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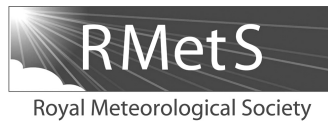
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## Notes and Correspondence

# Can a climate model reproduce extreme regional precipitation events over England and Wales?

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The ability of the High-Resolution Global Environmental Monitoring (HiGEM) climate model to represent high-impact, regional precipitation events is investigated in two ways. The first focuses on a case study of extreme regional accumulation of precipitation during the passage of a summer extratropical cyclone across southern England on 20 July 2007 that resulted in a national flooding emergency. The climate model is compared with a global numerical weather prediction (NWP) model and higher-resolution, nested limited-area models. While the climate model does not simulate the timing and location of the cyclone and associated precipitation as accurately as the NWP simulations, the total accumulated precipitation in all models is similar to the rain-gauge estimate across England and Wales. The regional accumulation over the event is insensitive to horizontal resolution for grid spacings ranging from 90–4 km.

Secondly, the free-running climate model reproduces the statistical distribution of daily precipitation accumulations observed in the England–Wales precipitation record. The model distribution diverges increasingly from the record for longer accumulation periods, with a consistent under-representation of more intense multiday accumulations. This may indicate a lack of low-frequency variability associated with weather regime persistence. Despite this, the overall seasonal and annual precipitation totals from the model are still comparable to those from ERA-Interim.

*Key Words:* extreme precipitation; climate model; distribution

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## 1. Introduction

The fifth Intergovernmental Panel on Climate Change Working Group I report stated in its Technical Summary that ‘Over most of the mid-latitude land-masses and over wet tropical regions, extreme precipitation events will very likely be more intense and more frequent in a warmer world’ (Stocker *et al.*, 2013). Globally, increases in extreme precipitation in simulations of a warmer climate are associated with increases in the availability of moisture from the Clausius–Clapeyron relation (Allen and Ingram, 2002; Pall *et al.*, 2007; Allan and Soden, 2008; Trenberth, 2011). However, to have confidence in climate model projections on regional scales, it is essential to evaluate the ability of the climate models to represent processes that give rise to extreme precipitation.

Questions remain regarding the ability of global climate models to represent regional processes, primarily due to the coarse

horizontal resolution required for century-long simulations. In addition, the regional evaluation of precipitation is challenging, as it requires long records of quality-controlled observations, for example those available as part of the England and Wales precipitation dataset (Alexander and Jones, 2001). Previous regional evaluations of the ability of climate models to represent the statistics of precipitation over the UK (Jones and Reid, 2001; Fowler *et al.*, 2005; Fowler and Ekström, 2009; Schindler *et al.*, 2012) have therefore focused on higher-resolution, regional climate models. Furthermore, recent work has evaluated the statistical representation of precipitation in a very high-resolution regional climate version of the Met Office Unified Model that can partially resolve convective-scale processes (Kendon *et al.*, 2012; Chan *et al.*, 2013).

The regional evaluation of precipitation in global climate models has generally received less attention. However, increases

Table 1. Summary of the different domains used by the models.  $N_{x,y,z}$  are the number of grid boxes in the relevant direction,  $\Delta_{x,y}$  is the grid spacing and  $\text{Lon}_0$  and  $\text{Lat}_0$  are the coordinates of the lower left corner in the rotated system.

Model	$N_x$	$N_y$	$N_z$	$\Delta_x$	$\Delta_y$	$\text{Lon}_0$	$\text{Lat}_0$
HiGEM	288	217	38	1.25°	0.833°	–	–
Global	640	481	50	0.5625°	0.375°	–	–
12 km LAM	146	182	38	0.11°	0.11°	–7.05°	–8.41°
4 km LAM	1110	776	38	0.036°	0.036°	–6.5°	–6.5°

in supercomputing power have enabled the development of global climate models with higher resolution, which may lead to an improved representation of regional climate (e.g. Shaffrey *et al.*, 2009; Jung *et al.*, 2012). In particular, higher resolution has allowed global climate models to represent better some of the processes associated with extreme precipitation, such as the structure of extratropical cyclones (Catto *et al.*, 2010). A second issue is that the evaluation of climate models has primarily focused on the assessment of the statistical characteristics of precipitation, without examining the representation of phenomena contributing to the precipitation. However, novel techniques are being adopted to evaluate climate models, for example initializing climate models as weather forecast models. This technique has been used to study the error growth of Southern Ocean biases as part of the Transpose-Atmospheric Model Intercomparison Project (AMIP) experiments (Williams *et al.*, 2013) and the representation of extreme precipitation events over the USA (Weller *et al.*, 2013). Both approaches will be adopted here: a case study comparing a forecast using a climate model with a suite of higher-resolution models and the statistics of regional precipitation in a multidecadal simulation.

The case study will focus on an extreme precipitation event during the summer of 2007, which is the second wettest on record for England and Wales (exceeded only by 2012). Intense rainfall events were associated with a series of extratropical cyclones. South Yorkshire and Hull in Northern England and Gloucestershire and Worcestershire in Southern England were particularly badly affected, with widespread flooding. Nationally, the effects were described as the ‘biggest civil emergency in British history’ and led to the Government commissioning of a thorough assessment of preparedness in the form of the Pitt Review (Pitt, 2008). The regional and synoptic meteorological conditions are described by Blackburn *et al.* (2008) and Grahame and Davies (2008). The extreme monthly rainfall total was not confined solely to the UK, but extended across most of northern and western Europe during June and July. This wide extent suggests the involvement of large-scale processes in the atmosphere. The area around Tewkesbury was among those areas worst hit by flooding. Heavy rainfall on 20 July, following two months of above average precipitation, led to extensive flooding, with the rivers Severn and Avon overflowing their banks. Operational forecasting by the UK Met Office had allowed an early warning for heavy rain to be issued on 18 July, with some uncertainty in the exact location. Increasing confidence in the rain rates and location over the next 24 h led to an updated warning for disruption for the specific areas subsequently affected (Grahame and Davies, 2008).

We aim to test the ability of a climate model (High-Resolution Global Environmental Monitoring (HiGEM)) to simulate extreme precipitation events with potential for flooding by addressing three questions. First, using the 20 July 2007 storm as a case study, how well does the HiGEM model represent the structure of precipitation in a cyclone bringing prolonged, widespread precipitation? Second, in the same case study is the country-wide precipitation total sensitive to the model resolution? Finally, how well does a multidecadal free-running simulation with the model represent the probability distribution of precipitation? We tackle the first two questions by comparing the model results from the climate model run in forecast mode with numerical weather prediction (NWP) models

run at a range of resolutions and with rain-gauge data. We study the final question by comparing rainfall statistics from the free-running HiGEM climate model with analysis data and the historical rain-gauge record.

## 2. Model and simulations

For the case study in section 3, the Met Office Unified Model version 6.1 was run in four configurations: three NWP forms and the HiGEM global climate model (Shaffrey *et al.*, 2009). The NWP models were run as a global model plus 12 and 4 km resolution limited-area models (LAMs). At the latitude of the UK, the global and HiGEM resolutions correspond approximately to 40 and 90 km, respectively. As such, the models range over an order of magnitude in resolution. The 12 and 4 km LAMs were nested inside and took their lateral boundary conditions from the global and 12 km models respectively. All three NWP models were run from initial conditions generated by the operational system at 0900 and 1200 UTC on 19 July and are subsequently referred to as ‘IC09’ and ‘IC12’ model runs. The HiGEM run was only initialized from the 1200 UTC set of initial conditions. The LAM domains used a rotated coordinate system, with the North Pole at (178°E, 38°N) for the 12 km models and at (177.5°E, 37.5°N) for the 4 km runs. The details of the domains are summarized in Table 1.

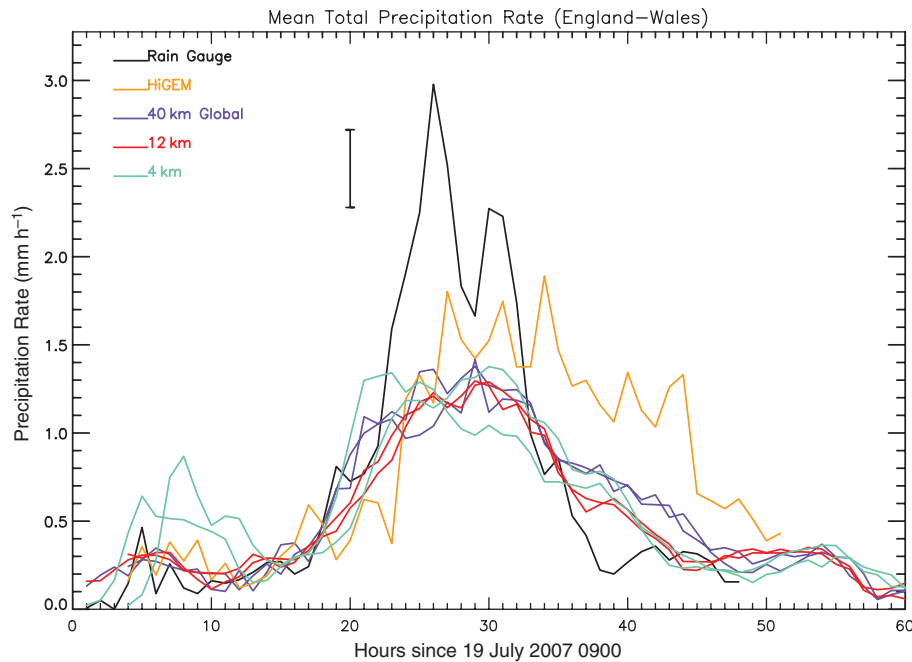
The Unified Model (Davies *et al.*, 2005) uses non-hydrostatic dynamical equations solved using a semi-implicit, semi-Lagrangian numerical scheme. Various subgrid-scale processes are parametrized, including those of subsurface and surface fluxes (Essery *et al.*, 2001), the boundary layer (Lock *et al.*, 2000) and mixed-phase cloud microphysics (Wilson and Ballard, 1999). The global model and 12 km LAM use a mass-flux convective parametrization scheme with convective available potential energy closure (Gregory and Rowntree, 1990). This is modified and tuned in the 4 km LAM, such that convection is mostly represented explicitly (Lean *et al.*, 2008). Typically, this results in less than 2% of the rainfall being generated by the convection scheme.

For the analysis of precipitation statistics in section 4, data were taken from a 51 year free-running simulation using the HiGEM model (Shaffrey *et al.*, 2009).

## 3. Case study of a summer cyclone

A depression moved slowly northward from France on 19 July 2007 and by midday on 20 July was centred over southeast England. The main occluded front extended eastward from the centre and a complicating cold front ran away from the centre to the northwest (see figure 2 of Prior and Beswick, 2008). Warm moist air was being fed into southeast England from France at 0000 UTC on 20 July, rotating to feed into central England from the east by 1200 (see figure 10 of Blackburn *et al.*, 2008). The system continued to move slowly northwards over the course of the next day, with the rain band weakening and rotating to lie eventually on an approximately north–south alignment. The most intense rainfalls were associated with localized convective updraughts embedded in these fronts.

The mean rainfall rate for England–Wales from the HiGEM and NWP model runs is shown in Figure 1. The contributing grid cells were those in the region (4.5°W–0.7°E, 50.6°–54.5°N),



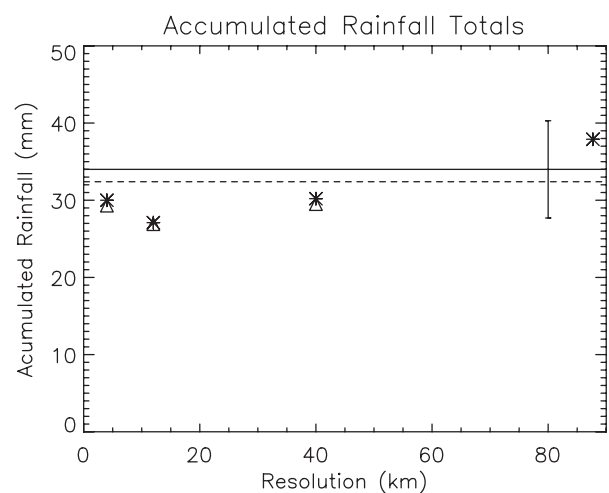
**Figure 1.** Hourly-mean precipitation rate averaged over a box representing England–Wales ( $4.5^{\circ}\text{W}$ – $0.7^{\circ}\text{E}$ ,  $50.6^{\circ}$ – $54.5^{\circ}\text{N}$ ), comparing model simulations with a rain-gauge estimate. Both the model runs are plotted for the global, 12 and 4 km NWP configurations using initial conditions at 0900 and 1200 UTC on 19 July 2007. The mean uncertainty estimated for the rain-gauge observations on 20 July 2007 is indicated by the bar.

**Table 2.** Accumulated mean rainfall values between 0900 on the day listed and 0900 on the following day for the various models and the rain-gauge datasets. Note that the ‘IC12’ models begin at 1200 on 19 July. *N* is the number of contributing data points: either grid boxes or rain-gauges as appropriate.

Data source	<i>N</i>	19 Jul (mm)	20 Jul (mm)	Total (mm)
HiGEM IC12	20	7.9	30.0	37.9
40 km Global IC09	99	9.9	19.6	29.5
40 km Global IC12	99	9.5	20.7	30.2
12 km LAM IC09	1035	9.0	17.9	26.9
12 km LAM IC12	1035	8.8	18.3	27.1
4 km LAM IC09	9518	12.8	16.5	29.3
4 km LAM IC12	9518	10.6	19.4	30.0
Rain gauges	63	10.1	23.9	34.0
EWP value	–	11.5	20.9	32.4

with a total area of  $151439 \text{ km}^2$ , as used by de Leeuw *et al.* (2014) to evaluate precipitation in ERA-Interim against the England–Wales Precipitation (EWP) record. Also plotted for comparison is the mean value from the rain-gauges in the Met Office Integrated Data Archive System (MIDAS) database (UK Meteorological Office, 2012) that lie within this region. We should bear in mind that these hourly gauge values have not been through the same quality control, scaling and regional weighting process that is used to calculate the climate record EWP values of Alexander and Jones (2001). The EWP methodology combines the available rain-gauges across the network in order to obtain reliable and robust area-average values for this region. However, the EWP time series is available for daily accumulations only. The MIDAS rain-gauges are well-distributed geographically but irregularly spaced and are also point observations. Error estimates for the MIDAS data at each time have been generated using a bootstrap method and the mean error over the 24 h of 20 July is indicated on the figure. A sense of the variability inherent in the model can be gained from the differences between the curves at a given resolution run from the two different initial conditions. The uncertainty from the two data sources is fundamentally different, with the rain-gauges susceptible to very small-scale variations that are not resolved by the area-average values from the models.

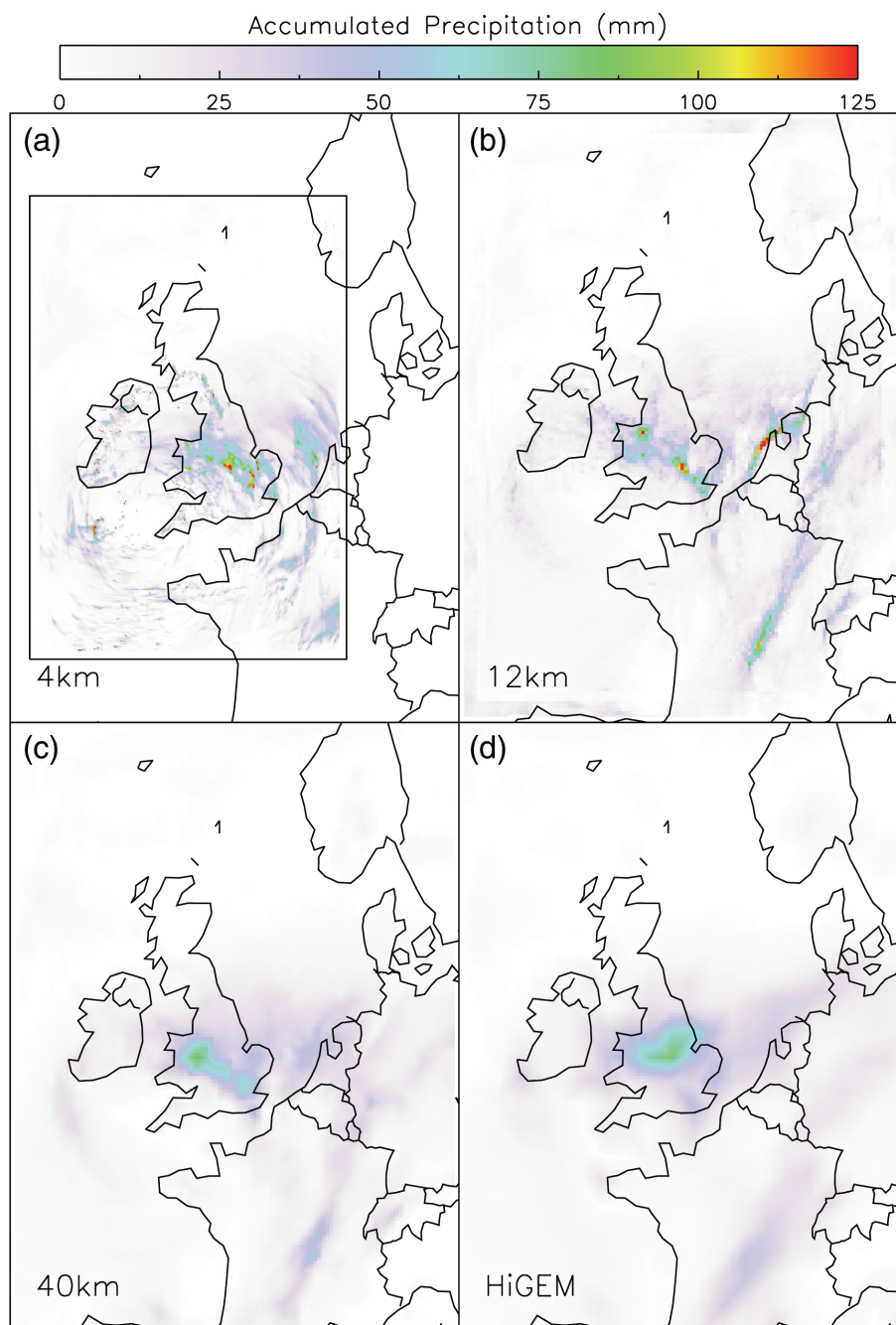
The mean of the rain-gauges has a higher peak intensity than all of the models, although the timing of the peak agrees well



**Figure 2.** Comparison of the total accumulated precipitation in the simulations from 1200 on 19 July to 0900 on 21 July. Triangles denote the IC09 model runs and asterisks the IC12 runs. The horizontal lines indicate the values derived directly from the rain-gauge observations (solid with error bar) and the daily EWP record (dashed).

with that of the NWP models. The six NWP simulations, when averaged over the region, are rather insensitive to resolution. However, the different initialization times have less influence on precipitation rate than the model resolution. In this case, regional average precipitation is obviously robust to small variations in initial conditions at a lead time of 1 day. The HiGEM run has a slightly higher peak intensity than the other models and declines noticeably more slowly than they do. All of the models decline more slowly than the observations.

Values for the daily accumulated rainfall are given in Table 2. All of the models but one underestimate the amount of precipitation relative to the observed EWP value on 19 July. The NWP values are in reasonable agreement with the measured value on 20 July, whereas the HiGEM run overestimates the amount on this day noticeably. Overall, however, considering the two-day precipitation total, the size of the overestimate by the HiGEM model (17%) is the same as the underestimate made by the 12 km LAM. The mean underestimate of all the NWP models combined for the two-day precipitation total is 11%. The total rainfall



**Figure 3.** Comparison of the accumulated precipitation of the four 'IC12' simulations from 1200 on 19 July to 0900 on 21 July: (a) 4 km LAM, (b) 12 km LAM, (c) global NWP and (d) HiGEM. The global NWP and HiGEM model data have been interpolated on to the 12 km LAM grid.

values are presented graphically in Figure 2. The robustness of the accumulated precipitation at a given resolution is apparent, as is the relative insensitivity to model resolution.

The accumulated precipitation maps for the four IC12 simulations over the two-day period are shown in Figure 3. All three NWP models show a similar northwest–southeast alignment over England and Wales. However, this is displaced slightly to the northeast of the two-day observed precipitation maps in figure 8 of Prior and Beswick (2008). This may reflect an error in timing in either or both of the movement of the rain band or the maximum precipitation. The later timing of maximum precipitation in the HiGEM model is reflected in the accumulated rain region lying closer to east–west as the rain band begins to rotate anti-clockwise. This behaviour is shown with greater clarity in maps of the accumulated model precipitation plotted with the equivalent rain-gauge data for the global and HiGEM models in Figure 4.

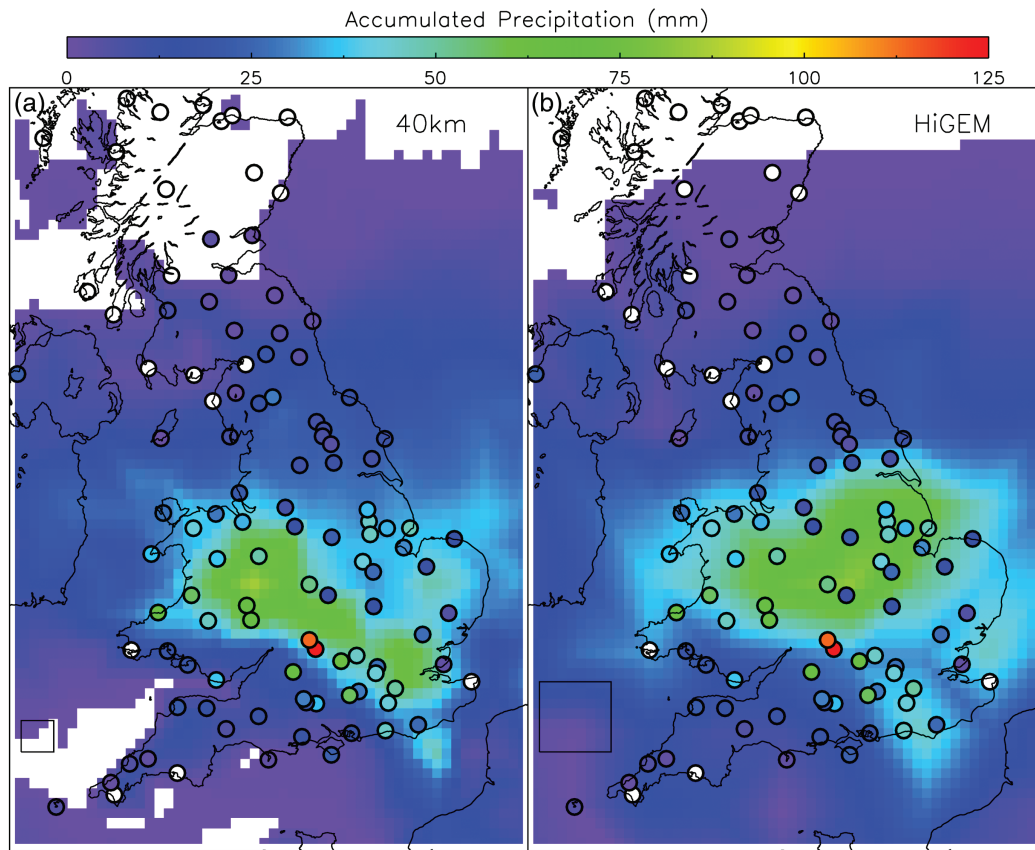
All of the models misplace their maximum accumulated precipitation compared with observations. The two rain-gauges with greatest accumulated precipitation in Figure 4, for

example, occur in the region of the Upper Thames and Avon catchments, with implications for the severe flooding affecting Tewkesbury. However, the region of peak accumulation in the global model simulation occurs significantly to the northwest. Improved resolution, while providing more realistic-looking rainfall patterns, does not necessarily imply an improved point forecast by a given simulation in general nor improved locations for the extremes specifically (e.g. the positions of the maxima for the 4 and 12 km models in Figure 3), due to the predictability time-scale being much shorter at smaller length-scales (Lorentz, 1969; Mittermaier *et al.*, 2013).

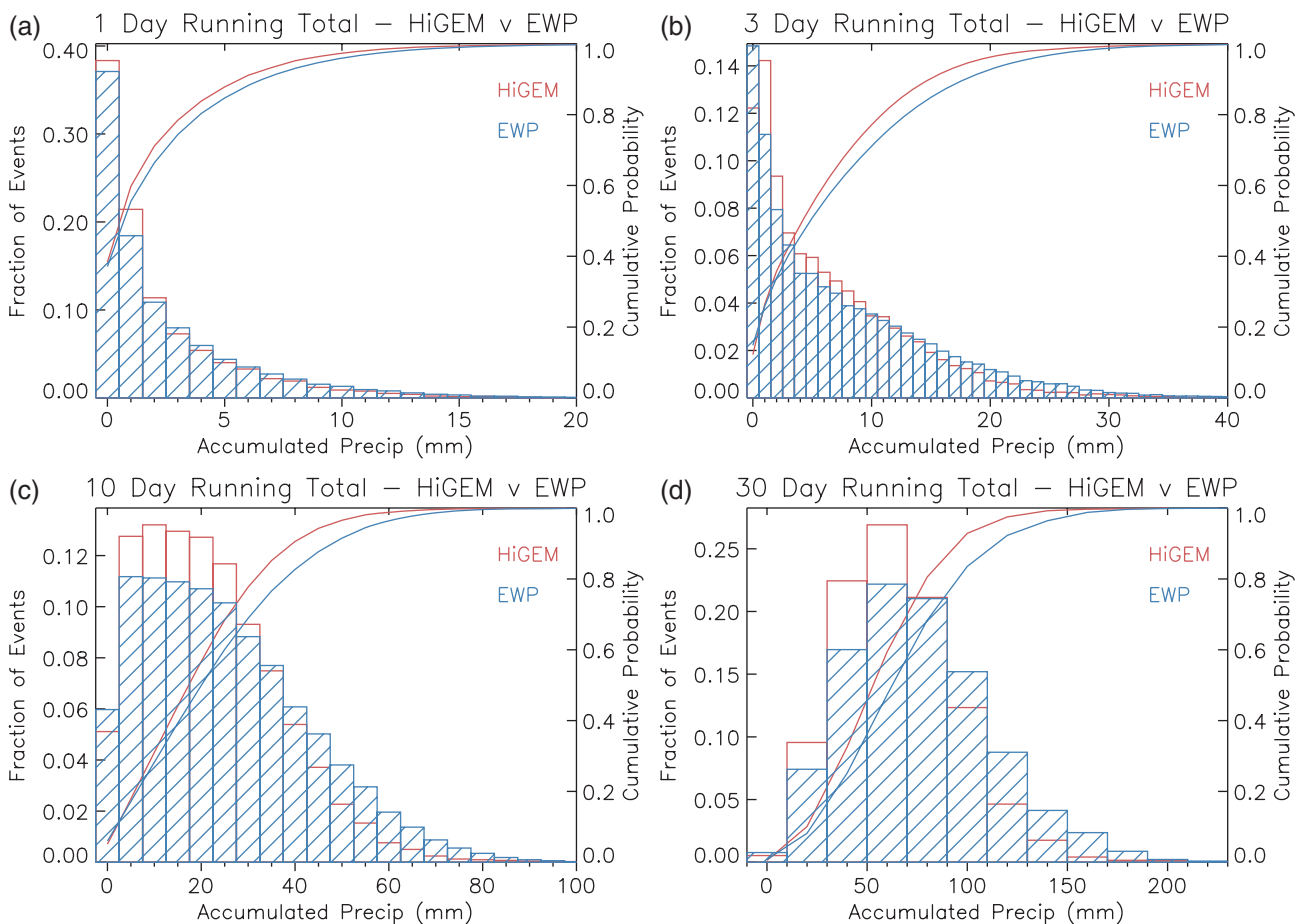
Overall, the case study illustrates that, on the scale of England and Wales, the daily accumulation of precipitation can be insensitive to model resolution and to small differences in initial conditions (or lead times).

#### 4. Statistics of rainfall distribution

The rainfall in the case study was associated with a slow-moving cyclone. Hawcroft *et al.* (2012) have shown that up



**Figure 4.** Comparison of the MIDAS rain-gauges with the accumulated (a) global and (b) HiGEM model precipitation from 1200 on 19 July to 0900 on 21 July. The model data have been interpolated on to the 12 km LAM grid and the size of the original grid boxes is indicated.



**Figure 5.** Comparison of the frequency distribution of the total precipitation for several accumulation lengths in the 80 year EWP record (blue) with an equivalent region from 31 years of HiGEM data (red). The accumulation periods are based on daily amounts aggregated over (a) 1, (b) 3, (c) 10 and (d) 30 days. The bin sizes are 1, 1, 5 and 20 mm, respectively. The curves shown are the cumulative frequency distributions.

Table 3. Mean annual and seasonal precipitation totals (in mm) from 31 years of HiGEM data and the 1931–2011 England–Wales record. Also shown for comparison is the fraction of the record over the period 1979–2011 generated by the ERA-Interim forecasts (from de Leeuw *et al.*, 2014) and that from GPCP over the period 1997–2011.

Data source	Annual	DJF	MAM	JJA	SON
EWP	925	252	190	214	269
HiGEM	773	223	175	154	221
	83.5%	88.3%	92.3%	71.7%	82.0%
ECMWF	82.1%	82.0%	87.9%	84.1%	79.4%
GPCP	104.2%	113.9%	103.1%	98.7%	100.8%

to 70% of the precipitation in this region is associated with the passage of extratropical cyclones. However, other phenomena, such as convective showers, are likely to be more sensitive to resolution. In this section, the statistics of precipitation in a multidecadal simulation using HiGEM are compared with rain-gauge observations as represented by the EWP time series. This addresses the ability of the climate model to represent the variability of regional precipitation.

Statistical distributions of daily precipitation accumulations from the last 31 years of the 51 year HiGEM run and for 80 years of observed EWP data (1931–2011) are plotted in Figure 5. This analysis uses the same region to represent the England–Wales domain as defined earlier. The probability density function for daily accumulations in HiGEM is similar to the observations, indicating that it is capable of simulating regionally aggregated precipitation across the full range of intensities. The cumulative distribution curves, however, highlight the tendency for the model to underestimate the number of days with heavy precipitation.

The degree of underestimation exhibited by the HiGEM model increases with longer accumulation periods, demonstrated by the increasing difference between the cumulative frequency curves. The appropriate formal test for equivalence of the two distributions in each case is a Kolmogorov–Smirnov test on the underlying unbinned data. This is based on the maximum distance between the cumulative frequency curves,  $D$  (range 0–1). The degree of disagreement increases with accumulation time with  $D = 0.061, 0.062, 0.090$  and  $0.137$  for 1, 3, 10 and 30 day accumulations, respectively. This may result from a relative lack of persistence or clustering of successive storms relative to reality. Alternatively, the model may be misplacing storm tracks so that the storms tend to miss the UK, although the results of Catto (2009) suggest that, if anything, the opposite is the case. As a result, the model will tend to under-represent the conditions where pluvial flooding occurs as a result of rain occurring over previously saturated ground conditions.

The mean total rainfall from these datasets is given in Table 3 on an annual and seasonal basis. The model results have been corrected by a factor to account for the true number of calendar days in each period. The underestimate in the mean annual accumulation by HiGEM relative to the EWP record is 16.5%, comparable to 17.9% in the ERA-Interim dataset (de Leeuw *et al.*, 2014). In this context, we note that our case study is somewhat atypical in that HiGEM overestimated the accumulated precipitation for a summer event relative to EWP.

From the seasonal figures in Table 3, the relative strength of the model in representing precipitation in winter over summer is apparent. This results from the origin of precipitation in winter tending more towards synoptic storms rather than convective events, which are less well represented at this resolution. For three out of four seasons, however, the HiGEM model reproduces a larger fraction of the observed EWP precipitation than the ERA-Interim forecasts did when compared over the period 1979–2011 by de Leeuw *et al.* (2014). Also included are values from the Global Precipitation Climatology Project (GPCP: Huffman *et al.*, 2001) expressed relative to the matched EWP data over the period 1997–2011. This is an observational

record, blending both satellite and rain-gauge data. The GPCP accumulated precipitation totals are similar to the EWP values, with the notable exception of the winter season.

## 5. Summary

Returning to the first of our three questions, the HiGEM climate model simulated a cyclone with intense regional precipitation in our case study, but errors in timing meant that the spatial distribution of the precipitation was not in as good agreement with observations as the NWP simulations. When the two-day accumulated precipitation from the storm is averaged at the national scale, HiGEM overestimates the EWP values by 17%, compared with a mean underestimate from all the NWP models combined of 11%.

Regarding the second question, the area-average precipitation in the case study was robust to the change in initial conditions between the two simulations at a given resolution. It was also relatively insensitive to the resolution of the model used.

Considering the final question, the accumulated England–Wales precipitation statistics for the HiGEM model are close to the observed distribution at the daily time-scale, but the difference increases with increasing accumulation periods, as the free-running model produces relatively few high-rainfall events compared with reality. This implies that, while the model is capable of reproducing individual events such as those in the case study, it will tend to underestimate instances of pluvial flooding resulting from extended periods of rain. This may result from a lack of low-frequency variability associated with weather regime persistence. On an annual mean basis, the model underpredicts the EWP value by 16.5%, comparable with the underestimate in the ERA-Interim reanalysis of 17.9%.

This article has focused on the UK region, due to the long, statistically homogeneous EWP dataset for model evaluation. However, to have confidence in the global projections from HiGEM, further work is needed to evaluate the performance over an expanded set of representative regions.

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