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Estimation of trends in rainfall extremes with mixed effects models

M. Kamruzzaman [a,*], S. Beecham [a,1], A.V. Metcalfe [b,2]

[a] Centre for Water Management and Reuse (CWMR), School of Natural and Built Environments, University of South Australia, Mawson Lakes, SA 5095, Australia
[b] School of Mathematical Sciences, University of Adelaide, SA 5005, Australia

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ABSTRACT

Estimates of seasonal rainfall maxima at durations as short as 6 min are needed for many applications including the design and analysis of urban drainage systems. It is also important to investigate whether or not there is evidence of changes in these extremes, both as an indicator of the sensitivity of rainfall to anthropogenic and natural climate change and as an aid to the calibration of future scenarios. Estimation of trends in extreme values in a region needs to be based on all the available data if precision is to be achieved. However, extremes at different periods of accumulation at neighbouring sites are not independent because there are temporal and spatial correlations, respectively. A linear mixed effects (lme) model allows for this correlation structure, and can be fitted to unequal record lengths at different sites. The modelling technique is demonstrated with an analysis of monthly maximum rainfall, at nine aggregations between 6 min and 24 h, from six sites, with record lengths between 10 and 25 years, from a region in South Australia. In terms of mean value, there is no evidence of a trend or change in the seasonal distribution of the monthly extreme rainfall. However, there is a strong evidence of an increase in variability of monthly extreme rainfall, estimated as a 58% increase in absolute value of deviation from the mean over a 25 year period. Rainfall records are often only available as a daily accumulation. A formula for the ratio of the monthly maxima at durations shorter than 24 h, down to 6 min, to the 24 h monthly maximum, in terms of: duration, month of the year, and a site specific adjustment is estimated. There is a clear seasonal variation in the ratios and there is evidence of a difference between rainfall stations.

1. Introduction

Analysis of extreme rainfall events needs to take account of the intensity-duration relationship. Relatively new applications such as Water Sensitive Urban Design (WSUD) need to consider rainfall over very short durations (typically 6 min in Australia) and it is important to monitor any changes in extreme values at these durations (e.g. Willems et al., 2012; Harremoës and Mikkelsen, 1995). Moreover, trends in rainfall extremes can have serious consequences in rural areas. For example, in Australia the unique flora, fauna and ecosystems are sensitive to even slight variations in climate (e.g. Alexander and Arblaster, 2009).

Allen and Ingram (2002) suggest that changes in rainfall distribution could have a greater effect on human communities than global warming. The Intergovernmental Panel on Climate Change (IPCC) gives global maps showing trends in annual precipitation 1901 relative to 2005 and 1979 relative to 2005 (Hegerl et al., 2007, Fig. 3.13). Examples of notable regional changes are a decrease of around 30% across Sahel from the 1950s to the 1980s, since when the mean rainfall appears to have remained at the same level (Hegerl et al., 2007, Section 9.5.4.3.1), and a decrease of early winter rainfall in the far south-west of Australia by around 15% in the 1970s with no subsequent recovery (Hegerl et al., 2007, Section 9.5.4.3.2). It is important to identify trends because: they indicate the sensitivity of the ecosystem to physical and anthropogenic changes; and they contribute to the calibration of regional climatic models that can be used to generate future scenarios. IPCC predicts a decrease in rainfall between 10% and 30% for the Iberian Peninsula by 2081–2100, relative to the two decades 1986–2005, based on multi-model mean projections (IPCC, 2014, Figure SPM.7). The IPCC also warns of an increase in the variability of extremes (IPCC, 2014, SPM 1.4). Martín-Vide and López-Bustins (2006) identified the relationship between extreme rainfall patterns in Andalusia in Spain and principal teleconnection indices such as the North Atlantic Oscillation (NAO) and the Western Mediterranean Oscillation (WeMO). Hidalgo-Muñoz et al. (2011) examined the significance of trends of extreme rainfall associated with synoptic patterns in Andalusia and suggested that "an understanding of the atmospheric mechanism controlling heavy rainfall is necessary for assessing natural hazard risk and for developing strategies of mitigation and response to these extreme events". Haylock and Nicholls (2000) reported three indices to describe extreme rainfall in a more objective way using an applied quantitative technique involving

* Corresponding author. Tel.: +61 8 8302 3108; fax: +61 8 8302 3386.
E-mail addresses: mohammad.kamruzzaman@unisa.edu.au (M. Kamruzzaman), simon.beecham@unisa.edu.au (S. Beecham), andrew.metcalfe@adelaide.edu.au (A.V. Metcalfe).
[1] Tel.: +61 8 8302 5141; fax: +61 8 8302 5082.
[2] Tel.: +61 8 8303 3236; fax: +61 8 8303 3696.

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the number of events above an extreme threshold (extreme frequency), the average intensity of rainfall from extreme events and the proportion of total rainfall from these events. Kuo et al. (2011) suggested a dynamic time series model for long duration extreme rainfalls to observe trends in annual maximum rainfall in Taiwan. Deng et al. (2014) present evidence from 68 stations of an increase in extreme precipitation and an increase in the annual maximum consecutive number of wet days in the arid region of northwest of China, over the period 1961–2010. Other large area studies include those by: Cinco et al. (2014) relating to the Philippines; Zhang et al. (2012) relating to China; Pingale et al. (2014) relating to India; and Almazroui et al. (2012), which focused on the Arabian Peninsula.

However, the impact of global changes can be affected by local conditions and this justifies local and regional studies (de Lima et al., 2013). There will typically be a number of meteorological stations within a region and hence multiple records. Generally, there have been two approaches to the analysis of these multiple records. One is to investigate the records separately, as it was done for time series of daily precipitation from 13 stations over 50 years in Northern Portugal (Santos et al., 2013). A limitation of this approach is that although the majority of trends were negative, few of these were statistically significant at a 5% level, and the overall significance of the study is equivocal. The second approach is to combine the time series and analyse the total precipitation (e.g. de Lima et al., 2013), or in the case of extreme values take the spatial maxima (e.g. Westra and Sisson, 2011; de Carvalho et al., 2013). This second approaches hypothesise a common trend over the region but lose some of the detail and information available in the data. In this paper we demonstrate the use of a linear mixed effects (lme) model that incorporates a common trend while using all the available data.

The aim of the study is to examine the intensity–duration relationship of monthly extreme rainfall in a region of South Australia using 6 minute rainfall accumulations from 6 stations with high quality records of at least 10 years length. The specific objectives are to: determine whether or not there is evidence of a trend in monthly extreme rainfall; determine whether or not there is evidence of a change in the seasonal distribution of monthly extreme rainfall; determine whether or not there is a change in the variability of the monthly extreme rainfall; and establish design requirements for sub-daily rainfall intensity. Previous studies have investigated trends in extremes and their variability (Villafuerte et al., 2014; Zwiers and Kharin, 1998; Jones et al., 1999; Yan et al., 2001; Westra and Sisson, 2011; Kamruzzaman et al., 2011). In this investigation, we combine the evidence on monthly maximum rainfall from six sites in the region of South Australia at different aggregations from 6 min to 24 h. However, rainfall extremes are typically due to unusual weather fluctuations such as cold surges and rainstorms which may occur at all durations and sites. So the additional data cannot be treated as arising from independent events. Variations of rainfall extremes at different spatial and temporal scales are caused by the influences of synoptic systems (e.g. those at the river basin or catchment scale) that come into effect during different seasons. They are also influenced by the topography of the land. The synoptic systems are influenced by sea surface temperature (SST) and associated ocean currents and pressure differences between different points on the earth. There are a number of climatic indices based on SST and pressure differences (e.g. Kamruzzaman et al., 2013). Such relationships can be used for short-term forecasting and may also be useful for investigating the effects of rainfall extremes.

For this study, we took original six minute rainfall data and accumulated these to durations of 30 min, 1 h, 2 h, 4 h, 6 h, 12 h, 18 h and 24 h. For each month, the maximum rainfall depth for each duration was recorded for further analysis. In the first analysis we investigate the relationship between monthly maximum rainfall at different durations and months of the year for different rainfall stations over the 29 year period. Specifically, the monthly maximum rainfall, is regressed on month of the year, rainfall station and duration accumulation. This regression must allow for the spatial correlation between rainfall stations and the correlation between monthly maximum rainfalls at different durations within the same month at the same rainfall station. The linear mixed effects (lme) regression model (e.g. De'ath et al., 2009; Galecki and Burzykowski, 2013; Corbeil and Searle, 1976; West et al., 2007) takes account of these correlations and was implemented with the open source software R (R Development Core Team, 2011). In the second analysis we consider the ratios of monthly maximum rainfall over a sub-daily duration to the monthly maximum rainfall over a 24 hour duration. The natural logarithms of these ratios, for wet months, are regressed on durations within a month and the rainfall stations using lme regression. A formula for converting 24 hour maxima to maxima at sub-daily durations for use in areas of South Australia is presented. The principle can also be applied to other regions.

2. Data

The analysis is based on data from six rainfall stations in South Australia: Adelaide Airport, Crafers, Halbury, Joslin Avenue, Kersbrook and Kent Town, as shown in Fig. 1. These stations were selected because they had the longest records of rainfall at 6 minute intervals and the highest Australian Bureau of Meteorology and SA Water Corporation quality designations for rainfall records for the period 1st January 1977 to 31st December 2005 (BoM, 2011). The data are rainfall depths at 6 minute intervals, giving, for example 2,190,000 depths over 25 years at Kent Town (Appendix A.1). A 6 minute interval is considered dry if recorded rainfall is less than 0.001 mm and in these cases the record is set to 0. The Kent Town rainfall station has 457,296 non-zero records, so the proportion of wet to dry 6 minute intervals is 21% over 25 years. The proportion of wet intervals for Adelaide Airport, Crafers, Halbury, Joslin Avenue, and Kersbrook are 19%, 21%, 22%, 17% and 20%, respectively. For wet days, the daily maximum at durations of 6 min and aggregated durations of 30 min, 1 h, 2 h, 4 h, 6 h, 12 h, 18 h and 24 h were calculated. The monthly maximum for a given duration was defined as the maximum of the daily maxima for that duration over the month.

3. Rainfall intensity by duration of accumulation

The monthly maxima rainfall depths for each duration accumulation were scaled to intensity (mm per minute). Statistics of these maxima are given in Table 1.

The reduction in rainfall intensity over the duration range from 6 min to 6 h is dramatic. For example, the mean monthly maximum intensity at Kersbrook over a 6 minute duration is 0.526 mm/min, but is only 0.014 mm/min over a 24 h duration. Also at Kersbrook the mean annual maximum intensity for 6 min duration is 6.57 mm/min, whereas for 24 h duration it is 0.047. The mean annual maximum is much higher than the mean monthly maxima because rainfall in South Australia has a seasonal pattern with the winter (May until August) being wetter. However, winter rainfall is generally more frontal than cyclonic (Atlas of South Australia, 1986), and intense rainfall over short periods is typically associated with cyclonic events. So, maximum rainfall intensities will not necessarily occur during the wetter seasons.

The mean monthly maximum intensities for each month for Adelaide Airport and Kent Town are shown in Fig. 2, while the corresponding intensities for the other four stations are presented in Appendix A.2.

Establishing a relationship between 24 h and shorter duration records is important because, rainfall records at many stations are restricted to daily data. Table 2 shows the statistics of the ratio of monthly maximum six-minute intensity to monthly maximum daily intensity for each month, calculated over the record length, the longest of which is 25 years in the case of Kent Town.

Taking Kent Town (with 25 years of record) as an example, the results from Table 2 indicate that for the three stations in the Adelaide Plain more extreme rainfall ratios of 6 minute to 24 hour intensities