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Assessment of the return period of near-PMP point and catchment rainfall for England and Wales

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ABSTRACT: The return periods of sub-daily rainfall events approaching Probable Maximum Precipitation (PMP) have been estimated for point locations and catchment areas using the assumptions made in a previously published storm model. It has been assumed that PMP of around 12 h duration is the result of severe thunderstorms for catchments up to about 200 km^2 and of mesoscale convective systems (MCSs) for larger catchments. The analysis suggests return periods ranging from around 1 in 10 000 years for point locations to 1 in 500 000 years for large catchments, though these are very dependent on the assumptions. The results are compared with estimates from a number of other sources. Copyright © 2010 Royal Meteorological Society

KEY WORDS PMP; return period; mesoscale convective systems

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1. Introduction

By definition the Probable Maximum Precipitation (PMP) is assumed to be the physical upper limit to the amount of precipitation that can fall over a specified area in a given time. The technique of estimating PMP currently used by engineers and other practitioners involved in flood forecasting and planning flood defences in the United Kingdom is set out in the Flood Studies Report (FSR) published in 1975. The development of a new approach to flood statistics published in the Flood Estimation Handbook (FEH) in 1999 did not update this procedure, but was limited to rainfalls with a return period of up to 2000 years. Although not in accord with the FEH recommendations, the FEH procedure has subsequently been applied to even rarer rainfalls. Studies which have done this (e.g. MacDonald and Scott, 2001) have found that, if rainfalls with very low probability of exceedence are derived using the statistical approach in the FEH, these are larger than FSR's PMP values. However, the FSR's PMP values have also been exceeded in some observed storms: for example the 1989 Halifax storm rainfall totals may have exceeded the FSR PMP for the area yet had an estimated return period of around 1 in 6000 years according to the FEH results (FEH, 1999; Dempsey and Dent, 2009).

Of course, the PMP values produced for the Flood Studies Report are only estimates, and these might be revised, either based on the same underlying methodology or on some new approach targeted on specifying an upper bound to the amount of rainfall. However, while PMP plays a formal role in current design procedures, developments of these procedures along the lines of cost-benefit analyses would require rainfalls to be estimated for sets of extremely low occurrence probabilities. Thus, there may be no explicit role for 'PMP', although the use of bounded distributions of rainfall is not precluded. If this transition is made, there would naturally be an interest in knowing the probabilities assigned by the new methodology to previously-used values of PMP. In addition, it would be useful if a probability of occurrence can be assigned to PMP values within the conceptual framework in which those values are determined: this might be used as a guide to selecting a design probability in cases where a rainfall amount would be determined to have that probability of exceedence.

The FEH procedure for determining rainfall frequency (Faulkner, 1999) is one example of how a probability of exceedence can be assessed for any rainfall amount, and this could be applied to PMP values. This procedure is currently being improved in a Defra/EA Long Period Rainfall Project led by CEH and will not be described further here. A rather different approach is described in Section 2, in which a resampling approach to past rainfall events, on the basis of transposing observed storms in space, is combined with a statistical model, This again leads to an approach that can assign a probability of exceedence to any rainfall amount: some previously published results of applying this, on the basis of transposing, to separately determined PMP values are reported. Section 3 outlines a conceptual model which might be

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used initially to assign a PMP value, while Sections 4 and 5 go on to ascribe a return period for PMP-like events using this framework, for moderately-sized areas (about 200 km^2) and large areas (about 2000 km^2), respectively. In particular, Section 4 evaluates the frequencies of occurrence of the orographic and convergence processes to derive the return period for a very severe storm, while Section 5 compares this analysis with observations of the occurrence of Mesoscale Convective Systems (MCSs) (Browning and Hill, 1984), which have been associated with the occurrence of severe flooding such as that which occurred at Lynmouth in 1952 (Collier and Hardaker, 1996). It is assumed that severe storms lasting 10–24 h are MCSs, i.e. storms producing both stratiform and convective rainfall. Figures 1 and 2 show satellite and radar images of an MCS that occurred on 10 May 2006. These figures show the early part of the life cycle of the storm (about the first 5 h), but the total lifetime of the storm is around 10 h with the storm continuing during the night. In fact an MCS has a particular dynamic structure, and it may be that storms of this duration may be more frontal in origin albeit containing significant convective rainfall. A further recent example which produced heavy rainfall in the Oxford area on 22 July 2006 was described by Webb and Pike (2007). The calculations in Sections 4 and 5 might, therefore, be valid for both meteorological types. Note that the July 2007 storm events in Hampshire, Gloucestershire, Worcestershire and Oxfordshire did have a structure involving stratiform and convective rainfall. The calculations in these sections assume representative fixed values of various parameters.

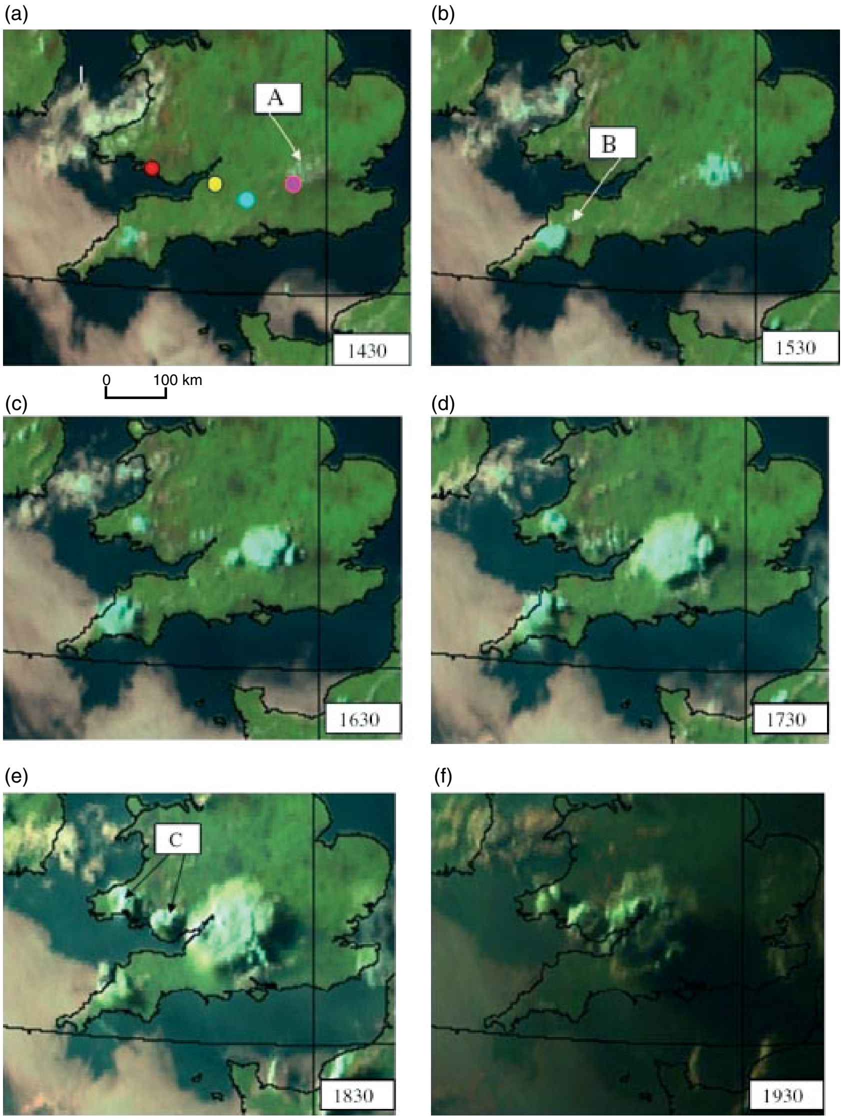

Figure 1. Meteosat 8 false colour cloud images (cloud brightness) showing the development of an MCS over southern England on 10 May 2006. Note the shadow from the cloud shown in Figure 1(b) indicating that the cloud grows to a high altitude. Label 'A' shows the area of cloud from which the thunderstorms developed northwest of London and label 'B' shows the location of the development of a separate area of thunderstorms over southwest England. Label 'C' shows new cells developing from an area of convergence over south Wales. Times are in UTC, and the coloured circles represent the locations of selected places: yellow Bristol; magenta Reading; cyan Larkhill; red Swansea. (From Young, 2007).

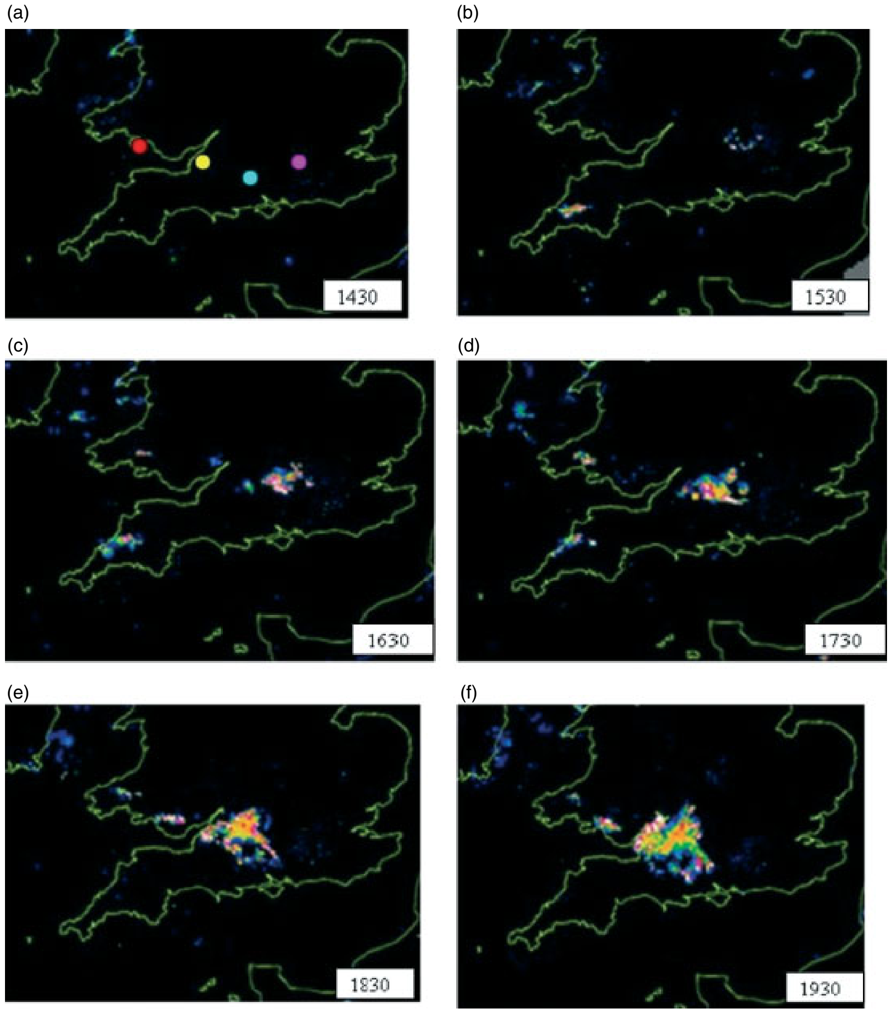

Figure 2. One kilometre resolution radar network images for 10 May 2006 with the times corresponding to the images in Figure 1. Colours represent rainfall rates: blue less than 1 mm h^{-1}; green greater than 1 mm h^{-1}; orange greater than 4 mm h^{-1}; white greater than 32 mm h^{-1}. (From Young, 2007).

2. Storm transposition approach

Fountaine and Potter (1989) investigated the estimation of probabilities of extreme rainfalls by adopting the stochastic storm transposition approach outlined by Alexander (1963), and developed by the US Committee on Techniques for Estimating Probabilities of Extreme Floods (1988). A summary of the analysis is also given by Austin *et al.* (1995). The context of these earlier studies was to estimate extreme catchment-average rainfalls.

Let $R_{\max}$ be a random variable representing the annual largest value of catchment-average rainfall of duration D occurring on a catchment of interest in 1 year. The aim is to estimate the probability of occurrence of intervals in which $R_{\max}$ exceeds r: that is, to find $p_{\max}(r)$, where $p_{\max}(r) = \mathrm{P}(R_{\max} \geq r)$. Assumptions are made that the catchment lies within an homogeneous region and that records of the spatial distributions of rainfall as a function of time of past storms are available on which to base the analysis. The assumption of spatial homogeneity is used to suggest an analysis based on assuming that a given recorded storm might equally well have occurred centred on any location within the homogeneous region. However, the requirements of this spatial homogeneity assumption are, in practice, loosened by modifying the spatial transposition of observed storms to allow adjustments to be made for differences in moisture potential due to different surface conditions, or moisture advection into the storm at low levels, across the region (Fountaine and Potter, 1989, p. 1563).

A further assumption is made that storm events occur as a Poisson process in time. It follows that $p_{\max}(r)$ is related to the similar function for storm-rainfalls, $p_{\text{storm}}(r)$, by:

$$p_{\max}(r) = 1 - \exp\{-\lambda p_{\text{storm}}(r)\} \qquad (1)$$

where $p_{\text{storm}}(r) = \mathrm{P}(R_{\text{storm}} \geq r)$. Here R_{storm} is a random variable representing, for any storm which is counted as affecting the homogeneous region, the largest catchment average rainfall in a duration D for the selected catchment. The quantity λ denotes the rate of occurrence (storms *per* year) of storms which affect the homogeneous region.

The above formula is used in practice by constructing estimates as follows:

$$\hat{\lambda} = \frac{m}{N} \tag{2}$$

$$\hat{p}_{\text{storm}}(r) = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{C}\sum_{c=1}^{C} b_{cj}(r) \tag{3}$$

where N is the length of record (years) during which data are available for significant storms that have occurred in the homogeneous region containing the catchment of interest and where m is the number of such storms. The letter j is used to index the storms available in the record while c is used to index the transposed storm centres of which there are C in total for each storm event: these are assumed to be uniformly spread over the homogeneous region (otherwise, a simple weighting can be applied). Finally, $b_{cj}(r)$ is an indicator variable such that $b_{cj}(r) = 1$ if the largest duration-D average catchment rainfall equals or exceeds r when calculated from the version of storm j which has been transposed to centre c, and $b_{cj}(r) = 0$ otherwise.

For storm j, the quantity:

$$\overline{b}_{j\bullet}(r) = \frac{1}{C}\sum_{c=1}^{C} b_{cj}(r) \tag{4}$$

is effectively the fraction of the homogeneous region at which the storm can be centred so as to give a catchment area rainfall of duration D which exceeds r. Further,

$$\overline{b}_{\bullet\bullet}(r) = \frac{1}{m}\sum_{j=1}^{m}\frac{1}{C}\sum_{c=1}^{C} b_{cj}(r) = \frac{1}{m}\sum_{j=1}^{m}\overline{b}_{j\bullet}(r) \tag{5}$$

is the average of such fractions. When applied to point rainfalls rather than to catchment area rainfalls, the quantity $\overline{b}_{\bullet\bullet}(r)$ is the average fraction of the homogeneous region for which storms have a duration-D rainfall at the target point which exceeds r.

A simplification used by the Yankee Atomic Electric Company is reported by Fountaine and Potter (1989) in which the rate of exceedence of the threshold r is small. Here:

$$\begin{aligned}\hat{p}_{\max}(r) &= 1 - \exp\{-\hat{\lambda}\hat{p}_{\text{storm}}(r)\}\\ &= 1 - \exp\left\{-\frac{m}{N}\overline{b}_{\bullet\bullet}(r)\right\} \approx \frac{m}{N}\overline{b}_{\bullet\bullet}(r).\end{aligned} \tag{6}$$

To summarize, data from observed events are combined with a probabilistic model to produce estimates of the probability that rainfall at a point or over a catchment will exceed any given amount r. The probabilistic model entails the assumptions that future storms will be limited to the range of storms that have occurred in the observed record, but that spatially transposed versions of the storms can occur with equal probability anywhere in the region, and that such storms will occur as a Poisson process.

Both the exact formula and its approximation were applied by Fountaine and Potter (1989) to a catchment of 220 miles^2 (569.8 km^2) in central Wisconsin, USA. An exceedence probability range for rainfall from 11 to 13 in. was found to be 3×10^{-5} to 4×10^{-5} (about 1 in 3×10^4 years).

The storm transposition technique remains rather subjective and further work needs to be undertaken. Newton (1980) notes that the probability of a storm producing the PMP over a particular catchment of the Tennessee Valley in the United States has been taken as 1 in 10^8 years, with a probability of 1 in 10^6 years defining the upper confidence limit. However, considering a storm antecedent to a storm-producing PMP, given that the total rainfall for the storm sequence should not exceed PMP for that duration, reduced this exceedence probability to about 1 in 6×10^5 years with a probability of 1 in 2×10^4 years defining the upper confidence limit.

3. A conceptual mechanism for explaining large rainfall events

The simple model of a convective storm used here is that of Collier and Hardaker (1996), although it is considered from a different viewpoint. It is considered applicable for rainfall events having a duration of up to 24 h. The model assumes that the physical processes mainly responsible for extreme convective rainfalls are associated with forced ascent over orography, local surface heating (thermals) and mesoscale convergence. No allowance is made for the contribution to storm development of latent heating due to the condensation of cloud droplets into rain water. This could increase the severity of a storm through increased vertical velocity, although not significantly during the initial stages of development. Further, treatment of the local heating due to solar radiation is simplified by evaluating it as the maximum monthly mean value from sunrise to the early afternoon without cloud being present. Clearly, as cloud forms, the amount of solar heating is reduced, but the present work assumes that no cloud forms initially before a storm. This assumption is discussed in Section 4. The Storm Model has also been applied in other countries (Hardaker, 1996). The use here is not to estimate rainfall amounts, but rather to identify combinations of conditions that will lead to the most extreme rainfalls.

The Storm Model described by Collier and Hardaker (1996) is based upon estimating the likely value of maximum surface heating producing an increase in temperature (ΔT) from the climatologically minimum temperature which leads to convection. It comprises three components:

- solar heating;
- orographic uplift expressed in terms of the air temperature increase that would have been required to produce an equivalent buoyancy, and,

- uplift resulting from convergence, expressed in terms of the air temperature increase that would have been required to produce an equivalent buoyancy.

This is expressed as:

$$\Delta T = T_{\max} - T_{\min} = \frac{G}{C_p \zeta H} + \frac{V^2 h T_{\min}}{g d^2} + \frac{w V T_{\min}}{g L} \quad (7)$$

where the three components are represented, respectively, by the three terms of the equation, and where the parameters are as defined in Collier and Hardaker (1996): $T_{\max}$ = the maximum temperature (degrees Kelvin), $T_{\min}$ = the observed minimum temperature before convection takes place, G = monthly average value of the daily available heat from sunrise to early afternoon, H = height to which solar heating is effective, approximately the surface boundary layer depth, ζ = air density, C_p = specific heat of dry air, V = horizontal wind speed, g = acceleration due to gravity, d = characteristic horizontal width of orography (orographic width), h = height of orography, L = characteristic length scale of the mesoscale convergence and w = vertical velocity.

Average heavy rainfall totals can be estimated by calculating the maximum dew-point temperature from the mean daily minimum temperature and the mean daily maximum temperature derived by adding ΔT to the minimum temperature. Thus, the occurrence of rainfalls close to PMP is directly related to the parameter values used in Equation (7). Examination of the equation reveals that the parameters fall into three categories, namely constants (g, ζ at given temperature and pressure, C_p, H and G, for given latitude and time of the year), catchment characteristics (h and d) and meteorological variables (V, $T_{\min}$, w and L).

It is proposed to estimate the return period of rainfalls close to PMP by examining the probability of occurrence of extreme values of the terms in Equation (7). Of these variables, the environmental temperature will be taken as fixed and determined by the time of the year under consideration (note that the ratio G/H does not vary greatly over the summer months (Table I)). Also, it is not thought likely that extreme values of $T_{\min}$ contribute substantially to the occurrence of PMP-sized events. When considering severe thunderstorms, predominately a summer phenomenon, the problem is reduced to examining the frequency of occurrence of the maximum values of convergence and orographic uplift. This is approached by analysing the frequency of observed extreme events and allowing for the likelihood of the storm direction being close to that of the steepest orographic gradient in a catchment.

4. Return period analysis for major thunderstorms in the United Kingdom

The following analysis estimates the likelihood of occurrence of the combination of conditions necessary for rainfall approaching PMP for durations of around 10 h over areas of around 200 km^2. Storms having durations of 10 h are taken as they are regarded as those which might have particular significance for the safety of medium to large reservoirs (see Austin *et al*., 1995).

Table I. Monthly values of available heat from sunrise to early afternoon in England (G), and the height (H) to which solar heating is effective, approximately the surface boundary layer depth (columns G and H): after Gold (1933), from Petterssen (1956)).

Month	G (cal cm^{-2})	H (km)	G/H (cal cm^{-3} × 10^5)
January	40	0.56	71
February	70	0.76	92
March	100	0.91	110
April	140	1.07	131
May	175	1.19	147
June	180	1.22	148
July	165	1.16	142
August	150	1.10	136
September	115	0.98	117
October	80	0.82	98
November	40	0.56	71
December	30	0.49	61

Collier and Lilley (1994) found that, on average, about 13 severe thunderstorms lasting 5 h or more occur somewhere in the United Kingdom (mainly England and Wales) each year. Analyses of radar and other data indicate such storms can contain areas of convergence over an area of around 200 km^2. Taking the area of England and Wales as 151 168 km^2, and assuming that such storms do not overlap or move, then, the average number of such storms *per* year occurring at any individual location = (13 × 200)/151 168 = 1/58 = 0.017.

For any individual 200 km^2 catchment, for PMP it would be necessary for the storm centroid to coincide with the catchment centroid and for the storm and catchment to be the same shape. Here, the storm centroid is allowed to lie within the central 10% of the catchment area and we assume a probability of 1 in 4 of the storm and catchment having a reasonably similar shape, a combined probability of 1/40 or 0.025.

For PMP, the wind direction should be in the direction of maximum orographic gradient in order to maximize uplift. The dependence here is not just on the steepness of the slope itself as the interest is on the maximum rainfall accumulation that is likely to arise from significant upslope motion. In this analysis we have chosen to use the range of wind directions that gives rise to a wind strength in the direction of maximum orographic gradient that is at least 90% of its strength were it to be exactly in the direction of maximum orographic gradient. This is a range of ±25.8 (since cos(25.8°) = 0.9). Making no assumptions about prevailing wind directions or orographic gradient directions, the probability of winds being within this range is 2 × 25.8/360 = 1/7, or 0.14. Note that the orographic term of Equation (7) is important

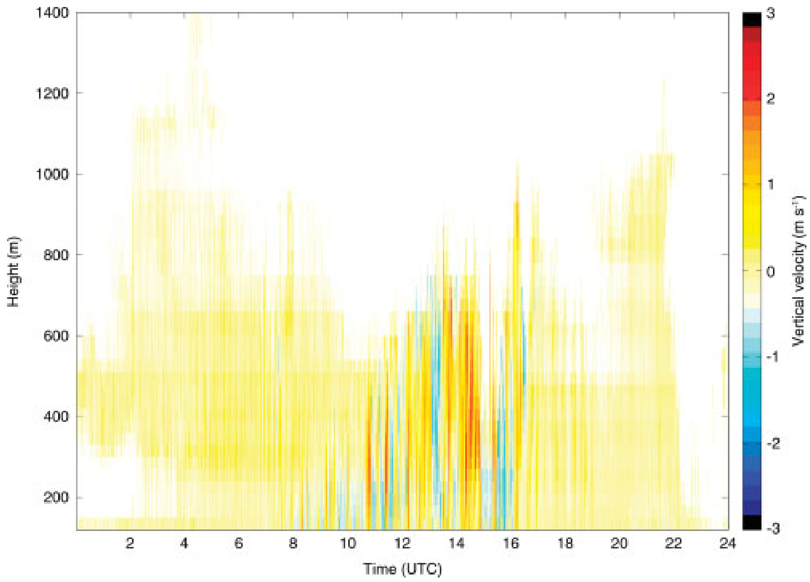

Figure 3. The development of thermals at Achern, Germany as observed using the University of Salford 1.5 μm Doppler lidar on 15 July 2007. The vertical velocity (m s^{-1}) of atmospheric aerosol is shown. Thermals grew over a period of 8 min reaching the top of the boundary layer located at a height of about 800 m, which they do not penetrate initially. At about 1600 UTC the thermals penetrated the inversion at the top of the boundary layer which has acted as a lid.

in the majority of catchments, not just those with high elevations, as it contains the ratio h/d^2. For example, the topographic effect of Hampstead Hill is thought to have contributed to the onset of the 1972 Hampstead storm (Bailey *et al.*, 1981).

Further, for PMP, a value of surface heating that is close to the maximum climatological value is needed. How frequent is it that there is no cloud before a storm forms, and the surface heating is a maximum? In fact such a situation is quite rare. Studies of the development of boundary layer thermals and associated cloud is an area of current research. Figure 3 shows an example of thermals observed with a vertically-pointing Doppler lidar. Convective cloud is shown to form before the thermals penetrate the boundary layer top marked by a temperature inversion and a heavy shower results. This inversion acts as a lid holding back the convective development. Hence, the surface heating is reduced when the cloud forms. Here it is assumed that the necessary conditions, with thermals penetrating the inversion and then leading to major ascent of the air to the top of the troposphere, will have occurred for 1 in 10 of the storm events. This is not an unreasonable assumption as the atmosphere for major storms will be potentially very unstable above the inversion. In other situations convection could occur but might not penetrate to the top of the troposphere and, therefore, would not lead to such severe events.

Multiplying the above four probability conditions, which implies that they are independent, gives the average number of PMP events *per* year (of around 10 h duration), for an individual 200 km^2 catchment in England and Wales $= 0.017 \times 0.025 \times 0.14 \times 0.1 = 0.000006$, i.e. 1 in 1.7×10^5 years.

For smaller catchments subject to the same storm, it could be argued that the return period would be similar, because whilst the chance of the catchment lying under the storm increases, if, as is likely, the storm rainfall is not spatially uniform, PMP will only occur if the catchment lies under the most intense part of the storm. PMP for larger catchments may be associated with different weather conditions, as discussed later.

If this mechanism is relevant to PMP at individual points, the assessment of return period of PMP for a point depends on the spatial variation of rainfall within the storm relative to the most intense point within the storm. For example, if 5% of the storm area experienced a rainfall at or very close to the storm maximum, the average number of PMP events *per* year for a point would be $0.017 \times 0.05 \times 0.1 = 0.000085$, i.e. 1 in 1.2×10^4 years.

5. Return period analysis for mesoscale convective systems (MCSs) in England and Wales

Mesoscale Convective Systems may be defined as continuous cloud systems of thunderstorms associated with an area of precipitation 100 km or more in horizontal extent in at least one direction (Houze, 1993).

Browning and Hill (1984) discuss the dynamical structure of MCSs. Young (2007) describes an MCS on the 10 May 2006 which brought severe weather to central southern England. Figures 1 and 2 show satellite and radar imagery for the event. Note that the cloud shield extends over a circle of approximately 100 km diameter (area 8000 km^2), and a compact area of intense radar echoes (locally exceeding 32 mm h^{-1}) developed and extended westwards in association with the expanding convective

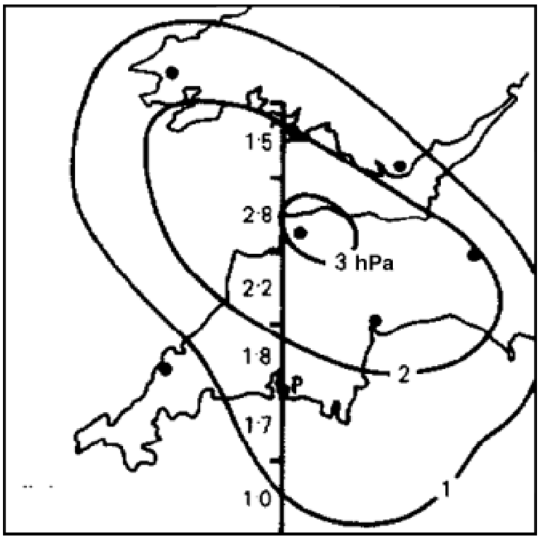

Figure 4. Spatial distribution of an MCS pressure anomaly at 0000 UTC, obtained by plotting the hourly anomalies along south-north lines at locations displaced according to the mean velocity of the rain area i.e. 40 km h^{-1}. Contours show smoothed anomalies at 1 hPa intervals. Actual values are plotted only for the Plymouth (P) barograph trace, however, the contours are based on barograph traces from all the stations indicated by dots. (From Browning and Hill, 1984).

cluster (Figure 2). Browning and Hill (1984) analysed the spatial distribution of the pressure anomaly for an MCS, and found that the core of this anomaly, within which the most intense rain fell, was not much larger than 200 km^2 (equivalent to a circle of 16 km diameter) (Figure 4).

Gray and Marshall (1998) identified 30 MCSs between 1981 and 1997, which might indicate a rate of about two *per* year. Although there are indications that this rate of occurrence might increase in the future as the climate changes (Maraun *et al.*, 2008) at present there is no firm evidence that this will be the case. Further work needs to be undertaken in this area. Hand *et al.* (2004) analysed all the twentieth century rainfall events that were categorized as extreme by Flood Studies Report (NERC, 1975) criteria. Of these 50 events, there were five of duration 10–24 h that could have been MCSs; these events were categorized as 'frontal with a significant convective component', a description which is consistent with the structure of MCSs, and comprised Boston (1931), Boston and East Leicestershire (1937), Lynmouth (1952), Martinstown (1955) and Whitstable (1968) (see Hand *et al.*, 2004). In addition, a storm at Chew Stoke (Bristol) in 1968 having a duration of 9 h is also included in this category. Other storms also have durations which might suggest that they could be MCSs. For example, Bruton (1917) has a duration of 8 h according to Hand *et al.* (2004), although this depends upon where one defines one storm ending and another starting. Clarke and Pike (2007) suggest that the duration of this storm is about 13 h. Therefore we will assume here that the recurrence interval for a very severe MCS, acting over 1000 km^2 and lasting around 15 h, is once every 10 years.

If the same approach as in Section 4 is used and if the same assumptions are made, for example regarding surface heating, this gives the average return period for the same number of PMP events *per* year (of around 15 h duration) for an individual large catchment (about 2000 km^2) in England and Wales $= 0.0053 \times 0.025 \times 0.14 \times 0.1 = 0.0000019$, i.e. 1 in 5.4×10^5 years.

6. Conclusion and risk context

The above analysis suggests that the return period of rainfall of around 10 h duration *approaching* PMP is approximately 1 in 2×10^5 years for catchments of around 200 km^2 in England and Wales. For larger catchments, a return period of 1 in 5×10^5 years has been estimated, and for point locations the estimate is 1 in 10^4 years.

It is clear that the results are highly sensitive to the various assumptions that it was necessary to make. It should be noted that any attempt to estimate the return period of PMP, rather than rainfall approaching PMP, using this approach would result in a return period of infinity. This should not be viewed as a weakness, since it is not inconsistent with the concept of PMP as an upper bound.

It is interesting to note that such a probability may be compared with the risk of death in the United States from a motor vehicle accident of 1 in 10^2 years (that is a risk of death of 0.001 *per* year), from a flood of 1 in 3×10^4 years and from a tornado of 1 in 6×10^4 years (Chapman and Morrison, 1994). However, these probabilities refer to risks to individuals, whereas the probability of occurrence of PMP does not necessarily lead to death, although the resulting flood conditions could do so. Also PMP for a catchment area does not impact one individual, but rather, possibly, many individuals. Nevertheless, this comparison is felt to give the reader a useful measure of the rarity of such events.

Further work to evaluate the PMP and the return period associated with it nationwide could be carried out using the approach articulated in this paper.

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