ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088151

Convection-Permitting Models Offer Promise of More Certain Extreme Rainfall Projections

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Key Points:

- Convection-permitting model (CPM) ensemble projects an intensification above the Clausius-Clapeyron relation for extreme precipitation
- Climate change signal for extreme precipitation appears to converge in the CPM ensemble, with uncertainty dominated by natural variability
- The correct representation of convection may lead to reduced model uncertainties in future changes in extreme precipitation

Supporting Information:

- Supporting Information S1

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Citation:
Fosser, G., Kendon, E. J., Stephenson, D., & Tucker, S. (2020). Convection-permitting models offer promise of more certain extreme rainfall projections. *Geophysical Research Letters*, *47*, e2020GL088151. https://doi.org/10.1029/2020GL088151

Received 26 MAR 2020
Accepted 2 JUN 2020
Accepted article online 9 JUN 2020

Abstract The future increase in extreme precipitation is likely to have a severe impact on society due to flooding. Previous research has shown the improved representation of precipitation in convection-permitting models (CPMs), but until now it has not been possible to quantify uncertainties in future changes at convective (<5 km) scales. Here we analyze the first-ever ensemble of convection-permitting climate projections run within the UK Climate Projections project. We find that the CPM ensemble shows a significantly stronger intensification of summer hourly precipitation compared to the driving 12 km ensemble, with increases above the Clausius-Clapeyron relation and natural variability dominating the ensemble spread for extremes. Results suggest that the climate change signal across different CPMs may converge thanks to the more realistic representation of the local storm dynamics. We conclude that CPMs offer the promise of reducing uncertainties for extreme summer precipitation projections due to the better and explicit representation of convection.

Plain Language Summary Accurate predictions of future changes in precipitation extremes are crucial for developing effective adaptation measures to avoid severe impacts on society due to flooding. State-of-the-art kilometer-scale models, called convection-permitting models, give a much better simulation of how rainfall varies hour by hour and thus provide credible projections of future changes in hourly rainfall extremes. Up to now it was not possible to evaluate uncertainties in the future changes in extremes at convective (<5 km) scales since only single simulations were available due to the high computational costs. Thus, the ensemble of 12 local (2.2 km) projections, run within the UK Climate Projections project, represents a key step forward for climate prediction. We find that the 2.2 km ensemble shows a significantly stronger future increase of summer hourly precipitation compared to the coarser resolution (12 km) ensemble. The climate change signals are found to be consistent across the 2.2 km ensemble simulations, with differences largely explained just by natural variations in the climate from year to year. This means that convection-permitting models could reduce the uncertainties in future changes in extreme summer precipitation and thus allow more robust and effective adaptation policy.

1. Introduction

Acknowledging and quantifying uncertainties in future climate projections are crucial to inform decision-making and achieve robust adaptation policy (Street & Nilsson, 2014). Uncertainties arise from uncertainties in the climate forcing, different model responses, and natural variability, with the latter being an intrinsic property of the climate system linked to its chaotic nature. The relative contribution of the various sources of uncertainty depends on the analyzed variable and statistic used (e.g., mean versus extreme), on the temporal and spatial scale, as well as on prediction lead time. Moving from global to regional scale, the relative importance of modeling uncertainty and internal variability increases (Hawkins & Sutton, 2009). Using regional instead of global climate models (GCMs) can add an additional degree of complexity. Over Europe, it has been found that the choice of the regional model is a major contribution to the total uncertainties for summer precipitation (Déqué et al., 2012), which is mostly of convective nature. This suggests that the correct representation of local processes, such as convection, could be important for determining and potentially reducing climate change uncertainties.

Thanks to their high spatial resolution, convection-permitting models (CPMs) represent convection explicitly without the need for parameterization, which is a known source of model error in global and regional climate models (RCMs; Kendon et al., 2014). Compared to coarser resolution models, CPMs allow a more realistic representation of precipitation and are able to capture extremes (Kendon et al., 2017; Prein et al., 2015), thus giving us higher confidence in the projections of future change. Previous studies showed a stronger intensification of future extreme precipitation in CPMs than in the RCMs (Kendon et al., 2014), but, up to now, an evaluation of the uncertainties was not possible given the substantial cost of running an ensemble at this resolution.

Here we investigate uncertainties in future changes in local precipitation extremes, using the first ensemble of convection-permitting climate projections. These 2.2-km projections span the UK and were carried out as part of the UKCP project (launched in September 2019). The 12-member ensemble is driven by a 12-km RCM, spanning Europe, produced by perturbing uncertain parameters in the model physics. Although no perturbations have been applied directly to the CPMs, the different boundary conditions lead to different fine-scale projections for the end of the century. Our analysis focuses on hourly summer precipitation where the difference with RCMs is likely to be more pronounced and the impacts due to flash-flooding particularly damaging.

2. Models and Methods

The UKCP Local 2.2 km ensemble consists of 12 members spanning UK, nested in a perturbed parameter ensemble RCM ensemble at 12 km over Europe. More details on the models description can be found in Text S1 in the supporting information. Each RCM member is in turn driven by a member of the Hadley Centre global coupled (HadGEM3-GC3.05) perturbed parameter ensemble at 60-km resolution. Based on previous literature (e.g., Déqué et al., 2012), an ensemble size of 12 members was considered large enough for a first evaluation of the uncertainties in future changes and this was all that could be afforded with the available computational resource, for the selected CPM resolution and simulation length (Fosser et al., 2020).

The global and regional models share the same parameter perturbations, while no parameter perturbations are applied to the CPM ensemble given the differences in the model physics between the CPM and driving model. However, all resolutions use the same: future changes in land use, daily sea surface temperature, sea ice cover, Representative Concentration Pathway 8.5 scenario, member-specific greenhouse gases, and the same volcanic, solar, and ozone forcing. The “Easy Aerosol” method (Stevens et al., 2017) is used to calculate the aerosol forcing for both the RCM and CPM ensemble from the driving global simulation. The CPM ensemble does not sample uncertainty in the CPM model physics itself but samples uncertainty in the driving model physics through the driving lateral boundary conditions, as well as uncertainty due to natural variability. The perturbed parameter ensembles do not sample structural model uncertainty, for example, due to different parameterization schemes or model architectures. One of the ensemble members, called the reference ensemble member, is not perturbed in the GCM, RCM, or CPM and it is thus considered as a reference to assess the perturbations.

For the comparison with the RCM, a conservative remapping to 12 km was applied to the CPM ensemble and the observational GEH-GEAR dataset, a 1-km gridded rainfall product at hourly resolution based on over 1900 rain gauge data across Great Britain covering the period 1990–2014 (Lewis et al., 2018).

We tested the significance of the climate change signal for each individual ensemble member, as well as the significance of the difference in climate change signal between the CPM and its parent RCM using a bootstrap approach (Efron & Tibshirani, 1993). For each member and time slice, 1,000 bootstrap surrogates were created by randomly selecting 20 years with replacement. Note that the same selection, for example, first, third, and tenth years, was applied in the past and in the future. The climate change signal is calculated for each ensemble member as the difference between the future (2061–2080) and baseline (1981–2000) periods. The differences are considered significant at the 5% level if the 2.5–97.5% confidence interval for the difference does not include zero.

To evaluate the uncertainties related to natural variability (called simply natural variability), we used the bootstrap of the reference ensemble member, while for the total uncertainties we put together the bootstraps of all members (i.e., s12 members * 1000 bootstraps), called the bootstrap ensemble. Thus, the bootstrap of the whole ensemble includes the uncertainties related to natural variability of each member. The ensemble spread is calculated as interval between the 2.5th and 97.5th quantiles of the bootstrap ensemble, while the

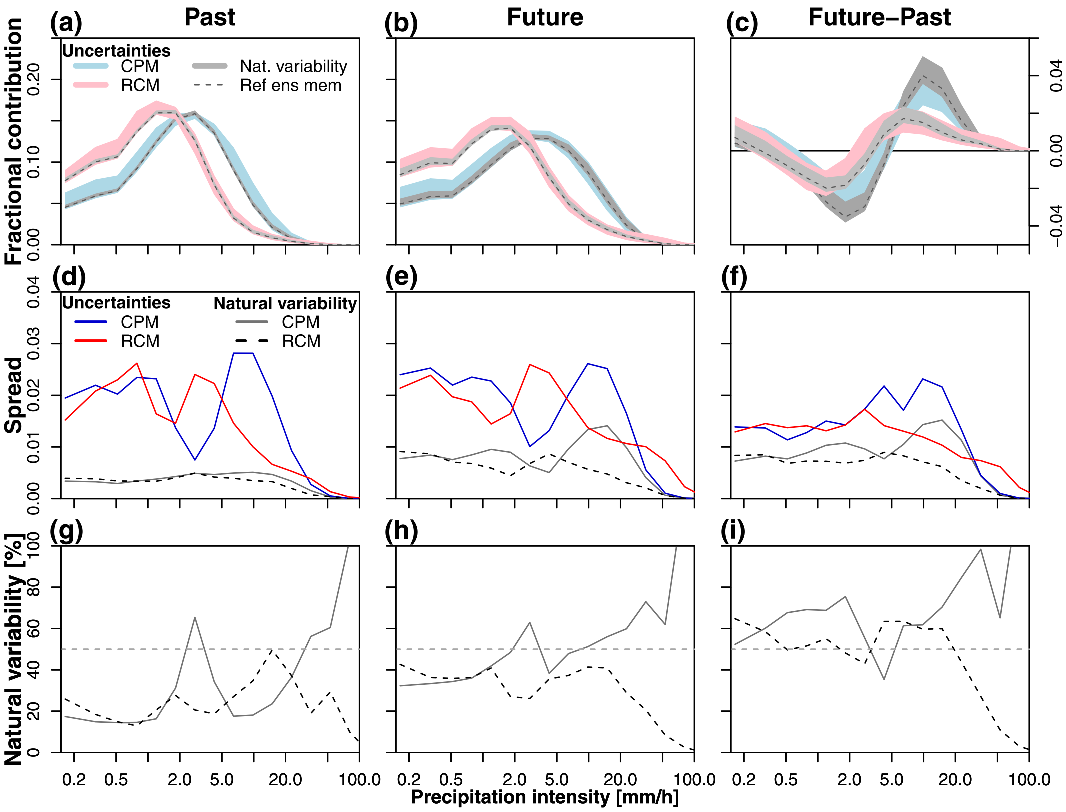

Figure 1. Fractional contribution for UK of hourly precipitation intensities to the total precipitation and related uncertainties in summer for the (a, d, and g) past (1980–2000), (b, e, and h) Representative Concentration Pathway 8.5 future (2060–2080), and (c, f, and i) difference between past and future. The top row shows the fractional contribution of hourly precipitation intensities for the reference ensemble member (dashed lines), its 97.5th confidence interval (gray region), and the total uncertainties for convection-permitting model (CPM; blue area) and for regional climate model (RCM; red area) 97.5th confidence interval. In the middle row, the spread in fractional contribution across the 12-member ensemble (blue, red) and due to natural variability (gray, black dotted), and in the bottom row, the contribution of natural variability to the total uncertainties calculated as natural variability/spread. Note the logarithmic *x* axis in all plots.

natural variability is calculated as interval between the above quantiles for the bootstrap of the reference ensemble member only. Given the ensemble design, the ensemble spread does not include structural model uncertainty nor emission scenario uncertainty.

3. Results

The UKCP report provided an evaluation of the CPM ensemble performance for the present-day climate, comparing it against both the driving RCM and different observational datasets, including CEH-GEAR (Kendon et al., 2019). The report showed that the CPMs give a more realistic representation of hourly precipitation over the UK, although they tend to overestimate heavy precipitation intensity especially away from high terrain. Figures from the report are reproduced here as Figures S2 and S3 in the supporting information. These show that the precipitation intensity of the 99.5th and the 99.95th percentiles of all hours is underestimated in the RCM, while overestimated by the CPM ensemble. This can partially be explained by the known deficiencies of convection-permitting resolution (Kendon et al., 2017; Prein et al., 2015), whereby at kilometer-scale grid spacing convection is not fully resolved, but also observational uncertainties and errors may contribute. In fact, localized intense events are likely to be underestimated by any observational dataset (Kotlarski et al., 2014; Rajczak & Schär, 2017) and thus lead to an overestimation of the CPM bias.

3.1. Fractional Contribution

The distribution of hourly precipitation intensities, represented here using the fractional contribution of each intensity bin to the total precipitation in summer, is significantly different between the CPM and RCM ensemble (Figures 1a–c). In future, both models show a significant decrease in the contribution

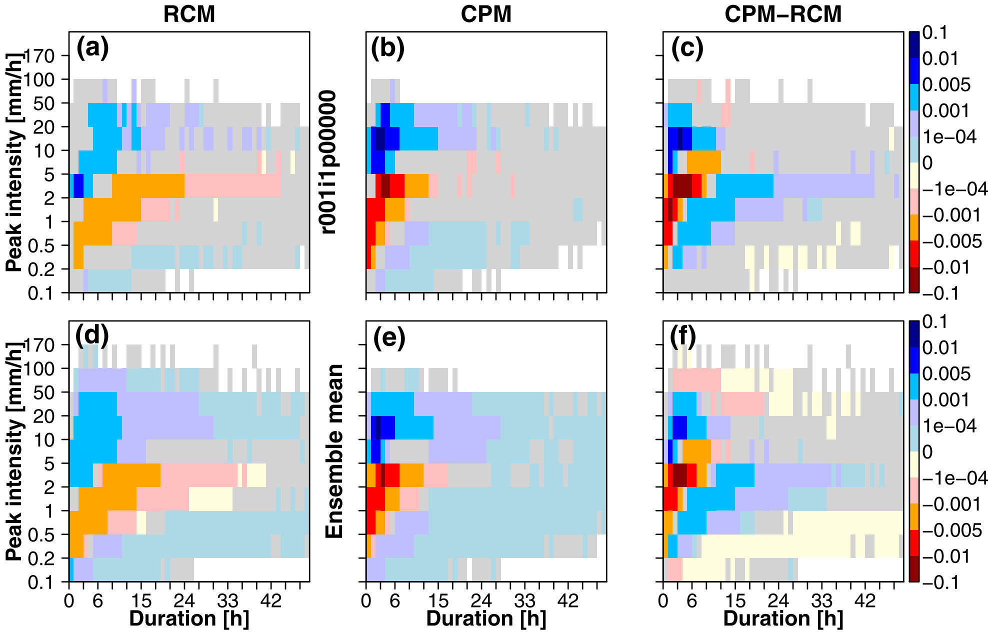

Figure 2. Future change in the peak precipitation intensity and duration of rainfall events. Plotted is the future change in the fractional contribution of each amount-duration bin for (a and d) regional climate model (RCM), (b and e) convection-permitting model (CPM), and (c and f) CPM-RCM difference for the reference ensemble member (a–c) and for the ensemble mean (d–f). An event is defined as a continuous period of precipitation exceeding 0.1 mm/hr. Fractional contribution is given by (joint probability of a given amount-duration bin) × (mean bin precipitation amount) / (total precipitation over all bins), pooling all grid cells over UK. Future changes or differences that are not significant at the 5% level are masked in gray.

from medium precipitation intensities (between 0.5 and 5 mm/hr for CPM and between 0.3 and 2 mm/hr for RCM) and increase from high intensities (above 8 and 5 mm/hr for CPM and RCM, respectively; Figures 1a–c) in line with previous studies (Kendon et al., 2014).

The stronger intensification of high intensities in the CPM compared to RCM could be linked to the differences in the representation of convection between the two models. Figure 2 presents the future change in the maximum precipitation intensity for different event durations, where an event is defined as continuous rainfall above 0.1 mm/hr. Compared to the RCM, the CPM shows a significantly more pronounced shift toward a greater contribution from short-duration higher-intensity events, usually associated with convective events, and a consequential stronger decrease in medium intensity (1–5 mm/hr) shorter duration (less than 6 hr) events. The CPM shows a smaller decrease in medium intensity longer duration (6–15 hr) events, possibly due to more events of this type in the RCM in the present climate. However, there is evidence of a future increase in longer duration events of low intensity in the CPM, which could relate to an increase in larger-scale or slower-moving systems.

The future changes in fractional contribution highlight the tendency of CPM and RCM uncertainties to diverge for higher intensities with the CPM showing a larger spread between 3 and 20 mm/hr that drops off faster than the RCM at high values above 30 mm/hr (Figures 1d–f). The large spread for the RCM for the most extreme precipitation is likely to be linked with some unphysical grid point storms, which are generated on a single grid square, usually in the middle of a larger area of heavy rainfall, to cope with the excess of convective instability (Chan et al., 2014). In the UK the heaviest hourly precipitation ever recorded was of 92 mm in Maidenhead, Berkshire, on 12 July 1901. This was the measurement at a station point, and the areal average value (e.g., over a 12-km grid box) would be much lower. By comparison, the RCM ensemble creates events in excess of 100 mm/hr, while the CPMs show more realistic maximum intensities over the UK of below 72 mm/hr averaged over a 12-km grid box.

The contribution of natural variability to the total uncertainties becomes stronger in the future especially for the CPM (from 20 to 50% and 40% respectively in CPM and RCM), although it is still not able to explain the

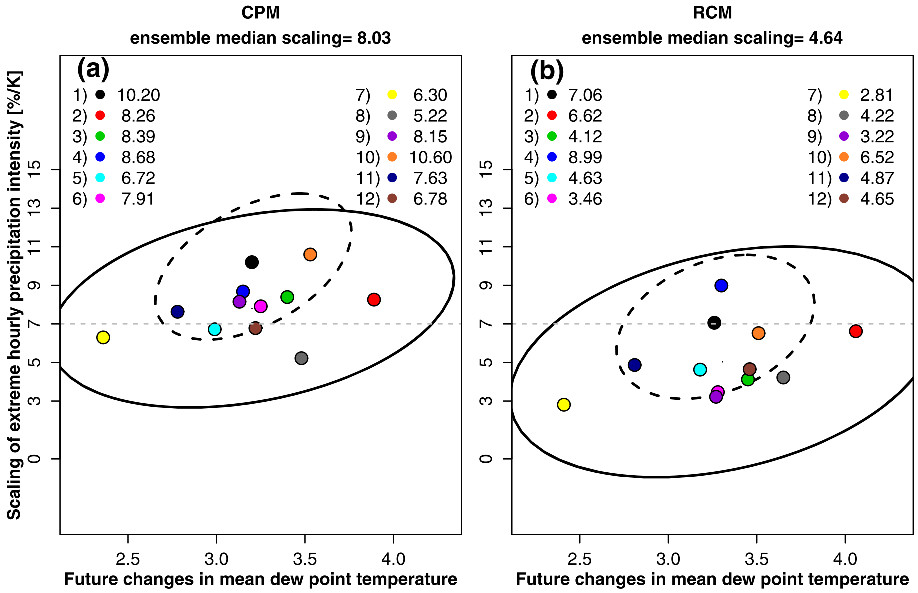

Figure 3. UK-average scaling between future changes in extreme hourly precipitation intensity and UK-average surface dew point temperature across the ensemble (colored dots) in summer for (a) convection-permitting model (CPM) and (b) regional climate model (RCM). The scaling coefficient (%/K), quoted for each member in the legend, is given by the change in the logarithm of extreme precipitation intensity divided by the change in mean dew point temperature. The dashed gray line shows the Clausius-Clapeyron scaling relationship of 7%/K. Extreme precipitation intensity is defined as the 99th percentile of wet values (>0.1 mm/hr) for hourly precipitation and corresponds to the values in Table S1 in the supporting information. The black solid (dashed) ellipses represent the 97.5th confidence interval for uncertainties related to the whole ensemble (natural variability).

whole ensemble spread (Figures 1g–i). The uncertainties related to higher intensities especially in the future are mainly linked to natural variability for the CPM and to model uncertainties for the RCM. A likely contributing factor is the more realistic representation of convection and local dynamical processes in the CPM, which amplify future increases in intensity within physical bounds and remove the need for convective parameterization and its associated uncertainties. The fact that parameter perturbations are not applied to the CPM itself, however, may also be a factor explaining the difference compared to the RCM. Interestingly, the contribution of natural variability to the uncertainties is larger for the changes than for the past climate, especially for the CPM. This suggests that the parameter perturbations in the RCM, while having considerable impact on the underlying present-day distribution, have a relatively weak influence on the future changes in the CPM.

3.2. Clausius-Clapeyron Relationship

Saturated water vapor pressure is expected to increase with temperature at 6–7%/K, following the Clausius-Clapeyron (CC) relation, setting a scale for change in precipitation extremes (Trenberth et al., 2003). The release of latent heat within convective storms can invigorate vertical motion and lead to an increase in hourly rainfall intensity above CC scaling in some regions of the world for sub-daily extremes (Westra et al., 2014). However, changes in moisture availability could be less than the temperature-dependent maximum and thus constrain the increase in precipitation totals. To account for this, here we have used surface dew point temperature, which is a measure of specific humidity translated to temperature using the CC relationship (Chan et al., 2016). In this analysis, we have defined precipitation extremes as the 99th percentile of wet hours, but similar results are also found using the 99th percentile of daily maximum hourly precipitation considering all hours (Kendon et al., 2019).

We find that the scaling of precipitation extremes in the CPM is higher than in the RCM, and above CC scaling in most ensemble members (CPM ensemble mean UK-average scaling of 8.0%/K, RCM 4.6%/K; Figure 3) consistent with previous findings over the UK (Kendon et al., 2014). The correlation between the CPM and driving RCM across the ensemble, calculated with the Kendall method, is high for changes in dew-point temperature, but not for scaling (correlation equal to 0.82 and 0.42, respectively). Thus, while the CPM changes in temperature and specific humidity are dominated by the large-scale changes in moisture associated with global warming in the driving model, the more realistic representation of local dynamical feedback within storms at convection-permitting scale leads to significant difference between the CPM and its parent RCM in terms of future changes in precipitation extremes. For both models, extreme precipitation changes are not just explained by changes in temperature or moisture availability given that a specific change in dewpoint temperature can give different precipitation responses depending on ensemble member. Other mechanisms like changes in uplift and/or precipitation efficiency could be responsible for the differences among ensemble members. In addition, surface dewpoint temperature might not be the optimal indicator of the moisture available to the storm. The analysis of the higher model levels and at the storm origin could be important and lead to different results (Chan et al., 2016).

The ensemble spread is wider for the RCM than CPM in terms of both dewpoint temperature and scaling, while the relative contribution of natural variability to the total uncertainty is larger for the CPM than RCM for scaling (70% in CPM, 60% in RCM) and similarly for dew point temperature change (44% and 42% in CPM and RCM respectively).

3.3. Emergent Constraint

The results from different models are often weighted based on their present-day performance to limit model biases and their impact on future changes. This is only valid where there is a relationship between present-day performance and future changes (i.e., the same processes are responsible for both), leading to an “emergent constraint” on future change uncertainty.

A strong emergent constraint, similar for the CPM and RCM but only significant for the RCM, exists between precipitation bias and future changes in mean precipitation (Figure 4a). Kendon et al. (2019) found that the future decreases in summer mean precipitation over the UK are driven by changes in the large-scale circulation, rather than the local soil moisture state. In fact, both models show almost no changes in evaporation, which plays a greater role in the atmospheric moisture budget than in winter, while they project a substantial decrease in moisture flux convergence (Kendon et al., 2019). Thus, the positive emergent constraint can be explained by specific perturbations in the model physics favoring more dry present-day circulation patterns and greater future decreases in these for some members. This also justifies the similarity of the relationship between the RCM and CPM and the strong correlation in the climate change signal of above 0.8 between the models.

When considering only wet hours, the behavior of the CPM and RCM diverges and the no correlation between models is found for extreme intensities (Figures 4b–d). No emergent constraints appear for the CPM, which shows an increase of 0–20% in mean precipitation intensity and 10–60% in extreme precipitation intensity, independent from the initial bias. Thus, the biases in the frequency of rainfall in the present-day appear to be related to future changes in occurrence, while the processes controlling precipitation intensity in the present day are different from those controlling the future changes, with local storm dynamical feedback being a contributing factor in the CPM. The RCM shows nonsignificant constraints with slopes of opposite sign depending on the quantile of the precipitation intensity distribution used. This behavior probably linked the limitation of this resolution in the representation of processes leading to extremes.

The spread in the bias and the climate change signal is larger in the CPM than RCM, except for the future changes in extremes in line with the fractional contribution results. We note that the large CPM spread is not just due to a single outlying ensemble member (i.e., marked in dark blue) since the findings do not change on excluding this member. This ensemble member showed a spurious, steady weakening of the strength in Atlantic circulation in the driving GCM, which could be responsible for an increasing dry bias in the corresponding RCM and CPM and could partly offset the warming effect of the greenhouse gases over western Europe. For both models, natural variability is explaining less than half of the ensemble spread in the present-day bias, but most of the ensemble spread in the future changes especially for extremes. Thus, as noted above, the different boundary conditions from the driving model have a strong impact on the bias, while the perturbations in the model physics have a weaker impact on the CPM future changes, which are instead dominated by natural variability especially for extreme intensities.

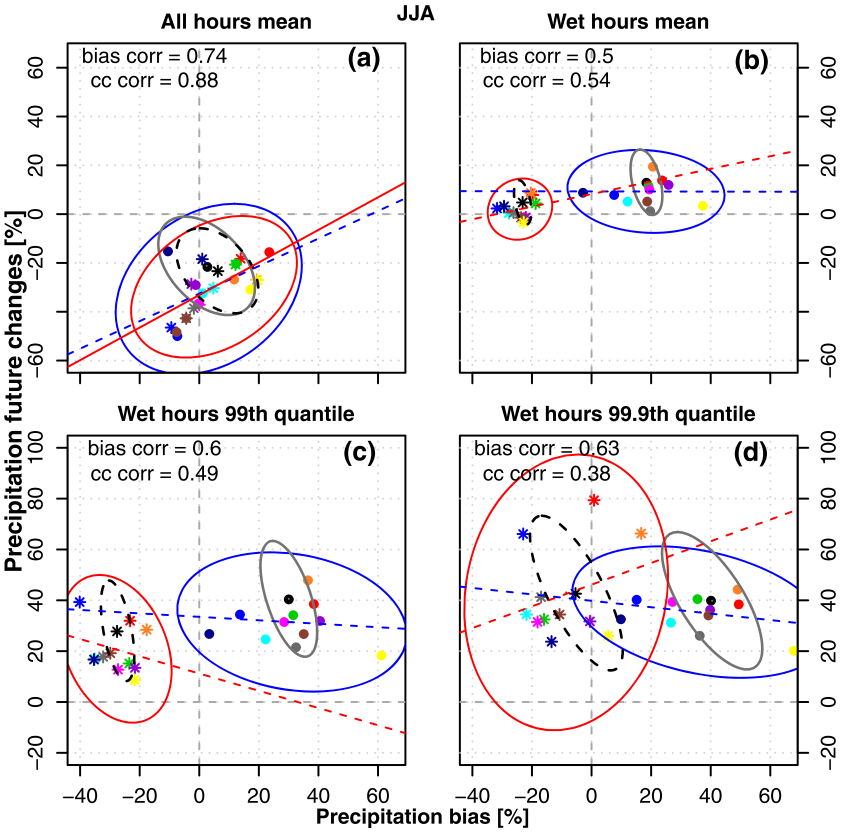

Figure 4. Emergent constraint between precipitation bias against the CEH-GEAR observational dataset and future changes averaged over Great Britain in summer. The plot shows the constraints for (a) mean precipitation, (b) precipitation intensity, and (c) extreme precipitation defined as 99th and (d) 99.9th percentile of wet values. A 97.5th significant emergent constraint is indicated by a solid line blue for convection-permitting model (CPM) and red for regional climate model (RCM); otherwise, the colored lines are dashed. The ellipses represent the 97.5th confidence interval for the CPM and RCM reference ensemble member (dark gray solid and black dashed respectively) and whole CPM and RCM ensemble (blue and red respectively). The colored dots are the ensemble members for CPMs (dots) and RCMs (asterisks). The correlations between the RCM and CPM in the legend are calculated with Kendall method for both bias and climate change signal.

4. Conclusions

In summary, the first-ever ensemble of convection-permitting climate projections confirms a stronger intensification of extreme precipitation, compared to coarser resolution models, even above CC scaling. This is possibly due local dynamical feedback within convective storms, which would explain the significant differences between CPM members and their parent RCM for all statistics used here.

We would have expected the uncertainties to be larger for the RCM since, unlike for the CPM, perturbations have been applied to the model physics itself as well as to the lateral boundary conditions. However, we find that the uncertainties in future precipitation changes are similar or larger in the CPM, except for the extremes. This might mean that the uncertainties related to the climate change signal might have been underestimated up to now by RCMs, but a CPM perturbated parameter ensemble is required to fully answer this question.

Natural variability contributes substantially to the total uncertainties especially for future changes in extreme precipitation in CPMs. Thus, providing ensemble projections are available to identify the underlying climate change signal from natural variability; this might mean that the climate change signal across different CPMs tends to converge, thanks to more realistic representation of the local dynamics. However, further research is required to exclude the possibility that this result is due to the absence of physics perturbations in the CPM itself. Thus, future work plans to carry out a perturbed CPM ensemble as well as explore uncertainties in changes in extremes across multimodel experiments at convection-permitting scale carried out as part of the EUCP project (Hewitt & Lowe, 2018).

CPMs provide more accurate estimates of future changes in local extremes, due to the better and explicit representation of convection. Results here also suggest that CPMs may lead to reduced model uncertainties in extreme precipitation change, which is likely due in part to uncertainties in the parameterization of convection no longer contributing. This offers promise that extreme precipitation projections from different CPMs may converge. However, this work has also shown that ensembles of CPM experiments are needed, since the climate change signal estimated from a single realization may be strongly influenced by natural variability.

Data Availability Statement

Hourly precipitation data from the UKCP Local 2.2 km projections and daily precipitation data from the UKCP Regional 12 km projections are publicly available from the Centre for Environmental Data Analysis (CEDA) archive (https://catalogue.ceda.ac.uk).

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Acknowledgments

Thanks to colleagues across the UK Met Office for their help in setting up the 12 and 2.2 km ensemble especially A. Lock, M. Bush, J. Edwards, D. Walter, J. Manner, and I. Boutle. Also, thanks to S. Chan for useful discussions. G. Fosser and E.J. Kendon are supported by the UK Met Office Hadley Centre Climate Programme funded by BEIS and Defra (GA01101) and acknowledge the INTENSE Project (grant holder and PI: Hayley J Fowler, Newcastle University) for providing the sub-daily precipitation gauge dataset.

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