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Changing Spatial Structure of Summer Heavy Rainfall, Using Convection-Permitting Ensemble

Yuting Chen[1], Athanasios Paschalis[1], Elizabeth Kendon[2], Dongkyun Kim[3], and Christian Onof[1]

[1]Department of Civil and Environmental Engineering, Imperial College London, London, UK, [2]Met Office Hadley Centre, Exeter, UK, [3]Department of Civil Engineering, Hongik University, Seoul, South Korea

Key Points:

- Projected summer heavy rainfall tends to be more intense, have a greater advection speed, and an increased spatial coverage
- Spatial coverage of extreme hourly rainfall will considerably increase over the UK, particularly in the northern region
- From intensity-duration-area-frequency curve, small-sized catchments (20–500 km^2) will be the most vulnerable to extreme event intensification

Supporting Information:

- Supporting Information S1

Correspondence to:
Y. Chen,
yuting.chen17@imperial.ac.uk

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Abstract Subdaily rainfall extremes have been found to intensify, both from observations and climate model simulations, but much uncertainty remains regarding future changes in the spatial structure of rainfall events. Here, future changes in the characteristics of heavy summer rainfall are analyzed by using two sets (1980–2000, 2060–2080) of 12-member 20-year-long convection-permitting ensemble simulations (2.2 km, hourly) over the UK. We investigated how the peak intensity, spatial coverage and the speed of rainfall events will change and how those changes jointly affect hourly extremes at different spatial scales. We found that in addition to the intensification of heavy rainfall events, the spatial extent tends to increase in all three subregions, and by up to 49.3% in the North-West. These changes act to exacerbate intensity increases in extremes for most of spatial scales (North: 30.2%–34.0%, South: 25.8%). The increase in areal extremes is particularly pronounced for catchments with sizes 20–500 km^2.

Plain Language Summary Understanding the future change of rainfall extremes is crucial to strengthen the resilience and adaptation to natural hazards. Although rainfall extremes on subdaily timescales are known to intensify, the change in its spatial structure remains very uncertain. Here, we analyzed the future changes of heavy summer rainfall by using a state-of-art, very high-resolution climate model over the UK. Future summers will be drier and less rainy but when rainfall occurs, events will be more intense. Those heavy rainfall events will move faster, and will cover a larger area. Those increases can lead to dramatically increased rainfall amounts over an area representative of typical UK watersheds, which can be up to 60.8% in the North. More intense events with larger areas can substantially increase flood risk beyond our expectations. Such an intensification of areal extremes is found for most of the catchment scales, and is particularly pronounced at 20–500 km^2 scales. The changing spatial extent and its effect on different catchment scales found in this study had not been well identified before for the UK region due to the limitation of climate model resolution. Future flood-related impact studies should take these changes into account.

1. Introduction

Under climate change, the potential impact of increasing heavy rainfall has become a societal concern. Heavy rainfall triggers landslides, flooding and leads to tremendous impacts on agriculture, ecosystems and livelihood (Kundzewicz et al., 2014). In the UK, the 2007 summer floods alone, the estimated economic costs reached £3.2 billion (DEFRA, 2010). To strengthen resilience and adaptation to natural hazards, it is critical to better understand the future change of rainfall extremes.

Climate models operating either at a global scale (General Circulation Models [GCMs]) or at regional scales (Regional Climate Models [RCMs]) are promising tools for assessing future rainfall patterns. A number of studies have projected changes of daily extremes using GCMs (Fischer & Knutti, 2015; Kharin et al., 2013; Pfahl et al., 2017). Observation studies show that subdaily rainfall extremes can increase more rapidly, following Clausius-Clapeyron (CC) relationship or even beyond that (Blenkinsop et al., 2015; Lenderink & van Meijgaard, 2008; Moustakis et al., 2020), a behavior attributed to the thermodynamics of the atmosphere, the large scale dynamic of atmosphere (O'Gorman & Schneider, 2009), or due to mixing of storm types (Molnar et al., 2015). Modeling rainfall at fine spatial and temporal scales is thus important but still a major challenge. Rainfall generation involves a wide range of processes such as synoptic features, forced ascent due to elevation change, local convective instability (Chan et al., 2013) and cloud microphysics. In

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particular, local convection, which can lead to heavy rainfall and flash floods, operates on a typical scale of a few kilometers (Fosser et al., 2015). In RCMs typically run at 10–100 km resolution, such km-scale processes are represented by using empirical subgrid parameterization schemes. The parameterization leads to uncertainties and errors in the precipitation estimates (Prein et al., 2015).

To explicitly represent convection in an RCM, a horizontal grid spacing of 4 km or less is necessary (Prein et al., 2015; Weisman et al., 1997). This very high resolution enables the model to switch off such parameterizations and allows for a better representation of orography and local convection (Prein et al., 2015). Such models are commonly used in short-term weather forecasting. In recent years, the availability of new computational resources has made it possible to carry out climate projections at convection permitting scales (convection permitting models [CPMs]; Ban et al., 2015; Kendon et al., 2014; Nakano et al., 2012; Rasmussen et al., 2017; Rockel et al., 2008).

The development of CPMs and improved realism of small-scale features enable us to assess hourly rainfall extremes for a future climate for the first time. A few modeling studies have analyzed extreme hourly rainfall intensity. In the UK, a 13-year climate simulation with a CPM shows intensifying summer downpours (Chan et al., 2018; Kendon et al., 2014). This overall trend is also found in the European Alpine region (Ban et al., 2015), Germany (Chan et al., 2020; Fosser et al., 2017), Southern France, Eastern Spain (Chan et al., 2020) and the United States (Prein, Rasmussen et al., 2017). Besides the intensity, the spatial structure in the future climate also changes due to increasing temperature and moisture availability (Lochbihler et al., 2019). A wider spatial extent can further aggravate flood risk due to increasing total rainfall amounts over a given area.

The variability of small-scale spatial structure of rainfall plays a critical role in flood generation (Paschalis et al., 2014; Peleg et al., 2020). Only a few studies have analyzed the spatial rainfall features at kilometer scales, whether it be in observed rainfall or future projections. Those studies present some broad areas of agreement as well as conflicting results. In those studies based on observations, temperature is taken as explanatory variable to detect the trend. By analyzing radar observations from the eastern Mediterranean, Peleg et al. (2018) found that with warmer temperature, the spatial extent of rain storms decreases whereas the areal convective rainfall increases. Wasko et al. (2016) also found a reduced spatial extent of rain storms with increasing temperature by analyzing a dense network of rain gauges data in Australia. Climate model projections, which consider both changes in thermodynamic and dynamic conditions, do not always show consistent results with those observation-based studies: in Sydney, by analyzing CPM projections, Li et al. (2015) found that the ratio of areal rainfall to point rainfall will increase at hourly scales in the future. This implicitly suggests a larger area with intense hourly rainfall extremes. Using a 4-km resolution CPM, Prein, Liu et al. (2017) also found an increasing rainfall volume of Mesoscale Convective Systems across the USA. Using a large eddy simulation, Lochbihler et al. (2019) found that the size of rain cells in the Netherlands will significantly grow along with increasing intensity due to warming. Because these modeling studies were based on a single model run, it was not plausible to assess the uncertainty related to climate projections and natural variability (Fatichi et al., 2016). So far, from the available literature, one gains limited insights into the changes in the spatial structure of rainfall extremes for the UK. Kendon et al. (2014) found that many of the heaviest events across the southern UK in the future will be large-scale storms, highlighting the importance of unraveling the details of the spatial structure of future rainfall extremes.

In this study, we addressed the question of how the spatial profile of extreme rainfall will change in a future climate over the British Isles, by using a state-of-the-art CPM. Using a 12-member CPM ensemble, we assessed the climate change effect on hourly rainfall events during summer over the UK. Physical characteristics were extracted and compared for the past and future periods, with the uncertainty included. For hydrological use, the resulting impact of those changes was then analyzed at different catchment scales, ranging from localized urban areas to large river basins.

2. Methods

Precipitation projections were obtained from the UKCP convection-permitting ensemble (Kendon et al., 2019; Kendon, Roberts et al., 2020). The CPM simulation for historical (1980–2000) and future (2060–2080) periods was used. The 12-member CPM ensemble with 2.2-km grid spacing was driven by perturbed

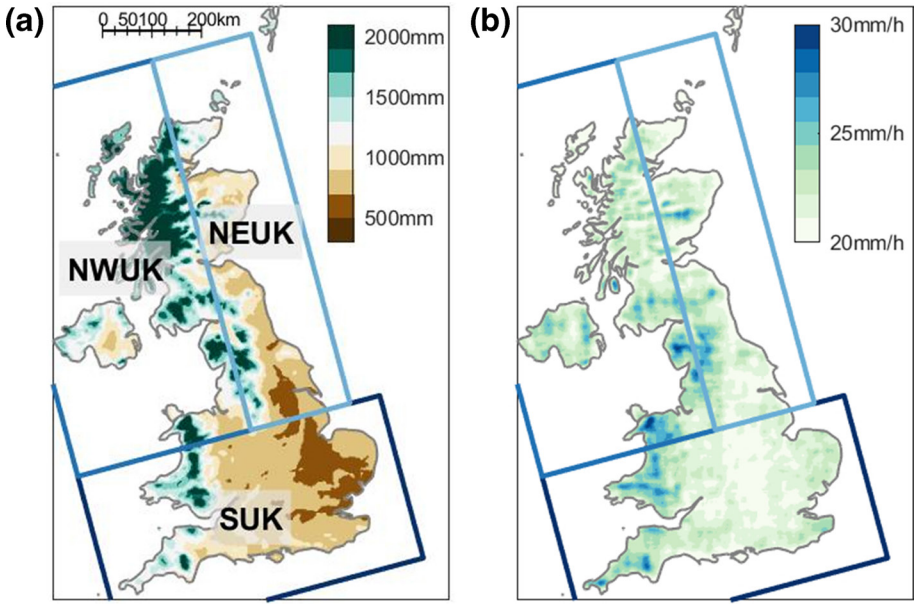


Figure 1. Separation of study region. Map of annual mean precipitation (1980–2000 period) and separation of study region (a). Map of 5-year return period annual maximum hourly precipitation (b).

parameter variants of the Hadley Center global model (HadGEM3-GC3.05) at 60 km with a 12 km intermediate nesting, under emission scenario RCP8.5. The model has been validated with multiple observed datasets, including Radar data (Met Office, 2016) and gridded hourly rainfall estimates (E. Lewis et al., 2019). The hourly rainfall characteristics closely matches observations in terms of the diurnal cycle, heavy rainfall amount, event duration, hourly extremes (Fosser et al., 2019; Kendon et al., 2019) and its spatial structure (Chan et al., 2013; Kendon et al., 2012; also in Text S4).

Subsequent to the release of the UKCP Local (2.2 km) projections an error has been found in the 2.2 km CPM in how snow is converted to graupel (which are small soft ice pellets). Initial results from a single member test suggest that this graupel code error has some impact on hourly precipitation extremes, and on fixing the error present-day values are reduced (by about 20%) and future changes may be increased depending on the metric (Kendon, Chan et al., 2020). Updated Local (2.2 km) projections with this graupel code error fixed are planned to be released in Spring 2021, which should improve the modeling of hourly extreme rainfall which is currently overestimated in the existing UKCP 2.2 km data (Figure S1). Figures S2 and S3 show the impact of the graupel code error on present-day values and future changes in high percentiles of hourly precipitation in summer, in the single ensemble member test. The 99.95th percentile of hourly precipitation corresponds to about 7.1 mm/h and the 99th percentile of wet values to 5.5 mm/h in the present-day, and for these metrics we see fixing the graupel error significantly reduces wet biases in the CPM by about 20% (Figure S2). Future changes in these metrics, however, are not significantly impacted, with any differences on fixing the error considerably smaller than the spread of responses across the UKCP CPM ensemble. Thus the key conclusions reported in this paper regarding the changing spatial structure of summer heavy rainfall are not expected to be strongly impacted by this graupel code error.

In this study, we undertook a comparison between the historical period and the future period over three subregions (land area) across the UK (Figure 1). The three regions (North West, North East, South) were separated according to their distinct climatology (Darwish et al., 2020; Kendon et al., 2019). Short-duration heavy rainfall is our focus. Since, in most regions of the UK, 1-h annual maximum observations are highly concentrated in summer (Darwish et al., 2018), our analysis were carried out for the summer season (June–July–August [JJA]).

The area having intensity (at a 2.2 km scale) greater than 0.1 mm/h is wet area. For each subregion, all hours with wet area fraction >2% were defined as "wet hours." Wet hours having peak intensity (P_{max}) > 10 mm/h were defined as "heavy rainy hours." For those hours, we computed the rain advection speed using the

optical flow method (Bowler et al., 2004), their spatial coverage of heavy rain (area >5 mm/h), mean areal intensity (P_{mean}, average over all grid cells, also known as rain yield (Lochbihler et al., 2019) and areal rainfall volume (P_{total}; for computational details, see Text S1). For each of those characteristics, we evaluated their changes between the past and future periods, in its occurrence frequency and magnitude (percentile values). The median of results from model simulations was taken as a central estimate, in which all members were treated equally. Their uncertainty is represented by the range of ensemble members.

To evaluate the spatial profile of heavy rainfall, the 480 heaviest hourly rainfall (i.e., about two events per year per ensemble member) were identified for each region. Other sample sizes between 120 and 840 events were also checked for statistical robustness where the results based on different thresholds did not impact the results. Those selected hours correspond to the times having the heaviest peak intensity. In order to exclude those hours where intense rainfall occurred at a very localized area only (e.g., a single grid cell), hours selection was based on rainfall images aggregated at a 11×11 km^2 scale. A storm separation method (Text S1) was applied in order to make sure the selected hours belong to different storms. In the separation, wet area fraction >2% is taken as spatial coverage threshold, 2-h consecutive dry period is taken as temporal separation threshold (Paschalis et al., 2013). The averaged storm profile was obtained by relocating each storm profile to its respective point of maximum rainfall intensity and taking the average among all relocated profiles. We used the relative difference of the rainfall intensity in the two periods to quantify the changes at a certain radial distance from the storm center. The relative differences, as well as the ensemble range of the differences were then estimated.

Changes of extremes at different spatial scales were quantified in terms of intensity-duration-area-frequency (IDAF) curves, commonly used for hydrological design. IDAF curves are computed for the 12 ensemble members separately, by extracting annual maxima of average rainfall over a fixed area and duration (1-h) for each region of interest, following the method of De Michele et al. (2011) (Text S2). Using method of maximum likelihood, the generalized extreme value distribution was fitted to estimate $I(D, A, T)$, the T-year return precipitation in JJA at 1-h duration D and different catchment scales A. Catchment areas ranged from 4.84 to 8,537.76 km^2, covering the spatial extent of rainfall events from small convective storms at a localized urban area to mesoscale convective systems influencing a much larger river basin such as River Trent (8,231 km^2). The signal-to-noise ratio (SNR; Hawkins & Sutton, 2011), estimated as the changes in mean value divided by the standard deviation, is estimated to quantify how large the future change is compared with the uncertainty in ensemble simulation.

3. Results

3.1. Spatial-Temporal Characteristics of Heavy Rain Storms

Changes in hourly rainfall characteristics including mean areal intensity, peak intensity, spatial coverage, and advection speed were analyzed. During summer, the occurrence of wet hours shows a relative decrease by 11.8%–36.2% (Table S1), consistent with an overall drier summer. However, for hours exceeding a high threshold (P_{max} > 70 mm/h, about 99.5th percentile of all hours), the occurrence frequency is projected to increase by 104.4%–139.9% in the north and 76.7% in the south.

Besides the occurrence frequency, trends in each heavy rainfall characteristic over various percentiles were examined. Peak intensity (P_{max}), for the 50th percentile or higher, increases by up to 15%–25% (Figure S4). The high percentiles of hourly spatial coverage tend to increase in all regions, reaching 30%–35% in the north. Similarly, mean areal intensity (P_{mean}) also shows an increase for high percentiles while a relative decrease by up to 20% for low percentiles. The increase in areal intensity accounts for a larger proportion in the north-west (about 20%) than in the south (about 10%).

The changes in peak intensity, advection speed and spatial coverage are not constant under different P_{mean} conditions. P_{max} shifts toward a higher value, which is more pronounced when the total areal amount is small (P_{mean} < 0.8 mm/h) in the southern UK (Figure 2a). Similar behavior is also found in the north, and more strongly in the north-west (Figures S5 and S6). As for the advection speed, the occurrence of fast-moving rainfall is projected to increase (Figure 2b). Such an increase occurs during low intensity hours (P_{mean} < 0.5 mm/h), while no significant change is observed (p > 0.05) for the higher P_{mean} hours. The

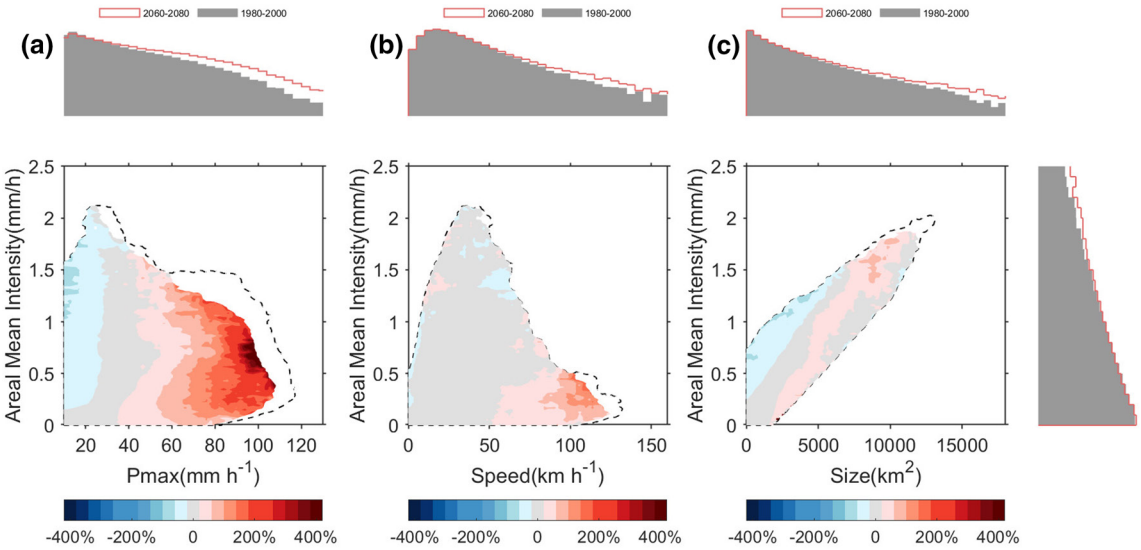


Figure 2. Relative difference of heavy rainfall features in the south UK. Relative difference in the future minus the past conditional probability of peak intensity (a), rain advection speed (b), spatial coverage(c), conditioned on areal mean intensity for all heavy rain hours. Filled contour shows the area with at least five heavy rain hours happening per 20 years, both in current and future climates. Gray area shows area not significantly different from zero with $p < 0.05$. Dashed line shows the boundary with at least five occurrences (hours) in the future. Bar charts in the upper and far right panel show the empirical density functions in a logarithmic scale for the dimension they are adjacent to.

spatial coverage of heavy hourly rainfall (Figure 2c) tends to increase regardless of the mean areal intensity. In the south, whether the spatial coverage increases or decreases is more dependent on the classes of peak intensity (P_{max}) (Figure S7), where the coverage shows an increase for high P_{max} (>20 mm/h) but a decrease for the rest.

3.2. Spatial Profile of Extreme Rainfall

The changes in the spatial structure of extremes in each subregion were quantified (Figure 3). In all three subregions, the peak intensity at the center of hourly events shows an increase, of which the relative increase is higher in the north-east (23.9%) and lower in the south (16.1%) and the north-west (14.76%).

Beyond peak intensity, significant changes regarding their overall spatial structure are found. The rainfall intensification is found to persist with radial distance in all three regions, and particularly in the north. The north-west has its maximum intensification at 13–30 km from the storm origin, where the relative increase is up to 53.6% (Figure 3a). This increase is beyond the relative increase at its rainfall peak, confirming that the changing spatial profile is not just the manifestation of the increasing rainfall intensity. Correspondingly, the spatial coverage of the storm shows an increase of 49.3% (ensemble range: 8.9%–201.7%). The south also experiences expanding spatial coverage by up to 24.2% (ensemble range: 0.78%–66.9%), and the relative increase of intensity is about 20% for the entire spatial domain of the storms (Figure 3c). Those changes in the spatial pattern of hourly events lead to an increase in areal rainfall amount (rainfall amount within a given hour focused in a 33 km radius domain around the storm center). The average increase is 35.7% in the north-west, 15.9%–16.3% in the north-east and the south.

3.3. Extreme Rainfall at Catchment Scales

The combined changes in the occurrence and the spatiotemporal dynamics of extremes can have a pronounced effect on natural hazard analysis (Figure 4). As quantified by IDAF curves, extreme intensity shows an increase for almost all return periods (2–40 years) and areas (4.84–8,000 km^2) in the three subregions. The relative increase reaches 34.0% ($A = 91$ km^2, $T = 2$ years) in the north-west, 30.2% ($A = 181$ km^2,

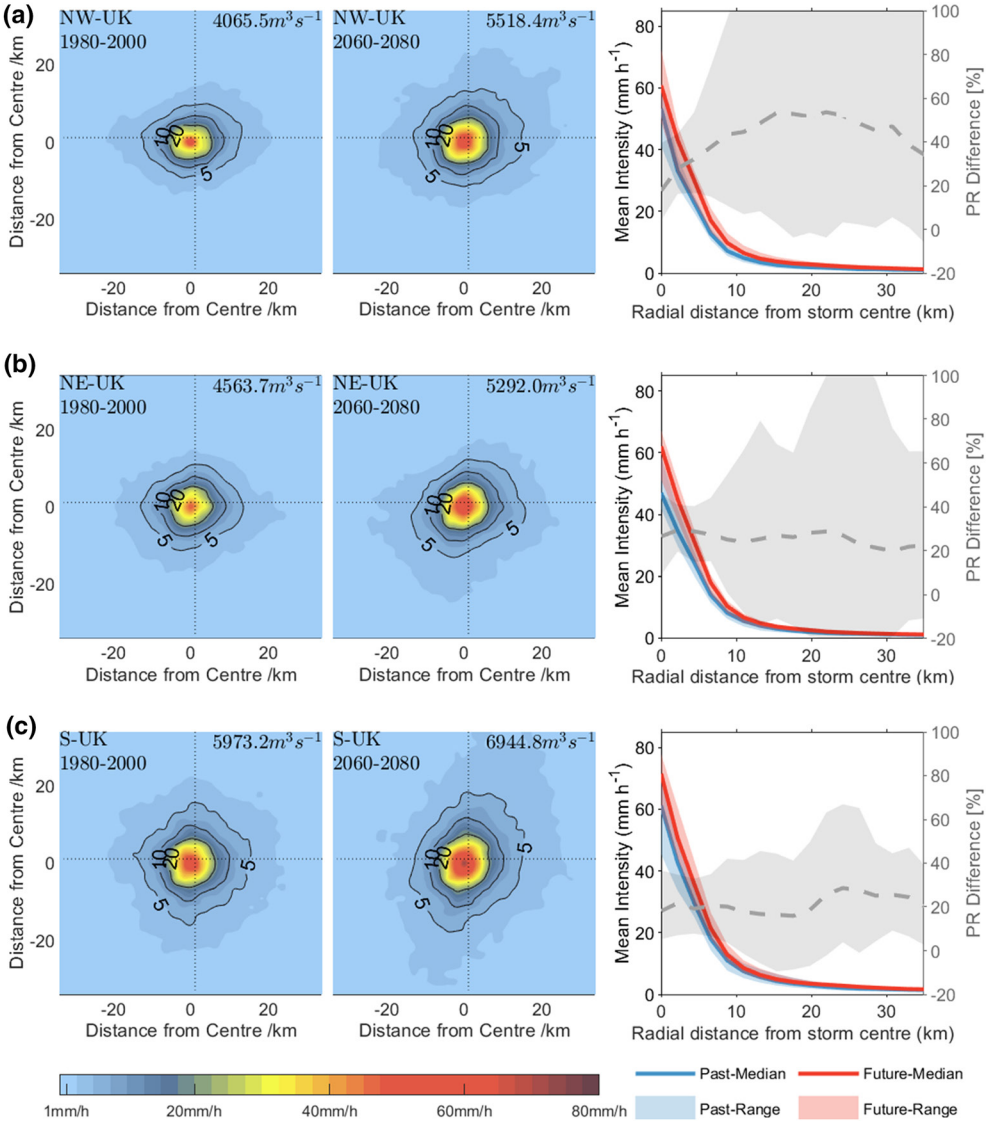


Figure 3. Changes of the heaviest 480 summer rainfall in North-West (a), North-East (b), and South (c). For each subregion: averaged spatial profile in 1980–2000 (left) and in 2060–2080 (middle); (right) ensemble-average rainfall rate (left side *Y*-axis) and ensemble-average relative differences of rainfall intensity (right side *Y*-axis) as a function of radial distance from the storm center. Where the corresponding filled area represents the range between the second lowest and the second highest value over the 12 members.

T = 40 years) in the north-east and 25.8% (A = 110 km^2, T = 27 years) in the south, An exception occurs in the high return levels (>10 years) at large spatial scales (>1,000 km^2) over the north-west and the south, where a decrease in areal extremes was found. However, the decrease is not statistically significant.

The strongest increase in extremes occurs for spatial scales between 50 and 500 km^2 (Figures 4d–4f). In the north-west, another peak of relative increase occurs at a 4,000 km^2 scale. The intensification (central estimate) of areal extremes also depends on the return period. For spatial scales representative of small- and medium-sized catchments in north-eastern UK a similar intensification is estimated for 2–40 years return levels. For the larger spatial scales and for the north-west, the intensification is higher for the lower return periods (<10 years). SNR is used to quantify the significance of the change signals. With catchment area enlarging, the SNR decreases. Specifically, when the area increases from several km^2 scale to ~8,000 km^2,

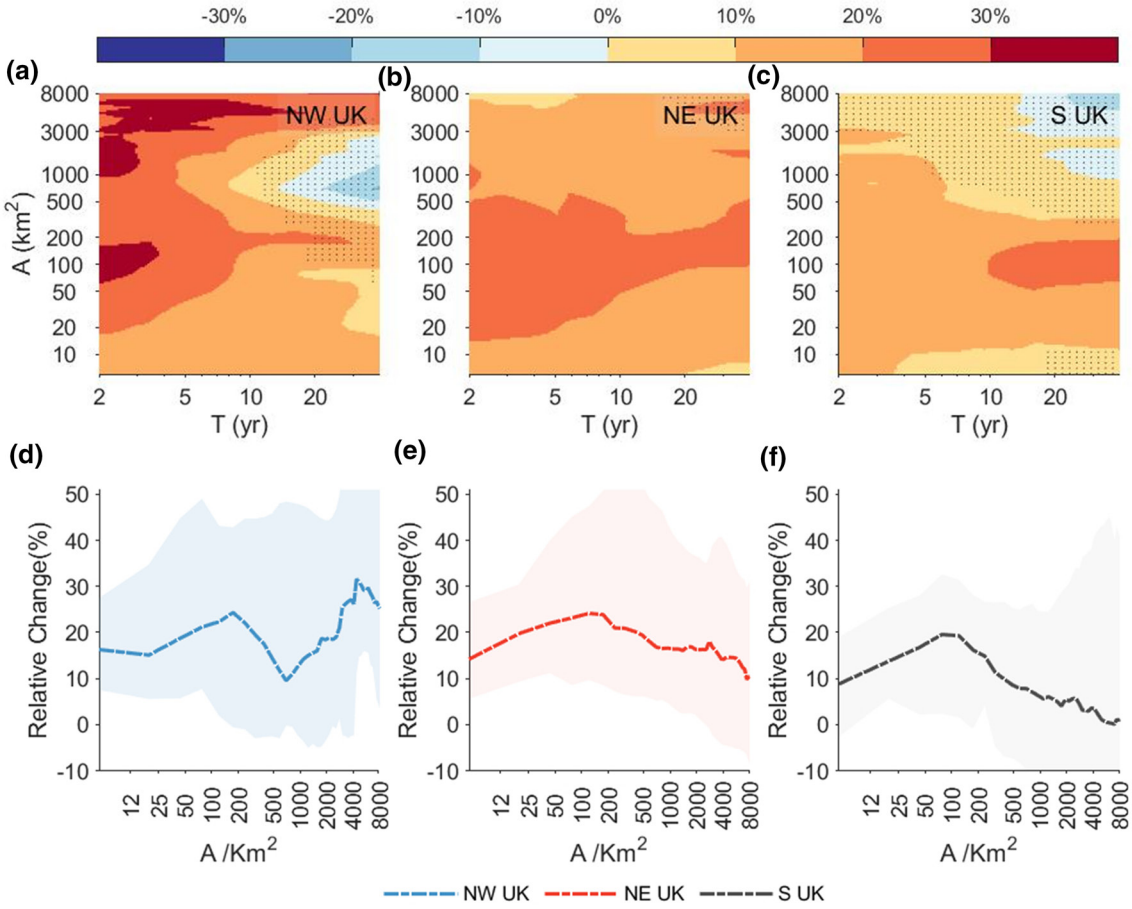


Figure 4. Relative change of areal rainfall intensity as a function of catchment scales and return levels. (a–c) filled contour shows an ensemble-average relative difference of $I(D, A, T)$) in the future minus the past period (dotted area represents a nonsignificant change at $p < 0.1$) in each subregion; (d–f) relative changes of extremes in 12 ensemble members as a function of catchment scales. The filled range represents the ensemble range between the second lowest and the second highest value, with a solid line representing the median value.

SNR drops down from 2.78 to 1.05 in the north-west, from 2.05 to 0.24 in the north-east, and from 3.03 to 1.14 in the south.

4. Discussion

4.1. Intensifying Extremes Revealed by Convection-Permitting Models

The 2.2 km models show a consistent spatial distribution of average precipitation with the driving models (12-km RCMs) but a more pronounced increase in extremes (Kendon et al., 2019). The greater increase can be explained by a more realistic representation of convection in the 2.2 km models than in the coarser-scale simulations (Kendon et al., 2012). Coarser-scale models represent convective showers as a broader area of precipitation, leading to too many low-intensity but long-duration rainfall events. It results in an underestimation of localized convective rainfall in coarse-scale models, particularly significant in the tropical regions and the regions with complex topography (Ban et al., 2014; Prein et al., 2015). In addition, the models we used also tend to overcorrect the bias in 12 km models (too many low-intensity events) and instead give too many moderate and intense events, as reported by Berthou et al. (2018).

Intensifying hourly extremes shown in our study are qualitatively in agreement with previous findings for the UK based on convection-permitting models (Chan et al., 2018, 2020; 2014; Kendon et al., 2014). Compared to previous 1.5 km RCMs for the UK (Chan et al., 2018; Kendon et al., 2014), our results show a

similar pattern with changes of annual extremes in the north (-west) greater than in the south. It is worth mentioning there are considerable improvements in the model used in this study, including developments in the CPM model physics (Fosser et al., 2019), the driving GCMs (Schiemann et al., 2016) and the simulation domain (Fosser et al., 2019). Differences in results are likely related to the above improvements in the climate models themselves. The rainfall intensification can be attributed to increasing atmospheric moisture with warming, according to the CC relation (Moustakis et al., 2020). The positive scaling stems from the fact that a warmer temperature can hold more moisture, which has been validated both from observations (Blenkinsop et al., 2015) and climate simulations (Chan et al., 2016) in the UK.

4.2. Expanding Spatial Extent of Rainfall Extremes

The spatial extent of heavy rainfall shows a regional difference, which can be explained by the rainfall mechanisms in each subregion. Since we set a threshold of a minimum peak intensity of 10 mm/h, most of the widespread and lower-intensity stratiform rain is filtered out (Rigo & Llasat, 2004). The analyzed rainfall events can be regarded as a group of events formed from intense frontal rainfall, orographic rainfall, and/or convective rainfall. Extremes from those are analyzed together without explicitly separating the different rainfall types. Among these, organized convective systems, which can result in large-scale extreme events mostly happen in the south UK in the present-day climate, whereas they seldom happen in the north (only one record between 1981 and 1997) (Gray & Marshall, 1998; M. W. Lewis & Gray, 2010). North-west region experiences strong orographic influence whereas the north-east region mostly lies within a rain shadow. The spatial variability in the occurrence of convective systems explains the broad spatial coverage of hourly extremes in the south (the past period in Figure 3c). In the north-west, which is less affected by the large organized convective systems, the extremes are expected to be more concentrated in specific locations (i.e., over high terrain), thereby show more localized events than the south.

In terms of future change in the spatial extent, we found a strong increasing trend regarding the spatial extent of extremes. The areal rainfall amount is found to increase by up to 60.8%, which is slightly lower than the model-based finding (80%) in the US (Prein et al., 2017). Difference can be attributed to the fact that the US receives mesoscale organized convective storms more frequently. Notably, our study is based on ensemble simulations. The simulation results show that the variability of changing spatial extent between ensemble members is large, where individual members can diverge in terms of the sign of the trend (Figures 3 and 4). This discrepancy needs to be emphasized when making comparisons because most of those previous studies were based on a single realization, and the natural variability might mask the general trend (Fatichi et al., 2016). The fixed value (5 mm/h) is taken as a threshold to identify the heavily rainy area of a rainfall event. Considering the changing distribution of rainfall intensity, we also examined a percentile-based threshold for ensuring the trend robustness (Figure S8).

The increase in spatial extent could be attributed to the changing thermodynamic and dynamic conditions. The warming temperature plays a role in changing the spatial organization of precipitation as reported by Lochbihler et al. (2019). Once the moist convection and precipitation set in, the spatial scale of areas of low-level moisture convergence and divergence become larger with the higher temperature (Haerter et al., 2017; Haerter & Schlemmer, 2018), thereby increasing spatial extent of rain cells. Our findings using the CPM are also strongly controlled by the driving GCM and its simulated large-scale circulation pattern in future climate. Dynamical changes in atmospheric circulation might result in a changing frequency of organized convective storms. Further investigation into the corresponding weather patterns of future extremes of the UKCP simulation (McSweeney & Thornton, 2020) will help to better understand the changes of extremes for each different storm types (Marra et al., 2019). These two factors potentially act together to give a future increase in the areal rainfall amount, over and above the increase in peak intensity. More investigation is needed to understand the relative importance of thermodynamic and dynamic changes in future changes in precipitation extremes. Besides, a rainstorm identification and tracking method (Chang et al., 2020) could be beneficial to segment the different rainstorms occurring at the same time in the study region; these are not separated in this study.

4.3. Impact of Changing Rainfall Regimes

Intensification of rainfall extremes is expected to have strong impacts on the hydrological cycle. Of this, one direct consequence is the increasing potential of flood hazard, as confirmed by the GCM results (Alfieri et al., 2017). Flood hazard analysis under climate change is generally assessed by the downscaled climate scenarios of GCMs (RCMs) and hydrological models. Under the widely used delta change or quantile mapping approach (Camici et al., 2014; Kay & Jones, 2012), changes in rainfall spatial structure have not been included. Our results for the high-resolution model show that the simultaneous increase of extreme intensities and the spatial extent will yield a much higher areal rainfall amount within 1 h. The small-scale feature is essential for the hydrological cycle over river basins and the peak discharge (Paschalis et al., 2014; Peleg et al., 2020) although the current flood impact studies did not include a representation of the changing spatial structure. This fact indicates that the increasing flooding hazards might be still underestimated. The related risk can further exceed our current expectations and impact a broader area at the same time. It is crucial to look into those changing rainfall regimes together in order to undertake the relevant impact studies.

Our results show that the highest intensification occurs for small catchment scales (20–500 km^2), corresponding to typical urban areas of the UK (e.g., Edinburgh urban area is about 119 km^2). The 10–30 years return periods are also the representative of the drainage design of urban cities. The increase in rainfall hourly extremes of up to 25.8%–34% at these catchment scales implies a significant underestimation of urban flood risk in current guidance. In the meantime, the changes at the larger return period and large spatial scales (more than 1,000 km^2) are not that pronounced (with the exception of north-western Scotland). Aside from the importance of peak intensity, the pluvial flooding at large scales might be less influenced than those small and urbanized areas by the changing spatial structure.

Average precipitation in summer is projected to decrease. The dry spells (consecutive hours with no rain) will last for longer at the end of the century (Figure S9). Besides the changing inner-storm structure as we discussed in previous section, the resulting changes in antecedent soil moisture conditions due to the long dry spells will also modulate the rainfall-runoff process and hence affect the flood hazard analysis. In addition, the increasing storm advection speed will affect the water dynamic in the catchment. Although the advection speed we computed is different from the speed of the individual rainfall cells (Figure S10), the increase represents an average behavior of the storm over space. In further investigations, coupling with the hydrological and hydraulic tool is recommended to quantify the combined impact of future rainfall changes on catchment response.

The resulting drought risk also implies that, in the future summer, coping with the increasing water stress might be more challenging, particularly in the south due to the high water demand. Adaptation strategies will be required for water supply companies to tackle the potential reduction of supply sources in the coming few decades in the UK. The altered rainfall regime also impacts agriculture and livestock production (Wilcox et al., 2017). Its direct (e.g., plant stress) and indirect (e.g., delayed agriculture activity, more irrigation water demand) impacts on agricultural yields will potentially increase the vulnerability of food production.

4.4. Value of CPMs and Projection Uncertainties

The convection-permitting models provide credible climate information about future precipitation at small spatial-temporal scales. The benefits of using CPMs lie in their ability to better resolve small-scale processes in the real atmosphere including local storm dynamics. Consequently, changes at the small scale can be captured, such as the higher scaling relationship with increasing temperature for hourly extremes (super CC; Lenderink & van Meijgaard, 2008), and the changing spatial organization reported in our study. For climate impact studies, such a high-resolution climate modeling system would be required globally, but that would create a much higher computational burden. How to achieve such a much more computationally expensive simulation is still a technical challenge.

Projection uncertainty is another factor to highlight. The use of perturbed parameter ensemble improves the effectiveness of climate projections by sampling uncertainties in the assumed deterministic outputs of

parameterizations (Tebaldi & Knutti, 2007). Interannual variability is also represented to some extent in the current 20-year ensemble simulation. However, the CPM ensemble only downscales Hadley Centre global models under the high-end RCP8.5 scenario. It does not sample uncertainties arising from the CPM model physics itself. Follow-on work for UKCP at the UK Met Office aims to address this, with more comprehensive sampling of uncertainties at CPM scales.

5. Conclusions

In the UK Climate Projections UKCP project, for the first time, ensemble simulations using the convection-permitting model are currently available. Using the two sets of 12-member ensemble simulations over the UK for the past and future periods, we showed that rainfall occurs less frequently in the future summer season, but when it rains, it tends to be more intense. The increase of extremes in both peak intensity and occurrence is projected in all three subregions (North West, North East, South). The future summer rainfall is found to move faster and also have a large spatial coverage. The increase in spatial extent and peak intensity of extremes leads to an increase in hourly areal rainfall amounts by up to 60.8% in the north-west. Such an intensification of rainfall extremes at 2–40 years return levels is projected for most of the catchment scales, reaching the highest increase at the scales with sizes 20–500 km^2. This spatial scale implies the significant underestimation of urban flood hazards in future climate in current guidance. In addition, ensemble results also indicated that, for large catchment areas (thousands of km^2) in the south, any trend may not be significant compared to variability across the 12-member ensemble.

Data Availability Statement

UKCP18 CPM model data are provided by UK Met Office, available from: https://catalogue.ceda.ac.uk/uuid/d5822183143c4011a2bb304ee7c0baf7.

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