Preliminary Assessment of the Impact of Climate Change on Design Rainfall IFD Curves

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Abstract

The new edition of Australian Rainfall and Runoff (hereafter designated ARR 2015) contains completely revised design rainfall Intensity-Frequency-Duration (IFD) curves prepared by the Bureau of Meteorology. These curves are estimated from current climate observations. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change states that "extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases." This suggests that the current-climate IFD curves may become unsuitable for infrastructure design in future decades. While ARR 2015 includes an interim guideline on incorporating climate change into design flood estimation, the guidance is based on a 'broad brush' approach due to the paucity of published regionally specific results. As a first step towards bridging this gap, a pilot project titled 'Rainfall Intensity-Frequency-Duration (IFD) Relationships under Climate Change' was commissioned in June 2013 and administered by Engineers Australia. Its principal aim was to provide insight into how the new design rainfall IFD curves might be affected by anthropogenic climate change. This paper describes the background for and components of the investigation, the challenges involved, the major research findings and recommendations for further action.

1. INTRODUCTION

The new edition of Australian Rainfall and Runoff (hereafter designated ARR 2015) contains completely revised design rainfall Intensity-Frequency-Duration (IFD) curves for current climate conditions. Climate change is expected to have an adverse impact on heavy rainfall intensities (or equivalent depths) which could increase the risk of flooding over time at many locations in Australia. In recognition of this challenge, the Council of Australian Governments in 2007 identified the revision of the now-previous edition of ARR as a priority in its National Climate Change Adaptation Framework. The revision was recognised as an important national initiative to facilitate better planning of new infrastructure and to reduce potential damage to existing infrastructure.

Estimating future changes to extreme rainfall of hourly through to multi-day durations represents a major scientific challenge, and numerous innovations were necessary to achieve the project aims. A multiple-lines-of-evidence approach was adopted to assess historical changes and develop future projections, combining multiple historical data sources (including rainfall stations operated by the Bureau of Meteorology — hereafter 'the Bureau' — and water utilities, a gridded daily rainfall dataset and the Bureau's weather radar data) with very-high resolution climate model output. State-of-the-art statistical methods were applied to assess historical change, adjust climate model estimates of rainfall IFD curves to match observed data, and estimate the uncertainty of the climate change projections.

The project team consisted of research staff from the Bureau of Meteorology, the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and the Universities of NSW and Adelaide. Together, the team's expertise covered many disciplines in engineering and the mathematical, physical and statistical sciences. Given the geographic spread of the research team (Adelaide, Canberra, Melbourne, Perth and Sydney), four workshops were held during the project life cycle to ensure scientific consistency and integration, disseminate early research findings, and identify and remedy any emerging impediments to progress. The project was administered by Engineers Australia and completed in June 2015.

2. APPROACH

Given the project's budget and timeline constraints, it was necessary to limit the scope of the climate modelling component of the pilot study to the experimental setting provided in Table 1. Further details, including explanations of acronyms, can be found in Sections 3 and 4.

Table 1. Experimental setting for climate modelling.

Global Climate Models (GCMs)	Dynamical Downscaling Models	Spatial Domain	Horizontal Resolution	Historical Runs (1990-2009)	Future Scenarios (2040-2059)
CSIRO Mk3.5	WRF	Greater Sydney Region (GSR)	2 km	NCEP-NCAR Reanalysis	SRES A2
ACCESS1.0	CCAM	Greater Sydney Region (GSR)	10 and 2 km	ERA-Interim Reanalysis	RCP8.5
		Southeast Queensland (SEQ)	10 and 2 km	ERA-Interim Reanalysis	RCP8.5

The remaining components of the study were:

- Trend estimation in annual maxima series for sub-daily rainfall. This was limited to the Greater Sydney Region (GSR).
- Evaluation of the realism of simulated rainfall extremes from the model combinations listed in Table 1. This involved the use of blended radar and rain gauge data for the GSR, and gridded station data from the Australian Water Availability Project (AWAP, Jones et al., 2009). The use of radar data in this context is a novel approach, motivated by their superior spatial and temporal resolution.
- Development and application of a spatial Bayesian Hierarchical Model (BHM) to incorporate climate change information from CCAM and WRF by relating the parameters of the probability distributions of rainfall station data to those for the extreme rainfall generated by the climate models. The resulting information was used to 'bias-correct' climate model estimates of what might happen to extreme rainfall under climate change and produce estimates of uncertainty in the projected rainfall IFD curves.
- Comparison of the rainfall IFD curves obtained from the BHM with those obtained through application of the ARR 2015 Interim Guideline on Climate Change.

3. DESCRIPTION OF DATA

3.1. Daily and recording rainfall gauges

The analysis of trends in sub-daily rainfall series was concentrated on the GSR. A total of 69 sub-daily rainfall stations (5-minute resolution) were selected in this region, due to their relatively high quality and long record length (1966-2012). Of these, 13 stations were operated by the Bureau and 56 stations by water regulators under the 2007 Water Act. Despite some missing years, the majority of the datasets analysed have more than 27 years of record.

For the BHM implementation, 310 sub-daily and 562 daily rainfall stations were selected for the GSR (Figure 1). The SEQ dataset contained 240 sub-daily and 1108 daily stations (see also Figure 1). Both datasets were subjected to a thorough quality assurance process, including a number of different exploratory analyses. The sub-daily data at 5 min intervals were accumulated over 12 different durations, namely 5, 10, 15 and 30 min, and 1, 2, 3, 6, 12, 24, 48 and 72 hours. All stations within these datasets provide at least eight years' worth of yearly rainfall maxima during the period from 1961 to 2000.

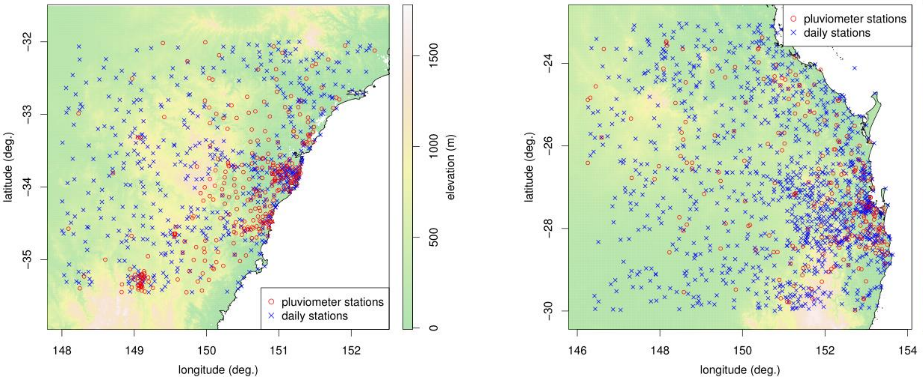

Figure 1 Locations of rainfall stations used for Bayesian Hierarchical Model implementation, for the Greater Sydney region (GSR, left) and South East Queensland (SEQ, right).

3.2. Australian water availability project (AWAP) rainfall

Analyses of daily AWAP rainfall were used in the evaluation of gridded rainfall data and their limitations relevant to the study of rainfall extremes. The resolution of the AWAP data is 0.05° × 0.05° (about 5 km × 5 km) and are based on *in-situ* observations only. The AWAP grids were developed for the purpose of monitoring of climate change and climate variability for the Australian region and are produced operationally at the Bureau. However, the accuracy of these gridded data is limited by the density of the station network. Errors tend to increase where rainfall gradients are strong, such as for regions with significant orography. King et al. (2013) assessed the adequacy of gridded daily rainfall extremes across Australia. Comparisons of the frequency and intensity of events above the 95th percentile were undertaken for 119 high-quality stations. Typically, the AWAP grids underestimated both intensity and frequency by about 10%. The rank correlation between AWAP and station rainfall for the GSR is high (0.8 to 0.9). AWAP rainfall estimates can therefore be expected to be a good indicator for where and when extremes occurred but are less reliable in terms of the magnitude of rainfall accumulations.

3.3. Radar data

The Australian weather radar network consists of a mixed collection of about 66 radars with an average age of 9 years. Multi-radar mosaics are available for three 500 km domains (Melbourne, Sydney and Brisbane). There is a fundamental difference between radar and ground based measurements: radars observe precipitation at height while rain gauges measure close to the surface. While gauge data provide accurate information at the gauge location, radar estimates are generally more accurate than a gauge-based estimates at distances from a gauge of more than 10 km or so.

The evaluation of radar data for the GSR was based on spatio-temporal characteristics derived from blended radar and gauge rainfall accumulations and are referred to as ‘Rainfields’ (Seed et al*.*, 2007). A new version of Rainfields (version 3) was produced using a sophisticated processing algorithm which provides improved quantitative precipitation estimates through improved quality control. A spatially varying calibration of radar against gauge data was implemented as well as measures to assess the quality of each 30-minute rain field. The resulting product is a mosaic of radar data from five radar sites (Wollongong, Newcastle, Sydney, Canberra and Kurnell), covering a 500 km × 500 km domain, centred on the Wollongong radar (150.87˚E and 34.26˚S) at a resolution of 0.01˚ (about 1 km) and 30 minute rainfall accumulations.

3.4. Reanalyses Data

An atmospheric reanalysis is a combination of a numerical weather prediction model and a comprehensive set of observations of the state of the atmosphere such that they represent a best estimate of actual atmospheric conditions at any time. The formulations of the data assimilation scheme and the weather prediction model are consistent throughout the length of the simulation. The reanalysis data sets are used frequently to drive GCMs and regional climate models (RCMs) enabling determination of the models’ ability to simulate the current climate and their biases. Two reanalyses are used in this study:

- The NCEP-NCAR Reanalysis Project (Kalnay et al., 1996). This is the longest ongoing reanalysis using past data from 1948 to the present. The data used in this study cover the period 1990 to 2009, are 6-hourly and interpolated to a 2.5° latitude-longitude grid.
- The ERA Interim reanalysis (Dee et al., 2011) which covers the period from January 1979 onwards, and continues to be extended forward in near real-time. The data used in this study cover the period 1980 to 2012, are 6-hourly and interpolated to a 1.5° latitude-longitude grid.

4. DESCRIPTION OF METHODS

4.1. Extreme Value Theory

Univariate extreme value theory describes the statistical behaviour of the maximum values of a sequence of observations in a long period, such as a year. The statistical distribution that describes these data is known as a generalized extreme value (GEV) distribution. This distribution is usually fitted to data whose statistical properties do not change over time; however it is possible to modify the distributional parameters to model increases or decreases in the intensity of extremes over time. This feature is used to explore whether there are statistically-significant temporal changes in the intensity of rainfall extremes. For the sub-daily rainfall trend analysis, the parameters of the model were fitted using the maximum likelihood method. A spatial version of the method was used in the sub-daily rainfall trends study which allowed the extremes from all of the 69 sites to be estimated jointly, as this increases the precision of the parameter estimates (Westra and Sisson, 2011).

4.2. Global Climate Models (GCMs)

The CSIRO Mk3.5 GCM consists of the CSIRO spectral atmospheric GCM coupled to the Geophysical Fluid Dynamics Laboratory MOM2.2 ocean model. It has been developed as a unified package including land and polar ice models. It was run using T63 resolution (about 2° × 2°) with 18 vertical levels. This model contributed to the Coupled Model Intercomparison Project Phase 3 ensemble (http://cmip-pcmdi.llnl.gov/) using a number of emission scenarios including the “Climate of the 20th Century” and the SRES A2 emissions scenarios used here.

The ACCESS1.0 coupled model has been developed at the Centre for Australian Weather and Climate Research, a partnership between CSIRO and the Bureau (Bi et al., 2013). It has an atmospheric horizontal resolution of 1.875° × 1.25° with 38 vertical levels. The coupled ocean model has 50 vertical levels and 1° horizontal resolution, increasing to 1/3° near the equator. ACCESS1.0 contributed several simulations to the Coupled Model Intercomparison Project Phase 5 ensemble (http://cmip-pcmdi.llnl.gov/cmip5/) using the revised Representative Concentration Pathway (RCP) method of providing climate forcings to model runs, including the RCP 8.5 scenario used here.

4.3. CSIRO Conformal Cubic Atmospheric Model (CCAM)

CCAM is a non-hydrostatic, semi-implicit, semi-Lagrangian atmospheric GCM, developed and maintained at CSIRO. The model uses a conformal cubic grid that can be stretched using a Schmidt transform to focus finer resolution grid points over a particular area. In this way, CCAM performs dynamical downscaling, avoids problems usually associated with lateral boundary conditions in RCMs and allows the regional climate to interact with the global circulation. The non-hydrostatic version of CCAM allows better representation of rainfall processes at length scales below 10 km. This project is the first use of CCAM for high resolution rainfall modelling at regional scales.

Each of the simulations performed progressed from a global 50 km resolution CCAM simulation, which was nudged towards the host model (or reanalysis) conditions every 3 hours via the spectral filter for the duration of the simulation (1980 to 2012 for ERA-Interim forced, and 1980 to 2065 for the ACCESS1.0-forced run), then through a continuous 10 km resolution run over south-eastern Australia performed over the same period (using the 50 km run to provide nudging). Ten km simulations provided the boundary forcing to 2 km domains over the GSR and SEQ and their surrounds.

Due to the computational resources and time required to perform a continuous simulation at such high resolution, the ACCESS1.0-forced 2 km simulations over Sydney and Brisbane were separated into two time slices; the baseline period was run from 1980 to 2012, while the future climate period was run from 2040 to 2065 using RCP8.5. From these periods a baseline (1990-2009) and a future (2040-2059) climate period were extracted for comparison with other components of the project.

4.4. Weather Research and Forecasting Model (WRF)

The Weather Research and Forecasting (WRF) model is a RCM. The modelling system is developed as a collaborative partnership between a number of agencies and universities in the USA, as well as the wider research community. The version used in this study is the Advanced Research WRF version 3. The boundary conditions for the 2 km simulation were taken from a previously performed and evaluated 10km simulation (Evans and McCabe, 2010). There are two sources of global boundary conditions for the model. First a simulation was performed using global boundary conditions from the NCEP/NCAR Reanalysis (Section 3.4). Using these boundary conditions allows this simulation to be compared directly with observations for a thorough evaluation of model performance. The second source of global boundary conditions is the CSIRO Mk3.5 GCM simulation using the SRES A2 emission scenario. Simulations for both the recent past (1990-2009) and a future time slice (2040-2059) were performed. Two continuous simulations were performed for the 1990-2009 period. The first used reanalysis boundary conditions and provides an indication of the regional models performance given accurate boundary conditions. The second used GCM boundary conditions. Evaluation of this simulation provides a quantification of the errors associated with the combined GCM-RCM system. The same GCM is then used to drive a future simulation (2040-2059).

4.5. Bayesian Hierarchical Modelling of Rainfall Extremes

The BHM developed is an extension of that of Davison et al. (2012). It incorporates the scale-duration relationship of Koutsoyiannis et al. (1998) which allows modelling of IFD curves, and provides a means of integrating climate model output in order to estimate changes in rainfall extremes at different durations. Earlier versions of the BHM are described by Lehmann et al. (2013) and Soltyk et al. (2014)

The analysis of extremes is based on the GEV distribution. It has location, scale and shape parameters that have to be estimated from station data or climate model output. The use of the scale-duration relationship of Koutsoyiannis et al. (1998) introduces two additional parameters. Estimation of the five parameters is carried out in a spatial Bayesian framework. Quantities of interest such as extreme rainfall intensities (or equivalent depths) across a range of durations and different annual exceedance probabilities can then be calculated. The BHM:

- Uses information from neighbouring sites, either recording or daily rainfall gauge data, to increase the precision of estimates of design rainfall IFD curves.
- Provides estimates of IFD curves at locations where there is only daily-read data or at ungauged locations.
- Produces estimates of uncertainty in rainfall IFD curves that are consistent in the sense that, for example, the uncertainty in an IFD curve at an ungauged location should be greater than the uncertainty at a gauged location. Also, the width of uncertainty bands reflects the effects of sampling variability on estimated IFD curves.
- Integrates information from regional climate models so that it is possible to estimate rainfall IFD curves under climate change scenarios.

5. MAJOR RESEARCH FINDINGS

- For durations less than two hours, the intensities of observed annual maximum rainfalls have increased in the GSR over the period 1966 to 2012, while for durations greater than three hours a decrease was found to be more likely. These trends are explained by two related findings: (1) that different trends were found in different seasons regardless of the duration, with summer maxima exhibiting increasing trends and winter/autumn maxima typically exhibiting limited changes or decreasing trends; and (2) that different seasons are characterised by different rainfall characteristics, with summer rainfall typically comprising shorter-duration higher-intensity rainfall compared to the other seasons (Zheng et al., 2015).
- Despite differences in methodology between the BHM used herein and the new design rainfall IFD curves in ARR 2015, the results were found to be remarkably similar. In most cases, the ARR 2015 IFD curves lie within the uncertainty bounds produced by the BHM.
- Biases exist in the Rainfields and AWAP datasets. Therefore, more than one observational dataset is recommended for use in similar evaluation studies.
- To produce credible projections of changes in rainfall extremes, GCMs and downscaling models need to be able to realistically simulate key mechanisms and characteristics of these extremes. Simulations driven by Reanalyses are typically a better match with observations than GCM-driven simulations, and WRF simulations typically provide a more realistic picture than the CCAM simulations analysed.
- The frequency distributions of observed and simulated rainfall exhibit marked differences. CCAM and WRF produced unrealistically high rainfall extremes. A simple bias correction reduced errors for modelled annual accumulations in WRF, but did not remove the tendency for overestimation of rainfall extremes and introduced artefacts. Simulated rainfall is less random in space and time than observed rainfall, which implies that not all rainfall-producing mechanisms have been correctly captured. This is important because changes in rainfall extremes are likely to be driven by changes in convective rainfall and low-pressure systems.
- For the GSR, neither CCAM nor WRF output is able to adequately reproduce the magnitude of extreme rainfall in the selected baseline period (1990 – 2009) at 2 km resolution although there is some relationship between patterns of extreme rainfall produced by WRF and those exhibited by rainfall station data. The BHM estimate for future extremes suggests that the 1% annual exceedance probability (AEP) for the 24 hour duration event will increase by up to 20% by 2050. To the west, in some parts of the Blue Mountains and beyond, decreases are possible. These results are subject to high levels of uncertainty (Section 6).
- For the GSR, projected rainfall IFD curves obtained from the ARR 2015 Interim Guideline on Climate Change match those produced by the BHM. While this result is encouraging, further

studies are needed to test the efficacy of the Guideline.

- For SEQ, projected changes in the 1% AEP 24-hour rainfall can also be very large. The ACCESS-CCAM model combination projects increases in the Brisbane region and in an arc to the west, whereas it projects a decrease in extreme rainfall near the Sunshine Coast and to the northwest. For an AEP of 10%, there is little difference between current and future extremes, whereas for rarer events (1% AEP), future extreme rainfall is much larger than current extreme rainfall. Spatial patterns at different durations are similar. These results are subject to high levels of uncertainty (Section 6).

6. RECOMMENDATIONS FOR FURTHER ACTION

Given the above knowledge gaps and research findings, areas for potential future research are:

- **Improvement of physical understanding.** Further research is required to understand the physical processes that drive the variations of the extreme rainfall with different durations.
- **Design rainfall temporal patterns for short and long duration storms**. Climate change may not only alter rainfall intensity, but also the temporal patterns of extreme rainfall events. Further research is required to quantify the impact of climate change on these patterns.
- **Structure of spatial dependence.** It is necessary to investigate the possible changes in the structure of the spatial dependence of rainfall extremes, thereby obtaining deeper insight into climate change impacts.
- **Implications for floods**. Possible changes in the seasonality of rainfall may change the catchment wetness prior to flood-producing rainfall events, leading to altered flood risks. The interaction between flood-producing rainfall events and antecedent catchment conditions is not well understood and should be investigated.
- **Augmentation of the Greater Sydney and south-east Queensland studies**. It is highly likely that uncertainty in the projections described herein is underestimated and the projected regional patterns of change are not robust. Accepted practice would involve the use of a larger number of host global climate models and a more systematic sampling of regional model uncertainty. The use of a low emissions scenario such as RCP4.5 should also be considered.
- **Climate model improvement.** Better understanding of the drivers of extreme rainfall from global to regional scales and their responses to greenhouse gases is required. Current models require further development and testing to improve their performance at the spatial scales required for the simulation of convective storms (< 4 km).
- **Bayesian Hierarchical Model improvement.** The BHM incorporates present and projected dynamically downscaled data in two separate steps. A more mathematically rigorous approach would be to construct a model that completely integrates data as well as the present and future climate model outputs within a unified framework.
- **Extension to other geographic domains**. The results of this study focus on the GSR and to a lesser extent SEQ. This study should be repeated over other geographic regions where different rainfall-generating mechanisms are likely to apply.

7. CONCLUDING REMARKS

The success of the project demonstrates the substantial potential embodied in the study of the behaviour of rainfall extremes under current and projected climate conditions. However, the current research infrastructure, institutional set up and funding environment in Australia create significant barriers to maximising the provision of clear, practical and science-based information and advice to support decision making and management policy and planning. With the completion of the pilot project, there no longer exists an ongoing critical mass of research activity to ensure the viability of this new field of endeavour in Australia.

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