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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

Deborah Abbs, Kathleen McInnes and Tony Rafter
CSIRO Division of Marine and Atmospheric Research
Private Bag 1, Aspendale, VIC 3195

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Enquiries should be addressed to:
Deborah Abbs
CSIRO Marine and Atmospheric Research
PMB 1, Aspendale, Victoria 3195
Email: deborah.abbs@csiro.au

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EXECUTIVE SUMMARY

In Australia, flooding causes the most damage of all natural disasters and each year extreme rainfall events cause significant damage in the highly urbanised regions along Australia's eastern coastline. The coastal regions of northern New South Wales and south eastern Queensland are the most flood-prone regions of the country. The Gold Coast and Broadwater region of south-east Queensland contains large areas of developed flood plain spanning several catchments, including the Nerang, Coomera, Pimpama and Albert/Logan, that are at risk of flooding during extreme rainfall events. These regions are also subject to high population growth.

Recently, the Intergovernmental Panel on Climate Change (IPCC) released its "Summary for Policy Makers" (IPCC, 2007) based on the Working Group 1 Fourth Assessment Report. That summary states, "*It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent."* Consequently, the community's exposure to extreme rainfall events is growing rapidly and if adaptive measures are to be put in place then planners and engineers need to have estimates of the likely changes in the frequency and intensity of severe rainfall events. Hydrological and hydraulic modelling can be used to establish Average Recurrence Intervals (ARIs) of flood levels and flood extent and thus increase preparedness for flooding through the development of strategies to respond to and mitigate the effects of severe rainfall. This study aims to quantify the changes in extreme rainfall intensity that may arise due to human-induced climate change.

This report presents results from a series of "dynamical downscaling" simulations designed to identify the likely change in the intensity and frequency of extreme rainfall events affecting the Gold Coast region of south-east Queensland. The dynamical downscaling technique is based on the assumption that the atmospheric "ingredients" (i.e. (1) high moisture content of the air, (2) a rapid ascent rate, (3) high time-averaged precipitation efficiency of the storm and (4) long duration of the precipitation-producing system) important for the development of extreme rainfall events will be present in Global Climate Model (GCM) simulations although their effect will be less pronounced than occurs. The function of the high-resolution model used in this study is to take these "ingredients" and to provide the mesoscale forcing that will in turn provide the lifting necessary for convective initiation. This forcing will be provided by both higher-resolution orography and better representation and organisation of high-intensity rainfall features embedded within synoptic scale weather systems, such as short wave troughs and cut-off low pressure systems (e.g. east coast lows or tropical cyclones).

Three climate simulations are considered in this study. They are from CSIRO's Mark 3 Atmosphere-Ocean Global Climate Model and the two regional model simulations, CC-Mk2 and CC-Mk3. The CSIRO Mark 3 model has been used to simulate the climate from 1961 to 2100 under an SRES A2 greenhouse gas emissions scenario (IPCC, 2000). Mark 3 has a horizontal grid spacing of approximately at 1.85°× 1.85° and has 18 levels in the vertical. The CC (cubic conformal) model is a regional climate model that utilises a stretched grid in which the Earth is mapped onto a cube. The mapping is such that higher resolution is focussed over the region of interest and lower resolution is on the opposite side of the Earth, remote from the region of interest. To overcome the potential errors that could result from the poor resolution in the remote areas, the model solution in the lowest resolution areas is nudged towards the solution of a GCM of more uniform resolution. The cubic conformal model simulations considered in this study had their highest resolution, of between 50 and 60 km, centred on Australia. Outside this region, the CC-Mk2 model solutions were nudged towards those of the CSIRO Mark 2 SRES A2 simulation and the CC-Mk3 model was nudged towards the simulation of CSIRO Mark 3 SRES A2 simulation. Extreme rainfall days simulated by these models have been downscaled using the Regional Atmospheric Modelling System (RAMS). RAMS is a high-resolution modelling system that has previously been found to be a suitable tool for the simulation of extreme rainfall events, as described in Abbs (1999) and McInnes *et al.* (2002). Each event was simulated from 2 days before to 2 days after the event and model fields were archived with a 30-minute increment. At least one hundred events were simulated for each of the current, 2030 and 2070 climates. The archived rainfall output from the simulations has been used to define the 2, 12, 24, 48, 72 and 96-hour rainfall maxima for each event. The following analysis concentrates on the maximum rainfall falling within the 2, 24 and 72-hour periods.

Key findings from the study are:

1. The dynamical downscaling technique provides a good qualitative and quantitative representation of the spatial distribution of extreme rainfall in the region.
2. Climate change is likely to result in an increase in 24-hour and 72-hour rainfall extremes for a large region that includes the McPherson Range. With time, the spatial extent of this area of increase enlarges. 2-hour rainfall events show much larger projected changes, with the largest changes occurring in the high terrain inland from the Gold Coast.
3. There is good inter-model agreement on a future increase in extreme rainfall events in the McPherson Range and the Great Dividing Range west of Brisbane and the Gold Coast, especially for the 2-hour and 24-hour events. Intensification of the 72-hour events is also likely, although there is less inter-model agreement on this result. By 2070, most regions are likely to experience an increase in the intensity of extreme rainfall events. The regions of highest inter-model agreement include the McPherson Range and the Great Dividing Range, stretching from the New South Wales border to the north of Brisbane, thus including the catchment areas for all rivers and streams flowing into the Gold Coast region.
4. Depth-area curves for the Gold Coast region show that area-averaged increases in extreme rainfall intensity are predicted for areas less than 1000 km^2 for 24-hour events. Area-averages for 2-hour events show a small increase. A small increase for 72-hour events is indicated for 2030 but the sign of change for 2070 is unclear.
5. Return period curves for the intensity of modelled 24-hour events in the Gold Coast region show close agreement with the observations, but return levels for 72-hour accumulations are underestimated. Climate change is likely to produce an increase in extreme rainfall for durations of 2 hours, 24 hours and 72 hours.
6. A comparison of the 2030 and 2070 temporal curves with those of the current climate suggests that in the future, the most intense period within a 24-hour rainfall burst is likely to occur earlier in the burst than at present for the Gold Coast region. Peak rainfall in 72-hour events is likely to occur later in the burst in the future.

1. INTRODUCTION

In Australia, flooding causes the most damage of all natural disasters and each year extreme rainfall events cause significant damage in the highly urbanised regions along Australia's eastern coastline. The coastal regions of northern New South Wales and south eastern Queensland are the most flood-prone regions of the country. These regions are also subject to high population growth, with one-quarter of Australia's total increase in population between 1991 and 1996 accommodated within three kilometres of the coast, mostly in the coastal strip between Bundaberg and Wollongong. The Gold Coast and Broadwater region of south-east Queensland contains large areas of developed flood plain spanning several catchments, including the Nerang, Coomera, Pimpama and Albert/Logan, that are at risk of flooding during extreme rainfall events.

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) states *"Precipitation extremes are projected to increase more than the mean and the intensity of precipitation events are projected to increase. The frequency of extreme precipitation events is projected to increase almost everywhere."* Recently, the IPCC released its "Summary for Policy Makers" (IPCC, 2007) based on the Working Group 1 Fourth Assessment Report. That summary states, "*It is very likely that hot extremes, heat waves, and heavy precipitation events will continue to become more frequent."* Consequently, the community's exposure to extreme rainfall events is growing rapidly and if adaptive measures are to be put in place then planners and engineers need to have estimates of the likely changes in the frequency and intensity of severe rainfall events.

Hydrological and hydraulic modelling can be used to establish Average Recurrence Intervals (ARIs) of flood levels and flood extent and thus increase preparedness for flooding through the development of strategies to respond to and mitigate the effects of severe rainfall. This study aims to quantify the changes in extreme rainfall intensity that may arise due to human-induced climate change. However, it should be noted that in addition to rainfall intensity and duration, hydraulic models require a downstream boundary condition representing the variation of tail water level due to tides and any additional contribution due to storm surge and wave setup. Some weather events will be more conducive to the generation of both extreme rainfall and adverse tail water conditions than others. This study also delivers to Part 3 of the project by providing high-resolution wind fields that are used to force the hydraulic model for the coincident events.

This study draws upon the results from Part 1 of the project (Abbs and McInnes, 2004), in which possible changes in extreme rainfall and wind events under future climate conditions were investigated. In that study the performance of three climate models (Mk3, CC-Mk3 and CC-Mk2) was assessed in terms of ability to reproduce observed current climate frequencies of synoptic weather conditions conducive to extreme rainfall and winds. The key finding from that study was that the CC-Mk2 model was able to capture the climatology of extreme rainfall and extreme wind weather events affecting south-east Queensland. The study also identified possible changes in frequency of these severe weather events due to climate change. It showed that the (most frequent) Type 1 summer event may become more frequent, increasing in frequency by 2-3% or, on average, an extra event every 10 years. Type 1 rainfall events are generally associated with extreme rainfall in the coastal ranges of south-east Queensland. Between 20 and 50% of Type 1 rainfall days occur with extreme wind speeds. Coincident rainfall and extreme wind events associated with the Type 1 category increase in frequency by 2.5 times by 2070. Over 50% of Type

3 events occur in conjunction with extreme winds. These events show a slight decrease in frequency by 2070 and the coincident wind and rainfall events increase in frequency. Tropical cyclones are a major contributor to the Type 3 category. In winter, Type 1 events may become 10-12% more frequent by 2070. These events produce widespread heavy rainfall, and over 50% of the most extreme events are associated with extreme winds. However, coincident rainfall and extreme wind events show a decrease in frequency under future climate conditions.

That study made the following recommendations for Part 2 of the project.

In Part 2:

1. Future downscaling work should use the RAMS model nested in the outputs from the CC-Mk2 simulation.
2. The events to be downscaled should be selected to ensure a large population that includes events that are associated with extreme winds.
3. Address uncertainty by analysing the outputs from the Abbs (2004) study, the AGO-funded project using CC-Mk3 and a modelling study based on CC-Mk2. These outputs should be analysed to identify likely changes in the spatial and temporal distribution of extreme rainfall events and changes in the frequency and intensity of those events.
4. Analyse the downscaled winds from existing simulations of observed events to determine the realism of simulated wind magnitudes in RAMS as compared with anemometer data in region.
5. Analyse the downscaled winds from current and future climate events to determine future changes in frequency, magnitude and direction.

This report presents a high-resolution downscaling study, based on Recommendations 1 to 3, that aims to quantify the changes in extreme rainfall intensities for the coastal region of northern New South Wales and south-eastern Queensland. Uncertainty is addressed by considering the results from RAMS nested in the CC-Mk2 model and from earlier downscaling studies using RAMS nested in both the Mk3 and CC-Mk3 models.

The remainder of this report is set out as follows: Chapter 2 presents a survey of relevant studies and recent climate change projections and research into changes in extreme rainfall over the south-east Queensland region. Chapter 3 describes the downscaling methodology and configuration and initialisation of the RAMS model. The observational data and results from the downscaling simulations are presented in Chapter 4. This chapter also quantifies the effect of climate change on extreme rainfall events affecting the Gold Coast region. Chapter 5 provides a discussion of the results and a summary.

2. BACKGROUND

2.1 Uncertainties and climate change

Projections of future regional climate are subject to three key uncertainties. The first of these is related to uncertainties in greenhouse gas emissions and the second is related to the climate sensitivity of climate models. Climate sensitivity is a measure of the strength and rapidity of the surface temperature response to greenhouse gas forcing. The third uncertainty is related to differing spatial patterns of change (i.e. response of regional climate) between climate models.

In 1996, the IPCC began the development of a new set of greenhouse gas emissions scenarios (IPCC, 2000) that attempt to account for future population growth, technological change and social and political behaviour. The resulting set of 40 scenarios is based around 4 different "storylines" that describe the relationships between the forces driving the greenhouse gas emissions and their evolution. These emissions scenarios are then used to calculate a corresponding trajectory in atmospheric greenhouse gas concentrations that affects the radiative forcing of the atmosphere and the global climate. Climate model responses are most uncertain in how they represent feedback effects, particularly those dealing with changes to cloud regimes and ocean-atmosphere interactions. Studies based on different climate models and emissions scenarios show that by 2100, differences in emissions scenarios and different climate model sensitivities contribute similar amounts to the uncertainty in global average surface temperature change.

The development of climate change projections on a regional scale relies upon analysing as many Global Climate Models (GCMs) and Regional Climate Models (RCMs) as is feasible to ensure that uncertainty due to the climate sensitivity of different models is captured. It is necessary to use model output available with a daily temporal resolution to identify severe weather events, such as extreme rainfall and wind events. However, daily model variables are not available for many of the GCM simulations to which there is general access. Thus, our analysis is limited to the results from CSIRO climate models. When considering results from a single model simulation, there is concern as to the reliability and generality of the results and this concern needs to be considered when using the results described here.

The coarse spatial resolution of climate models remains a limitation on their ability to simulate the details of regional climate change, especially changes in extreme events. However, there is the potential for increasing understanding of changes in extreme events, especially tropical cyclones and extreme rainfall events, by employing higher resolution models of the atmosphere.

2.2 The study region

The area chosen for the modelling component of this study is the coastal region of eastern Australia bounded by 150° East and 152° East and 26° South and 32° South. This area includes centres of high population growth and is frequently affected by major floods. The output from the models considered is analysed over the region shown in Figure 1.

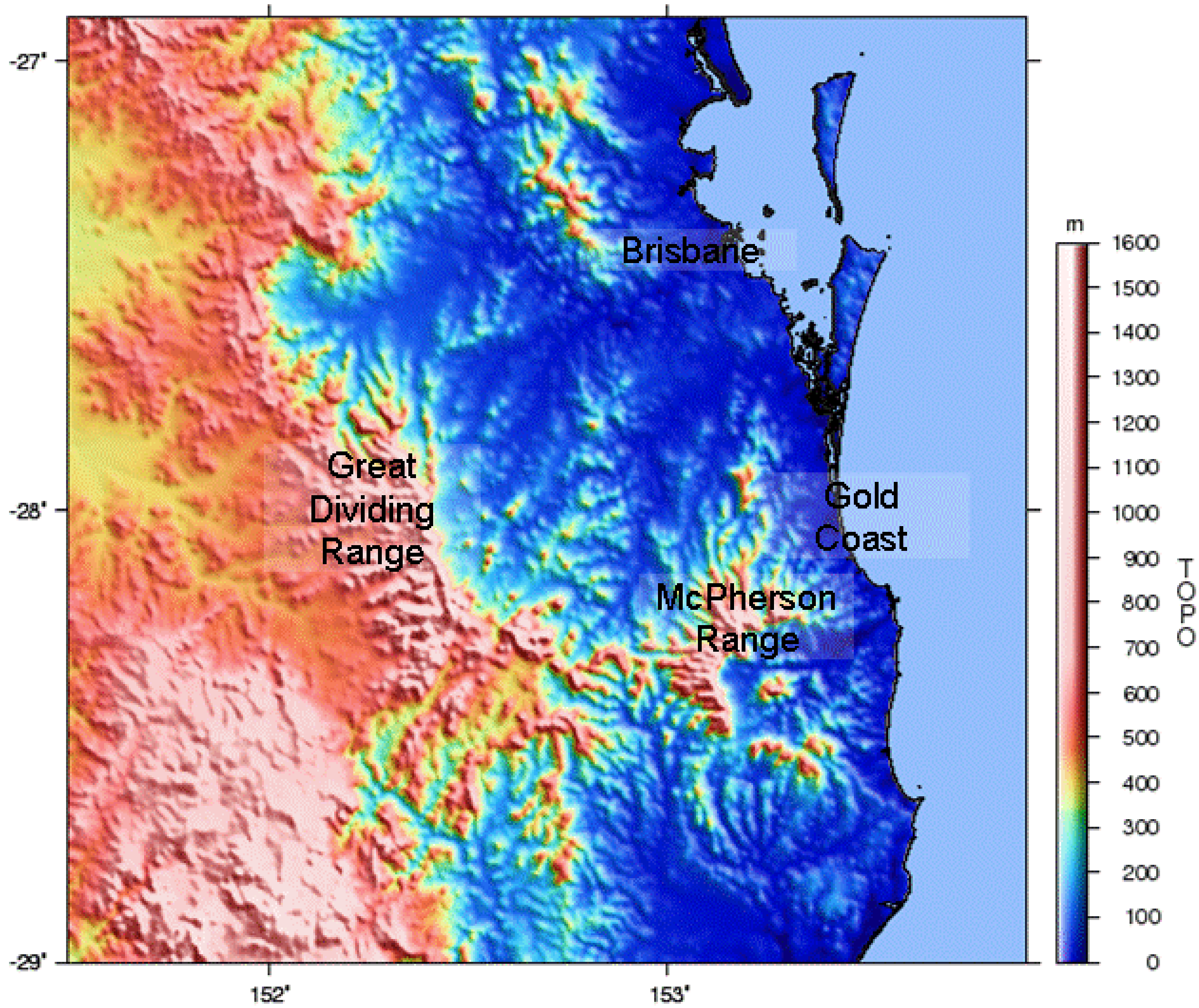

Figure 1: The focus region for this study. Locations referenced in the text are indicated.

The region experiences severe storms of both tropical and sub-tropical origin and is classified as a transition area by the Commonwealth Bureau of Meteorology for hydrological applications such as the estimation of Probable Maximum Precipitation. Tropical cyclones are potentially the most severe class of storm to affect the region although they are relatively infrequent. Depressions of sub-tropical origin, such as east coast lows, are more frequent but generally less intense than tropical cyclones. Monsoonal depressions may also cause heavy rainfall over the region especially if they interact with sub-tropical or extra-tropical systems. Extra-tropical systems affecting the region include cyclones, fronts and troughs. All system types are capable of causing severe rainfall that may lead to significant flooding. A more detailed description of the weather systems conducive to extreme rainfall in the region is provided in the Part 1 report.

2.3 Recent climate change projections for south-east Queensland

The most recent climate change projections for Queensland are presented in Walsh *et al.* (2002). For south-east Queensland, projected annual mean temperature increases range from 0.3 to 1.7°C for 2030 relative to 1990 values. Temperatures are projected to increase in all seasons of the year. In Brisbane, the average annual number of summer days with temperatures over 35°C is projected to increase from 3 days to between 3 and 6 days by 2030. For both mean temperatures and extremes, much larger ranges of change are projected for 2070. Projected changes in annual rainfall over south-east Queensland tend towards being slightly negative or neutral or indicate uncertain change. When broken down by seasons, rainfall tends towards increases along the coast in summer and decreases in spring. In autumn and winter the changes are either neutral or uncertain. Most models simulate an increase in extreme daily rainfall, leading to more frequent heavy rainfall events.

Projections for changes in extreme daily rainfall for New South Wales are presented in Hennessy *et al.* (2004). The techniques used in that study have been applied to output from five climate models for the region of Australia east of 152°E and between 25° and 32°S. The results of that analysis are shown in Figure 2 for 2030.

This analysis does not consider the ability of each of the models to simulate the weather systems conducive to extreme rainfall. A composite based on all available model simulations is likely to differ from that based on a subset that considers only those models that are known to be skilful at representing extreme rainfall weather systems. Results from such a subset are presented in Figure 12 and should be compared with the results from Figure 2.

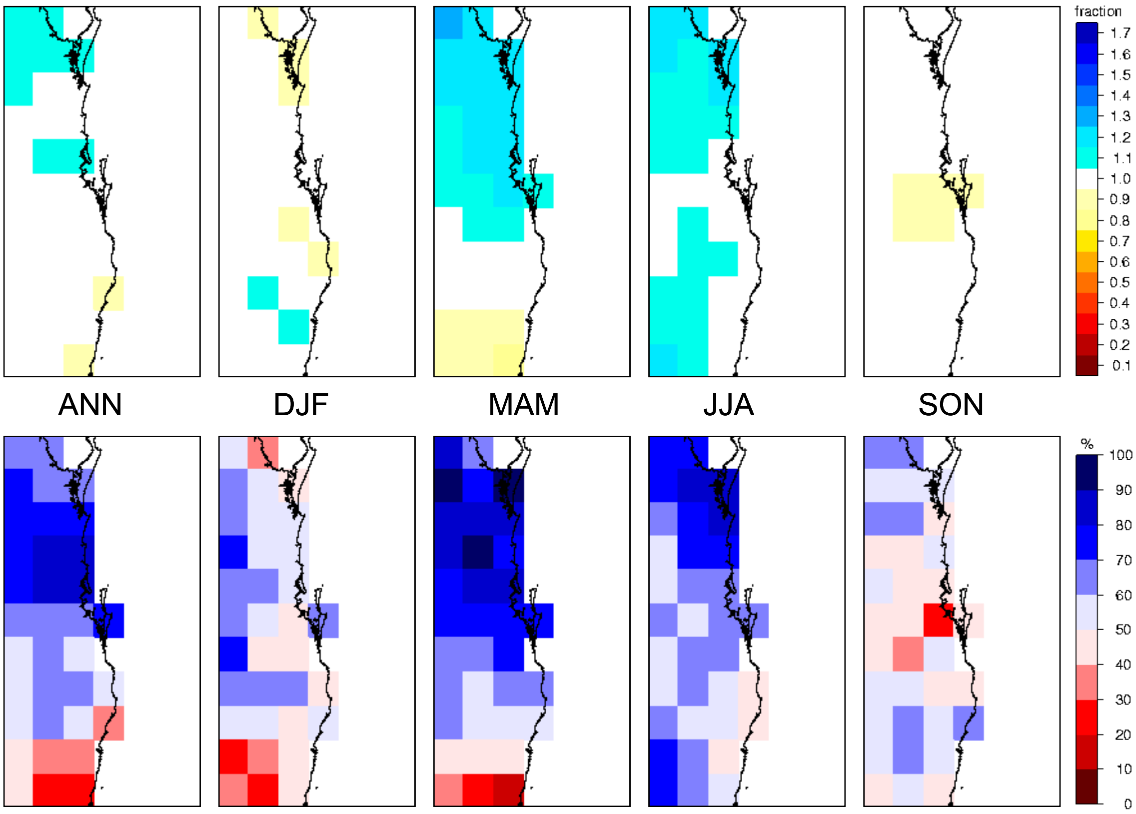

Figure 2: (top) Average fractional change in the intensity of 1-day extreme rainfall events for the year 2030 relative to the current climate. Yellow denotes regions of decrease in intensity and blue denotes regions with a projected increase in intensity. (bottom): The percentage likelihood of an increas) in 1-day extreme rainfall intensity (for return periods of 5, 10, 20 and 40 years) for 2030 relative to the current climate. Red regions are where the majority of models simulate a decrease in rainfall extremes and blue regions are those where the majority of models simulate an increase in extremes. ANN = annual, DJF = summer, MAM = autumn, JJA = winter, SON = spring.

The above analysis shows that the majority of models simulate an increase in extreme daily rainfall intensity for the coastal regions of south-east Queensland, for all seasons except spring. These increases are largest in the region north of Brisbane and the Gold Coast. However, more detailed modelling (Abbs *et al*., 2006) shows that even in regions in which extreme rainfall intensity is projected to decrease on average, localised areas of increase may occur.

Daily rainfall data have been extracted from an SRES A2 scenario simulation of the CSIRO Mark 3 GCM (Gordon *et al.,* 2002) and analysed for two forty year periods corresponding to the current climate (1960-2000), the climate of 2030 (2010-2050) and the climate of 2070 (2050-2090). For each model grid point, the 99.9th percentile daily rainfall total was determined for the current climate and used as a threshold to examine the change in the frequency of extreme events. The results from the analysis (not shown) show that, for the region of interest, extreme daily rainfall events are projected to occur more frequently but changes in intensity are uncertain. These conclusions are based on the results from a coarse resolution climate model simulation with grid cells measuring about 200 × 200 km in the regions of interest. Extreme rainfall intensity averaged over such large areas is much less than that found over small areas. For regional planning, there is a need to provide extreme rainfall scenarios with fine resolution if projected climate change is to be factored into major infrastructure projects that are designed to last for decades to come.

3. MODELLING OF EXTREME RAINFALL EVENTS

Doswell *et al*. (1996) have developed an "ingredients based methodology" to identify the conditions that are important for the occurrence of extreme rainfall events. Heavy rainfall occurs where the rainfall rate is high for a long time and this is achieved when moisture-laden air is lifted to condensation. This requires both a moisture source and a transport process to bring the moisture to the location in question. For the study region, the moisture source is the warm waters of the tropics. The moisture transport is usually provided by the winds associated with the synoptic weather systems affecting the region.

The second "ingredient" necessary for the production of extreme rainfall is a lifting mechanism. The lifting mechanism causes moist air to rise and cool, thus leading to the condensation of water vapour into clouds. Lift can be achieved by meteorological features such as fronts and convection or through topographic features such as orography and land-sea contrasts. The third requirement is an atmosphere that is buoyant. Buoyancy is required so that once lift is triggered the air will continue to rise to produce deep, moist convective clouds.

Some of these features will be present in GCM simulations although their effect will be less pronounced than occurs in reality due to the averaging that is an inherent part of the course resolution used by GCMs. Thus extreme rainfall days identified in a GCM simulation should be associated with some of these characteristics. The function of the high-resolution model used in this study is to take these "ingredients" and provide the mesoscale forcing that will provide the lifting necessary for convective initiation. This forcing will be provided by both higher-resolution orography and better representation and organisation of high-intensity rainfall features embedded within synoptic scale weather systems, such as short wave troughs and cut-off low pressure systems (e.g. east coast lows or tropical cyclones).

3.1 Downscaling methodology

The Regional Atmospheric Modelling System (RAMS) has been used to downscale extreme rainfall events simulated by three climate models. RAMS is a high-resolution, compressible, non-hydrostatic model. Physical processes represented by the model include those associated with the atmospheric boundary layer, soil, vegetation, long and short wave radiation, and the complex cloud processes involving ice, liquid water and water vapour that result in precipitation. RAMS is a suitable tool for the simulation of extreme rainfall events and has previously been used for this purpose, as described in Abbs (1999) and McInnes *et al.* (2002). A full description of RAMS and validation of the model for the configuration used in this study is presented in Abbs (2006).

Three simulations are considered in this study. They are a simulation using CSIRO's Mark 3 Atmosphere-Ocean Global Climate Model and two regional climate simulations referred to as CC-Mk2 and CC-Mk3 models. The CSIRO Mark 3 model has been used to simulate the climate from 1961 to 2100 under an SRES A2 greenhouse gas emissions scenario (IPCC, 2000). Mark 3 has a horizontal grid spacing of approximately at 1.85°× 1.85° and has 18 levels in the vertical. The cubic conformal model (CC) is a global model that utilises a stretched grid in which the Earth is mapped onto a cube. The mapping is such that higher resolution is focussed over the region of interest and lower resolution is on the opposite side of the Earth, remote from the region of interest. To overcome the potential errors that could result from the poor resolution in the remote areas, the model solution in the lowest resolution areas is nudged heavily towards the solution of a GCM of more uniform resolution. The cubic conformal model simulations considered in this study had their highest resolution, of approximately 65 km, centred on Australia (see Figure 3). Outside this region, the CC-Mk2 model solutions were nudged towards those of the CSIRO Mark 2 A2 simulation and the CC-Mk3 model was nudged towards the simulation of CSIRO Mark 3 A2 model (see Table 1).

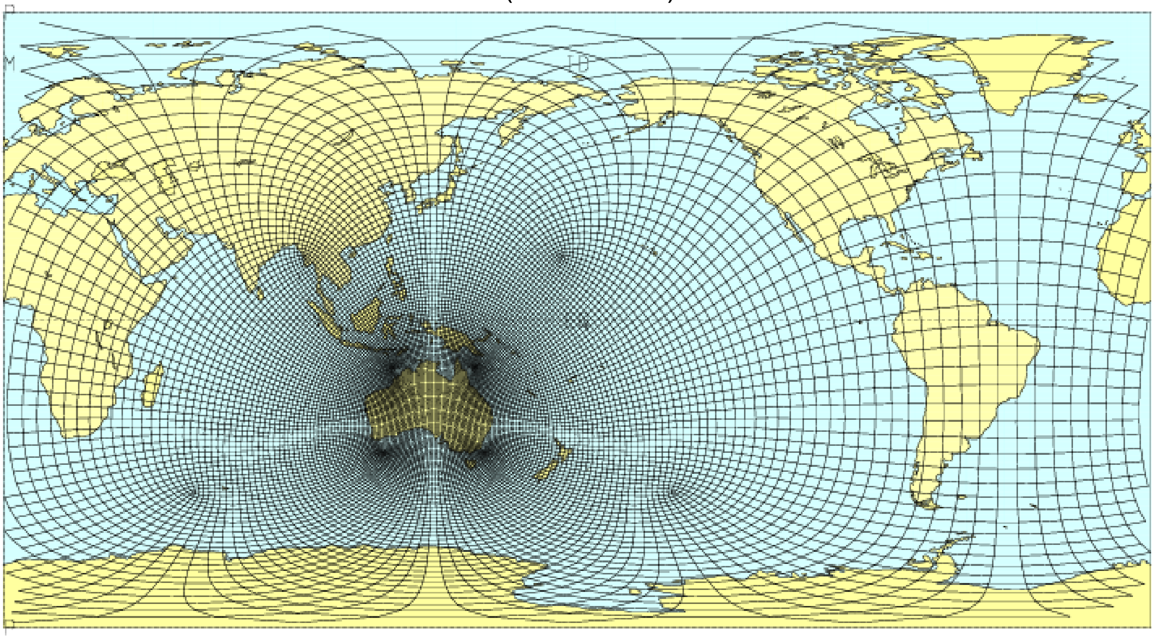

Figure 3: The stretched grid of the cubic conformal model.

Table 1: Details of the climate model simulations relevant to the present study.

Model	Emissions scenarios post-1990 (historical forcing prior to 1990)	Years of simulation	Horizontal resolution (km)	Abbreviations used in this report
Mark3	SRES A2	1961-2100	~200	MK3
CC-Mk2	SRES A2	1961-2100	~65	CC-Mk2
CC-Mk3	SRES A2	1961-2100	~65	CC-Mk3

In the simulations discussed here RAMS has been initialised using output from each of these models. For each set of GCM-based downscaling simulations, the most intense rainfall events were identified for the south-east Queensland and northern New South Wales grid points, for the "current" climate and the "2030" and "2070" climates[1]. The corresponding atmospheric output fields were then extracted and these outputs interpolated horizontally and vertically to the outer model grid of RAMS. That grid had a resolution of 48 km. The climate model output also provided the temporal forcing on the lateral boundaries of the outer model grid.

3.2 Model configuration

Three levels of interactive grid nesting were used, the middle and finest resolution grids having a horizontal grid spacing of 16 km and 4 km respectively[2]. The terrain used on all model grids was interpolated from the USGS 30 second data set. In the

[1] The downscaling of the Mark 3 simulation was undertaken as a pilot study and is for current and 2040 (2020-2060) time slices. The 2040 results are considered with the 2030 results from the other simulations and henceforth will be referred to as "2030".

[2] The Mark 3 simulation used a coarser grid with the finest mesh having a grid spacing of 7.5 km. The 2 outer grids used a grid of 90 and 22.5 km.

Australian region, the global topography dataset is supplemented with a 9-second gridded Digital Elevation Model available from Geoscience Australia. The vegetation was obtained from a USGS 30 second dataset. The sea surface temperatures were interpolated from the GCM output. This configuration is similar to that used in the extreme rainfall simulations of Abbs (1999) and McInnes *et al.* (2002).

Each event was simulated from 2 days before to 2 days after the event and model fields were archived with a 30-minute increment. The shortest simulations cover a 96-hour period centred on the rainfall event but most simulations are of longer duration. The 30-minute rainfall output from the simulations has been used to define the 2, 12, 24, 48, 72 and 96-hour rainfall maxima for each event. The following analysis concentrates on the maximum rainfall falling within the 2, 24 and 72-hour periods. Outputs for the other durations are available for further analysis if required. At least one hundred events were simulated for each of the current, 2030 and 2070 climates. This number was determined by simulating the highest-ranked current climate events in 25-member sub-samples as part of the Mark 3 downscaling pilot study. When the statistics (such as depth-area curves) derived from the total number of events no longer changed significantly the sub-sampling ceased. It was considered that the results for that sample size were robust and representative of the climate for current climate extreme rainfall events. It is assumed that an identical sample size is adequate for analysis of the 2030 and 2070 climates.

For the remainder of this report, unless otherwise stated, the nomenclature Mk3, CC-Mk3 and CC-Mk2 refers to results from RAMS nested in the respective parent model.

4. RESULTS

4.1 Comparison with observed extreme rainfall

Daily rainfall observations from the Commonwealth Bureau of Meteorology have been extracted for the region for the 40-year period 1960-1999. The entire rainfall station dataset was examined and stations with a record greater than 80% complete were used. This technique maximised the number of stations that were available for analysis on each day and also maximised the spatial rainfall information for the region. Additional quality control measures included rejecting multi-day rainfall records (this typically occurs on a Monday) and manually examining the heaviest rainfall days to ensure that the extreme values were consistent with the surrounding records for that day.

For each station, the daily rainfall time series has been sorted and the heaviest rainfall events in the 40-year period identified. The most extreme 1-day and 3-day rainfall events for each station are plotted in Figure 4.

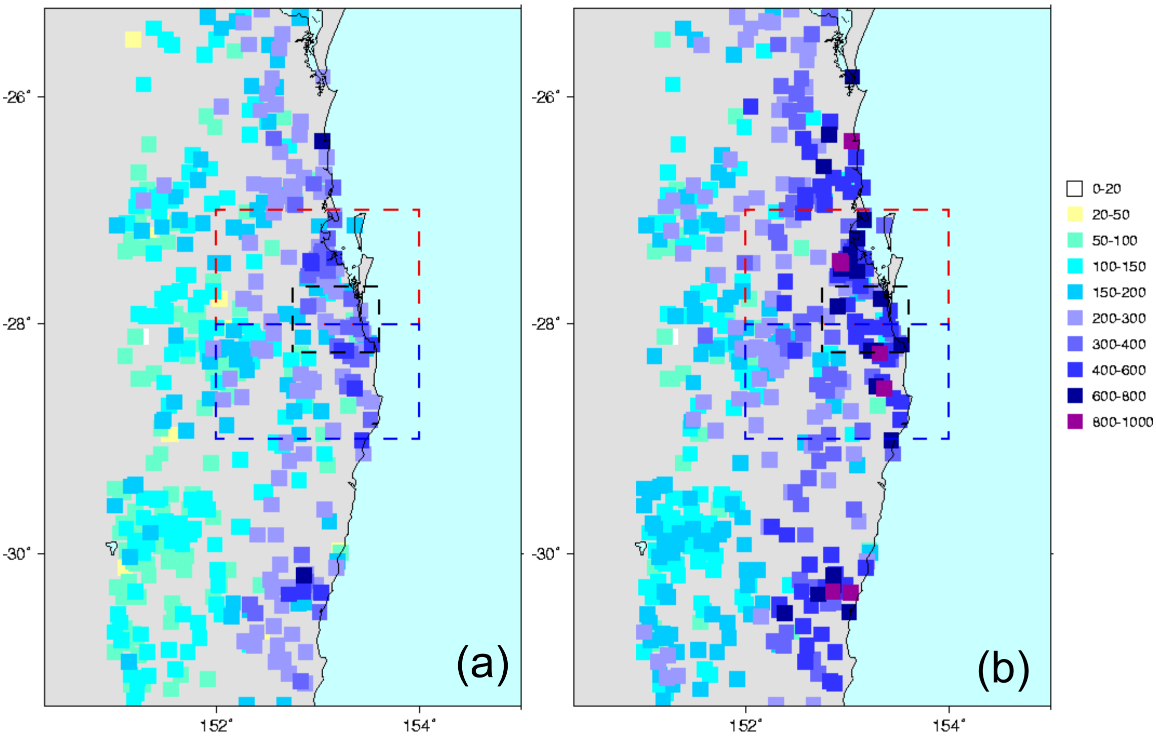

Figure 4: Observed most extreme (a) 1-day rainfall and (b) 3-day for each rain gauge location for the period 1960-1999. The dashed rectangles indicate sub-regions referred to in this study – black: the Gold Coast, red: Brisbane and blue: Border.

These figures show the preferred regions for extreme rainfall occurrences to be in the mountainous regions inland from Coff's Harbour, Cape Byron, Coolangatta and Brisbane. In each locality, daily rainfall events greater than 500 mm day^{-1} have been recorded. The 3-day totals in these regions exceed 800 mm.

A similar spatial pattern can be seen for the simulated 24-hour extreme events shown in Figure 5. The simulated intensities are, in general, similar to the observed intensities. The models have captured the extreme rainfall regions occurring near Coffs Harbour, inland from Coolangatta and in the mountainous terrain north of Brisbane. The model results also show coastal, extreme rainfall that is probably due to enhanced convection arising from the land-sea contrast.

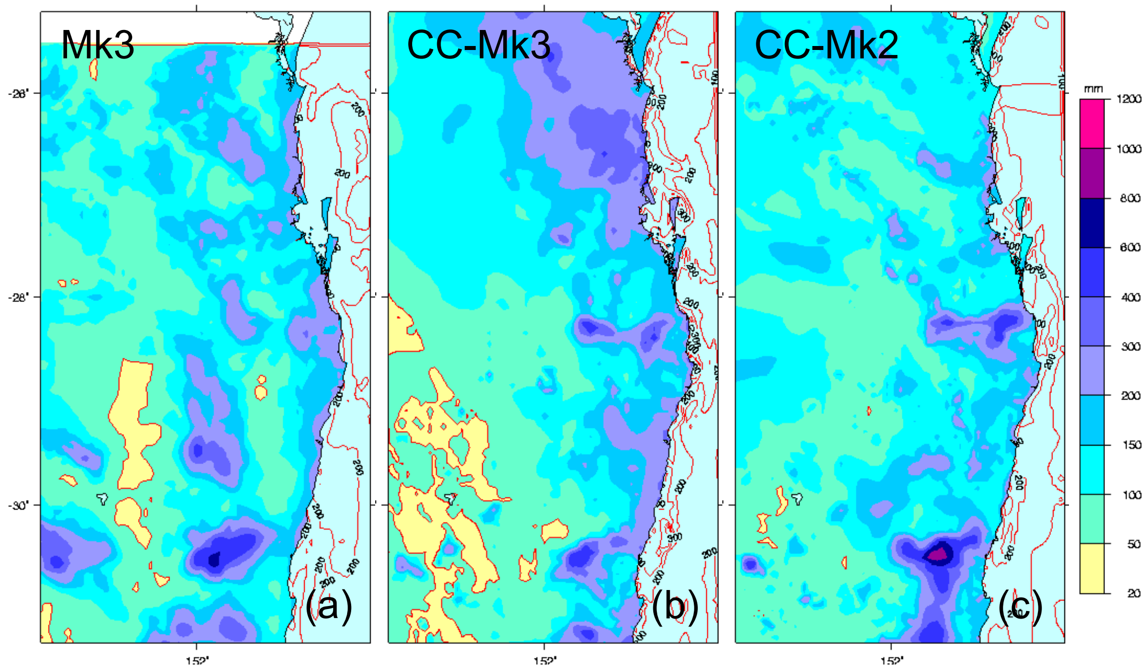

Figure 5: Simulated most extreme 24-hour rainfall for each of the three parent models considered in this study.

The spatial distribution of modelled 72-hour rainfall for each of the 3 models is shown in Figure 6(a)-(c). The 72-hour spatial pattern is similar to the corresponding 24-hour pattern, as expected. For each model, as in the observations, the highest rainfall totals lie east of 152°East, in the mountainous coastal hinterland. The model simulates 72-hour rainfall accumulations in excess of 800 mm. Inland from Coffs Harbour the modelled accumulations are greater than 1200 mm, which is greater than the 72-hour accumulations recorded for this region in the past 40 years.

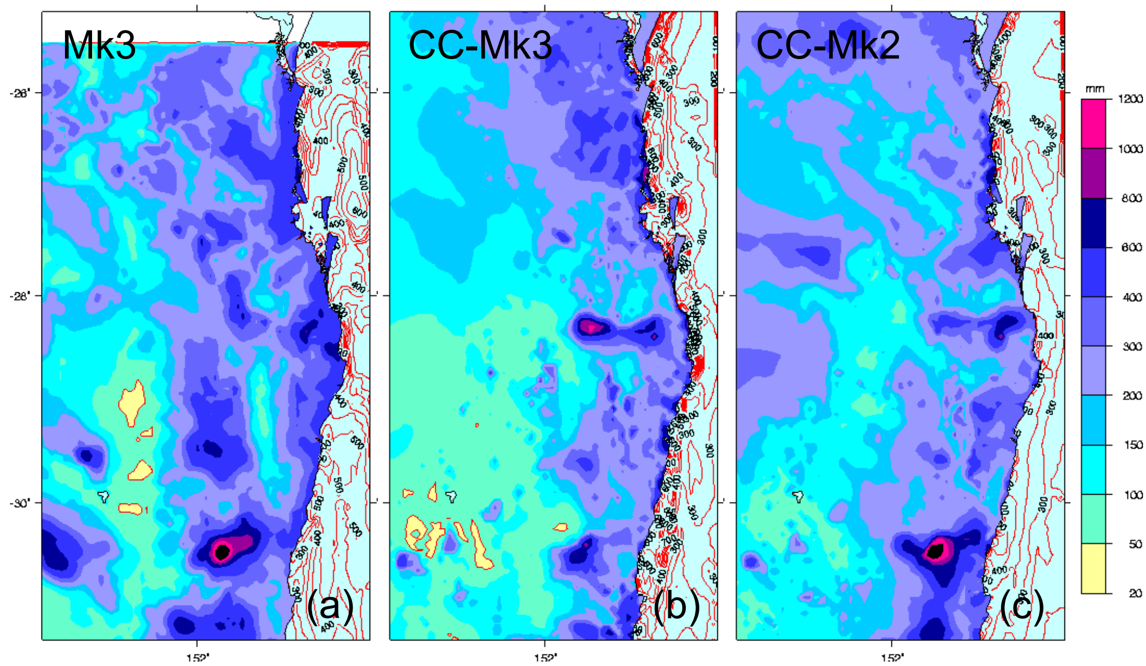

Figure 6: Simulated most extreme 72-hour rainfall for each of the three parent models considered in this study.

For completeness, the modelled 2-hour rainfall extremes are presented in Figure 7(a)-(c). These results show small regions, along the Border Ranges and inland from Coffs Harbour, where the 2-hour totals exceed 150 mm.

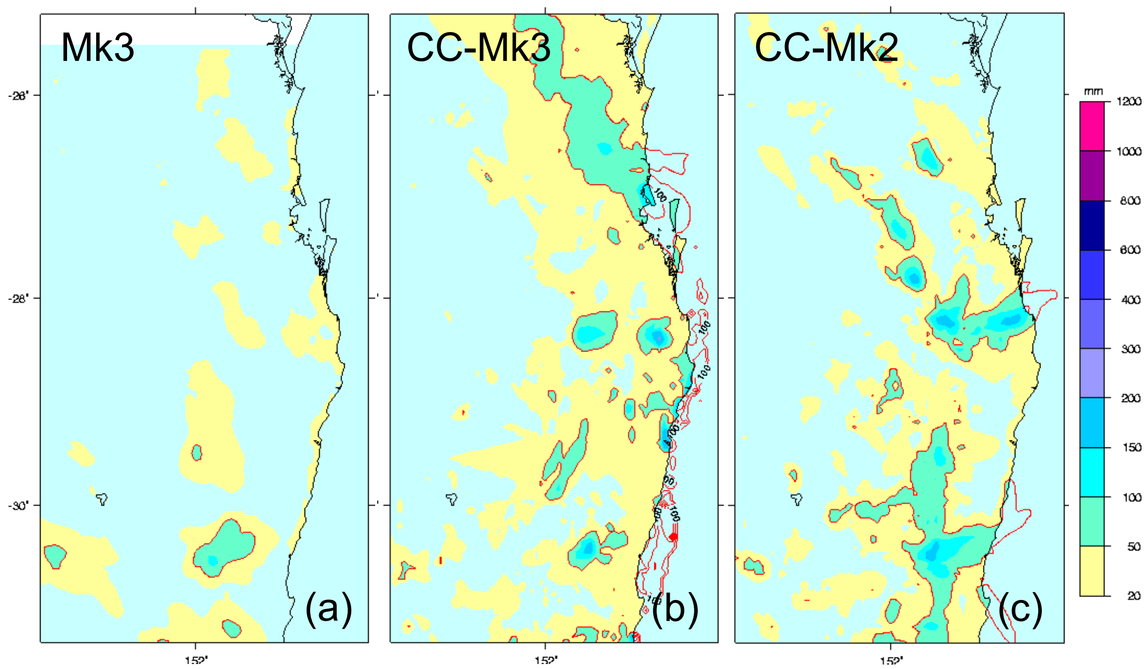

Figure 7: Simulated most extreme 2-hour rainfall for each of the three parent models considered in this study.

An examination of Figure 5 to Figure 7 indicates that each of the models is producing a different spatial pattern of extreme rainfall and that these also differ from the observations. This is because the individual weather events that contribute to each model extreme rainfall sample differ, as shown in Part 1 of this study (Abbs and McInnes, 2004), and also differ from the weather events that produced the observed rainfall accumulations presented in Figure 4. Despite these individual differences, each of the downscaled models is providing a good quantitative and qualitative representation of the spatial distribution of extreme rainfall in the region of south-east Queensland and northern New South Wales. A composite result, based on the CC-Mk2 and CC-Mk3 simulations, is presented in Figure 8.

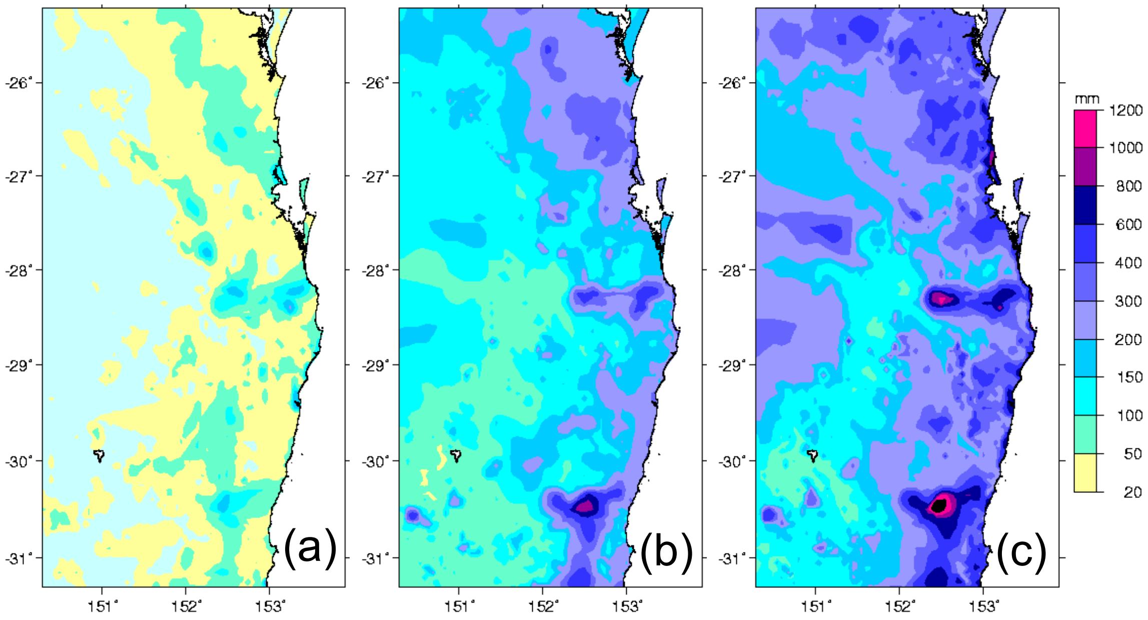

Figure 8: Simulated most extreme (a) 2-hour, (b) 24-hour and (c) 72-hour rainfall based on a composite from simulations nested in CC-Mk2 and CC-Mk3.

4.2 Effect of climate change

4.2.1 Spatial patterns of projected changes

The following analysis concentrates on the 10 most extreme events, at each model grid point, from each of the models for the current and future climates. This corresponds (roughly) to extreme rainfall events with return periods of 1-in-40 years through to 1-in-4 years. The analysis is performed for rainfall durations of 2, 24 and 72 hours.

For each model grid point, the rainfall accumulation from the 100 simulations has been sorted and ranked for the current climate experiment. A similar analysis has been conducted for the future climate extreme rainfall events and the results from this analysis compared with the results for the current climate. The average fractional change ($\overline{F}$) in extreme rainfall for the future climate, compared with the current, is presented in Figure 9 for 2030 and in Figure 10 for 2070.

Mathematically,

$$\overline{F} = \frac{\sum_{n=1}^{10} F_n}{10}$$

where

$$F_n = \frac{P_{current}(n)}{P_{future}(n)}$$

and $P_{current}(n)$ is the 2, 24 or 72-hour precipitation at the grid point for the n^{th} ranked current climate event. $P_{future}(n)$ is similarly defined.

The downscaled results from the 2 high-resolution climate runs show a number of similarities. In Part 1, these models were found to have a good representation of the weather systems conducive to extreme rainfall in the regions. By 2030, both sets of model results are showing increases in the intensity of extreme rainfall events in the McPherson Range. This increase is most evident for the shorter duration events, especially the 2-hour events. Both sets of results show a decrease in extreme rainfall for the coastal regions north of Brisbane for the 2030 climate. By 2070 this region of decrease has either decreased in size (CC-Mk2) or changed sign (CC-Mk3) to become a region of increase. Both models show large increases in the intensity of the short duration, 2-hour events by 2070. The Mark 3 based results (Mk3 and CC-Mk3) both show decreases in the intensity of extreme rainfall events in the coastal areas of northern New South Wales for 2030.

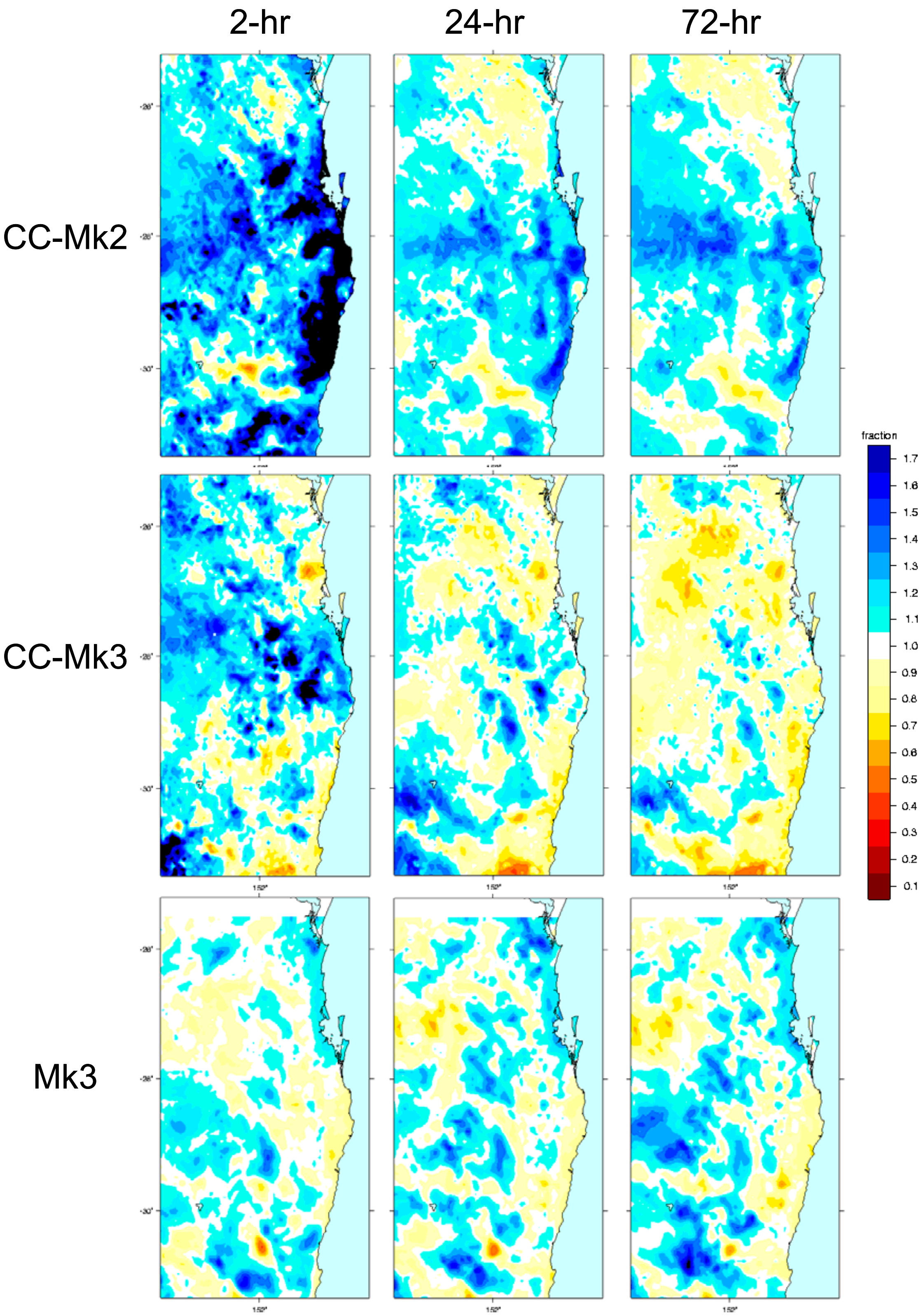

Figure 9: Average fractional change in accumulated rainfall for 2030 for the 10 most extreme rainfall events for durations of 2, 24 and 72 hours (vertical columns). Results for the three models are shown in rows.

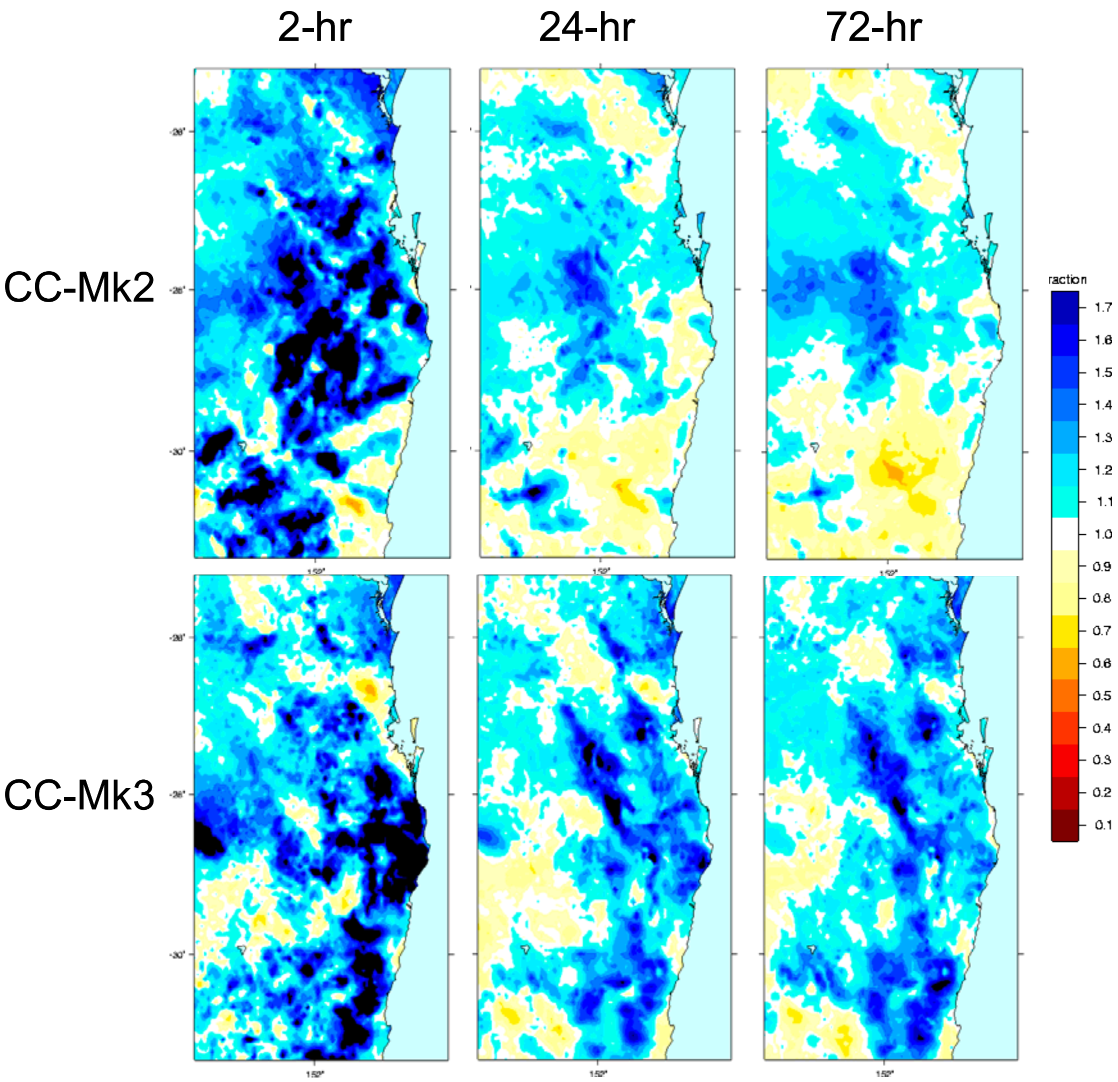

Figure 10: Average fractional change in accumulated rainfall for 2070 for the 10 most extreme rainfall events for durations of 2, 24 and 72 hours (vertical columns). Results for the two models are shown in rows.

The different spatial patterns of rainfall change make it difficult to determine areas of increase or decrease identified by most models. Thus, composite maps have been calculated to determine the average change likely for each location. The composite maps are based on the outputs from CC-Mk2 and CC-Mk3 only. Both models were shown, in Part 1, to provide a skilful representation of the weather systems that produce extreme rainfall in the region while the Mk3 model performed poorly. The results from the averaging are shown in Figure 11. They show a broad region of increase in the mountainous region straddling the Queensland-New South Wales border for the 24-hour and 72-hour events. With time, the spatial extent of this area of increase enlarges and the embedded maxima increase in magnitude to values greater than 1.4 (i.e. a 40% *average* increase in the intensity of the most extreme events).

Of the three event durations considered, the 2-hour rainfall events show by far the largest projected changes with the largest changes in the high terrain inland from the Gold Coast. These regions of rainfall increase increase in spatial extent with time. The 2-hour rainfall events have average increases in intensity of more than 70% in these regions for both 2030 and 2070.

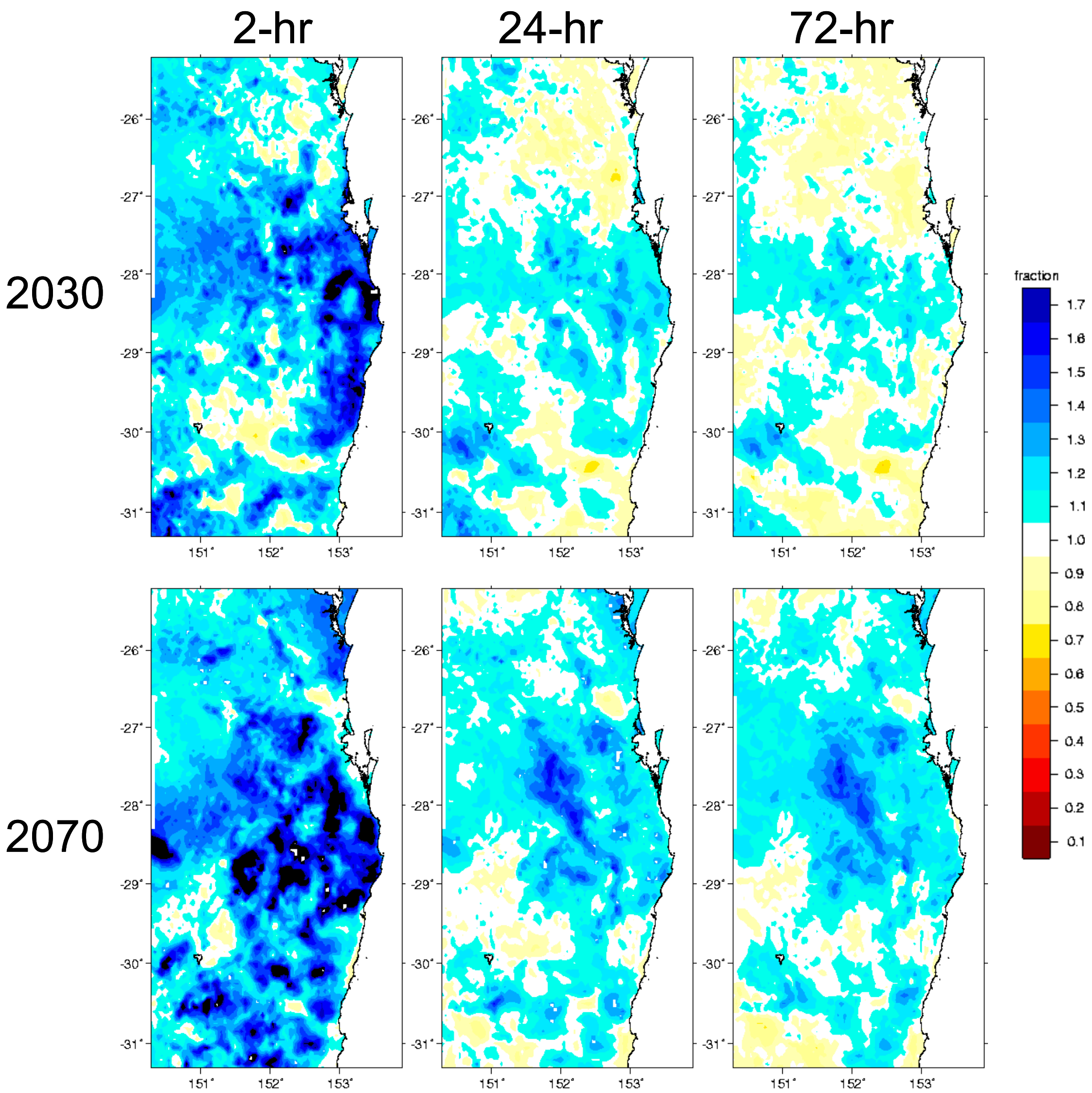

Figure 11: Average fractional change in accumulated rainfall for 2030 and 2070 for extreme rainfall events of 2, 24 and 72 hours (vertical columns), based on a composite of the projected changes from CC-Mk2 and CC-Mk3.

It is interesting to consider the value that the high-resolution downscaling adds to climate model output. The composite, average fractional change from the 65-km parent–model, CC-Mk2 and CC-MK3, simulations is shown in Figure 12. These results show broad qualitative agreement with the results presented in Figure 11. They show a region of extreme rainfall decrease to the north of Brisbane and a tendency for extreme rainfall to increase in intensity with time. However, there are also some notable differences. The 65 km model results do not capture the increases in rainfall intensity projected for the McPherson Range nor the localized maxima that are projected for the Great Dividing Range west of Brisbane by 2070. These projected localized maxima occur in the headwaters of the Brisbane and Albert-Logan River systems and are likely to result in significant increases in flooding for these rivers.

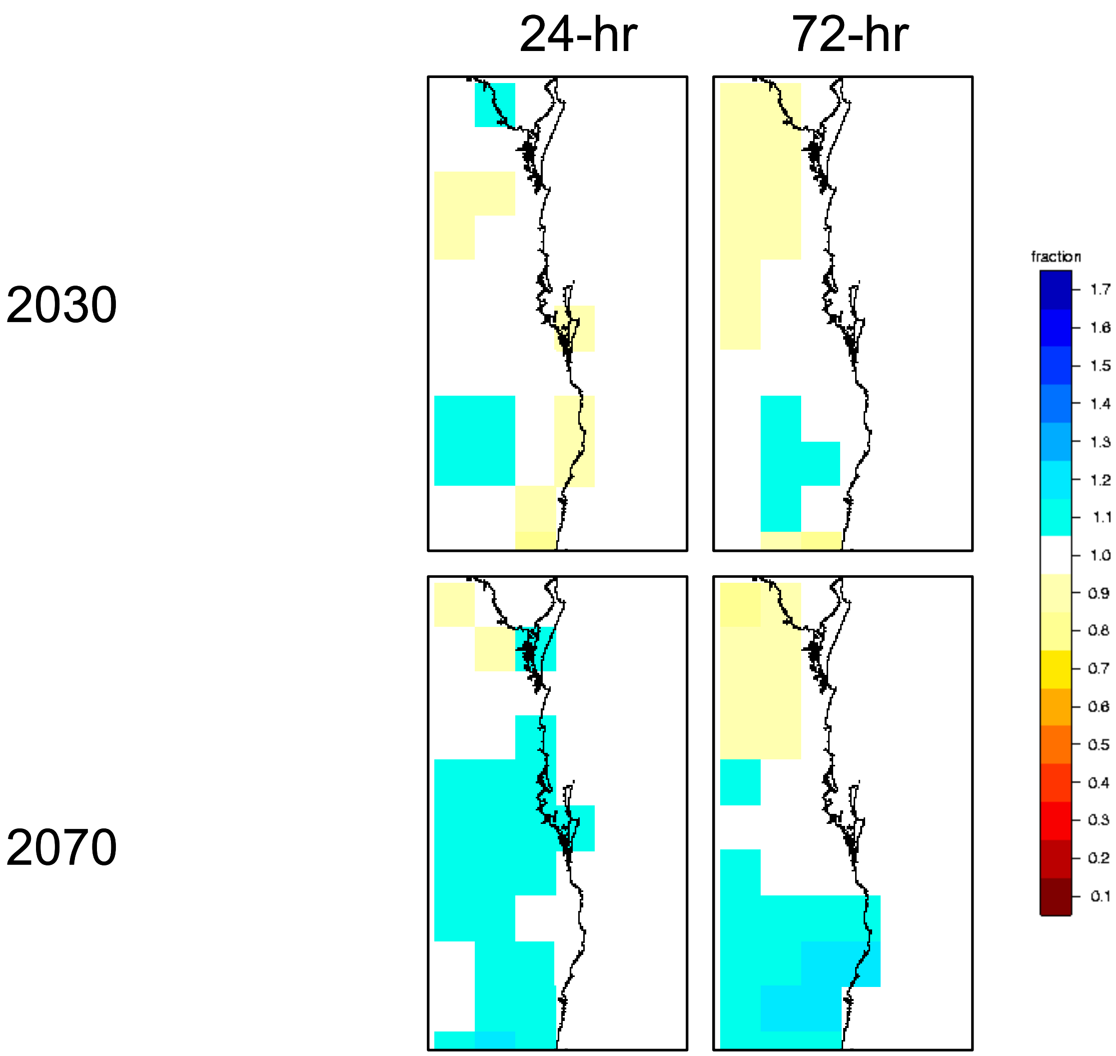

Figure 12: Average fractional change in accumulated rainfall for 2030 and 2070 for extreme rainfall events of 24 and 72 hours based on a composite of the projected changes from the 65-km parent models,CC-Mk2 and CC-Mk3.

It is possible that the average values presented above are overly influenced by 1 or 2 results that are substantially different to the remainder. For example, it is possible that the most extreme (i.e. rank 1) event may have a large fractional change while the events ranked 2 to 10 have much smaller fractional changes. Under these conditions the rank 1 event will make a large positive contribution to the average fractional change for that location. To address this issue "consensus maps" have been produced to identify those regions most likely to experience an increase in extreme rainfall for various fractional change thresholds. Thresholds of 1.0, 1.1, 1.2 and 1.5 were considered. The maps were created by considering the 10 most extreme events from each of the CC-Mk2 and CC-Mk3 models and determining the percentage that experienced a fractional change above the threshold in question. The results of this analysis are presented in Figure 13 for a threshold of 1.0 and in Figure 14 for a threshold of 1.2.

Figure 13 shows that there is good agreement on an increase in extreme rainfall intensity in the McPherson Range and the Great Dividing Range west of Brisbane and the Gold Coast, especially for the 2-hour and 24-hour events. Increases in the intensity of 72-hour events are also likely, although there is less agreement on this result.

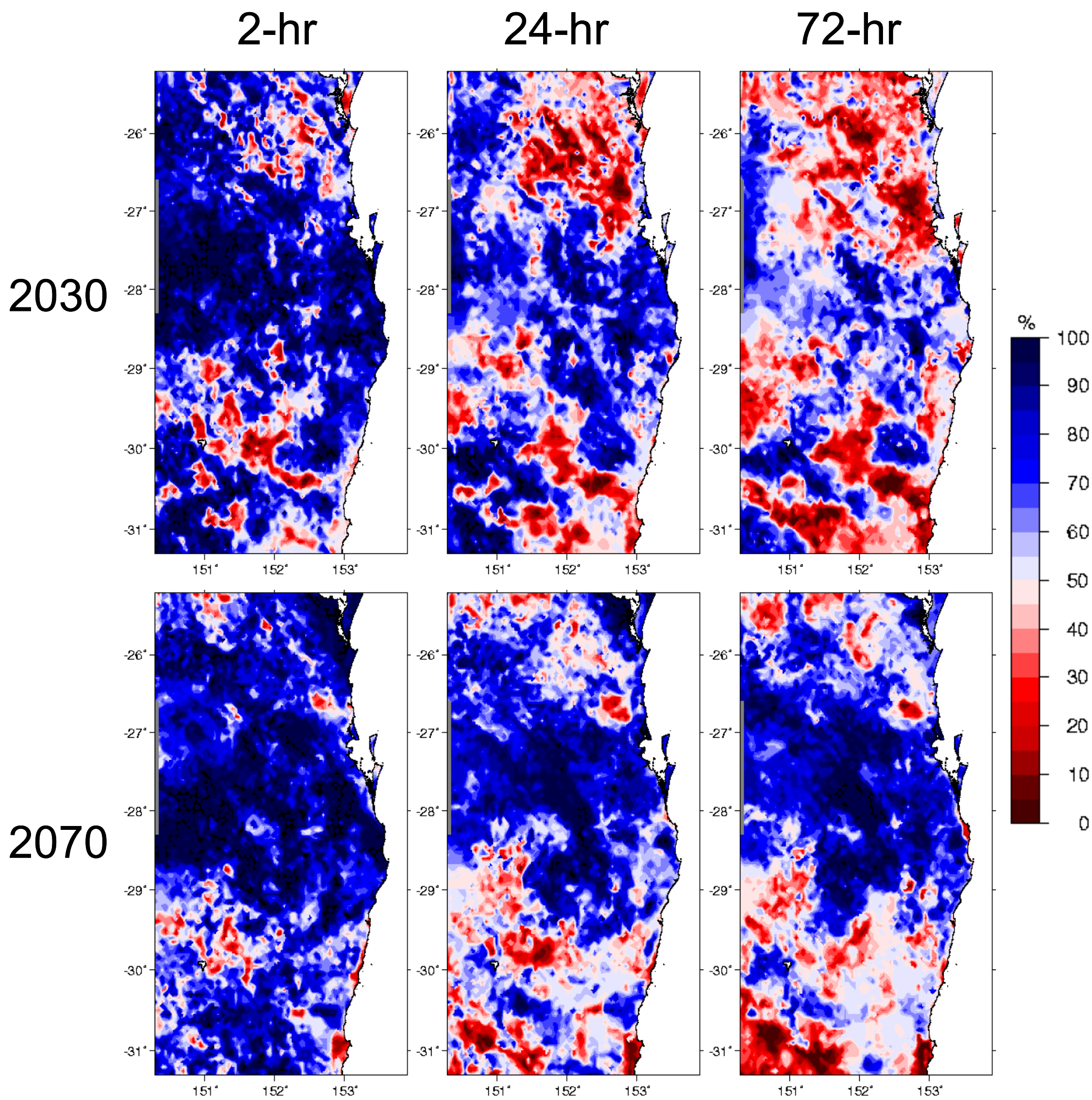

Figure 13: Regions likely to experience an increase/decrease in extreme rainfall. Regions of increase(decrease) are shown in blue(red). Darker shadings indicate greater agreement between the models.

There is high agreement on decreases in the intensity of 24-hour and 72-hour extreme rainfall events in the hinterland north of Brisbane and the coastal regions of northern New South Wales for 2030. By 2070, the regions of likely decreases in extreme rainfall intensity have almost disappeared and most regions are likely to experience an increase in the intensity of extreme rainfall events. The region of highest agreement includes the McPherson Range and the Great Dividing Range, stretching from the New South Wales border to the north of Brisbane. It includes the catchment areas for all rivers and streams flowing into the Gold Coast region.

Comparison of Figure 13 and Figure 14 indicates that for 2030 changes in extreme rainfall intensity for 24-hour and 72-hour events are most likely to be less than an increase of 20%, except for small areas along the Great Dividing Range and McPherson Range. By 2070, the region along the Great Dividing Range is likely to experience increases in 24-hour and 72-hour extreme rainfall intensity of 20% or more. 2-hour rainfall extremes are likely to increase in intensity by more than 20% over the region of the McPherson Range.

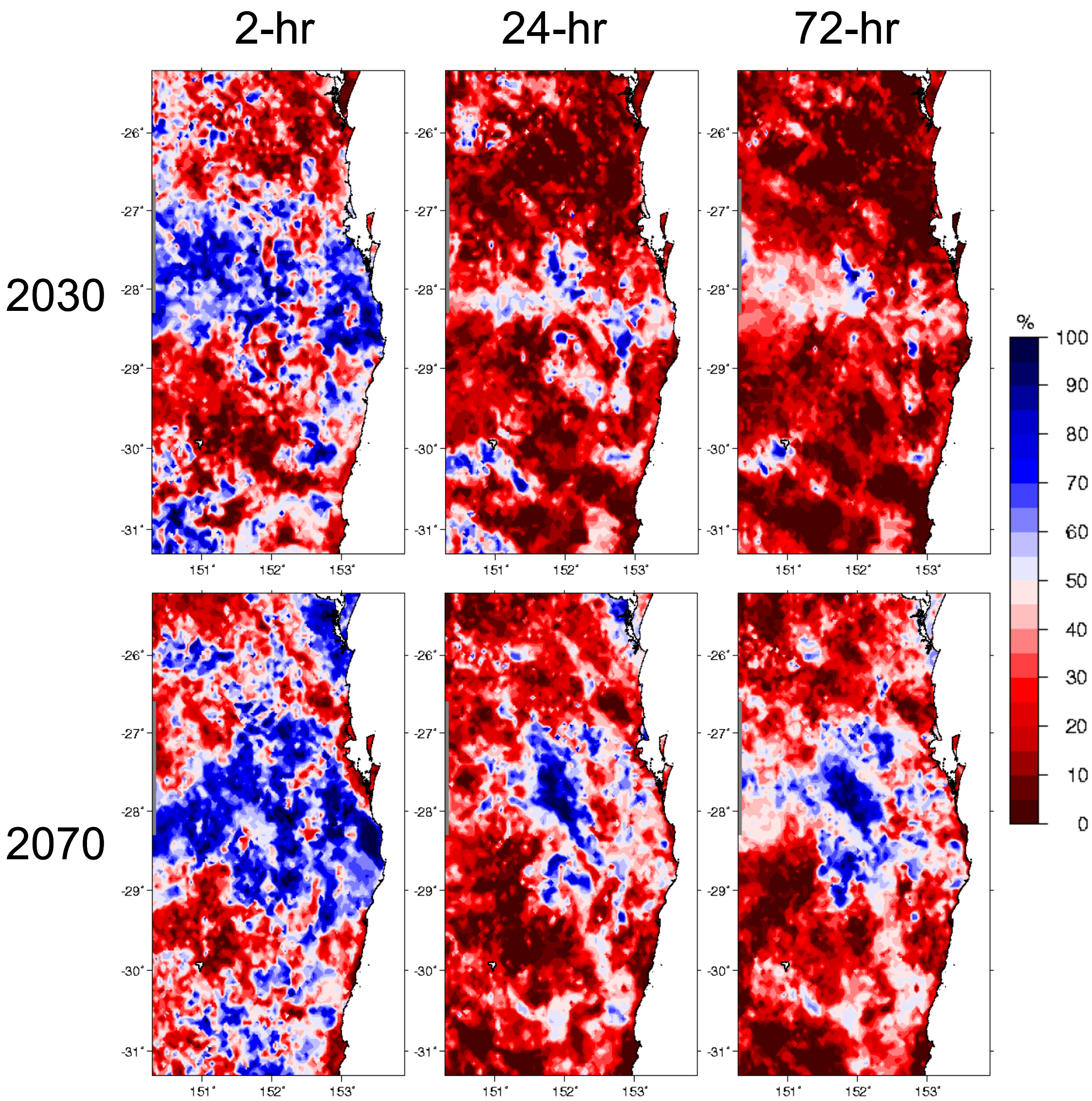

Figure 14: Regions likely to experience an increase in extreme rainfall of at least 20%. Regions of increase are shown in blue. Red denotes regions where the fractional change in extreme rainfall is less than 1.2. Darker shadings indicate greater agreement between the models

The consensus maps for a threshold of 1.5 (not presented) have been examined. They show that in the region of high projected extreme rainfall increase, along the Great Dividing Range, approximately 50% of the most extreme 24-hour and 72-hour rainfall events experience increases in intensity of 50% or more by 2070.

4.2.2 Depth-area curves

Depth-area curves for each of the 100 current-climate and future climate events have been calculated for each model. Those curves have been combined to create representative 2-hour, 24-hour and 72-hour depth-area curves for the current and future climates for the Gold Coast region (see Figure 4). The region used to determine storm centres is the dashed rectangle shown on Figure 4(a). The curves for each model, and for the composite, have been created by determining the envelope of maximum areal-averaged rainfall from the 100 events in the model time slice.

The CC-Mk3 and CC-Mk2 composite curves (Figure 15) show that area-averaged increases in extreme rainfall intensity are predicted for areas less than 1000 km^2 for 24-hour events. The area-averages for the 2-hour events show a small increase while the sign of change for the 2070 72-hour events is unclear. A small increase is indicated for 2030.

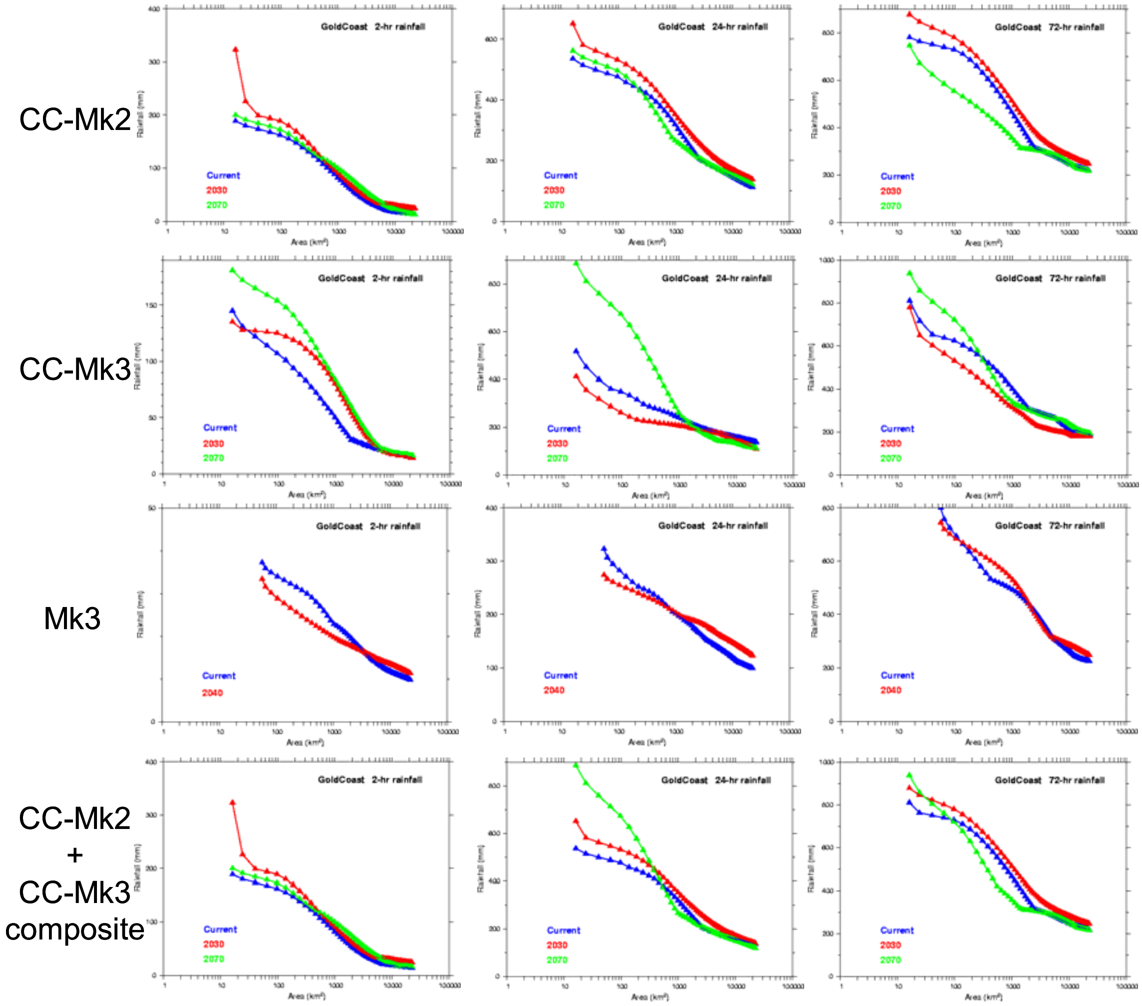

Figure 15: Depth area curves for the Gold Coast region for each model for (left) 2-hour, (centre) 24-hour and (right) 72-hour durations. Composite curves based on the results from the CC-Mk2 and CC-Mk3 models are also presented.

Composite curves for the Brisbane and Border sub-regions, based on CC-MK2 and CC-MK3, are shown in Figure 16.

The plots for 24-hour rainfall accumulations for both sub-regions indicate an increase in the area-averaged precipitation for areas greater than approximately 5000 km^2. The short duration (2-hour) curves for the Border sub-region are similar to those for the Gold Coast sub-region and show a small increase for these events. In contrast, the short duration events for the Brisbane sub-region show a likely decrease in the intensity of these events. The sign and magnitude of the change in intensity of the 72-hour rainfall events for the Border sub-region is unclear, but for the Brisbane sub-region the models project an increase in the intensity of these events.

The results presented in Figure 15 and Figure 16, based on three adjacent sub-regions, highlight the variability that may be found within a small spatial scale and illustrate the advantage of using high resolution modelling. They also illustrate the uncertainty that is inherent in developing climate change projections. They show differences that arise solely from the use of a different "parent" global climate model, and highlight the importance of using multiple models when developing projections.

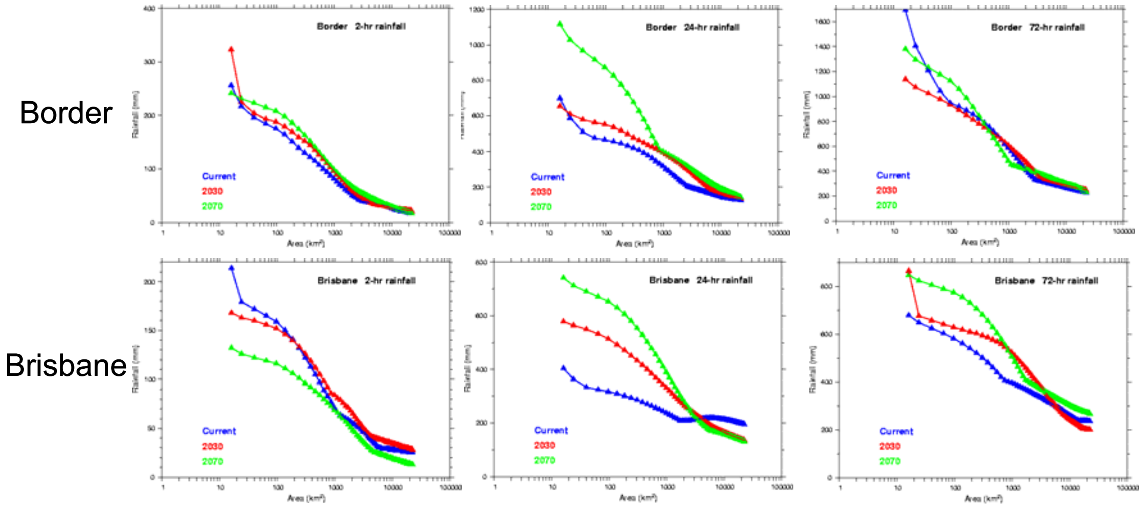

Figure 16: Composite curves for (left) 2-hour, (centre) 24-hour and (right) 72-hour durartions, based on the results from the CC-Mk2 and CC-Mk3 models, for the neighbouring sub-regions of Brisbane and Border.

4.2.3 Return period curves

Return period curves are a convenient way of presenting changes in extreme rainfall for a location. The return period curves presented here have been derived by identifying maximum rainfall accumulations in a time slice for each sub-region from each simulation. Thus the return period curves are representative of a sub-region rather than a specific location. Curves for individual locations are not presented.. Sub-region representative curves based on observed rainfall are presented in addition to the model data.

Curves from each of the models, as well as composite curves from the CC-Mk2 and CC-Mk3 models, are shown in Figure 17. There is significant variability between the downscaled results from each model and their ability to capture the statistical properties of extreme rainfall in the sub-region. The downscaled CC-Mk3 model results have properties similar to those of the observations for the Gold Coast sub-region, although it tends to under-estimate both the 24-hour and 72-hour accumulations. Abbs *et al.* (2006) have previously shown that this model is able to represent the statistical properties of extreme rainfall in the adjacent Brisbane and Border sub-regions. The downscaled CC-Mk2 results show that the model under-estimates the 72-hour extreme rainfall accumulations and the 24-hour intensities of the events more frequent than 1-in-10 years. Results based on the downscaled Mk3 model are poor for 24-hour accumulations.

The CC-Mk2 and CC-Mk3 downscaled results have been combined and assumed to represent 80-year time slices. The composite results for the Gold Coast sub-region are shown in Figure 17 and those for the Brisbane and Border sub-regions are in Figure 18.

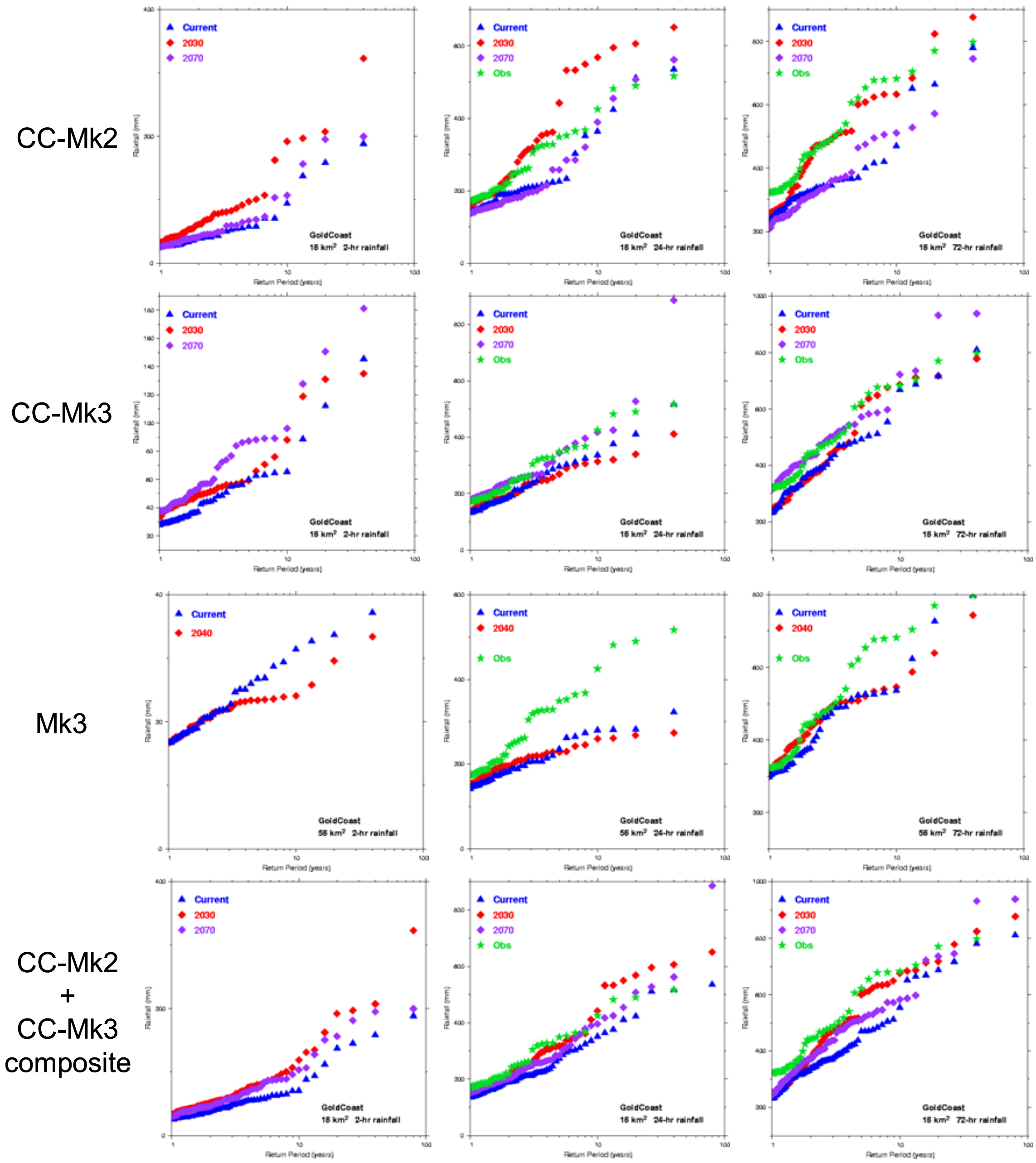

Figure 17: Return period curves for the Gold Coast sub-region for each of the downscaled experiments for (left) 2-hour, (centre) 24-hour and (right) 72-hour rainfall accumulations. Composite curves based on the CC-Mk2 and CC-Mk3 simulations are also shown.

Border

Brisbane

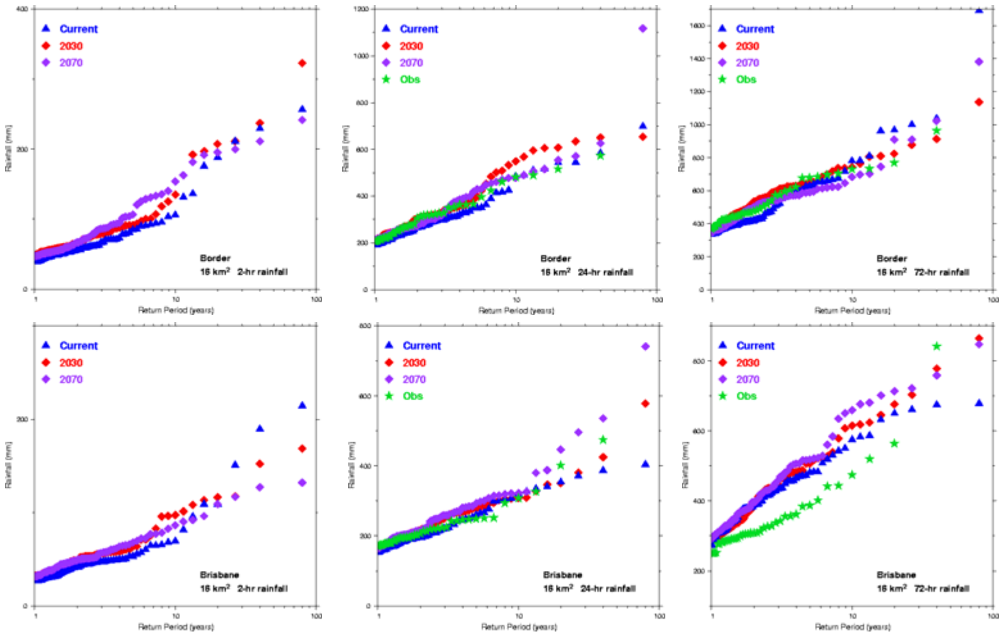

Figure 18: Composite return period curves for the Border and Brisbane sub-regions for (left) 2-hour, (centre) 24-hour and (right) 72-hour rainfall accumulations.

The 24-hour composite results for all sub-regions show close agreement with the observations, as do the 72-hour results for the Border sub-region. The downscaled results tend to over-estimate the 72-hour accumulations in the Brisbane sub-region. The 3 sub-regions show increases in extreme rainfall for durations of 24 hours and 72 hours. The Gold Coast and Border sub-regions show increases in 2-hour rainfall accumulations but short duration events are projected to decrease in intensity for the Brisbane sub-region. Work is currently being undertaken to use extreme-value statistics to convert these results into the more meaningful average recurrence intervals used by the hydrological community. These results will be reported as an Addendum to the current report.

The mean percentage changes in extreme rainfall intensities for the Gold Coast sub-region are presented in Table 2. These results are based on all grid points within the region shown on Figure 4 for the composite results presented in Figure 11. The largest increases occur for the short duration events, with increases of over 50% projected for the 2-hour events by 2030. Increases between 10 and 20% are projected for the longer durations.

Table 2: Average percentage change in extreme rainfall intensity for the Gold Coast sub-region, based on the CC-Mk2/CC-Mk3 composite curves. The range corresponds to the 10^{th} and 90^{th} percentile values of all grid points considered.

Duration (hrs)	Region	2030		2070	
		Mean	Range	Mean	Range
2	*All Gold Coast*	53	26-89	48	4-91
	Coastal	50	33-65	35	6-72
	Mountains	56	22-96	65	27-97
24	*All Gold Coast*	17	8-29	16	5-28
	Coastal	15	8-23	13	0-26
	Mountains	19	8-32	19	9-30
72	*All Gold Coast*	8	0-17	14	4-23
	Coastal	6	-2-13	10	-4-23
	Mountains	10	0-20	17	9-24

The table also presents these results stratified into mountainous and coastal sub-regions. The mountainous regions have been defined as those regions in which the elevation is greater than 100m, while the coastal regions have an elevation less than 100m. These results highlight that the largest increases in extreme rainfall occur over the mountainous part of the study region for all durations considered.

4.2.4 Temporal curves

Design flood estimation requires the formulation of a design rainfall event for input to a runoff routing model. A design rainfall event is specified by a rainfall duration and average rainfall intensity for a particular average recurrence interval (ARI) and a rainfall temporal pattern. A rainfall temporal pattern gives the proportion of total rainfall in different periods within a rainfall "burst". A rainfall burst is the period of heaviest rainfall of a given duration (e.g. 24 hours) that occurs within an extreme rainfall event.

Temporal curves for each of the sub-regions have been calculated using the method adopted by Australian Rainfall and Runoff (ARR87) (I. E. Aust., 1987, 1997) and described by Pilgrim *et al.* (1969) and Rahman *et al*. (2005). This method is known as the "Method of Average Variability" (MAV). The MAV was applied to 30-minute modelled rainfall rates to derive temporal curves of 30-minute resolution for durations of 24 hours and 72 hours. The 30-minute model rainfall archive is too coarse to identify any temporal variability within 2-hour events and so these were not considered. The 30-minute percentages are accumulated to the longer time periods used by ARR87: 1-hour steps for 24-hour bursts and 4-hour steps for 72-hour bursts. As in Rahman *et al.* (2005), rainfall bursts were selected by identifying those bursts with a rainfall intensity greater than 90% of the 1-year ARI value for a given duration. The temporal patterns derived using this approach are presented in Figure 19 and Figure 20.

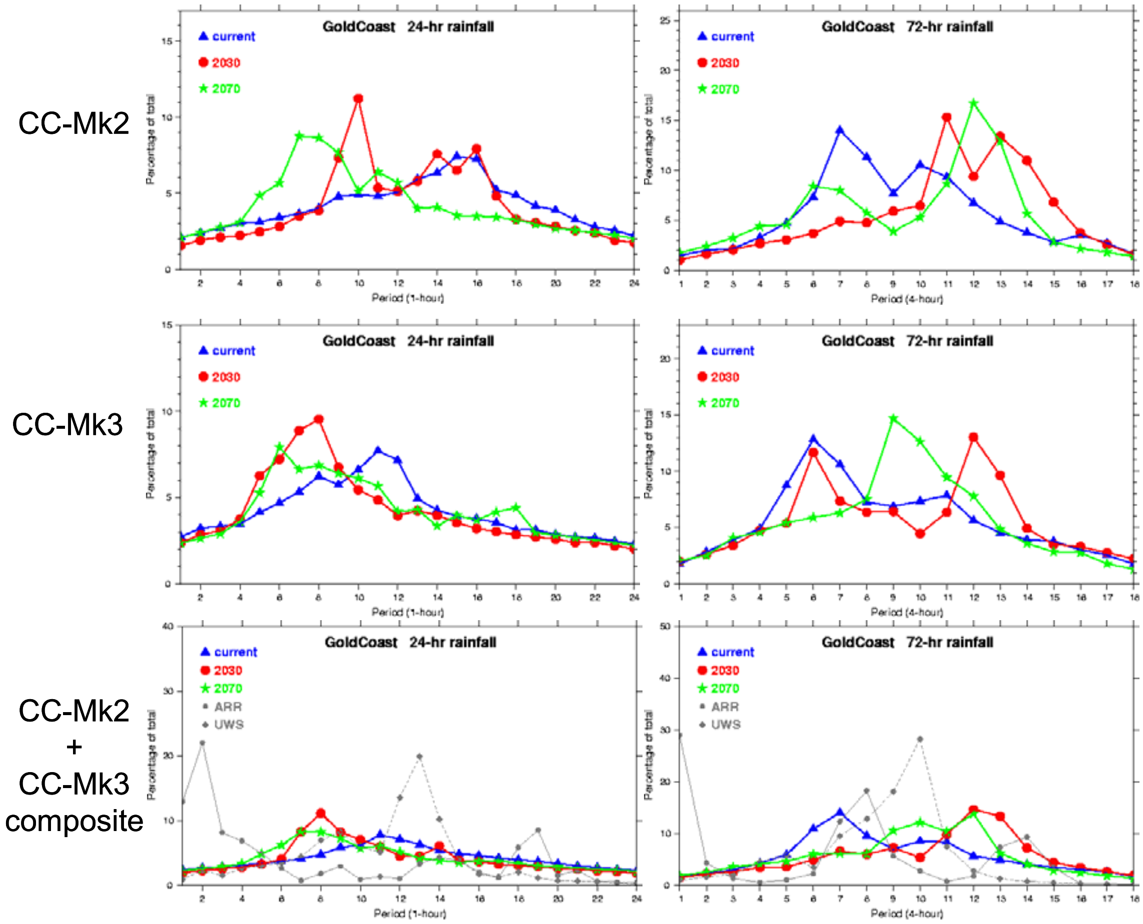

Figure 19: Temporal curves for the Gold Coast sub-region based on downscaled results from the CC-Mk2 and CC- Mk3 models for 24-hour and 72-hour rainfall bursts. Composite curves are also shown. The grey lines are the temporal curves from ARR87 and the UWS curves created by Rahman et al. (2005) for the Gold Coast.

The temporal patterns from the model output are compared (Table 3 and Figure 19) with those described in Tables 3 and 4 of Rahman *et al.* (2005) and the Region 3 curves of ARR87. The Rahman *et al.* (2005) curves are also referred to as UWS 2004.

Table 3: Comparison of ARR 87, UWS 2004 and RAMS-derived design rainfall temporal patterns for the current climate.

Duration	Peak of temporal pattern (%)			Position in burst (1- or 4-hour periods)		
	ARR87	UWS 2004	RAMS	ARR87	UWS 2004	RAMS
24 hours	22.0	19.9	7.7	2	13	11
72 hours	28.9	28.2	13.4	1	10	7

The 24-hour composite results indicate that the model-derived curves have a broad rainfall maximum centred close to the middle of the rainfall burst. The timing of the modelled rainfall maximum is similar to that of UWS 2004 but the percentage of the highest temporal pattern is lower. Similar results are obtained for the 72-hour curves. This tendency towards a broad maximum, rather than distinct peaks, is possibly related to the model resolution. Even with a 5 km grid spacing the model is unable to represent the very intense periods of rainfall that constitute these peaks. The temporal characteristics for the Border sub-region (not shown) produce a peak percentage of total rainfall that is higher than that of the other sub-regions, indicating a proportionally more intense period of rainfall at this time. The temporal curves based on the model output are significantly different to those from ARR87. The Gold Coast region is represented by Zone 3 of ARR87 which covers the eastern coast of Queensland extending over 3000 km of coastline. In the derivation of ARR87 temporal patterns for Zone 3, only 10 pluviograph stations were used from this vast region with only one station from the Gold Coast area. It is possible that the stations distant from the Gold Coast experience different temporal patterns in extreme rainfall.

Composite curves were also calculated for the Brisbane and Border sub-regions. From an examination of these curves (not shown) it is obvious that the final result is sensitive to the choice of region chosen for the calculation of the curves. The Gold Coast sub-region used in this study is much smaller than the region used to identify the extreme rainfall events used by Rahman *et al.* (2005). Consequently, the Brisbane and Border sub-regions were combined to provide curves representative of a region similar to that used by Rahman *et al.* (2005). This combined sub-region from each model has been used to create the curves presented in Figure 20.

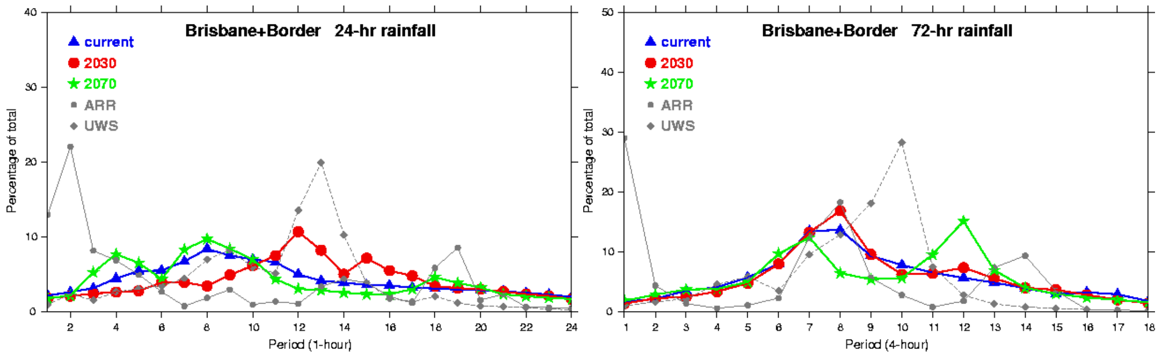

Figure 20: Composite temporal curves based on the CC-Mk2 and CC-Mk3 models for the combined Border and Brisbane sub-regions for 24-hour and 72-hour rainfall bursts.

A comparison of the 2030 and 2070 curves with those of the current climate suggests that the most intense period within a 24-hour rainfall burst is likely to occur earlier in the period than at present for the Gold Coast sub-region. Over the larger area the change in temporal pattern is less clear-cut with a later peak in the 2030 curve and an earlier peak in the 2070 curve.

The Gold Coast sub-region composite temporal curves for the 72-hour rainfall events show that the peak rainfall is likely to occur later in the future. A split peak is evident in the composite results for the combined Brisbane and Border sub-regions, with one peak occurring at a similar time to the current climate peak and a second peak developing later in the rainfall burst. This development of a split peak is consistent across both the CC-Mk2 and the CC-Mk3 models for both the Brisbane and Border sub-regions.

These results are consistent with the findings of Abbs (1999) and Zhou *et al.* (1997). Both studies examined the sensitivity of modelled extreme rainfall events to increases in the availability of atmospheric moisture, which may be expected in a warmer world. Their results show that as moisture availability is increased, the period of heavy rainfall (rainfall rates > 25 mm hr^{-1}) begins earlier and is more continuous.

5. CONCLUSIONS

This report presents the results from a series of dynamical downscaling simulations designed to identify future changes in the intensity and frequency of extreme rainfall events affecting the Gold Coast region of south-east Queensland. The work builds on the Abbs *et al.* (2006) study for other regions of Australia.

The downscaling provides a good qualitative and quantitative representation of the spatial distribution of extreme rainfall in the region, with high rainfall regions occurring close to the coast and along the higher terrain of the Gold Coast hinterland. Daily rainfall totals in excess of 500 mm occur in the observations and the model is able to capture these. It also captures the 3-day totals that exceed 800 mm.

Key findings from the study are:

- Climate change is likely to result in an increase in 24-hour and 72-hour rainfall extremes for a large region that includes the McPherson Range. With time, the spatial extent of this area of increase enlarges and the intensity-change maxima therein increase to more than 40% relative to the current climate. 2-hour rainfall events show much larger projected changes, with the largest changes occurring in the high terrain inland from the Gold Coast. These regions of rainfall increase also increase in spatial extent with time. The 2-hour rainfall events have average increases in intensity of more than 70% in these regions.
- There is good agreement on a future increase in extreme rainfall events in the McPherson Range and the Great Dividing Range west of Brisbane and the Gold Coast, especially for the 2-hour and 24-hour events. Intensification of the 72-hour events is also likely, although there is less agreement in this result. There is high agreement on decreases in the intensity of 24-hour and 72-hour extreme rainfall events in the hinterland north of Brisbane and the coastal regions of northern New South Wales for 2030. By 2070, the regions of likely decreases in extreme rainfall intensity have almost disappeared and most regions are likely to experience an increase in the intensity of extreme rainfall events. The region of highest agreement on this aspect includes the McPherson Range and the Great Dividing Range, stretching from the New South Wales border to the north of Brisbane, thus including the catchment areas for all rivers and streams flowing into the Gold Coast region.
- Depth-area curves for the Gold Coast region show that area-averaged increases in extreme rainfall intensity are predicted for areas less than 1000 km^2 for 24-hour events for both 2030 and 2070. Area-averages for 2-hour events show a small increase. A small increase for 72-hour events is indicated for 2030 but the sign of change for 2070 is unclear.
- Return period curves for the intensity of modelled 24-hour events in the Gold Coast region show good agreement with the observations, but return levels for 72-hour accumulations are underestimated. Climate change is likely to produce an increase in extreme rainfall for durations of 2 hours, 24 hours and 72 hours. Work is currently in progress to use extreme-value statistics to convert the results from this modelling study into the more meaningful average recurrence intervals used by the hydrological community. These results will be reported as an Addendum to the current report.
- A comparison of the 2030 and 2070 temporal curves with those of the current climate suggests that the most intense period within a 24-hour rainfall burst is likely to occur earlier in the period than at present for the Gold Coast region. Peak rainfall in 72-hour events is likely to occur later in the future. This result is consistent with those of previous studies (Abbs, 1999; Zhou *et al.,* 1997) that

found that as atmospheric moisture availability is increased, the period of heavy rainfall (rainfall rates > 25 mm hr^{-1}) begins earlier and is more continuous.

A major limitation of this work, especially for the study of coincident extreme wind and rain events, is that it uses output from the CC-Mk3 model, in which tropical cyclones are not well represented. It is likely that this is also true of the CC-Mk2 model. This problem with the CC model has now been "fixed" and that model now produces a good climatology of tropical cyclone occurrence in the Australian region (see Abbs *et al.,* 2006). Unfortunately the problem was not discovered until the high resolution modelling reported on herein was completed. Tropical cyclones are a relatively rare occurrence in the Gold Coast region and it is unlikely that the absence of these events in the model output described here has a major impact on the conclusions as they relate to extreme rainfall as other events such as east coast lows are represented by the models. However, it is possible that it will impact conclusions relating to coincident rain/wind events and is likely to be the reason for the absence of a significant storm surge in the Part 3 modelling for this study (McInnes, private communication). In an effort to overcome this problem, the revised CC-Mk3 simulation will be examined for tropical cyclones impacting southern Queensland and these events will be downscaled and the results used to supplement the events used for Part 3 of the study.

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References

Abbs, D. J., 1999: A numerical modeling study to investigate the assumptions used in the calculation of probable maximum precipitation. *Water Resour. Res.,* **35**, 785-796.

Abbs, D.J., and K.L. McInnes, K. L. 2004: The impact of climate change on extreme rainfall and coastal sea levels over south-east Queensland. Part 1, Analysis of extreme rainfall and wind events in a GCM. A project undertaken for the Gold Coast City Council, CSIRO Atmospheric Research. 48 pp.

Abbs, D.J., 2006: The atmospheric model component of the Relocatable Ocean Atmosphere Model – report on tasks 3, 5 and 6. Report prepared for the Royal Australian Navy as part of the BLUElink project. CSIRO Marine and Atmospheric Research.
(see http://www.cmar.csiro.au:8000/e-print/open/abbsdj_2006c.pdf)

Abbs, D. J., S. Ayral, E. Campbell, J.L. McGregor, K.C. Nguyen, M. Palmer, A.S. Rafter, I.G. Watterson, and B. Bates, 2006: Projections of extreme rainfall and cyclones. Final report to the Australian Greenhouse Office. CSIRO Marine and Atmospheric Research. 97pp.
(see http://www.cmar.csiro.au:8000/e-print/open/abbsdj_2006b.pdf)

Doswell, C.A., III, H.E. Brooks and R.A. Maddox, 1996: Flash flood forecasting: an ingredients based methodology. *Wea. Forecasting,* **11,** 560-581.

Gordon, H. B., L.D. Rotstayn, J.L. McGregor, M.R. Dix, E.A. Kowalczyk, S.P. O'Farrell, L.J. Waterman, A.C. Hirst, S.G. Wilson, M.A. Collier, I.G. Watterson and T.I. Elliott, 2002: The CSIRO Mk3 Climate System Model. CSIRO Atmospheric Research Technical Paper No. 60. CSIRO Atmospheric Research. 130 pp.

Hennessy, K. J., K.L. McInnes, D.J. Abbs, R.N. Jones, J.M. Bathols, R. Suppiah, J.R. Ricketts, A.S. Rafter, D. Collins, and D. Jones, 2004: Climate change in New South Wales. Part 2, Projected changes in climate extremes. Consultancy report for the New South Wales Greenhouse Office. CSIRO Atmospheric Research. 79 pp.
(see http://www.cmar.csiro.au/e-print/open/hennessy_2004c.pdf)

Institution of Engineers, Australia (I. E. Aust.), 1987: Australian Rainfall and Runoff: A Guide to Flood Estimation. Book IV, I. E. Aust., Canberra.

IPCC, 2000: *Special Report on Emissions Scenarios.* A special report of Working Group III of the Intergovernmental Panel on Climate Change. Nakićenović, N and R. Swart (Eds.). Cambridge University Press, UK. 570pp

IPCC, 2001: *Climate Change 2001: The Scientific Basis.* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.). Cambridge University Press, UK. 944 pp.

IPCC, 2007: Summary for Policymakers. 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* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 18pp.

McInnes, K.L., G. Hubbert, D.J. Abbs and S. Oliver, 2002: A Numerical Modelling Study of Coastal Flooding. *Meteorol. Atmos. Phys*., **80**, 217-233.

Pilgrim, D.H., I. Cordery, and R. French, 1969: Temporal patterns of design rainfall for Sydney, Institution of Engineers, Australia, Civil Eng. Trans., **CE11**, 9-14.

Rahman, A., S. M. Islam, K. Rahman, S Khan and S Shrestha, 2005: A Windows-based program to derive design rainfall temporal patterns for design flood estimation. In Zerger, A. and Argent, R.M. (eds) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2005, pp. 170-176.
(see http://www.mssanz.org.au/modsim05/papers/rahman_a.pdf)

Walsh, K. J. E., W.J. Cai, K..J. Hennessy, R.N. Jones, K.L. McInnes, K.C. Nguyen, C.M. Page, and P.H. Whetton, 2002: *Climate change in Queensland under enhanced greenhouse conditions: final report, 2002*. Aspendale: CSIRO Atmospheric Research. 84 p.
(see http://www.cmar.csiro.au/e-print/open/walsh_2004a.pdf)

Zhao, W., J.A. Smith and A.A. Bradley, 1997: Numerical simulation of a heavy rainfall event during the PRE_STORM experiment. *Water Resour. Res.,* **33**, 783-799.