in summer (Figure 4.2a, c). This pattern suggests that the Mediterranean Basin and Central Europe, which already experience warm summers, could face more intense heat events, potentially impacting agriculture, water resources, and public health. In contrast, the smaller increases in Northern Europe might indicate a lesser vulnerability to extreme heat, but these regions could still face other climate-related challenges.

Similarly, TXn and TNn occur in winter, both show a parallel spatial pattern with higher increases in the northern regions (Figure 4.2b, d). These findings align with the average temperature changes observed for summer and winter in Europe (Christensen *et al.*, 2019). End-of-century scaled models for TXx suggest global average temperature increases of 1.5-2 times for the Mediterranean region, including Türkiye and West Africa. However, a smaller increase is anticipated in the coastal areas of Morocco near the Atlantic Ocean and in certain regions of Libya and Egypt.

Patterns scaled for the end of the century appear to be on par with global average temperature increases in Western, Central and Eastern Europe. In northern Europe, the increase in TXx will be less significant compared to the southern region (Figure 4.2a). End-of-century scaled models showing maximum nighttime temperatures for TNx will increase more in the Mediterranean compared to other regions

(Figure 4.2c). This increase seems to be smaller for Western, Central, and Eastern Europe, and significantly lower for Northern Europe. End-of-century scaled models for TXn indicate a smaller increase in the Mediterranean compared to the northern region, yet it remains above the global average temperature rise (Figure 4.2b). In Eastern and Northern Europe, the increase is at least double the global average temperature rise. This is probably because less snow is predicted to fall in the region in the future. A similarly high increase is anticipated for Iceland and its surrounding areas. Scaled patterns for the end of the century in Western and Central Europe appear to be 1.5 times global average temperature increases. End-of-century scaled models for TNn reveal a greater increase spread to the southern region, including Türkiye (Figure 4.2d). A greater increase is expected for high-altitude regions, including the northern part of the Iberian Peninsula and the Atlas Mountains. However, it is estimated that there will be less increase in other parts of the Mediterranean.

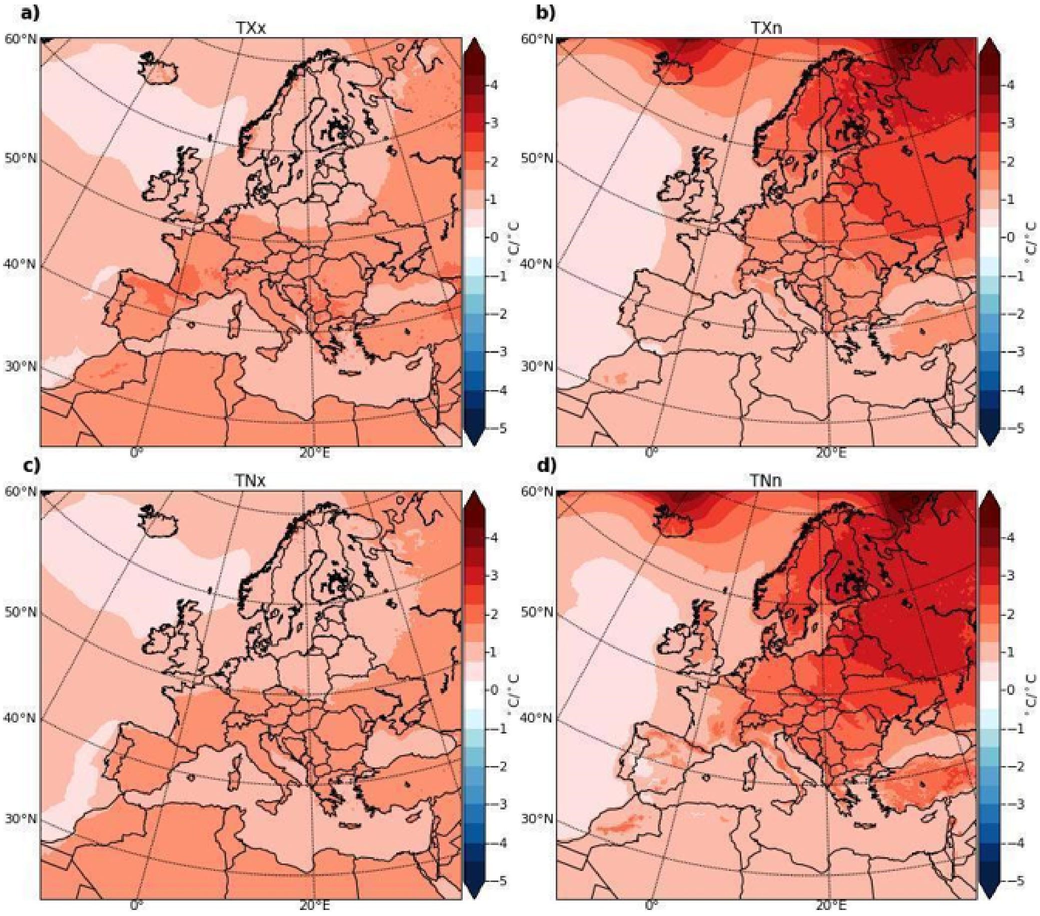


Figure 4.2. Change in the scaled patterns of (a) TXx, (b) TXn, (c) TXn, and (d) TNn for the period 2080-2099 compared to 1985-2004..

4.3. Simulated Change in PRCPTOT

The change in the 20-year running mean of PRCPTOT for the period 1981-2100 compared to the years 1985-2004 was calculated as a percentage. A substantial increase in the change of PRCPTOT is observed in the inner parts of Northern Scandinavia, the gulfs in the Western part of the Baltic Sea and the Northern parts of Iceland. This increase in precipitation could affect local hydrological cycles, potentially leading to more frequent flooding events and impacting local ecosystems. A smaller increase is observed in northern latitudes, starting from the northern part of Germany, the Czech Republic in general, the whole of Poland and the northern parts of Ukraine (Figure 4.3). Additionally, the increase in the Southeastern Black Sea region is also noteworthy

(Figure 4.3). On the other hand, decrease in PRCPTOT is observed throughout North Africa, noticeable in Morocco and Northeast Libya, highlights the increasing risk of drought and water scarcity, which could exacerbate socio-economic challenges in these regions (Figure 4.3).

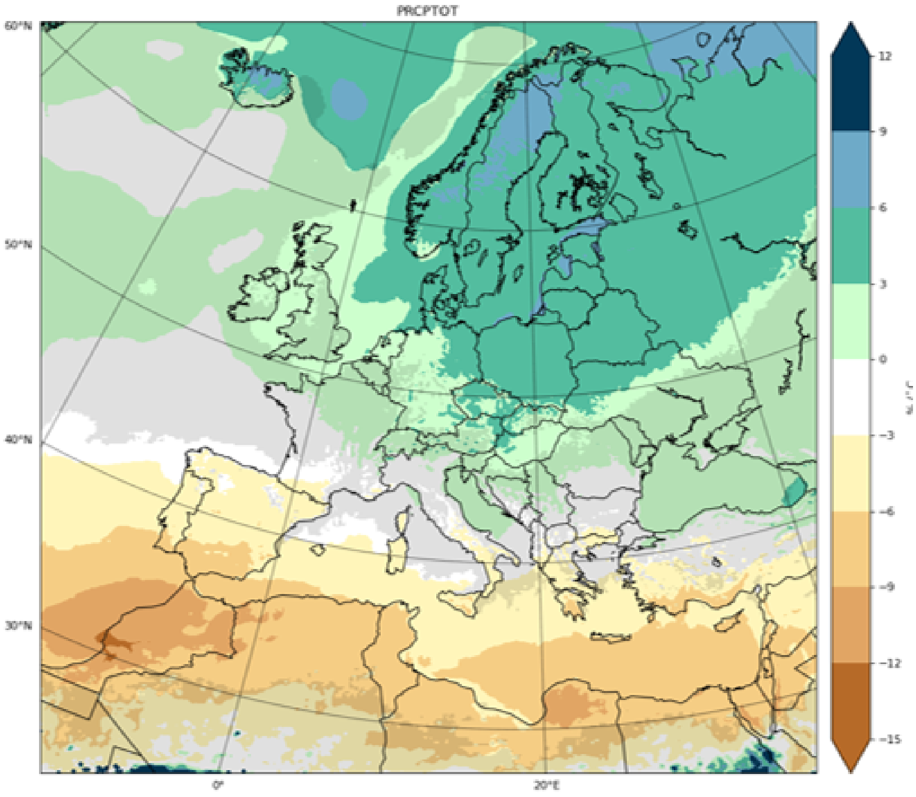


Figure 4.3. Percentage change of the scaled patterns of the PRCPTOT variable for the period 2080-2099 compared to 1985-2004.

4.4. Comparison of Scaled Patterns and Different Warming Levels

It was examined when the end-of-century scaled pattern is effective at different levels of global warming (Matte *et al.*, 2019). Figure 4.4 illustrates the spatially scaled patterns over the century for each grayscale index, indicating areas where S/N<1. The results demonstrate that the scaled pattern of change is robust for all indices at each warming level, with the exception of the 1^oC pattern for the TXn and TNn indices over the North Atlantic Ocean. This anomaly is likely due to the extensive warming across all indices and the consistency among individual model pairs. For all indices and different warming levels, the spatial pattern observed at the end of the century becomes apparent quickly, beginning from the year when the 1^oC pattern dominates. The findings show that the scaled patterns for each index remain nearly the same throughout the century, aligning with the early appearance of the ensemble mean pattern and its strong correlation until the century's end.

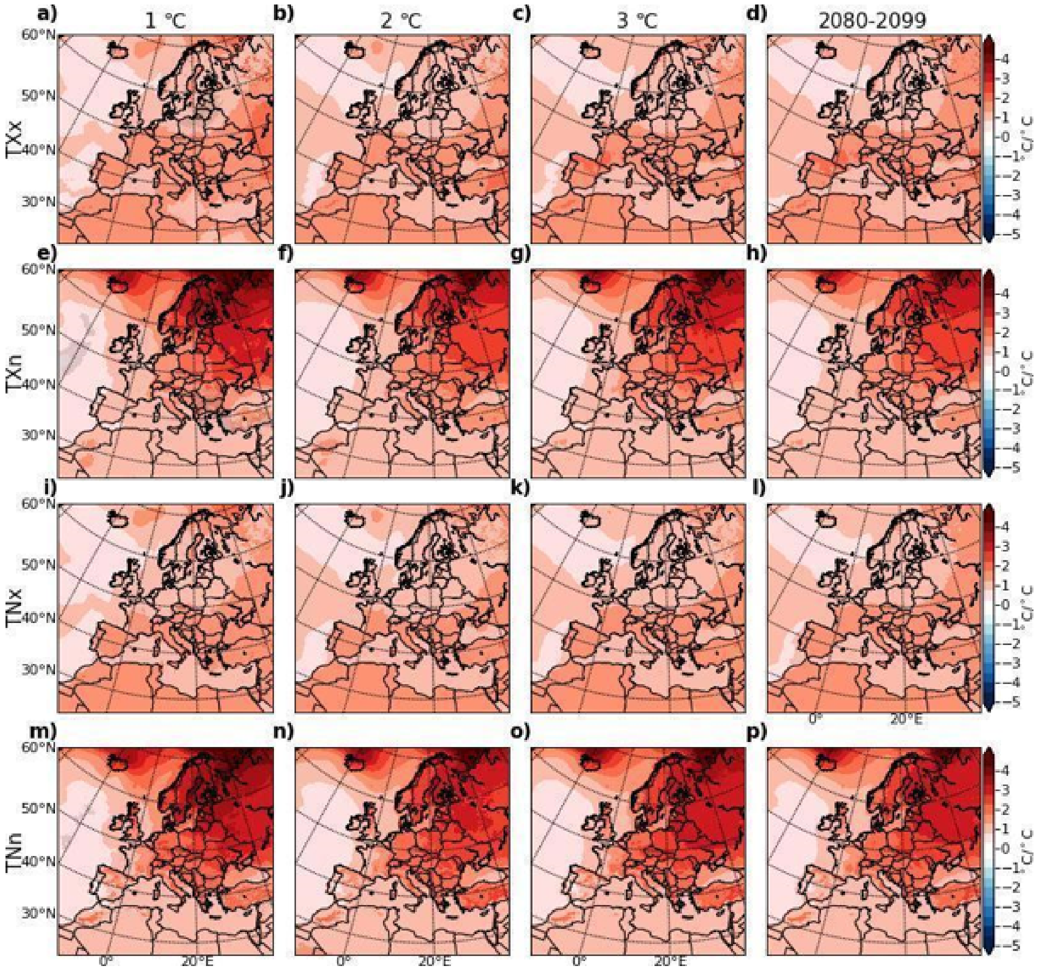


Figure 4.4. Scaled patterns of (a-d) TXx, (e-h) TXn, (i-l) TNx, and (m-p) TNn for the end of the century and different warming levels compared to 1985-2004.

4.5. Spatial Correlation of 20-Year Running Mean of Scaled Patterns

To better understand the emergence of the scaled pattern, the spatial correlation of the 20-year running mean of the scaled patterns from 1990 to 2089 (the median year of the 20-year running mean) was calculated by comparing it with the period 2080-

2099. Spatial correlations of the ensemble mean and individual model pairs for TXx, TXn, TNx, and TNn are shown in Figure 4.5, Figure 4.6, Figure 4.7, and Figure 4.8, respectively. The figures illustrate substantial variability in the early years of the period, with the correlation coefficient showing negative values. As the correlation coefficient increases, the dispersion decreases. This indicates that the scaled patterns become more consistent with the end-of-century patterns over time. Ensemble mean of model results for each index is consistent with the scaled pattern at the end of the century projections. Around 2020, the ensemble mean of TXx and TNx shows a high correlation with the end of the century (Figure 4.5 and Figure 4.7). On the other hand, the ensemble mean of TXn and TNn exhibits a high correlation with the end-of-century projections starting from very early years (Figure 4.6 and Figure 4.8). Looking at individual models, almost all models are consistent with the end-of-century scaled pattern from about 2040 for TXx and TNx (Figure 4.5 and Figure 4.7). Some regional climate model simulations run by CNRM show no correlation to 2030. Some even have a negative correlation with the turn-of-the-century pattern (Figure 4.6 and Figure 4.8). Nevertheless, all individual model pairs have strong correlations beginning in 2040, with correlation coefficients higher than those of TXx and TNx (Figure 4.5 and Figure 4.7).

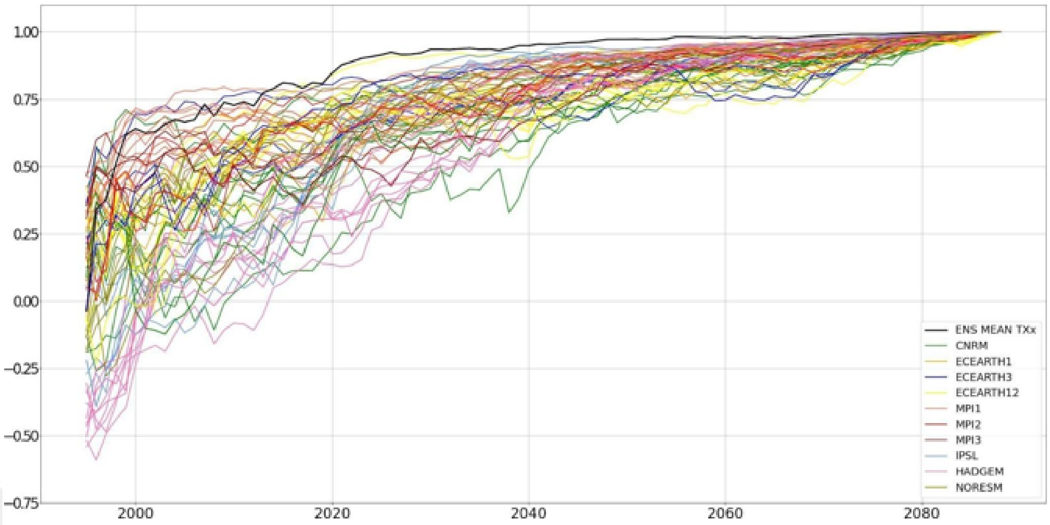


Figure 4.5. Correlation between the running mean of the 20-year scaled patterns of individual models and the ensemble mean of TXx (black line), from 1990 to end-of-century levels (2080-2099).

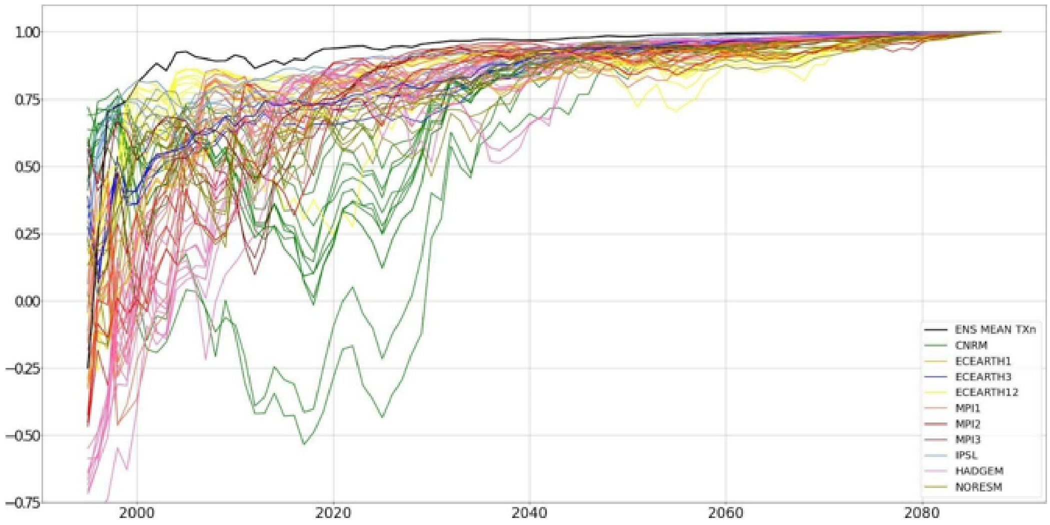


Figure 4.6. Correlation between the running mean of the 20-year scaled patterns of individual models and the ensemble mean of TXn (black line) from 1990 to end-of-century levels (2080-2099).

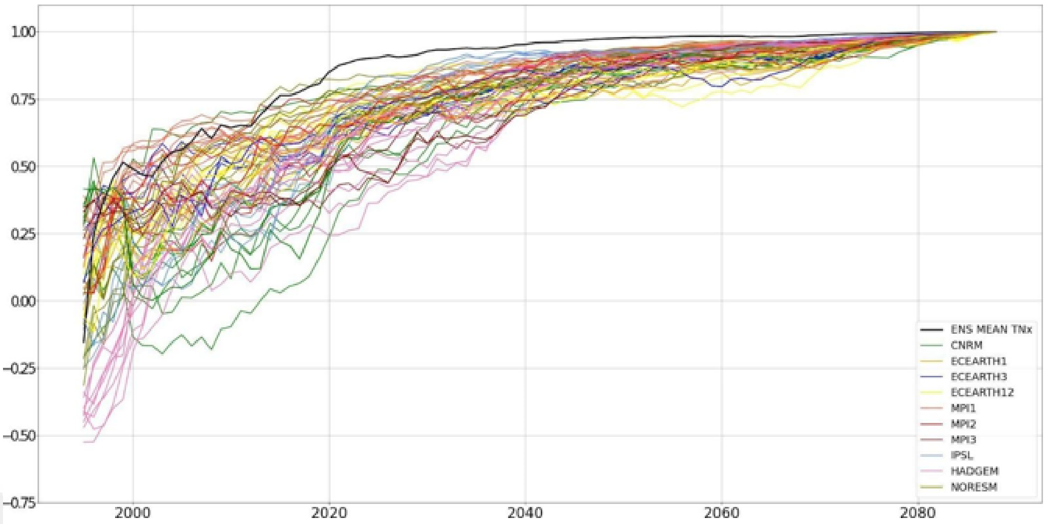


Figure 4.7. Correlation between running mean of 20-year scaled patterns of individual models and ensemble mean of TNx (black line), from 1990 to end-of-century levels (2080-2099).

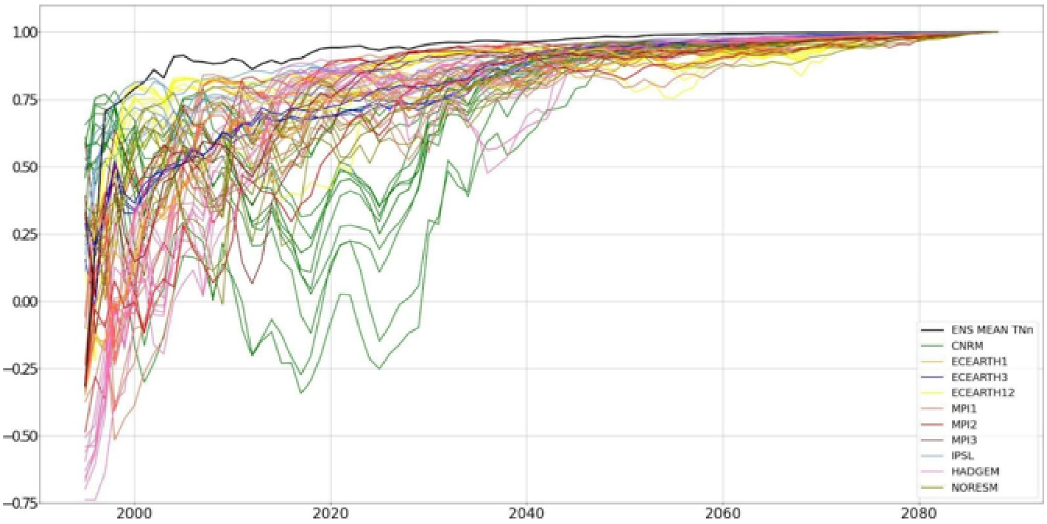


Figure 4.8. Correlation between running mean of 20-year scaled patterns of individual models and ensemble mean of TNn (black line), from 1990 to end-of-century levels (2080-2099).

4.6. Patterns of Extreme Temperature Indices Change Observed Using the ERA5 Dataset

Using the ERA5 dataset, the change in patterns of four extreme temperature indices was examined to determine whether end-of-century scale patterns could be detected for the conditions that were observed. The change of TXx, TXn, TNx and TNn for 2001-2020 compared to the period 1981-2000 was analyzed (Figure 4.9). For each of the four indices, a few similarities between model projections and observations were discovered. An increase in the annual maximum of daily maximum temperatures was observed in Western North Africa, the Mediterranean, Central, and Eastern Europe, as in the end-of-century scaled TXx models. It has been noticed that there is a smaller increase in the observed conditions in Scandinavia, in line with model predictions. The smaller increase in TXx over the North Atlantic Ocean is consistent with the model results for the same region. However, while the model results show an increase in TXx in eastern Iceland, no change is observed according to the ERA5 data. Changes in TNx have been observed and are consistent with model projections of an increase in western North Africa and central Europe, a smaller increase in Scandinavia, and in the North Atlantic.Under the observed conditions, the variation of TXn and TNn shows a similar spatial pattern, with an increase in the northern regions and a smaller increase in the southern regions. This pattern is also observed in the model projections. At the same time, a high increase in TXn and TNn was observed in Eastern Europe. There appears to be a high increase for both TXn and TNn in the northern region of Iceland and the North Atlantic, which is also observed in model projections for the end of the century. The emergence of the ensemble mean of the scaled pattern around 2010, which corresponds to the period 2001-2020, suggests a similar spatial pattern in the EURO-CORDEX simulations.

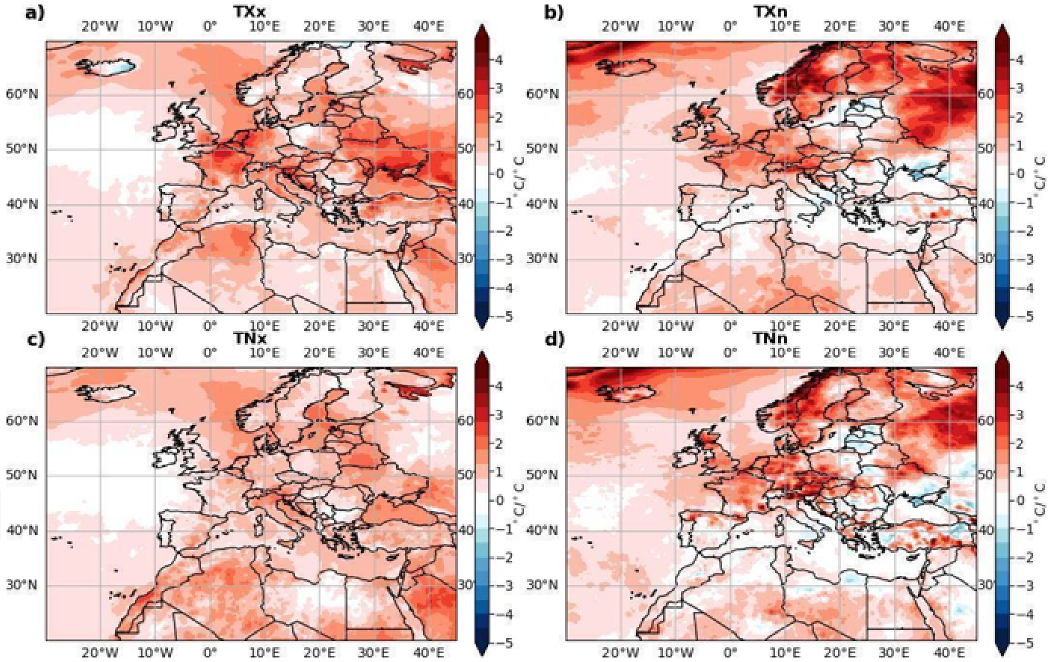


Figure 4.9. Change in (a) TXx, (b) TXn, (c) TNx, and (d) TNn for the period of 2001–2020 compared to 1981–2000 using the ERA5 dataset.

5. CONCLUSION

In this study, it was shown how robust scaled patterns of five indices—TXx, TXn, TNx, TNn, and PRCPTOT—describe the extreme precipitation and temperature patterns for the EURO-CORDEX regions. Findings for the ensemble mean of model pairings indicate that toward the end of the century, a positive change in these five indices is expected, and that this change is robust with respect to the S/N ratio. This approach is logical given the large geographical scope and diverse climatic patterns of the region. However, focusing solely on Turkey, a country with a complex topography and unique climatic conditions, suggests that a more targeted model might yield more precise results. Employing the most accurate model for Turkey's specific characteristics could enhance the fidelity of projections, potentially providing more reliable insights into local climatic changes.

The warmest day and night of the year, represented by the summer extreme indices of TXx and TNx, are more elevated in the Mediterranean and Central Europe and less elevated in Northern Europe. However, it is predicted that in Northern Europe, Scandinavia, and Northeastern Europe, the winter temperature indices, TXn and TNn, which represent the coldest day and night of the year, would rise higher. It was observed that TXn and TNn indices would occur in winter and both indices showed a similar spatial pattern with a greater increase in the north. It should be noted that these results are also consistent with the average temperature variation in summer and winter in Europe (Christensen *et al.*, 2019). In addition, the fact that less snow is anticipated in the region in the future explains why end-of-century scale patterns for TXn show a smaller increase in the Mediterranean than in the northern part of the region, but still higher than global warming, and why temperature increases in Eastern and Northern Europe are at least twice as high as global average temperature increases (Räisänen, 2021; Ivanov *et al.*, 2022). Furthermore, the fact that end-of-century scale models for TNn indicate a smaller increase in other parts of the Mediterranean but a larger increase in southern regions, including Türkiye, in higher topographic regions, such as the northern part of the Iberian Peninsula and the Atlas Mountains, may be related to significant cryospheric changes in these areas (Zekollari *et al.*, 2019).

Upon examining the temporal evolution of the scaled models for every indicator, it was observed that the end-of-century pattern emerged as early as 2010, predating its eventual robustness, which is indicated by a S/N ratio greater than 1 (Ozturk *et al.*, 2023). This indicates that future projections of climate models begin to produce consistent and reliable results earlier than expected. Although signal noise due to the low scaling parameter is initially evident, the pattern reveals itself at a very early stage, allowing the effects of climate change to be noticed. These differences emerge around 2040, although scale patterns show slightly different responses between individual pairs of climate models. In other words, most of the models start to show similar patterns that become evident from 2040 onwards. Almost all pairs of models quickly adapt to the end of the century pattern and combine consistently with each other. This result indicates that long-term projections of climate models are becoming increasingly reliable and that there is great agreement between various models. This agreement is important for understanding and predicting the future impacts of climate change. If models provide consistent results at an early stage, it gives decision makers and scientists valuable time to take necessary precautions and develop policies. Additionally, the fact that individual differences of models decrease over time and show a common pattern increases the accuracy and reliability of climate change research. The analysis of the PRCPTOT for 1981-2100 reveals significant changes in regions like Northern Scandinavia, Baltic Sea gulfs, Iceland, Germany, Czech Republic, Poland, Ukraine, Southeastern Black Sea Region, North Africa, Morocco, and Northeast Libya, with smaller increases in regions like Ukraine and Poland. These findings could play an important role in the development and implementation of strategies to combat climate change (Herger *et al.*, 2015).

The study also calculated the spatial correlation of the 20-year running average of the scale models from 1990 to 2089 by comparing it with the period 2080-2099. This analysis is an important method for assessing the consistency and reliability of future projections of climate models over time. The ensemble mean of model results is consistent with the end-of-century scale model, which increases the reliability of the overall model projections. Most of the individual models are consistent with the end-of-century scale model for TXx and TNx, indicating that these models can accurately predict temperature extremes. It has been observed that the group average of model projections begins to become evident around 2020 and shows a high correlation for TXn and TNn. This suggests that climate change impacts will emerge more clearly from the 2020s onwards and that models are able to capture these changes. However, some regional climate model simulations show no correlation or a negative correlation around 2030. This difference highlights the importance of regional differences and local climate dynamics. Such regional differences play a critical role in understanding the local-level impacts of global climate change projections and taking precautions accordingly. In order to determine whether the scale model could also be found in the observed changes, the study computed the change in four extreme temperature indices for the final 20 years of 1981-2020 compared to the first 20 years using the ERA5 dataset (Muñoz Sabater, 2019). The GCM-RCM sample's end-of-century scale patterns and the observed change patterns seemed to be showing similar changes. Even under the observed conditions, a pattern was seen to emerge at the century's end results for certain areas of the domain.

Given that this study includes the EURO-CORDEX domain, future work should consider extending the analysis to the EURO-CORDEX domain to leverage its updated datasets and higher resolution capabilities. Such an extension would allow for more detailed examinations of extreme weather events and provide enhanced insights into regional climate model projections. Additionally, focusing on the EURO-CORDEX domain could facilitate the integration of newer models and scenarios. This approach could further refine the accuracy of climate projections and their applicability to specific regions, including Turkey's unique and varied topography.

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