LETTERS
PUBLISHED ONLINE: 1 JUNE 2014 | DOI: 10.1038/NCLIMATE2258
nature climate change

Heavier summer downpours with climate change revealed by weather forecast resolution model

Elizabeth J. Kendon[1]*, Nigel M. Roberts[2], Hayley J. Fowler[3], Malcolm J. Roberts[1], Steven C. Chan[3] and Catherine A. Senior[1]

The intensification of precipitation extremes with climate change[1] is of key importance to society as a result of the large impact through flooding. Observations show that heavy rainfall is increasing on daily timescales in many regions[2], but how changes will manifest themselves on sub-daily timescales remains highly uncertain. Here we perform the first climate change experiments with a very high resolution (1.5 km grid spacing) model more typically used for weather forecasting, in this instance for a region of the UK. The model simulates realistic hourly rainfall characteristics, including extremes[3,4], unlike coarser resolution climate models[5,6], giving us confidence in its ability to project future changes at this timescale. We find the 1.5 km model shows increases in hourly rainfall intensities in winter, consistent with projections from a coarser 12 km resolution model and previous studies at the daily timescale[7]. However, the 1.5 km model also shows a future intensification of short-duration rain in summer, with significantly more events exceeding the high thresholds indicative of serious flash flooding. We conclude that accurate representation of the local storm dynamics is an essential requirement for predicting changes to convective extremes; when included we find for the model here that summer downpours intensify with warming.

Few studies have examined changes in rainfall on hourly timescales due to sparse sub-daily observations and the inability of climate models to reliably simulate sub-daily rainfall. The studies so far suggest greater increases in hourly compared to daily rainfall extremes[5,8], but as a result of model deficiencies we have low confidence in these projections. This is of concern as it is short-duration convective extremes which tend to be responsible for flash flooding events, such as the Boscastle flood in August 2004 (ref. 9), particularly important in urban environments and for small or steep river catchments.

The Clausius–Clapeyron (CC) relation describes the rate of change of saturated water vapour pressure with temperature as approximately 7% $^\circ\mathrm{C}^{-1}$, and sets a scale for change in precipitation extremes[1]. Increasing evidence from observational studies suggests intensities of sub-daily precipitation extremes increase more rapidly with temperature than for daily extremes; above the CC rate, at least in some regions[8,10]. This seems to be a property of convective precipitation[10] and may be explained by latent heat released within storms invigorating vertical motion, leading to greater increases in rainfall intensity. However, the extent to which this scaling may apply over the longer-term with global warming is uncertain.

Global and regional climate models (with typical grid spacings of 60–300 km and 10–50 km respectively) rely on a convective parameterization scheme to represent the average effects of convection. This simplification is a known source of model error, and leads to deficiencies in the diurnal cycle of convection[11] and the inability (by design) to produce hourly precipitation extremes[5,6,8]. Very high resolution models (order 1 km grid spacing), on the other hand, can represent deep convection explicitly without the need for such a parameterization scheme[3,12]. Such models are termed 'convection-permitting' because larger storms and meso-scale convective organization are permitted (largely resolved) but convective plumes and small showers are still not represented.

Convection-permitting models are commonly used in short-range weather forecasting. They give a much more realistic representation of convection and are able to forecast localized extreme events not captured at coarser resolutions[13]. However, there are few examples of convection-permitting resolutions being applied in climate studies, owing to their high computational cost. Previous studies have been limited to small domains and often just a single season[12,14,15] or selected events[16,17]. Some studies have built up multi-year climatologies through a sequence of seasonal[18,19] or shorter[20] simulations. However, long continuous simulations are needed to represent long-term memory in the soil and its feedbacks with precipitation[21]. We recently[3] carried out the first extended (20-year) length climate simulation with a convection-permitting (1.5 km) model over a region of the UK. Here we use the same model to examine future changes. To our knowledge this is the first time that continuous multi-year simulations at such high resolutions have been carried out to study rainfall change for a future climate scenario. Climate change experiments have been carried out at 4 km resolution over the western US (ref. 22), but this resolution is not high enough to adequately represent typical convection over the UK (ref. 13).

We compare future changes in hourly rainfall in the 1.5 km model with results from a 12 km regional climate model (RCM) over the southern UK. The models are run for 13-year present-day (1996–2009) and 13-year future (∼2100, under the Intergovernmental Panel on Climate Change RCP 8.5 scenario) periods, driven by a 60 km global climate model (GCM). Model biases for the present-day have been assessed by comparison with gridded hourly observations from radar, available for 2003–2012 (ref. 23). Because radar tends to systematically underestimate heavy rain[24], we apply a bias correction using daily gauge observations.

On hourly timescales, rainfall is heavier over the southern UK in summer than in winter (Figs 1 and 2). Model biases compared to radar data are also larger in summer. In particular, the 12 km-RCM significantly underestimates heavy rainfall in summer, whereas the 1.5 km model tends to provide an overestimate, particularly

---

[1]Met Office Hadley Centre, FitzRoy Road, Exeter, EX1 3PB, UK, [2]MetOffice@Reading, Reading, RG6 6BB, UK, [3]School of Civil Engineering and Geosciences, Newcastle University, Newcastle, NE1 7RU, UK. *e-mail: elizabeth.kendon@metoffice.gov.uk

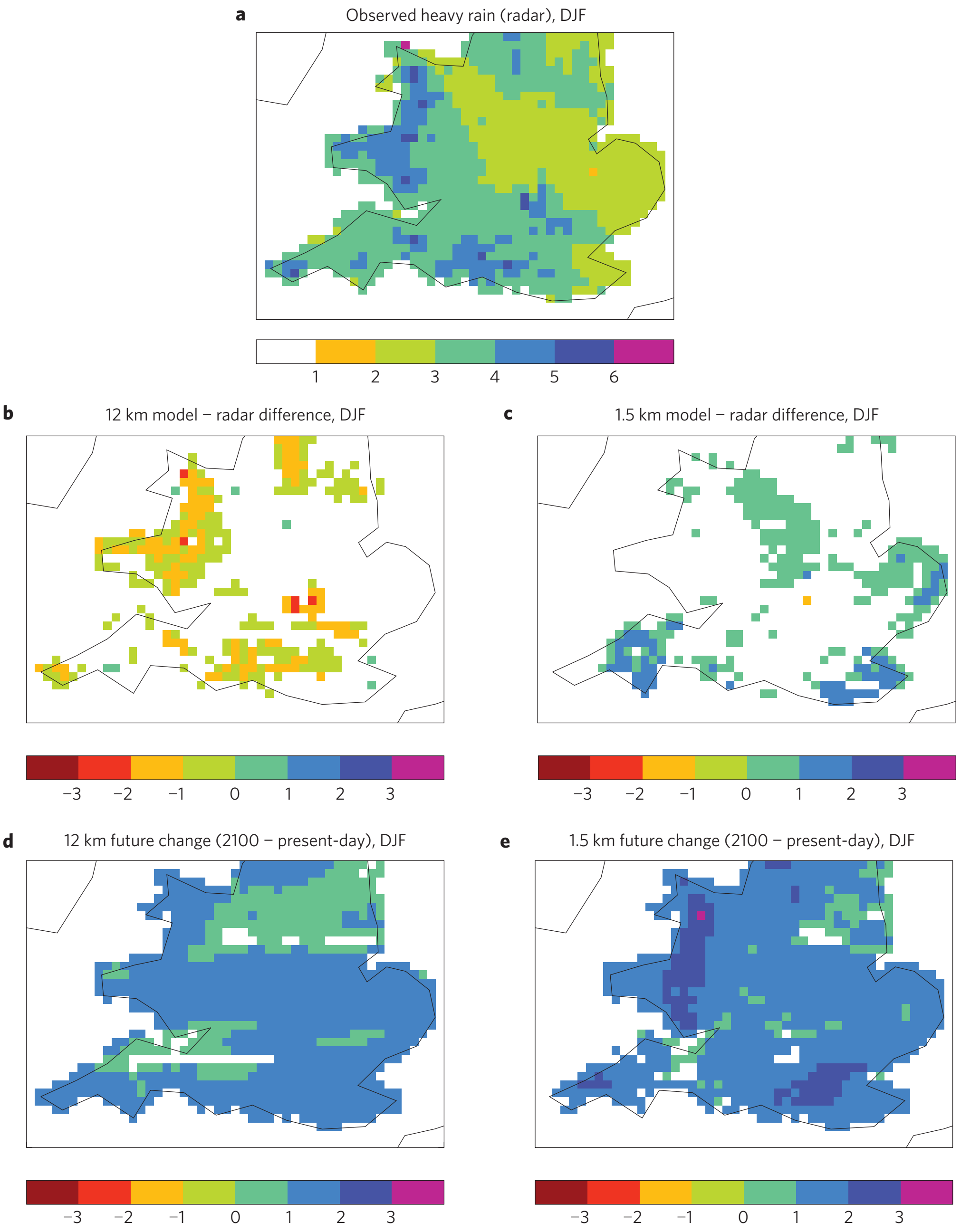

Figure 1 | Heavy rainfall on hourly timescales (mm h^{-1}) in winter (December–January–February; DJF). a, Observed radar. **b**,**c**, Difference between model and observed radar for 12 km and 1.5 km models, respectively. **d**,**e**, Difference between 2100 and present-day for 12 km and 1.5 km models, respectively. Heavy rainfall is defined as the mean of the upper 5% of wet values (>0.1 mm h^{-1}). White indicates differences or future changes not significant at the 1% level compared to year-to-year variability. The radar data has been bias corrected using daily rain gauge data.

in the south-east. The tendency for heavy rain to be too intense in small convective cores in the 1.5 km model is understood and is a current inherent weakness of a 'convection-permitting' model[13]. Smaller showers are not properly resolved, with some showers having updrafts on the wrong scale with insufficient turbulent sub-grid mixing. Nevertheless, the 1.5 km model gives a much better representation of hourly rainfall characteristics, including extremes[3,4], than the 12 km model, and extensive testing within numerical weather prediction trials at the Met Office has shown considerable benefit from the 1.5 km model, leading to its operational implementation as a replacement for the previous 4 km and 12 km models.

We find that both models show future increases in heavy rainfall in winter, consistent with studies on daily timescales[7]. The 1.5 km model also shows significant increases in heavy rain intensities in summer, which are not seen in the 12 km-RCM. Previous studies relying on coarser models have shown large uncertainties in changes in summertime extremes[5,7]. The summertime increases in the 1.5 km model are 36% for the southern UK on average, which, given a surface warming of about 4–5 °C for heavy rain days, are consistent or possibly higher than CC-scaling.

Looking at the heaviest 50 events (averaged to the 12 km grid) in the 1.5 km model in summer in the future simulation, about half of these are larger-scale storms (embedded convection within a front, mesoscale convective systems or squall lines) with the remainder being individually smaller storms (often clustered). The events seem physically plausible, with realistic evolution and the model responding to the environment in a sensible way. In particular,

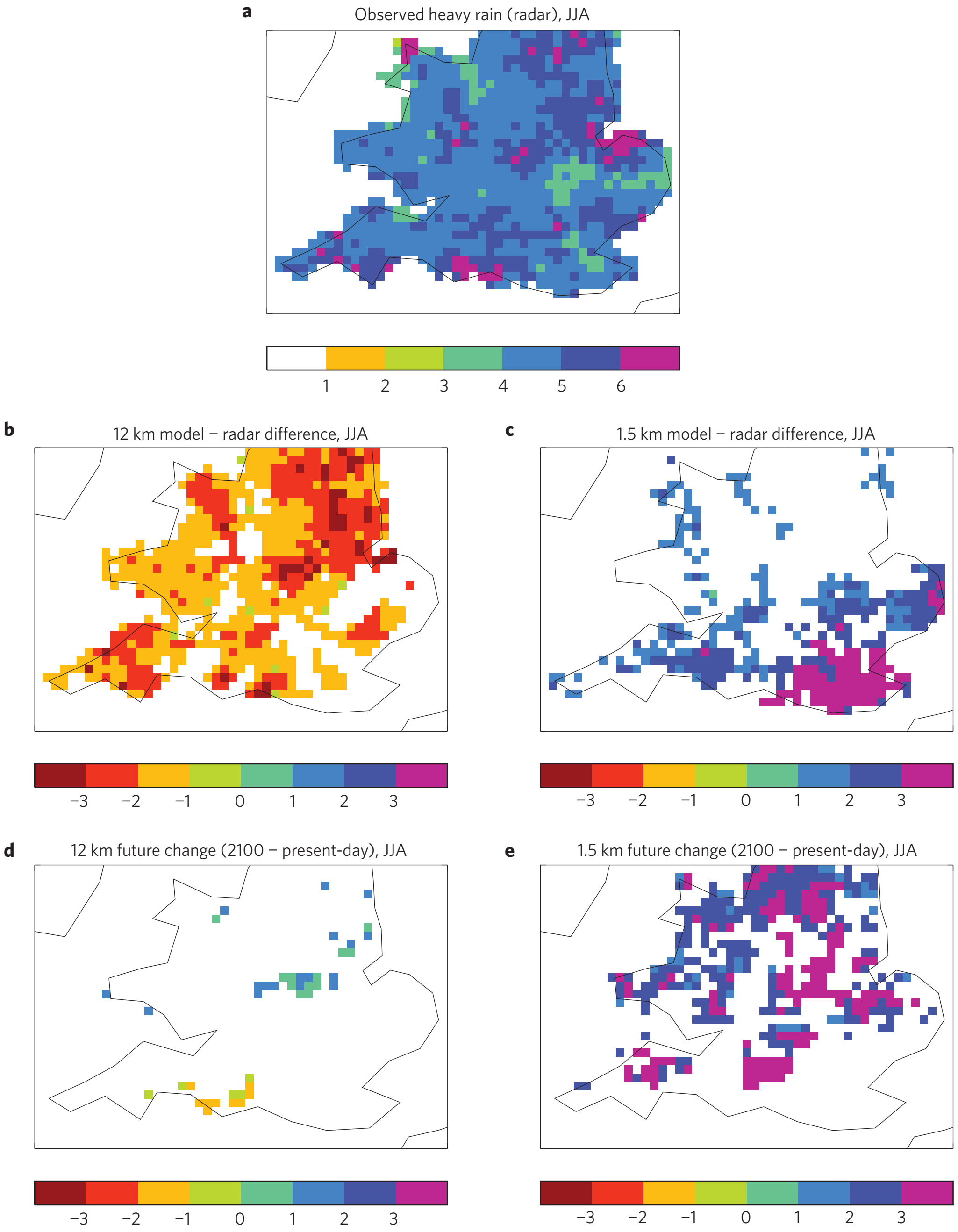

Figure 2 | Heavy rainfall on hourly timescales (mm h^{-1}) in summer (June–July–August; JJA). **a**, Observed radar. **b**,**c**, Difference between model and observed radar for 12 km and 1.5 km models, respectively. **d**,**e**, Difference between 2100 and present-day for 12 km and 1.5 km models, respectively. Heavy rainfall is defined as the mean of the upper 5% of wet values (>0.1 mm h^{-1}). White indicates differences or future changes not significant at the 1% level compared to year-to-year variability. The radar data has been bias corrected using daily rain gauge data.

nearly all events are associated with cyclonic flow and hot humid conditions (high 850 hPa wet-bulb potential temperature, θ_w). A recent observed event (27 July 2013) with similar conditions is shown in Supplementary Fig. 1, illustrating the ability of the 1.5 km model to capture rainfall accumulations associated with an intense squall line. In the present-day control run, a similar proportion of the heaviest events are larger organized systems, but these are associated with lower hourly accumulations (only 6 events have values exceeding 30 mm h^{-1} over a 12 km grid box compared to 22 in the future). We find that present-day θ_w is considerably lower (3–4 °C less for the heaviest events), suggesting that future increases in heavy rainfall intensities are associated with the warmer moister environment (Supplementary Methods).

Future changes in the number of exceedances above high thresholds are useful because of the relationship to flood risk. Here we examine the frequency of episodes exceeding present-day percentiles of wet hourly precipitation (Fig. 3), which removes any issues with model or radar absolute bias. Here an episode is a continuous period of exceedance at a given grid point, counted separately for different grid points; whereas an event refers to the rainfall field at a given time. For the 12 km-RCM, there are too few episodes exceeding low thresholds in both seasons (blue asterisks) and so individual episodes must be too persistent. By comparison the number of episodes is well captured in the 1.5 km model. Both models show a significant future increase in the number of episodes exceeding high thresholds in winter (red asterisks). In summer,

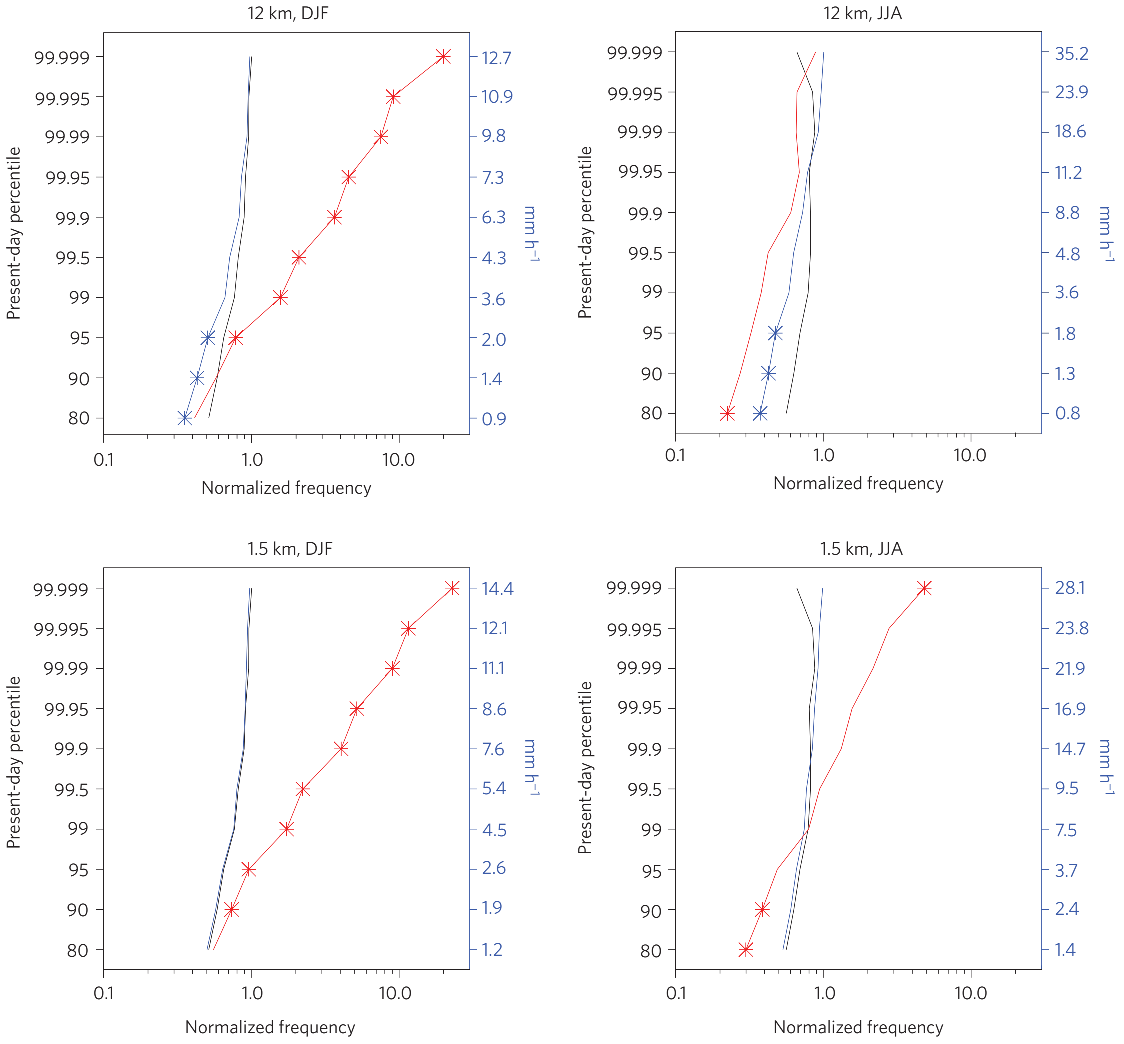

Figure 3 | Frequency of episodes across the southern UK exceeding present-day percentiles of wet hourly precipitation. Results are shown for 12 km (upper panels) and 1.5 km (lower panels) model runs for December–January–February (DJF; left panels) and June–July–August (JJA; right panels). Radar (black), present-day (blue) and future (red). Frequency is measured as the number of episodes (continuous periods of exceedance above threshold) over all land points normalized by the number of hours exceeding the threshold in the present-day. Percentile values (calculated for all grid boxes spatially pooled) are shown for the models on the right axis in blue. Blue (red) asterisks indicate model biases (future changes) significant at the 1% level.

both models show a significant decrease in the number of episodes exceeding low thresholds, consistent with it raining less often in the future, but only the 1.5 km model shows an increased frequency of episodes exceeding the higher thresholds. The interplay between fewer rainfall episodes overall and an increasing intensity of heavy rain means that for a high enough threshold (99.999th percentile of wet hours for the present-day, corresponding to 28 mm h^{-1}) the 1.5 km model shows a significant increase in the number of episodes in the future summer (24 episodes exceed 28 mm h^{-1} in the present-day and 117 in the future).

The duration–intensity characteristics of rainfall are of key importance for flooding. The 12 km-RCM has too little short-duration high-peak-intensity rain and too much long-duration low-intensity rain. This is shown for summer in Fig. 4, with similar biases seen in winter (Supplementary Fig. 4). These biases are considerably larger than possible radar error (Supplementary Fig. 3). The 1.5 km model, by contrast, is able to capture the observed characteristics with significantly reduced biases. Thus this model allows us to project in a much more reliable way how these characteristics may change in the future. In winter, both models show a very similar change, with significant increases in peak rainfall intensity across all durations (Fig. 4). Importantly, in summer, the two models show quite different signals of change. The 1.5 km model shows an intensification of short-duration rain which is not seen in the 12 km-RCM. This intensification of short-duration rain is not inconsistent with many of the heaviest events in the future being large-scale storms (Supplementary Methods).

It is perhaps surprising that the two models show consistent changes in winter, given that the biases in the 12 km-RCM seem to be responsible for different changes from those of the 1.5 km model in summer. We explain this difference by examining composites of the heaviest 50 events in the two seasons, where each event centre is relocated to a common point to produce a ‘typical’ heavy event (Supplementary Fig. 5). In winter, both models show an intensification of the whole event, whereas in summer the increase in the 1.5 km model is confined to the peak of the event. Because high peak intensities in summer are linked to convection (or convective enhancement within large scale storms), this points to deficiencies in the convection parameterization in the 12 km-RCM being the cause of the different summertime change. In winter, the more widespread increase is consistent with enhanced large-scale moisture convergence, and thus deficiencies in the convective enhancement of rain in the coarser-scale model (apparent from the control biases) do not impact on the future change.

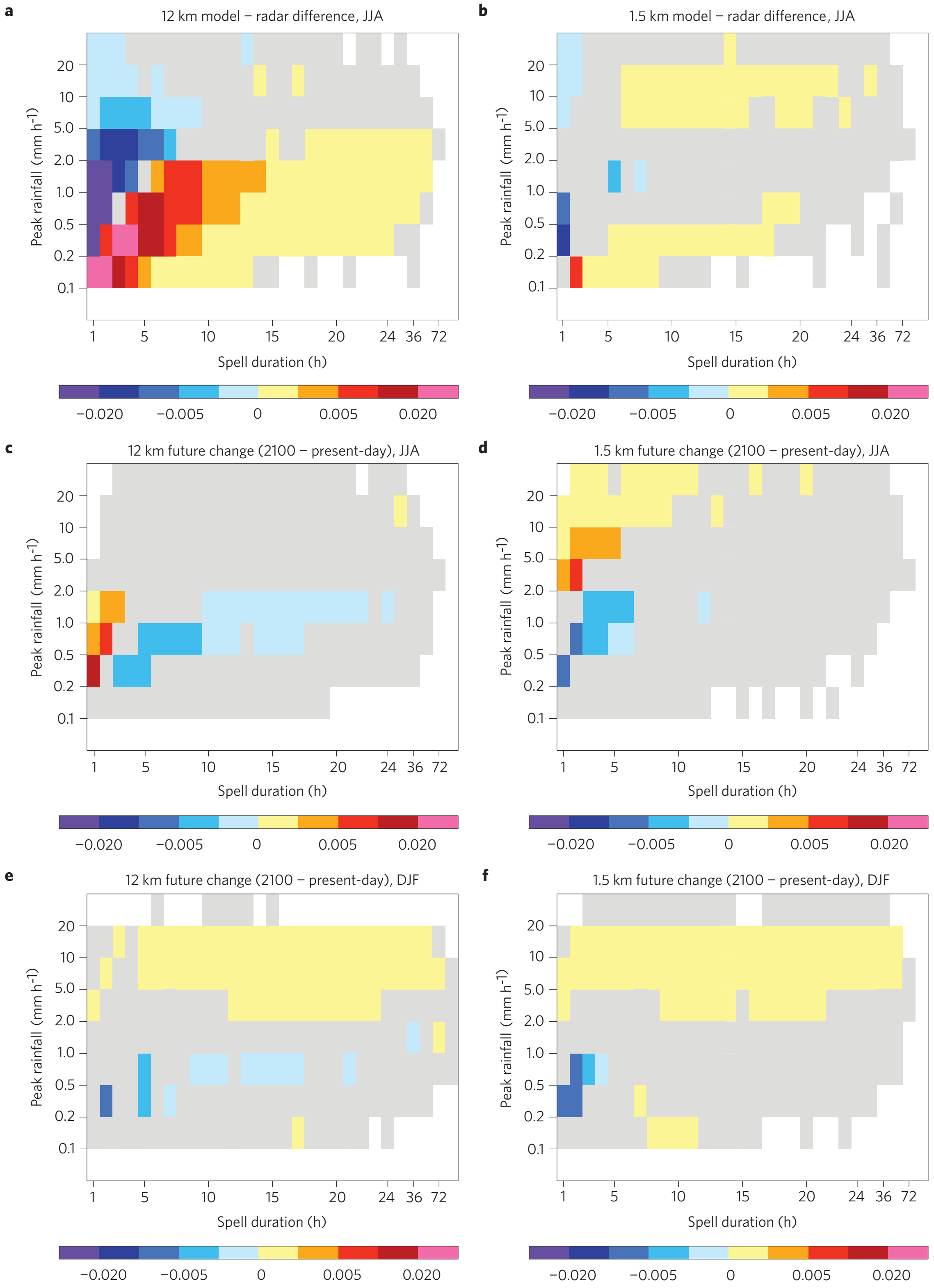

Figure 4 | Model biases and future changes in the joint probability distribution of wet spell duration versus peak intensity over the southern UK. **a**,**b**, Differences between the model and observed radar for June–July–August (JJA) using the 12 km and 1.5 km models, respectively. **c**,**d**, Future changes for JJA using the 12 km and 1.5 km models, respectively. **e**,**f**, Future changes for December–January–February (DJF) using the 12 km and 1.5 km models, respectively. Wet spells are defined as continuous periods when rain exceeds 0.1 mm h^{-1}. Peak intensity from the radar has been bias corrected using daily rain gauge data. Differences that are not significant at the 1% level are masked in grey.

In conclusion, future projections of changes to UK winter rainfall are robust from coarser to higher resolution models. However, in summer, deficiencies in the convective parameterization scheme in coarse resolution models seriously impact on projections of rainfall change. Using a convection-permitting model we find evidence of an intensification of hourly rainfall in summer not seen in a coarser 12 km resolution model. This is of major importance for flooding; in particular, an accumulation threshold of 30 mm h^{-1} is used by the Met Office/Environment Agency Flood Forecasting Centre as guidance to indicate likely flash flooding, and results here suggest this may be exceeded more often, over a wide area (12 km × 12 km), in the future. These results are based on one climate model, and so we cannot assess modelling uncertainty. However, the intensification of summertime convective events in a warmer moister environment is consistent with both theoretical expectations of super-Clausius–Clapeyron scaling and the limited observational studies of sub-daily rainfall to date. We conclude that accurate representation of the local storm dynamics is essential for predicting future change in convective storms (along with accurate representation of changes in the larger-scale environment inherited from the driving GCM). This implies that previous interpretations of future regional climate change scenarios should be revisited, as changes in convective rain events could have been underestimated.

Methods

The models used here are all configurations of the Met Office Unified Model (MetUM; ref. 25). The 1.5 km model spans the southern UK and is driven by the 12 km-RCM, which spans Europe and is in turn driven by the 60 km-GCM. The 1.5 km model is as described previously[3], with some upgrades to the model physics, particularly an improved microphysical parameterization of drizzle and fog (ref. 26). The 12 km-RCM and 60 km-GCM both have the UM Global Atmosphere 3.0 configuration[25], and have similar model physics to that in the 1.5 km model except that, at 1.5 km resolution, the convection scheme has been switched off and Smagorinsky–Lilly turbulence diffusion is applied.

For the present-day control runs, monthly sea surface temperature (SST) and sea-ice forcings from the Program for Climate Model Diagnosis and Intercomparison were used. Other forcings follow the Atmospheric Model Intercomparison Project II (AMIP-II) protocols, excepting that Shine–Li ozone climatology[27] was used for the 1.5 km and 12 km RCMs. For the future runs, SST was configured as time-varying monthly SST from the control run plus the (multi-year) mean SST change for each month between 1990–2010 and 2090–2110 in the HadGEM2-ES runs[28] under the IPCC RCP8.5 scenario. Carbon dioxide, methane, nitrous oxide, CFC and HFC concentrations were adjusted accordingly, but do not vary with time. Sea-ice comes directly from the HadGEM2-ES integration, as a repeat monthly cycle. Ozone and aerosol forcings were not changed between the present-day and future runs. In the 60 km-GCM and 12 km-RCM, aerosol mass mixing ratios provide the cloud droplet number for autoconversion. In the case of the 1.5 km model, however, autoconversion limits are based on droplet number assumptions[29]. Because aerosol forcings are not changed for the future simulations, this is not expected to have a large impact on the climate change results.

Soil moisture evolves freely using the Joint UK Land Environment Simulator (JULES; ref. 30). Soil moisture in the 1.5 km model is initialized from the 12 km-RCM, and takes a few months to 'spin-up' (except potentially in the very deepest layer, where it can take several years to fully reach equilibrium). Thus the first few months of the simulation were discarded (the simulations were actually 13 years 7 months), and the analysis here only uses 13 years of model data from December 1996 to November 2009 for the present-day and similarly for the future runs. We note that a key benefit of long-continuous simulations (rather than seasonal slices) is that long-memory land-surface feedbacks can be represented.

The radar data used here are 5 km hourly data from the Nimrod database[23]. Radar data offer good spatial coverage and are available for an extended period (2003–2012). However, the radar tends to underestimate heavy rain because of beam attenuation[24], and so we apply a bias correction using daily rain gauge observations (further details of the observational datasets are provided in the Supplementary Methods). In particular, at times when hourly rainfall is a major contributor to the daily total, it is possible to estimate an upward correction to the hourly radar intensity by comparing daily radar totals with daily gauge totals. Specifically we identify heavy hourly rainfall amounts in the radar data, and identify when these are $>0.3\times$ daily radar total. If this criterion is met, and the daily radar total $<$ the daily gauge total for that grid point on that day, then we upscale the radar hourly amount as follows:

$$P_{\text{adjusted}} = P_{\text{Hourly\_radar}} \times \frac{P_{\text{Daily\_gauge}}}{P_{\text{Daily\_radar}}}$$

If the daily radar total $>$ the daily gauge total, no correction is applied. This corresponds to the situation of a heavy localized shower missed by the gauges, for which the radar provides the best (although potentially biased) estimate. The sensitivity of the bias correction to the selection criterion and the impact of the correction on the results are discussed in the Supplementary Methods (Supplementary Figs 2 and 3).

All analysis here is carried out at the 12 km scale, with the hourly precipitation fields for the 1.5 km model and 5 km radar being first aggregated onto the 12 km-RCM grid. Bootstrap resampling is used to assess the significance of model biases and future changes with respect to year-to-year variability. A total of 1,000 bootstrap samples are produced for the model (radar) data by selecting 13 (10) years from the full dataset randomly with replacement. These are used to produce 1,000 estimates of the difference between the model and radar, or the future and present-day model runs, allowing a confidence interval for the difference to be calculated.

Received 7 February 2014; accepted 6 May 2014;

References

1. Trenberth, K. E., Dai, A., Rasmussen, R. M. & Parsons, D. B. The changing character of precipitation. *Bull. Am. Meteorol. Soc.* **84,** 1205–1217 (2003).
2. Min, S-K., Zhang, X., Zwiers, F. W. & Hegerl, G. C. Human contribution to more-intense precipitation extremes. *Nature* **470,** 376–379 (2011).
3. Kendon, E. J., Roberts, N. M., Senior, C. A. & Roberts, M. J. Realism of rainfall in a very high resolution regional climate model. *J. Clim.* **25,** 5791–5806 (2012).
4. Chan, S. C. *et al.* The value of high-resolution Met Office regional climate models in the simulation of multi-hourly precipitation extremes. *J. Clim.* http://dx.doi.org/10.1175/JCLI-13-00723.1 (in the press).
5. Hanel, M. & Buishand, T. A. On the value of hourly precipitation extremes in regional climate model simulations. *J. Hydrol.* **393,** 265–273 (2010).
6. Gregersen, I. B. *et al.* Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. *Climatic Change* **118,** 783–797 (2013).
7. Fowler, H. J. & Ekström, M. Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *Int. J. Climatol.* **29,** 385–416 (2009).
8. Lenderink, G. & van Meijgaard, E. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geosci.* **1,** 511–514 (2008).
9. Burt, S. Cloudburst upon Hendraburnick Down: The Boscastle storm of 16 August 2004. *Weather* **60,** 219–227 (2005).
10. Berg, P., Moseley, C. & Haerter, J. O. Strong increase in convective precipitation in response to higher temperatures. *Nature Geosci.* **6,** 181–185 (2013).
11. Brockhaus, P., Lüthi, D. & Schär, C. Aspects of the diurnal cycle in a regional climate model. *Meteorol. Z.* **17,** 433–443 (2008).
12. Hohenegger, C., Brockhaus, P. & Schär, C. Towards climate simulations at cloud-resolving scales. *Meteorol. Z.* **17,** 383–394 (2008).
13. Lean, H. W. *et al.* Characteristics of high-resolution versions of the Met Office Unified Model for forecasting convection over the United Kingdom. *Mon. Weath. Rev.* **136,** 3408–3424 (2008).
14. Langhans, W., Schmidli, J., Fuhrer, O., Bieri, S. & Schär, C. Long-term simulations of thermally driven flows and orographic convection at convection-parameterizing and cloud-resolving resolutions. *J. Appl. Meteorol. Clim.* **52,** 1490–1510 (2013).
15. Prein, A. F. *et al.* Added value of convection permitting seasonal simulations. *Clim. Dynam.* **41,** 2655–2677 (2013).
16. Mahoney, K., Alexander, M., Scott, J. D. & Barsugli, J. High-resolution downscaled simulations of warm-season extreme precipitation events in the Colorado Front Range under past and future climates. *J. Clim.* **26,** 8671–8689 (2013).
17. Attema, J. J., Loriaux, J. M. & Lenderink, G. Extreme precipitation response to climate perturbations in an atmospheric mesoscale model. *Environ. Res. Lett.* **9,** 014003 (2014).
18. Wakazuki, Y., Nakamura, M., Kanada, S. & Muroi, C. Climatological reproducibility evaluation and future climate projection of extreme precipitation events in the Baiu Season using a high-resolution non-hydrostatic RCM in comparison with an AGCM. *J. Meteorol. Soc. Jpn* **86,** 951–967 (2008).
19. Knote, C., Heinemann, G. & Rockel, B. Changes in weather extremes: Assessment of return values using high resolution climate simulations at convection-resolving scale. *Meteorol. Z.* **19,** 11–23 (2010).
20. Trapp, R. J., Robinson, E. D., Baldwin, M. E., Diffenbaugh, N. S. & Schwedler, B. R. J. Regional climate of hazardous convective weather through high-resolution dynamical downscaling. *Clim. Dynam.* **37,** 677–688 (2011).
21. Hohenegger, C., Brockhaus, P., Bretherton, C. S. & Schär, C. The soil moisture-precipitation feedback in simulations with explicit and parameterized convection. *J. Clim.* **22,** 5003–5020 (2009).

22. Pan, L-L. *et al.* Influences of climate change on California and Nevada regions revealed by a high-resolution dynamical downscaling study. *Clim. Dynam.* **37,** 2005–2020 (2011).
23. Golding, B. W. Nimrod: A system for generating automated very short range forecasts. *Meteorol. Appl.* **5,** 1–16 (1998).
24. Harrison, D. L., Driscoll, S. J. & Kitchen, M. Improving precipitation estimates from weather radar using quality control and correction techniques. *Meteorol. Appl.* **7,** 135–144 (2000).
25. Walters, D. N. *et al.* The Met Office Unified Model global atmosphere 3.0/3.1 and JULES global land 3.0/3.1 configurations. *Geosci. Model Dev.* **4,** 919–941 (2011).
26. Wilkinson, J. M. *et al.* Improved microphysical parametrization of drizzle and fog for operational forecasting using the Met Office Unifed Model. *Q. J. R. Meteorol. Soc.* **139,** 488–500 (2013).
27. Li, D. & Shine, K. P. *A 4-dimensional Ozone Climatology for UGAMP Models.* Technical Report 35 (UGAMP 1995).
28. Collins, W. J. *et al.* Development and evaluation of an Earth-System model—HadGEM2. *Geosci. Model Dev.* **4,** 1051–1075 (2011).
29. Bower, K. N. & Choularton, T. W. A parametrisation of the effective radius of ice free clouds for use in global climate models. *Atmos. Res.* **27,** 305–339 (1992).
30. Best, M. J. *et al.* The Joint UK Land Environment Simulator (JULES), model description—Part 1: Energy and water fluxes. *Geosci. Model Dev.* **4,** 595–640 (2011).

Acknowledgements

Thanks to colleagues across the UK Met Office for their help in setting up the 1.5 km and 12 km model experiments, especially C. Wang, J. Bornemann and W. Moufouma-Okia. Also thanks to J. Wilkinson, P. Field, C. Pilling and H. Lean for useful discussions. We gratefully acknowledge funding from the Joint Department of Energy and Climate Change (DECC) and Department for Environment Food and Rural Affairs (Defra) Met Office Hadley Centre Climate Programme (GA01101). This work also forms part of a joint UK Met Office and Natural Environment Research Council (UKMO-NERC) funded project on Convective Extremes (CONVEX, NE/1006680/1).

Author contributions

E.J.K. carried out the 1.5 km and 12 km model experiments and wrote the paper. N.M.R. analysed the performance of the 1.5 km model from weather forecasts, produced Supplementary Fig. 1, and along with H.J.F. extensively contributed to the manuscript. M.J.R. ran the 60 km global model experiments. All authors discussed the results and commented on the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to E.J.K.

Competing financial interests

The authors declare no competing financial interests.