

Evidence for trends in heavy rainfall events over the UK

BY TIMOTHY J. OSBORN¹ AND MIKE HULME²

¹*Climatic Research Unit and* ²*Tyndall Centre for Climate Change Research,
School of Environmental Sciences, University of East Anglia,
Norwich NR4 7TJ, UK (t.osborn@uea.ac.uk)*

Published online —

Daily precipitation in the UK has changed over the period 1961–2000, becoming on average more intense in winter and less intense in summer. Recent increases in total winter precipitation are shown to be mainly due to an increase in the amount of precipitation on wet days, with a smaller contribution in the western UK from a trend towards more wet days. If the wet-day amounts are modelled using a gamma distribution, then positive trends in its scale parameter are found across almost all of the UK, consistent with an increased frequency of heavy winter precipitation. Non-parametric analyses confirm an increase in the contribution of heavy events to winter precipitation totals. Analysis of multi-day sequences of heavy rainfall indicate a corresponding increase in their frequency. Results for summer show almost opposite trends: decreased precipitation totals (driven more equally by fewer wet days *and* reduced wet-day amounts), decreases in gamma scale parameter (although accompanied by a trend towards a less positively skewed distribution) and decreases in the occurrence of heavy precipitation (whether defined parametrically or non-parametrically). A more sparse network of weather stations with data back to 1901 suggests that the recent winter changes are unusual, while the recent summer changes are not, though the poorer coverage reduces the confidence in these longer-period results.

Keywords: UK climate; extreme weather; precipitation; climate change

1. Introduction

Global warming (induced by some combination of climate forcings, probably including anthropogenic emissions of greenhouse gases) has occurred over the past century, estimated to be in the range 0.4–0.6 K over that period (Folland *et al.* 2001). Analysis of numerical-climate-model simulations (see, for example, Hulme *et al.* 1998) and of short observational records suggests that globally averaged precipitation increases with increasing global-mean temperature, due to an intensification of the hydrological cycle. More extensive observational records exist over land, but here the picture is less clear: Hulme *et al.* (1998) found a positive relationship between global-mean precipitation over land and global-mean temperature, but only the interannual variability and the century-scale trends contribute to this—at the interdecadal time-scale there is no relationship between them. The reason for this more ambiguous relationship over land is that there is a closer balance between regions of drying and regions

OK?

of wetting over land than there is over the oceans. Nevertheless, there are coherent regions (see, for example, Folland *et al.* 2001, fig. 2.25(i)) where precipitation has increased during the 20th century, such as the extra-tropics of both hemispheres, though with some local and seasonal variation.

Given an increase in mean precipitation, we might expect an increase in the occurrence of heavy precipitation (though it is not guaranteed). There are various physical reasons (Trenberth 1999) why an increase in heavy precipitation may be greater than an increase in the mean (and indeed it is possible that heavy precipitation occurrence could increase even when mean precipitation decreases, if there is a more radical change in the precipitation distribution). While the relationship between precipitation and temperature at the local scale can be rather complicated, at the large or even global scale, warming will enhance the evaporation of water from the surface and will also increase the water-holding capacity of the air (the saturation vapour pressure). The atmosphere is not always saturated, however, and thus the mean vapour pressure is less than the saturation vapour pressure. If we assume that the relative humidity does not change, then the increase in mean vapour pressure due to a given warming will be less (in absolute units) than the increase in saturation vapour pressure. Given that the heavy precipitation events will only occur on days when the atmosphere is saturated, this implies that the increase in heavy precipitation events will be larger than the increase in mean precipitation. Further, the nonlinearity of the Clausius–Clapeyron relationship (see Appendix B of Hartmann 1994) between saturation vapour pressure and temperature means that the moisture precipitated by the cooling of a saturated parcel of air during a precipitation-forming event will be greater the higher the initial air temperature. This enhanced condensation also releases more latent heat, which may strengthen the intensity of the circulation in the storm or frontal system, increasing moisture convergence and providing a positive feedback on precipitation rate. There are additional reasons why precipitation extremes may increase by more than the mean (e.g. if the atmospheric lapse rate is enhanced, resulting in reduced stability), though all remain to be quantified in the real climate system. Note that temperature has only an indirect influence on precipitation intensity and these arguments will not hold in every instance.

Some consideration is given next to statistical issues. Daily precipitation totals (excluding dry days) often follow a gamma distribution, whose probability density function, $f(x)$, is given by

$$f(x) = \frac{(x/\beta)^{\alpha-1} e^{-x/\beta}}{\beta \Gamma(\alpha)},$$

where the precipitation amount (x), the gamma shape (α) and scale (β) parameters are all greater than zero, and Γ is the gamma function (see eqns 4.23 and 4.24 of Wilks 1995). The mean and variance of x are $\alpha\beta$ and $\alpha\beta^2$, respectively. Gregory *et al.* (1993) fitted the gamma distribution to precipitation amounts from various UK regions and report typical parameter values. The shape parameter controls the skewness of the distribution (figure 1a), varying from a highly skewed exponential distribution when $\alpha = 1$ to a more Gaussian-like distribution for high values of α . The scale parameter simply stretches the distribution out while maintaining the skew given by α (increasing the scale parameter by some factor is equivalent to multiplying each value by the same factor). $f(x)$ can be integrated from X to ∞ to obtain $P(x > X)$, i.e. the probability of exceeding a particular threshold X , given

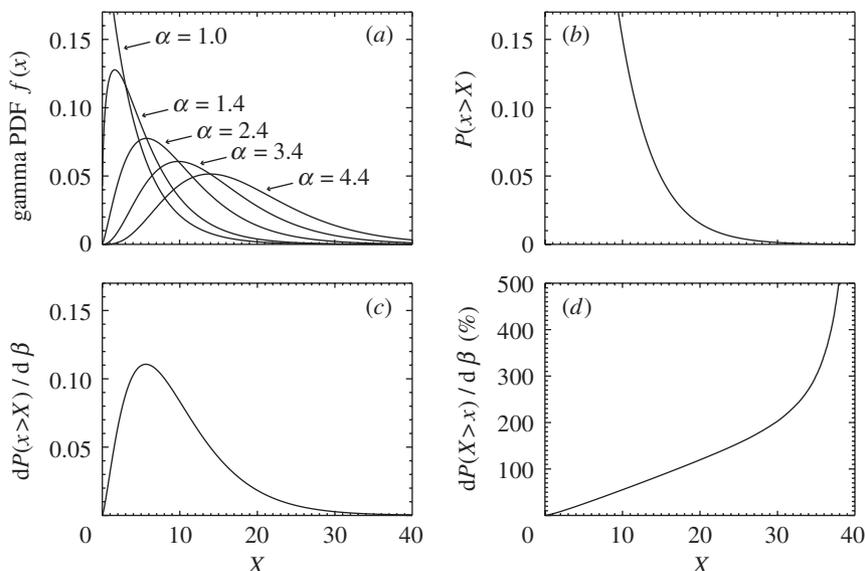


Figure 1. (a) Gamma-distribution probability density functions with $\beta = 4.1$ mm and various values of α (1.0, 1.4, 2.4, 3.4 and 4.4). (b) Integral of (a) from X to ∞ to give the probability of precipitation exceeding X . (c) Derivative of (b) with respect to β . (d) Derivative of (b) with respect to β , expressed as a percentage of the initial probability (b). Results in (b)–(d) are shown for $\beta = 4.1$ mm and $\alpha = 1.4$.

that it is a wet day. This is shown in figure 1b for parameter values ($\alpha = 1.4$ and $\beta = 4.1$ mm) that are typical of daily precipitation totals in the UK.

Various observation- and simulation-based studies (see, for example, Groisman *et al.* 1999; Wilby & Wigley 2001) indicate that it is variations in β , the scale parameter, that explain most of the seasonal, spatial, interannual and climate-change-related variability in precipitation (though, over large spatial distances, or in regions with strong seasonality, the shape parameter can become important). The effect of a change in the scale parameter on the probability of precipitation exceeding a threshold is given by the first derivative of $P(x > X)$ with respect to β . Figure 1c shows this derivative evaluated for $\alpha = 1.4$ and $\beta = 4.1$ mm. If β increases, the distribution $f(x)$ is stretched out in the x -direction and the probability of exceeding any threshold is increased: hence $dP/d\beta$ is positive everywhere. For these particular values of α and β , $dP/d\beta$ exhibits a peak at the $X = 6$ mm threshold. If the derivative (figure 1c) is expressed as a percentage of the initial probability (figure 1b), then it becomes clear (figure 1d) that the *relative* change in the frequency of extreme events, due to an increase in β , is greater the higher the extreme (see also Groisman *et al.* 1999).

The final point to consider in this introductory discussion is that the likelihood of detecting real trends in the frequency of extreme events is low, and becomes lower the more extreme the event. This was demonstrated by Frei & Schär (2001), who applied known trends in the scale parameter to synthetic data series and then attempted to identify (using logistic regression) statistically significant trends in the frequency of various extreme events. Given a time-series length equal to 100 seasons of daily data, the effect of increases of up to 20% in the scale parameter on the frequency of (various magnitude) events was rarely detected. With increases of 20–30% in the

scale parameter, they detected more often than not trends in the frequency of events that had an initial return period of between 10 and 100 days—hardly very ‘extreme’! For rarer events than this, the sampling noise grew and trends were unlikely to be detected in individual series.

The purpose of the present study is to consider the evidence for changes over recent decades in the occurrence or magnitude of heavy precipitation events over the UK, in the context of the physical and statistical considerations discussed in this introduction. It is clear that we cannot focus on very extreme events (though they may be of most concern) because we would be unlikely to detect any significant changes; instead we focus on heavy, but quite frequent, events and combine information spatially across the UK to reduce sampling error and increase the chance of detecting any real trends that may exist. This study greatly extends the earlier work reported by Osborn *et al.* (2000) by improving the spatial coverage (§ 2), by considering additional precipitation statistics (§ 3), by bringing the analysis period through to 2000/2001 (§ 4), and finally by undertaking a brief analysis of multi-day precipitation events (§ 5).

2. UK daily precipitation data

A set of 146 weather-station records with daily precipitation observations was extracted from the archives of the British Atmospheric Data Centre (BADC, see www.badc.rl.ac.uk/), selected on the basis of record length and completeness, the requirement that there were no major site moves during the analysis period, and to provide a reasonable spatial and temporal coverage over the UK. The location of these stations is clear in figures 2 and 3. All these stations have complete, or nearly complete, data for the period 1961–1995. Compared with the earlier study of Osborn *et al.* (2000), there is additional coverage of the Channel Islands, Isles of Scilly, Northern Ireland and some of the Scottish islands. In addition, data up to autumn 2000 from about 100 (depending on season), and through to spring 2001 from about 75, stations were available. To provide a longer temporal context for the recent decades, analysis of the period 1901–1995 is also undertaken, but based on only 32 station records of which none are in Wales and only two are in Scotland. The spatial coverage is rather poor for the entire century, though notably better than the 11 station records covering the 1908–1995 period used by Osborn *et al.* (2000).

Author: sense of last sentence of caption?

3. Observed trends in precipitation statistics

Figures 2 and 3 show trends in various statistical parameters computed over the period of best data coverage, 1961–1995, for winter and summer (note that we assign winters to the year in which the January falls). Total winter precipitation (figure 2*a*) has increased almost everywhere, with largest relative increases in the western UK—especially northwestern England and western Scotland, where some stations exhibit trends of more than a 50% increase over the 35-year period. An increased number of wet days in the western UK (figure 2*b*) has contributed to the increased precipitation totals, but the main factor (affecting the whole of the UK) has been an increase in the amount of precipitation falling on those days when it does rain (figure 2*c*). A gamma distribution has been fitted (using a maximum-likelihood approximation) to these

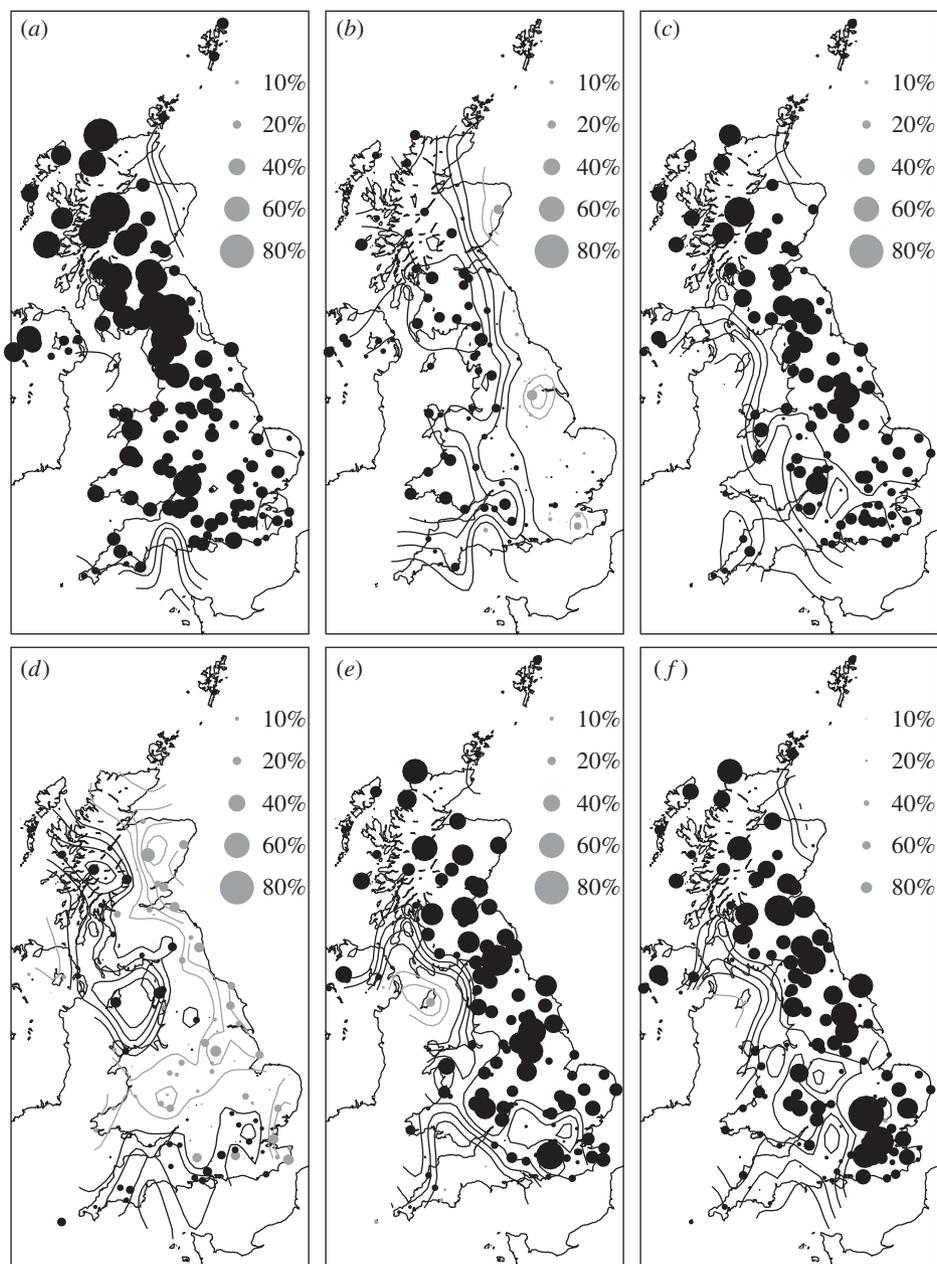


Figure 2. Trends in winter (a) total precipitation; (b) wet day (above 0.4 mm) probability; (c) mean wet-day amount; (d) gamma shape parameter; (e) gamma scale parameter; and (f) heavy precipitation (above 15 mm) probability; evaluated over the period 1961–1995, and expressed as a percentage change over that 35-year period (relative to the 1961–1990 baseline mean of each parameter). Each station is represented by a dot whose radius is a linear function of the trend magnitude, black for positive trends, grey for negative trends. A key is included and contour lines are marked corresponding to + (black) or – (grey) 5, 10, 15 and 20% per 35 years (15, 30, 45 and 60% per 35 years for panel (f)).

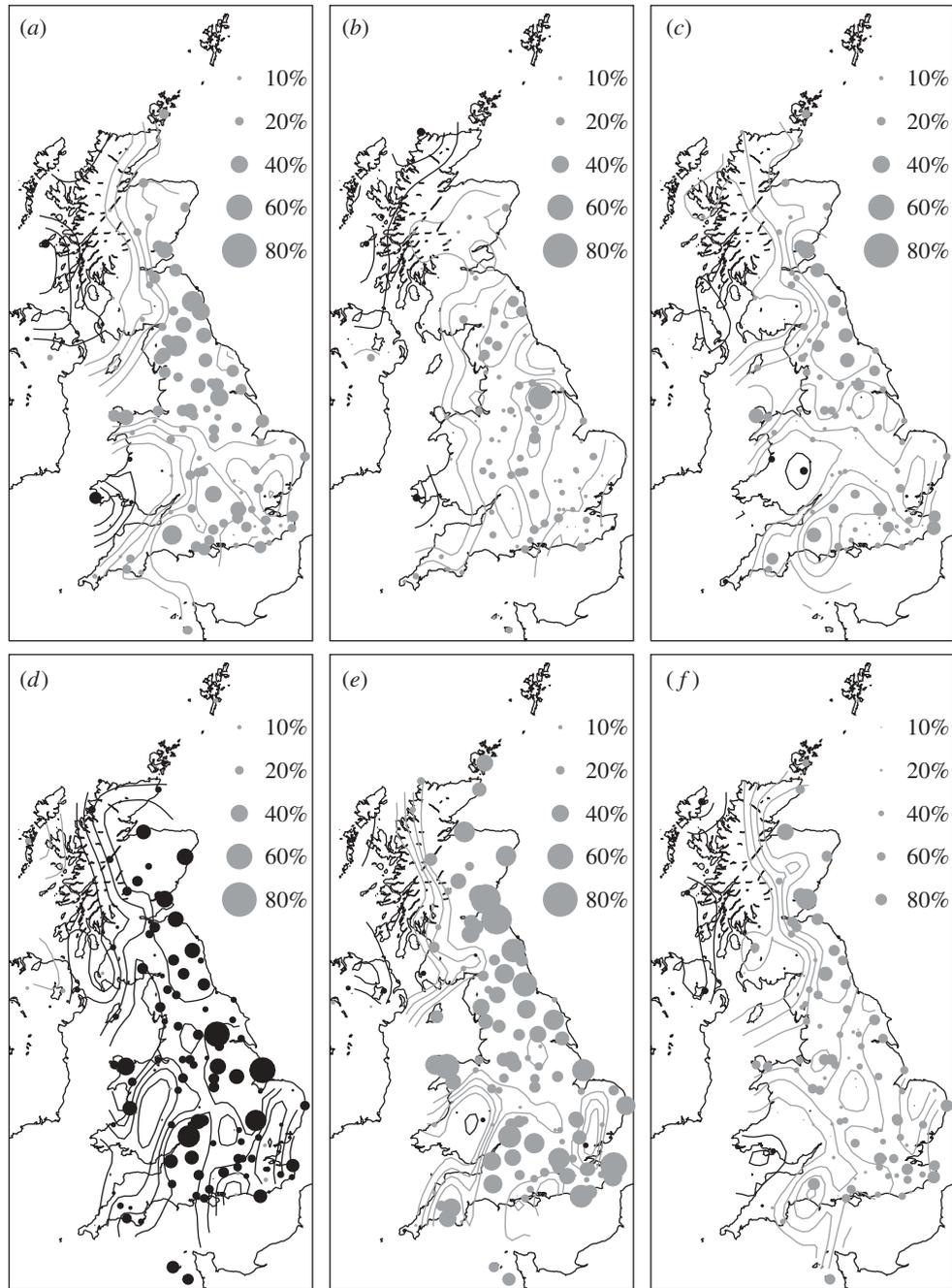


Figure 3. Same as figure 2, but for summer.

wet-day amounts, on a year-by-year basis, and the trends in the gamma distribution parameters indicate heterogeneous changes in the distribution shape (figure 2*d*, with decreases in this parameter in the eastern and central regions corresponding to enhanced distribution skewness), while a much more uniform increase in the dis-

tribution scale (figure 2e) with the exception of little change or small decreases in scale for the Isle of Man and southwestern UK. Assuming that the gamma distribution is a good fit to the wet-day amounts at each station, the arguments presented in §1 would suggest that this increase in the scale parameter, which is responsible for much of the increase in the mean winter precipitation, implies an even greater increase in the frequency of heavy rainfall events. Figure 2f shows the results for a single, arbitrarily selected, heavy-event definition: the probability of a single daily precipitation total exceeding 15 mm. In winter, this probability has increased in the areas where the scale parameter has increased (and this is despite the small decreases in the number of wet days in some eastern regions). Note also the different scale used in figure 2f compared with the other panels; many stations exhibit trends exceeding a 100% increase over the 1961–1995 period.

In contrast, summer precipitation totals (figure 3a) have declined in all regions except western Scotland, south Wales and parts of Northern Ireland, with typical decreases of between 10 and 40% over the 1961–1995 period. This decrease has been driven by a combination of fewer wet days (figure 3b) and reduced precipitation amounts on wet days (figure 3c). The wet-day amounts have exhibited near-uniform trends in both shape and scale parameters: the shape parameter has increased (figure 3d), resulting in a less-skewed distribution and an increase in the mean amount, which has been more than offset by a decrease in the scale parameter (figure 3e). Overall, the scale parameter changes dominate to obtain the decreased mean wet-day amounts seen in figure 3c. The combined effects of the changes in the shape and scale parameters is difficult to predict, because they can have opposing influences on the probability of extremes. For the 15 mm threshold (figure 3f), the scale parameter dominates and there is a decrease in the occurrence of these events except in western Scotland, Northern Ireland and southwestern England and Wales.

Results of a similar analysis for spring and autumn (not shown) show much less coherent patterns of trends, with trends of opposite sign occurring in different parts of the UK. What they do confirm, however, is the importance of the gamma scale parameter changes in controlling both the mean wet-day amount and the probability of heavy precipitation (again, for the arbitrary 15 mm threshold), since all three spatial patterns are very similar in each season.

Analysis of the slightly more sparse datasets that run through to 2000 or 2001 results in very similar trend patterns as for the 1961–1995 period, for all four seasons. There are slight reductions in trend magnitude in most cases, except for the probability of heavy precipitation in autumn, which shows stronger positive trends in southern and central England when data through to autumn 2000 are included.

4. Trends in single-day precipitation extremes

(a) Spatial patterns of trends

If the gamma distribution is assumed to be a good fit to daily precipitation measurements from UK weather stations, then the analysis reported in §3 suggests that extremes have increased in frequency in winter and decreased during summer, and this is supported by the analysis of the occurrence of events over an *arbitrarily selected* threshold. Next we present results from a non-parametric approach that does not rely upon any distributional assumptions, and that uses data-adaptive thresholds to categorize precipitation events (by ‘data adaptive’ we mean that the thresholds are

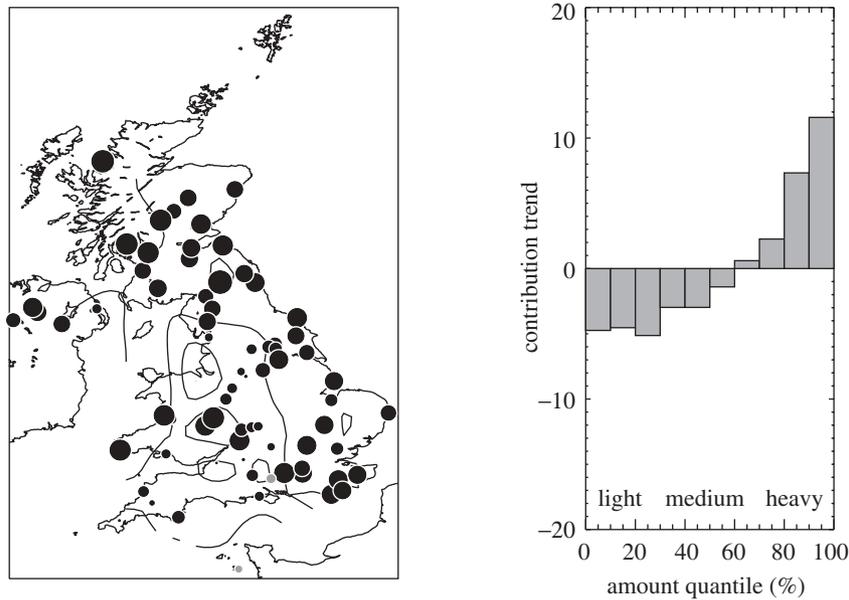


Figure 4. Dominant spatial pattern and associated trend structure of the contribution to winter totals of the 10 categories of precipitation events. The bars indicate positive or negative trends over 1961–2001 in the contribution from the 10 categories. Large black dots on the map indicate agreement between this overall trend structure and the trends at a particular station; large grey dots indicate that the opposite trends are occurring at that station; small dots indicate that the signal of changing contributions shown by the bars is *not* a good description of the changes that have taken place at that station. Idealized contouring is used to indicate the broad-scale patterns.

allowed to vary according to the characteristics of the precipitation data at each location and with the time of the year). Each daily precipitation amount is assigned to one of 10 different categories, from the lightest (1) to the heaviest (10), where the category ranges are defined so that events in each category contribute 10% of the total precipitation over a long reference period (1961–1990) (see Osborn *et al.* (2000) for further details).

Of most interest here is the category containing the heaviest precipitation events, category (10). The minimum threshold for this category depends upon location and time of year, varying in western UK from *ca.* 20 mm d⁻¹ in spring to *ca.* 35 mm d⁻¹ in autumn, and in eastern UK from *ca.* 15 mm d⁻¹ in winter to *ca.* 35 mm d⁻¹ in late summer. This variation in category definition is useful from a climatological point of view, since it allows identification of changes that are unusual for that location or time of year. For some impacts sectors, however, it is the absolute magnitude of the events that is most important, and for those sectors it is important to note that changes in the late summer and autumn category (10) events will be more important than changes in the winter or spring category (10) events.

The contribution from precipitation events in each category to the seasonal total precipitation is computed for each season in the time-series. Linear trends are fitted to these contribution time-series at each station and for each category, over the period 1961–2000 (to 2001 for winter and spring). Principal component analysis of these

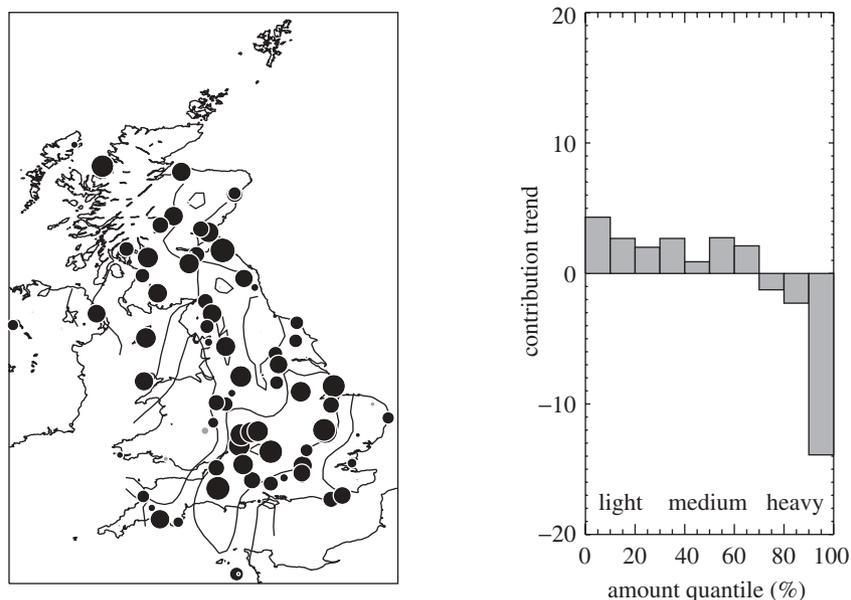


Figure 5. Same as figure 4, but for summer and for the period 1961–2000.

station and category trends is used to identify the most dominant spatial pattern of change and its associated trend structure for each season. For winter (figure 4), the dominant structure has decreasing contributions from the lightest six categories and increasing contributions from the heaviest four categories, especially the top category. This trend structure is a reasonable representation of trends across most of the UK, especially Scotland, Northern Ireland, eastern England and South Wales.

The *opposite* trend structure is found as the dominant change in summer (figure 5), and is applicable to most locations across the UK, except for parts of Wales. Thus there is a decreasing contribution during 1961–2000 from the heaviest category of daily precipitation events in summer at many locations. The analysis of Osborn *et al.* (2000) for the period 1961–1995 found that changes in spring and autumn were not of uniform sign across the country, with areas of increasing intensity being matched by areas of decreasing intensity. Now that the results are updated to 2000 or 2001, the regions with increasing intensity trends (i.e. positive trends in the higher categories) have expanded (not shown) and are now predominant in both spring and autumn.

(b) Temporal variability

It is clear from figures 4 and 5 that there are near-uniform changes across the UK in the contributions from the precipitation categories, and it is therefore meaningful to compute an average of the contribution time-series across all stations in the dataset (Osborn *et al.* (2000) showed that this averaging was not sensitive to the weighting used, so here we use an unweighted mean). For the contribution of the heaviest category events to the seasonal totals, these UK mean time-series are shown in figure 6. For winter (figure 6a), there is a clear increase in the contribution series from the low values before 1975 to the high values that have occurred since 1989, and this trend is statistically significant at the 95% confidence level (based on a *t*-test

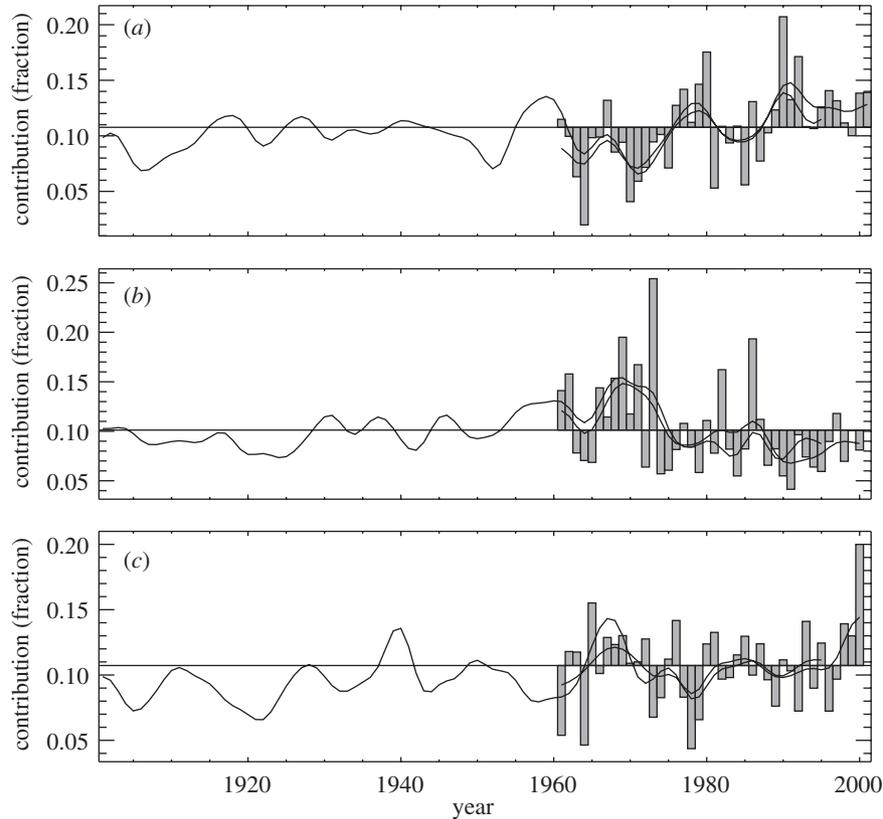


Figure 6. Time-series of the fractional contribution of the heaviest category of precipitation events to seasonal total precipitation in (a) winter, (b) summer and (c) autumn, averaged over the UK. Individual seasonal bars are shown above and below the baseline mean (about 0.1) for the period 1961–2000 (or 1961–2001 for winter), together with a decadal smoothed curve. Overlaid on this is a decadal smoothed curve computed from the more sparse 1901–1995 dataset.

of the least-squares regression slope, with degrees of freedom reduced to account for temporal autocorrelation). The 1961–2001 dataset captures well the interdecadal variations exhibited by the full 1961–1995 network of station observations (see § 2), so the latter is not shown here. The much more sparse 1901–1995 network of stations does not fully capture the 1961–1995 increases (the decadal smoothed result from this network is included in figure 6a), so it is uncertain whether these few longer records can provide an adequate comparison of recent increases in winter precipitation intensity with periods earlier in the century. Certainly, however, the only other time that the decadal smoothed series reaches the values seen in the 1990s was in the late 1950s, but Osborn *et al.* (2000) have already shown with an intermediate coverage dataset that the 1950s values were not as high as those in the 1990s.

The contribution of the heaviest category in summer (figure 6b) shows a clear (and, again, statistically significant) decrease from the high values before 1973 to the low values since then, though with a slight recovery during recent summers. The dataset that runs through to 2000 captures well the interdecadal variations shown by the full

1961–1995 network of stations (not shown). The more sparse dataset that runs back to 1901 captures most of the decreases over 1961–1995, and demonstrates that it is the 1955–1975 period that is unusual in terms of the full 20th century, with recent values being a return to the levels experienced earlier in the century.

The UK mean combines regions of opposing changes during spring, and exhibits no significant trends (not shown). The same is true for autumn, but it is shown here (figure 6c) to provide a context for the particularly wet autumn of 2000. The heavy category precipitation events contributed 20% of the total autumn 2000 precipitation, and this is much higher than any other autumn contribution since 1961 (the more sparse network with data prior to 1961 is only useful for estimating changes on the decadal time-scales, rather than individual yearly values).

5. Trends in multi-day precipitation events

The results described in §§3 and 4 indicate that there have been significant and spatially coherent changes in precipitation totals, variability and extremes in the UK during winter (increases) and summer (decreases). For *absolute* precipitation amounts, the decreases in single-day extremes in summer are likely to dominate over the winter increases, because at most locations the definition of the precipitation categories have higher thresholds during summer than winter. If we consider multi-day precipitation events, this is no longer true at most locations within the UK because the higher number of wet days during winter results in higher multi-day totals, despite the fewer very high single-day precipitation totals. A detailed analysis of multi-day precipitation totals would be of great interest. Here, however, we report results from a preliminary analysis only. The single-day precipitation totals have already been assigned to 10 precipitation categories (§4a), and we simply take a weighted mean of the category numbers for a sliding window of n days (from 3 to 10 days in length). For a five-day window, the number of days per season that exceed an arbitrary value (we selected five, indicating that the day in question came at the end of a run of five days whose weighted-mean precipitation category was five or above) was computed, and then averaged across all UK stations. For spring, summer and autumn, there are no trends in the frequency of these five-day events, though autumn 2000 had a particularly high frequency of events and the four most recent springs have had above-average values. During winter, however, there has been an increase in the frequency of five-day heavy-rainfall events that is statistically significant, even in the context of the more sparse 1901–1995 dataset.

6. Conclusions

Over 100 weather stations with daily precipitation totals for the last four decades provide a record of precipitation characteristics across most of the UK. They indicate increased precipitation totals and increased frequency and contribution of heavy-precipitation events during winter, and decreases in these characteristics during summer. These trends are consistent with changes in the full precipitation probability distributions and are spatially coherent across most of the UK. In relation to the entire 20th century, there is an indication that recent winter increases in heavy precipitation are unusual, while recent summer decreases may not be, but the sparseness of the longer observational records leads to reduced confidence in the extended results.

The analysis presented here provides a climatological context for recent hydrological changes (such as the flooding during autumn 2000), though the relationship between heavy precipitation events and fluvial flooding is not straightforward (Pielke & Downton 2000). The results also raise the question of whether the observed changes (particularly those in winter, which may be unusual compared with the longer records) are a natural multi-decadal climate fluctuation or are part of a climate-change signal that may continue or even strengthen during the next century. This is not a simple question to answer, especially given the difficulties outlined in the introduction with regard to the detection of trends in extremes. The sign of the change is consistent with the simulated climate-change signal due to increasing greenhouse-gas concentrations, though the magnitude of the observed change is greater than that expected from the model simulations. There have certainly been substantial changes in the atmospheric circulation over the Atlantic and western Europe in winter over the past 40 years, related principally to an increase in the North Atlantic Oscillation (Hurrell 1995). Osborn & Hulme (2000) showed, however, that this was linked to increased precipitation intensity only in the parts of the UK that experience significant orographic rainfall (especially western Scotland, northern Wales, and southwestern and northwestern England), whereas the observed increases are more uniform across the whole country. In addition, it is likely that the recent changes in the North Atlantic Oscillation are themselves partly a response to some combination of climate forcings, and thus may not be simply natural variability (Osborn *et al.* 1999). We conclude, therefore, that there is some evidence that the recent winter changes have some component of a climate-change signal within them, but the evidence is not sufficiently strong on its own to suggest that the observed trends will continue with the same magnitude into the future.

Author: or 'south'
(not clear from
original)?

The UK Department of Environment, Transport and the Regions (EPG1/1/85) supported the earlier analysis of the 1961–1995 dataset (reported in Osborn *et al.* 2000) and the extraction of more recent weather station data (which was undertaken by David Lister). The remaining analyses were performed with support from the Tyndall Centre for Climate Change Research (IT1.16). The weather-station records were collected by the UK Met Office and were kindly provided via the BADC (www.badc.rl.ac.uk). The BADC provided excellent technical support regarding the precipitation data.

References

- Folland, C. K., Karl, T. R., Christy, J. R., Clarke, R. A., Gruza, G. V., Jouzel, J., Mann, M. E., Oerlemans, J., Salinger, M. J. & Wang, S.-W. 2001 Observed climate variability and change. In *Climate change 2001: the scientific basis, contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change* (ed. J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell & C. A. Johnson), pp. 99–181. Cambridge University Press.
- Frei, C. & Schär, C. 2001 Detection probability of trends in rare events: theory and application to heavy precipitation in the Alpine region. *J. Climate* **14**, 1568–1584.
- Gregory, J. M., Wigley, T. M. L. & Jones, P. D. 1993 Application of Markov-models to area-average daily precipitation series and interannual variability in seasonal totals. *Climate Dynam.* **8**, 299–310.
- Groisman, P. Ya. (and 13 others) 1999 Changes in the probability of heavy precipitation: important indicators of climatic change. *Climatic Change* **42**, 243–283.

- Hartmann, D. L. 1994 *Global physical climatology*. International Geophysics Series, vol. 56, p. 411. Academic.
- Hulme, M., Osborn, T. J. & Johns, T. C. 1998 Precipitation sensitivity to global warming: comparison of observations with HadCM2 simulations. *Geophys. Res. Lett.* **25**, 3379–3382.
- Hurrell, J. W. 1995 Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. *Science* **269**, 676–679.
- Osborn, T. J. & Hulme, M. 2000 Observed trends in the intensity of daily precipitation over the UK. In *Proc. 12th Conf. Applied Climatology, Asheville, May 2000*, pp. 111–114. Boston, MA: American Meteorological Society.
- Osborn, T. J., Briffa, K. R., Tett, S. F. B., Jones, P. D. & Trigo, R. M. 1999 Evaluation of the North Atlantic Oscillation as simulated by a coupled climate model. *Climate Dynam.* **15**, 685–702.
- Osborn, T. J., Hulme, M., Jones, P. D. & Basnett, T. A. 2000 Observed trends in the daily intensity of United Kingdom precipitation. *Int. J. Climatol.* **20**, 347–364.
- Pielke, R. A. & Downton, M. W. 2000 Precipitation and damaging floods: trends in the United States, 1932–97. *J. Climate* **13**, 3625–3637.
- Trenberth, K. E. 1999 Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change* **42**, 327–339.
- Wilby, R. L. & Wigley, T. M. L. 2001 Future changes in the distribution of daily precipitation totals across the United States. *Geophys. Res. Lett.* (In the press.)
- Wilks, D. S. 1995 *Statistical methods in the atmospheric sciences*. International Geophysics Series, vol. 59, p. 467. Academic.

Details?