How does the CMIP6 ensemble change the picture for European climate projections?

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Abstract
We compare Coupled Model Intercomparison Project (CMIP) ensemble (CMIP6) projections for seasonal mean temperature and precipitation to CMIP5 for northern Europe, central Europe and the Mediterranean. The CMIP6 ensemble shows increased projected summer warming compared to CMIP5, which was found to be statistically significant in central Europe and the Mediterranean. Precipitation projections for Central Europe in CMIP6 were found to have a stronger drying trend in the summer months, there was also a substantially narrower projection range. Spatial comparisons indicate that this stronger drying trend also extends into a large part northern Europe. We show that warmer projected summer temperatures in northern Europe and the Mediterranean are largely driven by the higher global climate sensitivities in CMIP6 models, while regional changes are broadly similar. In central Europe a significant difference in the regional responses was found and in these cases the picture can be said to have changed. We find the difference in regional sensitivity is important in central Europe where it accounts for roughly 40% of the differences between ensembles in projected regional temperature.

1. Introduction

1.1. Rationale and motivation
Climate projections are needed for strategic adaptation and mitigation planning at the global, regional and national level. Inferences about robustness are heavily influenced by what is learnt about future climate change from multi-model ensembles, which can be used to sample the known uncertainties in climate change responses due to intrinsic variability, structural differences in the models and different socio-economic pathways.

A new generation of climate models provides an opportunity to assess if the new developments in the latest Coupled Model Intercomparison Project (CMIP) ensemble (CMIP6), changes the picture regarding what is know about climate projections for Europe. Here we explore whether there are substantial differences in the CMIP6 projections for Europe, compared to CMIP5, which warrant further investigation and, potentially, re-assessment of existing impacts and risk assessments. We aim to investigate how the CMIP6 ensemble may change the overall picture for projections from CMIP5.

Previous generations of ensembles such as CMIP3 and CMIP5 have not lead to much change in the overall projections (Knutti and Sedláček 2013, Kumar et al 2014), despite improvements in the model science and better integrated earth systems models. Early indications are that CMIP6 may be different in this regard with a number of models showing much higher climate sensitivity (e.g. Forster et al 2020). These new models may have a large impact on projected climate responses for European regions and it is unknown to what extent our picture of the known risks of global warming may be changed in regions already considered climate change ‘hot spots’ such as the Mediterranean (Giorgi 2006, Lionello and Scarascia 2018).

In this study we have chosen to consider seasonal averages of two key climate variables; near-surface temperature and precipitation, for the European SREX regions. Natural and human systems can be vulnerable to a diverse range of climate changes with a
range of impacts. For example, seasonal water deficits (water companies), peak river flow (flooding) or icy days with winds above certain thresholds (electricity networks). There are two aspects that make seasonal mean, large scale changes useful indicators of climate change driven changes for other impact variables:

Firstly, annual and seasonal mean changes are often taken as indicative measures of changes in a wide range of climate variables. This may be tied to changes in other metrics for the same variable (for example projections indicating an increase in mean temperatures are likely to also be associated with increases in temperature extremes and decrease in cold extremes) but temperature, in particular, is often taken as a proxy for changes in other variables. Relationships between mean temperature change and changes in other variables is well established and used (for example) in pattern scaling approaches (Ruosteenoja et al 2007, Arnell et al 2013, Tebaldi and Arblaster 2014, Gosling and Arnell 2016, Zelazowski et al 2018). These relationships are likely to hold more strongly between regional mean temperature changes and the regional response in other variables. Larger mean temperature changes would be associated with larger changes in other impact areas.

Secondly, the focus on regional scale means is important to isolate the climate change signal. It is often the case that impact relevant metrics are local scale, where internal variability (and the ability of models to capture local scale processes, like land sea contrast) play a larger role in projected changes. By focusing on the large scale mean temperature and precipitation changes we provide information about the consistency (or otherwise) of the climate change signal between different CMIP generations. This provides important context for those considering other impacts, as it points to whether existing assessments (for other variables) need to update their climate change signal, or not.

The analysis presented here was carried out as part of the European Climate Prediction Project (EUCP), which has an overarching objective to develop a European regional ensemble prediction system that is designed to support practical and strategic climate adaption and mitigation on a range of scales from local to global. This study aims to contribute to these aims by assessing if the new CMIP6 results change the picture of future climate for Europe and warrant further investigation.

Where CMIP6 does show differences, we will discuss whether advancements in the models suggest these supersede existing projections, or supplement them. The question of whether CMIP6 represents a significant improvement from CMIP5, in terms of our understanding of the physical processes and model skill is an important one, although outside the scope of this paper.

1.2. Regional and global CMIP6 projections

There are a number of previous studies in the literature that investigate regional climate projections in Europe due to global climate change and identify areas such as central Europe and the Mediterranean as particularly sensitive to global warming (e.g. Giorgi et al 2001, 2004, Pal et al 2004, Lionello et al 2006, 2012, Christensen et al 2007, Ruosteenoja et al 2007, Gualdi et al 2013, IPCC 2013, Ulbrich et al 2013, Lionello and Scarascia 2018). Overall findings are an expectation of increased summer temperatures in central and southern Europe along with a decrease in precipitation (e.g. Senevirante et al 2006, Giorgi and Lionello 2008, Vautard et al 2014, Vogel et al 2017, Brogli et al 2019, Senevirante and Hauser 2020). There is therefore considerable interest in new climate projections and whether these are consistent with these earlier findings.

While there is a large body of literature comparing previous CMIP ensembles, studies for CMIP5 and CMIP6 are only recently beginning to emerge. Key differences in the CMIP6 models from their CMIP5 predecessors include, in particular the improved representation of clouds and changes in the model physics (Zelinka et al 2020). There is however considerable debate in the climate modelling community about the greater surface warming from these models and the plausibility of the model projections from the models with an ECS higher the IPCC AR5 likely range (66% probability) (IPCC 2013). These studies so far suggest that while the higher warming predicted by the CMIP6 ensemble may be considered unlikely it should not be discounted and projections at the regional scale need to be investigated further. In this study we address the impacts on the picture at the regional scale in Europe. Questions regarding the likelihood or plausibility of some of the CMIP6 models are beyond the scope of this study.

2. Materials and methods

The models from CMIP6 and CMIP5 that are included can be viewed in tables S1 and S2 (available online at stacks.iop.org/ERL/16/094042/mmedia) in the supporting material, see also Taylor et al (2018) and ENES (2019) (European Network for Earth System Modelling). The experiments in CMIP archives represent a core strand of evidence that informs adaptation (and mitigation) planning. The CMIP5 and CMIP6 scenarios are based on representative concentration pathways (RCPs) (van Vuuren et al 2011). In this study we focus on the highest emission scenario (RCP8.5/SSP5-8.5), from which we would generally expect to see the strongest climate signal to noise and therefore the clearest basis for comparison. We also find the largest number of models with data available for this scenario. We note that although the
RCPs and SSPs scenarios have nominally equivalent forcing level in 2100, the actual forcing levels are shown by Ribes et al (2021) to be somewhat higher in SSPs. This discrepancy was investigated by Fyfe et al (2021) it found that the higher CO\textsuperscript{2} and greenhouse gas (GHG) concentrations account for a 0.55 K increase in SSP585 compared to RCP8.5. This affect was offset to some extent by aerosol forcing by about 0.19 K so we can expect about a 0.3 K increase in global mean temperature in SSP585 due to these forcing differences.

We use a baseline period of 1995–2014 and two future periods: 2041–2060 (mid century) and 2081–2100 (end of century). These time periods have been selected for consistency with IPCC analyses (IPCC 2012) and existing EUCP analyses (e.g. Brunner et al 2020).

The regions we use in this study refer to SREX regions as used for EUCP, (see Brunner et al 2020), for northern Europe (North Europe), central Europe (central Europe) and the Mediterranean, with a focus on summer (JJA) and winter (DJF). The model data for large area averages was regridded onto a 2.5° × 2.5° grid and land-sea mask applied as used in Brunner et al (2020), using a standard nearest neighbour interpolation. It was found that this approach did not introduce any significant error for averaging over large areas, the data was averaged spatially using a weighted area mean.

For the spatial comparisons the data was regridded to a 1° × 1° grid using a nearest neighbour interpolation and the median, 25th and 75th percentile of the ensemble calculated at each grid square.

We used the Kolmogorov–Smirnov two sample, two sided test (KS two-sample test) to determine whether the difference between the CMIP5 and CMIP6 projections are considered significant at 95% confidence. This test has been applied with the caveat that the individual model projections in each sample cannot be considered to be truly independent due significant amounts of shared code between the models (Sanderson et al 2015a, 2015b).

3. Results

3.1. Area average differences

3.1.1. Near surface temperature

In the summer the CMIP6 ensemble projects a warmer range of temperatures than the CMIP5 ensemble in all regions. The change in projected temperature for the CMIP6 ensemble (compared to CMIP5) for summer is statistically significant \((P < or = 0.05\), see tables S4 and S5 for KS tests in supporting material and hatching on figure 1) in the central Europe and the Mediterranean regions by mid-century (see figure 1(a)) and this difference has increased by the end of century (figure 1(b)). Projected temperature differences between MIPs in the northern Europe region are smaller for summer than the other two regions and were not found to be statistically significant. End of century projections for the central Europe and the Mediterranean regions show an increased interquartile range for both ensembles compared to mid-century (figures 1(a) and (b)).

In the winter the differences between the CMIP5 and CMIP6 projections at the regional scale are small for all European regions. Central Europe and the Mediterranean do see higher median temperatures projected in CMIP6 (figures 1(c) and (d)), but these changes are smaller than in the summer (with the Mediterranean showing the largest increase in mean of approximately 0.5\(^\circ\)C, compared to about 1.5\(^\circ\)C in JJA) by end of century. The overall projected range for the Mediterranean and central Europe areas are almost unchanged. No statistically significant differences were found between the ensembles for winter temperature projections in for mid-century or end of century.

CMIP6 projected temperatures are consistently higher (shown here for both lower and upper percentiles) for all land regions of Europe, (figures 2(a) and (b)). CMIP6 land temperatures for central Europe, the Mediterranean and parts of northern Europe are consistently warmer and less uncertain as they project a narrow range of future temperature changes for all but parts of the most northern land regions of Europe (figure 2(d)). More than 80% of CMIP6 projected temperatures are warmer than median CMIP5 projected changes, in these regions, (figure 2). There is a hint that CMIP6 projects a wider range of changes of the North Atlantic SSTs, which may be important given their role in driving European circulation.

Generally the temperature increases are much smaller for winter than for summer with parts of Northern Europe slightly cooler (figure S2). Spatial maps of the end of century temperature projections for CMIP6 and CMIP5 are included in the supplementary information (figures S1 and S2).

Overall the difference between the MIPs are clearer by the end of century due to a stronger climate signal and larger signal to noise. Where there are differences between the MIPs these are usually already apparent by mid-century however.

3.1.2. Precipitation

Precipitation changes are important for central Europe and the Mediterranean regions, where further drying may have significant impacts on agriculture. In previous studies higher temperature projections for central Europe and the Mediterranean are also linked to greater drying in these regions (Lionello et al 2012, IPCC 2013, Lionello and Scarsascia 2018). We show here that there is a large reduction in the projected range of precipitation change in the summer CMIP6 ensemble for northern Europe and central Europe regions (figures 3(a) and (b)), which is projected for both mid-century and end of century. CMIP6
suggests a clearer shift to drier conditions in northern Europe in summer, however, these differences can not be said to be statistically different from the prior CMIP5 distribution.

For winter the difference in all regions between CMIP5 and CMIP6 is small, for mid-century and whilst there is a suggestion that CMIP6 projects wetter conditions in northern and central Europe by the end of the century, neither can be excluded as being statistically different (see tables S4 and S5 for KS tests in the supporting material) from the earlier CMIP5 responses by the end of century (figures 3(c) and (d)).

The spatial comparison differences for the 25th and 75th percentiles (figures 4(a) and (b)), show that the stronger drying signal in central Europe for CMIP6 also extends to parts of northern Europe, with a drier pattern from the north of Spain extending to Moscow and in to a large part of Scandinavia. This is largely due to a decrease range in CMIP6 (d) which is from the upper quantile ((c) and (d)).

The spatial changes for winter show a small increase in precipitation in most European land regions. Smaller regions, such as the southern UK, France and the eastern Mediterranean have a small projected increase in CMIP6 (figure S4). Spatial maps for end of century precipitation changes for CMIP5 and CMIP6 are also included in the supplementary information (see figures S3 and S4).

The difference between MIPs is only statistically significant by the end of century for the combined regions. The reduced range of predictions for northern Europe in the summer is not significant. While the difference for northern Europe is not found to be significant it does also indicate more of a trend in the northern Europe of a neutral or slight drying response to regional warming in the CMIP6 projections.

3.2. Global change vs regional changes
Where CMIP6 projections diverge from the existing CMIP5, it is helpful to understand whether the differences arise mainly due to differences in the global mean response of the models between the two ensembles, or differences in regional responses. In figure 5 we show scatter plots of the relationship between the regional temperature and precipitation response to global mean warming in each ensemble for end of century responses. Mid-century responses are included to provide a visual indicator of whether the end of century regional sensitivities hold for this earlier period, but this data was not used to inform the linear statistical model in section 3.2.3. These plots help identify where the differences in regional temperature arise due to different annual global warming responses (indicated by the x-axis) or the regional sensitivity (RC) to the global warming (indicated by the slope and spread of responses for a
Figure 2. Spatial comparison plots of the difference between CMIP6-CMIP5 summer (JJA) near surface temperature projections for end of century (baseline: 1995–2014, end of century: 2081–2100). (a, b) Difference for the 25th and 75th percentile respectively, (c) percentage of the CMIP6 range above CMIP5 median, (d) ratio of the CMIP6/CMIP5 interquartile range.

given warming). The bottom two plots of figures 5(d) and (h), the projected changes in summer temperature and precipitation normalised by the annual global mean temperature change (to give the summer regional change per degree of global warming) for end of century.

3.2.1. Near surface temperature
For summer temperature (left panels (a)–(c), figure 5) the regional temperature response is largely a function of the global warming change, in both ensembles. The small vertical spread, for a given global temperature change, is indicative of this. For summer temperature, the warmer shift towards higher regional responses in CMIP6 relative to CMIP5 appears to be driven largely by the large global warming responses. The similar slopes and widths of the relationships in figure 5(left panels (a)–(c)) suggest that the relationship between regional and global responses remain similar between the two ensembles for northern Europe (NEU) and the Mediterranean (MED).

Whilst individual quantiles visually differ for temperature in figure 5(d), for most regions there is no consistent shift between the two ensembles, across the quantiles. Central Europe, however, shows consistently larger normalised temperature response across all the quantiles, highlighting a change in the RC consistent with the differences in slope identified in figure 5(b). These normalised differences between MIPs were statistically significant in central Europe, by mid-century and have increased by end of century (mid-century \( P = 0.05 \) and end of century \( P = 0.03 \)). What is apparent (from all panels, figure 5) is that CMIP6 explores a number of larger global warming responses compared to CMIP5, particularly at end of century.

3.2.2. Precipitation
There is more scatter in the relationship in the right panels showing the regional precipitation response to global temperature (figures 5(e)–(g)), this illustrates the greater uncertainty in the regional response to global warming. Both ensembles show a similar overall response, with summer precipitation decreasing in response to increasing global mean temperatures. The difference in slope between the two ensembles is visibly greater than for temperature indicating that there is a larger difference between MIPs in their regional responses.

The summer precipitation change per °C global warming (figure 5(h)), has similar median values for CMIP5 and CMIP6 for most regions and timescales. CMIP6 projections are largely consistent with
CMIP5 in terms of central estimates of the projected changes. The most evident difference between the two ensembles is the narrow spread of the projected range for northern and central Europe in CMIP6. This smaller range of projected changes is an interesting result, as it suggests a more confident picture of future precipitation change in both regions. The differences between the two normalised ensembles in nearly all cases are not significant.

3.2.3. Linear statistical model

To attempt to quantify the contribution of the RC, compared to that of the global temperature change, to the total regional projected summer temperature change, we applied a simple statistical model to the end of century projections. The linear model is described by equation (1):

\[ Y \approx XS, \]  

where \( Y \) is the ensemble mean regional change, \( X \) is the ensemble mean global change (GC) and \( S \) is the slope of the linear regression line (which is a measure of the RC to GC).

The total difference (\( \delta Y = Y_6 - Y_5 \)) in regional change between the two ensembles can be approximated by equation (2):

\[ \delta Y \approx X_5 \times \delta S_5 + S \times \delta X, \]

where:

\[ \delta S = (S_6 - S_5), \]

\[ \delta X = (X_6 - X_5). \]

The numbers given relate to the CMIP5 (\( X_5, S_5 \)) and the CMIP6 (\( X_6, S_6 \)) ensembles respectively.

The contribution from the change in RC is taken from \( X_5 \times \delta S \) and the contribution from the GC is \( S_5 \times \delta X \).

The actual total value (\( \delta Y \)) of the mean regional change between CMIP5 and CMIP6 is given by equation (5) and it is assumed that the difference \( \delta Y - (RC + GC) \) is a relatively small residual this has been recorded in table S3.

\[ \delta Y = (Y_6 - Y_5). \]
The change in the slope of the linear fit is taken to represent the contribution of the RC to the overall regional mean change. This simple statistical model is able to capture the differences in regional mean responses, within both MIPs, to the first order (see table S3 and text S3 in the supporting material where some further details of the method and full table of the calculations is included).

We can now assess the relative importance of either differences in the global response (represented by global mean temperature differences) or the RC (captured by the figure 5 regression slope) in explaining the CMIP6/CMIP5 differences in the mean regional response, by comparing the contribution to $\delta Y$ from $X_5 \times \delta X$ (the contribution from the RC), to $S_5 \times \delta X$ (the contribution to the change in the global annual mean temperature, GC). Further description and details of the calculation is given in the supporting material (text S3 and table S3).

The results for temperature confirm and help quantify what is seen visually in figure 5. For the Mediterranean the higher global sensitivity of the CMIP6 models accounts for nearly all of the increase in projected temperature for this region (93%). There is some RC in northern Europe (21%), but most of the change is due to the annual global temperature increase (79%). In central Europe a significant percentage of the total mean regional temperature anomaly (42%) is due to the RC (table 1). The level of scatter around the linear regression fit in figure 5 indicates that it is unclear how sensitive this result is to any sub-setting of the model ensemble. To address this a bootstrap resampling without replacement of 10 000 resamples was applied, drawing a subsample of 20 models from each ensemble per sample. The results are summarised in table 1. The interquartile range from the bootstrap resampling does indicate some sensitivity in the result with sub-setting (with a range of about 15%–20% for the Mediterranean and central Europe). Northern Europe has a larger uncertainty range with the 75th percentile suggesting RC changes may be important for some CMIP6 models. It is noted however that the only region where the interquartile range of the contribution of the RC reaches over 40% to nearly 50% for the 75th percentile, is central Europe. This indicates that the finding of a greater contribution from the RC in central Europe is not due only to a couple of outlying models in the ensemble but is a result that appears to be consistent across the CMIP6 ensemble.

The same model was applied to the precipitation results where equation (1) was found to be a good model of mean regional precipitation response in both ensembles (see supporting material table S3).
Figure 5. Left panel (a)–(c): regional seasonal (summer) temperature change by end of century (2080–2100) with annual global temperature change mid-century responses are included to provide a visual indicator of whether the end of century regional sensitivities hold for this earlier period, but this data was not used to inform the linear statistical model (section 3.2.3). Left panel (d): projections of average summer normalised temperature change (change per °C) for CMIP5 and CMIP6 ensembles. Baseline: 1995–2014. Mid-century: 2041–2060. End of century: 2081–2100. Boxes show the interquartile range, whiskers are at 10th and 90th percentiles. Right panel (e)–(g): Regional seasonal (summer) precipitation change by End of century (2080–2100) with annual global temperature change. Right panel (h): projections of average summer normalised precipitation change (change per °C) for CMIP5 and CMIP6 ensembles. Hatching is shown on the box plots where the MIPs were found to be significantly different.

Table 1. Summary table of linear model results. The results from the linear fit from the model ensemble is given in the first two columns RC (contribution from regional sensitivity), GC (contribution from annual global temperature change). The median, 25th and 75th percentile of contribution of the regional sensitivity (RC) from the bootstrap resampling is also summarised.

| Region | %RC | %GC | Median %RC | 25th %RC | 75th %RC |
|--------|-----|-----|------------|----------|----------|
| NEU    | 21  | 79  | 21         | 7        | 32       |
| CEU    | 42  | 58  | 42         | 35       | 49       |
| MED    | 7   | 93  | 7          | −3       | 18       |

Temperature (tas)

| Region | %RC | %GC | Median %RC | 25th %RC | 75th %RC |
|--------|-----|-----|------------|----------|----------|
| NEU    | 102 | −2  | 102        | 99       | 104      |
| CEU    | 70  | 30  | 71         | 56       | 80       |
| MED    | 200 | −100| 190        | 156      | 252      |

Precipitation (Pr)

The greater scatter for precipitation illustrates the greater uncertainty in the regional response to global warming. Further this scatter indicates that changes in the mean precipitation are less informative of the changes in the broader distribution of the precipitation response. The results of the linear model can still provide some indicative insights in the relative roles of contribution of global warming and RC in the mean regional response. In this case the results showed a considerably larger contribution from RC than to the global mean temperature change. The contribution of the RC was found to be 102% for northern Europe,
71% for central Europe and 200% for the Mediterranean (with the GC acting in the opposite direction to the regional in northern Europe and the Mediterranean). It is interesting in the Mediterranean that the RC in CMIP6 results in slightly less drying than in CMIP5 (shown by a slightly less negative gradient in the slope) despite the increased global sensitivity in CMIP6 (the large percentage changes are due to the small absolute values in this region). It is the opposite case in the other two regions (where RC in CMIP6 results in further drying), although the difference in regional change between MIPs is small (see supporting information text S3 and table S3). The regional precipitation sensitivity to global temperature change has a larger degree of uncertainty than regional temperature as can be seen in the scatter and the projected ranges in figure 5. Bootstrap resampling of this result is summarised in table 1.

4. Discussion

The differences between the CMIP5 and CMIP6 projections for the European regions are small for winter in all three regions, for both temperature and precipitation. In the summer, however higher temperatures are projected in all European land regions, with the largest differences in central Europe and the Mediterranean. The interquartile range and ensemble median is shifted towards greater projected warming in the central Europe and the Mediterranean by the end of century for CMIP6 and these differences are found to be statistically significant.

For precipitation the projected range for summer precipitation is narrower in CMIP6 than in CMIP5. This is particularly the case for the northern Europe region where the upper quantile is reduced in CMIP6 by the end of century. The entire summer range of precipitation projections is also reduced in central Europe. CMIP5 and CMIP6 both show a overall trend for drying in summer for central with increasing global temperatures, this drying trend appears to be stronger in the CMIP6 ensemble for central Europe. Spatial comparisons show that the drying in central Europe extends into much of the habitable parts of northern Europe, with only the very northern parts of north Europe showing any increase in precipitation in CMIP6. These areas appear to obscure the signal when the entire area of northern Europe is averaged. There is a large degree of disagreement between individual models in both ensembles in the northern and central Europe regions in response to global temperature, where there is also disagreement on the sign of the change.

Regional precipitation projections have always been more uncertain than temperature, due to differences in model representation of the local thermodynamic and dynamic drivers of rainfall. In northern and central Europe in particular, model differences in the regional rainfall responses to global warming explain a larger fraction of the spread in future projections, in both ensembles. In northern Europe, reductions in the upper quantile of projected changes in CMIP6, suggests that the possibility of summer increases in rainfall is less likely, especially in parts of Scandinavia and the UK. CMIP6 suggests that net summer rainfall in northern Europe is less likely to diverge from what has been historically observed, however it is not clear why. This could be due to improved model physics and representation of precipitation patterns, which may lead to greater confidence in these predictions but further investigation is needed. Early comparisons of CMIP6 performance with previous ensembles indicate an improvement in number of atmospheric features such as storm tracks and blocking over Europe (including a reduction in the negative bias for blocking over Europe) (Davini and D’Andrea 2020, Harvey et al 2020, Priestley et al 2020) and for the North Atlantic sea surface temperatures (Borchert et al 2020) There is no clear indication at this time that this is linked to greater confidence in the summer precipitation for Europe however. CMIP6 suggests both a stronger but also a tighter range of projections for precipitation response in central Europe, pointing to a clearer shift to drier conditions than found in CMIP5.

Our results show that regional increases in summer temperature projections for CMIP6 are largely due to increases in the global mean warming response. The exception was in central Europe where the RC was found to contribute over 40% (range of 35%–49%) to the difference between MIP’s central temperature estimates. In contrast the differences in precipitation projections were found to be due largely to the regional responses and processes that drive precipitation at a regional scale.

Seneviratne and Hauser (2020) examined extreme regional temperature and precipitation projections as a function of the global warming. In general the RC for extremes was found to be very similar in CMIP5 and CMIP6 (as opposed to the global sensitivity). However differences in the central European region were found for RC in temperature extremes which suggested a lower RC for extreme (hottest day) temperatures in CMIP6 compared to CMIP5. While Seneviratne and Hauser (2020) found no significant difference in RC for annual mean temperatures in central Europe we find an increased RC for mean summer temperature in CMIP6 compared to CMIP5.

These results have a number of implications for assessing the risks and potential impacts of climate change. Whilst there are differences between CMIP5’s and CMIP6’s RCP8.5 emissions, which explain part of this increased warming (Ribes et al 2021). These differences have been calculated to account for about net 0.3 °C of the increase in CMIP6 by Fyle et al (2021) and about 0.2 °C by ScenatioMIP using a simple climate model (O’Neill et al 2016). We find a
mean increased global warming of 0.4 °C in CMIP6 relative to CMIP5, indicating that the increase in global temperatures is not due to differences in forcing alone. The global climate sensitivity is an emergent property of simulation of the underlying climate feedback processes (e.g. cloud, water vapour, albedo feedbacks). Emergence of larger climate sensitivities in CMIP6 compared to CMIP5 is unlikely to have arisen by chance sampling of the same underlying distribution (Flynn and Mauritsen 2020) but is being linked to further development of the underlying cloud processes (Meehl et al. 2020, Zelinka et al. 2020), and aerosol-cloud interactions (Bodas-Salcedo et al. 2019, Meehl et al. 2020, Wyser et al. 2020).

For the regions and seasons where any differences between MIPs have been found to be largely driven by global temperature response, there may be no need to change the projection advice in light of new CMIP6 projections. Risk adverse users, however may want to sample simulations from the high CMIP6 end, as whilst these simulations can be considered less likely (in terms of their global climate sensitivity) they remain plausible samples (Meehl et al. 2020) of potential high end change.

For other variables, where we have shown differences in RC between CMIP5 and CMIP6, then users of climate projection data may want to take account of new information within CMIP6. The central Europe region is an example of this, showing changes in the MIP differences are RC for both temperature (approximately 42% of the increase is due to regional processes) and precipitation (over two thirds of the summer drying shift is due to regional processes).

When using projections for variables/regions where CMIP6 identifies changes in the RC, then there are questions about whether CMIP6 simulations should supersede CMIP5 or supplement it. The answer to this question is important, as it will strongly influence projected range of future climate, particularly in central Europe. We find that in many cases the regional responses in the two MIPs are similar and the differences in temperature are largely driven by an increase in global temperature in CMIP6. Where this is the case it may be reasonable to consider the two ensembles as from the same population (with a slightly larger magnitude of change in CMIP6). In some cases however the regional responses differ significantly which suggests a change in the way that regional processes are represented and the two ensembles should be treated separately.

5. Conclusions

The CMIP6 projections differ from CMIP5 in the summer, with warmer projections (all regions) and narrower ranges of rainfall projections in northern and central Europe, where a reduction in precipitation is projected. The magnitude of CMIP6 temperature changes indicate an increase in the severity of the impact of global warming on the central Europe and the Mediterranean regions compared to CMIP5. This increase in projected warming is largely attributed to increased global sensitivity in some of the CMIP6 models, in these cases the overall picture for European projections is otherwise largely unchanged, except that the upper end of the projections are more frequently sampled in CMIP6. However, in some cases a significant difference in the regional responses was found and in these cases the picture can be said to have changed. In our cases central Europe was found to show a significant increase in temperature projections for CMIP6 and a higher degree of RC, this was found to be the case across the CMIP6 ensemble and not due to a few outlying models. Further, the spread of changes in Northern European mean summer rainfall is substantially reduced in CMIP6 in central Europe and parts of northern Europe. It is not clear why this is the case, but the impact of improved understanding of physical processes in these models on projections at the regional scale should not be ruled out at this stage and warrants further investigation.

A consideration for projections in Europe (and for other regional projections) is whether the CMIP5 and CMIP6 ensembles should be considered as separate ensembles or if they can be combined as a single set of projections? Due to differences in the forcing for the two ensembles this may not always be an appropriate approach; however our results provide pointers to how combinations of the two ensembles can be used in assessing the risks posed by global warming.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://esgf-node.llnl.gov/projects/esgf-lnl/.

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