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

Can a Climate Model Reproduce Extreme Regional Precipitation Events over England and Wales?

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The ability of the HiGEM climate model to represent high-impact, regional, precipitation events is investigated in two ways. The first focusses on a case study of extreme regional accumulation of precipitation during the passage of a summer extra-tropical 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 90km to 4km.

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 multi-day 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. Copyright © 2014 Royal Meteorological Society

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 in supercomputing power have enabled the development of global climate models with higher resolutions 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 better represent 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 initialising 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-AMIP experiments (Williams *et al.* 2013) and the representation of extreme precipitation events over the U.S.A. (Weller *et al.* 2013). Both approaches will be adopted here: a case study comparing a forecast using a climate model with a suite of higer-resolution models and the statistics of regional precipitation in a multi-decadal 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 extra-tropical 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, Methven and Roberts (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 the 18th with some uncertainty in the exact location. Increasing confidence in the rain rates and location over the next 24 hours 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 (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 multi-decadal 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 to Numerical Weather Prediction models run at a range of resolutions and to rain gauge data. We study the final question by comparing rainfall statistics from the free-running HiGEM climate model to 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 numerical weather prediction (NWP) forms and the HiGEM global climate model (Shaffrey *et al.* 2009). The NWP models were run as a global model plus 12 km and 4 km resolution limited area models (LAMs). At the latitude of the UK, the global and HiGEM resolutions correspond approximately to 40 km and 90 km respectively. As such the models range over an order of magnitude in resolution. The 12 km 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 UTC and 1200 UTC on the 19th July, and are subsequently referred to as 'IC09' and 'IC12' model runs. The HiGEM run was only initialised 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 summarised in Table I.

The Unified Model (Davies *et al.* 2005) uses non-hydrostatic dynamical equations solved using a semi-implicit, semi-Lagrangian numerical scheme. Various sub-gridscale processes are parametrized including those of sub-surface 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 was 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 the 19 July 2007 and by midday on the 20th was centred over south-east England. The main occluded front extended eastward from the centre and a complicating cold front ran away from the centre to the north-west (see Fig. 2 of Prior and Beswick 2008). Warm moist air was being fed into south-east England from France at 0000 UTC on the

Model	N_x	N_y	N_z	Δ_x	Δ_y	Lon_0	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°

Table I. 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 Lon_0 and Lat_0 are the coordinates of the lower left corner in the rotated system.

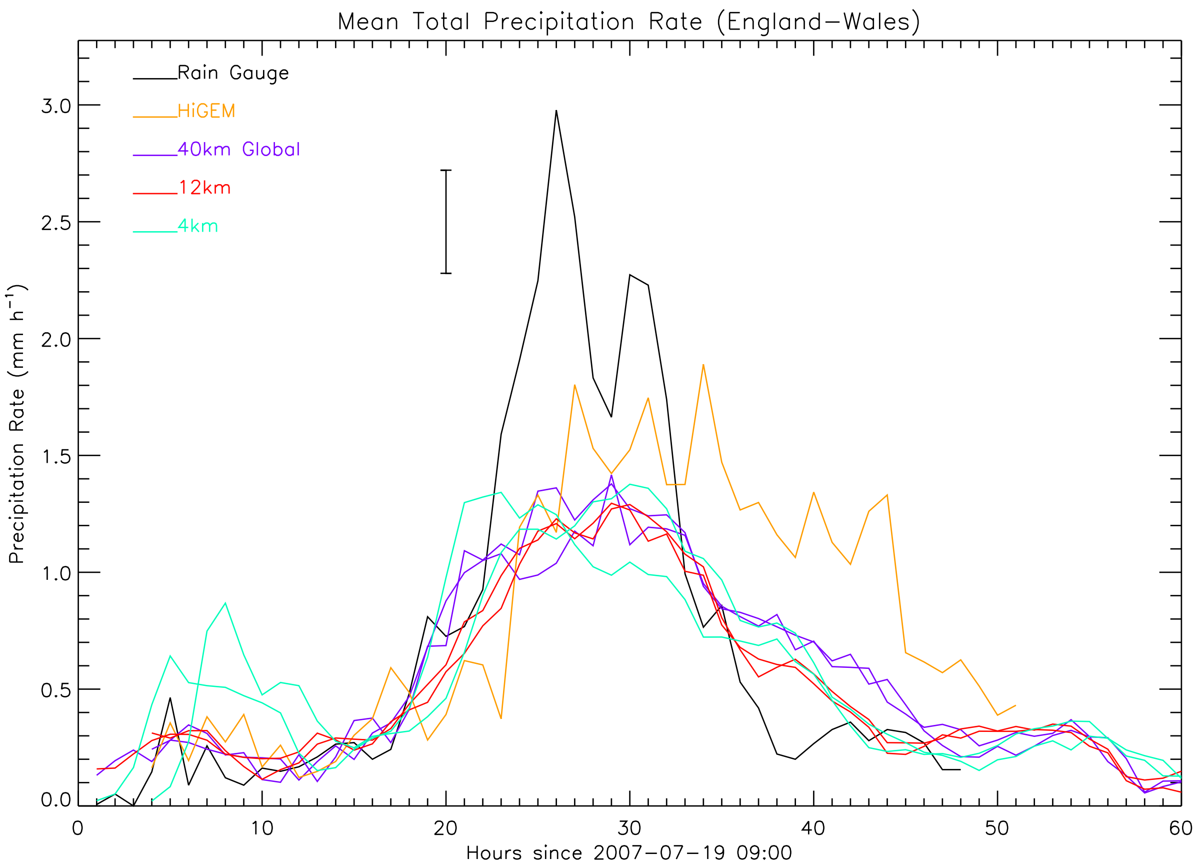

Figure 1. Hourly-mean precipitation rate averaged over a box representing England-Wales ($4.5°$W–$0.7°$E, $50.6°$–$54.5°$N) comparing model simulations with a rain gauge estimate. Both the model runs are plotted for the Global, 12 km and 4 km NWP configurations that used initial conditions at 0900 and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

20$^{\text{th}}$ rotating to feed into central England from the east by 1200 (see Fig. 10 of Blackburn, Methven and Roberts 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 localised convective updrafts embedded in these fronts.

The mean rainfall rate for England-Wales from the HiGEM and NWP model runs are shown in Figure 1. The contributing grid cells were those in the region ($4.5°$W–$0.7°$E, $50.6°$–$54.5°$N) with a total area of $151,129\ \mathrm{km}^2$, 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 boostrap method and the mean error over the 24 hours of the 20$^{\text{th}}$ 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

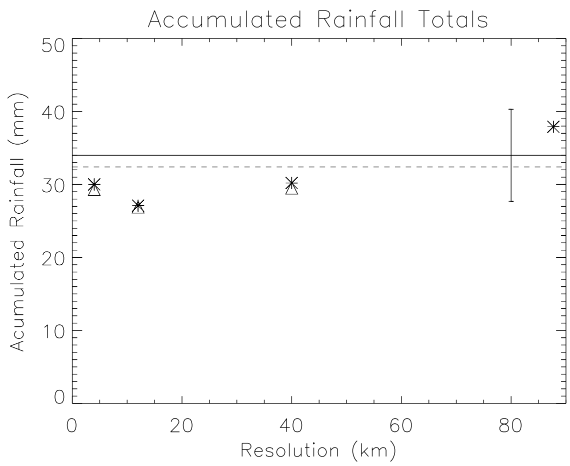

Figure 2. Comparison of the total accumulated precipitation in the simulations from 1200 on the 19th until 0900 on 21st. Triangles denote the IC09 model runs and asterisks the IC12 runs. The horizontal lines indicate the values derived directly from the rain gauge observations (solid with error bar)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

the rain gauges susceptable 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 with that of the NWP models. The six NWP simulations, when averaged over the region, are rather insensitive to resolution. However, the different initialisation 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 II. All of the models but one underestimate the amount of precipitation relative to the observed EWP value on the 19th. The NWP values are in reasonable agreement with the measured value on the 20th whereas the HiGEM run noticeably overestimates the amount on this day. Overall, however, considering the 2-day precipitation total, the size of the overestimate by the HiGEM model (17%) is the same as the *under*estimate made by the 12 km LAM. The mean underestimate of all the NWP models combined for the 2-day precipitation total is 11%. The total rainfall 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 NW-SE alignment over England and Wales. However, this is displaced slightly to the NE of the 2-day observed precipitation maps in Fig. 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 E-W 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 mis-place their maximum accumulated precipitation compared to 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 (eg. the positions of the maxima for the 4 km and 12 km models in Figure 3) due to the predictability timescale being much shorter at smaller length scales (Mittermaier *et al.* 2013; Lorentz 1969).

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 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 multi-decadal simulation using HiGEM are compared with rain gauge observations as represented by the EWP timeseries. 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 functions 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 underestimate exhibited by the HiGEM model increases with longer accumulation periods, demonstrated by the increasing difference in the cumulative frequency curves. The appropriate formal test for equivalence of the two distributions in each case is a Kolmogrov-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. The model may alternatively be mis-placing 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

Data source	N	19^{th} (mm)	20^{th} (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

Table II. Accumulated mean rainfall values between 0900 on the day listed to 0900 the following day for the various models and the rain gauge datasets. nb. The 'IC12' models begin at 1200 on the 19^{th}. N is the number of contributing data points: either grid boxes or rain gauges as appropriate.

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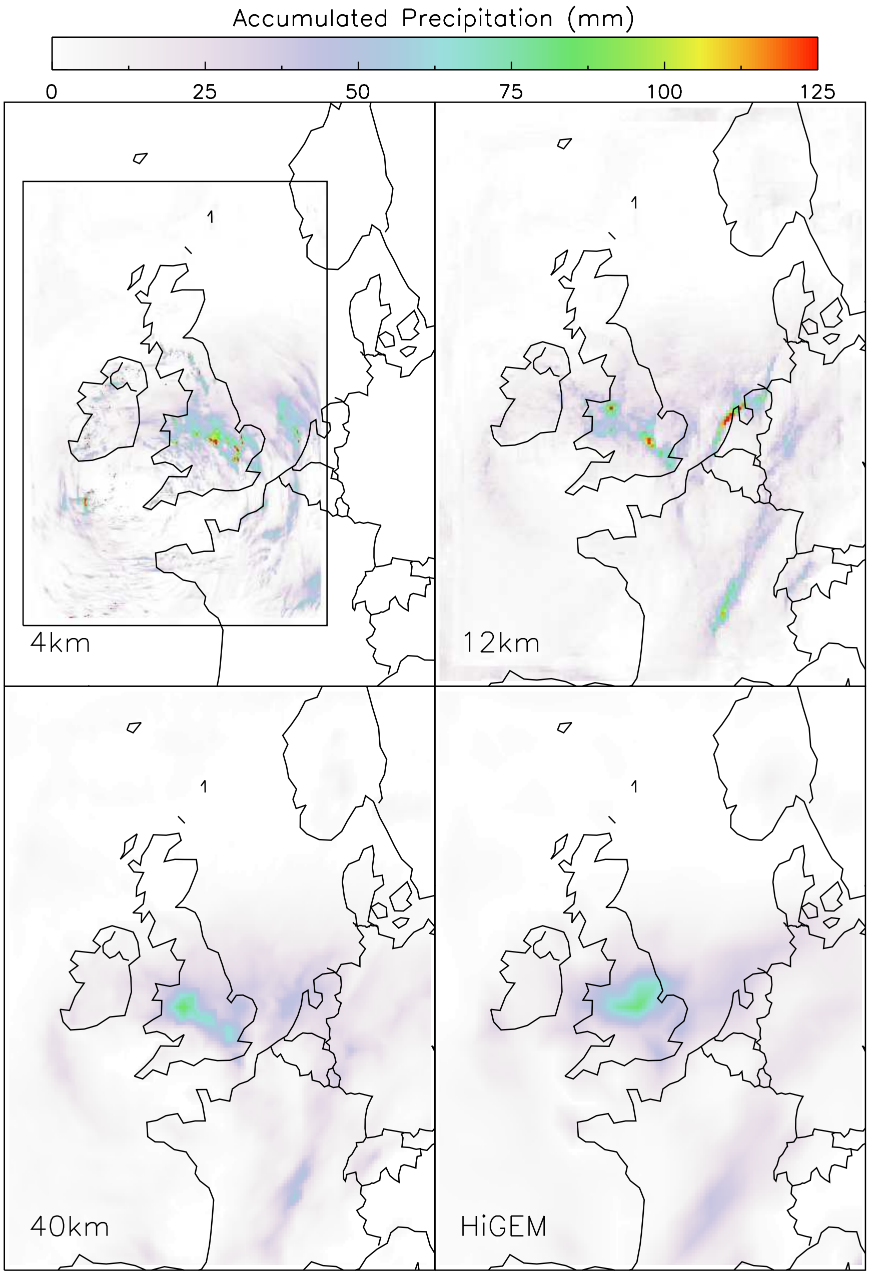

Figure 3. Comparison of the accumulated precipitation of the four 'IC12' simulations from 1200 on the 19^{th} until 0900 on 21^{st}: 4 km LAM (top left), 12 km LAM (top right), Global NWP (bottom left) and HiGEM (bottom right). The global NWP and HiGEM model data have been interpolated onto the 12 km LAM grid.

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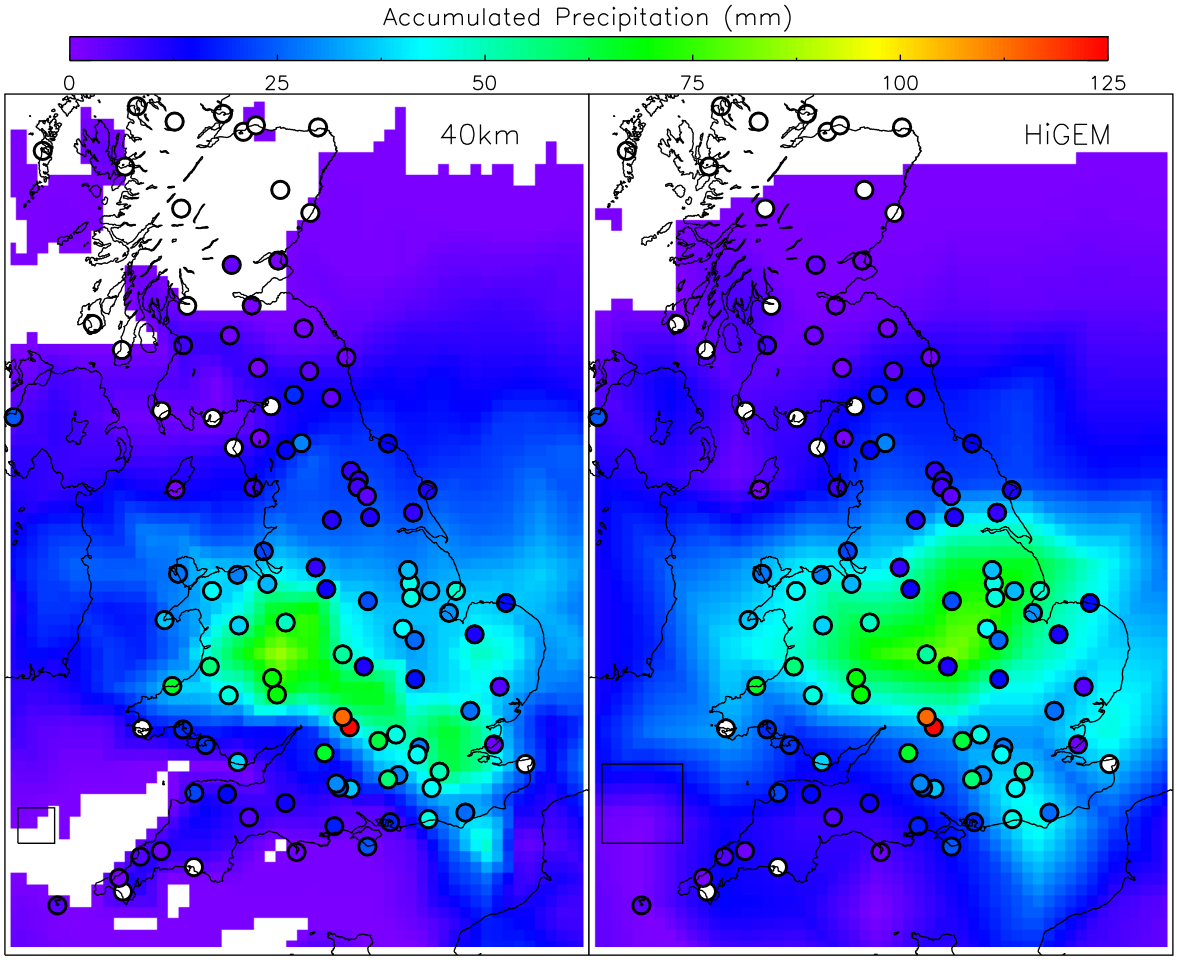

Figure 4. Comparison of the MIDAS rain gauges to the accumulated global (left) and HiGEM (right) model precipitation from 1200 on 19th to 0900 on 21st. The model data have been interpolated onto the 12 km LAM grid and the size of the original gridboxes is indicated.

flooding occurs as a result of rain occurring over previously saturated ground-conditions.

The mean total rainfall from these datasets are given in Table III 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 the 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 III, 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 that 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 2-day accumulated precipitation from the storm is averaged at the national scale, HiGEM overestimates the EWP values by 17% compared to 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 the 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 timescale but the difference increases with increasing accumulation periods as the free-running model produces relatively few high rainfall events compared to reality. This implies that, while the model is capable of reproducing individual events such as those in the case study, it will

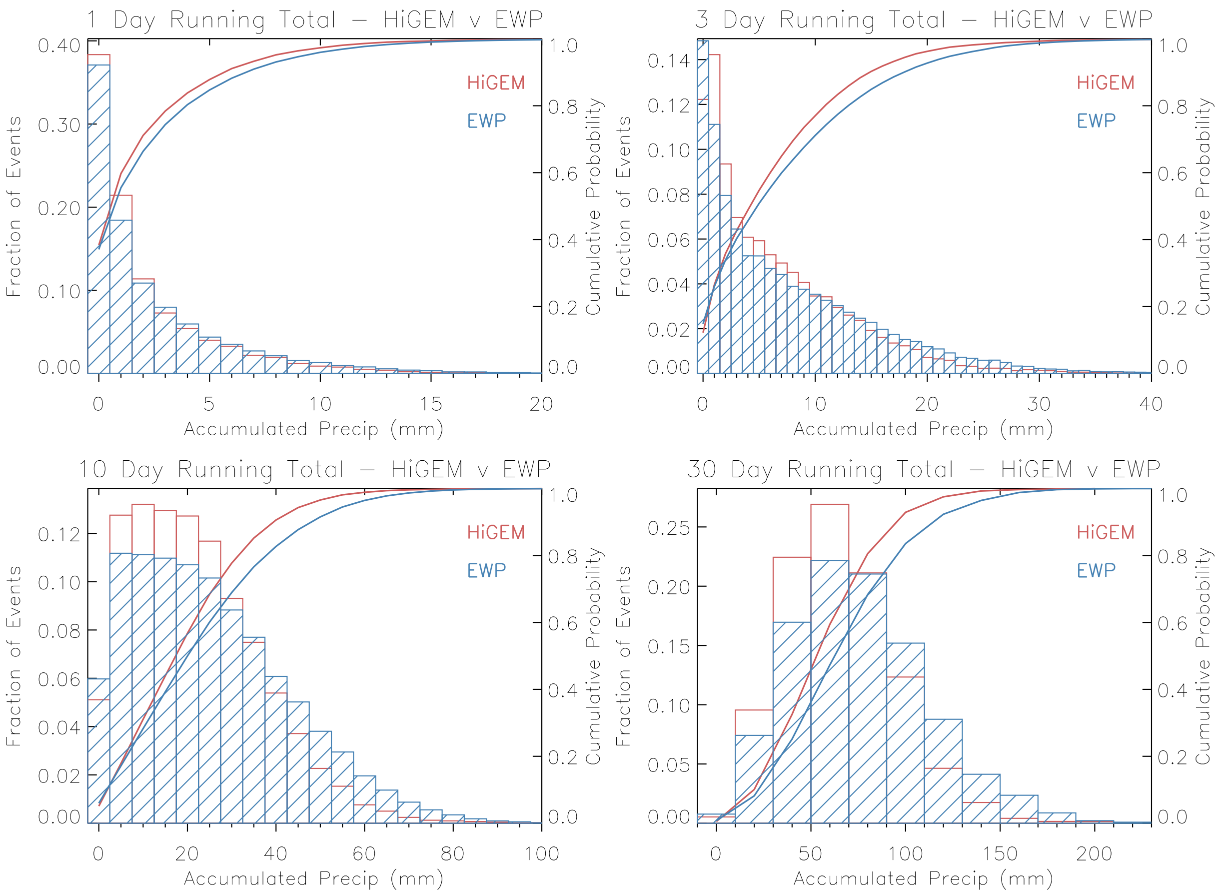

Figure 5. Comparison of the frequency distribution of the total precipitation for several accumulation lengths in the 80-year EWP record (blue) with an equivalent region from 31 years of HiGEM data (red). The accumulation periods are based on daily amounts aggregated over 1 (top left), 3 (top right),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

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%

Table III. 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.

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 under-predicts the EWP value by 16.5% comparable to the underestimate in the ERA-Interim reanalysis of 17.9%.

This paper 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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References

Alexander L.V., Jones P.D. 2001. Updated precipitation series for the U.K. and discussion of recent extremes. *Atmos. Sci. Lett.* **1**: 142–150.

Allan R.P., Soden B.J. 2008. Atmospheric warming and the amplification of precipitation extremes. *Science*. **321(5895)**: 1481-1484. ISSN 1095-9203, doi:10.1126/science.1160787

Allen M.R., Ingram W.J. 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature.* **419**: 224–232.

Blackburn M., Methven J., Roberts N. 2008. Large-scale context for the UK floods in summer 2007. *Weather.* **63**: 280-288.

Catto J.L. 2009. Ph.D. Thesis. Extra-tropical cyclones in HiGEM: climatology, structure and future predictions. University of Reading.

Catto J.L., Shaffrey L.C., Hodges, K.I. 2010. Can climate models capture the structure of extratropical cyclones? *J. Clim.* **23(7)**: 1621–1635. ISSN 1520-0442.

Chan S.C., Kendon E.J., Fowler H.J., Blenkinsop S., Ferro C.A.T., Stephenson D.B. 2013. Does increasing the spatial resolution of a regional climate model improve the simulated daily precipitation? *Clim. Dyn.* **41**: 1475–1495

Davies T., Cullen M.J.P., Malcolm A.J., Mawson M.H., Staniforth A., White A.A., Wood N. 2005. A new dynamical core for the Met Office's global and regional modelling of the atmosphere. *Q. J. R. Meteorol. Soc.* **131**: 1759–1782.

Essery R., Best M., Cox P. 2001. MOSES 2.2 Tech. Doc. Hadley Centre Tech. Rep. 30, Met. Office Hadley Centre.

Fowler H.J., Ekström M., Kilsby C.G., Jones P.D. 2005. New estimates of future changes in extreme rainfall across the UK using regional climate model integrations. 1. Assessment of control climate. *J. Hydrol.* **300**: 212-233.

Fowler H.J., Ekström M. 2009. Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *Int. J. Climatol.* **21.11**: 1337–1356.

Grahame N., Davies M. 2008. Forecasting the exceptional rainfall events of summer 2007 and communication of key messages to Met Office customers. *Weather.* **63**: 268-273.

Gregory D., Rowntree P.R. 1990. A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure. *Mon. Wea. Rev.* **118**: 1483–1506.

Hawcroft M.K., Shaffrey L.C., Hodges K.I., Dacre H.F. 2012. How much Northern Hemisphere precipitation is associated with extratropical cyclones? *Geophys. Res. Lett.* **39**: L24809.

Huffman G.J., Adler R.F., Morrissey M., Bolvin D.T., Curtis S., Joyce R., McGavock B., Susskind J. 2001. Global Precipitation at One-Degree Daily Resolution from Multi-Satellite Observations. *J. Hydrometeor.* **2**: 36-50.

Kendon E.J., Robers N.M., Senior C.A., Roberts M.J. 2012. Realism of Rainfall in a Very High-Resolution Regional Climate Model. *J. Clim.* **25**: 5791–5806

Jones P.D., Reid P.A. 2001. Assessing future changes in extreme precipitation over Britain using regional climate model integrations. *Int. J. Climatol.* **21.11**: 1337–1356.

Jung T., Miller M.J., Palmer T.N., Towers P., Wedi N., Achuthavarier D., Adams J.D., Altshuler E.L., Cash B.A., Kinter III J.L., Marx L., Stan C., Hodges K.I. 2012. High-resolution global climate simulations with the ECMWF model in Project Athena: Experimental design, model climate and seasonal forecast skill. *J. Clim.* **25**: 3155–3172. doi:10.1175/JCLI-D-11-00265.1

de Leeuw J., Methven J., Blackburn M. 2014. Evaluation of ERA-Interim reanalysis precipitation products using England and Wales observations. *Q. J. R. Meteorol. Soc.* doi:10.1002/qj.2395.

Lean H.W., Clark P.A., Dixon M., Roberts N.M., Fitch A., Forbes R., Halliwell C. 2008. Characteristics of high-resolution versions of the Met Office Unified Model for forecasting convection over the United Kingdom, *Mon. Wea. Rev.* **136**: 3408–3434.

Lock A.P., Brown A.R., Bush M.R., Martin G.M., Smith R.N.B. 2000. A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests, *Mon. Wea. Rev.* **128**: 3187–3199.

Lorentz E.N. 1969. Atmospheric Predictability as Revealed by Naturally Occurring Analogues, *J. Atmos. Sci.* **26**: 636–646.

Mittermaier M., Roberts N., Thompson S.A. 2013. A long-term assessment of precipitation forecast skill using the Fractions Skill Score, *Meteorol. Appl.* **20**: 176–186.

Pall P., Allen M.R., Stone D.A. 2007. Testing the Clausius-Clapeyron constraint on changes in extreme precipitation under CO_2 warming. *Clim. Dyn.* **28**: 351–363.

Pitt M. 2008. Learning lessons from the 2007 floods. *The Pitt Review*. The Cabinet Office.

Prior J., Beswick M. 2008. The exceptional rainfall of 20 July 2007. *Weather.* **63**: 261–267.

Schindler A., Maraun D., Toreti A., Luterbacher J. 2012. Changes in the annual cycle of heavy precipitation across the British Isles within the 21st century. *Env. Res. Lett.* **7**: 044029.

Shaffrey L.C., Stevens I., Norton W.A., Roberts M.J., Vidale P.L., Harle J.D., Jrrar A., Stevens D.P., Woodage M.J., Demory M.E., Donners J., Clark D.B., Clayton A., Cole J.W., Wilson S.S., Connolley W.M., Davies T.M., Iwi A.M., Johns T.C., King J.C., New A.L., Slingo J.M., Slingo A., Steenman-Clark L., Martin G.M. 2009. U.K. HiGEM: The New U.K. High-Resolution Global Environment Model - Model Description and Basic Evaluation. *J. Clim.* **22**: 1861–1896.

Stocker T.F., Qin D., Plattner G.-K., Alexander L.V., Allen S.K., Bindoff N.L., Bron F.-M., Church J.A., Cubasch U., Emori S., Forster P., Friedlingstein P., Gillett N., Gregory J.M., Hartmann D.L., Jansen E., Kirtman B., Knutti R., Krishna Kumar K., Lemke P., Marotzke J., Masson-Delmotte V., Meehl G.A., Mokhov I.I., Piao S., Ramaswamy V., Randall D., Rhein M., Rojas M., Sabine C., Shindell D., Talley L.D., Vaughan D.G. and Xie S.-P., 2013: Technical Summary. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Trenberth K.E. 2011. Changes in precipitation with climate change. *Clim. Res.* **47**: 123-138.

UK Meteorological Office. 2012. Met Office Integrated Data Archive System (MIDAS) Land and Marine Surface Stations Data (1853-current), [Internet]. NCAS British Atmospheric Data Centre, Available from http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_ukmo-midas.

Weller G.B., Cooley D., Sain S.R., Bukovsky M.S., Mearns L.O. 2013. Two case studies on NARCCAP precipitation extremes. *J. Geophys. Res. Atmos.* **118**: 10475–10489. doi:10.1002/jgrd.50824.

Williams K.D., Bodas-Salcedo A., Déqué M., Fermepin S., Medeiros B., Watanabe M., Jakob C., Klein S.A., Senior C.A., Williamson D.L. 2013. The Transpose-AMIP II Experiment and Its Application to the Understanding of Southern Ocean Cloud Biases in Climate Models. *J. Clim.* **26**: 3258–3274. doi:10.1175/JCLI-D-12-00429.1

Wilson D.R., Ballard S.P. 1999. A microphysically based precipitation scheme for the UK Meteorological Office Unified Model, *Q. J. R. Meteorol. Soc.* **125**: 1607–1636.