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Implications of changes in seasonal and annual extreme rainfall

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[1] Future projections from climate models and recent observations show a worldwide increase in both the frequency and intensity of heavy rainfall, coinciding with widespread flooding and landslides in Europe. It is estimated, using regional frequency analysis, that the magnitude of extreme rainfall has increased two-fold over parts of the UK since the 1960s. Intensities previously experienced, on average, every 25 years now occur at 6 year intervals; a consequence of both increased event frequency and changes in seasonality. These climatic changes may be explained by persistent atmospheric circulation anomalies and have huge economic and social implications in terms of increased flooding. *INDEX TERMS:* 1821 Hydrology: Floods; 1854 Hydrology: Precipitation (3354); 3364 Meteorology and Atmospheric Dynamics: Synoptic-scale meteorology; 9335 Information Related to Geographic Region: Europe; *KEYWORDS:* Extremes, rainfall, UK, flooding, seasonality, climate change. **Citation:** Fowler, H. J., and C. G. Kilsby, Implications of changes in seasonal and annual extreme rainfall, *Geophys. Res. Lett.*, *30*(13), 1720, doi:10.1029/2003GL017327, 2003.

[2] The autumn and calendar year 2000 were the wettest on record [*Alexander and Jones*, 2001] in the England and Wales record back to 1766, with several other regions in western Europe receiving twice their long-term annual average rainfall [*Lawrimore et al.*, 2001]. This caused widespread severe flooding [*Lawrimore et al.*, 2001; *Marsh*, 2001] and prompted public debate on the apparent increased frequency of extremes: was this just a natural phenomenon or can it be attributed to climate change? Climate model integrations predict increases in both the frequency and intensity of heavy rainfall in high latitudes of the northern Hemisphere under enhanced greenhouse conditions [*McGuffie et al.*, 1999; *Palmer and Raisanen*, 2002; *Jones and Reid*, 2001]; consistent with recent increases in rainfall intensity seen in the UK [*Osborn et al.*, 2000; *Osborn and Hulme*, 2002]; (*H. J. Fowler et al.*, A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000, accepted by the *International Journal of Climatology*, 2003) and worldwide [*Groisman et al.*, 1999; *Karl and Knight*, 1998; *Frich et al.*, 2002]. These are particularly pertinent questions given the reluctance of the Association of British Insurers to provide flood insurance for the 10% of UK properties, worth some £200 billion, considered to have inadequate flood defenses after 31st December 2002, and a similar global insurance response to flood hazard [*Crichton*, 2002]. Currently, the UK government spends in excess of £300 M annually on flood defenses. This is likely to rise by another £200 M from also taking climate change impacts into account [*DEFRA*, 2001]. Recent flood events in the UK in winter 2000/01 and Europe in summer 2002 have produced insurance claims of £1 billion and 19 billion Euros respectively.

[3] Changes in seasonality may be important in recent European flooding and also in a broader ecological perspective [*Stenseth et al.*, 2002; *Walther et al.*, 2002]. Here we attempt to address these concerns by examining changes in seasonal extreme rainfall intensities in the UK during 1961–2000, as it is easier to detect a change signal in regional rainfall data than in flood data [*Milly et al.*, 2002]. These are then related to regional climate model projections for 2070–2100.

[4] We use two methods to examine changes to the frequency and intensity of extreme rainfall events: a regional frequency analysis (RFA) based on L-moments [*Hosking and Wallis*, 1997] and a peak-over-threshold (POT) analysis. The RFA uses regional pooling [*Wigley et al.*, 1984; *Robson and Reed*, 1999] of rainfall maxima to fit Generalized Extreme Value distribution curves and estimates long return period rainfall events for 1-, 2-, 5- and 10-day durations. These include estimates of uncertainty, measured using a bootstrap method [*Efron*, 1979]. For the POT analysis, we define a POT event as when the daily rainfall exceeds two standard deviations above the long term (1961–2000) mean wet day rainfall at a specific location. The standardized POT data is regionally pooled [*Wigley et al.*, 1984] and used to examine changes in timing and frequency, using the statistical measures of POT modal month and annual POT frequency [*Bayliss and Jones*, 1993]. Temporal variability in extremes is analyzed in decades from 1961–1970, 1971–1980, 1981–1990 and 1991–2000, with seasons defined as: winter (December–February), spring (March–May), summer (June–August) and autumn (September–November).

[5] These techniques are used to analyze the changing probability of extreme rainfall events for two contrasting datasets: (a) observed data from 1961–2000 for 204 daily rainfall records across the UK; pooled into nine regions [*Wigley et al.*, 1984] with each containing at least 20 records, and (b) regionally pooled daily 50 km × 50 km gridded rainfall data simulated for a control (1960–1990) and future (2070–2100) scenario from the HadRM3 regional climate model [*Hulme et al.*, 2002; *Hudson and Jones*, 2002]. A discordancy analysis [*Hosking and Wallis*, 1997; *Robson and Reed*, 1999] was used to establish that the distributions of rainfall maxima within a region were acceptably similar (H. J. Fowler et al., A regional frequency analysis of United

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Kingdom extreme rainfall from 1961 to 2000, accepted by the *International Journal of Climatology*, 2003).

[6] We find that there have been significant, seasonally and regionally varying, changes in the intensity of extreme rainfall events across the UK. The largest changes are observed in autumn and spring, but considerable change is also seen in winter and summer extremes. These findings are different to those of [*Osborn et al.*, 2000; *Osborn and Hulme*, 2002] who suggest that the largest changes to daily and multi-day rainfall intensity respectively have been experienced in winter and summer, as do daily analyses of regional climate model projections for future climate scenarios [*Jones and Reid*, 2001]. In many seasons, however, we find the largest changes are in autumn and spring, and for 5- and 10-day duration events.

[7] We find a consistent downward trend in estimated summer rainfall for both short and long-duration return periods, ranging from 2 to 100 years (from 50% to 1% annual exceedance probability). This is observed particularly at 1- and 2-day durations (see Figure 1a) and most prominently in the south and east of the country, where there are also significant decreases in estimated rainfall for 5- and 10-day events. This is a result of a significant decrease in the median seasonal maximum event (SMED) since the 1970s. In winter, changes are spatially variable across the UK (see Figure 1b). In Scotland, there is an increase in estimated rainfall for a specific return period event, particularly at 5- and 10-day durations but, conversely, little or no change in England and Wales.

[8] Figures 2a and 2b show decadal rainfall estimates for a 25-year return period event for autumn and spring respectively. The most recent decade from 1991–2000 provides a dramatic departure from previous estimates in all regions and for all durations. In autumn, increases in rainfall estimates for a specific return period at 5- and 10-day durations are mainly seen in Scotland and the east of England, but increases at 1- and 2-day durations are observed across the country. This is due to increases in SMED, particularly at shorter durations. In spring, the picture of change is similar, with increases in extreme rainfall most prominent at 1- and 2-day durations but also increases at 5- and 10-day durations in northern and western parts of the UK.

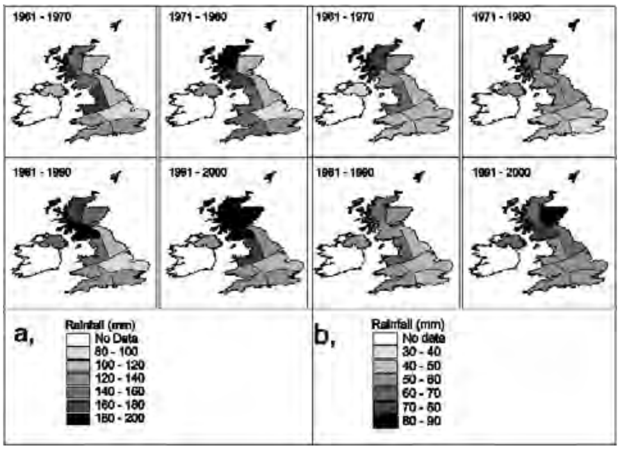

Figure 2. 25-year return period (or 4% chance) rainfall event estimates shown for nine regions and four decadal periods, 1961–1970, 1971–1980, 1981–1990 and 1991–2000. (a) Autumn, 10-day duration. (b) Spring, 2-day duration.

[9] If these changes are examined on an annual basis then significant differences can be seen between the past decade (1991–2000), and the previous 30 year period, particularly at 5- and 10-day rainfall durations. In Figures 3a and 3b we consider observed changes in the 10-day duration, 25-year return period event. These indicate significant increases in the expected rainfall amount in northern and western parts of the UK but decreases in southeast England. The largest increase of 45% is seen in eastern Scotland (a change from a 25-year to a 6-year event). Estimated return periods for

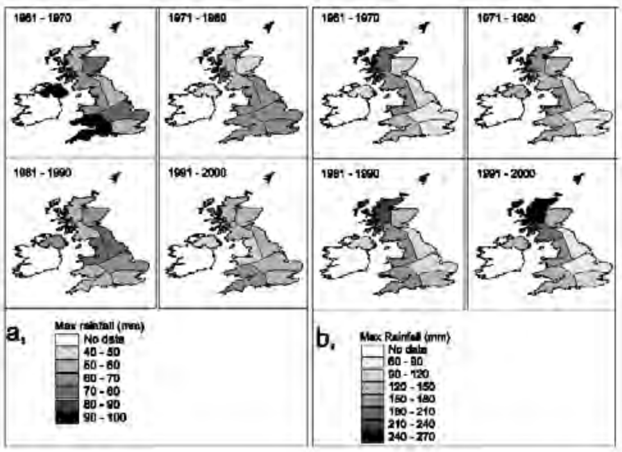

Figure 1. 50-year return period (or 2% chance) rainfall event estimates shown for nine regions and four decadal periods, 1961–1970, 1971–1980, 1981–1990 and 1991–2000. (a) Summer, 1-day duration. (b) Winter, 10-day duration.

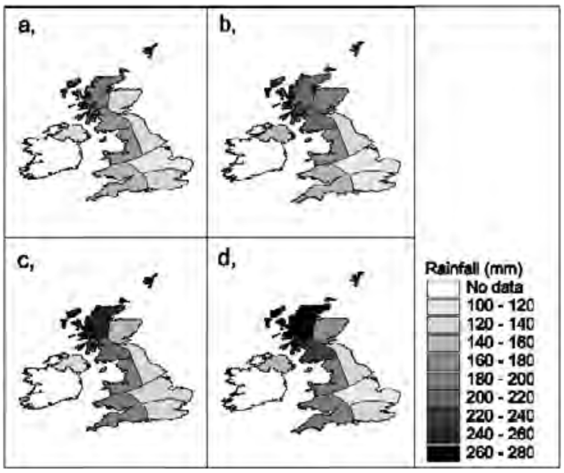

Figure 3. Comparison of estimates of 10-day duration, 25-year return period (or 4% chance) rainfall event for both observed and regional climate model data. (a) observed 1961–1990. (b) observed 1991–2000. (c) HadRM3 control (1961–1990) scenario, ensemble mean (d) HadRM3 future (2070–2100) scenario, ensemble mean.

other northern parts of the UK are also lowered significantly, to between 7 and 16 years. We would estimate therefore, that the annual exceedance probability of an extreme rainfall event of a specific magnitude for 5- and 10-day durations has increased by a factor of 4 in Scotland and 2 in northern England, and decreased by a factor of 1.5 in southeast England, respectively over the past decade.

[10] Observed changes are compared to those projected by regional climate model (HadRM3) integrations [*Hulme et al.*, 2002; *Hudson and Jones*, 2002] for the control and future scenarios in Figures 3c and 3d respectively. It can be seen that the control integration of HadRM3 (Figure 3c) simulates the distribution of 10-day extreme rainfall well in most regions, excepting north Scotland where the estimates are too high. The future integration (Figure 3d) shows a similar pattern of change to that observed during the 1990s (Figure 3b), with increases in Scotland and decreases in southern England, but little change in northern England. These estimates should, however, be viewed with caution due to significant differences in both the magnitude and direction of future changes in extreme rainfall projected by the HadRM3 model and its predecessor, HadRM2 [*Noguer et al.*, 1998]; with HadRM2 estimating large increases in extreme rainfall across the UK.

[11] For the generation of floods, a change to the frequency and timing of extreme rainfall events may be as important as changes in magnitude and duration. Antecedent wetness of catchments, or soil saturation, is a key factor determining the timing of major flood events [*Bayliss and Jones*, 1993]. For rural catchments, autumn is the dominant season of flooding in northern and western parts of the UK, whereas further south, until recently, it has been winter [*Bayliss and Jones*, 1993]. We find little change to the timing and frequency of extreme rainfall events in northern and western parts of the UK. However, in southern and eastern regions, we find significant changes in both the timing and frequency of intense rainfall that may have severe implications for flooding. Figure 4a shows the increasing annual frequency of 5-day POT events in south west England, particularly during the late 1990s. This is also apparent in Figure 4b, which demonstrates both the increased frequency of 10-day POT events in central and eastern England during the 1990s, and the change in timing from predominantly summer to greater concentrations in autumn and winter months. We find similar modifications to the timing and frequency of intense rainfall throughout the southern UK during the 1990s.

[12] The estimated changes in rainfall return period, extreme event frequency and timing have serious economic and social implications and may provide a mechanism for recent severe autumnal flooding in both the UK [*Marsh*, 2001] and Europe [*Lawrimore et al.*, 2001]. These seasonal changes may be a consequence of anomalies in large-scale circulation patterns such as the Scandinavia Pattern (SP) [*Barnston and Livesey*, 1987] and the North Atlantic Oscillation (NAO) [*Jones et al.*, 1997]. A correlation has been shown between wet UK autumns and winters, and the SP and NAO respectively (M. Blackburn et al., Atmospheric variability and extreme autumn rainfall in the UK, submitted to *Geophysical Research Letters*, 2002). Further research is needed to establish the links between flood generating mechanisms, large-scale circulation patterns and climatic forcing, anthropogenic or otherwise, if we are to fully understand the flood risk implications of the estimated changes in extreme rainfall occurrence.

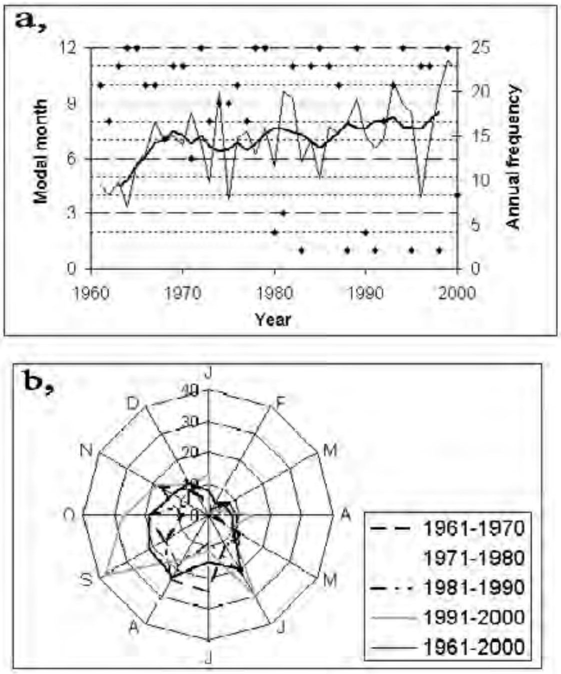

Figure 4. The change in timing of extreme rainfall events over southern parts of the UK from 1961–2000, measured using peak-over-threshold analysis. (a) The annual station frequency and modal month (January to December, represented by diamonds) of 5-day POT events in the south west of England, overlain by 5-year moving average annual POT frequency. (b) The decadal station frequency of 10-day POT events in central eastern England.

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