

Observations of Flood Extent above Corston during an Extreme Rainfall Event

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Summary

The Gauze Brook valley immediately upstream of Corston floods regularly, and parts of it are designated as Flood Zone 2 or 3. Nevertheless the Applicant proposes to build solar panels and other infrastructure in these areas, relying on the Flood Maps to predict flood extent. Storm Bert in November 2024 provided a good opportunity to test the quality of the maps against observations, as it was roughly a 1% AEP event. Photographs show clearly that flooding is greater than predicted by the EA's models, and that it would be unwise to site infrastructure in these areas.

Author

1. I am an Emeritus Professor of Geography and Environmental Science at the University of Reading. I have been involved in hydrological research since 1977, first as an environmental scientist in the electrical generation industry working on the effects of acid rain on freshwaters, and after I returned to academic life in 1999, working on modelling and monitoring freshwaters, and hydrology and climate change. I am a co-author of the standard paper on climate change and the water environment in England and Wales, and co-led the modelling workpackages of two large EU-funded projects, EUROLIMPACS and REFRESH, which investigated the predicted effects of climate change on waters across Europe. My publications on hydrological topics have been referenced more than 1000 times. I live adjacent to the Lime Down area. The evidence I have produced is based upon my professional expertise, and is my true and professional opinion.

Introduction: Storm Bert

2. On Sunday 24th November 2024 extensive flooding occurred in North Wiltshire due to heavy rain from a Met Office named storm, "Storm Bert". The flooding also affected other parts of SW England and S Wales. Not only did the floods affect the area proposed for the Lime Down Solar Park, but the adjacent towns and villages such as Malmesbury and Corston, and larger communities downstream on the Bristol Avon such as Chippenham, Melksham and Bradford on Avon. In Chippenham several large shops suffered serious damage.
3. The Lime Down area was extensively flooded by Storm Bert, but this note is concerned only with the Gauze Brook valley immediately upstream of Corston. This is occupied by the east side of Area D in the Lime Down scheme, and also contains substantial areas of Environment Agency Flood Zones 2 and 3, which are defined by their respective Annual Exceedance Probabilities (AEP) of >0.1% and >1%. The position of the flood zones in relation to the panels is shown in Fig. 1

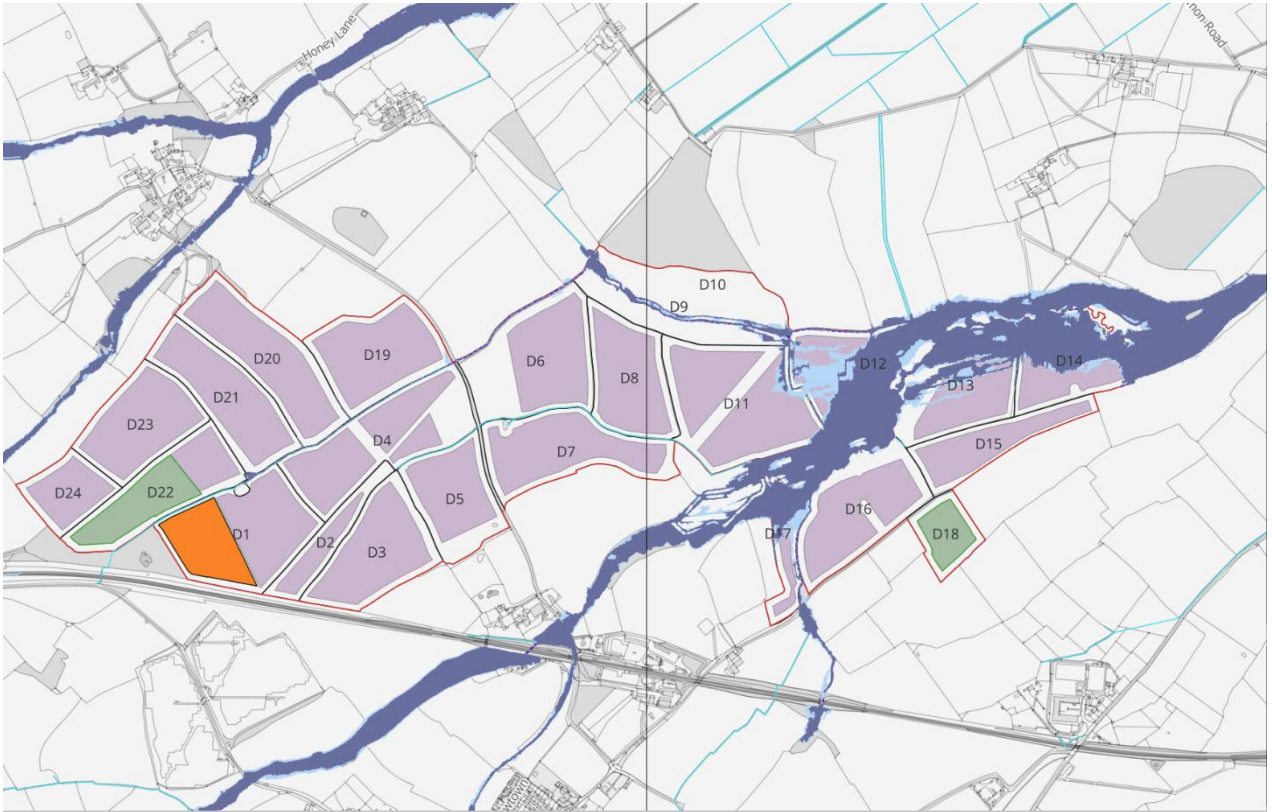


Fig 1: Area D in relation to EA flood zones. Pinkish areas in numbered fields are solar panels. Green areas are substations, orange, the BESS. EA Flood Zone 3 (>1% AEP) is shown in dark blue; Flood Zone 2 (0.1 to 1% AEP) in light blue; remaining areas are Flood Zone 1 (<0.1% AEP)

- Storm Bert provides a good test of the flood zone extents because it was an extreme rainfall event with an approximately 2% AEP. Rainfall totals during Storm Bert at three local rain gauges are shown in Table 1.

Site	Location	Height (m OD)	Rain Total (mm)	Rain 23 rd Nov	Rain 24 th Nov	24-hour maximum	Maximum Hourly rain
Shipton Moyne	ST899886	95	78.4	20.4	58.0	64.5	10.7
Great Somerford	ST964833	60	58.1	17.3	41.8	46.6	5.1
Badminton	ST815831	115	70.5	19.0	51.5	57.8	8.0

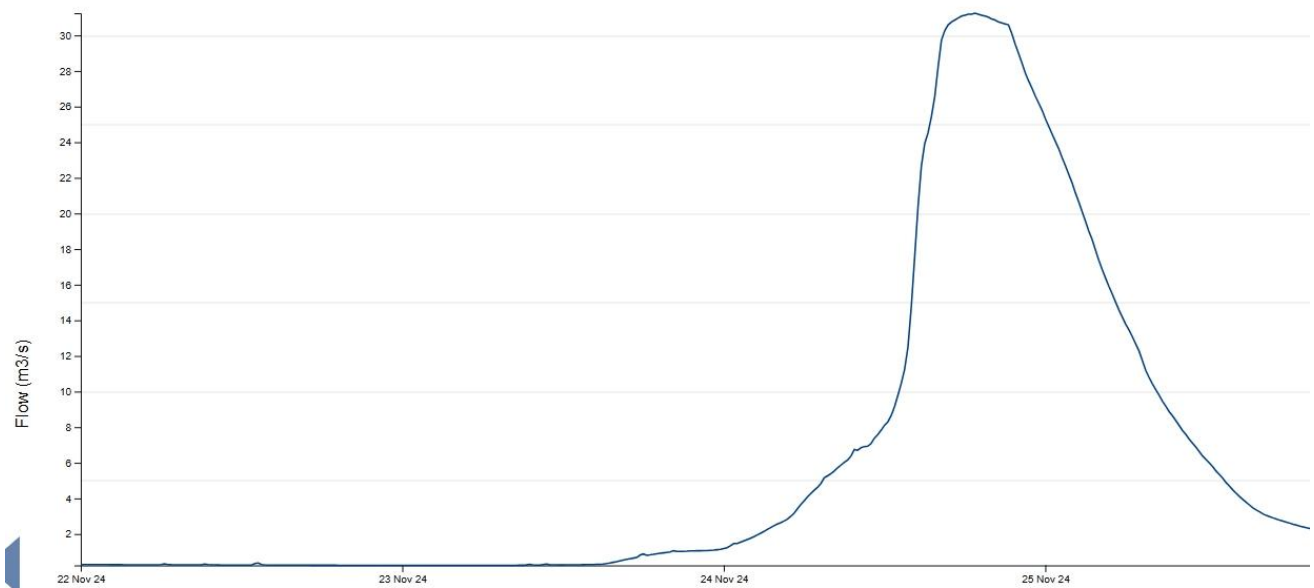
Table 1: Rainfall statistics for Storm Bert. All rainfall values are in mm. All hydrological data is from DEFRA’s Hydrology Data Explorer site.

- An extreme rainfall event is defined as more than 50 mm in 24 hours (e.g. Cotterill et al., 2021). Two of the three local rain gauges exceeded that total on the 24th November 2024, the other was a little less. The return period for a 50 mm, 24 hr rainstorm in this area is about 50 years (i.e. 2% AEP) see

Fig. 2 in Cotterill et al., (2021). The return period for the corresponding flood will be greater (AEP less) as the catchment needs to be in flood-sensitive condition to generate a flood. In summer, when there is little saturated ground and groundwater levels are lower, the catchment would have probably absorbed Storm Bert rainfall without generating a serious flood. Higher groundwater levels and saturated ground near watercourses are the typical winter condition, and rainfall is then transmitted more rapidly into the rivers. Serious flooding thus requires both heavy rain and a more saturated catchment implying a reduced probability compared to the probability of heavy rain alone. However, this is unlikely to do more than halve the AEP. Storm Bert should therefore have generated something close to the 1% AEP flood depicted as Flood Zone 3.

Photography

- A Stop Lime Down supporter braved the elements during Storm Bert to take a video recording of some of the area shown in Fig. 1. The video was taken at 15:26 on 4 November 2026, just beyond Field D15. The co-ordinates of the viewpoint are 51.552622 N, 2.1222193 W, What3Words: soda.sunblock.leader. The video was taken just over 3 hours before the flow peak of Storm Bert at



18.45 (Fig. 2), as measured at the flow gauge at Rodbourne about 500 m downstream from the East edge of Fig. 1. The flow at the gauge was $25 \text{ m}^3 \text{ s}^{-1}$ at the time of the video compared to $31.2 \text{ m}^3 \text{ s}^{-1}$ at the peak.

Fig. 2 Flow in the Gauze Brook during Storm Bert

- Still pictures from the video are shown in Figs 3 and 4, together with approximate angles of view on the Flood Risk Map

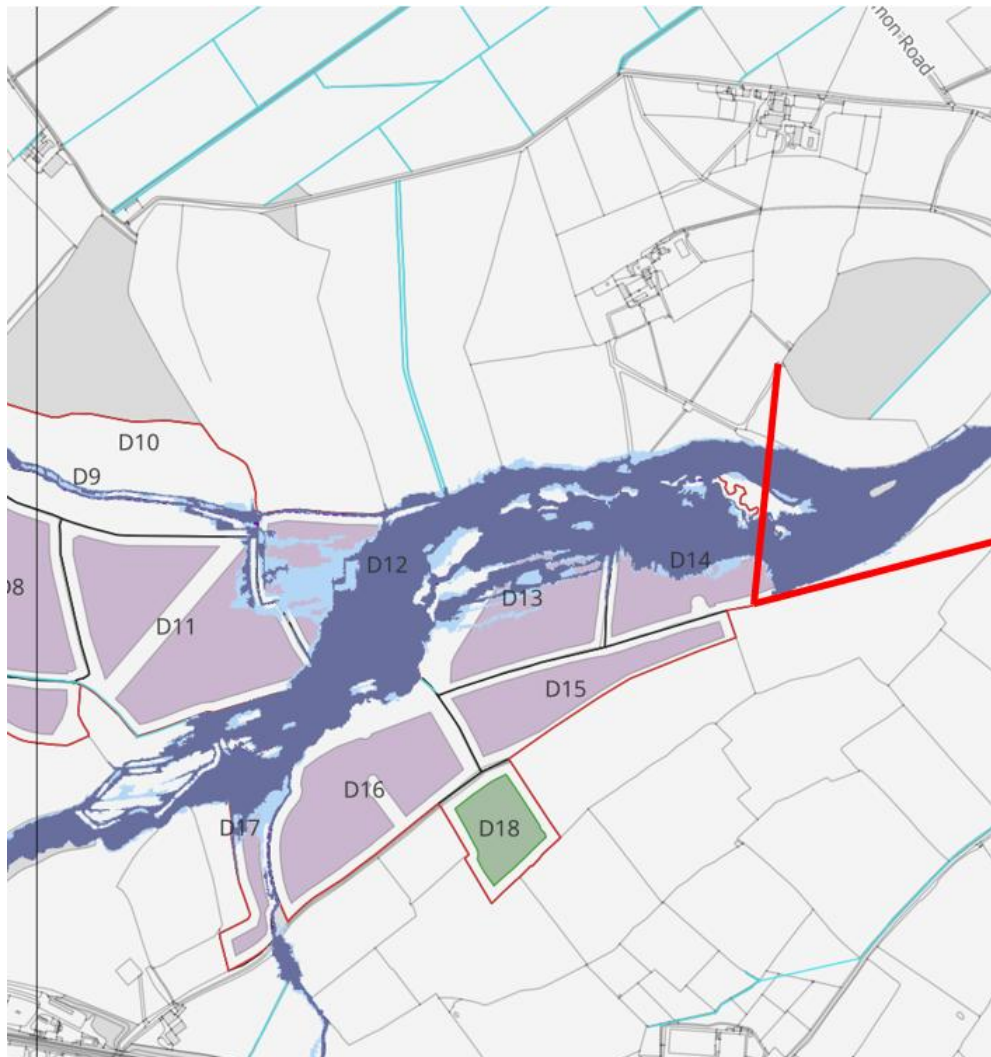


Fig. 3 Photographs of flooding from Storm Bert and viewpoint and approximate angle of view (red lines) on the Flood Risk Map.



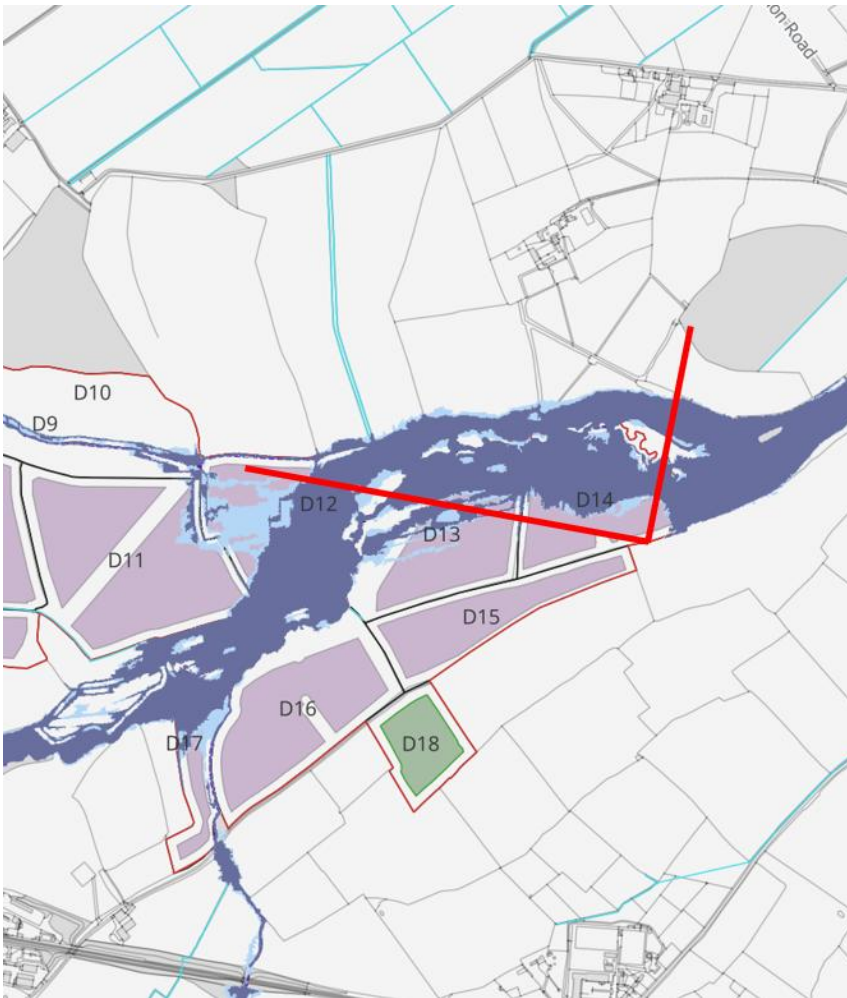


Fig 4. Photographs of flooding from Storm Bert and viewpoint and approximate angle of view (red lines) on the Flood Risk Map.

Conclusion

8. Although the photographs vindicate the area being classified as Flood Zone 3, there is clearly more flooding than is predicted by the flood map for what should be close to a 1% AEP event. The areas on the south side of the fence in Fig. 3 and in the foreground in Fig. 4 are flooded when the flood maps predict it should need a 0.1% AEP (1000-year) flood to do this. Fields D14 and D13 have more floodwater than predicted, which will inundate more panels than the Applicant predicts in their FRA for Area D [APP-215], and the depth looks greater than predicted too, though this could be checked against LIDAR data. The flooding extent looks very similar to the historical flood from 1932 shown in Figure 6 in [APP-215], when the whole of D13 and D14 were flooded. As the Applicant notes in [APP-215], 2.3.16, the flood extents in the EA's latest modelling are reduced compared to the model used to produce the maps in Figs 1, 3 and 4. This reinforces my subjective impression that throughout the area the flood extents are underestimated by the EA's latest model and should be treated with caution. A substantial current can also be seen in the video. If the Scheme is consented, it would be prudent to avoid putting panels and converter units in Fields D12 to D15 to avoid risks to the public and the infrastructure itself.

9. If requested, the relevant recording can be provided to the ExA.

Reference

Cotterill, D., Stott, P., Christidis, N. & Kendon, E. (2021) Increase in the frequency of extreme daily precipitation in the United Kingdom in autumn. *Weather and Climate Extremes* **33**, 100340



Increase in the frequency of extreme daily precipitation in the United Kingdom in autumn

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ABSTRACT

The flooding in South Yorkshire in the United Kingdom (UK) in autumn 2019 saw one fatality, at least 500 properties flooded and 1 200 households evacuated. The worst of the flooding occurred after very high 24-h rainfall totals of up to 82 mm fell on already saturated ground. This followed very high 24-h rainfall totals in the region just two weeks earlier of up to just under 50 mm. In the light of anthropogenic climate change, it is expected that extreme rainfall events are set to become more intense as a result of increased global mean temperatures and the Clausius-Clapeyron relation. Here we investigate the change in risk of such extreme rainfall events in the UK in autumn using a new index R_{50mm_OND} , representing the mean number of daily precipitation totals in excess of 50 mm in October–December each year. Using high resolution regional model datasets and observations we show that extreme rainfall totals for the UK are increasing exponentially as a result of anthropogenic climate change. Observations show that the frequency of extreme daily precipitation in the form of R_{50mm_OND} has already increased by 60% (95% CI: 44–76) in the UK between the beginning of the 20th and 21st centuries. R_{50mm_OND} is projected to increase even further between 2019 and 2080, by 85% (95% CI: 73–97) according to a Representative Concentration Pathway (RCP) 8.5 scenario of anthropogenic emissions. While higher resolution models (12 km spatial resolution) were able to capture the observed changes, lower resolution models were not. This underlines the importance of high-resolution models for modelling extreme precipitation seen in late autumn and early winter, not just for convective rainfall in the summer. A more specific analysis of the November 2019 event looked at the mean of the two highest daily precipitation totals in October–November in the South Yorkshire region. This found a long-term shift to higher daily rainfall totals for this mean with an increase in intensity of the top 10% of events, suggesting that the South Yorkshire region in autumn is more at risk of flooding in the future without effective adaptation measures.

1. Introduction

In the autumn of 2019, South Yorkshire in the United Kingdom (UK) saw some severe flooding with two rivers bursting their banks on the 7th of November after extremely high 24-h rainfall totals of up to 82.2 mm at some locations (Kendon M., 2019). These high totals were more than the average monthly rainfall and came about through a very slow-moving weather front, falling on already saturated ground, following high daily precipitation totals just two weeks earlier (Kendon M., 2019). The impacts included a fatality (BBC News, 2019), over 500 properties being flooded, 1 200 households being evacuated and potential insurance losses of up to £120 million (FloodList News, 2019).

The UK has seen many other big flooding events since the start of the 21st century, including during the winters of 2013/14, 2015/16 and

2019/20, the autumn of 2000 and the summer of 2007. Research suggests hourly and daily rainfall intensities will increase in the UK in winter, and hourly rainfall intensities will also increase in the summer (Kendon E.J. et al., 2014). The State of UK Climate Report 2017 finds that observations have shown that extremely wet days (99th percentile of daily precipitation) have increased in intensity for the UK by 17% when comparing the 1960–1990 and 2008–2017 averages (Kendon M. et al., 2017). An analysis of UK rainfall extremes between 1961 and 2000 found that there were regional variations in changes in the rainfall extremes. In particular, for 5 and 10 day annual maxima there were large increases in the western and northern parts of the UK in contrast to slight decreases in 5 and 10 day annual maxima in the South of the UK (Fowler and Kilsby, 2003).

Several attribution studies have been carried out for heavy rainfall

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events causing flooding in the UK in this century. Many of them found that the probability of the flooding or the corresponding precipitation event was enhanced by climate change, such as the winter flooding in 2013/14 (Christidis and Stott, 2015; Schaller et al., 2016), Storm Desmond in the winter of 2015/16 (Otto et al., 2018) and the autumn floods in 2000 (Kay et al., 2011; Pall et al., 2011). In most cases it was shown that both atmospheric circulation and anthropogenic climate change played a role.

A change in extreme rainfall events has also been seen in other European countries. The probability of daily extreme precipitation events in southern France has increased significantly (Luu et al., 2018) and in Germany stratiform precipitation extremes are increasing, with convective precipitation extremes increasing at an even faster rate with temperature (Berg et al., 2013). This is also occurring on a global scale with more regions getting more frequent heavy precipitation events than not worldwide (IPCC Summary for Policymakers, 2013).

The Clausius-Clapeyron (CC) relation, which relates saturation vapor pressure to temperature and describes the main mechanism responsible for the change in intensity of precipitation events, shows that the air can hold around 6–7% more moisture per degree Kelvin temperature rise at the Earth's surface (Chan et al., 2016). Work looking at the change in intensity of extreme precipitation events with global mean temperatures shows a change of 5.9–7.7%/K based on observations (Westra et al., 2013). This is very close to the CC rate, however dynamic effects can influence this rate locally, leading to considerable spatial variation in scaling rates (Norris et al., 2020). This suggests that the future climate may see noticeably different scaling rates in different regions based on dynamical changes than are currently being observed. For example, Lavers et al. (2011) link extreme autumn and winter precipitation events to Atmospheric Rivers which transport a large flux of moisture to the mid latitudes from the subtropics.

The intensity at which extreme rainfall events change with increased temperatures vary temporally, with greater increases seen in sub-daily rainfall intervals than daily intervals (Chan et al., 2016; Fowler et al., 2021; Lenderink and van Meijgaard, 2008). Fowler et al., (2021) link

these faster changes seen at sub-daily timescales to convective cloud feedbacks acting in addition to increases due to thermodynamic changes following Clausius-Clapeyron. There is also a difference between extreme and mean precipitation, with mean precipitation only likely to increase at a rate of approximately 2%/K globally (Stocker et al., 2013). This is because the energy budget constrains global mean precipitation and not the CC equation (Allen and Ingram, 2002).

In the case of the South Yorkshire 2019 flooding, two extreme daily rainfall totals were seen in the space of 2 weeks as shown in Fig. 1, with almost 50 mm recorded on the 25th of October and 63.8 mm on the 7th of November in Sheffield (Kendon M., 2019). Therefore, examining the frequency of these extreme events and how they are changing are very important indicators of future flood risk.

In this paper, the transient evolution of such extreme rainfall events UK-wide in October–December (OND) are examined through a new index $R_{50\text{mm_OND}}$. This index is a measure of the frequency of daily extreme rainfall totals above a fixed value for a grid box, and in this case the index is the number of days during OND each year with daily precipitation totals of over 50 mm. This has been chosen because extreme daily rainfall totals greater than or of that magnitude led to the November 2019 flooding in South Yorkshire. In the case of river flooding, changes in river flow are a better indicator of the impact of climate change on flooding than precipitation. However, with detailed precipitation data covering a much longer time period, observed changes in precipitation can much more easily be attributed to climate change than changes in river flow (Hannaford, 2015).

This paper will investigate how the frequency of extreme rainfall events $R_{50\text{mm_OND}}$ has already changed UK-wide and how much it is projected to change in the future. It will also look at the transient evolution of the two most extreme daily precipitation totals in October and November (ON) in the South Yorkshire region in order to examine the specific nature of the November 2019 floods. For this we analyse the HadUK-Grid observations, a 12 km resolution regional climate model from UKCP 2018 climate projections and a global climate model HadGEM3-A at 60 km resolution.

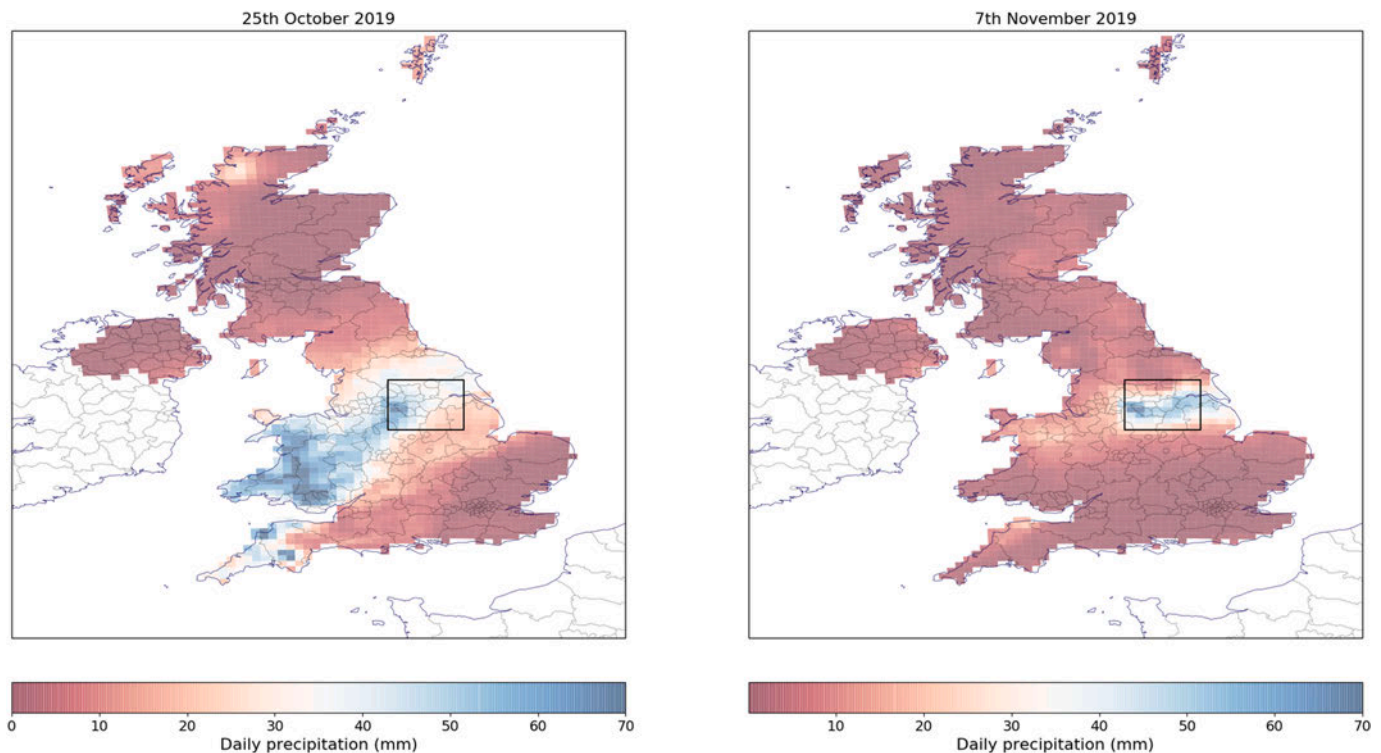


Fig. 1. Daily precipitation totals over the UK on the 25th of October and 7th of November 2019 using HadUK-Grid observations gridded at 12 km. High precipitation totals in excess of 40 mm on both days can be seen over South Yorkshire and the surrounding region outlined by the box.

2. Data and methods

2.1. Data

UKCP 2018 Regional Climate Model Projections:

This paper uses the UK Climate Projections 2018 (UKCP18) from both regional and global climate models. The regional climate model data consists of 12 ensemble-member projections at 12 km resolution for the UK and Europe from 1980 to 2080 based on a Representative Concentration Pathway RCP 8.5. The global climate model data contains 28 ensemble-members (15 Hadley Centre and 13 CMIP5 models), providing projections at 60 km resolution from 1899 to 2099. The 12 km resolution regional climate model is able to simulate extreme daily precipitation to a greater extent than the global climate model, which underpredicts the number of these extreme events, especially over the UK (Lowe et al., 2019). The regional model slightly overpredicts rainfall extremes and a bias correction is used to account for this. The 12 km UKCP regional climate model data is used rather than the 2.2 km UKCP18 local convective permitting model data, as the 12 km model covers 100 years of data, compared to the 60 years of data covered by the 2.2 km model. The projections use Met Office global and regional climate models, as well as other global climate models (Lowe et al., 2019).

HadUK-Grid Observations:

The HadUK-Grid dataset is a set of gridded UK climate observations produced by the Met Office Hadley Centre based on land surface observations (Hollis et al., 2019). This dataset contains data for daily rainfall from 1891 to 2019 and monthly temperatures from 1884 with grid box resolutions of 1 km, 5 km, 12 km, 25 km and 60 km for UK countries.

HadGEM3-A model:

The UK Met Office HadGEM3-A global atmospheric climate model has grid boxes with 60 km horizontal resolution at the mid latitudes and 85 vertical levels. Two sets of 15-member ensembles from 1960 to 2013 sample different atmospheric states (Vautard et al., 2018). One of them representing a world with changes only in natural forcings and anthropogenic forcings held constant at 1850 levels (NAT), and the other 15-member ensemble representing a world in which both natural and anthropogenic forcings change as observed (ALL). For the period 2013–2019, there is a larger number of ensemble members for ALL and NAT (105 for 2014–2015 and 525 for 2016–2019). The atmospheric model simulates ALL and NAT simulations using sea surface temperature and sea ice as boundary conditions (Christidis et al., 2013; Ciavarella et al., 2018). One main advantage of this model, as well as having separate ALL and NAT ensembles, is the relatively high spatial resolution it has for a Global Climate Model. The model has a good ability to capture weather regimes in the North-Atlantic and reproduce observed weather patterns important for driving temperature and precipitation extremes (Vautard et al., 2018).

2.2. Definition of extreme precipitation days R_{50mm}

2.2.1. Index choice

The index that has been chosen to examine extreme rainfall events for the UK in this paper is R_{50mm_OND} , which is a measure of the frequency of daily extreme rainfall totals, where an extreme daily rainfall total is defined as anything higher than 50 mm/day. Numerically, this index is the number of times per year where there are daily precipitation totals of over 50 mm in OND for a given grid box. Over a larger area, R_{50mm_OND} is calculated for all the grid boxes individually and then the mean is taken over all grid boxes. The index R_{50mm} may also be referred to, this is the same as R_{50mm_OND} but is a more general index that accounts for any choice of months.

In this paper the focus is October, November and December (OND), as the main two extreme daily rainfall totals in Yorkshire occurred between the 25th of October and the 7th of November 2019. For the 3-month period examined, December was chosen over September as

September is becoming more of a summer month, with summer starting earlier and winter slightly later, based on changes in weather regimes over the North Atlantic (Vrac et al., 2013).

The return period for R_{50mm_OND} is shown for the UK in Fig. 2, showing significant regional variation. Daily totals of over 50 mm in OND are very rare in the east of England, having occurred once or less in over 125 years in most grid boxes, but can occur between 1.0 and 3.5 times a year in parts of Scotland and Wales. Daily precipitation totals of 50 mm for the UK in OND are in the 99.9th percentile overall for 12 km resolution grid boxes. This daily total is the 96.2nd percentile for the grid box with the largest number of daily precipitation totals exceeding 50 mm.

As well as a strong spatial dependence, the observed trend in R_{50mm} also has a strong seasonal dependence, as seen in Fig. 3. These extreme events have occurred more in autumn than in any other season between 1960 and 2018, with a positive trend in these events over the last 59 years in both autumn and winter for the UK. The trend is even larger for the OND 3-month period investigated in this paper.

2.2.2. Bias correction

A bias correction is applied to the index R_{50mm_OND} by equating return times of R_{50mm_OND} in the model and the observations over a 30 year baseline period. The bias correction is carried out so that the equivalent X_{mm} event in the model R_{Xmm_OND} follows:

$$R_{Xmm_OND}(\text{Model ensemble mean } 1981\text{--}2010) = R_{50mm_OND}(\text{Observations } 1981\text{--}2010) \quad (1)$$

This bias correction takes into account the model overpredicting or underpredicting the extreme rainfall totals examined. This assumes that the bias does not change over time and that the 30-year observational period contains some extreme values. The resolution of the gridded observations and model data are always the same when carrying out the bias correction.

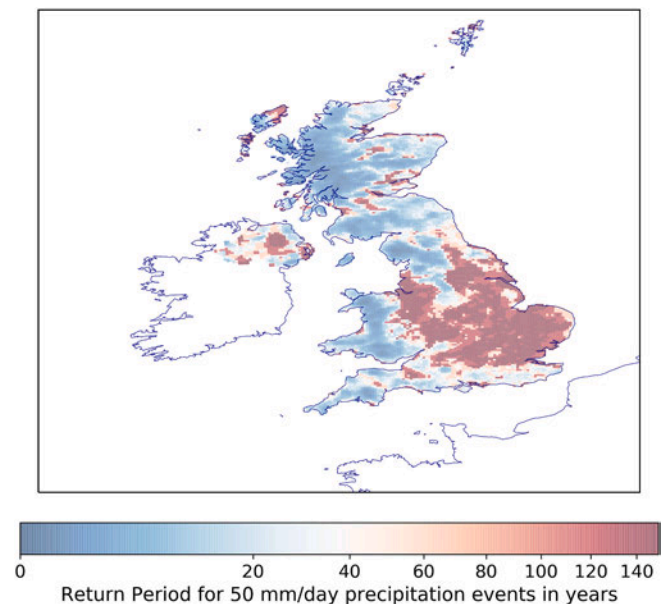


Fig. 2. Map showing the spatial distribution of the return period for days with daily rainfall totals in excess of 50 mm over the UK in OND. This uses HadUK-Grid 1 km resolution gridded data covering the 125 year period 1893–2017. The darkest red areas represent areas where this type of event has never occurred, which can be seen in some areas of central and eastern England. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

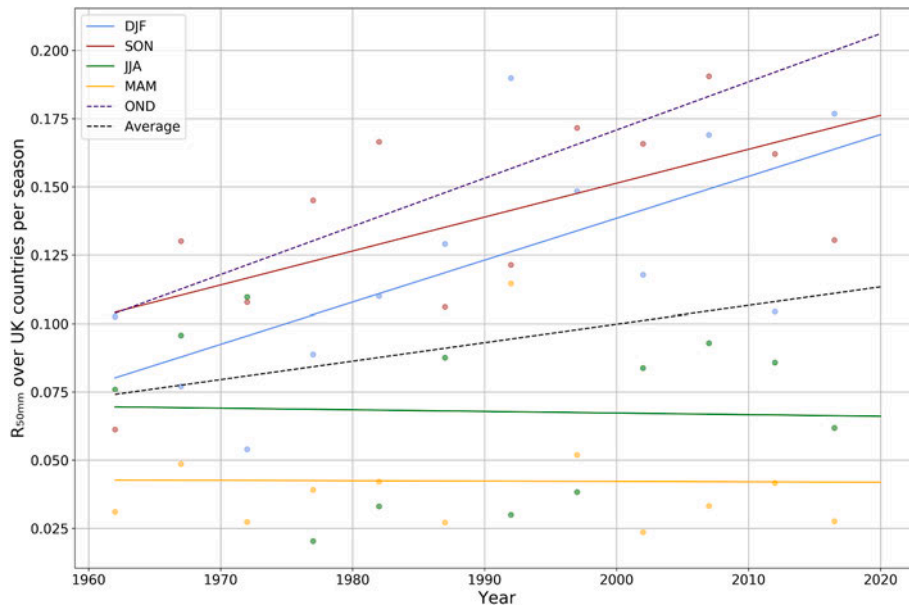


Fig. 3. Scatter plot showing the transient evolution of 5-year means of R_{50mm} for each season, averaged over the UK. Data is from the HadUK-Grid observations at 12 km resolution from 1960 to 2018.

2.2.3. Index scale and grid box size

The magnitude of R_{50mm_OND} is impacted by the resolution the data is gridded/re-gridded at, even from the same model run. This is because when gridded at a low resolution, spatial averaging will result in some areas with daily totals exceeding 50 mm locally being lost within the larger grid box. For models with low-resolution, small-scale precipitation events are likely to be averaged out, and hence R_{50mm_OND} is larger for higher resolution gridded data. Therefore, when comparing observations and model output, both datasets are gridded to the same resolution to allow for direct comparisons. Comparison between different resolutions for the same model gives information on the spatial scale of the events included in the index. In addition to the size the data is gridded or re-gridded at for a model run at a given resolution, the resolution the model is run at is also likely to impact R_{50mm_OND} . The ability of lower resolution models to pick up extreme events is examined in section 3.3.

For an index such as this there is also likely to be uncertainty from the observations. One caveat is that the gridded observations are based on station data and therefore values averaged over grid boxes with more sparse data are more influenced by fewer of these point stations. There are however two factors here that limit this uncertainty for the R_{50mm_OND} analysis. Firstly, the extreme events being examined occur from October to December and are likely to be larger scale rainfall events rather than summer convective downpours over small areas, meaning that even when there are areas with a sparse data network the event should be picked up. In addition to this, this index only captures the frequency of events greater than 50 mm/day and not their exact magnitude.

2.3. Statistical techniques for data

2.3.1. Linear regression

Over time periods where there is a linear relation between R_{50mm} and the difference between year y and the first year in the time series y_0 , the relation can be expressed as follows, with fit parameters m and c :

$$R_{50mm} = m(y - y_0) + c \tag{2}$$

The line of best fit is calculated by using the method of the least squares. When carrying out the regression, the errors on m and c , Δm and Δc can be calculated as followed for the equation in the form $y = mx$

+ c , where $D = \sum (x_i - \bar{x})^2$ and d_i are the residuals $d_i = y_i - mx_i - c$:

$$\Delta m = \sqrt{\frac{1}{D} \frac{\sum d_i^2}{(n-2)}} \quad \Delta c = \sqrt{\left(\frac{1}{n} + \frac{\bar{x}^2}{D}\right) \frac{\sum d_i^2}{(n-2)}} \tag{3}$$

Using the known values m , c , Δm and Δc , the error in R_{50mm} , ΔR_{50mm} can be calculated using equation (2) for each year.

2.3.2. Exponential trend fitting

The Clausius Clapeyron rate is an exponential relationship between saturation water vapor pressure and the change in temperature, approximately 6.5%/K. An empirical exponential relationship between R_{50mm} and ΔT can be modelled as:

$$R_{50mm} = Ab^{AT} \tag{4}$$

Where A and b are fit parameters, this becomes:

$$\ln(R_{50mm}) = \ln(b)AT + \ln(A) \tag{5}$$

The fit parameters can be found using data for R_{50mm} and ΔT . For a linear relationship between ΔT and y' , ΔT can be replaced with calculated fit parameters and y' where $y' = y - y_0$.

$$\Delta T = fy' \tag{6}$$

$$\ln(R_{50mm}) = \ln(b)fy' + \ln(A) \tag{7}$$

Therefore, an exponential fit can be fitted to relate R_{50mm} and y' , where the parameter b represents the percentage increase in the magnitude of R_{50mm} per Kelvin increase in temperature over the chosen region. The uncertainties in the parameters can be calculated in the same fashion as described in 2.3.1. It is important to note that this relationship does not represent the CC rate but gives an estimate for the rate at which the frequency of these extreme rainfall totals is changing UK-wide with temperature.

2.4. South Yorkshire November 2019 flooding attribution method

2.4.1. Index Rx2days

The major flooding in 2019 occurred after high daily precipitation totals on the 7th of November as two rivers burst their banks in the South Yorkshire region. The river catchments were already saturated from

very high autumn rainfall totals preceding the event, with another day of extremely high rainfall totals over that region on the 25th of October just two weeks before. To capture both the intense precipitation events of the 7th of November and the 25th of October and their contribution to the flooding, a different index is used for the attribution of this specific event. This is the mean max R_{x2days} , which is the mean of the two days with the highest daily precipitation totals over the chosen region in October–November (ON). The higher the first total the more likely the ground will be saturated for the second event and the more extreme the second event the more likely there is to be flooding. This index tries to capture both the extremity of the main event that causes flooding and the pre-existing conditions in a simple way. The limitations of this approach is that this could represent an event so widely spaced apart (e.g. at the beginning of October and end of November) that the daily total of the first event may have little impact on the flooding caused by the second event. However, this would only apply to a very small percentage of years and the aim of this index is to best represent the meteorology of the South Yorkshire autumn flooding event in 2019 in a relatively simple index.

2.4.2. Attribution method

The region chosen shown in Fig. 1 has coordinates (53°N–54°N, 2.0°W–0.5°W), which covers the sources of the two rivers that burst their banks: the River Don and the River Derwent. This region is extracted from both the HadUK-Grid 12 km Observations and the UKCP18 12 km Regional Climate Model (RCM). Firstly, the daily precipitation values are averaged over all grid boxes for this region. Then, using data for ON only for each year, the two days with the highest daily precipitation values over this region are averaged for the observations/model ensembles to produce $R_{x2days,ON}$.

This study uses three 15-year time slices, one centred on the past in 1990 (1983–1997), one centred on the present for 2019 (2012–2026) and one centred on the future for 2070 (2063–2077). The distributions combining data from all 12 ensembles over the 15-year time slices give 180 points to fit generalized extreme distribution curves. It is important to note that this is a perturbed physics ensemble and therefore may not be identically distributed for all ensembles. They are all however

reasonable representations of reality and are still a good approximation. The probability of the $R_{x2days,ON}$ exceeding the threshold from the event in 2019 is then compared for all 3 distributions (where the threshold is bias corrected using HadUK-Grid observations). The 95% confidence intervals were calculated using a bootstrapping with replacement procedure in which the data were resampled 1 000 times, leading to 1 000 values for the chosen percentile for each of the corresponding 1 000 fitted curves.

3. Analysis and results

3.1. Trend in the observations

Fig. 4 shows that $R_{50mm,OND}$ is strongly influenced by the spatial averaging scale of the gridded data with smaller $R_{50mm,OND}$ values at lower resolution gridded data. The transient evolution of $R_{50mm,OND}$ is similar for all resolutions. For all 1 km, 25 km and 60 km gridded resolutions a strong increase is seen in $R_{50mm,OND}$ from the 1980s with only small increases up to that point. Applying a Mann-Kendall test to the raw data shows that this trend is positive and statistically significant for all grid resolutions, with p values for all three resolutions less than 0.006 between 1891 and 2018.

To estimate the climate signal in $R_{50mm,OND}$, two 30-year periods of observational data are compared. The first representing the time period in the dataset most representative of the natural world without human influence 1891–1920, and the second time period best representing the current climate 1989–2018. Changes between these periods will not only reflect the impact of greenhouse gas emissions but may also reflect changes in uncertainty of the recorded data over time, as well as multi-decadal natural variability. The results are shown in Table 1 with $R_{50mm,OND}$ having increased by 60% (95% CI: 44–76) in the last century. This trend in $R_{50mm,OND}$ over time does not vary much with grid box size, and alongside Fig. 4 it can be concluded that $R_{50mm,OND}$ is increasing at a similar rate for all gridded resolutions.

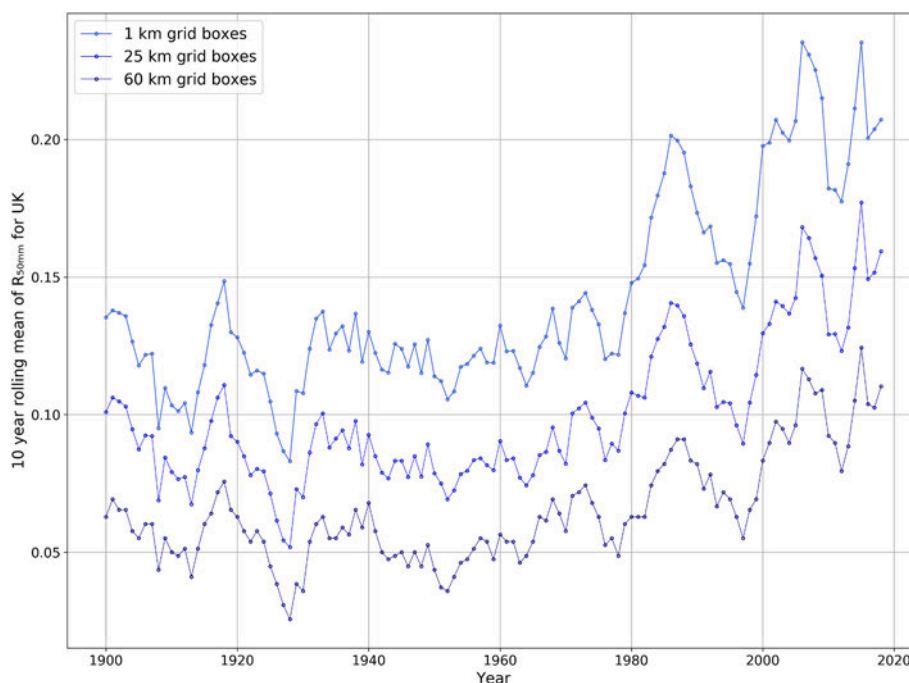


Fig. 4. Scatter plot showing the transient evolution of the 10 year rolling average of $R_{50mm,OND}$ gridded at 1 km, 25 km and 60 km resolutions, averaged over all UK grid boxes. Data is from the HadUK-Grid observations between 1891 and 2018.

Table 1

Table showing the average increase in $R_{50\text{mm_OND}}$ over the UK between the start of the 20th and 21st centuries (1891–1920 and 1989–2018) for HadUK-Grid observations at different spatial resolutions along with their 95% confidence intervals.

Gridded Resolution	Increase % $R_{50\text{mm}}$	95% Confidence Intervals
1 km	60	44–76
5 km	60	44–76
12 km	63	45–80
25 km	56	38–73
60 km	61	38–85

3.2. Trend in the UKCP18 projections

The UKCP18 projections from the regional climate model at 12 km resolution, show that an increase in $R_{50\text{mm_OND}}$ is present over almost all regions of the UK between 1990 and 2070 (Fig. 5b). This figure shows that for a large majority of the UK, the percentage increase in $R_{50\text{mm_OND}}$ is over 100%. This is true for both regions that have seen none/one of these events before, such as the East of England, and regions such as Wales and Western Scotland that see these events once or more per year. This change in $R_{50\text{mm_OND}}$ can already be seen when comparing past (1990) to present (2019), with extreme daily rainfall totals becoming more likely in most regions (Fig. 5a). However, it is important to note

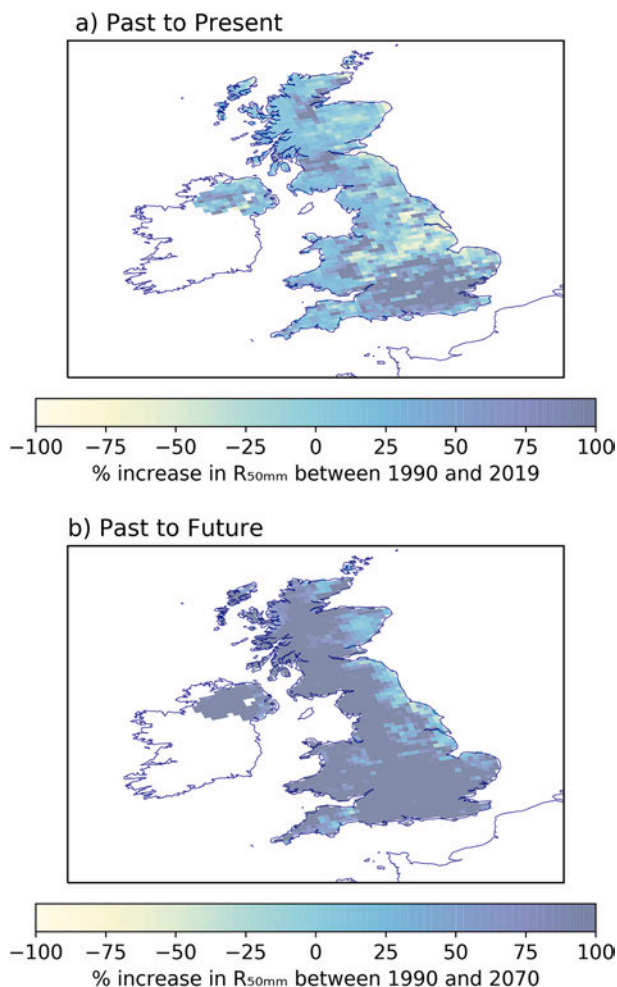


Fig. 5. Map showing the spatial distribution of the change in $R_{50\text{mm_OND}}$ between a) 1990 and 2019 and b) 1990 and 2070 using UKCP18 regional 12 km projections averaged over all ensembles over the UK. The data compares the mean of $R_{50\text{mm_OND}}$ over the following 20 year periods a) 1981–2000 and 2009–2028 and b) 1981–2000 and 2060–2079.

that over this short time period the observations may be dominated by multi-decadal natural variability rather than a climate signal.

Fig. 6a compares the transient evolution of $R_{50\text{mm_OND}}$ for both the observations and the UKCP18 regional climate projections, both at 12 km resolution. The observations show a linear trend from 1981 to 2018, with the UKCP18 projections also showing a linear trend over that time period. There is a small bias to overpredict the magnitude of $R_{50\text{mm_OND}}$ in the UKCP18 projections, when comparing it to the observations over that time period. A bias correction is applied by calculating the return period of $R_{50\text{mm_OND}}$ (Observations 1981–2011) and calculating the equivalent X mm daily precipitation total $R_{X\text{mm_OND}}$ (UKCP18 data 1981–2011) with the same return period (see section 2.2.2). This shows the model bias is quite small with $R_{50.00\text{mm_OND}}(\text{Obs}) = R_{52.67\text{mm_OND}}(\text{UKCP})$ for the same return period. Therefore, when analysing $R_{50\text{mm_OND}}$, $R_{52.67\text{mm_OND}}$ (UKCP) is used for the UKCP18 regional data as a bias correction.

The long-term trend in the UKCP18 projections shows an exponential increase in $R_{50\text{mm_OND}}$ over time (Fig. 6b). The exponential curve was fitted by using the transient evolution of UK mean surface temperature for OND (UKMST) and the relationship between $R_{50\text{mm_OND}}$ and UKMST. UKMST was chosen over North Atlantic mean surface temperature or Global mean surface temperature as it had the highest correlation with $\ln(R_{50\text{mm_OND}})$, with a correlation coefficient of $r = 0.91$. This found a 24% increase in $R_{50\text{mm_OND}}$ per Kelvin increase in UKMST using equations (4)–(7).

Using the fitted exponential trend, $R_{50\text{mm_OND}}$ has increased by 47% (95% CI: 43–51) between 1981 and 2019 and is projected to increase further by 85% (95% CI: 73–97) between 2019 and 2080. Over a 100-year period $R_{50\text{mm_OND}}$ is projected to increase by 172% (95% CI: 149–195) when comparing 1981 to 2080. These % increases in $R_{50\text{mm_OND}}$ between past, present and future were calculated with the following results for each step:

- The transient evolution of the UKCP18 12 km ensemble mean UKMST was found to be linear between 1981 and 2079, with a correlation coefficient of $r = 0.98$. The results showed that UKMST increases at a rate of 0.046 ± 0.001 K/year.
- The best empirical fit relating $R_{50\text{mm_OND}}$ to UKMST was exponential and not linear. The exponential relationship between the change in temperature smoothed over 1981–2079 and $R_{50\text{mm_OND}}$ using equation (4) was examined. This gives results of $A = 0.13 \pm 0.01$ and $b = 1.24 \pm 0.05$, translating to a 24% increase in the magnitude of $R_{50\text{mm_OND}}$ per Kelvin increase.
- Equation (7) was then used to calculate the theoretical $R_{50\text{mm_OND}}$ value for a given year, with the uncertainty calculated using the uncertainties on all three calculated parameters from (5) and (6).

These results show how the probability of the number of extreme precipitation events in the form of $R_{50\text{mm_OND}}$ has already changed over a small time period, from 1981 to 2019.

3.3. Climate signal in low resolution models >60 km

3.3.1. Anthropogenic climate change signal

The ALL and NAT simulations from HadGEM3-A 1960–2019 are compared to the HadUK-Grid observations of the same resolution (60 km) in Fig. 7. A bias correction is applied by calculating the return time of $R_{50\text{mm_OND}}$ (Observations 1970–2000) and calculating the equivalent X mm daily precipitation total return period for $R_{X\text{mm_OND}}$ (HadGEM3-A ALL simulations data 1970–2000). This X mm threshold is used for both ALL and NAT simulations. The bias corrected X mm threshold is 43.65 mm such that $R_{50.00\text{mm_OND}}(\text{Observations } 60 \text{ km}) = R_{43.65\text{mm_OND}}(\text{HadGEM3-A model } 60 \text{ km})$.

The trends of increased extreme daily precipitation totals seen in the observations at 60 km resolution and the higher 12 km resolution UKCP18 projections are not seen in the HadGEM3-A ALL simulation

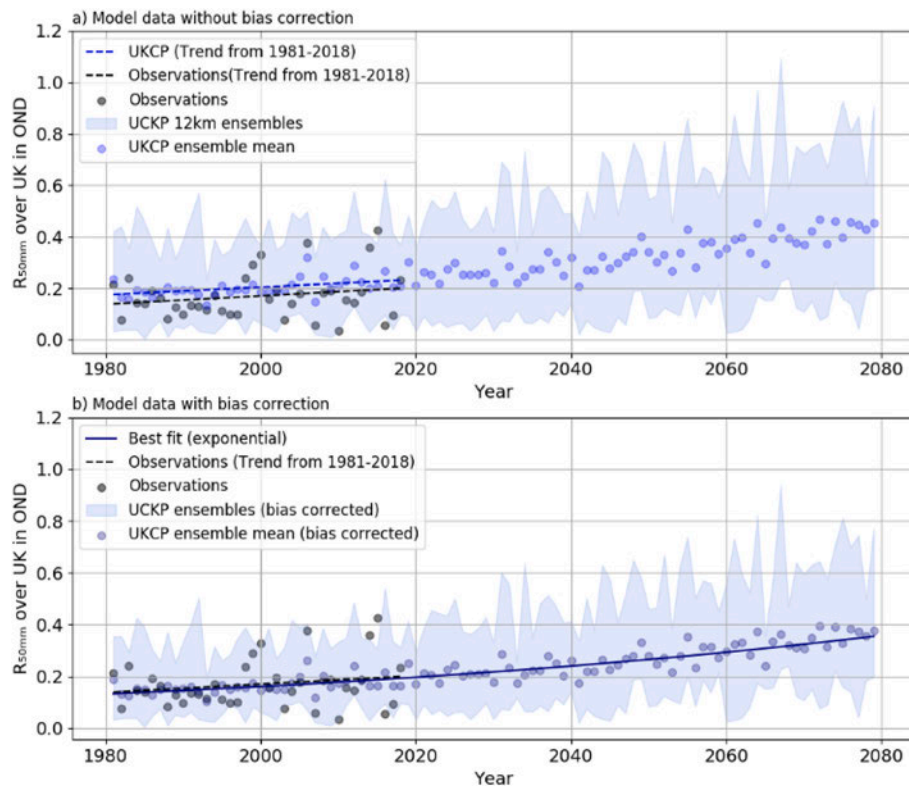


Fig. 6. Scatter plot showing the transient evolution of $R_{50mm,OND}$ between 1980 and 2080. a) This includes UKCP 2018 12 km rcm ensemble data, ensemble mean each year and observations. The linear best fit trend of the HadUK-Grid observations and UKCP18 rcm ensemble mean over the same period (1981–2018) are also plotted. b) This includes bias corrected UKCP 2018 data with a fitted exponential trend from 1981 to 2079, based on changes in UK mean surface temperature (UKMST).

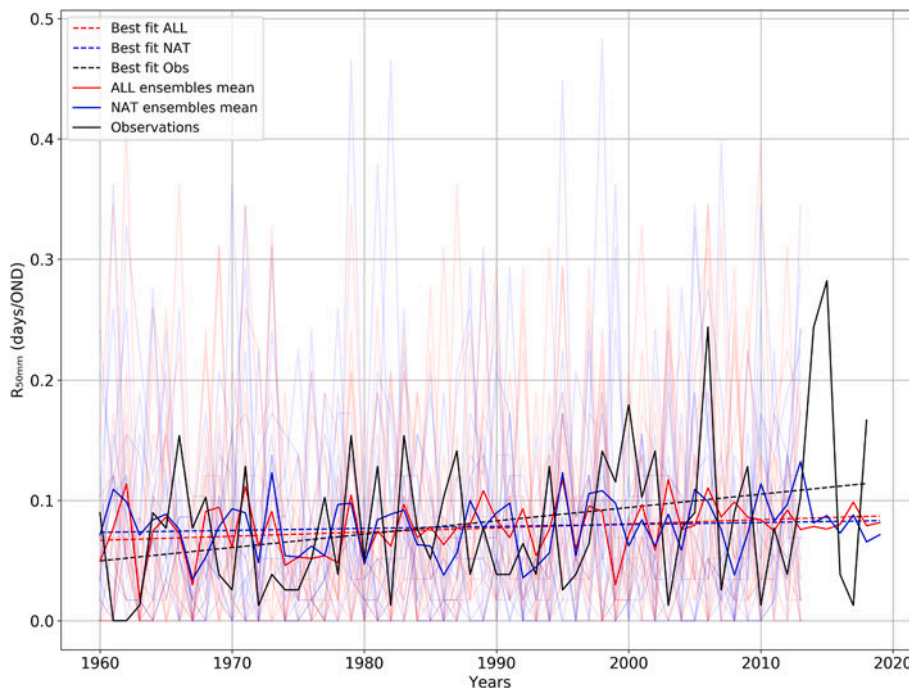


Fig. 7. Plot showing the transient evolution of $R_{50mm,OND}$ between 1960 and 2020 for grid boxes covering the UK. The bias corrected ALL (red) and NAT (blue) ensembles from HadGEM3-A model are shown along with the ensemble means and best linear fit. The HadUK-Grid 60 km observations (black) are also plotted along with the best linear fit over that period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

runs. Only a slight increase is seen in the HadGEM3-A ALL simulation runs for $R_{50.00\text{mm_OND}}$ over time, compared to the strong increases seen in the observations and regional UKCP18 projections. The NAT and ALL simulations show no strong statistical differences in the data or trend, suggesting no anthropogenic climate change impacts on $R_{50.00\text{mm_OND}}$. However, given the large differences between the transient evolution of $R_{50\text{mm_OND}}$ in HadGEM3-A and the observations at 60 km, the model is deemed not suitable for the analysis of extreme daily rainfall totals of such extremity for the UK.

3.3.2. Global models vs regional climate models

The UKCP18 global projections at 60 km resolution also underpredict extreme rainfall events for the UK. This is examined more specifically for $R_{50\text{mm_OND}}$ in Fig. 8, along with the HadGEM3-A ALL simulations. In the figure, the 15 Hadley Centre model simulations are examined from the UKCP18 projections.

The UKCP18 GCM ensembles, just like the HadGEM3-A ALL simulations at 60 km resolution, significantly underpredict the increasing trend in the number of extreme daily rainfall totals $R_{50\text{mm_OND}}$ seen in the HadUK-Grid observations at the same resolution. This suggests that for analysing indices of extreme rainfall such as $R_{50\text{mm_OND}}$, models with higher resolution than 60 km are required. Therefore, the importance of high-resolution models is not only important for convective rainfall which requires UKCP18 local 2.2 km (Lowe et al., 2019), but also for other forms seen in late autumn and winter, which for this study requires less than 60 km resolution.

3.4. Attribution of November 2019 South Yorkshire flooding

For the attribution of the 2019 South Yorkshire flooding, the $R_{x2\text{days_ON}}$ index described in section 2.4 is examined over 3 time slices. These 3 time slices; past (1983–1997), present (2013–2027) and future (2063–2077), contain 15 years of data for each of the 12 ensemble-members from the UKCP18 12 km regional climate model. The $R_{x2\text{days_ON}}$ index for the observations over the South Yorkshire region was 39.6 mm. The probability of the ON 2019 event in the observations was used to calculate the equivalent event in the UKCP18 data. This, after

rounding, was also approximately 39.6 mm (95% CI: 35.9–43.2), with the uncertainties calculated by bootstrapping the model data. The data used for the bias correction covered the period 1981–2019.

The fitted GEV distributions comparing past to present and past to future are shown in Fig. 9, along with the event threshold. The distribution of $R_{x2\text{days_ON}}$ has already shown a change in shape, as well as a shift to higher values, showing an increase in this index between 1990 and 2019. This change is projected to increase even further by 2070, where the probability of large $R_{x2\text{days_ON}}$ totals is set to become

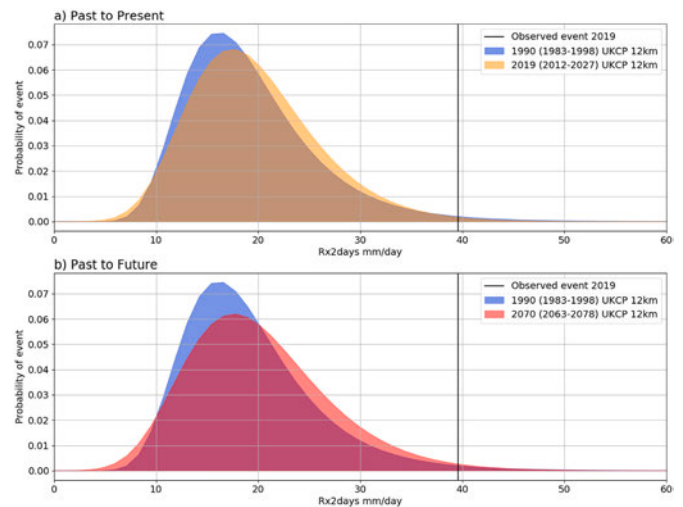


Fig. 9. Plot comparing the fitted GEV distributions of $R_{x2\text{days_ON}}$ for the South Yorkshire region with coordinates (53°N–54°N, 2.0°W–0.5°W) over past, present and future time slices. Each contains 15 years of data for each of the 12 ensemble-members from the UKCP18 12 km regional climate model. The threshold of the 2019 South Yorkshire observed event $R_{x2\text{days_ON}}$ after the bias correction is 39.6 mm. a) Compares the distributions centred on 1990 and 2070. b) Compares the distributions centred on 1990 and 2070.

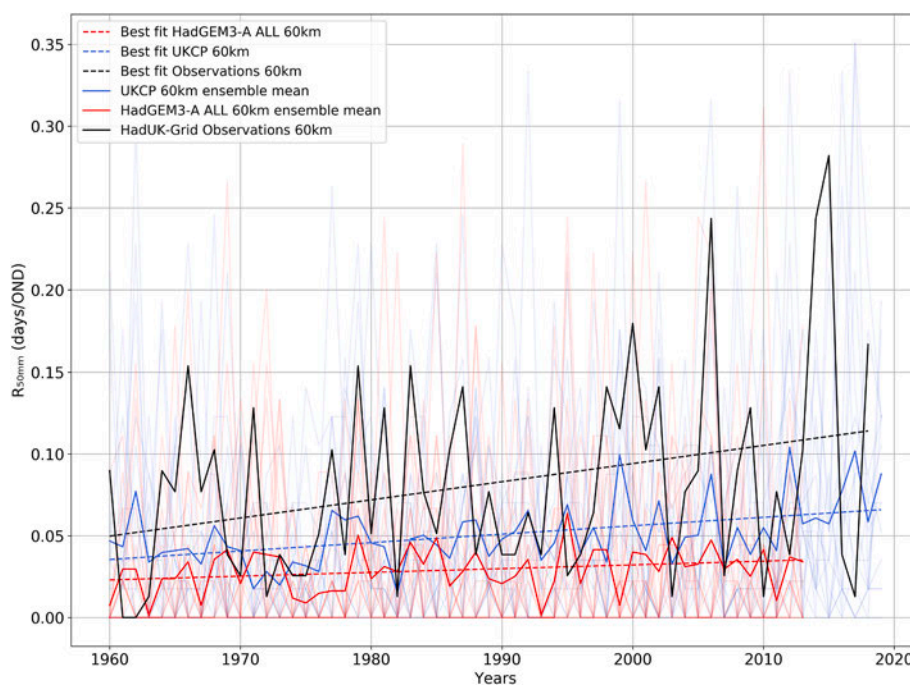


Fig. 8. Plot showing the transient evolution of $R_{50\text{mm_OND}}$ between 1960 and 2020 for grid boxes covering the UK before any bias corrections. The UKCP18 GCM (blue) and HadGEM3-A ALL (red) ensembles, ensemble mean and their best linear fits are plotted. The HadUK-Grid 60 km observations (black) are also plotted along with the best linear fit over that period. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

noticeably higher. The index value corresponding to the 75th percentile in 1990 shifts to the 71st (65–76) percentile in 2019 and the 67th (62–73) percentile in 2070. The intensity of the top 10% of events is also set to increase according to the projections. The 90th percentile for the sum of the two highest daily precipitation totals in ON for the past (1990), present (2019) and future (2070) are 55.1 mm (95% CI: 51.3–59.0), 56.1 mm (95% CI: 52.2–59.6) and 58.6 mm (95% CI: 55.3–62.0) respectively. The index seen in ON 2019 ($R_{x2days_ON} = 39.6$ mm) with two extreme daily precipitation totals is very far in the tail of the distribution as can be seen in Fig. 9. The number of samples (180 for each distribution) is insufficient to provide probability ratios in the far tail without large uncertainties when comparing different time slices. These changes do suggest however that the precipitation totals for the two most extreme daily events each October–November are likely to be more extreme in future for the top 10% of years, which will result in a higher risk of flooding. This risk has already increased since the end of the 20th century. However, with only a 5% increase in R_{x2days_ON} between 1990 and 2070 for the 90th percentile, this change in risk is relatively small compared to the projected increases in daily rainfall extremes.

4. Discussion and conclusions

Extreme daily rainfall totals in excess of 50 mm/day on a UK wide scale, seen most often in the seasons of autumn and winter have increased noticeably between 1960 and 2020. The index R_{50mm_OND} for the UK is the number of times per year where there are daily precipitation totals of over 50 mm in OND per grid box on average. R_{50mm_OND} has already increased in the observations by 60% (95% CI: 44–76) between the start of the 20th and 21st centuries (1905–2003). The UKCP18 projections 12 km regional climate model with an emissions scenario of RCP 8.5 shows that there will be an exponential increase in R_{50mm_OND} . Between 2019 and 2080, R_{50mm_OND} is projected to increase by 85% (95% CI: 73–97). The model showed an increase of 47% (95% CI: 43–51) from 1981 to 2019, and an increase of 172% (95% CI: 149–195) over the 100 years of data between 1981 and 2080. This increase is already growing noticeably within the space of less than 40 years (1981–2019) and over the last century in the observations, suggesting current extreme daily rainfall totals are already being influenced by climate change. R_{50mm_OND} is shown to increase at a rate of 24% per Kelvin increase in UKMST, based on UKCP18 projections using regional climate model data and the RCP8.5 scenario. This increase in the number of extreme events with temperature may be linked to anthropogenic climate change and the CC relation, however an attribution study would be required to establish this. Other factors contributing to the increase could include changes in patterns of the atmospheric circulation, but these have not been investigated in this paper.

These events are significantly more likely to occur in Wales, Northern Ireland and the West Coast of Scotland and will have the largest fingerprint on this increase. However, examining changes in R_{50mm_OND} over all regions of the UK using UKCP18 projections shows increases in the number of these events in almost all regions. This includes those in central and eastern England, where such events have not yet been seen in the observations, to Western Scotland, which can experience these daily totals multiple times a year. This therefore has relevance for all parts of the UK. Regions that have not experienced those extreme daily precipitation totals before, whose likelihood is set to increase significantly in the 21st century, could be at considerable risk of flooding.

This paper has not examined the direct impacts of flooding over time which could be looked at for further work. Changes in land surface, seasonal precipitation totals, potential evapotranspiration, as well as adaptive measures such as flood defences will have significant bearings on the risk of flood events. However, a key component, extreme rainfall totals, are set to increase at an exponential rate as a result of climate change. This paper shows that for the study of some extreme rainfall indices, such as the one used, the GCMs did not simulate the increasing

trend or number of totals seen in the observations and regional climate model. This is likely to be because larger grid boxes are not as good at capturing local rainfall. Therefore, the importance of high-resolution models is not only important for convective rainfall, which requires UKCP18 local 2.2 km projections, but also for other forms seen in late autumn and winter, which for this study required less than 60 km resolution.

The combination of the two extreme rainfall totals seen over the South Yorkshire region in October–November 2019 were extremely unusual for that region. The combination of both contributed to the large flooding event seen in that region on the 7th of November 2019, where two rivers burst their banks. The R_{x2days_ON} index examined over 15-year time slices representing past, present and future showed a shift in the mean of the two highest daily rainfall totals in ON to higher values in the South Yorkshire region over time. The 75th percentile of R_{x2days_ON} in 1990 becomes the 71st (65–76) percentile for 2019 and is projected to become the 67th (62–73) percentile for 2070, based on emission levels for RCP 8.5. The event which saw 79.2 mm fall on that region over the two days with highest daily totals was far in the tail of the GEV and is unprecedented in the South Yorkshire region. The only other event over 60 mm in the HadUK-Grid observations record was 65.6 mm in ON 2000. For the 2019 specific extreme event we were unable to show whether climate change had changed the probability of the event occurring with the data available. However, we showed that the intensity of the top 10% of R_{x2days_ON} are set to increase. The 90th percentile for the sum of the two highest daily precipitation totals in ON for the past (1990), present (2019) and future (2070) are 55.1 mm (95% CI: 51.3–59.0), 56.1 mm (95% CI: 52.2–59.6) and 58.6 mm (95% CI: 55.3–62.0) respectively.

Author statement

Daniel Cotterill: Conceptualization, Investigation, Methodology, Software, Validation, Formal Analysis, Writing - Original Draft and Visualisation. Peter Stott: Supervision, Writing- Review & Editing and Project Administration. Nikolaos Christidis: Supervision, Writing- Review & Editing, Software and Formal Analysis. Elizabeth Kendon: Supervision and Writing- Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Allen, M., Ingram, W., 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature* 419, 228–232. <https://doi.org/10.1038/nature01092>.
- BBC News, 2019. England flooding: woman dies after being swept away in Derbyshire. <https://www.bbc.co.uk/news/uk-england-50343977>. (Accessed 6 August 2020).
- Berg, P., Moseley, C., Haerter, J., 2013. Strong increase in convective precipitation in response to higher temperatures. *Nat. Geosci.* 6, 181–185. <https://doi.org/10.1038/ngeo1731>.

- Chan, S., Kendon, E., Roberts, N., Fowler, H., Blenkinsop, S., 2016. Downturn in scaling of UK extreme rainfall with temperature for future hottest days. *Nat. Geosci.* 9, 24–28. <https://doi.org/10.1038/ngeo2596>.
- Christidis, N., Stott, P.A., Scaife, A., Arribas, A., Jones, G.S., Copsey, D., Knight, J.R., Tennant, W.J., 2013. A new HadGEM3-A based system for attribution of weather and climate-related extreme events. *J. Clim.* 26, 2756–2783. <https://doi.org/10.1175/JCLI-D-12-00169.1>.
- Christidis, N., Stott, P.A., 2015. Extreme rainfall in the United Kingdom during winter 2013/14: the role of atmospheric circulation and climate change [in “explaining extremes of 2014 from a climate perspective”]. *Bull. Am. Meteorol. Soc.* 96 (12), S46–S50.
- Ciavarella, A., Christidis, N., Andrews, M., Groenendijk, M., Rostron, J., Elkington, M., Burke, C., Lott, F.C., Stott, P.A., 2018. Upgrade of the HadGEM3-A based attribution system to high resolution and a new validation framework for probabilistic event attribution. *Weather Clim. Extrem.* 20, 9–32. <https://doi.org/10.1016/j.wace.2018.03.003>.
- FloodList News, 2019. UK – insurance losses from northern England floods could reach \$250 million. Insurance UK. <http://floodlist.com/insurance/uk/insurance-losses-northern-england-floods-november-2019>. (Accessed 6 August 2020).
- Fowler, H.J., Kilsby, C.G., 2003. A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *Int. J. Climatol.* 23, 1313–1334. <https://doi.org/10.1002/joc.943>.
- Fowler, H.J., Lenderink, G., Prein, A.F., et al., 2021. Anthropogenic intensification of short-duration rainfall extremes. *Nat Rev Earth Environ* 2, 107–122. <https://doi.org/10.1038/s43017-020-00128-6>.
- Hannaford, J., 2015. Climate-driven changes in UK river flows: a review of the evidence. *Prog. Phys. Geogr.: Earth Environ.* 39 (1), 29–48. <https://doi.org/10.1177/0309133314536755>.
- Hollis, D., McCarthy, M., Kendon, M., Legg, T., Simpson, I., 2019. HadUK-Grid—a new UK dataset of gridded climate observations. *Geosci Data J* 6, 151–159. <https://doi.org/10.1002/gdj.378>.
- IPCC, 2013. Summary for Policymakers. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Kay, A.L., Crooks, S.M., Pall, P., Stone, D.A., 2011. Attribution of Autumn/Winter 2000 flood risk in England to anthropogenic climate change: a catchment-based study. *J. Hydrol.* 406, 97–112. <https://doi.org/10.1016/j.jhydrol.2011.06.006>.
- Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C., Senior, C.A., 2014. Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Change* 4, 570–576.
- Kendon, M., McCarthy, M., Jevrejeva, S., Matthews, A., Legg, T., 2017. State of the UK climate 2017. *Int J Climatol.* 2018 38 (Suppl. 2), 1–35. <https://doi.org/10.1002/joc.5798>.
- Kendon, M., 2019. Met Office national climate information Centre. Severe flooding South Yorkshire. November 2019. https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/2019/2019_012_november_rain.pdf. (Accessed 6 August 2020).
- Lavers, D.A., Allan, R.P., Wood, E.F., Villarini, G., Brayshaw, D.J., Wade, A.J., 2011. Winter floods in Britain are connected to atmospheric rivers. *Geophys. Res. Lett.* 38, L23803. <https://doi.org/10.1029/2011GL049783>.
- Lenderink, G., van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nat. Geosci.* 1, 511–514. <https://doi.org/10.1038/ngeo262>.
- Lowe, J.A., Bernie, D., Bett, P.E., Bricheno, L.M., Brown, S.C., Calvert, D., Clark, R., Karen, Eagle, Edwards, T.L., Fosser, G., Maisey, P., McInnes, R.N., McSweeney, C., Yamazaki, K., Belcher, S., 2019. UKCP18 science overview Report november 2018 (Updated March 2019). <https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf>.
- Luu, L.N., Vautard, R., Yiou, P., van Oldenborgh, G.J., Lenderink, G., 2018. Attribution of extreme rainfall events in the South of France using EURO-CORDEX simulations. *Geophys. Res. Lett.* 45, 6242–6250. <https://doi.org/10.1029/2018GL077807>.
- Norris, J., Chen, G., Li, C., 2020. Dynamic amplification of subtropical extreme precipitation in a warming climate. *Geophys. Res. Lett.* 47, e2020GL087200 <https://doi.org/10.1029/2020GL087200>.
- Otto, F.E.L., van Oldenborgh, G.J., van der Wiel, K., Philip, S., Kew, S., Uhe, P., Cullen, H., 2018. Climate change increases the probability of heavy rains in Northern England/Southern Scotland like those of storm Desmond - a real-time event attribution revisited. *Environ. Res. Lett.* 13 (2), 024006.
- Pall, P., Aina, T., Stone, D.A., Stott, P.A., Nozawa, T., Hilberts, A.G.J., Lohmann, D., Allen, M.R., 2011. Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature* 470, 382–385. <https://doi.org/10.1038/nature09762>, 2011.
- Schaller, N., Kay, A.L., Lamb, R., Massey, N.R., van Oldenborgh, G.J., Otto, F.E.L., Sparrow, S.N., Vautard, R., Yiou, P., Ashpole, I., Bowery, A., Crooks, S.M., Hausteiner, K., Huntingford, C., Ingram, W.J., Jones, R.G., Legg, T., Miller, J., Skeggs, J., Wallom, D., Weisheimer, A., Wilson, S., Stott, P.A., Allen, M.R., 2016. Human influence on climate in the 2014 Southern England winter floods and their impacts. *Nat. Clim. Change* 6 (6). <https://doi.org/10.1038/nclimate2927>.
- Stocker, T.F., Qin, D., Plattner, G.-K., Alexander, L.V., Allen, S.K., Bindoff, N.L., Bréon, 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., Mikhov, I.I., Piao, S., Ramaswamy, V., Randall, D., Rhein, M., Rojas, M., Sabine, C., Shindell, D., Talley, L.D., Vaughan, D.G., Xie, S.-P., 2013. Technical summary. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Vautard, R., Christidis, N., Ciavarella, A., Alvarez-Castro, M., Bellprat, O., Christiansen, B., Colfescu, I., Cowan, T., Doblas-Reyes, F., Eden, Jonathan, Hauser, M., Hegerl, G., Hempelmann, N., Klehmet, Katharina, Lott, F., Nangini, C., Orth, R., Radanovics, S., Seneviratne, S., Yiou, P., 2018. Evaluation of the HadGEM3-A simulations in view of detection and attribution of human influence on extreme events in Europe. *Clim. Dynam.* <https://doi.org/10.1007/s00382-018-4183-6>.
- Vrac, M., Vaittinada Ayar, P., Yiou, P., 2013. Trends and variability of seasonal weather regimes. *Int. J. Climatol.* 34, 472–480. <https://doi.org/10.1002/joc.3700>.
- Westra, S., Alexander, L.V., Zwiers, F.W., 2013. Global increasing trends in annual maximum daily precipitation. *J. Clim.* 26, 3904–3918. <https://doi.org/10.1175/JCLI-D-12-00502.1>.