A Comparative Study of the Magnitude, Frequency and Distribution of Intense Rainfall in the United Kingdom

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ABSTRACT: During the 1960s, a study was made of the magnitude, frequency and distribution of intense rainfall over the UK, employing data from more than 120 daily-read rain gauges covering the period 1911 to 1960. Using the same methodology, that study was recently updated utilizing data for the period 1961 to 2006 for the same gauges, or from those nearby. This paper describes the techniques applied to ensure consistency of data and statistical modelling. It presents a comparison of patterns of extreme rainfalls for the two periods and discusses the changes that have taken place. Most noticeably, increases up to 20% have occurred in the north west of the country and in parts of East Anglia. There have also been changes in other areas, including decreases of the same magnitude over central England. The implications of these changes are considered.

KEY WORDS: climate change; climate variability; extremes; United Kingdom; daily rainfalls; intensities; frequencies
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1. Starting Point

For the estimation of flood risk and for the design of drainage schemes, reservoir spillways and other hydraulic structures, knowledge of the relationship between magnitude, frequency and distribution of intense falls of rain is vital. This knowledge is also valuable in studies of erosion, landslides, volcanic eruptions, propagation of radio waves and in other fields. With the growing concern about global warming, the comparison of these variables in space and time is proving pertinent to investigating climate change (New *et al.* 2001, Kundzewicz *et al.* 2007), a number of studies being made in the UK (Jones and Reid 2001, Osborn *et al.* 2000, Fowler and Kilsby 2003) and elsewhere as reported by Bates et al (2008).

In the past, the laborious analysis of chart records from autographic rain recorders deterred investigations of intense falls over short periods. Hence methods were developed to estimate the frequency and magnitude of heavy rainfalls in other ways, in Britain for example by Bilham (1936), Maclean (1945), and Collinge (1961). Again for the UK, the distribution and other characteristics of intense falls were described annually in British Rainfall from 1862 to 1968 when the publication ceased. The most severe storms were also detailed by Bleasdale (1963) and there have been numerous accounts in the literature of individual intense falls. However, since the development of tipping bucket raingauges, automatic weather stations and the extensive use of telemetry, this analysis problem has been largely overcome (Strangeways 2003). Similarly the archiving of daily rainfall records from the 4000 or so standard gauges currently comprising the UK network has simplified data retrieval and use. The compilation of an archive of the data, maps and accounts of days with extreme rainfalls from each of the volumes of British Rainfall to form the British Rainfall Data Archive is a further aid to analysis and understanding (Rodda *et al.* 2009). Indeed, use of records from the standard raingauge network has several advantages. In particular, the network is more dense, better distributed and of much longer standing than the network of rain recorders. And by comparison with other national networks, gauges in the UK network are more likely to provide observations that are closer to the “true” rainfall for the different historical time periods. This is because the level of the orifice of the Meteorological Office Mark II gauge making up the network, at 30.4 cm, is lower than that of the majority of other national gauges, resulting in a smaller loss of catch due to wind, leading to a smaller systematic error in the observations (Rodda

Figure 1. Raingauge stations used in the 1960s study.

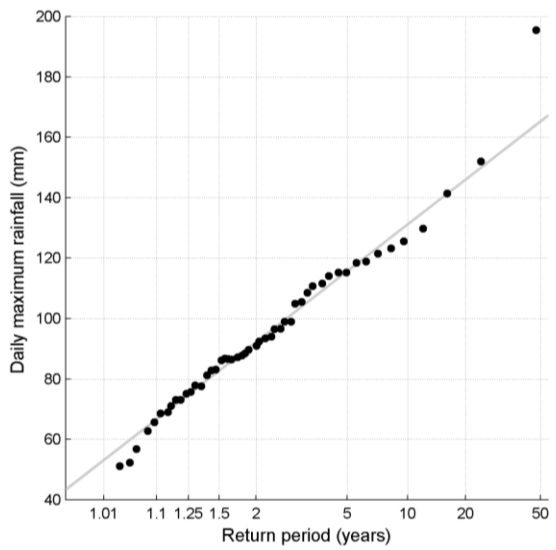

Figure 2. Gumbel extreme value analysis for Blaenau Ffestiniog.

1968, Sevruk 1989). That the quality control of these observations and their archiving has always been rigorous is another factor of importance, one that has applied since 1860. Of course, the advent of the radar network covering the United Kingdom provides a far better appreciation of the spatial distribution of rainfall than ever before.

2. Methodology

Rodda (1966 and 1972) gleaned the annual maximum daily rainfalls from the records of 121 selected rainfall stations (Figure 1), nearly all with 50 years of records. Each of the 121 annual maximum series was processed using a Gumbel Type I extreme value analysis (Gumbel 1954 and 1958), (Figure 2). The results for estimated return periods from 10 to 100 years were mapped and isohyets drawn in by hand. Figure 3 shows the distribution of the estimated 100 year return period daily maximum rainfalls. By way of comparison, the largest recorded daily rainfalls for the period 1881 to 1964 are shown in Figure 4.

For the several stations which registered exceptional falls; such as Sprowston, Norfolk (182mm, August 1912), Cannington, Somerset (238mm August 1924) and Martinstown, Dorset (279mm July 1955), it was found that these falls did not conform to the pattern of those in the remainder of the series of annual maximums (Figure 5). They appeared to be what could be part of a separate population, or part of the annual maximum series but with a return period considerably greater than 100 years. Consequently they were omitted from the overall analysis.

For the period from 1961 to 2006, a period slightly than in the earlier study, data were extracted from the Met Office Integrated Data Archive System (MIDAS) data base for the stations used in the 1960s study, apart from those in Northern Ireland._Where the record had ceased, stations were sought within 10km of the original station: the selected stations proving to be located at a mean distance of 710m from the original gauge. Statistical appropriateness of the fit of the Gumbel Type I model to each record was assessed using the Kolmogorov-Smirnov test (1992). These records were subjected to the same Gumbel Type I extreme value analysis that was employed in the earlier study. Again maps of the United Kingdom were produced showing the daily maximum falls for return periods from 10 to 100 years (Figures 6 and 7). For these maps the isohyets were drawn in using an automatic interpolation technique.

3. Results

Like most isohyetal maps of the UK, Figures 3, 6 and 7 demonstrate totals rising from the drier south east to the wetter north west. Areas of higher relief, such as Exmoor, the Brecon Beacons, Snowdonia, the Lake District and the Western Highlands stand out for all return periods. Perhaps the gradients are not as steep as might be anticipated, possibly

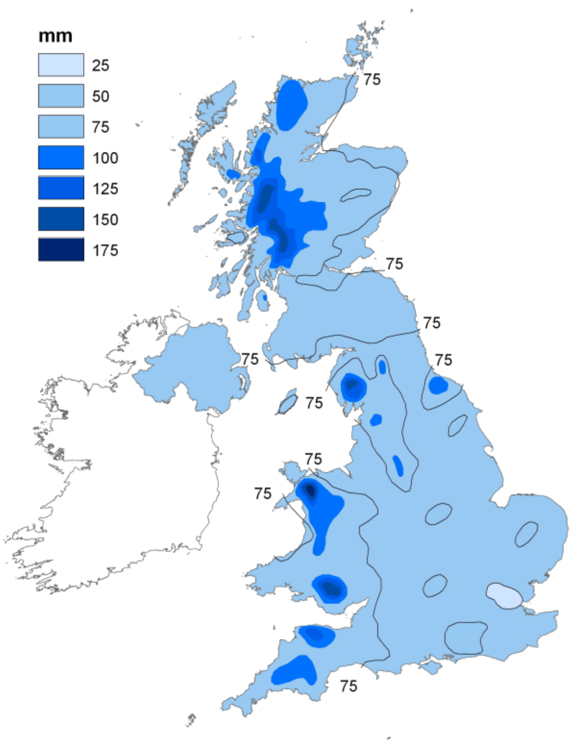

Figure 3. 100 year return period daily maximum rainfalls.

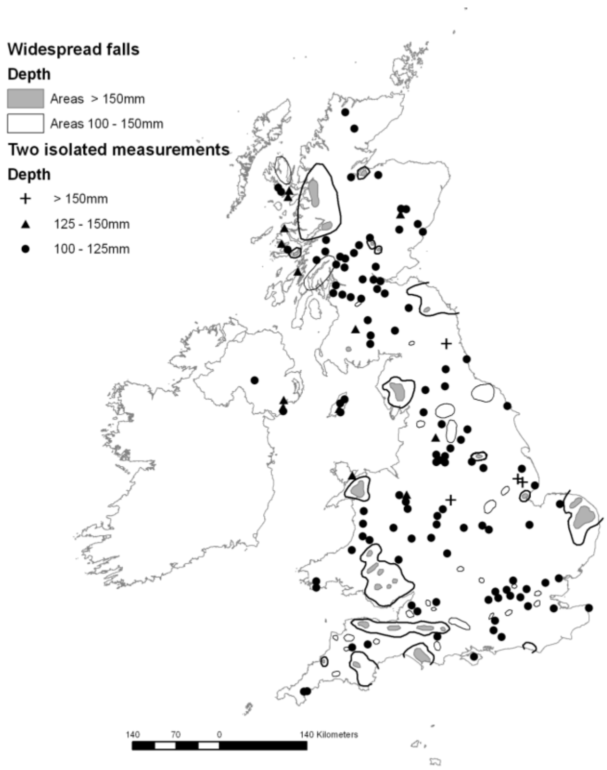

Figure 4. Largest recorded daily rainfalls for the period 1881 to 1964.

because there are too few stations at higher altitudes, or because in those areas the longer duration frontal storms are more likely to be split between two rainfall days. In the earlier study Rodda (1967), found that the probability of rain falling at 9am increased from 0.04 at Hampstead to 0.17 at Cwm Dyli in Snowdonia. For this reason, in the Flood Studies Report (NERC 1975) use was made of 2-day maximum rainfalls.

For the earlier period in higher areas, the 100 year fall generally exceeds 127mm, but over most of the remainder of the country the total varies on either side of 76mm in one day. Figure 4 shows that for much of lowland Britain a daily fall of over 100mm has been exceeded on some occasion, suggesting a return period of 500 years or greater. For the higher areas this total has a much lower return period, probably between 20 and 50 years. Of course the exceptional falls in Norfolk and in the South West Peninsula do not conform to this pattern. For the period from 1961 to 2006 the distribution of daily maximum rainfalls for the estimated 100 year return period (Figure 7) is, in general, similar to that for the earlier one. However, some of the areas with larger totals have increased in extent, particularly that from the Western Highlands through the Southern Uplands to the Lake District.

The differences between the totals for the two periods are readily apparent in Figure 8. Amounts appear to have increased by 20% and over in the north west of Britain. Coastal parts of Lincolnshire and the south eastern corner of the country from north Norfolk to Kent experienced a similar rise and there are also increases over patches of the Midlands and the West Country. By way of contrast, there are large areas where totals have decreased by up to and above 20%. They extend from the north east to the south west, with Snowdonia and the Atlantic coast of Devon and Cornwall being noteworthy. However there are also locations where no changes have occurred.

4. Discussion

The results of studies of this type depend on the nature of the data employed and the methods of analysis, set against the background of the trends and changes in atmospheric circulation patterns. No tests were undertaken of the mathematical and statistical approaches involved as these were thought to be less likely to explain the differences between the two periods than sources of error in the data, or climate change or climate variation. Among these errors, limitations imposed by the distribution of the 121 gauges and changes to the characteristics of the sites of the gauges were discounted. Shifts in wind speed and drop size regimes were thought to be more important, as these variables largely control the performance of the raingauge (Robinson and Rodda 1969, Folland 1988). Changes in the patterns

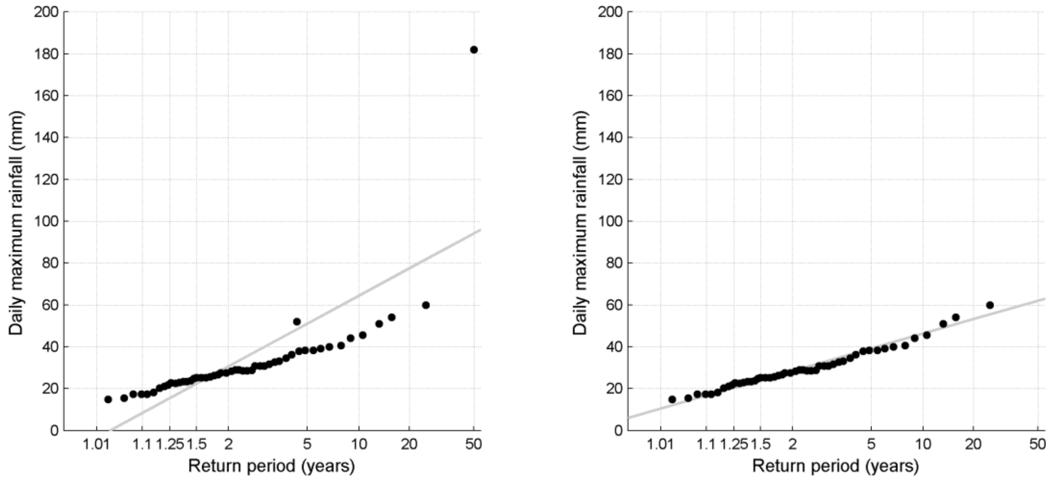

Figure 5. Gumbel analyses for Sprowston with and without the highest maximum fall.

of one or both could alter gauge catch from the first period to the second. However it might be expected that wind velocities would increase during the more recent period to reduce gauge catch, but this is not what the results show consistently across regions where gauges are most exposed. Of course, for much of the country the heaviest storms occur during the summer half year, but at higher altitudes maximums were recorded during the winter. Hence a more likely cause for the increase in the north west is that less precipitation fell as snow and more as rain which a gauge will catch more effectively (Jones *et al.* 1997). Over the remainder of the country the changes upwards and downwards may simply reflect the increasing variability of rainfall.

These results appear to be broadly similar to those found in most previous studies of extreme rainfall distribution over the UK which, except for Dales and Reed (1989), identified trends and changes in the incidence of daily and longer duration falls of rain. Most comparable are the findings contained in the Flood Estimation Handbook (Institute of Hydrology 1999) where the ratios of the 1-day maximum rainfalls for a 100 year return period from the Handbook are mapped against those in the Flood Studies Report (NERC 1975). Increases of up to 40% are displayed for certain locations in the North West Highlands and the Welsh mountains, while large parts of eastern and south eastern England register 20% increases. Decreases of up to 20% are found over wide areas of central Scotland, the west Midlands and Wessex. Studies by Osborn and Hulme (2002) and Fowler and Kilsby (2003a) have investigated the intensity of annual and seasonal rainfall over Britain for different durations, some up to 10 days, using networks of various sizes and records different lengths. Totals have been classed in different ways and the country divided into a number of regions. Changes in the intensity of extreme daily precipitation have been found with regional variations. Osborne and Hume (2002) identified more intense falls during the winter and less in the summer, while Osborne and Maraun (2008) indicate that more frequent spells of wet weather have occurred. In contrast, autumn and spring were the seasons when Fowler and Kilsby (2003) observed the largest changes, with a downward trend in summer rainfalls for short and long durations. This is consistent with the rise in anticyclonic weather conditions experienced in the last decades of the twentieth century (Folland *et al.* 2009).

5. Ending

Whether the changes to extreme rainfalls described here can be ascribed to changes in climate induced by human activity is problematical. Frequencies have altered and distribution patterns modified — features which could be indicative of climate variability. There is also the point that the results may be influenced by the two time periods selected for study — a matter not investigated. Would the findings have been different if intense falls for 1900 to 1950 had been compared to those for 1951 to 2000? And it is remarkable that the exceptional falls like Martinstown which occurred between 1911 and 1960 have been followed by far fewer outstanding events. Indeed the changes that have taken place between the first and second periods fall within the range of variations that have already occurred. If this is the case and there has been no upward displacement of the line enveloping the observed United Kingdom maxima (Figure 8), the arguments in favour of human effects increasing extreme rainfalls have yet to be proved. That is not to say that the observed changes are not consistent with the findings of Marsh and Hannaford (2007) and

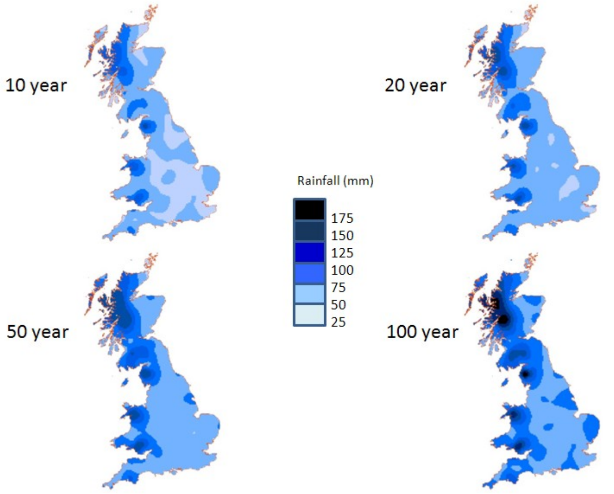

Figure 6. Daily maximum rainfalls for return periods of 10, 20, 50 and 100 years.

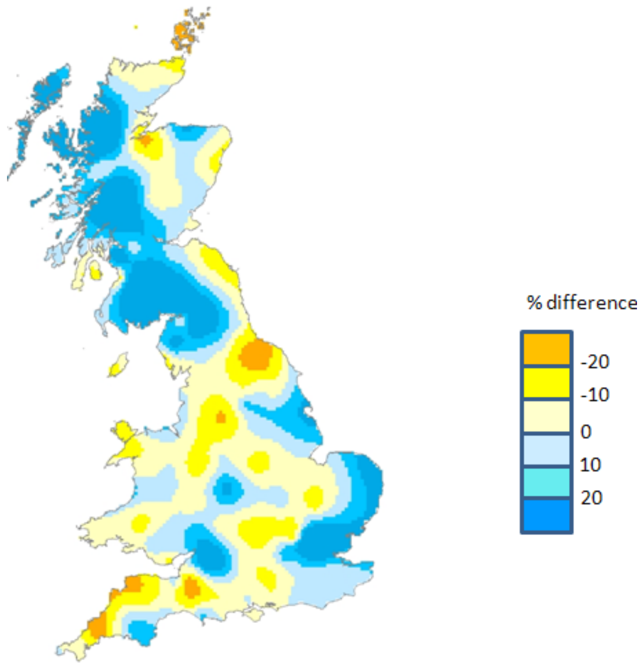

Figure 7. Percentage difference between the estimated 50 year return period daily maximum rainfall for the period 1911 to 1960 and for 1961 to 2006.

Hannaford and Marsh (2008) for more protracted high flows in northern and western areas of the UK and a somewhat confused picture for the lowlands of Britain. The changes in the North Atlantic Oscillation Index since 1911 and particularly the preponderance of positive values latterly (Osborn 2006), together with the changes to more extremes of rainfall predicted by certain climate scenarios, lend weight to the evidence for human induced climate change. However the signals found in this study are not clear and require further work for elucidation, such as by relating changes in extremes of rainfall to trends and variations in the seasonal atmospheric circulation over the UK.

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References

Bates, B., Kundzewicz, Z.W., Shahong Wu., Palutikof, J., (Eds) Climate Change and Water, WMO/UNEP Intergovernmental Panel on Climate Change. Technical Paper, June 2008.

Bilham. E.G., (1936) Classification of heavy falls of rain in short periods. *British Rainfall 1935*, 262-280.

Bleasdale. A., (1963) The distribution of exceptionally heavy daily falls of rain in the United Kingdom 1863 to 1960. *J. Inst.Wat. Engrs*. 17, 45-55.

Collinge, V.E., (1961) The frequency of heavy rainfalls in the British Isles. *Civ. Eng. & Publ. Wrks. Rev*. Part 1.341-344 and Part II 497-500.

Dales, M.Y., and Reed, D.W., (1989) Regional flood and storm hazard assessment. Institute of Hydrology Report No. 102.

Folland, C.K. (1988) Numerical models of raingauge exposure, field experiments, and a new collector design. *Q. J. Roy. Met. Soc*., 114, 1485-1516.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S., and J.W. Hurrell (2009) The summer North Atlantic Oscillation: past, present and future. *Journal of Climate,* 22, 1082–1103, DOI: 10.1175/2008JCLI2459.1

Fowler, H.J., and Kilsby C.G., (2003) A regional frequency analysis of United Kingdom extreme rainfall from 1961 to 2000. *International Journal of Climatology*, 23, 1313-1334.

Fowler, H.J., and Kilsby,C.G., (2003a) Implications of changes in seasonal and annual extreme rainfalls. *Geophysical Research Letters*, 30, 53.1-53.4.

Gumbel, E.J., (1954) Statistical Theory of Extreme Values and some Practical Applications. U.S. National Bureau of Standards, Applied Mathematics Series 33.

Gumbel, E.J., (1958) Statistics of Extremes. Columbia University Press, New York.

Hannaford, J., and Marsh, T.J., (2007) An assessment of runoff trends in undisturbed catchments in the Celtic regions of

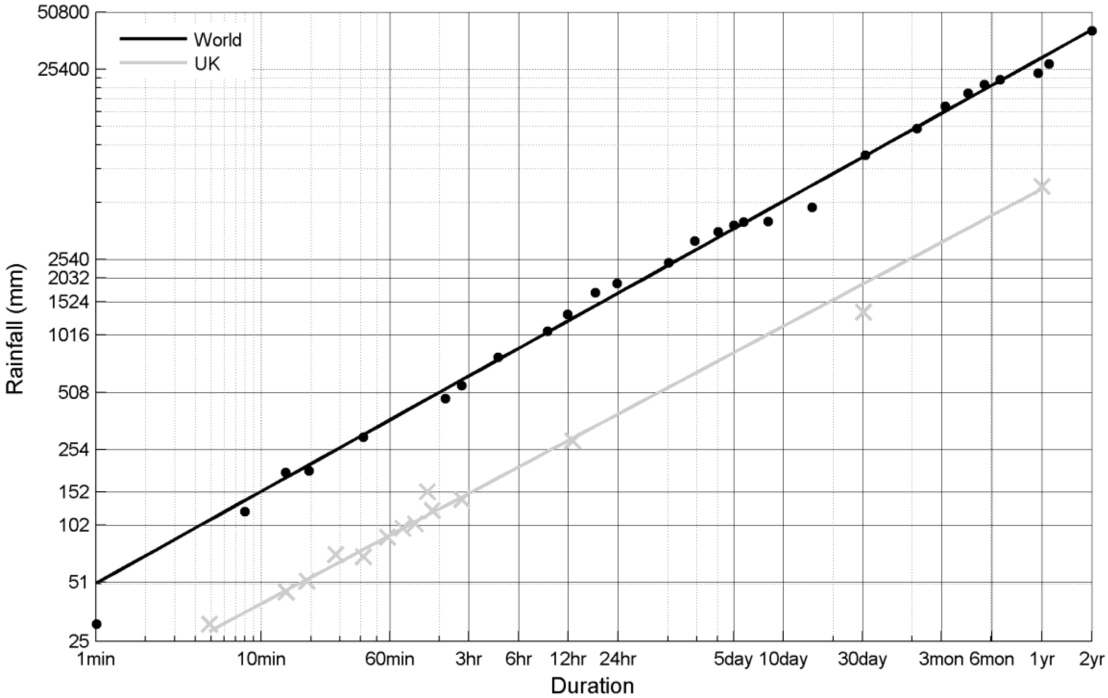

Figure 8. Magnitude duration relationships for World and UK extreme rainfalls up to 1964.

North West Europe in: Water in Celtic Countries: Quantity, Quality and Climate Variablity (Lobo Ferreira, J.P., and Vieira, J.M., Eds.) International Association of Hydrological Sciences, Pub. No. 310. 78-85.

Hannaford, J., and Marsh, T.J., (2008) High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology*, 28, 1325-1338.

Institute of Hydrology (1999) Flood Estimation Handbook, in 6 volumes and software, Institute of Hydrology, Wallingford.

Jones, P., Conway, D., and Briffa, K., (1997) Precipitation variability and drought. in: Climates of the British Isles: past present and future. (Hulme, M., and Barrow, E., Eds) Routledge, 197-219.

Jones, P., and Reid, P.A., (2001) Assessing future changes in extreme precipitation over Britain using regional climate model integration, *International Journal of Climatology*, 21, 1337-1356.

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, P.,. Jiménez, B., Miller, K.A., Oki, T., Sen Z.,and Shiklomanov, I.A., (2007) Freshwater Resources and their Management in Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (Parry, M.L.. Canziani, O.F., Palutikof, J.P., van der Linden P.J., and Hanson, C.E., Eds.,) Cambridge University Press, Cambridge, UK, 173-210. Intergovernmental Panel on Climate Change, (2007) Fourth Assessment Report (WG II AR4)

Maclean. D.J., (1945) Rainstorm data. *Survr. Munic. Cty. Engr.*, 104, p.36 and p.37.

Marsh, T.J., and Hannaford, J., (2007) The summer floods in England and Wales — a hydrological appraisal. Centre for Ecology and Hydrology, British Geological Survey, Natural Environment Research Council Wallingford. 30.

NERC (1975) Flood Studies Report in 5 Volumes, Natural Environment Research Council, London.

New, M., Todd, M., Hulme, M., and Jones, P., (2001) Precipitation measurements and trends in the Twentieth Century, Review. *International Journal of Climatology*, 21, 1899-1922.

Osborn, T.J., Hulme, M., Jones, P.D., and Basnett, T.A., (2000) Observed trends in the daily intensity of United Kingdom precipitation. *International Journal of Climatology* 20, 34-364.

Osborn, T.J., and Hulme M., (2002) Evidence for trends in heavy rainfall events over the UK. *Phil. Trans. Roy. Soc., Lond. A*, 360, 1313-1325.

Osborn, T.J., (2006) Recent variations in the winter North Atlantic Oscillation. *Weather*, 61, 353-355.

Osborn, T.J., and Maraun, D., (2008) Changing intensity of rainfall over Britain, Climatic Research Unit Information Sheet no.15, 2.

Press, W. H., Flannery, B. P., Teukolsky, S. A. and Vetterling, W. T., (1992) Kolmogorov-Smirnov Test. Numerical Recipes in FORTRAN: The Art of Scientific Computing, 2nd ed. Cambridge, England: Cambridge University Press, pp. 617-620.

Robinson, A. C., and Rodda, J.C., (1969) Rain, wind and the aerodynamic characteristics of rain gauges, *Met. Mag.*, 98, 113-120.

Rodda, J. C., (1967) A country-wide study of intense rainfall for the United Kingdom. *J. of Hydrology*, 5, 58-69.

Rodda, J.C, (1968) The rainfall measurement problem, Proc. General Assembly of the International Association of Hydrological Sciences, Bern 1967, Pub No.78, 215-231.

Rodda, J.C., (1972) A study of magnitude, frequency and distribution of intense rainfall in the United Kingdom. *British Rainfall 1966*, 204-215.

Rodda, H.J.E., Little, M.A., Wood, R.G., MacDougal, N., and McSharry, P.E.,(2009) A digital archive of extreme rainfalls in the British Isles from 1866 to 1968 based on British Rainfall, *Weather*, 64, 71-75.

Sevruk, B., (Ed) (1989) Precipitation Measurement. Proc WMO/IAHS/ETH Workshop, St Moritz, Swiss Federal Institute of Technology, Zurich. 584.

Strangeways, I.C., (2003) Measuring the Natural Environment. 2nd Edition. Cambridge University Press, 534.