**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**

**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 with 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 such as interpolation or re-gridding is required, ultimately reducing errors (Kjellstro, 2011). Once the biases are established, the changes in temperature and precipitation by the end of the century (2081-2100) simulations are compared against the 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).

**Explain the robustness and uncertainty significance measure**

**Results**

Simulated control climate

In terms of 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 for all of the timescales considered (Fig1). This is relatively 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 Northern regions of Norway (between ~5°E-20°E, 60°N-70°N) for all timescales considered, with a temperature difference of ~-3°C. This is consistent with the values given from Kjellstro. **WHY**

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 is calculated a gridded box average 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.

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 the winter months, particularly for the Mediterranean and Northern where predictions are ~3mm/day more than the observations. (Fig1). During the summer months these overestimations are restricted more towards the northern Italian border and the northern countries; which is relatively close to the 6 GCM ensemble mean precipitation changes shown in Kjellstro, although in this study the Northern Italian border appears to underestimate average precipitation by ~15%. This is highly similar to the work of Kjellstro which highlights regional biases that can extend beyond 100% in Northern Scandinavia.

Further research into this spatial bias, managed to simulate the observations successfully in the Scandinavian region, by prescribing RCMs with ERA40 reanalysis data at the lateral boundaries, which suggests that these large uncertainties are likely to stem from the E-OBS observational dataset (Lind and Kjellstrom, 2009). This could 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). 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. This is in line with similar research, and it elucidated that these estimation anomalies are 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 show a consistent warming trend across Europe by the end of the century, when compared to the baseline, with the majority of warming within 2°C. This is consistent with existing literature, and is explained through projections showing a reduction in Mean Sea Level Pressure (MSLP) over the Meditteranean, which ultimately reduces cyclonic activity in this region and increases zonal flow to Northern Europe, and subsequently leads to greater atmospheric temperatures (Kjellstrom). The greatest warming projections are in areas of Northeast Europe of up to 5°C across all timespans (Fig2). This is consistent with Kjellstrom, however it is understood that this is not solely due to changes in circulaton 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).

**Refer back to page 32 when talking about the uncertainties**

The trends for precipitation are not as consistent (Fig2). Across the year and seasonally, the simulations show consistent drier conditions in Southern Europe and wetter conditions in Northern regions (both up to 30%) , compared to the baseline observations at the beginning of the century (Fig2). The border between these two distinct zones migrates North to South, throughout the year, which is supported by findings in Kellstrom and studies that have used large ensembles of RCMs derived from GCMs (Christensen et al, 2007). The increased precipitation in the Northern regions is in line with the increasing temperatures discussed previously, which suggests that the feedback which increases the atmosphere’s moisture-holding capacity in line with increasing temperatures is playing an important role (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% per °C of warming, which is consistent with values stated in Kellstrom (5.6% per °C). It is important to note that this is considerably greater than the observed 4% per °C of warming for this region stated from Held and Soden (2006), which higlights 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.