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Evaluating the effect of climate change on areal reduction factors using regional climate model projections

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SUMMARY

Areal reduction factors (ARFs) are commonly used to transform point design rainfall to represent the average design rainfall for a catchment area. While there has been considerable attention paid in the research and engineering communities to the likely changes in rainfall intensity in future climates, the issue of changes to design areal rainfall has been largely ignored. This paper investigates the impact of climate change on ARFs. A new methodology for estimating changes in ARFs is presented. This method is used to assess changes in ARFs in the greater Sydney region using a high-resolution regional climate model (RCM). ARFs under present (1990–2009) and future (2040–2059) climate conditions were derived and compared for annual exceedance probabilities (AEPs) from 50% to 5% for durations ranging from 1 h to 120 h. The analysis shows two main trends in the future changes in ARFs. For the shortest duration events (1-h) the ARFs are found to increase which implies that these events will tend to have a larger spatial structure in the future than the current climate. In contrast, storms with durations between 6 and 72 h are likely to have decreased ARFs in the future, suggesting a more restricted spatial coverage of storms under a warming climate. The extent of the decrease varies with event frequency and catchment size. The largest decreases are found for large catchments and rare events. Although the results here are based on a single RCM and need to be confirmed in future work with multiple models, the framework that is proposed will be useful for future studies considering changes in the areal extent of rainfall extremes.

1. Introduction

The design of hydraulic structures such as dams, spillways and culverts, requires information on the maximum amount of rainfall that could occur for a particular catchment area over a specific duration. Design rainfall estimates are generally derived from rainfall gauge measurements and therefore represent rainfall at a point rather than over a catchment. To transform the point design rainfall to an appropriate areal average design rainfall, areal reduction factors (ARFs) are commonly used.

The ARFs account for the fact that the extreme rainfall when averaged over the catchment area is likely to be lower than the intensity of the extreme rainfall at any individual point (i.e. gauge). This effect is more pronounced as the size of the catchment area increases, so that the ARF values are lower for larger catchments. Another factor that affects the point to areal rainfall relationship is the prevailing meteorological and climatological conditions in an area. For different types of synoptic conditions, it is possible that storm events will have different areal extents, leading to differences in the point and areal averaged rainfall relationship. The different synoptic conditions are also likely to lead to different rainfall intensities and therefore the ARFs are often found to be a function of the severity of the rainfall event. This severity is defined in terms of the frequency of occurrence, i.e., the annual exceedance probability (AEP) of the event.

There are two groups of methods used to derive ARFs. Empirical fixed-area methods (Myers and Zehr, 1980; NERC, 1975; Omolayo, 1993; Shaw et al., 2011) are computationally intensive but applicable over a comprehensive range of spatial and temporal scales. In contrast, analytical methods (Bacchi and Ranzi, 1996; Bengtsson and Niemczynowicz, 1986; Rodriguez-Iturbe and Mejía, 1974; Veneziano and Langousis, 2005) require less computation but are only applicable within limited scales as they often rely on simplified assumptions. Rodriguez-Iturbe and Mejía (1974) estimated

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ARFs using the correlation between two gauges, which was assumed to follow either an exponentially decaying distribution or a Bessel-type correlation structure. This method also assumed that the point rainfall was isotropic and Gaussian distributed with a zero mean. Bengtsson and Niemczynowicz (1986) deduced ARFs from the movement of convective storms by assuming that the rainfall intensity distribution transverse to the storm was exponential. Bacchi and Ranzi (1996) derived ARFs using a stochastic method based on the assumptions that the number of crossings of high rainfall intensity levels was Poisson distributed and that the process of crossings was stationary and independent of events. Veneziano and Langousis (2005) derived ARFs based on the assumption that rainfall intensity was multifractally scale-invariant.

Until recently in Australia, the recommended ARFs were based on the US National Weather Service method (IEAust, 1987). This method is a combination analytical–empirical method and adopted ARF values were based on data from Chicago (Myers and Zehr, 1980) and Arizona (Zehr and Myers, 1984). This method uses frequency analysis of annual maximum rainfall at pairs of stations to derive the statistical characteristics, and then estimates ARFs based on the derived statistics. Due to the concern that the precipitation characteristics in the US are not necessarily representative of the conditions in Australia, studies based on Australian local rainfall records have been conducted for most parts of Australia using the modified Bell's method, which is an empirical fixed-area approach (Jordan et al., 2013). The new Australian ARFs are considered to better capture the spatial patterns of Australian rainfall and also allow for more regional variations in the ARF relationships, although the arbitrariness of using state boundaries to define rainfall relationships could be questioned.

Generally ARFs have been calculated and used with an implicit assumption of stationarity, i.e. that the statistical properties associated with the areal patterns of extreme rainfall events will be the same in the future as in the observational record. Until recently this assumption has served as a useful basis for engineering and hydrologic design (Milly et al., 2008). But with high resolution climate simulations now available and extensive research on changes in extreme rainfall, the assumption of stationarity is now being questioned.

Both climate model and observation studies have suggested that the intensity of extreme rainfall will increase due to global warming (Alexander et al., 2006; Allan and Soden, 2008; Groisman et al., 2005; O'Gorman and Schneider, 2009; Tebaldi et al., 2006; Zhu et al., 2013). A common explanation for the increase in precipitation extremes is the Clausius–Clapeyron (C–C) relationship, which states that for a 1 K increase in temperature, the saturation pressure of atmospheric water vapor increases by about 7%, leading to more atmospheric water vapor available to produce more intense rainfall events (Radermacher and Tomassini, 2012). However, the increase of extreme rainfall does not necessarily follow the C–C scaling. Recent studies have found that temperature scaling rate for precipitation extremes can either be above or below the C–C scaling depending on various aspects including storm duration, climate region, temperature range, and the analysis method used (Hardwick Jones et al., 2010; Kanemaru and Masunaga, 2012; Lenderink and van Meijgaard, 2008; Panthou et al., 2014; Shaw et al., 2011; Westra et al., 2012).

Although there have been a number of studies into changes in the intensity and frequency of extreme rainfall affecting engineering design due to anthropogenic climate change (Jakob, 2013; Liew et al., 2013; Madsen et al., 2009; Prodanovic and Simonovic, 2007; Zhu et al., 2013), less attention has been given to possible changes in the temporal and spatial patterns of extreme rainfall. A recent study (Wasko and Sharma, 2015) using a quantile scaling approach based on data from 79 rain gauges around Australia (Wasko and Sharma, 2014) demonstrated conclusively that storm temporal patterns are intensifying with increasing temperatures. There is reason to speculate that changes may be also found in storm spatial patterns, which is an important input for flood estimation. This study presents an investigation of the likely changes in rainfall spatial patterns in the future, which is achieved by estimating ARFs derived using rainfall simulations from a regional climate model (RCM) over Sydney, Australia under present (1990–2009) and future (2040–2059) climate conditions. The advantage of using a RCM to assess climate impacts on ARFs is that the high spatial resolution of the RCM better represents the spatio-temporal patterns of precipitation and accounts for complex topographical features and land use inhomogeneity that are usually not resolved by large-scale general circulation models (GCMs).

Despite the advantage of the higher resolution, RCMs are still prone to biases and cannot simulate processes at a point scale, which is the reference scale traditionally used in deriving ARFs. This paper presents a novel approach for estimating ARFs for future climates in the absence of future point scale information. The RCM skill in simulating the area-grid relationship is evaluated for the current climate before future changes in the ARFs are considered. Following standard practice for climate model assessments (Argüeso et al., 2012), the ARFs derived from the RCM driven by the reanalysis data are first examined for the current climate. Then the GCM driven RCM is evaluated in terms of reproducing the observed area-grid relationship of extreme rainfall. Finally, the model-simulated changes of ARFs are evaluated and the statistical significance of these changes is tested.

2. Data

2.1. Observational data

The observation-based ARFs used in this study are based on the equations derived by Jordan et al. (2013) for New South Wales (NSW) and the Australian Capital Territory (ACT) for durations between 1 and 120 h, catchment areas between 1 and 10,000 km^2, and AEP between 1% and 50%. The derivation of these equations is different for long durations (18–120 h) and short durations (less than 18 h). Long duration ARFs were estimated from the rainfall record at more than 6000 stations across NSW and ACT using the modified Bell's method (Siriwardena and Weinmann, 1996). These results indicated that ARFs decrease with catchment area and AEP, but increase with storm duration. Therefore, ARFs for long duration can be expressed as a function of these three factors, with the AEP effect found to be relatively small compared with catchment area and rainfall duration. As such, the ARF equations for long duration were derived in two stages. The relationship of ARF with catchment area and rainfall duration was first established for an AEP of 50%, and then the effect of AEP is added as an adjustment term. However, for short duration ARFs, observed rainfall over this region was not used due to the sparse gauge density. Instead, the 1-h ARFs published in the UK Flood Studies Report (NERC, 1975) were assumed to be applicable to this region. These were used with station-based NSW estimates of the 18-h ARFs for an AEP of 50% to interpolate the ARFs for durations in between. Since the ARFs in the UK Flood Studies Report are independent of AEP, the ARFs for short durations are also independent of the return period. Fig. 1 shows the variation of ARFs with catchment area, rainfall duration and AEP (Jordan et al., 2013).

2.2. Model simulated data

The data used to evaluate the climate impact on ARFs are from regional climate simulations over the greater Sydney region using