UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Adapting to Climate Change – Revising our Approach to Estimating Future Floods

Dr Seth Westra

23rd August 2011

This paper is adapted from a discussion paper entitled ‘Implications of Climate Change on Flood Estimation’ which was prepared on behalf of the Department of Climate Change and the Australian Rainfall and Runoff (ARR) technical committee, and was presented at an ARR workshop on flooding and climate change in Sydney on 30 November 2010. The funding from the DCC, and the intellectual contributions of the workshop participants, are gratefully acknowledged.

NCCARF
National
Climate Change Adaptation
Research Facility
Adaptation Research Network
SETTLEMENTS AND INFRASTRUCTURE

water@
UNSW
water research centre

1. Introduction and Background

It is becoming increasingly clear that human-induced climate change will impact on almost all facets of the hydrological cycle. Modelling and observational studies are finding evidence of change at the planetary scale, including large increases in atmospheric water vapour; changes to various circulation patterns resulting in shifts in the spatial distribution of precipitation; an increase in the frequency and intensity of extreme precipitation events; an increase in evaporation and changes to soil moisture; and the melting of snow and ice and an increase in ocean heat content which both are causing mean sea levels to rise [see detailed review in *Bates et al.*, 2008]. At least in terms of the global scale, such changes support the expectation of an increase in flood risk.

Despite this evidence there is considerable uncertainty about: (1) the absolute magnitude of change to key flood-producing variables such as extreme rainfall; (2) the much more significant changes of continental and regional-scale hydroclimatology which are masked by global averages and which may not be as well simulated by general circulation models; and (3) the role of physiographic catchment characteristics in decreasing or augmenting flood risk at the local scale. Thus, while it is now widely accepted that stationarity – the assumption that the future climate will mirror the past climate – may no longer be regarded as the 'central, default assumption in water-resource risk assessment and planning' [*Milly et al.*, 2008], the identification of an alternative framework for flood estimation remains elusive.

The objective of this discussion paper is to describe some of the principal issues associated with accommodating climate change into Australian flood estimation practice. Given that the vast majority of Australia's historical effort to manage and mitigate flood risk has been underpinned by the assumption of stationarity, the development of an alternative framework that accounts for future changes will form a critical input into how we adapt to future risks. The emphasis of this paper is therefore on summarising the science linking climate change to flooding, and reviewing some of the tools which can be used to quantify future flood risk, as these will form a necessary input in any future adaptation effort. A brief overview will also be provided of official guidance that is currently available on incorporating changes to rainfall and sea level in planning and design, although it should be noted that much more detailed guidance is expected as part of the upcoming revision to Australian Rainfall and Runoff (ARR http://www.ncwe.org.au/arr/index.html).

There are a range of broader questions related to how to adapt to the changes that might take place, including the relative roles of engineering solutions (such as levees, reservoirs, storm water drainage, seawalls and so on), planning controls (such as land-use zoning), and numerous other potential tools that can aid in reducing or better living with flood risk. Further details on these issues will be reserved for future discussion papers. However as this paper will argue, any research on adaptation options must be done in parallel with research which improves our understanding of the hydrology which causes floods to occur in the first place, to ensure that adaptation efforts are deployed wisely and make the best possible use of finite resources in addressing this complex problem.

This paper is largely drawn from a discussion paper entitled "Implications of Climate Change on Flood Estimation" [*Westra*, 2010], which was prepared on behalf of the Department of Climate Change and the ARR technical committee, and was designed to inform the current round of ARR revision projects related to incorporating the impacts of human-induced climate change into flood estimation practice. That paper was presented at a workshop in Sydney on 30 November 2010, and is currently assisting to inform the next phase of research into how flooding might change under a future climate.

2. Climate Impacts Relevant to Flood Risk

As described in the previous section, the foundation of any adaptation effort to address future flood risk is an understanding of how such flood risk will change as a result of historical and future greenhouse gas emissions. This section contains a review of key physical processes relevant for flood risk which are likely to change as a result of anthropogenic climate change. The discussion is intentionally brief, with further information available from a range of synthesis reports [e.g. *Bates et al.*, 2008; *CSIRO & Bureau of Meteorology*, 2007; *IPCC*, 2007; *The Copenhagen Diagnosis*, 2009]. The latter report was authored largely by IPCC lead authors, with a view to providing an interim update on climate science following on from the IPCC [2007] report, and is therefore cited in several cases where the science has evolved rapidly. Emphasis is placed on studies that are relevant to Australian conditions.

1) The global average temperature has increased by ~0.74°C over the 100 years up to 2005 [*IPCC*, 2007] with a slightly higher increase in Australia of 0.9°C since 1950 [*CSIRO & Bureau of Meteorology*, 2007]. Projections of future warming in Australia are for an additional 1°C (0.6°C-1.5°C) relative to 1990 levels by 2030, and between 1°C and 5°C warming by 2070, with larger warming for inland regions relative to coastal regions [*CSIRO & Bureau of Meteorology*, 2007].

2) The specific humidity and total column water vapour content increased globally, at a rate consistent with the Clausius-Clapeyron relationship of approximately 7%/°C over oceans, indicating approximately constant relative humidity. In contrast, there has been an observed decline in relative humidity over mid-latitude land areas, including an observed decline in relative humidity over Australia over the previous decade [*Jung et al.*, 2010; *Simmons et al.*, 2010; *Willett et al.*, 2007]. This is generally consistent with modelling studies which show smaller increases in specific humidity (and thus decreases in relative humidity) in most mid-latitude land areas [*O'Gorman and Muller*, 2010; *Sherwood et al.*, 2010].

3) Globally averaged precipitation is expected to increase much more slowly than the water vapour content, with a multi-model mean sensitivity of ~2%/°C [*Held and Soden*, 2006]. Observations also suggest limited mean change on a background of significant inter-annual and inter-decadal variability [*Gu et al.*, 2007; *Huffman et al.*, 2009].

4) Small changes to global mean precipitation mask more important regional features, with a recent review of land precipitation finding decreases in the subtropics and tropics outside of the monsoon trough, and increases in land precipitation at higher latitudes and also a possible increase in the monsoon trough [*Trenberth et al.*, 2007]. In Australia there has been an observed decline in precipitation since the 1950s in the southern parts of the continent and an increase in the northwest [*CSIRO & Bureau of Meteorology*, 2007], broadly consistent with GCM projections [*CSIRO & Bureau of Meteorology*, 2007; *IPCC*, 2007]. A study of the recent decline in southern Australian rainfall attributes this change to the intensification of the subtropical ridge, which represents the strength of the downward branch of the Hadley cell, and is consistent with projections of Hadley circulation associated with global warming [*CSIRO*, 2010].

5) Recent observational studies are suggesting a significant increase in the width of the tropical belt, and poleward migration of mid-latitude storm tracks and changes to other aspects of Hadley circulation [*Lu et al.*, 2009; *Seidel et al.*, 2008], which generally are under-simulated in models [*Johanson and Fu*, 2009]. Such shifts are likely to yield especially large changes to precipitation on the edges of current climatic zones.

6) Models are consistent in finding that extremes[1] will change more rapidly than the means [e.g. *Frei et al.*, 2006], with a multimodel ensemble of 20-year return interval 24-hour precipitation suggesting an average increase of about 6%/°C globally, and with decreases only occurring in a few subtropical regions [*Kharin and Zwiers*, 2007]. This is generally confirmed by global-scale observational studies which show that even in areas where mean precipitation is not changing, heavy precipitation events are becoming more common [*Alexander et al.*, 2006; *Groisman et al.*, 2005; *Trenberth et al.*, 2007]. Results from Australian studies on trends in extreme daily rainfall are less clear and usually not statistically significant [e.g. *Alexander et al.*, 2007; *Gallant et al.*, 2007 and numerous others referenced therein], although generally the direction of trends in indices of extreme daily rainfall reflect trends in mean annual rainfall, with declines since the 1950s observed in southwest Western Australia, southeast Australia and the eastern coastal region [*Gallant et al.*, 2007]. The Australian Bureau of Meteorology [2010] also recently conducted an analysis on daily annual maximum precipitation, and found few statistically significant increasing or decreasing trends, and no strong spatial pattern of the significant trends. It is likely that at least part of any observed change to extreme precipitation is due to natural variations in climate at interannual and interdecadal timescales, although the relative contribution of natural and anthropogenic influences on extremes has not been quantified. Finally, it is noted that the definition of 'extreme' in these studies typically relates to the annual or seasonal maxima, or the 95 or 99%ile daily rainfall event, and the extent to which the results can be extrapolated to rarer events is uncertain.

7) There is mounting evidence that much of the increase in extreme rainfall is likely to occur at much finer sub-daily timescales. For example, Hardwick-Jones et al [2010] find that extreme rainfall scales with temperature for most temperature ranges (with the exception of the highest temperatures) across the continent for hourly and shorter-duration rainfall, but not for daily-scale rainfall [see also *Fraser et al.*, 2011]. Similar conclusions have been found in a range of international studies [e.g. *Hanel and Buishand*, 2010; *Lenderink and van Meijgaard*, 2008]. In the assessment of trends using Australia's sub-daily precipitation record, the Bureau of Meteorology [2010] found some statistically significant increases in sub-daily rainfall trends. The strongest trends were found for durations below one hour, where approximately half of the 58 stations analysed had statistically significant increases in annual maximum rainfall [see also *Westra and Sisson*, 2011]. Although there are several outstanding questions regarding the suitability of the data used to undertake climate change detection and attribution studies, due to the larger percentage of missing data and instrumentation changes over the period of record, these results are qualitatively consistent with several dynamical modelling conducted by [*Abbs and Rafter*, 2009; *Abbs et al.*, 2007] who also find much stronger increases in 2-hour rainfall compared to 24- or 72-hour rainfall.

8) The detection of change to flood frequency remains much more difficult, due to the confounding influence of land-use changes and the construction of flood protection works and reservoirs, with two recent global studies yielding ambiguous results [*Kundzewicz*, 2005; *Milly et al.*, 2002]. Furthermore, numerous studies in Australia have found significant modulation of flood risk due to natural modes of climate variability, such as the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO) [*Erskine and Warner*, 1988; *Franks and Kuczera*, 2002; *Kiem et al.*, 2003; *Micevski et al.*, 2006] , making attribution of any changes in flood frequency specifically to the anthropogenic climate change a difficult task. A preliminary study on trends in Australian flood data using a recently compiled dataset of 491 stations with minor anthropogenic influences and with annual

---

[1] There are differing definitions of extreme events by the climate science and engineering hydrology communities. In this discussion paper the term is interpreted in the climate science sense (typically comprising the 1 percentile or 5 percentile daily rainfall event, or annual maximum event), unless otherwise specified.

maximum flood records of length between 30 and 97 years found approximately 30% of stations with a statistically significant trend at the 10% significance level, which are in a downward direction in southern parts of the Australian continent and an upward direction in the northern regions [*Ishak et al.*, 2010], although this study did not evaluate the contribution of natural or anthropogenic causes to these observed changes.

9) The IPCC [2007] report recently provided sea level rise projections for 2090-2099 relative to 1980-1999 of between 0.18 and 0.59m, excluding dynamical changes in ice flow, with an additional 0.1-0.2m assuming the contribution of ice flow from Greenland and Antarctica increases linearly with temperature. It is generally considered likely that this report has underestimated likely sea level rise, with a recent summary of the literature on behalf of the Sydney Coastal Councils group providing estimates ranging from 0.18m through to 1.4m [*Preston et al.*, 2008], and another recent review of the literature projecting sea level rise until 2100 likely to be at least twice as large as the IPCC [2007] estimates, with an upper limit of 2m [*The Copenhagen Diagnosis*, 2009].
10) Several studies of the implications of storm surge along the east Victorian coast and southern Queensland find increases in storm surge to be generally second-order compared to increases in mean sea level (with typical projections of ~0.1m increase by 2100); however greater sensitivity might exist for tropical cyclones with an increase in storm surge of 0.3m for the 1 in 100 year event projected for Cairns by 2050 in addition to any mean sea level contribution [see *CSIRO & Bureau of Meteorology*, 2007 and references therein]. Other reports suggest much greater increases in storm surge of about 0.5m along the Queensland coastline, with potentially greater increases in southeast Queensland [*Queensland Government*, 2004].
11) Several recent summary reports suggest that tropical cyclones are expected to increase in intensity, with higher wind speeds and increased precipitation resulting from increased tropical sea surface temperatures, although the total number of cyclones may decrease [*CSIRO & Bureau of Meteorology*, 2007; *The Copenhagen Diagnosis*, 2009]. Furthermore, CSIRO & Bureau of Meteorology [2007] projects a southward migration of almost 3 degrees latitude (~300km) in the average decay location for east Australian cyclones by 2070. A study currently underway [*Abbs*, 2010] also has found a statistically significant decrease in tropical cyclone occurrence and a southward migration in the genesis and decay regions by 100km by 2051-2900, and a dynamical downscaling study using the Regional Atmospheric Modelling System (RAMS) to develop quantitative estimates of likely changes to intensity is currently in progress.

Based on the research described here, the current understanding of the implications of anthropogenic climate change on flood risk in Australia can be summarised as follows:

Intensity-Frequency-Duration (IFD) relationships: IFD relationships are empirical/statistical relationships between the recurrence interval (the frequency) of a precipitation event, the length of a given storm burst (the duration) and the average intensity of precipitation over that duration (intensity). IFD estimates form the basis of a large part of flood estimation practice in Australia, which involves translating the design rainfall event obtained from IFDs to the design flood event via some form of rainfall-runoff model. The most recent Australia-wide IFD maps were generated under the previous ARR revision [*Pilgrim*, 1987], and are still in common use today.

At the daily timescale, there is still no clear observational evidence for increases in extreme daily precipitation [*Australian Bureau of Meteorology*, 2010], although there is a possibility of a decrease in extreme rainfall in the regions where mean rainfall is also decreasing [*Alexander et al.*, 2007; *Gallant et al.*, 2007; *Li et al.*, 2005]. It is likely that different periods of record used by different studies, different metrics to define extremes, and the important role of low-frequency (inter-annual and inter-decadal) variability, are the dominant reasons for subtly different conclusions in each of the trend detection and attribution studies.

Coarse-resolution modelling of the 99th percentile daily precipitation summarised by CSIRO [2007] for 2050 suggest a small increase in intensity over most of the country, although projections for southwest Western Australia also show a decrease. Qualitatively similar results were found by Alexander and Arblaster [2009] using a set of extreme precipitation indices from nine of the IPCC AR4 models, including changes to heavy precipitation days (number of days with precipitation > 10mm), maximum 5-day precipitation, and very heavy precipitation contribution (fraction of the annual total precipitation due to events exceeding the 1961-1990 95th percentile). A recent study by Rafter and Abbs [2009] on 20-year daily rainfall in 2055 and 2090 using an extreme value theory downscaling approach showed increases in all regions, across most GCMs considered. The spatial patterns were consistent with previous studies, with smaller increases in the south and larger increases in the north.

In contrast to daily rainfall results, at the sub-daily timescale there is mounting evidence that annual maxima may be increasing, both based on statistically significant trends in the historical pluviograph reported in [*Australian Bureau of Meteorology*, 2010; *Westra and Sisson*, 2011] for sub-hourly data, and regional climate model studies undertaken in southeast Queensland and Western Sydney [*Abbs and Rafter*, 2009; *Abbs et al.*, 2007] for 2-hour rainfall. Furthermore, studies on the temperature scaling of extreme rainfall in Australia by Hardwick-Jones et al [2010] show strong changes to the scaling relationship with event duration, suggesting different processes influence extreme rainfall at different durations. It should be cautioned that observational results using sub-daily rainfall are inherently uncertain, in particular given the shift to digital instrumentation from the mid 1980s potentially affecting any long-term trend studies [*Westra and Sisson*, 2011]. Nevertheless the increased sensitivity of precipitation at sub-daily timescales is also found in a range of observational and modelling studies internationally [*Lenderink and van Meijgaard*, 2008; *Lenderink et al.*, 2011; *Sugiyama et al.*, 2010], such that the observed changes are consistent with broader evidence.

Finally, the spatial distribution of likely change to extreme rainfall represents an important issue which thus far has not been addressed in the scientific literature. Whereas projections of changes to mean rainfall appear to follow large-scale circulation features (e.g. declines in subtropical regions, increases in tropics and higher latitudes), dynamical modelling studies by [*Abbs and Rafter*, 2009; *Abbs et al.*, 2007] suggest the sign and magnitude of change varies at the scale of only several kilometres. For example, Abbs et al [2007] provide projections of >70% increases for extreme 2-hr rainfall by 2030 in certain locations yet with small decreases only several kilometres away. In Sydney and nearby regions, Mehrotra and Sharma [2010] used a statistical downscaling approach based on a multi-site modified Markov model, and also found large spatial variability in the sign of change to extreme rainfall (number of wet days >35mm) ranging from an increase of 25-35% in the northeast of the domain to a decrease of 0-15% in the southwest of the domain, although it is difficult to compare the spatial consistency of this work with the work of [*Abbs and Rafter*, 2009]. The extent to which local-scale features such as coastal effects, orography and other land-surface features influence the sign and magnitude of change to extreme precipitation represents an important outstanding question, and will influence the spatial scale at which future IFD relationships can be expected to change.

Changes to precipitation type: This includes changes to storm type, frequency, depth, and rainfall spatial and temporal patterns. The temporal patterns, in particular, are an essential component of existing Australian flood estimation practice, with standard temporal patterns used in conjunction with IFDs as part of the methods recommended in Australian Rainfall and Runoff [*Pilgrim*, 1987]. Spatial patterns have an equally important role, particularly through the use of Areal Reduction Factors, which describe how area-averaged rainfall intensity relates to point-based rainfall intensity obtained from rainfall gauges [*Pilgrim*, 1987]. Therefore changes to the temporal and spatial character of precipitation can have a significant impact of the resulting flood estimates, above and beyond any issues related to mean storm intensity as described in the previous section.

There is some evidence that the nature of storm types is likely to change under a future climate, probably by a large extent in climatological transition zones. For example, the poleward migration of mid-latitude storm tracks suggests that the spatial extent of these storm systems will change. Similarly, projections for an increase in intensity, decrease in occurrence and southward migration of tropical cyclones highlight that changes might be expected in areas affected by these storm systems. Increases in extreme precipitation even when average precipitation decreases, and the disproportionate projections of increases in short-duration (sub-daily) precipitation by regional climate modelling studies, suggest that precipitation events are likely to become less frequent and more intense. Nevertheless, quantitative projections associated with many of these features are either unavailable, or highly uncertain.

Antecedent conditions: Antecedent conditions relate to the state of the catchment prior to the flood-producing rainfall event, and can often have a significant bearing on the size of the ensuing flood. Depending on the nature of the catchment, antecedent conditions can relate to the moisture stored in various soil and groundwater stores, natural lakes, large reservoirs such as those used for water supply or hydroelectricity, or smaller distributed reservoirs such as on-farm dams, rainwater tanks or stormwater retention devices. Therefore the catchment sensitivity to antecedent moisture conditions can vary widely, and the period of antecedent precipitation that needs to be considered can range from hours through to many months depending on the specific features of the catchment being analysed.

Changes in mean annual rainfall, precipitation intermittency, relative humidity, evapotranspiration and soil moisture in Australia have each been documented, suggesting that changes in the catchment moisture content prior to the flood-producing event is likely. Such changes are unlikely to be uniform in space, with the greatest declines in catchment moisture likely in the southern parts of Australia, and a possible (but poorly gauged and therefore more uncertain) increase in northern Australia. It is likely that the documented declining trends in annual maximum flood peaks in southern Australia cannot be completely explained by changes in annual maximum rainfall, which were found by the Australian Bureau of Meteorology [2010] to be approximately stationary at least at the daily timescale. This is analogous to the situation whereby the significant modulation of historical flood risk by the Inter-decadal Pacific Oscillation suggested by Kiem et al [2003] was found in a recent study to be largely due to variability in antecedent moisture conditions, rather than the flood-producing rainfall event itself [*Pui et al.*, 2010], although some modulation of .

There has been little research on how changes to catchment antecedent conditions due to climate change will influence flood risk. Much of the difficulty stems from the influence of a range of catchment characteristics, such as slope, soil type, vegetation, extent of urbanisation, as well as the presence of major storages [*Hill*, 2010], therefore making the role of antecedent conditions on flood risk difficult to generalise across large spatial areas. Furthermore, antecedent moisture conditions may also have complex effects on the shape of the flood hydrograph, affecting peaks, volume and rate of rise differently. Limited research is available linking loss parameters in event-based models to pre-event catchment conditions , although some recent research [*K Fowler et al.*, 2010] has used historical and future climate sequences derived from the Murray-Darling Basin Sustainable Yields Project [*Chiew et al.*, 2008] to estimate historical and future loss rates. Interestingly, this study found that, at least for the case study location, increases to extreme rainfall and increases to catchment losses had approximately equal but opposing influence on flood magnitude.

Finally, although the pre-flood baseflow is unlikely to be a large contributor to the flood hydrograph for larger events, for smaller events such as the 2-year average recurrence interval (ARI) event baseflow might become important. Furthermore, baseflows can be a significant component of reservoir inflows and can thus affect antecedent conditions in large storages. Nevertheless, there is limited research available on how baseflow is likely to change under a future climate.

Changes in ocean levels and joint probabilities of rainfall and storm surge: There are two separate issues when considering the implications of ocean levels on flood estimation under a future climate. Firstly, it is necessary to quantify the changes in extreme ocean levels, which will be influenced by changes in mean level as well as any changes to the storm surge component due to the potential for more vigorous storm activity under a future climate. As summarised in items (9) and (10) above, it is likely that the largest contribution to changes in extreme sea levels due to anthropogenic climate change will come from increases in mean sea level, with changes to storm surge expected to be minimal along large sections of the Australian coastline. A possible exception is in regions affected by tropical cyclones, with projections of increases in storm surge and a southward migration of cyclone storm tracks. In particular, the projected increase in storm surge of 0.3m for the 1 in 100 AEP event in Cairns by 2050 [*CSIRO & Bureau of Meteorology*, 2007], or projected increases of 0.5m or more described in [*Queensland Government*, 2004], suggests the need for more detailed investigation into the possible effects of changes in tropical cyclones on storm surge magnitudes.

The second issue relates to the ocean level that can be expected during an intense rainfall-derived flood event in the coastal zone, as extreme rainfall events will not always occur during periods of extreme ocean level. As such, it is necessary to evaluate whether there will be any changes to the joint probability between storm surge and rainfall-induced flooding due to the changes to the synoptic systems. Work is underway [*Abbs and McInnes*, 2010] looking at synoptic classification of historical large events using the ERA-40 and ERA-interim reanalyses, and then using the CSIRO Conformal-Cubic Atmospheric Model (CCAM) forced to a GCM-derived bias-corrected sea surface temperature field. This study finds projected increases in coincident events in southwestern Australia (including Fremantle and Esperance) due to increased occurrence of closed low systems, with little change or a decrease in coincident rainfall and sea level events for eastern coastline south of Brisbane. Quantitative assessments of the implications of this on flood risk are unavailable.

3. Estimating change to flood quantiles

The previous section provided a brief summary of likely changes to a range of variables that influence flood risk. A conclusion from this review is that the changes to flood risk will arise through a complex interplay between a range of climate variables (notably: extreme rainfall, antecedent precipitation and evapotranspiration, sea level and storm surges), and the particular features of each catchment (including size, infiltration rates, presence of reservoirs or other human-made features, height above mean sea level, and so on) where estimates flood quantiles are required.

This section provides an overview of several different methods which can be used to assess likely changes in future flood quantiles, and consists of two distinct parts. In the first part, an overview will be given of three methods which offer potentially viable approaches for estimating changes to future precipitation; namely (1) temperature scaling; (2) statistical downscaling; and (3) dynamical downscaling. These methods were raised in the first ARR Climate Change Workshop that was held in Melbourne on the 19th August 2010, and a discussion of the associated strengths, weaknesses and uncertainties of each method will be given based both on published literature and the views of workshop participants. Some issues with method implementation in the context of simulating flood variables will also be discussed. The second part then describes the suitability of the methods in the context of simulating variables relevant to the estimation of flood risk, and includes a brief outline of a set of research areas which might support the accommodation of climate change estimates into the Australian Rainfall and Runoff guidelines.

a. Overview of methods for estimating future change

The estimation of how rainfall will change under a future climate has been a difficult area of research, in part because the general circulation models which are used for many climate change assessments usually operate at too coarse a scale (with grids often several hundred kilometres across) to capture the physical processes associated with precipitation. As such, a range of statistical and dynamical methods have been developed to account for these issues, and a brief review of three of these is now provided.

Temperature scaling

An area which has received considerable recent attention by the research community is the use of scaling relationships between extreme precipitation and (usually land-surface) temperature as a method for estimating future change. The theoretical basis for this approach was described by [*Trenberth et al.*, 2003], who suggest that unlike average precipitation, extreme precipitation should scale with the water holding capacity of the atmosphere, which increases on average at a rate of ~7%/°C following on from the Clausius-Clapeyron scaling relationship (although O'Gorman and Muller [2010] highlight that assuming C-C scaling, changes in the zonal-mean total column water vapour will vary from 6% to 12%/°C depending on the latitude). The main assumptions in this relationship as described by Trenberth et al [2003] are that relative humidity will remain constant (an assumption that is approximately true globally, but as discussed earlier not in mid-latitude land areas [*O'Gorman and Muller*, 2010; *Sherwood et al.*, 2010]), and that vertical velocities in individual storm systems will also stay constant, with Trenberth et al [2003] suggesting that the latent heat released from the additional water vapour could further invigorate the storm and thus result in scaling greater than the C-C relationship. Such 'super' Clausius-Clapeyron rates of increase were also found in dynamical modelling results based on changes to daily precipitation extremes in the tropics (defined as 30°S-30°N), with increases in 10- to 100-year recurrence interval extreme precipitation scaling found to be ~17%/°C [*Sugiyama et al.*, 2010].

An approach to estimating whether this scaling is indeed occurring was proposed by Lenderink and van Meijgaard [2008], who grouped high-percentile hourly and daily precipitation events by temperature bin, and estimated the rate of change accordingly. This study, based on precipitation data in The Netherlands, found a ~7% increase per degree at temperatures for hourly rainfall below 12/°C, with this relationship doubling to 14%/°C at higher temperatures, with these results also found using a regional climate model covering much of Europe. Daily scaling relationships were somewhat lower than this. Lenderink and van Meijgaard [2008] attribute this super-Clausius-Clapeyron scaling rate to the additional latent heat release as described above, although Haerter and Berg [2009] question whether this shift is more likely to be attributable to the mixture of different precipitation types from largely stratiform rainfall at lower temperatures to largely convective rainfall at higher temperatures. A similar conclusion was found by Abbs [1999] who found using the meso-scale atmospheric model RAMS that when the temperature of the atmosphere was increased, heavy (convective) rainfall began earlier, lasted longer and was more continuous. The interpretation would be expected to have a significant bearing on how these results are extrapolated to future climate.

In Australia, Hardwick-Jones et al [2010] repeated this analysis and found a scaling relationship of ~7%/°C for hourly and shorter durations and across most temperatures until about 26°C. Once again at the daily timescale scaling relationships become somewhat lower, and the rate of decline above 26°C becomes steeper. Above these temperatures it is hypothesised that the decline in intensity is due to moisture availability limitations [see also *Berg et al.*, 2009, who found similar conclusions for Europe], although this hypothesis has not otherwise been tested. Assuming this hypothesis to be confirmed, then it becomes the temperature of the moisture source regions (largely the oceans surrounding Australia) which would become important, although the implications of differential warming of the ocean and land surface under a future climate [*IPCC*, 2007] are unknown, and the possibility that changed circulation regimes may alter the moisture source region under future climates may also have a bearing on future projections. All these issues require further investigation.

Other issues not accounted for by temperature scaling of extreme precipitation are the latitudinal gradients of change found in some dynamical modelling studies [*Alexander and Arblaster*, 2009; *CSIRO & Bureau of Meteorology*, 2007; *Rafter and Abbs*, 2009] which could not be reproduced by Hardwick-Jones et al [2010], and the conclusion by Haerter et al [2010] using German data that the rate of change of extreme precipitation varies continuously as a function of both the temperature and the percentile, leading those authors to caution that the Clausius-Clapeyron relation may not provide an accurate estimate of the temperature relationship of precipitation at any temporal resolution.

Statistical downscaling

Statistical downscaling involves the development of statistical relationships between large-scale climate variables and local-scale weather [*Maraun et al.*, 2010], and is used to develop projections for a range of hydrological processes which are at a finer scale than the relevant general circulation model (GCM) resolution. In some ways statistical downscaling can be viewed as an extension to the temperature scaling approach described above, except that for statistical downscaling, rather than conditioning only on land-surface (or sea-surface) temperature, a much larger set of (usually atmospheric) variables can be incorporated. Furthermore, by using GCM-derived projections of the atmospheric variables in a future climate, factors such as large-scale circulation changes, meridional changes to relative and specific humidity, differential warming between the ocean and land surface and a diversity of other processes, can be implicitly accommodated.

Although a large range of statistical downscaling methods are currently available [for recent reviews see *H J Fowler et al.*, 2007; *Maraun et al.*, 2010], methods developed specifically for the simulation of hydrological extremes are less common, with calibration of statistical models to mean conditions not necessarily being appropriate for handling extremes [*Wilby et al.*, 2004]. Furthermore, statistical downscaling models that have been developed to simulate sub-daily precipitation are limited, with only a few attempts described in the literature [*Marani and Zanetti*, 2007].

The most common statistical approaches for simulating extremes are based on extreme value theory [*Abbs and Rafter*, 2009; *Katz*, 2010; *Rafter and Abbs*, 2009], which represents the natural statistical theory for addressing the tail end of the distribution. Other methods which have been used to provide projections for extremes in Australia, such as the multi-site modified Markov model by Mehrotra and Sharma [2010], have simulated the full range of precipitation magnitudes including both dry and wet spells, and have evaluated the performance of the model in that context, rather than in the context of whether the physical processes leading specifically to extreme rainfall are correctly simulated.

There are at least three conceptual approaches for predictor selection in statistical models [*Maraun et al.*, 2010]. Arguably the most common is the identification of predictors based on an evaluation of the fit between the historical predictors and observed precipitation. The second approach, advocated by [*Charles et al.*, 1999b; *Charles et al.*, 2007; *Johnson and Sharma*, 2009], involves selection of predictors based on the capacity of GCMs to simulate these variables. Thus, a strong predictor variable in the historical climate may not be useful in simulating future change if that variable exhibits low skill in GCM simulations. A related approach involves using metrics of GCM performance as a basis for selecting downscaling predictors [*Perkins and Pitman*, 2009]. The third approach considers whether the key physical drivers of change in extreme precipitation are captured in the statistical model [*Charles et al.*, 1999b; *Wilby et al.*, 2004]. For example, as discussed in Section 2, it is likely that in Australia specific humidity will increase even as relative humidity decreases, whereas the high dependence between these variables in historical climate might lead to only one of these predictors being selected. Each of these issues will need to be considered carefully before designing a statistical model for developing projections of future extremes.

An important part of downscaling involves evaluating model performance, with the difficulty in establishing whether the statistical model is capable of correctly simulating future change suggesting a multi-pronged approach. Probably the most common evaluation measure is the extent to which statistical models reproduce various statistics of historical climate, whether it involves using reanalysis data for calibration and using GCM-derived sequences of historical climate for evaluation, or split-sample approaches [*personal communication, Rajeshwar Mehrotra, 1 November 2010*]. The evaluation of whether the downscaling approach is able to simulate the presence or absence of historical trends, or reproduce scaling relationships summarised in the previous section, might also represent a useful metric. A further approach to test physical realism may be to evaluate whether the model correctly simulates extremes from the correct synoptic systems [*personal communication, Debbie Abbs, 21 October 2010*]. Finally, to ensure correct predictor selection, one avenue may be to calibrate the model using GCM/RCM historical-climate precipitation as the response, and evaluate the model on future GCM/RCM precipitation sequences [*Charles et al.*, 1999b]. Although the GCM precipitation field is generally considered to be simulated poorly with climate models often not agreeing even on the direction of change of precipitation [*Johnson and Sharma*, 2009], this might nevertheless assist in ensuring the selected predictors are the ones which will drive future precipitation changes.

Lastly, uncertainty associated with the precipitation projections will need to be quantified. Sources of uncertainty include historical precipitation measurements, greenhouse gas emission scenarios, GCM performance, statistical model structure, and model parameters. In this regard, the computational speed associated with statistical downscaling approaches provides an important strength, as sensitivity to a large range these sources of uncertainty can be quickly evaluated.

Dynamic downscaling

The term 'dynamic downscaling' typically refers to either stretched grid atmospheric general circulation models (AGCMs), or limited area models (LAMs; often known as nested or regional climate models). In all cases the objective is to dynamically simulate aspects of the earth system (usually the atmosphere) at a much finer spatial and temporal resolution, by targeting a smaller spatial, and sometimes also temporal, domain. This allows for better simulation of local scale features such as orographic effects, land-sea contrast and other land surface characteristics [*Maraun et al.*, 2010], as well as better simulation of the various physical processes which influence precipitation. A brief summary of the advantages and disadvantages of these modelling techniques is provided in Table 1 below.

The CSIRO conformal cubic atmospheric model (CCAM) is an example of a stretched grid AGCM. This model covers the entire global domain, however the grid has been adjusted to focus on Australia. CCAM has been described more fully in McGregor and Dix [2008], with outputs available over all of Australia at a grid resolution of approximately 65km x 65km, and with outputs available at a temporal resolution of three hours. CCAM has thus far been run for the Australian domain using six AGCMs, although the outputs have thus far not been analysed for changes to extreme precipitation.

By contrast, limited area modelling involves nesting a regional climate model (RCM) into a GCM to represent atmospheric physics at a higher spatial and temporal resolution, over a smaller spatial domain. The grid scale for such models still can be quite large (e.g. 50km), however increasingly such models are operating at finer grid scales including implementation of the Regional Atmospheric Modelling System (RAMS) at various locations in Australia with the finest grid spacing of 4km. This smaller grid scale is thought to be the largest scale for which many of the physical processes for sub-daily extreme precipitation are explicitly modelled (*personal communications, Steven Sherwood (UNSW), 20 October 2010; Debbie Abbs (CSIRO), 21 October 2010*), and thus provides a useful source of information on changes to IFDs.

Thus far the only regional climate model downscaling performed in Australia with a view to assessing changes in extremes has used the RAMS model, with the results already summarised earlier. Investigation is currently underway to consider using an ensemble of downscaling models (e.g. WRF, RAMS, ACCESS), to better capture RCM model uncertainty (*personal communication, Debbie Abbs (CSIRO), 21 October 2010*). The approach of using multiple RCMs is consistent with recommendations elsewhere to focus on multi-model ensembles to increase skill, reliability and consistency of the predictions [*Kendon et al.*, 2008; *Tebaldi and Knutti*, 2007], with ensemble modelling for extreme precipitation becoming increasingly common in practice [*Beniston et al.*, 2007; *H J Fowler and Ekstrom*, 2009].

Table 1: Summary of main advantages and disadvantages of stretched grid and regional climate models (personal communication, Bryson Bates (CSIRO), 21 December 2010).

Downscaling Tool	Advantages	Disadvantages
Stretched-grid AGCMs	Provide information at much finer resolution than AOGCMs	Computationally intensive
	Information derived from physically consistent processes and self-consistent interactions between global and regional scales	Small number of ensembles and small ensemble size
	Globally consistent and allow for climate system feedbacks	Dependent on SSTs, sea ice distribution, and GHG and aerosol forcing from host AOGCM
	Do not require lateral boundary forcing from GCMs, and are therefore free of associated computational problems	Problems in maintaining viable parameterisations across length scales
	Output contains many variables on a regular grid	Model formulations may need to be 'retuned' for use at finer resolution
Regional Climate (Limited Area) Models	Provide information at much finer resolution than AOGCMs	Computationally intensive
	Produce responses based on physically consistent processes	Small number of ensembles and small ensemble size
	Output contains many variables on a regular grid	Strongly dependent on GCM boundary forcing
	Better representation of some weather extremes than GCMs	Climate system feedbacks not included

There are a range of sources of uncertainty associated with dynamical climate models. In addition to uncertainty from the model structure (including resolution, numerical scheme, and physical parameterisations), other sources of uncertainty include large-scale forcing from the GCM providing lateral boundary conditions (in the case of RCMs), the emissions scenario, as well as internal (chaotic) variability in the climate system. This suggests that to properly sample the uncertainty space, it would be necessary to use multiple RCMs forced by multiple GCM boundary conditions, potentially with a range of emissions scenarios, sufficient times to distinguish chaotic climate variability from a coherent long-term climate change signal. It is expected that performing such a study across all of Australia would quickly become computationally prohibitive, although more targeted studies addressing specific research questions may still be viable.

Another limitation associated with computational time required in RCM studies is that it becomes necessary to focus on simulating individual extreme events, rather than generating continuous sequences which can be used for continuous hydrological models. Nevertheless, using GCM precipitation, temperature and other fields it may be possible to record antecedent moisture conditions prior to the large rainfall event for both current and future climate conditions, which can be used in specifying changes to catchment moisture conditions.

Finally, in addition to simulating precipitation extremes, there are various other applications which are well suited to dynamical studies. For example, dynamical models at larger grid scales have been used for present- and future-climate synoptic classification, which can be used to determine changing probabilities of different precipitation regimes [*Abbs and Rafter*, 2009] and thus may potentially yield information on changing spatial and temporal patterns. A similar approach also has been used to assess the likely co-occurrence of extreme rainfall and storm surge under future climates [*Abbs and McInnes*, 2010]. Finally, dynamical downscaling is arguably the only method for capturing changes to tropical cyclone occurrence, intensity, and locations of genesis and decay [*Abbs*, 2010].

b. Comparison of the suitability of different modelling approaches

In Section 2 of this discussion paper, a brief summary was provided on what is currently understood about changes to variables relevant to the estimation of flood quantiles, using a combination of observational and modelling studies. In the first part of Section 3, an overview of the capabilities of different modelling techniques was described, including strengths, weaknesses, and sources of uncertainty associated with each method. Here an attempt will be made to bring these two topics together, to both identify key questions which remain – the resolution of which will assist in providing valuable information for flood estimation practitioners – and to discuss the capabilities of existing modelling techniques to address these questions.

The outcomes of this analysis are summarised in Table 2 below. In drafting the list of questions and issues, every effort has been made to maintain consistency with the scientific literature and the outcomes of the first ARR Climate Change workshop, as well as the outcomes of discussions with workshop participants and others in preparation of this paper. The list is not designed to be comprehensive but rather it aims to focus on key issues which have some chance of being addressed within the timeframe of the forthcoming revision of ARR, and thus there are many important research questions which may require longer timeframes that have not been considered.

Finally, a multiple-lines-of-evidence approach was taken in assembling the information in the table, since it is increasingly clear that the assumptions and limitations involved with any single method are generally too severe to be relied on as the sole source of information on likely changes to Australian flood risk. Such an approach is increasingly being adopted elsewhere, in which multiple dynamical and statistical approaches are often combined to properly sample the uncertainty associated with individual methods [e.g. *H J Fowler et al.*, 2007; *Haylock et al.*, 2006].

Table 2: Summary of present understanding of likely changes, and outstanding questions and issues

Flood variable	Current understanding	Key issues and questions
IFD relationships (daily or longer durations)	• Limited evidence of change can be observed in historical annual maximum data. The extent to which future change can be inferred based on the historical record is uncertain, however given an increase of 0.9°C in Australia since 1950, this may provide a constraint on short time-horizon projections. • Large-scale climate modelling projections for extreme daily rainfall (defined using different metrics) are already available in several studies [*Alexander and Arblaster*, 2009; *CSIRO & Bureau of Meteorology*, 2007; *Rafter and Abbs*, 2009], and suggest increases in most locations with greatest increases in the northern part of Australia and lowest increases in the south (with decreases projected in southerly locations by some models). • Fine-scale regional climate modelling has been performed at several locations [*Abbs and Rafter*, 2009; *Abbs et al.*, 2007] and suggest slight increases in daily precipitation on average, although with very large fine-scale spatial variability.	• It is important to note that the inability of trend detection methods in the historical data to find an increasing trend does not imply the absence of such a trend. However the magnitude of any trend, should it exist, that could be identified by a trend detection method has not been quantified and would be useful to evaluate consistency between observational data and climate model projections [e.g. see *Frei and Schar*, 2001; *Zhang et al.*, 2004]. • There are large model-to-model variations in extreme precipitation projections from GCMs [e.g. refer to Tables 2 and 3 in *Rafter and Abbs*, 2009], suggesting high uncertainty. Furthermore, there are serious questions about the degree to which projections of extreme precipitation from GCMs capture the key physical processes leading to future change. The value of directly using GCM-based precipitation outputs as evidence for projections on future IFDs should be considered. • A suite of six regional climate models at a scale of 65km grid spacing for the A2 scenario is currently being analysed by CSIRO to create projections of extreme rainfall [*Personal communication, Debbie Abbs, 17 November 2010*]. The capacity of using such a modelling framework for simulating extreme precipitation at different durations and frequencies should be evaluated. • Dynamical downscaling results at resolutions <5km are much more likely to capture the key physical processes which will drive future precipitation change. Computational issues mean that such projections cannot be made available across all of Australia, however results from carefully targeted case study regions may provide insight into larger-scale changes. • A key issue associated with fine-scale dynamical models is the spatial scale at which changes to extreme precipitation take place. Changes associated with large-scale circulation patterns are becoming better understood, but what physical processes cause the direction and magnitude of change in extreme precipitation to vary at the scale of several kilometres? The extent to which this represents statistical 'noise' or a coherent climate signal requires further investigation. • Statistical downscaling does not suffer from the same computational issues as dynamical downscaling, and therefore might be useful in providing projections across larger spatial domains. Furthermore, computational speed means that different sources of uncertainty (e.g. predictor variables from different GCMs, parameter uncertainty, etc) can be more easily sampled. At the daily scale at least two main classes of approaches have been developed and/or adopted in Australia. The first class involves a non-stationary generalised extreme value (GEV) approach in which parameters are conditioned to larger-scale GCM or RCM outputs [*Abbs and Rafter*, 2009; *Aryal et al.*, 2009; *Coles*, 2001], with a Bayesian hierarchical spatial GEV model with atmospheric and oceanic forcings currently under development by CSIRO [*Personal communication, Bryson Bates, 22 October 2010*]. The second approach comprises a modified Markov model described in [*Mehrotra and Sharma*,

		2010], with this approach designed to simulate continuous sequences and thus can also account for antecedent moisture conditions. Comparisons of these and other methods have not been conducted.
IFD relationships (sub-daily durations)	• There is mounting evidence that sub-daily rainfall will change more rapidly than daily rainfall. • Although the Clausius-Clapeyron approach has received considerable attention as an approach to scale sub-daily rainfall, it is cautioned that this represents neither a lower nor an upper bound, with rates double the Clausius-Clapeyron rate or higher being physically possible. • Observational data shows numerous stations having statistically significant increases for sub-hourly rainfall [*Australian Bureau of Meteorology*, 2010], although changes in gauge type over this period as well as a lack of a clear spatial pattern suggest that further investigation is required before this data is extrapolated for future climate situations. • The work of [*Abbs and Rafter*, 2009; *Abbs et al.*, 2007] provide quantitative projections for increases to 2-hour rainfall.	• Although fine-scale rainfall projections could be derived from dynamical studies such as from using RAMS, which also can provide information at sub-hourly timescales, data storage issues would likely preclude the use of this method across Australia [*personal communication, Debbie Abbs, 21 November 2010*]. • Nevertheless, in evaluating the scaling between daily and sub-daily precipitation at a set of case study regions it may be possible to evaluate the dominant physical processes which cause this scaling, and thus evaluate the extent to which this scaling can be used at other locations. The selection of key urban locations for such case studies might be beneficial as these are most heavily affected by short-duration rainfall. • There has been limited research on the application of statistical downscaling techniques to sub-daily timescales. It is possible that parametric extreme value models can be conditioned to sub-daily predictor variables such as outputs from coarse-scale RCMs, and thus capture the physical processes which determine this change. • An alternative framework may be to extend the non-parametric sub-daily resampling logic which has been used to simulate current-climate continuous rainfall sequences as part of ARR Project 4 to a downscaling setting. This builds on the Clausius-Clapeyron scaling work in [*Hardwick-Jones et al.*, 2010] except that conditional resampling is to be based on a more diverse set of predictors such as surface temperature, relative humidity, specific humidity and so on, and that rather than just focus on the peak rainfall burst in a given day, resampling will consider the full sub-daily rainfall sequence. Embedding this within a daily downscaling model such as [*Mehrotra and Sharma*, 2010] would then ensure that rainfall occurrence processes and other large-scale circulation effects are also accommodated. • The UNSW Climate Change Research Centre (CCRC) is currently working on multiple projects, including recently awarded Linkage and Super Science grants, to examine the performance of high-resolution models (both RCMs and cloud resolving models) in simulating climate extremes, as well as examining the situations under which extremes would be expected to increase (e.g. influence of different atmospheric forcing, orographic effects, etc) [*personal communication, Steven Sherwood, 20 October 2010*]. Although this work is not associated with ARR and may not be completed within the ARR timeframe, research on extremes in Australia is currently highly fragmented [*personal communication, Bryson Bates, 22 October 2010*] and improved linkages between the diversity of research presently underway around Australia on extreme precipitation is likely to be of benefit to the ARR revision process.

Antecedent conditions	• Antecedent moisture conditions appear to be changing based on observational work on average annual rainfall, evapotranspiration and soil moisture. • It is unlikely that the trend detection results on annual maximum streamflow by [*Ishak et al.*, 2010] can be explained without some reference to antecedent moisture. • Some projections on future antecedent moisture are already available, such as changes in average seasonal rainfall and temperature provided by [*CSIRO & Bureau of Meteorology*, 2007]	• There are two distinct parts associated with addressing antecedent moisture in flood models: developing projections for future climate variables relevant to catchment wetness conditions, and relating catchment wetness to parameters in rainfall-runoff models. • In event-based modelling, it will be necessary to link loss parameters (most likely the initial loss) either to seasonal rainfall, temperature and evapotranspiration, or to some precipitation-based index such as the Antecedent Precipitation Index [API; *Cordery*, 1970]. Use of historical data from largely unmodified catchments such as described in [*Ishak et al.*, 2010] may be sufficient for this purpose. • A related study, again using historical records such as [*Ishak et al.*, 2010], may be to assess the sensitivity of various aspects of the flood hydrograph (e.g. peak, volume, rate of rise) to different atmospheric variables such as various attributes of extreme precipitation as well as antecedent precipitation and evapotranspiration. Such a study might be analogous to the investigation of the sensitivity of mean runoff to changes in precipitation and evapotranspiration described by Chiew [2006]. • Projections for seasonal variables such as precipitation, temperature and evapotranspiration are already available. In contrast, developing projections for the antecedent precipitation sequence prior to the extreme event for future climate could be undertaken in various ways. For example, although fine-scale dynamical downscaling only simulates individual large rainfall events, the GCM-derived precipitation sequence prior to this event could be saved and compared for current- and future-climate conditions. Alternatively, a continuous downscaling approach could be used. • The use of continuous rainfall-runoff models, using future sequences of precipitation, represents an alternative framework and could be investigated. • Improved understanding of the linkages between baseflow, atmospheric processes (precipitation, temperature etc) and the flood hydrograph may also be required, particularly for lower recurrence interval floods.
Storm type, frequency and depth, and rainfall spatial and temporal patterns	• Although there is evidence that synoptic patterns, and thus types of storm events, may change, there is little quantitative evidence on the nature of this change. • A possible approach involves synoptic classification using re-analysis/GCM output.	• Limited research on quantifying changes to storm type and associated attributes. GCMs generally have poor skill at simulating the correct proportions of convective/stratiform rainfall [*Dai*, 2006], although regional models are likely to provide a significant improvement. Nevertheless there is little information in the literature on the nature of such changes, and the capacity of models to simulate these changes. • A possible approach involves synoptic classification using re-analysis/GCM output, and then using historical information on spatial and temporal patterns conditional to individual synoptic types to estimate how this will change in the future. In a statistical downscaling context this could be achieved using either an automated weather classification-based approach such as the non-homogeneous hidden Markov model (NHMM) that relates the daily precipitation to synoptic

		atmospheric patterns [*Charles et al.*, 1999a; *Hughes et al.*, 1999], or by explicitly specifying weather states outside the downscaling model [*Vrac and Naveau*, 2007]. Research is currently lacking on how to disaggregate this information to sub-daily timescales to yield spatial and temporal patterns.
Changes in mean sea level	• Numerous studies are available providing various projections on sea level rise, such as summarised in [*IPCC*, 2007; *Preston et al.*, 2008; *The Copenhagen Diagnosis*, 2009]	• Given the global nature of change to mean sea level (notwithstanding small variations due to regional changes in sea surface temperatures), it is unlikely that further studies are warranted as part of ARR.
Changes in storm surge	• Current evidence suggests that storm surge changes will be small relative to sea level changes, with the possible exception of areas affected by tropical cyclones. A quantitative estimate of 0.3m increase in the 1 in 100 AEP storm surge event by 2050 in Cairns is provided in [*CSIRO & Bureau of Meteorology*, 2007]	• Further research in quantification of possible changes to storm surge associated with tropical cyclones may be warranted, and some work already underway in this area [*Abbs*, 2010; *CSIRO & Bureau of Meteorology*, 2007].
Changes to the joint probability of storm surge and flood-producing rainfall	• Limited evidence on changes to the dependence between storm surge and flood-producing rainfall is available. • The primary exception is projected increases in coincident events in southwestern Australia (including Fremantle and Esperance) due to increased occurrence of closed low systems, with little change or a decrease in coincident rainfall and sea level events for eastern coastline south of Brisbane [*Abbs and McInnes*, 2010].	• Work is currently underway as part of ARR Project 18 to characterise the joint probability between storm surge and extreme rainfall under historical climate conditions. Although aspects of the dependence between these two quantities are likely to change due to changes in the frequency and/or intensity of different synoptic systems, given the relatively small changes in absolute magnitude of storm surge across most of Australia, explicit consideration of these changes may not result in large changes to flood quantile estimates. • A possible exception appears to be the coastal areas affected by tropical cyclones, and an assessment of the joint dependence conditional to different dominant synoptic systems in these regions using historical climate may be useful in order to evaluate the sensitivity of joint dependence to synoptic type.

4. Australian and overseas guidance on estimating flood risk under a future climate

In this final section a brief overview of guidance information in Australia and overseas is synthesised. Given the on-going nature of the research into non-stationary flood estimation methods, the development of guidance manuals or other policy documents associated with incorporating future flood risk into current design and planning applications is still in its infancy. As described in the background section, in Australia work is currently underway on providing much more complete guidance on flood estimation under the auspices of the revised Australian Rainfall and Runoff guidance document.

Once again, the emphasis of the following summary is on guidance describing the likely impacts of climate change on a range of variables such as extreme rainfall and sea levels which can be expected to influence flood risk. Guidance on different strategies which are available for adapting to future flood risk is planned for discussion in a future paper.

Australia

Currently the most detailed guidance is provided by the New South Wales Department of Environment, Climate Change and Water (DECCW) [*NSW Department of Environment and Climate Change*, 2007], and recommends that a sensitivity analysis be undertaken with between 0.18m and 0.91m for sea level rise, and between 10% and 30% increase in extreme rainfall. The sea level rise section recently has been updated [*NSW Department of Environment Climate Change and Water*, 2010] with sea level rise benchmarks relative to 1990 being 0.4 metres by 2050, and 0.9 metres by 2100.

In Queensland, the Queensland Government and the Local Government Association of Queensland conducted a joint project, the Inland Flooding Study, to provide local governments with a benchmark figure for taking climate change into account when assessing inland flooding risk. The project's final report [*DERM*, 2010] was released in November 2010, and recommendations included:

1. Local governments should factor a 5% increase in rainfall intensity per °C of global warming into the 1% (Q100), 0.5% (Q200), and 0.2% (Q500) AEP flood events recommended in State Planning Policy 1/03 for the location and design of new development.
2. The following temperatures and timeframes should be used for the purposes of applying the climate change factor in Recommendation 1: 2°C by 2050, 3°C by 2070, and 4°C by 2100. These values are based on modelling projections of increases in global mean temperature (relative to 1990) for the A1FI emissions scenario.
3. The Queensland Government will review and update this climate change factor when a national position on how to factor climate change into flood studies is finalised as part of the current review of Australian Rainfall and Runoff.

With regards to the most extreme precipitation events, the Bureau of Meteorology recently concluded that, based on observational and modelling evidence, it was 'not possible to confirm that probable maximum precipitation will definitely increase under a changing climate' [*Jakob et al.*, 2009], and highlights that further research is needed as to how the probable maximum precipitation might change in the future.

New Zealand

In New Zealand, information on accommodating the implications of climate change on extreme rainfall and flooding is provided in the document 'Preparing for Climate Change – a Guide for Local Government in New Zealand' [*New Zealand Ministry of the Environment*, 2008c]. In particular, scaling factors for 'Screening Assessment Scenarios' are given, which involves multiplying the projected temperature increase by a factor which depends on the storm burst duration and the event recurrence interval. For detailed assessments, the methodology of modifying the shape and scale parameters from a Gamma distribution described in [*Semenov and Bengtsson*, 2002] is recommended [*New Zealand Ministry of the Environment*, 2008b]. Information on accounting for sea level rise and storm surge is provided in [*New Zealand Ministry of the Environment*, 2008a], and further complementary information on flood estimation in climate change has also recently been provided [*New Zealand Ministry of the Environment*, 2010].

Recently, NIWA has developed a framework for assessing the impacts of climate change on river flow and floods using precipitation outputs from a dynamically downscaled model (bias corrected using a quantile mapping approach) to develop continuous sequences of daily precipitation of 30-year durations for the periods 1970-2000 and 2070-2100. The long-term objective is to use outcomes from this study to develop national projections of climate change impacts [*McMillan et al.*, 2010].

United Kingdom

A supplementary note on the implications of climate change for flood estimation is available from the UK Defra [*UK Department for Environment Food and Rural Affairs*, 2006]. This document provides a rate for sea level rise (ranging from 2.5-4mm/yr up to 2025 through to 13.0-15.0mm/yr in 2085-2115), as well as providing “national precautionary sensitivity ranges” for peak rainfall intensity (up to 30% increase), peak river flow (up to 20% increase), offshore wind speed (up to 10% increase) and extreme wave heights (up to 10% increase) for the purposes of sensitivity analysis.

Recently a research report was released entitled ‘Regionalised impacts of climate change on flood flows’, with the primary objective of assessing the suitability of the advice provided in the above note [*UK Department for Environment Food and Rural Affairs*, 2010]. This report suggests that future guidance should account for regional changes in both climate and catchment characteristics, as well as emphasising that the sensitivity assessment using a 20% increase in flood flows does not encompass the range of changes expected in flood flows, and therefore cannot be regarded as ‘precautionary’. This report also recommends a ‘scenario neutral’ approach to providing guidance by evaluating the sensitivity of catchment response to a range of possible climate change scenarios, as this will allow risk assessments for individual catchments to be easily updated when new climate change projections become available.

United States

At present there is an absence of national guidance on accounting for climate change in flood estimation practice. For example the NOAA Atlas 14 publications do not have any guidance about future IFDs (IDFs) in the U.S. [*Personal communication, Geoff Bonnin (NOAA), 23 October 2010*], nor do the national guidelines for determining flood flow frequency (Bulletin 17B) provided by the U.S. Geological Survey (USGS), although there some on-going work in revising aspects of this bulletin [*Personal communication, Timothy Cohn (USGS), 23 October 2010*]. A workshop was held in January 2010 on how to deal with issues of non-stationarity in water resource management, with conference proceedings available on (http://www.cwi.colostate.edu/NonstationarityWorkshop/index.shtml).

5. Conclusions and future research needs

This discussion paper has addressed a range of issues related to accommodating climate change estimates of various flood-related variables into flood estimation practice. The focus of this discussion paper has been on reviewing the science linking climate change to flooding as it relates to the Australian environment, as well as providing a brief introduction to a number of modelling techniques that can be used to estimate future flood risk.

A central theme through this paper, first raised in the introduction, is that assumption of stationarity – that the past climate will reflect future conditions – can no longer be used as the default assumption in the estimation of flood risk. This represents a major break with past practice, in which the stationarity assumption has underpinned almost all techniques for estimating the design flood, ranging from using IFD relationships to estimate design rainfall, through to calibrating rainfall-runoff models to historical flood events and using the calibrated parameters (such as the loss parameters) for future conditions. In addition, the notion that the climatic drivers of flooding are changing through time not only poses profound challenges on how we estimate future floods, but also challenges the way we design and manage floods, since the design flood can no longer be regarded as a static or fixed quantity.

The mechanisms by which future climate change assumptions can be incorporated into design flood estimates are likely to vary widely. In reviewing Australian and international guidance in Section 4, it is clear that in most cases the recommendations involve imposing a ‘climate change factor’ onto either the historical climate design rainfall or runoff estimates (estimated assuming stationarity), together with the addition of a sea level rise component onto historical mean and peak sea levels. More complex approaches might include dynamical or statistical downscaling to develop future precipitation and evapotranspiration sequences, followed by continuous rainfall-runoff models which can account for the interaction between the flood-producing rainfall event and the rainfall which occurred in the hours, days or months prior to the flood. The most appropriate techniques will therefore depend on nature of the specific situation, and therefore guidance will also be required on the relative strengths and weaknesses – and likely sources of uncertainty – associated with each flood estimation approach.

As can be seen in the discussion surrounding Table 2, however, there are a number of fundamental research questions relating to how flooding will change under a future climate, as there are still significant uncertainties on several of the main climatic drivers of flooding. Probably most important among these are: (a) the direction and magnitude of change to extreme rainfall, particularly in areas whether the annual average rainfall is expected to decrease as might be the case across large parts of the Australian continent; (b) the role of antecedent catchment moisture conditions prior to the flood-producing rainfall event in modifying the magnitude of the ensuing flood peak; and (c) the interaction between inland flooding processes due to extreme rainfall, and coastal flood processes due to high tide and storm surge, in influencing the magnitude of flooding in low-lying catchments near the coastal fringe. To assist in ensuring that our efforts on adaptation are well targeted and make the best possible use of finite resources, further focused research in each of these areas will be essential.

In conclusion, this paper has provided a summary of the current state of knowledge of how flood risk will change in Australia, as well as providing a path forward for developing improved flood risk estimates in the future. There is clearly an urgent need for more research in this area, and it is hoped that progress can be made in the coming years to better constrain future flood risk estimates. Nevertheless a significant degree of residual uncertainty will inevitably remain in any assessment of future flood risk, and it is hoped that the review provided in this paper will make a positive contribution in ensuring that any future climate adaptation efforts are informed by the best available science and modelling techniques as they stand today.

6. Acknowledgements

A large number of individuals assisted in providing input and answering questions in the preparation of this document. Specifically I would like to acknowledge Debbie Abbs (CSIRO), Lisa Alexander (UNSW), Bryson Bates (CSIRO), Geoff Bonnin (NOAA), Timothy Cohn (USGS), Jason Evans (UNSW), Janice Green (BoM), Peter Hill (SKM), Matt McCabe (UNSW), Rajeshwar Mehrotra (UNSW), Rory Nathan (SKM), Ataur Rahman (UWS), Ashish Sharma (UNSW) and Steven Sherwood (UNSW). Errors and omissions are nevertheless my own.

7. References

Abbs, D. (1999), A numerical modelling study to investigate the assumptions used in the calculation of probable maximum precipitation, *Water Resources Research*, *35*(3), 785-796.

Abbs, D. (2010), The Impact of Climate Change on the Climatology of Tropical Cyclones in the Australian Region (draft report)*Rep.*, CSIRO.

Abbs, D., and T. Rafter (2009), Impact of Climate Variability and Climate Change on Rainfall Extremes in Western Sydney and Surrounding Areas: Component 4 - Dynamical Downscaling*Rep.*, 84 pp, CSIRO.

Abbs, D., and K. McInnes (2010), Coincident extreme rainfall and storm surge events in southern Australia (draft report)*Rep.*, CSIRO.

Abbs, D., K. McInnes, and T. Rafter (2007), The impact of climate change on extreme rainfall and coastal sea levels over south-east Queensland. Part 2: A high-resolution modelling study of the effect of climate change on the intensity of extreme rainfall events*Rep.*, 39 pp, CSIRO.

Alexander, L., and J. M. Arblaster (2009), Assessing trends in observed and modelled climate extremes over Australia in relation to future projections, *International Journal of Climatology*, *29*, 417-435.

Alexander, L., P. Hope, D. Collins, B. Trewin, A. Lynch, and N. Nicholls (2007), Trends in Australia's climate means and extremes: a global context, *Australian Meteorological Magazine*, *56*, 1-18.

Alexander, L., et al. (2006), Global observed changes in daily climatic extremes of temperature and precipitation, *Journal of Geophysical Research*, *111*(D05101).

Aryal, S. K., B. C. Bates, E. P. Campbell, Y. Li, M. J. Palmer, and N. R. Viney (2009), Characterizing and Modelling Temporal and Spatial Trends in Rainfall Extremes, *Journal of Hydrometeorology*, *10*, 13.

Australian Bureau of Meteorology (2010), IFD Revision Proposed Method - Draft Report*Rep.*

Bates, B. C., Z. W. Kundzewicz, S. Wu, and J. P. Palutikof (2008), Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change*Rep.*, 210 pp, IPCC Secretariat, Geneva.

Beniston, M., et al. (2007), Future extreme events in European climate: an exploration of regional climate model projections, *Climatic Change*, *81*, 71-95.

Berg, P., J. O. Haerter, P. Thejll, C. Piani, S. Hagemann, and J. H. Christensen (2009), Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature, *Journal of Geophysical Research*, *114*(D18102).

Charles, S. P., B. C. Bates, and J. P. Hughes (1999a), A spatio-temporal model for downscaling precipitation occurrence and amounts, *Journal of Geophysical Research*, *104*(D24), 31657-31669.

Charles, S. P., B. C. Bates, P. H. Whetton, and J. P. Hughes (1999b), Validation of downscaling models for changed climate conditions: case study of southwestern Australia, *Climate Research*, *12*, 1-14.

Charles, S. P., M. A. Bari, A. Kitsios, and B. C. Bates (2007), Effect of GCM bias on downscaled precipitation and runoff projections for the Serpentine catchment, Western Australia, *International Journal of Climatology*, *27*, 18.

Chiew, F. H. S. (2006), An Overview of Methods for Estimating Climate Change Impact on Runoff, in *30th Hydrology and Water Resources Symposium*, edited, Launceston.

Chiew, F. H. S., et al. (2008), Rainfall-runoff modelling across the Murray-Darling Basin*Rep.*, CSIRO.

Coles, S. G. (2001), *An Introduction to Statistical Modelling of Extreme Values*, 208 pp., Springer, London.

Cordery, I. (1970), Antecedent Wetness for Design Flood Estimation, *Civil Engineering Transaction, Institution of Engineers Australia*, *CE12*(2), 181-184.

CSIRO (2010), Climate variability and change in south-eastern Australia - A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI)*Rep.*, 36 pp.

CSIRO & Bureau of Meteorology (2007), Climate Change in Australia*Rep.*

Dai, A. (2006), Precipitation Characteristics in Eighteen Coupled Climate Models, *Journal of Climate*, *19*, 4605-4630.

DERM (2010), Increasing Queensland's resilience to inland flooding in a changing climate - Final report on the Inland Flooding Study*Rep.*

Erskine, W. D., and R. F. Warner (1988), Geomorphic effects of alternating flood and drought dominated regimes on a NSW coastal river, in *Fluvial Geomorphology of Australia*, edited by R. F. Warner, pp. 223-244, Academic Press, Sydney.

Fowler, H. J., and M. Ekstrom (2009), Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes, *International Journal of Climatology*, *29*, 385-416.

Fowler, H. J., S. Blenkinsop, and C. Tebaldi (2007), Linking climate change modelling to impact studies: Recent advances in downscaling techniques for hydrological modelling, *International Journal of Climatology*, *27*, 1547-1578.

Fowler, K., P. Jordan, P. Hill, R. J. Nathan, and K. Sih (2010), A Framework for Incorporating Available Climate Science in Extreme Flood Estimates, in *Practical Responses to Climate Change*, edited, Melbourne.

Franks, S. W., and G. Kuczera (2002), Flood frequency analysis: evidence and implications of secular climate variability, New South Wales, *Water Resources Research*, *38*(5).

Fraser, G. W., J. O. Carter, G. M. McKeon, and K. A. Day (2011), A new empirical model of sub-daily rainfall intensity and its application in a rangeland biophysical model, *The Rangeland Journal*, *33*, 37-48.

Frei, C., and C. Schar (2001), Detection probability of trends in rare events: theory and application to heavy precipitation in the alpine region, *Journal of Climate*, *14*, 1568-1584.

Frei, C., R. Scholl, S. Fukutome, J. Shchmidli, and P. L. Vidale (2006), Future change in precipitation extremes in Europe: An intercomparison of scenarios from regional climate models, *Journal of Geophysical Research*, *111*(D06105).

Gallant, A., K. J. Hennessy, and J. Risbey (2007), Trends in rainfall indices for six Australian regions: 1910-2005, *Australian Meteorological Magazine*, *56*, 223-239.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, and V. N. Razuvaev (2005), Trends in intense precipitation in the climate record, *Journal of Climate*, *18*, 1326-1350.

Gu, G., R. F. Adler, G. J. Huffman, and S. Curtis (2007), Tropical rainfall variability on interannual-to-interdecadal and longer time scales derived from the GPCP monthly product, *Journal of Climate*(20), 4033-4046.

Haerter, J. O., and P. Berg (2009), Unexpected rise in extreme precipitation caused by a shift in rain type?, *Nature Geoscience*, *2*, 372-373.

Haerter, J. O., P. Berg, and S. Hagemann (2010), Heavy rain intensity distributions on varying time scales and at different temperatures, *Journal of Geophysical Research*, *115*(D17102).

Hanel, M., and T. A. Buishand (2010), On the value of hourly precipitation extremes in regional climate model simulations, *Journal of Hydrology*, *393*(3-4), 265-273.

Hardwick-Jones, R., S. Westra, and A. Sharma (2010), Observed relationships between extreme sub-daily precipitation, surface temperature and relative humidity, *Geophysical Research Letters*, *37*(L22805).

Haylock, M., G. C. Cawley, C. Harpham, R. L. Wilby, and C. M. Goodess (2006), Downscaling heavy precipitation over the United Kingdom: A comparison of dynamical and statistical methods and their future scenarios, *International Journal of Climatology*, *26*, 1397-1415.

Held, I. M., and B. J. Soden (2006), Robust responses of the hydrological cycle to global warming, *Journal of Climate*, *19*, 5686-5699.
Hill, P. (2010), Project 6: Loss Models for Design Flood Estimation*Rep.*
Huffman, G. J., R. F. Adler, D. T. Bolvin, and G. Gu (2009), Improving the global precipitation record: GPCP Version 2.1, *Geophysical Research Letters*, *36*(L17808).
Hughes, J. P., P. Guttorp, and S. P. Charles (1999), A non-homogeneous hidden Markov model for precipitation occurrence, *Applied Statistics*, *48*(1), 15-30.
IPCC (2007), Summary for Policymakers*Rep.*, Cambridge Univeristy Press, Cambridge, United Kingdom.
Ishak, E. H., A. Rahman, S. Westra, A. Sharma, and G. Kuczera (2010), Preliminary Analysis of Trends in Australian Flood Data, in *World Environmental and Water Resources Congress, American Society of Civil Engineers (ASCE)*, edited, Providence, Rhode Island, USA.
Jakob, D., R. Smalley, J. Meighen, K. Xuereb, and B. Taylor (2009), Climate Change and Probable Maximum Precipitation*Rep.*, 179 pp, Australian Bureau of Meteorology, Melbourne.
Johanson, C., and Q. Fu (2009), Hadley cell widening: Model simulations vs observations, *Journal of Climate*, *22*, 2713-2725.
Johnson, F., and A. Sharma (2009), Measurement of GCM skill in predicting variables for hydroclimatological assessments, *Journal of Climate*.
Jung, M., et al. (2010), Recent decline in the global land evapotranspiration trend due to limited moisture availability, *Nature*, *467*.
Katz, R. W. (2010), Statistics of extremes in climate change, *Climatic Change*, *100*, 71-76.
Kendon, E. J., D. P. Rowell, R. G. Jones, and R. Buonomo (2008), Robustness of Future Changes in Local Precipitation Extremes, *Journal of Climate*, *21*, 4280-4297.
Kharin, V. V., and F. W. Zwiers (2007), Changes in Temperature and Precipitation Extremes in the IPCC Ensemble Global Coupled Model Simulations, *Journal of Climate*, *20*.
Kiem, A. S., S. W. Franks, and G. Kuczera (2003), Multi-decadal variability of flood risk, *Geophysical Research Letters*, *30*.
Kundzewicz, Z. W. (2005), Trend detection in river flow series: 1. Annual maximum flow, *Hydrological Sciences Journal*, *50*(5).
Lenderink, G., and E. van Meijgaard (2008), Increase in hourly precipitation extremes beyond expectations from temperature changes, *Nature Geoscience*, *1*, 511-514.
Lenderink, G., H. Y. Mok, T. C. Lee, and G. J. Van Oldenborgh (2011), Scaling and trends of hourly precipitation extremes in two different climate zones - Hong Kong and the Netherlands, *Hydrological Earth Systems Science*, *8*, 4701-4719.
Li, Y., W. Cai, and E. P. Campbell (2005), Statistical Modeling of Extreme Rainfall in Southwest Western Australia, *Journal of Climate*, *18*, 12.
Lu, J., C. Deser, and T. J. Reichler (2009), Cause of the widening of the tropical belt since 1958, *Geophysical Research Letters*, *36*(L03803).
Marani, M., and S. Zanetti (2007), Downscaling rainfall temporal variability, *Water Resources Research*, *43*(W09415).
Maraun, D., et al. (2010), Precipitation downscaling under climate change: recent developments to bridge the gap between dynamical models and the end user, *Reviews of Geophysics*, *48*(RG3003).
McGregor, J. L., and M. R. Dix (2008), An updated description of the Conformal-Cubic Atmospheric Model, in *High Resolution Simulation of the Atmosphere and Ocean*, edited by K. Hamilton and W. Ohfuchi, pp. 51-76, Springer.
McMillan, H., J. Bethanna, and S. Poyck (2010), Flood Risk Under Climate Change - A framework for assessing the impacts of climate change on river flow and floods, using dynamically-downscaled climate scenarios*Rep.*, 63 pp, National Institute of Water and Atmospheric Research, Christchurch.
Mehrotra, R., and A. Sharma (2010), Development and application of a multisite rainfall stochastic downscaling framework for climate change impact assessment, *Water Resources Research*, *46*(W07526).

Micevski, T., S. W. Franks, and G. Kuczera (2006), Multidecadal variability in coastal eastern Australian flood data, *Journal of Hydrology 327*, 219-225.
Milly, P. C. D., R. T. Wetherald, K. A. Dunne, and T. L. LDelworth (2002), Increasing risk of great floods in a changing climate, *Nature 415*, 514-517.
Milly, P. C. D., J. Betancourt, M. Falkenmark, R. M. Hirsch, W. Zbigniew, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer (2008), Stationarity is Dead: Whither Water Management?, *Science*, *319*, 573-574.
New Zealand Ministry of the Environment (2008a), Coastal Hazards and Climate Change - A Guidance Manual for Local Government in New Zealand, edited, p. 139, Wellington.
New Zealand Ministry of the Environment (2008b), Climate change effects and impacts assessment - A Guidance Manual for Local Government In New Zealand, edited, p. 167, Wellington.
New Zealand Ministry of the Environment (2008c), Preparing for climate change - A guide for local government in New Zealand, edited, p. 44, Wellington.
New Zealand Ministry of the Environment (2010), Tools for Estimating the Effects of Climate Change on Flood Flow, edited, p. 71, Wellington.
NSW Department of Environment and Climate Change (2007), Floodplain Risk Management Guideline - Practical Consideration of Climate Change, edited.
NSW Department of Environment Climate Change and Water (2010), Flood Risk Management Guideline - Incorporating sea level rise benchmarks in flood risk assessments, edited.
O'Gorman, P. A., and C. G. Muller (2010), How closely do changes in surface and column water vapour follow Clausius-Clapeyron scaling in climate change simulations?, *Environmental Research Letters*, *5*.
Perkins, S. E., and A. J. Pitman (2009), Do weak AR4 models bias projections of future climate changes over Australia?, *Climatic Change*, *93*, 527-558.
Pilgrim, D. H. (1987), Australian Rainfall and Runoff, edited, The Institution of Engineers, Australia.
Preston, B. L., T. F. Smith, C. Brooke, R. Dorddard, T. G. Measham, G. Withycombe, K. McInnes, D. Abbs, B. Beveridge, and C. Morrison (2008), Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group*Rep.*
Pui, A., A. Lall, and A. Sharma (2010), How does the Interdecadal Pacific Oscillation affect Design Floods in Eastern Australia? , *Water Resources Research*, *under review (submitted Feb 2010)*.
Queensland Government (2004), Queensland Climate Change and Community Vulnerability to Tropical Cyclones - Ocean Hazards Assessment - Synthesis Report*Rep.*
Rafter, T., and D. Abbs (2009), An analysis of future changes in extreme rainfall over Australian regions based on GCM simulations and Extreme Value Analysis, in *The Centre for Australian Weather and Climate Research*, edited, pp. 44-49.
Seidel, D. J., Q. Fu, W. J. Randel, and T. J. Reichler (2008), Widening of the tropical belt in a changing climate, *Nature Geoscience*, *1*, 21-24.
Semenov, V. A., and L. Bengtsson (2002), Secular trends in daily precipitation characteristics: greenhouse gas simulation with a coupled AOGCM, *Climate Dynamics*, *19*, 123-140.
Sherwood, S. C., W. Ingram, Y. Tsushima, M. Satoh, M. Roberts, P. L. Vidale, and P. A. O'Gorman (2010), Relative humidity changes in a warmer climate, *Journal of Geophysical Research*, *115*(D09104).
Simmons, A., K. M. Willett, P. D. Jones, P. W. Thorne, and D. Dee (2010), Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: inferences from reanalyses and monthly gridded observational datasets, *Journal of Geophysical Research*, *115*(D01110).
Sugiyama, M., H. Shiogama, and S. Emori (2010), Precipitation extreme changes exceeding moisture content increases in MIROC and IPCC climate models, *Proceedings of the National Academy of Sciences*.
Tebaldi, C., and R. Knutti (2007), The use of the multi-model ensemble in probabilistic climate projections, *Philosophical Transactions of the Royal Society A*, *365*, 2053-2075.

The Copenhagen Diagnosis (2009), Updating the World on the Latest Climate Science*Rep.*, 60 pp, The University of New South Wales Climate Change Research Centre, Sydney.
Trenberth, K. E., A. Dai, R. M. Rasmussen, and D. B. Parsons (2003), The changing character of precipitation, *Bulletin of the American Meteorological Society*, *84*, 1205-1217.
Trenberth, K. E., et al. (2007), Observations: Surface and Atmospheric Climate Change, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, Cambridge University Press, Cambridge.
UK Department for Environment Food and Rural Affairs (2006), Flood and Coastal Defence Appraisal Guideline FCDPAG3 - Supplementary Note to Operating Authorities - Climate Change Impacts, edited.
UK Department for Environment Food and Rural Affairs (2010), Regionalised Impacts of Climate Change on Flood Flows, edited.
Vrac, M., and P. Naveau (2007), Stochastic downscaling of precipitation: from dry to heavy rainfalls, *Water Resources Research*, *43*(W07402).
Westra, S. (2010), Implications of Climate Change on Flood Estimation: Discussion Paper for the Australian Rainfall and Runoff Climate Change Workshop No. 2*Rep.*, Engineers Australia.
Westra, S., and S. A. Sisson (2011), Detection of non-stationarity in precipitation extremes using a max-stable process model, *Journal of Hydrology*, *Manuscript accepted for publication on 16/6/2011*.
Wilby, R. L., S. P. Charles, E. Zorita, B. Timbal, P. Whetton, and L. O. Mearns (2004), Guidelines for use of climate scenarios developed from statistical downscaling methods *Rep.*, Geneva, Switzerland.
Willett, K. M., N. P. Gillet, P. D. Jones, and P. W. Thorne (2007), Attribution of observed surface humidity changes to human influence, *Nature*, *449*, 710-713.
Zhang, X., F. W. Zwiers, and G. Li (2004), Monte Carlo Experiments on the Detection of Trends in Extreme Values, *Journal of Climate*, *17*, 1945-1952.