**Exploring temperature and precipitation changes in Europe across the 21st Century.**

* **Abstract (100 words)**
* **Introduction – Why the topic is important. What previous work has looked at this (mini lit review)**
* **Methods**
* **Results**
* **Discussion**

**ChatGPT Intro**

As global warming intensifies, understanding regional climate changes has become critical for informing adaptation and mitigation strategies. Europe, with its diverse climate zones, faces significant temperature and precipitation shifts that can impact ecosystems, water resources, and socio-economic systems. The urgency of these issues aligns with global climate targets set by agreements like the Paris Accord, which aims to limit global temperature rise to 1.5–2°C above pre-industrial levels. Achieving these targets necessitates regional insights into climate dynamics under various future scenarios, especially given Europe's vulnerability to both warming and precipitation variability. This study examines projected temperature and precipitation changes across Europe through the 21st century, focusing on the RCP4.5 scenario. This scenario, representing a stabilization pathway with medium greenhouse gas emissions, provides a nuanced look at possible regional climates by balancing continued emissions with proactive mitigation efforts.

Although there is a strong scientific consensus regarding human-induced climate change, fundamental uncertainties remain when projecting climate impacts over the 21st century, particularly on a regional scale. Climate models are essential tools for understanding the dynamics of climate change, providing insights into both past and potential future climates (Hegerl, Lecture 4). While models have reliably explained past climate patterns, predicting future climate involves greater uncertainty, primarily due to three main sources: scenario uncertainty, model uncertainty, and natural variability (Kjellström et al.). Scenario uncertainty reflects the unpredictability of future human actions, model uncertainty arises from the limitations and differences among climate models, and natural variability represents the inherent fluctuations within the climate system.

To investigate regional climate changes, scientists commonly employ General Circulation Models (GCMs), which are downscaled into Regional Climate Models (RCMs) to capture finer details of Europe’s varied topography and climate. Many RCMs have been developed specifically for Europe, allowing researchers to perform simulations across different emission scenarios, thus generating ensembles that address the uncertainties mentioned above (Kjellström et al.; Christensen et al.). These ensembles enable researchers to identify common regional trends while also highlighting the range of uncertainties associated with different models. To manage natural variability, climate simulations are often re-run under identical emission scenarios but with varying initial conditions, allowing scientists to evaluate the degree of variability or "noise" inherent in the results (Kjellström et al.).

Previous studies have shown that a significant portion of the uncertainties in RCM simulations is linked to the downscaling process from GCMs (Hawkins & Sutton, 2009; Kjellström et al.). For most European RCMs, statistical downscaling successfully preserves the large-scale atmospheric patterns from the GCMs, which largely govern precipitation and temperature trends across Europe (Kjellström et al.). These foundational uncertainties underline the importance of using a multi-model ensemble approach, as employed in this study, to capture the range of possible outcomes and improve confidence in regional projections.

Building on these studies, our analysis leverages the CORDEX-Europe simulations under the RCP4.5 scenario to investigate temperature and precipitation shifts over the 21st century. We aim to provide a comprehensive assessment of how climate patterns across Europe might evolve, focusing on spatial variability and seasonal dynamics. This research contributes to a deeper understanding of Europe's climate under an intermediate emission pathway, offering valuable insights into the region-specific impacts of climate change and supporting informed decision-making in climate policy and adaptation planning.

**Introduction**

Although the scientific consensus of human-induced climate change is strong, there are fundamental uncertainties that exist when considering this over the 21st century, especially on a regional scale. In order to understand the dynamics of climate change, scientists often use climate models to investigate past and future climate change (Hergerl paper Lecture 4). Although models have shown to explain past climate change to a high degree of confidence, the ability to model the future is more uncertain. These uncertainties can be grouped into three main categories: scenario uncertainty, model uncertainty and natural variability (Kellstrom). In order to explore climate change on regional scales, General Circulation Models (GCMs) are often downscaled to provide higher-resolution on the diverse climates and topography, to constitute Regional Climate Models (RCMs). Many RCMs exist for the European region, which are commonly used to run various simulations over different emission scenarios to create ensembles that can be used to address the uncertainties previously mentioned (Kellstrom; Christensen). By using various emission scenarios and simulations, this allows us to assess common regional trends, but also highlight the extent of the model uncertainties. In order to approach the natural variability conundrum, models are commonly re-run under the same emission scenarios, but with different initial conditions, to comprehend the extent of the noise (Kellstrom references).

Previous studies suggest that a large proportion of the uncertainties in RCM simulations is linked to the downscaling of the GCMs (Hawkins and Sutton, 2009; Kellstrom). There is a strong scientific consensus, that for a large proportion of the European RCMs, the statistical downscaling manages to retain the large-scale features present in GCMMs, which ultimately determines the precipitation and temperature signals for a large proportion of Europe (Kellstrom refs).

This paper explores

**Methods**

This study makes use of various General Circulation Model (GCM) simulation outputs from the Advanced IPCC Interactive Atlas; looking at mean near-surface temperature (°C ) and total near-surface precipitation in particular (mm/day) (**ref)**. To explore how these change throughout the 21st century across Europe, the CORDEX Europe simulations for the RCP4.5 scenario are considered. CORDEX Europe is primarily based on GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5), which have been downscaled to Regional Climate Models (RCMs) at higher resolutions in order to generate simulations for Europe in greater detail (Change ref). These simulations are based off of Relative Concentration Pathway (RCP) scenarios (Change). Unfortunately, the Interactive Atlas does not include RCP6.0 simulation outputs, which is more comparable to existing literature, so the decision has been made to explore RCP4.5 instead.

Before exploring the projections across the century, model results are compared against the observed climate at the end of the 20th century (1981-2010) to understand the ability for these models to successfully replicate observations and whether there are spatial anomalies that exist. The model simulations are compared against the E-OBS daily observational dataset, which dates back to 1960 (Haylock et al, 2008; Klok and Klein Tank, 2008; Kjellstro, 2011). Due to the gridded average structure of this dataset, it is directly comparable to model outputs, meaning that no transformational techniques are required, ultimately reducing errors (Kjellstro, 2011). Once the biases are established, the simulated changes in temperature and precipitation by the end of the century (2081-2100) are compared against baseline observations to understand how European Climate may develop across this timeframe, along with a critical analysis of the uncertainties regarding these projections. These changes are explored for an annual timescale alongside the summer months of June, July, August (JJA) and winter months of December, January and February (DJF).

The robustness of these changes are tested using the simple and advanced uncertainty scales that the IPCC Interactive Atlas provides. For a change to be deemed as robust, more than 66% of the models within the ensemble must show change, of which 80% must agree on the direction of change. This change must exceed the magnitude of internal climate variability. The Interactive Atlast shows spatial uncertainties spatially using a hatching system (not shown), which is commented on within the discussion.

**Results**

Simulated control climate

For temperature, the simulated climate is relatively comparable to the historical observations, with the models consistently underestimating the mean temperature (up to 2°C) for a large proportion of Europe annually and seasonally (Fig1); which is consistent with similar studies (Samuelsson et al, 2011; Kjellstro et al, 2011). The greatest underestimates are visible at the Northern border of Italy (~10°E, 45°N) and the Scandinavian region (between ~5°E-20°E, 60°N-70°N), with temperature differences between 3-4°C. Despite the models simulating a general cooler climate, there is a clear overestimation of temperatures in the Mediterranean region (between ~10°E-40°E, 40°N-50°N) by ~2°C. These extremities are most prominent in the winter months, and are consistent with similar research; although the overestimations shown in Kellstrom extend further across the Mediterranean. It is understood that the Mediterranean anomalies can be largely explained through land cover differences that are essentially ignored when the RCM calculated gridded spatial averages (Kellstrom). This is evidenced well in Samuellson et al, 2011; Nikulin et al, 2011 which displayed a reduction in these warm anomalies when the simulated climate was compared solely to open land areas.

For precipitation, the models consistently simulate wetter conditions on average across the majority of Europe by ~1mm/day (Fig1). The greatest precipitation rates are experienced in DJF, with the Mediterranean and Scandinavian regions displaying ~3mm/day more than the observations (Fig1). During the summer months these overestimations are restricted more towards the Northern-Italian border and the Scandinavian region (Fig1). These trends are relatively close to those from the 6-GCM ensemble given in Kjellstro, where regional biases exceed 100% in the North Scandinavian region, although in this study the average precipitation is underestimated by ~15% over the Alps. Further research concluded that these biases stem from the E-OBS observational dataset, by managing to simulate observations successfully through prescribing the RCMs with ERA40 reanalysis data at the lateral boundaries (Lind and Kjellstrom, 2009). This is likely to explain the projected differences in the Alps between this research and the work of Kellstrom as the observations are likely to be uncertain due to its mountainous terrain. The annual and winter trends are relatively similar, however during JJA the model simulations underestimate average precipitation rates over small regions of Eastern Europe by ~1mm/day (Fig1). This is in line with similar research, and is likely a result of topography, as it appears that precipitation anomalies are strongly overestimated over mountain regions, and weakened, or negative, in the neighbouring lowland areas (Kjellstro).

A screenshot of a graph showing the temperature of the earth

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End of the century simulations

Temperature

The simulations displays statistically significant warming across Europe by 2100, both annually and seasonally, with the majority of warming occurring within 2°C. This significance is highlighted particularly well in Fig3, which shows that even at the extreme percentiles, all of the models display a projected warming. For the near-term and mid-term, the temperature changes are statistically significant for approximately 70% and 95% of Europe respectively.This is consistent with existing literature, and is explained through projected reductions in Mean Sea Level Pressure (MSLP) over the Mediterranean, leading to reduced cyclonic activity and increased zonal flow to Northern Europe (Kellstrom). Projections display the greatest warming in areas of Northeast Europe of up to 5°C across all timespans (Fig2). The reasoning for these extremities extend beyond solely MSLP changes and instead is strongly correlated to the reduction in Arctic sea-ice and snow cover positive feedback loops; although it is difficult to ascertain whether this is a causal effect or merely a by-product of these processes (Chapin et al, 2005; Perovich et al, 2007; Kjellstrom).

The trends for precipitation are not as consistent (Fig2). Both annually and seasonally, the simulations show consistent drier conditions in Southern Europe and wetter conditions in Northern regions (both up to 30%) by the end of the century (Fig2. The border between these two distinct zones migrates North to South throughout the year, which is supported by similar studies (Kellstrom, Christensen et al, 2007). The increased precipitation in the Northern regions is in line with projected warming, which suggests that the temperature-moisture holding capacity feedback is playing an important role in this region (Kelstrom, Christensen et al, 2007). It is also possible that changes in atmospheric circulation may have a partial effect but is not the main driver (Kellstrom). In the Scandinavian regions, the increase in precipitation is ~6%/°C of warming, which is consistent with values stated in Kellstrom (5.6%/°C). It is important to note that this is considerably greater than the observed 4%/°C of warming for this region (Held and Soden, 2006), which highlights the amplification of the hydrological cycle that was discussed in the simulated control climate section (Kellstrom).

A screenshot of a computer screen

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**Robustness and Uncertainty**

By the end of the 21st century, the projected temperature changes across Europe exceed the natural variability in more than 80% of the models; making temperature change robust and statistically significant both annually and seasonally. This is shown visually in Fig3, which shows that even a t the extreme values, all models show consistent warming across the 21st Century. The temperature change for the near-term and mid-term is statistically significant for approximately 70% and 95% of Europe respectively. This is in perfect agreement with the figures given in Kellstrom, and highlights the the strong natural variability across Europe.

Despite the robust signal in temperature, the precipitation changes are more complicated. Across all terms annually, large regions of central and Northeastern Europe alongside the Scandinavian countries have high model agreement on an increase in precipitation (>80% of the models agree). However, when this is inspected in further detail, this change is not robust as only 66% of the models display a statistically significant change in the long-term in North-eastern Europe and the Scandinavian region.

For DJF, the majority of models agree on the increase in precipitation in Central, Northeast Europe alongside the Scandinavian region, by the end of the century. This high model agreement is evidenced in Fig3, which shows that at the 5% bounds, all projections are above 1% of the observation values. Despite this, further inspection shows that the majority of models cannot project changes that exceed the internal variability across Europe, which shows that these changes are not statistically significant.

Across annual and the seasonal timescales considered, the statistical significance increases slowly with time; which is in line with the findings from Kellstrom.

For JJA, there is little agreement on the sign of change for precipitation across the whole of Europe, with approximately 90% of Europe not showing a robust signal. JJA is the worst season for model agreement which is clearly evidenced in Fig3, which shows that at the 5% boundaries, the change can fluctuate from ~-4% to +8% by the end of the century.

A graph of different types of temperature

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**References**

Change, R.E., EURO-CORDEX: new high-resolution climate change projections for European impact research.

Kjellstro¨ M, E., Nikulin, G., Hansson, U.L.F., Strandberg, G. and Ullerstig, A., 2011. 21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations. *Tellus A: Dynamic Meteorology and Oceanography*, *63*(1), pp.24-40.

These trends are highly comparable with the work from Kellstrom.

Despite the models simulating a general cooler climate, there is a clear overestimation of temperatures in the Mediterranean region (between ~10°E-40°E, 40°N-50°N) by ~2°C for all timescales, but this is the most prominent in the winter (Fig1). This is comparable to the work of Kjellstro, however their overestimations extend further across this region for both summer and winter. Research suggests that simulated warming in the Mediterranean regions can be largely explained through the difference in land cover (Kjellstro). This is because observational data is usually taken from open areas, which tend to be warmer than forested regions, due to sunlight exposure. As the model calculates gridded box averages over areas with multiple land areas, this could be causing warming anomalies. This has been explored in further detail by Samuelsson et al, 2011 and Nikulin et al, 2011, which showed a reduction in these warm biases when the simulated climate is compared solely to open land areas of the grid areas.

The varying terrainThis reasoning couldcould also explain the difference in anomalies between this research and the work of Kjellstro for the Northern Italian border, as this region has varying terrain making observations very uncertain (Kjellstro).

This is consistent with Kjellstrom, however it is understood that this is not solely due to changes in circulation patterns mentioned previously. Instead, this is strongly connected to the Arctic sea-ice and snow cover reduction positive feedback loops; although it is difficult to ascertain whether these temperature changes are a cause or result of these processes. (Chapin et al, 2005; Perovich et al, 2007; Kjellstrom).