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Discussions

Climate change increases the probability of heavy rains like those of storm Desmond in the UK – an event attribution study in near-real time

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Abstract

On 4–6 December 2015, the storm "Desmond" caused very heavy rainfall in northern England and Scotland, which led to widespread flooding. Here we provide an initial assessment of the influence of anthropogenic climate change on the likelihood of one-day precipitation events averaged over an area encompassing northern England and southern Scotland using data and methods available immediately after the event occurred. The analysis is based on three independent methods of extreme event attribution: historical observed trends, coupled climate model simulations and a large ensemble of regional model simulations. All three methods agree that the effect of climate change is positive, making precipitation events like this about 40 % more likely, with a provisional 2.5–97.5 % confidence interval of 5–80 %.

1   Introduction

Atlantic storm "Desmond" passed over Ireland, Scotland and northern England from early Friday, 4 December to early Sunday, 6 December, causing very heavy rainfall and gale-force winds. Its severity is illustrated by reports that the UK provisionally set a new record for the greatest 24 h rainfall recorded with 341.1 mm in Honister, Cumbria between 18:30, 4 December and 18:30 (all times are in UTC, which is also local time), 5 December. The UK Met Office issued a rare red "take action" warning (http://www.metoffice.gov.uk/news/releases/archive/2015/storm-desmond-red-warning)) – the first since 12 February 2014 – for parts of Cumbria and the Scottish Borders as a result of this powerful storm. The heavy rainfall indeed led to widespread flooding in these regions. It was reported that about 5000 homes and businesses were flooded and 60 000 people lost power (The Telegraph 8 December 2015, CNN 7 December 2015). The excessive nature of this record rainfall event has led many to question whether climate change played a role, especially since there have been several large floods over the last decades. These questions are asked on the days following the event when

usually no scientific information is available, so answers are given based on opinions or generalities rather than specific scientific evidence. Here we demonstrate that it is possible to provide a robust estimate of the overall role anthropogenic climate change played in the likelihood of this type of heavy precipitation events to occur on a time
5 scale of a week.

Although the Clausius-Clapeyron relation points to the possibility of about 6 %/K more water vapour in a warmer atmosphere, this is not the only factor influencing heavy precipitation as changes in the atmospheric circulation may also play an important role (Otto et al., 2016). Hence the answer to the question of attribution depends on the
10 region and season. Earlier work found no trend in the chance of heavy precipitation causing the Thailand floods (van Oldenborgh et al., 2012) or the Elbe and Danube floods (Schaller et al., 2014), but a strong increase in Southern France (Vautard et al., 2015).

We investigated the precipitation leading to the UK floods of early December us-
15 ing three independent methods of probabilistic event attribution (Allen, 2003): a statistical analysis of the observations (van Oldenborgh, 2007), the trend in a coupled climate model (similar to Lewis and Karoly, 2013), and the difference between the actual climate and one without anthropogenic emissions in a very large ensemble of atmosphere-only general circulation model run by volunteers designed to address this
20 question (Massey et al., 2014). The observational analysis gives a probability p_1 of the event occurring in the current climate, typically expressed as a return time $\tau_1 = 1/p_1$. This can in principle also be estimated from the models, but only after careful bias correction, which was not available at the time of writing. All methods provide changes in the return time, $f_1/f_0 = \tau_0/\tau_1$. However, these are calculated to answer subtly different
25 questions: how much the probability changed due to the observed trend for the observations, due to all forcings in the coupled model and due to anthropogenic forcings in the large ensemble. In the limit that the trend is completely due to anthropogenic forcings these coincide. In the UK in winter this is as far as we know a reasonable approximation. The influence of natural forcings is small: solar forcings have very little

influence (van Oldenborgh et al., 2013a) and there were no major volcanic eruptions the last few years. Low-frequency variations also play a minor role here. The largest uncertainties arise from the random weather, which affects all three methods equally.

2 Event definition

As shown in Fig. 1, most rain fell in Northwestern England, with orographically-driven maxima in Cumbria and southern Scotland. The rain mostly fell from 18:30 on 4 December to 09:00 on the 6th. This implies that the 24 h period from midnight to midnight 5 December (00:00–00:00) captured most of the precipitation, but the 09:00–09:00 rain stations only show the full extent by adding the precipitation recorded on 5 and 6 December. The Met Office reported two-day sums of more than 170 mm at four stations (http://blog.metoffice.gov.uk/2015/12/06/wind-and-rain-records-for-storm-desmond/). However, stations very close to these stations received much less rain, due to the mountainous terrain.

We investigated the event at two spatial scales to capture both the orography-driven localised events of very high rainfall and increase confidence in the results by making use of model simulations that only simulate much larger scales. A large area with heavy precipitation was defined as the land area of 54–57° N, 6° W–2° E. Results were checked against smaller areas and local station data. Over the large area, the ECMWF analysis gives an average precipitation of 36.4 mm on 5 December 2015 (00:00–00:00).

3 Observational analysis

To investigate trends in daily and two-daily sums of precipitation we analysed two relatively long area-averaged time daily series available from the Met Office in areas with severe precipitation: Northwest England and Southern Scotland precipitation. Since the underlying station data are obtained from different networks operated by various

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agencies and have to undergo quality control, the area averages are only publicly released the following month. The observations for December 2015 are therefore not yet available, so we can only study the trends over 1931–2014; the return time of this event could not be computed at the time of writing. A preliminary indication was obtained from the ECMWF analysis, which gives about 28 mm day^{-1} for Northwest England and 31 mm day^{-1} for South Scotland. There is only one publicly available precipitation series in the area, Eskdalemuir in southern Scotland, which recorded 77 mm on the morning of December 5 and 139 mm over the two days.

The daily and two-daily maxima occurring over the period October–February were computed for each year. As can be seen in Fig. 2 this encompasses the season of heavy large-scale precipitation in this area and excludes the season of heavy thunderstorms in the (late) summer. Adding the months of October and November increases the signal-to-noise ratio greatly. These block maxima were fitted to a Generalised Extreme Value function (GEV) scaled with the low-pass filtered global mean temperature, a proxy for anthropogenic climate change. The results are shown in Fig. 2 for the two regions. The horizontal line denotes the preliminary indication for precipitation in these areas.

The Northwest England region shows no trend in the maximum daily precipitation over October–February, with a 95 % uncertainty margin on the change in return times of these extremes of a factor 0.3–2.1 (1 indicates no change). In South Scotland there is a strong positive trend in precipitation, giving an increase in probability of 1.8–4 times what it used to be at the beginning of the series, 1931. This is due to large extent to a heavy precipitation event in 2005. However, even without that year the trend is positive. The trends in the two regions are compatible with each other, with the difference mainly due to natural variability: the maxima are uncorrelated. Averaging them gives an increase in probability of a factor 1.3–2.8 (95 % confidence interval).

The Eskdalemuir series shows a strong increase in daily mean precipitation, in agreement with the South Scotland series (which likely includes this station). Again, the trend is already positive over the period before a spate of high-precipitation events

starting in 2004. The 77 mm observed in one day has a return time of 4 to 13 years in the current climate, the more relevant two-day sum of 139 mm a return time of 20 to 250 years. At this location the heavy rain associated with storm "Desmond" was a fairly rare event even in the current climate. In the early twentieth century this fit indicates that it would have been even more rare, with a return time of hundreds of years and a lower bound of 75 years.

4 Coupled climate model

We applied the same method on general circulation model data to decrease the statistical uncertainty at the expense of an increased systematic uncertainty. We used 16 experiments covering 1861–2100 of the EC-Earth 2.3 model (Hazeleger et al., 2010) using the CMIP5 protocol (Taylor et al., 2011). This model is very similar to the ECMWF seasonal forecasting model. The resolution is T159, this is about 150 km, too low to resolve the mountains that show the highest precipitation in Fig. 2. We therefore only use the large area, 54–57° N, 6° W–2° E. Precipitation in this area shows a climatology comparable to ERA-interim (which is made with a very similar model; Dee et al., 2011). Extreme winter precipitation is concentrated in October–December, as in the observations.

Figure 5 shows the return times of winter precipitation in this area based on the EC-Earth simulations with a GEV fit under the same assumptions as for the observations. The figure shows an increase in the return time for an extreme event of the magnitude of 36.4 mm as calculated from ERA-Interim (pink horizontal line) due to the external forcings of 1.2 to 2.3 (95 % CI). However, we do not trust this result or return time itself as the ECMWF forecast on which the horizontal line is based has a much higher resolution and hence the precipitation includes orographic effects that are absent in EC-Earth. For a 1 in 100 year event, which is roughly the return time of the event in observations calculated from the one station and from ERA-interim, the likelihood of such an event to occur has increased by a factor of 1.1–1.8 (Fig. 5, for 30 mm day^{-1}).

The increase in return time (a shift to the left in Fig. 5) can be translated to a shift in intensity (upwards shift) of such an event in intensity (Otto et al., 2012). For heavy precipitation in northern England in the EC-Earth model this is about 4 %. The full CMIP5 ensemble for annual maxima (Sillmann et al., 2013), a much softer extreme, gives a range of 3 to 8 % (interquartile range) using the methods of van Oldenborgh et al. (2013b) (not shown). We do not use this CMIP5 range in our synthesis as this ensemble includes many models with a resolution that is too low to resolve events like storm "Desmond".

The increase in probability of these kinds of events in EC-Earth is in line with the observational one, although we expect a difference due to the different framing of the attribution question within the different methodologies. The observational analysis considers the change due to the observed trend, independent of the cause of this trend, while the coupled model shows the change due to the external anthropogenic and natural forcing prescribed in the model. The differences are mainly in the response to the aerosol and greenhouse gas forcings of the climate model used, which may differ somewhat from the real world. Very low frequency natural variability could also cause the results to diverge.

5 Large ensemble of regional climate models

The fact that the northern part of England is a mountainous region led to very heavy precipitation observed at some stations and almost none in neighbouring stations. Therefore capturing the nature of the precipitation event requires relatively high resolution climate models that include local orography. Furthermore, using a very large ensemble it is not necessary to fit an extreme value distribution to analyse the rare events, hence no assumptions about the shape of the tails of the distribution is made, nor is the change in softer extremes related to the change in larger extremes.

Using the distributed computing framework weather@home very large ensembles of regional climate models at 50 km resolution over Europe are available for the last

decade. Corresponding to these simulations of possible weather in Europe under current climate conditions ("all forcings") ensembles of counterfactual simulations of possible weather in a world as it might have been without anthropogenic climate drivers ("natural") are run. As weather@home is an atmosphere-only modelling framework, observed SSTs are necessary to drive the model. SST for the "natural" simulations is obtained by subtracting various estimates of the difference between pre-industrial and present-day conditions from CMIP5 (Schaller et al., 2014).

Because current SSTs are not yet available, simulations are only available up to October 2015. We therefore analyse the winter season DJF of the last year, 2014/2015, and the previous year, 2013/2014, for which the largest number of simulations are available. SST patterns like El Niño have very little influence over winter precipitation extremes in England and Scotland, so these years can be taken as equivalent to 2015. The two winter seasons were investigated separately at first (not shown) to confirm that the assumption is justified that the specific SST patterns have a negligible influence on the possible winter precipitation in the Northern UK. As simulations of October/November 2013 were not available, only DJF is analysed with an ensemble size of over 8800 for the all forcing simulations and 17 800 natural ensemble members. This allows us to obtain a good signal to noise ratio for events more frequent than 1 in 880 years.

Figure 5 shows the return time of the winter maximum precipitation averaged over the area (54–57° N, 6° W–2° E) in the combined ensemble simulations. The results are remarkably similar to those from the coupled model, in spite of slightly different definition of seasons. As in the EC-Earth results the return time of an event of the magnitude estimated from the high-resolution ECMWF analysis, without bias corrections, would be very high, with a return time of about 1600 years and a 5–95 % confidence interval of 1000 to 2500 years under actual climate conditions. The confidence interval represents the sampling uncertainty after bootstrapping.

Previous studies using the same model in a very similar region have shown however that the model in the region is biased towards too low precipitation (Schaller et al.,

2015). This is not unexpected given that for heavy precipitation in mountainous, or at least hilly, terrain a resolution under 10 km would be needed to simulate the mechanisms leading to the heaviest rainfall. As before we therefore use the return time calculated from observations rather than the magnitude of the observed event. This leads to a more realistic estimate of changes in the likelihood of the occurrence of an event like the one observed on the 5th of December, which is on the order of a 1 in 100 year event. In the weather@home ensemble simulations the return time for a 1 in 100 year event in the world that might have been without anthropogenic climate change is now an approx. 1 in 83 (72 to 95) year event, increasing the likelihood of such an event to occur by a factor of 1.05 to 1.4.

Again, the question addressed with the atmosphere-only large ensemble method is slightly different from the other two methods. Here we ask how much the probability has changed given the influence of prescribed anthropogenic forcings and the observed SST patterns. We checked that the different SST patterns in 2012/2013 and 2013/2014 indeed did not make an appreciable difference. The natural forcings, that were included in the coupled climate model but not here, also have a small influence, as argued in the introduction.

6   Discussion

There is remarkable agreement between all three methods used here to investigated the role of anthropogenic climate change in the type of heavy precipitation events as associated with storm "Desmond" that passed over the Northern Part of the UK from 4–6 December 2015. We find that climate change clearly increased the likelihood of large precipitation events in all three analyses. The likelihood of a 1 in a 100 year event of daily autumn/winter precipitation averaged over the land area of 54–57° N and 6° W–2° E increased by a factor of between 1.3–2.8 (95 % confidence interval) based on the past trends in the observations, 1.1–1.8 in the coupled climate model EC-Earth and 1.05–1.8 in the large ensemble of regional climate model simulations. The fits to

the observations and the coupled model are dominated by the more frequent events and the assumption that the two distributions scale with the global mean temperature propagates that information to the high tail. This assumption is not made in the large ensemble.

All methods show a small increase in this factor as the return time increases, showing that the scaling assumption in the GEV fitting method is not unreasonable in this case. Given the fact that all three applied methodologies frame the attribution question in a different way (e.g., Otto et al., 2015; Uhe et al., 2016) and that the station data includes the effects of local orography that the climate models cannot capture, the quantification of the increase agrees surprisingly well. This corroborates the assumption that this increase is indeed mainly due to anthropogenic climate forcings made in the observational analysis, and that the influence of other factors such as SST patterns is small.

This initial analysis looks at the combined effect of a thermodynamic increase in precipitation and potential changes in the atmospheric circulation and thus gives an estimate of the overall change of the likelihood of occurrence of this type of event. However, it only considers trends in precipitation and does not take into account other factors that influenced the flooding in northern England, such as flood defenses and increased exposure due to development in flood-prone areas (e.g., Crichton, 2005).

7 Conclusions

After a an impactful climate event like the floods in the UK following heavy rains around 5 December 2015, the question arises immediately what role climate change has played in it. Using real-time observations and weather analyses, historical data, re-analyses and climate model output we can now give a first scientific assessment of the effect of climate change in a relatively short time. For the analysis of the heavy precipitation event in North England and South Scotland caused by the storm "Desmond" we used three independent methods: a statistical analysis of observed trends, coupled

climate model simulations and a large ensemble of regional climate model simulations. In this case a lack of observations of the event precluded us from establishing the return time of the event with accuracy, but statements can be made about relative return times under various scenarios. Based on the currently available data it appears to be very roughly a one in a hundred year event when averaged over a large region, but with an uncertainty range from about 20 years to many hundreds of years. Locally return times may be very different from this. As more observations become available these will be better-defined.

The increase in likelihood of the event does not depend strongly on the return time and was found to be in remarkable agreement between the three methods. Overall, we find a roughly 40 % increase in likelihood, with a 95 % uncertainty range of 5 to 80 % for a return time of 100 years. The reference for this change is different for all three methods: a century ago, due to all forcings and due to anthropogenic forcings respectively. However, the results coincide within the uncertainties of natural variability, showing that for this event these different framings largely agree. Techniques for the attribution of the resulting floods to climate change, or even the damages, are being developed, but not yet mature enough for use on this time scale. Further analyses should also take into account all other factors that affect flooding apart from the small but robust contribution of climate change.

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Figure 1. Precipitation on 5 December 2015 in mm day^{-1} (ECMWF 24 h forecast from 00:00).
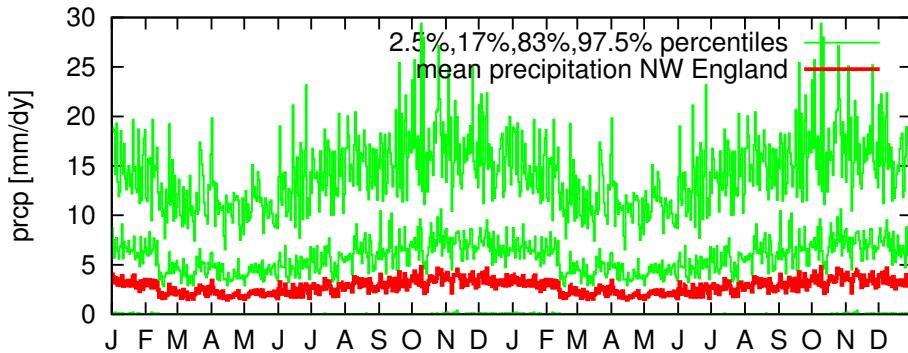
Figure 2. Climatology of rainfall in Northwest England. South Scotland is very similar. (The seasonal cycle is repeated twice). Source: UK Met Office.
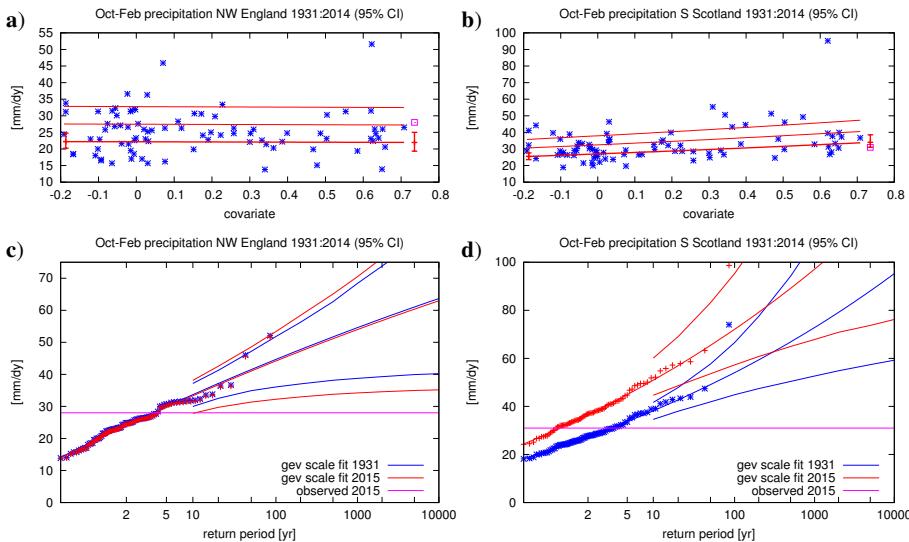
Figure 3. The maximum of daily precipitation amount over October–February in **(a)** Northwest England and **(b)** South Scotland precipitation from the Met Office, 1931–2014, plotted against the smoothed global mean surface temperature (GMST). The thick line is the position para-mater μ and the thin lines are drawn σ and 2σ above it. **(c, d)** Gumbel plots of the same values and GEV fit. The red lines indicate the fit in the current climate, the blue ones in the climate of 1931. The stars denotes the observed block maxima, shifted up with the fitted trend to 2015 (red) or down to 1931 (blue). The values for 2015 (purple lines) are preliminary indications based on the ECMWF 24hr forecast.

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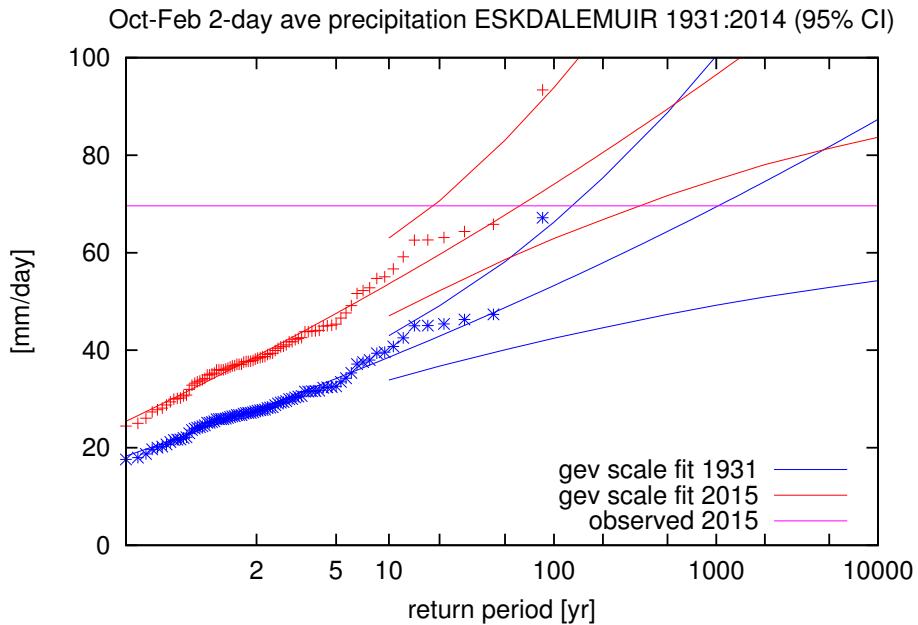
Figure 4. Gumbel plot of the maximum of 2-day precipitation amount over October–February at Eskdalemuir, Scotland. The lines indicate a GEV fit assuming the distribution scales with the smoothed observed global mean temperature. Red values indicate the climate of 2015, blue lines the climate of 1931. The stars denotes the observed block maxima, shifted up with the fitted trend to 2015 (red) or down to 1931 (blue). The purple line denotes the maximum observed so far in 2015/2016. Source: ECA&D.

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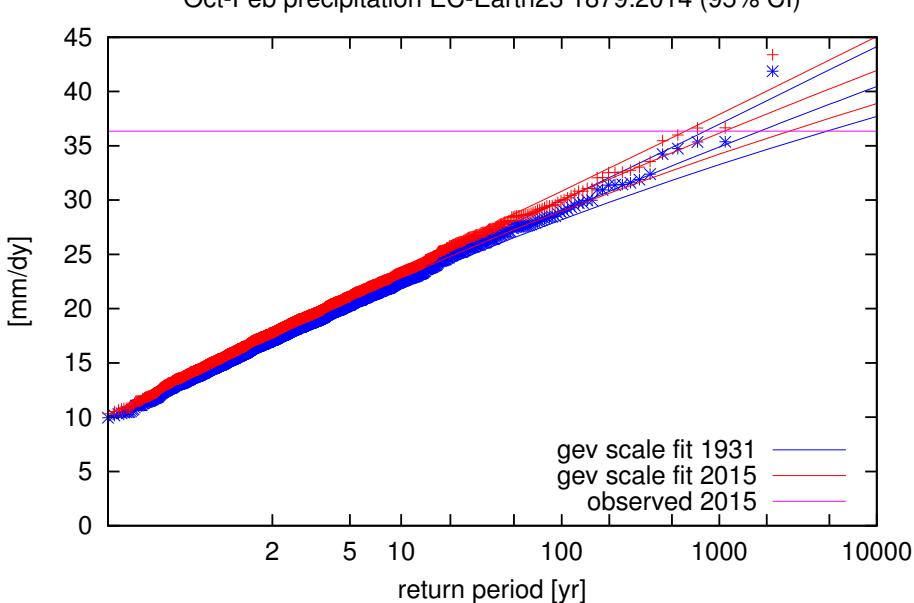
Figure 5. Gumbel plot of the maximum daily precipitation amount in October–February in 16 EC-Earth experiments 1889–2014. The lines indicate a GEV fit assuming the distribution scales with the smoothed observed global mean temperature. Red values indicate the climate of 2015, blue lines the climate of 1931. The stars denotes the simulated block maxima, shifted up with the fitted trend to 2015 (red) or to 1931 (blue). The value from the ECMWF analysis is taken for 2015 (purple line).
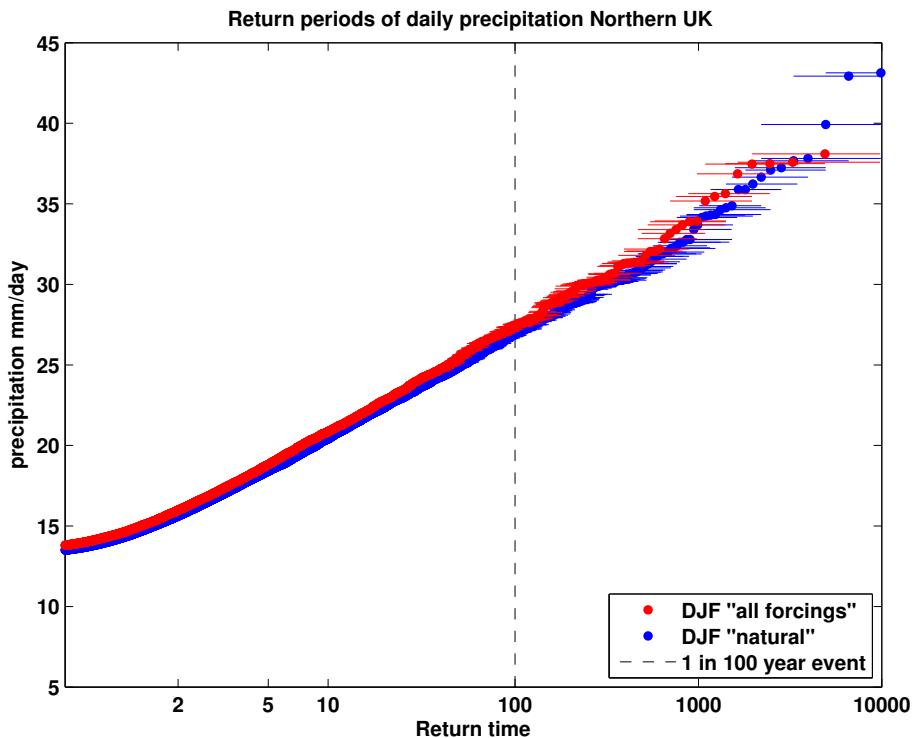
Figure 6. The maximum of winter (DJF) daily precipitation averaged over the Northern UK, 54–57° N, 6° W–2° E. Red indicates the probability of daily mean precipitation under observed climate conditions, blue in the counterfactual simulations. The black dashed line marks the 1 in 100 year event.

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