# The Effect of Climate Change on Extreme Rainfall Events in the Westernport Region

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A report prepared for the study “Impacts of Climate Change on Human Settlements in the Western Port Region: an Integrated Assessment”

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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, as a result of flooding, in the highly urbanised regions along Australia's coastline. 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 this in turn can increase the 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 Westernport region of Victoria. 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).

This study uses the output from the cubic conformal atmospheric model (CCAM). This is a regional climate model that utilises a stretched grid on 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, CCAM was nudged towards the CSIRO Mark 3 SRES A2 simulation. Mark 3 has a horizontal grid spacing of approximately at 1.85°× 1.85°. Herein, this CCAM simulation will be referred to as CC-Mk3. Extreme rainfall days simulated by the CC-Mk3 model 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 30-minute and 1, 2, 3, 6, 12, 24, 48, 72 and 96-hour rainfall maxima for each event. The analysis reported herein concentrates on the maximum rainfall falling within the 2, 24 and 72-hour periods.

Key findings from the study are:

1. The CC-Mk3 model is able to simulate the weather conditions, and their likelihood of occurrence, conducive to summertime extreme rainfall in the region. However, we have found that this model does not produce the correct climatology of wintertime extreme rainfall.

2. Climate changes simulations based on climates representative of 2030 and 2070, show that there is considerable spatial variation in the pattern of extreme rainfall increase and the magnitude of that increase across the study region. The largest increases in extreme rainfall intensity occur over the Mornington Peninsula and along the Bass Strait coastline. These projections have been constructed for an annual basis, however, these results should be used with care, due to the inability of CC-Mk3 to capture the climatology of extreme rainfall events in winter in this region.

3. Each of the catchments shows an increase in the magnitude of future extreme rainfall events and the size of this increase is greater in 2070 than in 2030.

4. The largest increases occur for the short duration events, with increases of 10-20% projected for the 2-hour events by 2030. In general, decreases are projected for the longer durations in 2030. By 2070, all catchments are projected to experience increases, on average, in extreme rainfall intensity for each of the durations considered. These increases may be more than 60% in some locations for the short duration events and up to 30-40% for the 24-hour and 72-hour events.

5. It is difficult to draw in robust conclusions related to the impact of climate change on the temporal pattern of extreme rainfall events. This study suggests a tendency for the rainfall to occur earlier in the burst for the 72-hour and 96-hour patterns. These results are consistent with the findings of Abbs (1999) and Zhou *et al.* (1997).

The production of the return period curves has highlighted the need to employ more rigorous statistics to both the observations and the model outputs so that they may be more readily compared and changes inferred both quantitatively and qualitatively. Work is currently in progress to use extreme value statistics so that future climate change projections apply to a defined ARI (such as the 1-in-100 year event) rather than the mean value used here

These dynamical downscaling techniques are also being used to downscale other climate models for this region and thus it will be possible to consider the uncertainty due to different models in future studies.

# 1. INTRODUCTION

In Australia, flooding causes the most damage of all natural disasters and each year extreme rainfall events cause significant damage, as a result of flooding, in the highly urbanised regions along Australia's coastline. 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 this in turn can increase the 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.

This study draws upon the results described in Abbs *et al.* (2006) in which downscaling of extreme rainfall events was undertaken for 3 distinct regions – (1) South-east Queensland and northern New South Wales, (2) the central coast of New South Wales and (3) Victoria and the southern Murray-Darling Basin. This report presents an analysis of possible changes in extreme rainfall for the Westernport region of Victoria based on the high-resolution downscaling study for Region 3 of the Abbs *et al.* (2006) study.

The remainder of this report is set out as follows. Chapter 2 presents some recent climate change projections of changes in extreme rainfall over the Australian continent and provide some background on dynamical downscaling and the climate models used. Chapter 3 describes the synoptic climatology of extreme rainfall events affecting the Westernport region and assesses how well the models represent these events. The modelling study is described in Chapter 4. The methodology, configuration and initialisation of the atmospheric model are discussed and the observational data and results from the downscaling simulations are presented in this chapter. This chapter also quantifies the effect of climate change on extreme rainfall events affecting the Westernport region. Chapter 5 provides a summary and discussion of the results.

# 2. BACKGROUND

The most recent climate change projections for Australia are presented in CSIRO and Australian Bureau of Meteorology (2007) while Macadam and Ricketts (2008) present projections for the study region.

Projections for changes in extreme daily rainfall for Australia for events with a recurrence interval of 5 years and 100 years are presented in Figure 1 for 24-hour rainfall events based on the outputs from 5 simulations using CSIRO climate models forced with the A2 emissions scenario.

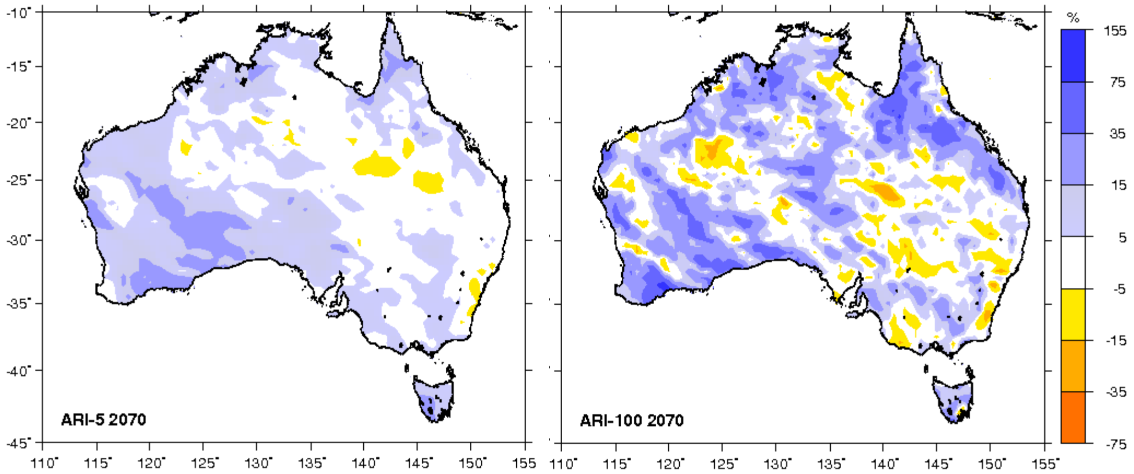


Figure 1: Projected fractional change for 2070 in 24-hour extreme rainfall events with a recurrence interval of (left) 5 years and (right) 100 years. The maps are based on the outputs from 5 simulations using CSIRO climate model forced with the A2 emissions scenario.

These results are based on application of extreme-value statistical techniques to the output of each of the models. The results shown are the median value of the fractional change for the 2070 (2050-2090) climate relative to the current (1960-2000) climate. The results indicate significant increases in extreme rainfall intensity for northern Australia and coastal Queensland. In the southeast of the continent the projected changes are for smaller increases or decreases in extreme rainfall intensity. The projected changes for the Port Phillip Bay and Westernport regions are for increases of approximately 10% in the intensity of both the 5-year and 100-year rainfall events. For most locations, the projected increase in intensity of extreme rainfall events is greater for the more intense (100-year) events than for the 5-year events.

However, more detailed modelling (Abbs *et al.*, 2006) shows that even in regions in which extreme rainfall is projected to decrease on the average, localised areas of increase may occur. The results presented above are based on the results from 5 climate model simulations. The coarsest of these simulations have grid cells measuring 200 × 200 km while the finest simulations have grid cells of 65 × 65 km. Extreme rainfall 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 being designed to last for decades to come. The technique that is used to provide these projections is “Dynamical Downscaling”

Dynamical downscaling uses a hierarchy of climate models to focus in on the region of interest with increasing levels of detail. In this study, the finest detail (4 km spacing) is provided by the Regional Atmospheric Modelling System (RAMS). RAMS is "nested" in CSIRO's Conformal Cubic Atmospheric Model (CCAM) which has been forced by outputs from CSIRO's Mark 3 (Mk3) Atmosphere-Ocean Global Climate Model (GCM). A more detailed discussion of this aspect of the downscaling study is provided in Section 4.1. Mk3 has been used to simulate the climate from 1961 to 2100 under an SRES A2 greenhouse gas emissions scenario (IPCC, 2000). Mk 3 has a horizontal grid spacing of approximately at 1.85°× 1.85° and has 18 levels in the vertical. CCAM is a global model but 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 the lower resolution is on the opposite side of the earth. 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 weighted heavily towards the solution of a GCM of uniform resolution. The cubic conformal model simulations considered in this study had their highest resolution, of approximately 60 km, centred on Australia (see Figure 2). Outside this region, the CCAM model solutions were nudged towards those of Mk 3. Herein this CCAM simulation will be referred to as CC-Mk3.

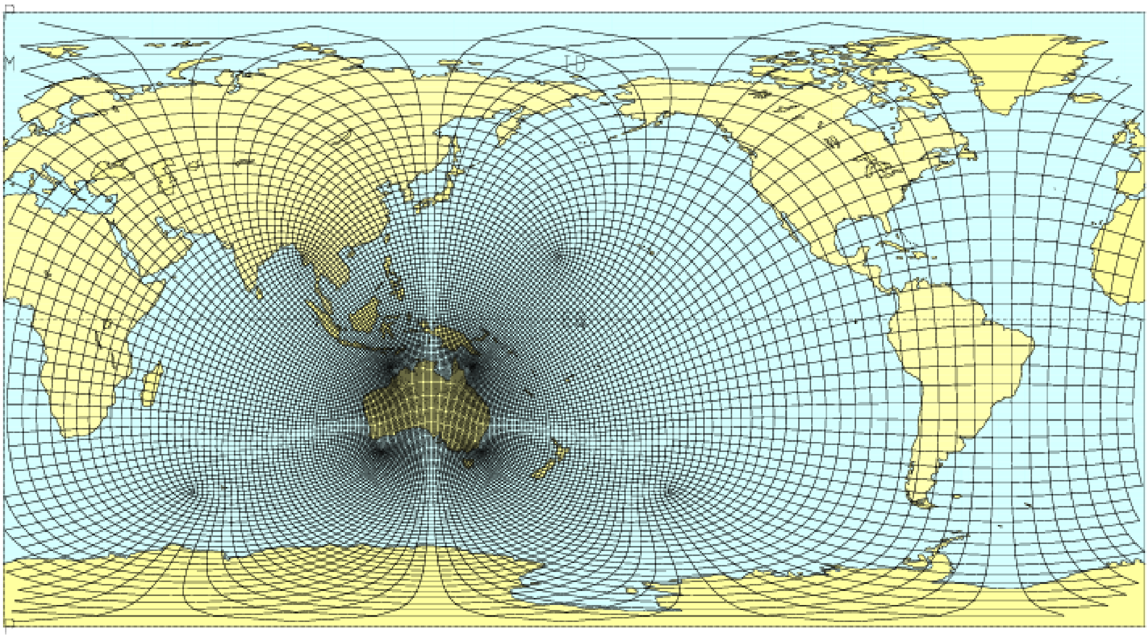

Figure 2: Diagram illustrating the stretched grid of the cubic conformal model.

# 3. SYNOPTIC CLIMATOLOGY OF EXTREME RAINFALL EVENTS AFFECTING THE WESTERNPORT REGION

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. 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 Comparison with observed extreme rainfall and the impact of climate change.

Daily rainfall observations from the Commonwealth Bureau of Meteorology (BoM) have been extracted for the Victoria and the lower Murray-Darling Basin 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 maximises the number of stations that were available for analysis on each day and also maximises 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. It should be noted that these data are 24 hr accumulations for the period ending at 9:00 a.m. on each day rather than 24 hour totals such as those that may be obtained from a continuously recording rain gauge. This means that if 200 mm of rainfall fell between 3:00 p.m. of day 1 and 9:00 a.m. of day 2 and 300 mm fell between 9:00 a.m. and mid-day of day 2 then the observational dataset would record daily rainfall data of 200 and 300 mm for two consecutive days rather than a 24-hour value of 500 mm. Thus there is the potential to underestimate the observed rainfall maxima for some locations.

### 3.1.1 Synoptic climatology of observed extreme rainfall events

Abbs *et al.* (2006) discuss the synoptic climatology of extreme rainfall events affecting Victoria and the lower Murray-Darling Basin region using the techniques described in Appendix 1. Those techniques have been used to classify the weather events associated with extreme rainfall in the Westernport study region. The "observations" used in this analysis are daily rainfall observations from the (BoM) and daily, gridded mean sea level pressure (MSLP) analyses obtained from the NCEP reanalysis dataset. Extreme rainfall events were chosen by identifying those days on which at least 50 mm of rainfall occurred at one location or more within the study region. Small thunderstorms were removed from the record by requiring that at least 10% of the region's rainfall stations recorded at least 17mm of rainfall during the day. The resultant dataset was further examined to ensure that the days selected were the maximum rainfall days from individual events rather than being days within a multi-day event.

#### *Summer*

There are 3 main synoptic types associated with extreme summer rainfall events in this region and composites of these types are presented in Figure 3.

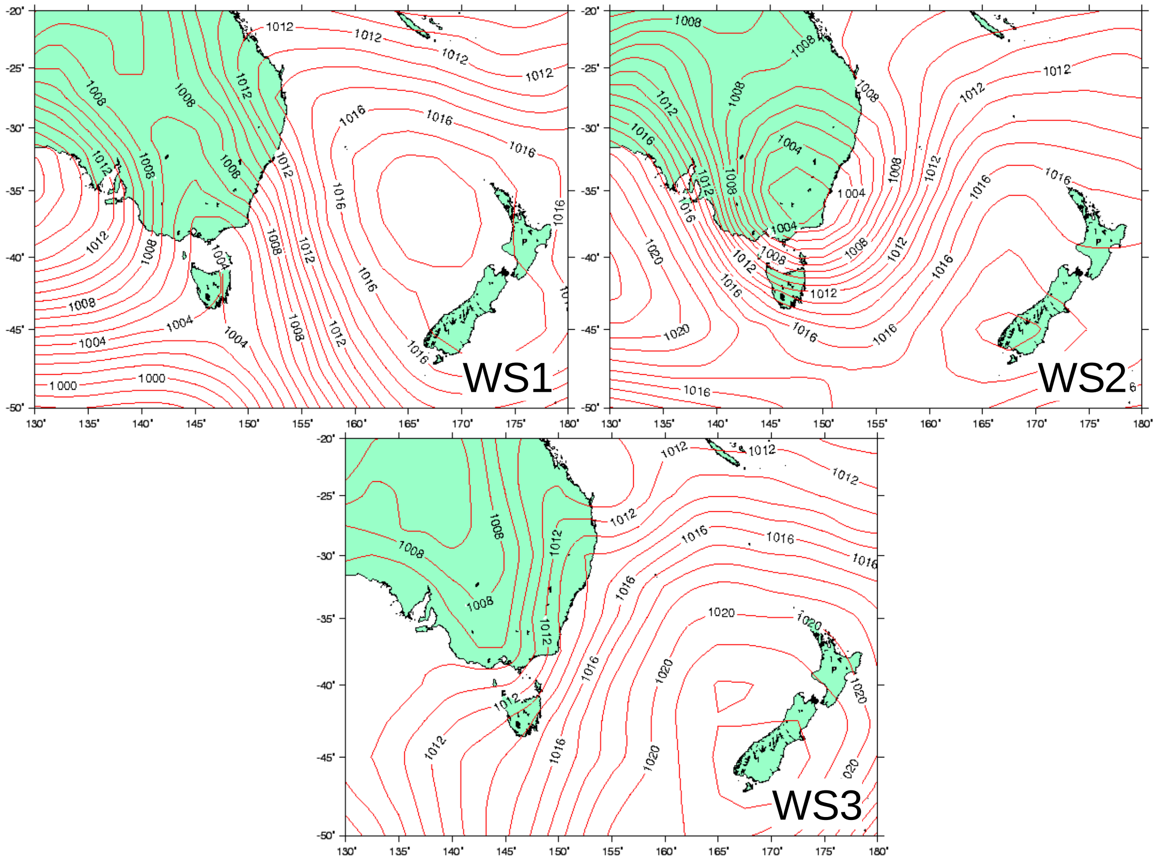


Figure 3: Composite MSLP fields for the synoptic types associated with extreme summer rainfall in the Westernport region. Type 1 (WS1) systems account for 45% of events, type 2 (WS2) for 39% and type 3 (WS3) for 16% of summer events.

Type 1 (WS1) events are characterised by a cold front at the surface that is crossing, or has recently crossed, eastern Victoria. The majority of Type 1 events are characterised by anomalously high moisture values that are transported into the region from north western Australia over the previous days. A smaller number of these events are accompanied by lower moisture values at the surface, with the highest moisture anomaly occurring over the Tasman Sea. Types 2 events (WS2) are associated with a cut-off low at the surface that is accompanied by either a deep trough or a cut-off low at upper levels. In these cases, warm moist air from north eastern Australia and/or the Coral Sea is transported into the study region, with the highest moisture values occurring to the east of the study region. The Type 3 (WS3) events are characterised by a southward incursion of the monsoon trough into Victoria. This acts to transport warm, moist air into the region. All types are accompanied by strong ascent over the region.

### *Winter*

The synoptic types that result in extreme winter rainfall in this region are presented in Figure 4.

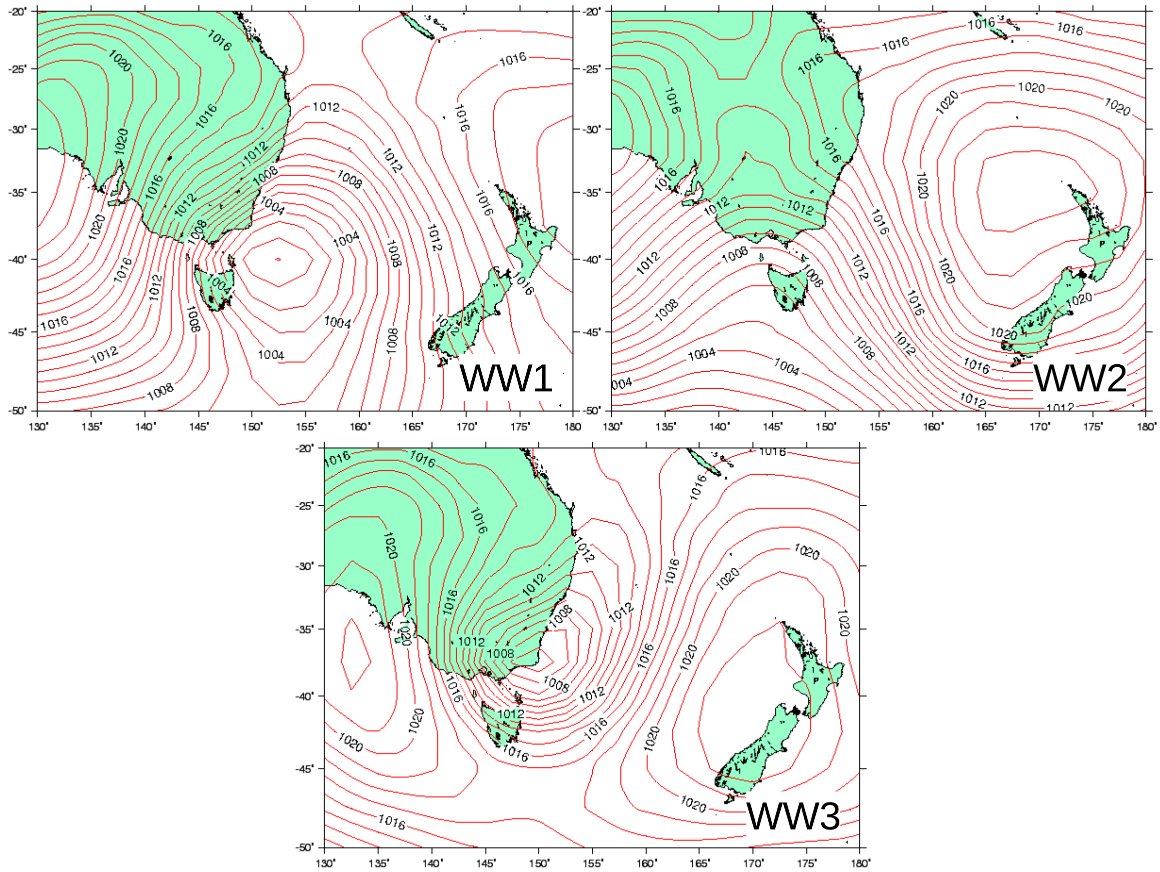


Figure 4: Composite MSLP fields for the synoptic types associated with extreme winter rainfall in the Westernport region. Type 1 (WW1) systems account for 51% of events, type 2 (WW2) for 24% and type 3 (WW3) for 22% of events. 2% of events are unclassified.

Extreme winter rainfall in this region is most commonly due to a cut-off low-pressure system in the Tasman Sea. The Type 1 (WW1) systems form when a trough in the mid-latitude westerlies amplifies and “pinches-off” to form a cut-off circulation in Bass Strait that moves into the

Tasman Sea. These lows are accompanied by relatively modest levels of atmospheric moisture and ascent. The Type 3 (WW3) systems are predominantly east coast lows. These lows form at, or close to, the east coast of Australia and are often accompanied by strong winds, sometimes of hurricane force. They are characterised by transport of moisture from the Coral Sea into the Tasman Sea and very strong ascent in the Tasman. The Type 2 (WW2) events are associated with a mid-latitude trough or cold front. The surface trough is accompanied by above-average moisture values and a core of ascending motion that passes across Victoria during the period of heavy rainfall.

### 3.1.2 Synoptic climatology of modelled events and the impact of climate change

The extreme rainfall days selected from the CC-Mk3 dataset have been classified into the synoptic types determined for the observations. The method used is described in Appendix 1 and the results from the analysis are presented in Table 1. In this section, the frequency of occurrence of extreme rainfall for each synoptic type, based on the modelled rainfall, is compared with that based upon the observations and described above.

For the summer half years, CC-Mk3 has a relatively good representation of the synoptic weather systems that are associated with extreme rainfall over the Westernport region. It has a tendency to over-estimate the proportion of monsoon trough (summer Type 3) events and under-estimate the proportion of cut-off lows. The modelled frequency of cold frontal systems associated with heavy rainfall is well represented. Overall, there is a tendency for high rainfall events to increase in frequency, rising from 59 events in the current climate period to 83 events in 2070. The model climate suggests that in 2070, more summer extreme rainfall events will be due to cold fronts than at present, while the contribution of cut-off lows will decrease. There is no consistent signal in likely changes to the frequency of monsoonal troughs.

Table 1: The number of summer & winter extreme rain days corresponding to each synoptic class for the Westernport region. Values are expressed as a percentage of the total number of rain days selected for the model interval.

| **Summer** | | | | | **Winter** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Type | Obs | CC-Mk3 Control | CC-Mk3 2030 | CC-MK3 2070 | Type | Obs | CC-Mk3 Control | CC-Mk3 2030 | CC-Mk3 2070 |
| Type 1. *Cold Front* | 45 | 41 | 39 | 54 | Type 1. *Tas. Low* | 51 | 1 | 0 | 0 |
| Type 2. *Cut-off low* | 39 | 29 | 28 | 23 | Type 2. *Cold Front* | 25 | 71 | 63 | 70 |
| Type 3. *M'soon trough* | 16 | 22 | 28 | 19 | Type 3. *ECoast Low* | 22 | 10 | 14 | 10 |
| Un-class. | 0 | 8 | 5 | 6 | Un-class. | 2 | 18 | 24 | 20 |
| No. of days | 43 | 59 | 60 | 83 | No. of days | 49 | 83 | 88 | 120 |

In contrast, the model's representation of the synoptic weather systems associated with winter extreme rainfall in the Westernport region is poor. The model under-estimates the contribution of cut-off lows to winter extreme rainfall in the region, while over-estimating that of cold-fronts. In addition, a high proportion of winter events were unclassified. Abbs *et al.* (2006) reached similar conclusions for extreme rainfall events affecting a much larger region of south eastern Australia. Further analysis in that study found that in CC-Mk3 most extreme rainfall events are due to a broad mid-latitude trough. Cut-off low-pressure systems do result in extreme winter rainfall in CC-MK3 but the frequencies of these events is less than the observed frequency. These findings agree with those of McInnes *et al.* (2005) who studied the weather patterns associated with extreme winds and storm surge along the east Victorian coastline. Their study also found that the CC-Mk3 model underestimates the frequency of cut-off low patterns and overestimates that of mid-latitude troughs. Other studies by Abbs and McInnes (2004) and Hennessy *et al.* (2004) have suggested that the relatively poor performance of the CC-Mk3 model in winter is related to the Mark 3 global model from which it obtains its boundary forcing.

The Mark 3 global model has been found to have a more zonal global pressure pattern, relative to observations, leading to more frequent westerly winds along the south coast of Australia. This is thought to be related to a cool bias in temperatures off the east coast of the continent. However, despite improved spatial resolution and the correction of the cool bias in the CC-MK3 model, the model performance has not improved significantly for these extreme weather events. It appears that the boundary forcing provided by the Mark 3 model dominates the synoptic patterns that evolve in the higher resolution CC-Mk3 model. Due to the poor representation of CC-Mk3 synoptic types for this region, it is not possible to make any conclusions related to possible changes in the frequency of extreme rainfall weather systems for winter.

# 4. MODELLING OF EXTREME RAINFALL EVENTS

## 4.1 Background

RAMS has been used to downscale extreme rainfall days simulated by the regional climate model CCAM. RAMS is a high-resolution, compressible, non-hydrostatic model. The physical processes represented by the model include an atmospheric boundary layer, soil and vegetation effects, long and short wave radiation, and the complex cloud processes that result in precipitation (ice, liquid and water vapour). RAMS is a suitable tool for the simulation of extreme rainfall events and has previously been used to model the extreme rainfall events described in Abbs(1999) and McInnes *et al.* (2002). A full description of RAMS and validation of the model for the current configuration is presented in Abbs (2006).

## 4.2 Model Configuration and Initialisation

The extreme rainfall events identified from the CC-Mk3 output have been downscaled, with a grid spacing of 4 km for the study region shown in Figure 5 – hereafter this region will be referred to as Vic-SNSW. In the simulations discussed here the numerical model has been initialised using output from the CC-Mk3. Three levels of interactive grid nesting were used; the outer grid had a spacing of 48km with the middle and finest resolution grids having horizontal grid spacings of 16 km and 4 km respectively. The terrain used on all model grids was interpolated from the Geosciences Australia 9 second digital elevation model. The vegetation was obtained from a USGS 30 second dataset. The sea surface temperatures were interpolated from the CC-Mk3 output. This configuration is similar to that used in the extreme rainfall simulations of Abbs (1999) and McInnes *et al.* (2002). The domain and terrain used for the 4-km grid is shown in Figure 5.

In the simulations discussed here RAMS has been initialised using output from CC-Mk3 after first identifying the most intense CC-Mk3 rainfall events occurring in the study region for the “current” climate (1960-2000), the “2030” (2010-2050) and “2070” (2050-2090) climates. 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.

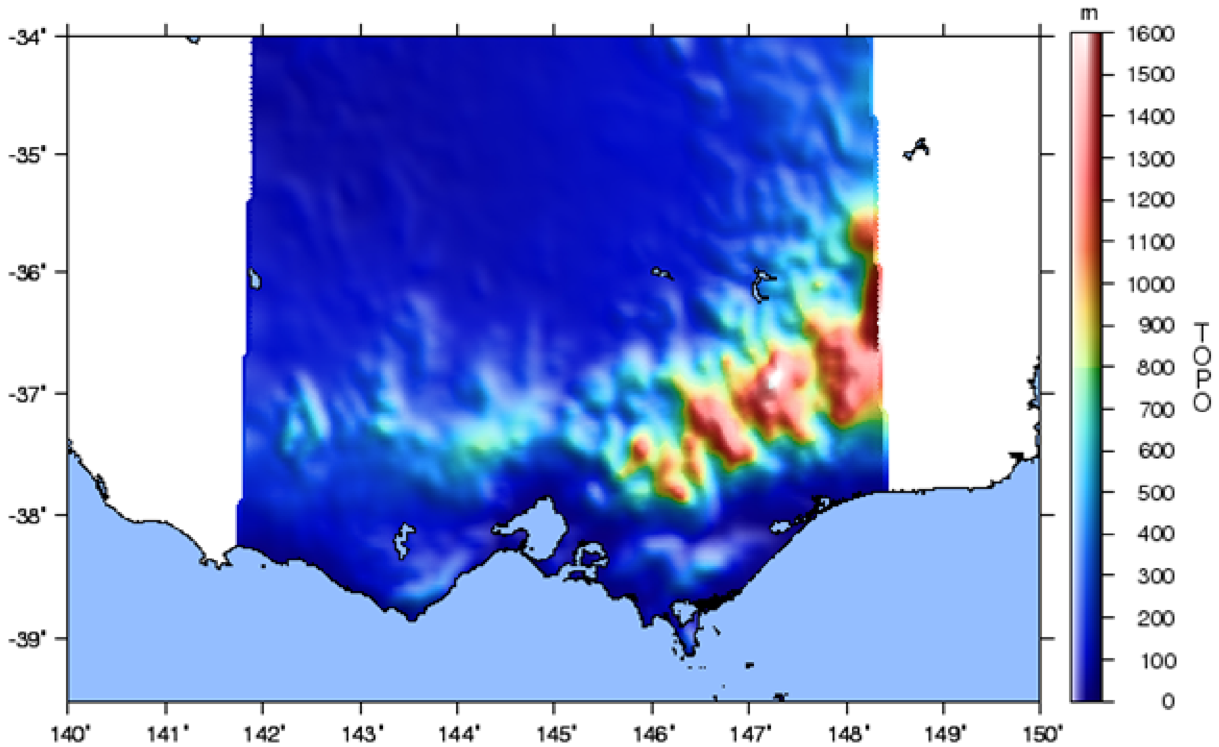


Figure 5: High resolution model domain and terrain used in this study.

Each case 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 30-minute and 1, 2, 3, 6, 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 and have been supplied for the hydrological component of the project. At least one hundred events were simulated for 40-year time slices representative of the current (1960-1999), 2030 (2010-2049) and 2070 (2050-2089) climates. Previous experience has shown that this sample size is large enough for robust results to be obtained and for these to be representative of current-climate extreme rainfall events.

## 4.3 Dynamic downscaling of extreme rainfall

For each time slice, the 100 extreme rainfall cases identified in earlier sections of the study have been dynamically downscaled using the methodology described above. An analysis of the modelled rainfall from these simulations is compared with that based on the observed rainfall. For each rain gauge station in the Vic-SNSW region, the daily rainfall time series has been sorted and the ten heaviest rainfall events in the 40-year period identified.

The most extreme rainfall event for each BoM rain gauge station in the Vic-SNSW region is plotted in Figure 6(a) and shows the preferred regions for extreme rainfall occurrences to be in the mountainous regions west of Melbourne, along the Great Dividing Range and along the coastline of east Gippsland. There is a relative lack of observations along the Great Dividing

Range but daily rainfall events greater than 200 mm day$^{-1}$ have been recorded there and in east Gippsland.

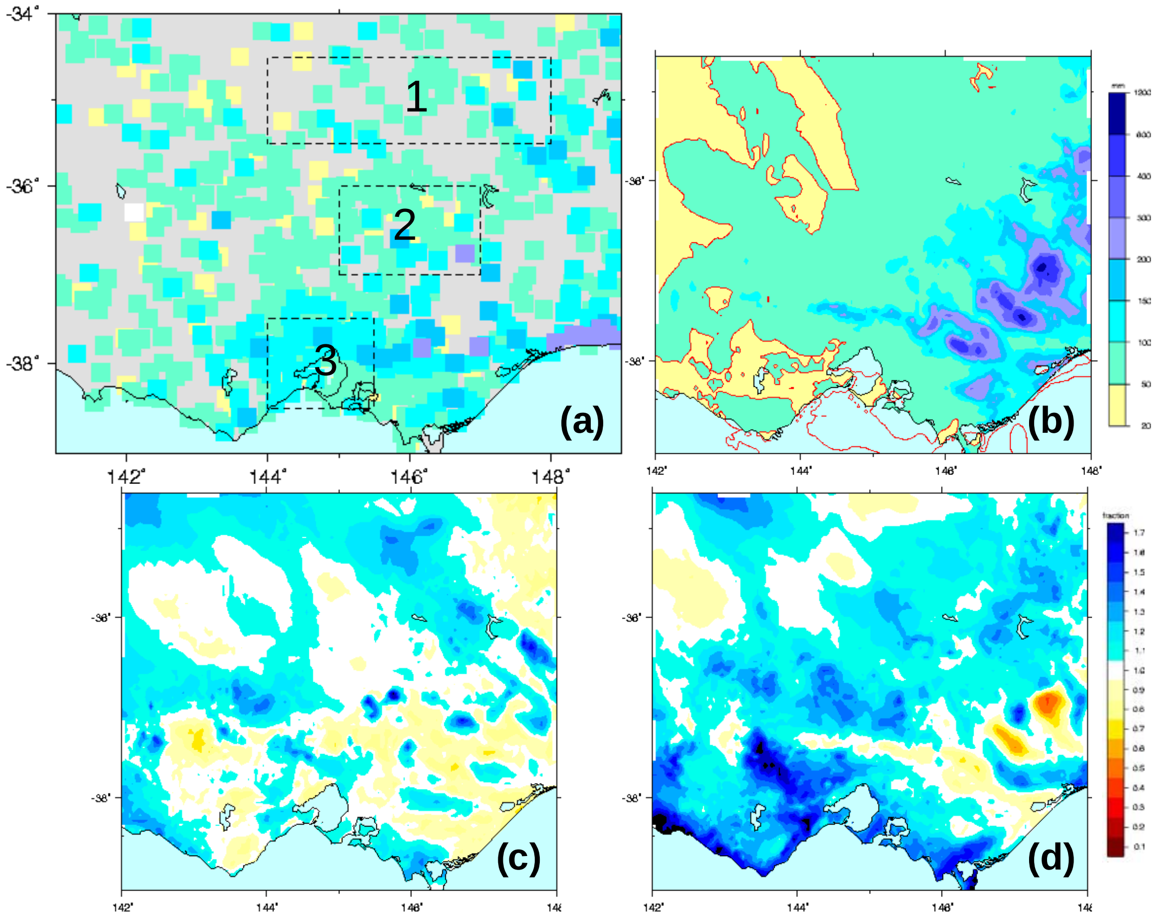


Figure 6 (a) Observed most extreme rainfall event for each location for the period 1960-1999, (b) the most extreme 24-hour rainfall event simulated from the population of 100 current climate events, (c) the average change in the intensity of the rank 1-10 extreme rainfall events for 2030 and (d) for 2070. In (a), sub-regions 1-3 are the Murrumbidgee, Goulburn and Melbourne regions referred to in Abbs *et al.* (2006).

A similar spatial pattern can be seen for the simulated extreme events shown in Figure 6(b) although larger simulated extremes occur on the highest mountains of the Great Dividing Range. There is also a secondary maximum along the Gippsland coastline. The downscaling study has not captured the higher rainfall region to the west of Melbourne and the rainfall amounts in the west of the study region are too low. It is quite likely that this deficiency is related to the preponderance of frontal systems in the model climatology compared to cut-off lows combined with the rain-shadow effect caused by the locally high terrain of the Otway Ranges.

## 4.4 Effect of climate change

### 4.4.1 Spatial patterns of projected changes

The following analysis concentrates on the 10 most extreme events, at each model grid point, 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 6(c) for the 2030 events and in Figure 6(d) for the 2070 events.

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.

There is considerable spatial variation in the projected change in the intensity of rainfall extremes, however, in this region the characteristics of the pattern of change differs to that found in other studies such as those over southeast Queensland - northern NSW and the Central Coast of New South Wales (Abbs *et al*., 2006) In the Vic-SNSW region the impact of terrain differs, as these results do not show a coherent and relatively large increase in extreme rainfall events over the mountainous terrain – extreme rainfall shows a slight decrease in these areas. Small increases occur over the plains of south western New South Wales with slightly larger increases occurring on the western and northern flanks of the Great Dividing Range. The largest increases in extreme rainfall intensity occur along the coastline of southern Victoria and west of Melbourne.

The projected patterns of change for the 2, 24 and 72 hour events for 2030 and 2070 are shown in Figure 7. Of the three event durations considered, the 2-hour rainfall events show the largest projected changes with the largest changes along the Mornington Peninsula and Bass Strait coastlines in the study region. The magnitude of the projected rainfall increase for the short duration events increases from 20% in these areas in 2030 to up to 60% by 2070.

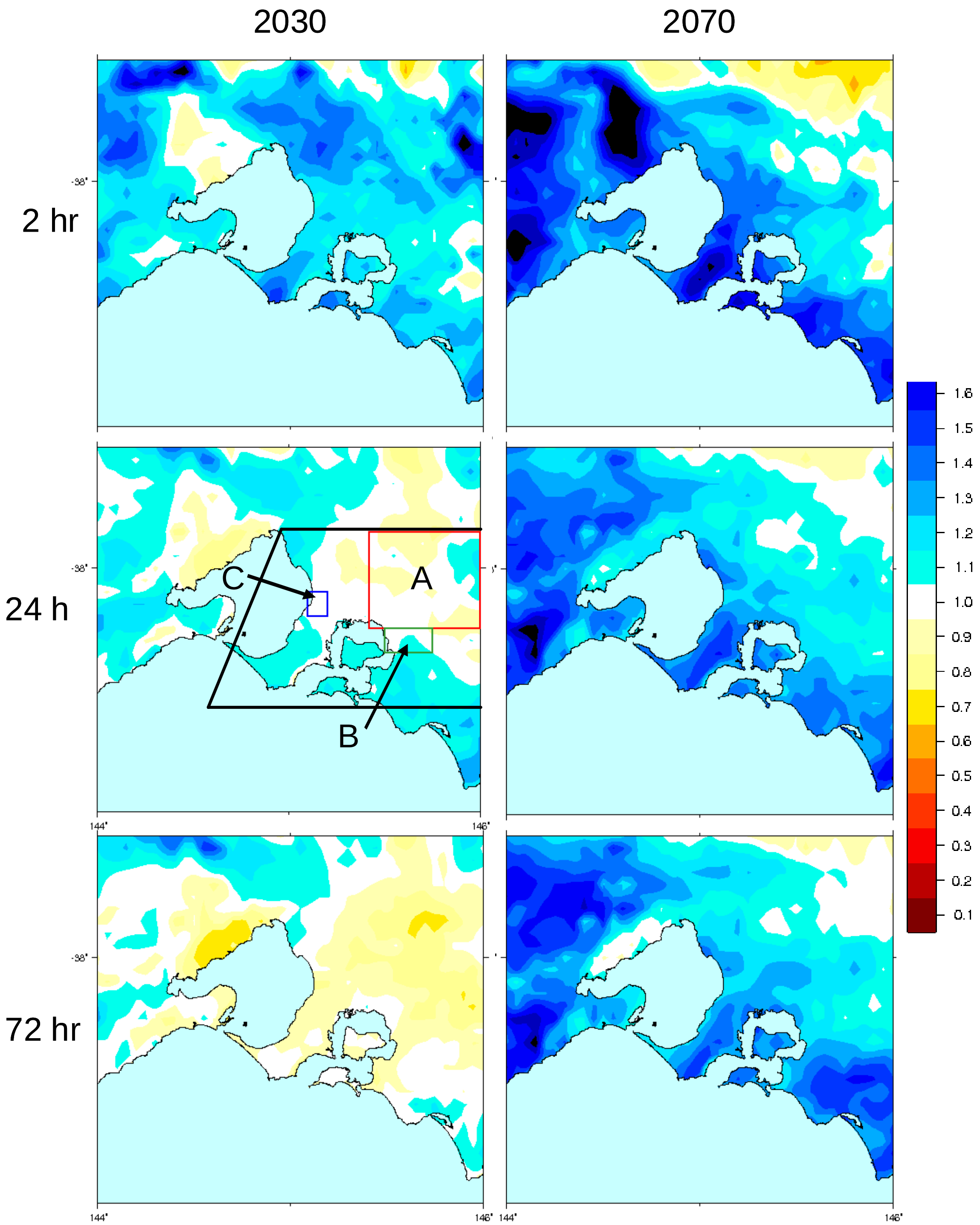


Figure 7: Average fractional change in accumulated rainfall for 2030 and 2070 for extreme rainfall events of 2, 24 and 72 hours. The sub-regions labelled as A, B and C refer to the Bunyip, Lang Lang and Lee-Sandgate catchments used in the later analyses. The land points contained in the black quadrilateral define the Westernport region used in the calculation of the temporal curves.

The projected changes for the longer duration rainfall events are mixed. Twenty-four hour events are projected to increase in intensity along the Mornington Peninsula and Bass Coast parts of the region by 2030 but the remainder of the region is projected to experience no change or a small decrease in extreme rainfall intensities. The 72-hour events are most likely to experience a decrease in rainfall intensity by 2030. By 2070, increases in rainfall intensity are projected for the entire study region with the greatest increases occurring over the Mornington Peninsula and Bass Strait coast.

### 4.4.2 Return periods curves

Return period curves are a convenient way of presenting changes in extreme rainfall for a location. The return period curves presented in Figure 8 have been derived by identifying maximum rainfall accumulations in a time slice for each sub-region/catchment (shown on Figure 7) from each simulation. Thus the return period curves are representative of a catchment rather than a specific location. Curves for individual locations are not presented. Observations are not included on these figures, but Abbs *et al.* (2006) concluded that the modelling techniques used here were able to capture adequately the statistics of extreme rainfall events for their Melbourne sub-region which includes the Westernport study region. Lower intensity events in the Melbourne region were under-estimated by approximately 10mm in that study. The results for all catchments indicate increases in the intensity of extreme rainfall events for 2030 and 2070.

In an effort to provide a single, representative figure for likely changes in the intensity of extreme rainfall events in each catchment, mean percentage changes in extreme rainfall intensities for each catchment are presented in Table 2. These results are based on all grid points within the 3 regions shown on Figure 7 for the results presented in Figure 7. The largest increases occur for the short duration events, with increases of 10-20% projected for the 2-hour events by 2030. In general, decreases are projected for the longer durations in 2030. By 2070, all catchments are projected to experience increases, on average, in extreme rainfall intensity for each of the durations considered. These increases may be more than 60% in some locations for the short duration events and up to 30-40% for the 24-hour and 72-hour events.

Table 2: Average percentage change in extreme rainfall intensity for each of the catchments of the Westernport study region. The range corresponds to the 10th and 90th percentile values of all grid points within the catchment.

| Duration (hrs) | Region | 2030 | | 2070 | |
|---|---|---|---|---|---|
| | | Median | Range | Median | Range |
| 2 | *Bunyip* | 19 | -7 - 96 | 9 | -11 - 36 |
| | *Lang Lang* | 10 | 3 - 23 | 18 | 8 - 25 |
| | *Lee-Sandgate* | 20 | 7 - 29 | 40 | 35 - 63 |
| 24 | *Bunyip* | -4 | -19 - 20 | 13 | -1 - 38 |
| | *Lang Lang* | 3 | -11 - 11 | 17 | 9 - 29 |
| | *Lee-Sandgate* | 0 | -4 - 5 | 27 | 18 - 43 |
| 72 | *Bunyip* | -16 | -29 - 5 | 13 | -4 - 42 |
| | *Lang Lang* | -9 | -15 - 0 | 20 | 4 - 33 |
| | *Lee-Sandgate* | -14 | -17 - -10 | 24 | 17 - 38 |

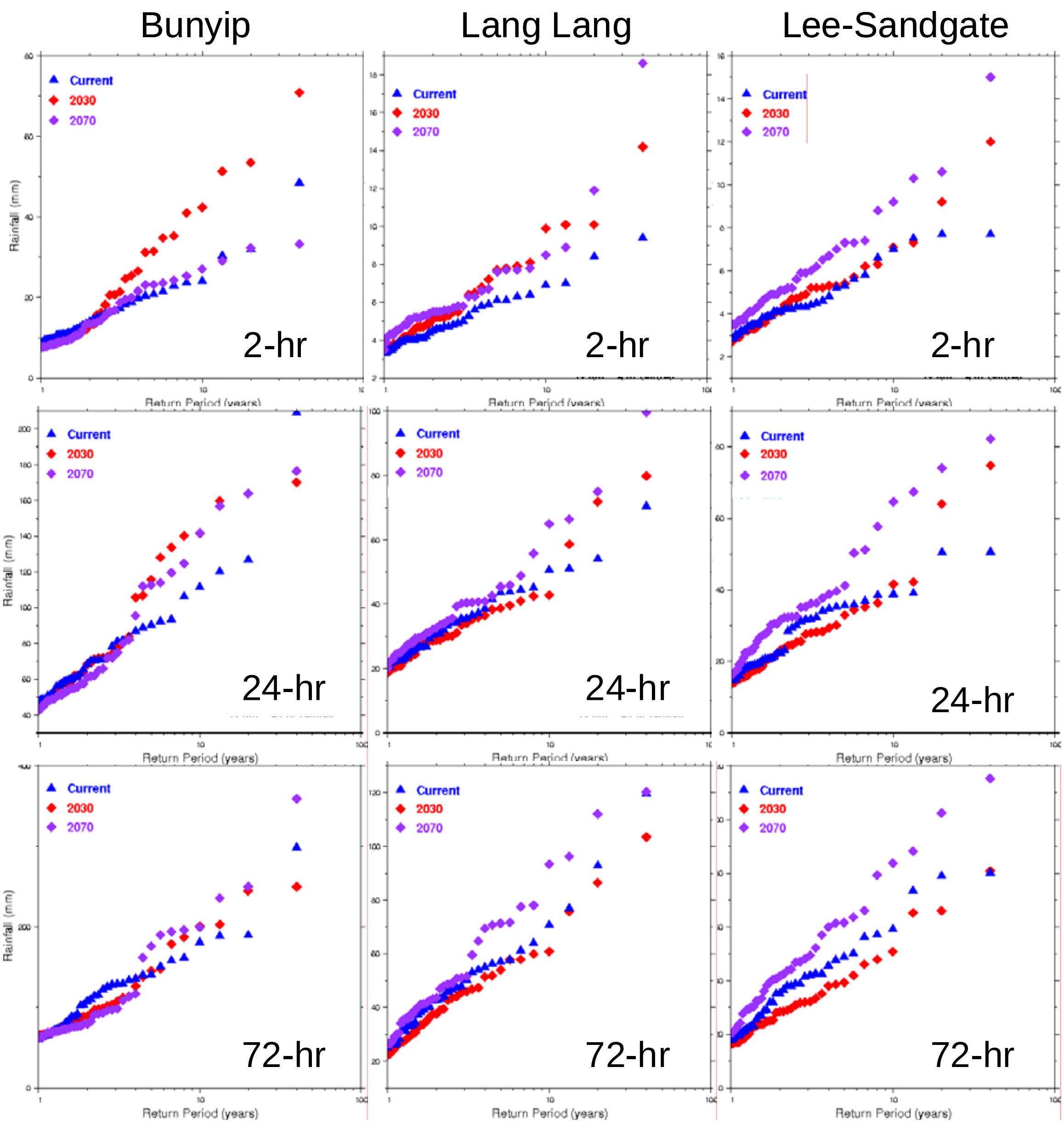


Figure 8: Return period curves for the 3 catchments for each of the downscaled experiments for (left) 2-hour, (centre) 24-hour and (right) 72-hour rainfall accumulations.

### 4.4.3 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) 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 various rainfall durations of 3, 6, 12, 24, 48, 72 and 96 hours.

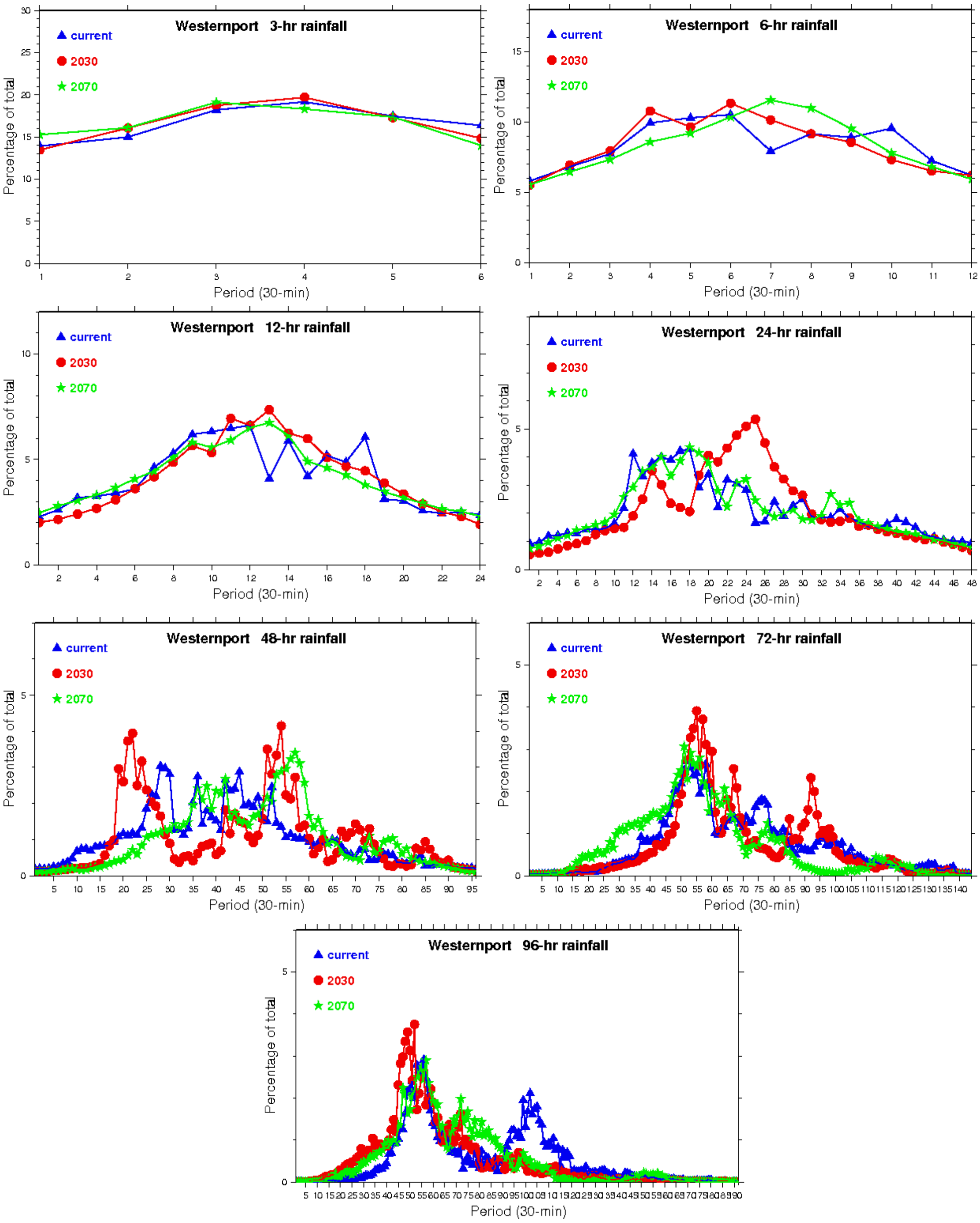


Figure 9: Temporal curves for the Westernport region based on downscaled results from the CC-Mk3 model.

The 30-minute model rainfall archive is too coarse to identify any temporal variability for shorter duration events and so these were not considered. As in Rahman *et al.* (2005), rainfall bursts were selected by identifying those bursts with intensity greater than 90% of the 1-year

ARI value for a given duration. The method has been applied to the rainfall events for the entire Westernport region, rather than the individual catchments as it was found that the small catchments (Lang Lang and Lee-Sandgate) produced temporal curves that were very noisy. The temporal patterns derived using these methods are presented in Figure 9.

The results indicate that the model-derived curves have a broad rainfall maximum centred close to the middle of the rainfall burst for rainfall durations of 12 hours or shorter. For longer durations, the timing of the modelled rainfall maximum tends to occur in the first half of the rainfall burst. For the 96-hour bursts a split peak is evident, with the greatest percentage of rainfall occurring during the first peak and a smaller amount occurring in the second peak. It is difficult to draw in robust conclusions related to the impact of climate change on the timing of extreme rainfall events, although the split peak has either disappeared, or decreased in magnitude, in the future-climate, long-duration events. For the 72-hour and 96-hour events there is a tendency for the rainfall to occur earlier in the burst. 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 begins earlier and is more continuous.

# 5. DISCUSSION & FUTURE WORK

In this section we have identified the synoptic-scale weather systems that are conducive to extreme rainfall for the Westernport region of Victoria. The results from that analysis has been used to determine the ability of the CC-Mk3 model to simulate these events and their likelihood of occurrence. We have found that CC-Mk3 is able to simulate the weather conditions, and their likelihood of occurrence, conducive to summertime extreme rainfall in the region, however, we have found that this model does not produce the correct climatology of wintertime extreme rainfall. This finding concurs with other studies such as those of Abbs and McInnes (2004), Abbs *et al.* (2006) and McInnes *et al.* (2005). Previous studies by Abbs and McInnes (2004) and Hennessy *et al.* (2004) have suggested that this relatively poor performance is related to the Mark 3 global model from which CC-Mk3 obtains its boundary forcing. The Mark 3 global model has been found to have a more zonal global pressure pattern, relative to observations, leading to more frequent westerly winds along the south coast of Australia. Despite improved spatial resolution and the correction of the cool bias in CC-MK3, the model performance has not improved significantly for these extreme weather events and it appears that the boundary forcing provided by the Mark 3 model dominates the synoptic patterns that evolve in the higher resolution CC-Mk3 model. It is suspected that this is most likely due to the use of wind nudging toward an interpolation of the large-scale fields from Mark 3.

This study, and those of Abbs and McInnes (2004) and Hennessy *et al.* (2004), has illustrated the value of using synoptic typing, or similar techniques, as a measure of climate model skill. If a climate model is unable to reproduce the observed distribution of synoptic scale weather events for the current climate then any projections or downscaling based on that model for future climates should be used with care. Research is continuing aimed at refining these synoptic typing techniques and at creating new methods that will objectively identify cut-off low-pressure systems.

The CC-Mk3 model has provided the initial and boundary forcing for high-resolution (4 km grid spacing) downscaling over the study region. In general, these high-resolution simulations have been able to represent the spatial distribution of extreme rainfall realistically and the magnitude of the extremes is close to observed.

Climate changes simulations based on climates representative of 2030 and 2070, show that there is considerable spatial variation in the regions of extreme rainfall increase and the magnitude of that increase. In the study region, the largest increases in extreme rainfall intensity occur over the Mornington Peninsula and along the Bass Strait coastline. However, these results should be used with care, due to the inability of CC-Mk3 to capture the climatology of extreme rainfall events in winter in this region.

It is interesting that the downscaled RAMS simulations are so good given the systematic failure of CC-Mk3 to accurately capture the synoptic scale weather systems, especially in winter. Extreme rainfall in the study region is most often associated with cut-off low-pressure systems. As discussed earlier, neither CC-Mk3 nor its parent Mark 3 model produce enough of these events. A possible reason for the good performance of the model is that although the CC-Mk3 model does not reproduce the climatology of cut-off lows it still does produce cut-off lows. These systems are likely to be the stronger systems associated with high rainfall amounts, thus affecting the high return period portion of the model-derived curves. In addition, most of the extreme rainfall signal is related to the orography. This signal is well represented in these high-resolution simulations and is able to be captured through the use of an atmospheric model with numerics and physics suitable for the simulation of extreme rainfall events.

Return period curves have been created for three catchments in the study area. A previous study has shown that return period curves derived from the model output for the Melbourne region are close to the curves based on observed rainfall. Each of the catchments shows an increase in the magnitude of future extreme rainfall events and the size of this increase is greater in 2070 than in 2030. The short duration events are projected to experience greater increases in intensity than the longer duration events.

The production of the return period curves has highlighted the need to employ more rigorous statistics to both the observations and the model outputs so that they may be more readily compared and changes inferred both quantitatively and qualitatively. Work is currently in progress to use extreme value statistics so that future climate change projections apply to a defined ARI (such as the 1-in-100 year event) rather than the mean value used here

These dynamical downscaling techniques are also being used to downscale other climate models for these 3 regions and thus model uncertainty may be considered in future studies.

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# APPENDIX 1: SYNOPTIC TYPING

The pressure patterns associated with extreme rainfall and wind days are analysed to determine the synoptic-scale weather patterns that are conducive to the extreme weather conditions in the study region. The technique used is known as synoptic typing and follows the method of Yarnal (1993). This is a correlation-based, gridded map-typing technique in which days are grouped based on the Pearson product-moment correlations $r_{xy}$ to establish the degree of similarity between map pairs. Similar fields are identified on the basis of similar spatial structures (i.e. highs and lows in similar positions) with little emphasis on the magnitude of the patterns.

To establish a synoptic climatology compatible with the output from the climate models, this technique was first applied to NCEP 00 UTC MSLP fields valid for the extreme rainfall days for the study region. These fields were extracted for the 81 points (9×9) in the region between 140 and 165°E and 35 and 20°S. These fields were further divided in summer (Nov-Apr) and winter (May-Oct) series. The following steps were then applied to both the summer and winter datasets.

In this procedure, each daily MSLP grid is first normalised:

$$Z_i = \frac{x_i - \overline{X}}{s} \qquad (1)$$

where $Z_i$ is the normalised value of grid-point $i$, $x_i$ is the observed value at grid-point $i$, $\overline{X}$ is the mean of the $N$ -point grid and $s$ is the standard deviation of the grid. The effect of this normalisation is to eliminate the seasonal impact on pressure pattern intensity, thus permitting direct inter-seasonal map comparisons.

Once normalised, Pearson product-moment correlations $(r_{xy})$ are used to compare each daily map pattern in the extreme rainfall subset with all other maps in the subset.

$$r_{xy} = \frac{\sum_{i=1}^{N}\left[\left(x_i - \overline{X}\right)\left(y_i - \overline{Y}\right)\right]}{\sqrt{\sum_{i=1}^{N}\left(x_i - \overline{X}\right)^2 \sum_{i=1}^{N}\left(y_i - \overline{Y}\right)^2}} \qquad (2)$$

In this formula, $x_i$ and $y_i$ represents the variable at each of the $N$ grid points of the two maps being compared. $\overline{X}$ and $\overline{Y}$ represent the means of the $N$ -point grids. Pairs of MSLP maps are considered similar if $r_{xy} \geq 0.7$. Yarnal (1993) discusses the numerous sources of subjectivity in choosing a correlation threshold. The value of 0.7 was chosen after experimentation showed that it provided an acceptable balance between the number of patterns produced and the number of days that were not classified.

Once all days have been compared with all other days in the dataset, the day with the largest numbers of $r_{xy}$ values meeting the threshold criteria is designated "key day" 1 and is considered representative of the first map type. This "key day' as well as all the days with which it is considered to be similar on the basis of the correlations are then removed from the analysis. All days deemed to be similar to each of those days are also removed. The analysis is then repeated with the reduced dataset to find "key day 2", and so on, until all days are classified into $m$ groups of 3 days or more. The remainder are considered unclassified.

Once the "key days" are established, a second pass over the entire data set is made. This is necessary because it is possible for any grid to be significantly correlated with more than one grid. In this step, each map pattern is assigned to the map pattern represented by the "key day" for which it produces the highest correlation. A second pass was also made over the unclassified days so that days that had a relatively high correlation value could be classified into the most appropriate synoptic type. A correlation threshold of 0.5 was chosen for this step.

After the typing procedure was completed for the observed days of extreme rain or wind using the NCEP re-analyses, the gridded MSLP patterns corresponding to the extreme rainfall days from the CC-Mk3 model over the 1961 to 2000 period were extracted and correlated against the observed "key days" to determine how realistically the model captured the weather patterns associated with the extreme events. The extreme rain days for the two 40-year periods representing 2030 (2011-2050) and 2070 (2051-2090) were then correlated against the observed synoptic types for the respective variable to determine whether the frequency of the synoptic situations change with global warming.

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