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

by

D. J. Abbs and K.L. McInnes
CSIRO Atmospheric Research

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**Important Disclaimer**

This report relates to climate change scenarios based on computer modelling. Models involve simplifications of the real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO for the accuracy of projections in this report or actions on reliance of this report.

Address for correspondence

Deborah Abbs  
CSIRO Atmospheric Research  
PMB No 1, Aspendale, Victoria, 3195  
Telephone (03) 9239 4660  
Fax (03) 9239 4444  
E-mail Deborah.Abbs@csiro.au

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Executive Summary

Flooding due to severe rainfall can be exacerbated if downstream water levels are elevated due to wind generated storm surge and wave setup. An understanding of the degree to which extreme rain and wind events overlap is required if effective flood plain modelling is to be carried out. Furthermore, knowledge of the possible future changes in the nature of extreme rain and wind events and their coincidence is necessary for long-term flood plain management.

This report presents results from the first stage of a project undertaken for the Gold Coast City Council to investigate the incidence and overlap of extreme rainfall and wind events over southeast Queensland and examine how such events may vary under future global warming. Results focus on extreme rainfall events over south-east Queensland in the observational records, extreme winds over the adjacent ocean in gridded re-analysis data sets, the synoptic weather conditions associated with the extreme events and the degree to which wind and rain events coincide.

The aim of this project has been to assess how well three climate model simulations are able to capture the weather conditions associated with extreme rainfall and wind under current climate conditions. This is a necessary step before more detailed modelling can proceed, as it identifies the strength and weaknesses of the underlying model so that the possible impact of future global warming can be assessed. The best performing models are used to examine how these weather conditions change by 2030 and 2070.

Background

Recent climate projections for south-east Queensland indicate increases in annual temperature in the range 0.3 to 1.7°C by 2030 and average annual rainfall changes tending towards decreases, with large associated uncertainty. Extreme daily rainfall however, is projected to increase by between 10 and 20% by 2030 over southeast Queensland with the mountainous areas that are currently prone to rainfall extremes, experiencing the largest increases. A study of extreme rainfall events in the CSIRO Mark 3 GCM using a dynamical downscaling technique ascertained that the 1 in 40 year event under current climate conditions became a 1 in 15 year event by 2040.

Extreme rainfall events

Extreme rainfall events were selected from rain gauge data east of 150°E and between 25 and 29°S on the basis that at least 100 mm fell in a single 24-hour period and was embedded in a three-day total of at least 250 mm. This selection criterion was devised to select events that occurred as part of longer-lived larger scale synoptic weather patterns rather than the heavy, short-lived rainfall produced by severe thunderstorms and squall lines. The selected events were most common in the first six months of the year with the highest occurrence of events in January to March.

For the summer half-year from November to April, five key synoptic weather patterns were identified. Synoptic type 1 is characterised by a high-pressure system to the south east of the continent that acts to produce a large area of onshore northeasterly flow into the study region. Type 2 is an inland monsoonal trough that acts to transport warm moist onshore flow onto the southeast Queensland coast. In many cases the Type 3 and 4 patterns are associated with a tropical cyclone that is moving southwards slightly offshore from the coast. The Type 5 pattern is a cut-off low in the Tasman Sea and is accompanied by an extensive region of high atmospheric moisture content.
The synoptic weather patterns responsible for extreme summer rainfall and their relative frequencies.

The distribution of the synoptic types as a function of rainfall total (below left) indicates that the Type 1 synoptic situation is dominant in almost all rainfall classes for which events occur. The exception is a single high rainfall event of between 700 and 750 mm that was due to a Type 2 synoptic pattern. Type 5 events were found to be associated with lower rainfall totals of between 100 and 200 mm. The highest percentage of coincident days occurs for rainfall totals of between 100 and 200 mm. The frequency distribution for extreme rain events that coincide with extreme wind events (below right) shows that a small proportion of the total Type 1 events coincide with extreme winds. On the other hand, Type 3 events, comprising a much smaller percentage of heavy rainfall days overall, are much more likely to be associated with extreme winds. In the 300-500 mm rainfall range, there is greater likelihood of extreme winds occurring. Above 500 mm of rain, no overlap with extreme winds occurs.

Frequency of the five summer synoptic types as a function of rainfall totals (left) and the frequency of summer rainfall events that overlap with extreme wind events (right).

Of the two synoptic patterns identified for extreme winter-rainfall events, the Type 1 pattern produces widespread, heavy rainfall in both southeast Queensland and northern New South Wales. The heaviest rainfall totals occur in the mountainous coastal areas.
north and south of Brisbane and in the high terrain west of Coffs Harbour. The Type 2 pattern produces widespread heavy rainfall with the heaviest rainfall events occurring in the coastal ranges to the north and south of Brisbane.

The synoptic weather patterns responsible for extreme winter rainfall and their relative frequencies.

The distribution of the rainfall synoptic types as a function of rainfall total for winter indicates that the Type 1 synoptic situation is dominant in almost all rainfall classes for which events occur. Type 2 events are associated with lower rainfall totals of between 100 and 250 mm. The frequency distribution for extreme rain events that coincide with extreme wind events (below right) shows that although fewer heavy rain days occur in winter compared to summer, a higher proportion of these days coincide with extreme wind days and nearly all coincide with Type 1 events for winter. As with summer, there is no overlap with extreme winds for rainfall events of 500 mm or above.

Frequency of the two winter synoptic types as a function of rainfall totals (left) and the frequency of winter rainfall events that overlap with extreme wind events (right).

The analysis of output from the climate models showed that CC-Mk2 was able to capture the climatology of extreme rainfall and extreme wind weather events affecting southeast Queensland. The analysis also identified possible changes in frequency of these severe weather events, resulting from climate change. The results show that the 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 southeast Queensland. Between 20 and 50% of Type 1 rainfall days occur with extreme winds. Coincident wind and rainfall events associated with the Type 1 category show an 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 wind and rainfall events show a decrease in frequency under future climate conditions. These conclusions are based on the analysis of a single model, thus it is impossible to estimate the uncertainty associated with these conclusions. Ideally, outputs from other climate models should be examined to minimise the uncertainty associated with these results.

The results from this analysis, consideration of the uncertainties associated with climate change, ongoing research within CSIRO, and the authors’ understanding of the data needs for flood modelling have led to the following recommendations for future stages of this project.

In Stage 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 changes in frequency, magnitude and direction.

These recommendations allow the following tasks to be completed in Stage 2 of the project.

- Model the population of extreme rainfall and wind events identified in Stage 1 using the RAMS atmospheric model to derive high spatial and temporal resolution rainfall and wind information.
- Analyse the model output to derive estimates of the intensity-frequency curves for durations of 1, 3, 6, 12, 24, 48 and 72 hours.
- Analyse the model output to derive estimates of the depth-area curves for durations of 1, 3, 6, 12, 24, 48 and 72 hours.
- Analyse the model output to derive the temporal patterns for the severe rainfall events.
- Compare the statistics of the current climate simulations with the statistics derived from observed storms.
- Estimate the change in these quantities for the future climate.
- Use the model output to derive a refined analysis of the return periods of extreme rainfall and storm surge heights and their joint probability.

In Stage 3:
6. Increases in sea level due storm surge and wave set-up in the Broadwater, associated with the range of possible extreme wind events to be determined through hydrodynamic and wave modelling to provide a range of plausible tail water boundary conditions to apply to flood modelling.
1 Introduction

The Gold Coast and Broadwater region of southeast Queensland contains large areas of developed flood plain spanning several catchments including the Nerang, Coomera, Pimpama and Albert/Logan and is at risk of flooding during extreme 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.

However, 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. For any particular rainfall event, the downstream boundary condition will depend on tidal and wind conditions (wind speed and direction) and the choice of suitable boundary condition is largely a statistical problem. However, some weather events will be more conducive to the generation of both extreme rainfall and adverse wind conditions than others. In this study, the synoptic rainfall and wind conditions that affect southeast Queensland are investigated under current and future climate conditions. The rainfall and wind events are investigated in terms of the associated synoptic weather conditions and the degree to which the events are likely to coincide.

To investigate the possible changes in extreme rainfall and wind events under future climate conditions, the performance of three climate model simulations is assessed in terms of their ability to reproduce the frequencies of synoptic weather conditions identified in observations. The best performing models are then used to assess possible future changes to the nature of severe wind and rainfall events. The overlap between extreme rainfall and wind days is also investigated in terms of synoptic types and rainfall totals in the observations as well as the climate model simulation.

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 observational data and climate model simulations utilised in this study as well as outlining the synoptic typing procedure. Chapters 4 and 5 present the extreme rainfall and wind results respectively while in chapter 6 the coincident wind and rainfall events are analysed. Chapter 7 provides a summary of results and recommendations for future work.
2 Background

2.1 Uncertainties and climate change

Climate change projections are subject to 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.

In 1996, the IPCC began the development of a new set of emissions scenarios that attempt to account for 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 emissions and their evolution. These emissions scenarios are then used to calculate a corresponding concentration trajectory that in turn affects the radiative forcing of the atmosphere and thus affects 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 in the scenarios and different climate model sensitivities contribute similar amounts to the uncertainty in the range of global temperature change.

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

The development of climate change projections on a regional scale relies upon analysing as many Global Climate Models (GCM) and Regional Climate Models (RCM) as feasible to ensure that uncertainty due to the climate sensitivity inherent in different models is captured. For severe weather events, such as extreme rainfall and wind events, it is necessary to use daily model output to identify the event. However, daily model variables are not available for many of the GCM simulations to which there is general access. Thus, our studies of these phenomena are limited to the results from the CSIRO climate models at present. 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 from the techniques described here.

2.2 Recent climate change projections for southeast Queensland

The most recent climate change projections for Queensland are presented in Walsh et al (2002). For southeast Queensland, projected annual mean temperature increases range from 0.3 to 1.7°C for 2030. Temperatures are projected to increase in all seasons. In Brisbane, the number of summer days with temperatures over 35°C is projected to increase from its present average of 3 days to between 3 and 6 days by 2030. For both mean temperatures and extremes, much larger ranges of changes are projected for 2070. Projected changes in the sign of annual rainfall changes over southeast Queensland tend towards slightly negative, neutral or 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 climate model outputs, from 4 models, for the region east of 152°E and between 25° and 32°S. The results of that analysis are shown in Figure 1 for 2030.

This analysis shows that most models simulate an increase in extreme daily rainfall for the coastal regions of southeast Queensland, for all seasons except spring. These increases are larger further north, but in the region of the Gold Coast increases of between 10 and 20% are projected.

In a pilot study, Abbs (2004) has used high-resolution atmospheric modelling techniques to investigate possible changes in the intensity of extreme rainfall events in the region. In that study an atmospheric model with a grid spacing of 7.5 km was used to downscale a statistically representative sample of extreme rainfall cases (100 events) chosen from the CSIRO Mark 3 output for both the present climate (1960-2000) and the climate representative of 2040 (2020-2060).

An analysis of daily rainfall observations shows that the preferred locations for extreme rainfall occurrences are in the mountainous regions inland from Coffs Harbour, Coolangatta and north of Brisbane. In each locality, daily rainfall events greater than 500 mm day\(^{-1}\) have been recorded. A similar spatial pattern was found for the modelled
extreme events. A comparison of the rainfall intensities from the observations and the modelled extreme events shows that they are, in general, similar and the model was able to capture the extreme rainfall regions occurring near Coffs Harbour, Coolangatta and further north.

A similar analysis was conducted for the 2040 extreme rainfall events and the results from this analysis compared with the results for the current climate. The fractional change in extreme rainfall for the 2040 climate, compared with the current, shows considerable spatial variation. Averaged results for the top-10 most extreme events (Figure 2) show that the extreme rainfall events increase in intensity over the mountainous terrain but tend to decrease elsewhere. The largest increases in extreme rainfall intensity occur in the regions that currently experience the most extreme rainfall events. Average increases are between 20 and 40%. Decreases in extreme rainfall intensity are found for the low-rainfall-intensity areas of the domain and also for the coastal regions south of Cape Byron.

![Figure 2: Average projected fractional change in intensity for the top-10 most extreme rainfall events for 2040 relative to the current climate.](image)

Depth-area curves for each of the 100 current-climate and 2040-climate events were calculated and those curves combined to create domain representative 24-hour depth-area curves for the current and 2040 climates. The study found that areal-averaged rainfall intensity increases for areas less than 6000 km². These increases range from approximately 30% for the smallest areas to 15% for areas larger than 1000 km². For areas larger than 6000 km² there was no significant change in the average intensity of extreme rainfall events.

The most extreme events from the current and 2040 climate datasets were also used to determine return periods (Figure 3) for 24-hour grid-point rainfall. The return period curves represent changes in the frequency and intensity of extreme rainfall events for the domain, rather than for a particular location. This method was chosen as the population of events for an individual location is likely to be too small to provide a meaningful result, but for the entire domain there are 100 events to consider.
A comparison of the observations and the current-climate curve presented in Figure 3 show that the modelling study was able to capture the intensity of extreme rainfall events for return periods between 4 and 40 years. The 2040-climate curve shows that extreme rainfall events are projected to become both more intense and more frequent. The most extreme rainfall events are up to 30% more intense. The most extreme current-climate rainfall events will become more frequent, with the 1-in-40 year event of today corresponding with a 1-in-15 year event in 2040. The less intense events are not shown but they show a decrease in intensity for the climate of 2040 compared with the current climate.

Figure 3: Modelled return period curves for the current climate (triangles) and the climate of 2040 (diamonds). The return period curve based on the observed rainfall is also shown (stars).

2.3 Severe winds and elevated sea levels

Severe storms can produce temporary increases in sea-surface height. These increases may occur as a result of several different mechanisms such as wind setup, inverse barometer effect, current setup which may be considered collectively as the storm surge and wave effects such as wave setup and wave run-up. The relatively narrow continental shelf that flanks the southeast Queensland coast limits the size of storm surges due to wind driven effects (e.g. McInnes et al. 2000, 2001, 2002). However, an intense cyclone situated at the coast would elevate sea levels due to the inverse barometer effect. The narrow continental shelf on the other hand favours adverse wave conditions during severe storms since the deeper water off the coast allows larger waves to travel closer into shore before finally steepening, breaking and losing energy and height. Wave-breaking is a transient effect of storm conditions, whereas wave setup produces a temporary increase in still water conditions close to the coast and therefore can be considered to contribute to the overall inundation produced by the storms along with the surge and tide components.

McInnes et al. (2000) established return periods of sea levels (tide, surge and wave setup) in the Broadwater and found that the one in 100 year sea level varied from 2.1 ± 0.1 m at the Seaway entrance to 1.95 ± 0.10 m at the Coomera River. This study used a
Monte-Carlo approach to generate a population of plausible tropical cyclone and east coast low events and simulated their effect on water levels using a wave model and a hydrodynamic ocean model. The effect of climate change through increased storm intensity or sea level rise was not considered in this study. However, Walsh et al. (1998) provided sea level rise estimates for the Gold Coast of between 2-34 cm by 2030 with a central estimate of 11 cm and 3-58 cm by 2050 with a central estimate of 18 cm. An assessment of the impact of climate change on storm surge along the Queensland coast has recently been completed (e.g. Queensland Government; 2001).

While the two classes of weather system considered in the study of McInnes et al. (2000, 2002) as being the main cause of storm surges on the Gold Coast, a wider variety of weather systems contribute to large wave events (Allan and Callaghan, 1998). For the NSW coast, a study by PWD (1985) identified six synoptic situations leading to extreme sea levels along the NSW coast from manually drawn synoptic charts as follows:

- Anticyclones
- Easterly trough lows
- Inland trough lows
- Continental lows
- Tropical cyclones
- Secondary lows

The anticyclone events consist of an anticyclone in the southern Tasman Sea with onshore winds along the eastern seaboard. Easterly trough lows developed in an easterly trough situated at the coast, while inland trough lows formed over inland Australia and moved to the coast. Continental lows formed between anticyclones over the Indian Ocean or the Bight. The large number of synoptic classes, particularly in relation to lows, comes about because of the strong focus on the formation mechanisms and locations of the storm systems.
3 Data, Models and Methodology

The data set used for the analysis of extreme rainfall days is the daily rainfall data set maintained by the Australian Bureau of Meteorology. This dataset consists of daily rainfall records for stations throughout Australia. The length and quality of the rainfall record varies for each station. The methods for dealing with this variability are discussed below.

The data set used for the analysis of extreme winds is the National Centers for Environmental Prediction (NCEP) reanalysis data set. The NCEP reanalyses consist of the output of a global numerical weather prediction model into which all available global weather observations throughout the simulation period have been assimilated. The output of the model is dominated by the observations over the regions for which observations are available and provides a dynamically consistent representation of the weather conditions in data sparse parts of the globe. The 10 m winds from this data set are available in a gridded format at a horizontal resolution of approximately 1.9°×1.9° every six hours from 1958 to the present.

In the present study, the wind data are analysed on a once daily basis over the forty-year interval from 1961 to 2000. The use of once daily wind data is to align the analysis of observed winds with those of the climate model from which winds are available only once daily.

Mean sea level pressure (MSLP) data from this dataset have been used to characterise the synoptic scale weather systems that are conducive to either extreme rainfall or winds in the study region. The MSLP data are available in a gridded format at a horizontal resolution of approximately 2.5°×2.5° every six hours from 1958 to the present. In this study the MSLP data have been analysed twice daily for the extreme rainfall events. Specific humidity, vertical velocity and winds at 850, 700 and 500 hPa have also been analysed for the extreme rainfall days. These fields help identify the mechanisms that produce extreme rainfall in the region.

Three climate model simulations are considered in this study. They are CSIRO’s Mark 3 Atmosphere-Ocean Global Climate Model and the two regional models, CC-Mk2 and CC-Mk3. The CSIRO Mark 3 model (Gordon et al., 2002) has been used to simulate the climate from 1961 to 2100 under an SRES A2 greenhouse gas emissions scenario (IPCC, 2001). Mark 3 has a horizontal grid spacing of approximately 1.85°×1.85° and has 18 levels in the vertical. Winds and rainfall from this model have been archived at reduced space-time resolution and thus were available once daily at 3.75°×3.75° grid spacing. The CC or cubic conformal model (McGregor and Dix, 2001) 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 towards the solution of a GCM of uniform resolution. The cubic conformal model simulations considered in this study had their highest resolution, of between 50 and 60 km, centred on Australia (see Figure 1). 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). Once-daily rainfall totals and winds from these models were analysed.
Figure 4: Diagram illustrating the stretched grid of the cubic conformal model.

<table>
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<th>Centre</th>
<th>Model</th>
<th>Emissions Scenarios post-1990 (historical forcing prior to 1990)</th>
<th>Years</th>
<th>Horizontal resolution (km)</th>
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<td>1961-2100</td>
<td>~55</td>
<td>CC-Mk3</td>
</tr>
</tbody>
</table>

3.1 Rainfall Analysis

Bureau of Meteorology rain gauges located east of 150°E between 25° and 29°S are used to identify extreme rainfall events. The daily rainfall record based on these gauges is for the period 9:00 am on the preceding day to 9:00 am on the day of the record. On a site-by-site basis the daily rainfall record is variable both in length and quality. The stations considered in this analysis were required to have a record length of at least 15 years between 1960 and 2000, and the record was required to be at least 80% complete as identified by the “quality flag” for the station.

Daily rainfall records for stations that meet these criteria were used to create station time series for 1-day, 2-day, 3-day, 4-day and 5-day totals. A regional time-series was created by extracting the maximum rainfall that fell within the study region for each day. This was further sub-divided to create subsets for 1-day rainfall totals exceeding 100mm and 3-day totals exceeding 250 mm. A total of 612 1-day events that satisfied this criterion were identified over the forty-year period. 302 3-day events were identified. The 1-day and 3-day rainfall subsets were further analysed to identify days which contributed to 3-day totals in excess of 250 mm and in which at least 100 mm of rainfall occurred in the daily record. This analysis produced 291 days, approximately half of the 1-day subset. 96% of the 100 most-extreme 1-day rainfall events occurred in this final dataset. The seasonal distribution of events for both the 1-day and 3-day datasets was also determined.

A similar technique was used to analyse the extreme rainfall days from each of the climate models. Daily rainfall from each model was interpolated to a 0.5°×0.5° grid and 1-
day and 3-day totals calculated for each grid point. A regional time-series was then created for both the 1-day and 3-day events and the extreme rainfall days extracted from these time-series. The resulting subsets contained 612 1-day events and 302 3-day events (as in the observational datasets) with a seasonal distribution that was the same as that of the observations.

Thus the model data sets have been used to provide a set of extreme rainfall days based on the modelled rainfall. Modelled rainfall is very sensitive to the horizontal resolution of the parent model, and thus with a model grid spacing (eg. 1.85° × 1.85° in Mark 3) the model is unable to capture the small-scale convective processes that produce extreme rainfall. In reality, many extreme rainfall events are embedded within larger synoptic-scale systems such as east coast lows, monsoon depressions and mid-latitude frontal systems. These events are often associated with the “ingredients” conducive to extreme rainfall – high levels of atmospheric moisture; strong ascent, high time-averaged precipitation efficiency and they are long-lived. Weather systems such as these are captured by the global and regional scale climate models, and thus any change in their frequency and intensity may impact on the characteristics of extreme rainfall in a region.

The synoptic patterns associated with the climate model summer and winter extreme rainfall days were then determined for the current, 2030 and 2070 climates. The MSLP pressure pattern for each extreme rainfall day was first interpolated from the model grid to the 2.5° × 2.5° NCEP grid. The MSLP fields from each model were correlated with the MSLP grid for the “key days” identified in the synoptic typing (see Section 3.3) of the observational dataset for the appropriate season. The extreme rainfall days were classified into the synoptic type with the highest correlation above a threshold of 0.5. This analysis provides a measure of the number of extreme rainfall days in each of the models that can be classified according to the observed synoptic types.

3.2 Wind Analysis

The analysis of wind conditions in the NCEP and Mark 3 data sets has been based upon the identification of the most extreme wind events that have occurred over the forty years from 1961 to 2000 over the region indicated in Figure 5 spanning 26°S to 32°S and 153°E to 158°E. Wind extremes have been defined as the top 1% of winds to occur on a half-yearly basis in both the analyses and the model. In other words, over the 40-year period from 1961-2000, the winds at each grid point over the summer and winter half-years comprising November to April and May to October respectively were ranked and the top 1% of wind values (i.e. approximately the top 72 values) and their associated dates were stored. The dates of occurrence of extreme winds within the region of interest were then pooled, and sorted into a list of dates for which MSLP was to be synoptically typed.

Upper percentile winds have been used since the magnitude of the extreme winds in model simulations is resolution dependent. The lower the resolution of the model, the lower the wind speed is likely to be for a given synoptic weather situation. For example, the small scales and severe intensities of tropical cyclones cannot be captured by the Mark 3 model, although it can capture the broader features of the tropical depression associated with the cyclone. The winds that accompany the depression will nevertheless be extreme in a comparative sense to other synoptic weather situations produced by the model.

Depending on the resolution of the model, the number of events selected from this region differed. Figure 5 shows the placement of the grid-points in the NCEP re-analyses and the Mark3 model that fall within the region of interest, with nine grid-points for NCEP and four grid points for Mark3. The CC50 model with its finer spatial resolution had 81 grid-points located in the region. Although this means that potentially the CC50 model can
contribute a significantly larger pool of extreme wind events for synoptic classification (81 grid-points x 72 values per half-year), in reality, the spatial scale of the synoptic systems that often cause extreme winds usually means that large numbers of grid-points register extreme winds on the same date. The number of events (i.e. dates) selected for synoptic typing in the NCEP re-analyses and the CC50-Mk2 and CC50-Mk3 was typically in the range of 800-900 in each 40-year period. The CC50 model was only between 50 and 60% higher than NCEP despite there being 9 times the number of grid-points in the region.

The dates, wind speeds and directions of the upper percentile wind events over the forty years are stored grid point by grid point for each season. The data captured within a region spanning 26°S to 32°S and 153°E to 158°E were analysed (see Figure 2). This yields nine grid points in the NCEP reanalyses and four grid points in the Mark 3 model.

![Figure 5: The region for which wind extremes from the NCEP reanalyses and the CSIRO Mark 3 climate model were analysed.](image)

### 3.3 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 x 9) in the region between 140 and 165°E and 35 and 20°S. These fields were further divided into 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:

\[ Z_i = \frac{x_i - \bar{X}}{s} \]  

where \( Z_i \) is the normalised value of grid-point \( i \), \( x_i \) is the observed value at grid-point \( i \), \( \bar{X} \) 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, each daily map pattern in the extreme rainfall subset is compared with all other maps in the subset using Pearson product-moment correlations (\( r_{xy} \)).

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

In this formula, \( x_i \) and \( y_i \) represent 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 on the rain or wind extreme days in the three climate models over the 1961 to 2000 period were extracted and correlated against the observed “key days” for the respective variable to determine how realistically the models captured the weather patterns associated with extreme events. The extreme rain and wind days for the two 40-year periods from 2011 to 2050 and 2051 to 2090, representing 2030 and 2070 respectively, 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.
4 Extreme Rain Events

4.1 Observed Rainfall Results

The focus of this study is on the large-scale extreme rainfall events that result in riverine flooding, rather than the localised events associated with flash flooding. A frequency histogram of the 1-day events on a monthly basis is shown in Figure 6 and indicates the larger frequency of high rainfall events from December to March.

![Figure 6: Frequency histogram of days in which total accumulated rainfall exceeded 100 mm from 1960 to 2000 over south-east Queensland.](image)

As discussed in section 3.1, the 1-day and 3-day rainfall subsets were further analysed to identify days which contributed to 3-day totals in excess of 250 mm and in which at least 100 mm of rainfall occurred in the daily record. This analysis produced 291 days, approximately half of the 1-day subset.

![Figure 7: Frequency histogram of days in which total accumulated rainfall exceeded 100 mm from 1960 to 2000 and which contributed to 3-day total greater than 250 mm over south-east Queensland.](image)
A frequency histogram of these events is shown in Figure 7 and indicates that these events are most frequent between January and June. These days were further analysed and shown to contribute to 92 cases in which heavy rainfall occurred on consecutive days. These 291 days are the focus of the present study. The remaining 321 days are single day events, or have contributed to a lighter intensity multi-day event. In some cases these days will be associated with heavy, short-lived rainfall produced by severe thunderstorms and squall lines. These days are referred to as "non-overlap" days and are only briefly considered in this study.

The correlation-based classification procedure was then applied to the pressure patterns associated with each of these 291 days. Five synoptic patterns were identified as characteristic of extreme summer rainfall and two patterns for extreme winter rainfall.

**Summer**

Figure 8 shows the composite pressure patterns for each of the five summer types. The composite patterns have been obtained by averaging the MSLP patterns for the days that contribute to each synoptic type. These five synoptic types account for 99.5% of days considered. The remaining days were unclassified.

Synoptic type 1 is the most frequent type and is characterised by a high-pressure system to the southeast of the continent that acts to produce a large area of onshore northeasterly flow into the study region. There is also a weak offshore trough in the easterly flow. Type 2 is an inland monsoonal trough that acts to transport warm moist onshore flow onto the southeast Queensland coast. This onshore flow originates over the Coral Sea and is quite deep, thus resulting in a deep layer of warm moist air. Strong ascent is triggered as the moist onshore flow encounters the coastline and the coastal ranges.

In many cases the Type 3 pattern is associated with a tropical cyclone that is moving southwards slightly offshore from the coast. The upper level features associated with Type 3 are presented in Figure 9. On average, these cases have a source region of higher than average atmospheric moisture (shown by shading) off the coast. This high moisture region is co-incident with strong ascent (dashed lines) and the systems are well organised in the vertical as shown by the strong cyclonic circulation at 700hPa that is coincident with the surface low.

Type 4 is very similar to Type 3 and consists of a low just off the southern Queensland coast. This low is mostly due to a tropical cyclone but in a small number of cases its origins are in the monsoon trough.

The main feature of the Type 5 pattern is a cut-off low in the Tasman Sea. This pattern is mostly representative of a translating low-pressure system, such as a tropical cyclone or monsoonal trough and is accompanied by an extensive region of very high moisture contents and a closed circulation at 700 hPa. These systems are not as well organised in the vertical, with the upper level low trailing the surface low.
Figure 8: Composited MSLP fields for the synoptic types associated with extreme summer rainfall in south east Queensland. Type 1 accounts for 74% of events, type 2 for 12%, type 3 for 8%, type 4 for 3% and type 5 for 2%. <1% of days are unclassified according to the above patterns.
Figure 9: Composited upper level fields for Type 3 events. The shaded region identifies the area with above average moisture content, the dashed lines enclose the region of strong ascent and the vectors indicate the direction and speed of the wind at 700hPa.

It is possible that the intensity and spatial distribution of rainfall may vary in distinct ways for different synoptic classifications. Thus the rainfall distribution has also been examined for each of the synoptic types and the spatial patterns of the maximum rainfall for each type are shown in Figure 10. The spatial patterns of average rainfall for each type have also been examined. These show a similar distribution to the patterns shown in Figure 10.

Type 1-rainfall events are associated with widespread heavy rainfall along the southeast Queensland and northern New South Wales coasts, with the highest rainfall totals occurring in the mountainous region close to the coast. Type 2 cases produce extreme rainfall in the coastal regions immediately to the north and south of Brisbane. The rainfall in the south of the region tends to be less. The Type 3 and Type 4 rainfall events are similar in distribution with the main affects along the coastal regions. The heavy rainfall from these events is more localised than from Type 1, but the inland rainfall in the Type 4 events is heavier that in the Type 3 events. The Type 5 rainfall distribution reflects the onshore flow from the southeast. In this case, the heaviest rainfall region occurs in northern New South Wales.
Figure 10: Geographic distribution of maximum rainfall associated with each of the 5 summer synoptic types.
The distribution of the rainfall synoptic types as a function of rainfall total for summer is shown in Figure 11. It indicates that the Type 1 synoptic situation is dominant in almost all rainfall classes for which events occur. The exception is a single high rainfall event of between 700 and 750 mm that was due to a Type 2 synoptic pattern. Type 5 events were found to be associated with lower rainfall totals of between 100 and 200 mm.

Figure 11: Frequency of synoptic types as a function of rainfall totals for summer rainfall. ‘u’ denotes the unclassified days.

**Winter**

Figure 12 shows the composite pressure patterns for each of the two winter types. The Type 1 and Type 2 patterns are similar to those in summer. Both patterns are characterised by a high-pressure system to the south east of the continent that acts to produce a large area of onshore easterly flow into the study region. In both cases there is a trough in the easterly flow, with this being much better developed in the winter Type 1 cases. The upper level conditions are different for each type. The Type 1 pattern is associated with a strong cut-off low-pressure system at 700 hPa, above average moisture values off the southeast Queensland coast and strong ascent coincident with the high moisture values in the coastal and offshore regions.

The Type 2 pattern is not accompanied by a cut-off low-pressure system at 700 hPa. In this case there is strong northeasterly flow at upper levels that transports warm, moist tropical air inland from the Coral Sea. In these cases, anomalously high moisture values occur over both the coastal regions of southeast Queensland and the inland region of New South Wales. This moisture-laden air is coincident with a broad area of strong ascent.
Figure 12: Composited MSLP fields for the synoptic types associated with extreme winter rainfall in south east Queensland. Type 1 accounts for 75% of events and type 2 for 15% events. 10% of events are unclassified.

The rainfall distributions associated with the two winter-rainfall types are shown in Figure 13. The Type 1 pattern produces widespread, heavy rainfall in both southeast Queensland and northern New South Wales. The heaviest rainfall totals occur in the mountainous coastal areas north and south of Brisbane and in the high terrain west of Coffs Harbour. The Type 2 pattern produces widespread heavy rainfall but the extremes are less than those of the Type 1 cases. The heaviest rainfall events occur in the coastal ranges to the north and south of Brisbane.

Figure 13: Geographic distribution of maximum rainfall associated with each of the winter synoptic types.

The distribution of the rainfall synoptic types as a function of rainfall total for winter is shown in Figure 14. It indicates that the Type 1 synoptic situation is dominant in almost all rainfall classes for which events occur. Type 2 events are associated with lower rainfall totals of between 100 and 250 mm.
4.2 Extreme Rainfall in the CSIRO Climate Models

The ability of global climate models to represent extreme rainfall events is limited by both the coarse grid resolution and by the physical parameterisation schemes that are used to represent the sub-grid scale processes such as convection. In this section we use an analysis similar to that used for the observations, to assess the skill of the models in capturing the synoptic climatology of extreme rainfall events. This analysis has been performed on the extreme rainfall events selected from the forty years representing 1961 to 2000 in the three climate models. A previous study examining extreme rainfall days extracted from the Mark 3 model has identified deficiencies in the climatology of Mark 3 extreme rainfall events. That study found that the Mark 3 climate model produced too many heavy rainfall events in summer and too few events in winter. Thus, extreme rainfall events selected from the models for this study were chosen to reflect the seasonal variation of the observed heavy rainfall events.

The synoptic weather patterns associated with the dates on which extreme rainfall occurred in the model are correlated against the key synoptic types identified in the NCEP reanalyses for the particular season. For the comparison of the model pressure fields with the NCEP-based synoptic types, the correlation threshold was reduced to 0.5 to reduce the number of unclassified days in the model datasets. The results from the analysis are summarised in Table 2.

The Mark 3 model performs poorly in capturing the synoptic weather conditions associated with extreme summer rainfall events. Severe rainfall events due to the Type 1 pattern are underestimated and the Type 2 events overestimated. Both the CC-Mk3 and CC-Mk2 models perform well in terms of capturing the proportion of events associated with each synoptic type in the observations although Types 3 to 5 are underestimated in both models. The number of days for which the patterns cannot be typed against the 5 key types in the observations is very small.
Table 2: The representation of synoptic types in the Mark 3, CC-Mk3 and CC-Mk2 models in summer and winter on extreme rain days.

<table>
<thead>
<tr>
<th></th>
<th>Summer</th>
<th></th>
<th></th>
<th>Winter</th>
<th></th>
<th></th>
<th></th>
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<tr>
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<td>Mk 3</td>
<td>CC-Mk3</td>
<td></td>
<td>Type</td>
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</tr>
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<td>-</td>
<td>-</td>
</tr>
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<td>3</td>
<td>2</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>-</td>
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<td>-</td>
</tr>
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<td>&lt;1</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>&lt;1</td>
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<tr>
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<td>188</td>
<td>159</td>
<td>133</td>
<td>No. of days</td>
<td>75</td>
<td>115</td>
</tr>
</tbody>
</table>

In winter, all models perform poorly in terms of representing the two synoptic patterns associated with winter-time extreme rainfall events. Synoptic type 1 is underestimated with all models producing this pattern on 30-40% of days compared with occurrence of this pattern in 75% of days in the observations. Type 2 events are overestimated by CC-Mk3 by about three times the number that occurs in the observations but they are underestimated by about 50% in the CC-Mk2 model. The number of unclassified days is largest in the CC-Mk2 model with 63% of days for which patterns were dissimilar to types 1 and 2.

The relatively poor performance of the models in the winter half year compared to the summer half year is related to the relatively small number of extreme rainfall days that occur in winter compared to summer. However, this is exacerbated by deficiencies in the models and their ability to simulate the extreme rainfall processes associated with these synoptic types. Thus, there is a high proportion of unclassified days as indicated by the last row in Table 2.

The Mark 3 model pressure patterns have also been synoptically typed to identify the main patterns associated with Mark 3 heavy rainfall events. This analysis identified the standard types but also produced a number of types that were representative of mid-latitude frontal systems. These cases account for approximately 35% of the Mark 3 Control climate heavy rainfall events. These results do not mean that the Mark 3 model is producing too many frontal systems, but they do suggest the frontal systems are being associated with heavy rainfall events due to the poor representation of cut-off low-pressure systems and tropical cyclones in the models. The CC-Mk3 has captured the synoptic climatology of the most common extreme summer rainfall events, however, it has poorer results for the Type 3 events that are dominated by tropical cyclones. The CC-MK3 model performs poorly in winter.

The best performing model for both summer and winter extreme rainfall events is CC-Mk2. The following discussion related to rainfall events will focus on the results from this model.

4.3 The Impact of Climate Change

If the frequency of a particular synoptic pattern associated with extreme rainfall events is found to change as a result of climate change, then there will obviously be effects on the frequency, and possible the intensity, of extreme rainfall events. Table 3 presents the
results from the above analysis for the current climate and the climates of 2030 and 2070 for the extreme rainfall events in CC-Mk2.

**Table 3:** The representation of synoptic types in the CC-Mk2 model in the current, 2030 and 2070 climates for summer and winter.

<table>
<thead>
<tr>
<th>Type</th>
<th>Type</th>
<th>Summer</th>
<th>Type</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2030</td>
<td>2070</td>
<td>Control</td>
</tr>
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</tr>
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</tr>
<tr>
<td>No. of days</td>
<td>133</td>
<td>140</td>
<td>150</td>
<td>No. of days</td>
</tr>
</tbody>
</table>

For summer, the Type 1 events increase in frequency by 2-3%. Since about 140 days were typed, this amounts to 3-4 more events over the 40-year period or an extra event every 10 years. Type 2 events are simulated to decrease in frequency by 5%. For the remaining summer synoptic patterns the changes in frequency are minor. In winter, both the Type 1 and Type 2 events increase in frequency. The Type 1 events increase by between 10 and 12%, which amounts to 18 more events over the 40-year period. The Type 2 events increase in frequency by 4% by 2070.
5 Extreme Winds

5.1 Observed Winds

The top 1% of wind events amounting to the top 36 wind speed values over the forty seasons were selected from the NCEP reanalyses over the region spanning 26°S to 32°S and 153°E to 158°E. The extreme wind days over the region shown in Figure 5 are then grouped and sorted into extreme wind days and the synoptic typing procedure applied. Figure 15 shows the frequency of extreme (top 1%) of winds by month over the 40-year interval. This indicates a wintertime maximum in extreme winds with June experiencing the greatest number of extreme wind days.

![Frequency histogram of the number of days, winds equalled or exceeded the top 1% of all winds over the 1961-2000 interval using the NCEP Reanalyses data.](image)

Figure 15: Frequency histogram of the number of days, winds equalled or exceeded the top 1% of all winds over the 1961-2000 interval using the NCEP Reanalyses data.

The average of the top 1% of events is shown in Figure 16 for summer and winter. In summer the strongest winds, mainly from a westerly direction, occur to the south of the continent attaining values in excess of 18 ms\(^{-1}\). Along the east coast of Australia the most extreme winds are around 14 ms\(^{-1}\) and are southwesterly turning southeasterly north of 30°S. In winter, the overall pattern is similar except that stronger winds, exceeding 18 ms\(^{-1}\), occur along the east coast.

![Seasonally averaged extreme (top percentile) winds for the period 1961-2000 from the NCEP Reanalyses data.](image)

Figure 16: Seasonally averaged extreme (top percentile) winds for the period 1961-2000 from the NCEP Reanalyses data.
Summer

Figure 17 shows the six dominant synoptic types associated with extreme wind days during summer. Type 1 features a tropical depression over the Coral Sea and a ridge of high pressure in the southern Tasman Sea producing a southeasterly flow over the central east coast. This synoptic situation is the most common cause of extreme winds accounting for 46% of cases. It is similar to synoptic type 3 for extreme rainfall days. The second synoptic type, amounting to 29% of cases, consists of a cut-off low-pressure system in the Tasman directing south-southeasterly winds onto the central east coast.

Figure 17: The synoptic types responsible for summer extreme wind days.
Synoptic type 3, accounting for 12% of extreme wind days, is similar to Type 1 with a ridge in the southern Tasman Sea. However it features a well developed depression located just to the north of the Gold Coast. Synoptic types 4 and 6 consist of low-pressure systems situated off the east coast to the south of the Gold Coast. Type 6 is broader in spatial scale than Type 4. These types account for 5 and 3% of cases respectively. Type 5 accounts for 5% of days and consists of a depression located over the southeast of the continent and an anticyclone over the eastern Tasman Sea. Winds in the vicinity of the Gold coast are directed offshore.

Synoptic patterns 1 and 3 are similar to the synoptic patterns 1 and 3 identified for summer rainfall although the wind patterns feature a better developed depression in the north. Types 4 and 6 contain similarities to types 4 and 5 for summer rainfall. Type 5 is similar to Type 2 for summer rainfall but has a more fully developed low over the southeast of the continent. Where synoptic patterns arising from extreme rain are similar to those arising from extreme wind, there are obvious implications for combined extreme rain and wind events coinciding. These will be addressed in more detail in section 6.

Winter
The dominant synoptic patterns contributing to extreme wind days during the winter half year are shown in Figure 18. The first synoptic type comprises 53% of days and consists of a low in the Tasman directing southerly flow along the east coast. The second synoptic type consists of a high-pressure system in the southern Tasman and a pressure trough in the Coral Sea producing southeasterly winds onto the east coast. It accounts for 23% of events. Synoptic type 3 is a Tasman low-pressure system that produces westerlies on the central east coast and accounts for 14% of events. Synoptic type 4 is a cut-off low that directs southeasterly winds onto the east coast and accounts for 5% of events. The final pattern, comprising 5% of days, consists of a coastal trough with a ridge in the southern Tasman directing north-easterlies onto the east coast. Synoptic types 2 and 5 are similar to the two wintertime patterns arising from extreme rainfall events.

5.2 Extreme Winds in the CSIRO Climate Models
The performance of the three CSIRO regional climate model simulations, Mark 3, CC50-Mk2 and CC50-Mk3, are now assessed. The averaged top 1% of winds for summer and winter in Mark 3 are shown in Figure 19. Compared with Figure 9, these show that the Mark 3 model represents the spatial pattern of extreme winds reasonably well. The main difference is the underestimation of the wind magnitude, by around 2 ms\(^{-1}\), along the east coast of Australia. Wind direction along the southeastern coast has more of a westerly component compared with the southwesterly component seen in the Figure 9. This is related to a much more zonal structure in pressure pattern in the Mark 3 model, compared to the observed pattern, leading to more frequent occurrence of westerly winds along the south of the continent.
Figure 18: The synoptic types responsible for winter extreme wind days.
The ability of the models to represent the main synoptic types identified in the NCEP re-analyses under present climate conditions was accomplished by correlating synoptic patterns from the model simulation against each of the patterns identified in the NCEP re-analyses for the particular half year. Maps were considered to be similar if they had a correlation coefficient of 0.5 or greater. The results are summarised in Table 4.

As was found for rainfall, the control climate of the Mark 3 model over the summer half year contains fewer extreme wind days that can be classed according to the six standard extreme wind synoptic patterns identified in the observations. The number of residual days makes up 20% of the total extreme days. The type 2 pattern, which consists of a cut-off low in the central Tasman is significantly underestimated whereas, type 5 consisting of a low over southeast Australia situated between ridges of high pressure is overestimated. Detailed investigation of the performance of the Mark 3 in Hennessy et al. (2004) using the same procedure as applied here for extreme wind days affecting the NSW coast found that it significantly underestimated the number of Tasman highs (type 1 events in Figure 18) and the number of Tasman lows. Instead, many of the extreme wind days were associated with the movement of cold fronts across the east of the continent and the Tasman Sea.

One contributing factor in the performance of the Mark3 model is likely to be a bias in the sea surface temperature (SST) patterns which results in temperatures that are up to 3°C too cool off the east coast of Australia and up to 3°C too warm in the southern ocean to the south of Australia. This bias in temperatures arises from the coupling of the ocean model to the atmospheric model via temperature and momentum fluxes. Small discrepancies in the fluxes that are exchanged between the ocean and atmosphere can produce large discrepancies in SSTs. Many climate models apply a flux correction to avoid such a bias although the argument against doing this is that the correction may constrain the response of the coupled model to enhanced greenhouse forcing. The goal of the modelling community is to improve the coupling between ocean and atmospheric models so that flux correction is not necessary.

In relation to the Mark3 model performance in the east Australian region, the presence of a cool bias is likely to suppress the intensification of low pressure systems travelling across the region and possibly even suppress the formation of intense cut-off lows. Modelling and observational studies have established a strong relationship between warm SSTs off the east coast and the formation of intense east coast low-pressure systems (e.g. McInnes and Hess, 1992; McInnes et al., 1992; Lynch, 1988; Hess, 1990; Holland et al., 1987; Leslie et al., 1987). It is therefore not surprising that most of the
extreme wind days in the model in this region are made up of a smaller proportion of intense low pressure systems off the east coast and that other systems such as fronts are making up a larger percentage of the extreme wind days.

**Table 4: The representation of synoptic types in the Mark 3, CC-Mk3 and CC-Mk2 models in summer and winter on extreme wind days.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Summer</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NCEP (Obs)</td>
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</tr>
<tr>
<td>1</td>
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<td>34</td>
</tr>
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<tr>
<td>No. of days</td>
<td>234</td>
<td>219</td>
</tr>
</tbody>
</table>

Despite the improved spatial resolution and the correction of the cool bias in the CC-Mk3 model, this model behaves in a similar manner to Mark 3 in terms of its representation of the different synoptic types. Clearly the boundary forcing provided by the Mark 3 model dominates the synoptic patterns that evolve in the higher resolution CC model. Over the summer half-year, types 1 to 4 are under-represented by CC-Mk3 while Type 5 is significantly over-represented. In winter, this model performs more poorly than the Mark 3 model and 34% of events remain unclassified.

In view of the relatively poor performance of this model in this regard, the extreme wind days were synoptically typed to investigate what types of synoptic conditions in the model were producing extreme winds. In summer, ten synoptic types were identified in which six of the patterns, accounting for just over half of the extreme wind days, were associated with cold fronts at various stages of progression across southeast Australia and the southern Tasman Sea. This result is similar to the finding for the Mark 3 model reported in Hennessy et al., (2004) for NSW extreme wind events. Cold fronts can produce both extreme pre- and post-frontal winds. However, in the case of the patterns emerging from CC-Mk3, the winds would mainly fall into the pre-frontal category over southeast Queensland (Figure 20). The remaining patterns consist of a ridge in the southern Tasman Sea with onshore winds over southeast Queensland. About 40% of days during winter were also associated with cold fronts and about 26% of days were due to a ridge in the southern Tasman Sea. Cut-off low patterns did not emerge as a significant cause of extreme wind days in either summer or winter highlighting a significant deficiency in this particular model for the present study.
Unlike the Mark 3 and CC-Mk3 model, the CC-Mk2 model in summer performs well against the observations obtaining close to the correct proportions of synoptic types 1, 2, and 4. Types 3 and 6 are under-represented while Type 5 is over-represented and 1% of maps are unclassified. In winter, synoptic pattern 1 is underestimated, while other patterns are well represented. The number of unclassified patterns is higher at 6%. Overall, this model is the most realistic in terms of simulating the synoptic patterns associated with extreme winds.

5.3 Impact of Climate Change

The CC-Mk2 model demonstrated superior performance in representing observed weather patterns associated with extreme wind days and so this model will be considered under enhanced greenhouse conditions. The results of the synoptic typing for the 2030 and 2070 climates are presented in Table 5. These show that the during summer, Type 1 consisting of a Tasman high pressure system with a depression over the Coral sea increased in frequency by 4% by 2030 and by 2% by 2070. Since about 400 days were synoptically typed, this amounts to between 8 and 16 more events over the 40-year period or an extra event every 3-6 years. The Type 2 pattern, consisting of a low pressure system in the central Tasman, decreased in frequency by 7% or there were 24 fewer events occurring over the 40 years centred on 2070. Type 5 consisting of a low over the southeast of the continent increased by 3%. All other changes were minor.

In winter, synoptic pattern 1 increased in frequency by 8% by 2030 although by 2070, the increase was only 5%. Type 5 events decrease in frequency by 4%. All other changes are minor. The lack of a clear trend in some of the figures indicates that there is likely to be relatively low signal-to-noise in the results. Therefore results should be used with caution and allow for large uncertainty.
Table 5: The representation of synoptic types in the CC-Mk2 model in current, 2030 and 2070 climates in summer and winter.

<table>
<thead>
<tr>
<th>Type</th>
<th>Summer</th>
<th></th>
<th></th>
<th>Winter</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
<td>CC-Mk2</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>2030</td>
<td>2070</td>
<td>Control</td>
<td>2030</td>
<td>2070</td>
</tr>
<tr>
<td>1</td>
<td>44</td>
<td>48</td>
<td>46</td>
<td>1</td>
<td>36</td>
<td>44</td>
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<td>6</td>
<td>11</td>
<td>8</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>U</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>U</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>No. of days</td>
<td>376</td>
<td>418</td>
<td>419</td>
<td>No. of days</td>
<td>404</td>
<td>390</td>
</tr>
</tbody>
</table>
6 Combined Rain and Wind Events

6.1 Overlap days in the observations

In this section, the events for which extreme rainfall and wind conditions overlap are investigated in more detail. In terms of the potential to elevate sea levels through wave or storm surge conditions, all of the rainfall types for summer, except Type 2, have a large onshore wind component and therefore could potentially increase sea levels. The rainfall distribution associated with coincident extreme rain and wind conditions is illustrated in Figure 21 for summer. The highest percentage of coincident days occurs for rainfall totals of between 100 and 200 mm. When compared to Figure 11 for all summer rain days, it can be seen that for the combined wind and rain events, only a small proportion of the total Type 1 events coincide with extreme winds.

![Figure 21](image-url)

*Figure 21: The percentage of observed summer rainfall events, categorised by synoptic type, that overlap with extreme wind days.*

<table>
<thead>
<tr>
<th>Synoptic Type</th>
<th>Rainfall (mm)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100-150</td>
<td>18</td>
<td></td>
<td></td>
<td>83</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150-200</td>
<td>14</td>
<td>20</td>
<td></td>
<td>61</td>
<td>56</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200-250</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>250-300</td>
<td>28</td>
<td></td>
<td></td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>300-350</td>
<td>22</td>
<td></td>
<td></td>
<td>56</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>350-400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400-450</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>450-500</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
</tr>
</tbody>
</table>

*Table 6: The percentage of each rainfall synoptic type that overlaps with extreme wind for summer*

On the other hand, Type 3 events, comprising a much smaller percentage of heavy rainfall days overall, are much more likely to be associated with extreme winds. These results are summarised in Table 6. Figures 11, 21 and Table 6 also show that in the 300-
500 mm rainfall range, there is greater likelihood of extreme winds occurring. Above 500 mm of rain, no overlap with extreme winds occurs.

A histogram of frequency of coincident days in winter, as a function of total rainfall days is presented in Figure 22. Although fewer heavy rain days occur in winter compared to summer, a higher proportion of these days coincide with extreme wind days and nearly all coincide with synoptic Type 1 for winter. This is highlighted in Table 7, which shows that over 50% of Type 1 events occur in conjunction with extreme winds for rainfall totals in the range of range of 150-350 mm. As with summer, there is no overlap with extreme winds for rainfall events of 500 mm or above.

![Figure 22: The percentage of winter rainfall events, categorised by synoptic type, that overlaps with extreme wind days.](image)

<table>
<thead>
<tr>
<th>Rainfall (mm)</th>
<th>Synoptic Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>100-150</td>
<td>14</td>
</tr>
<tr>
<td>150-200</td>
<td>54</td>
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<tr>
<td>200-250</td>
<td>56</td>
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<tr>
<td>250-300</td>
<td>66</td>
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<tr>
<td>300-350</td>
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<tr>
<td>350-400</td>
<td></td>
</tr>
<tr>
<td>400-450</td>
<td></td>
</tr>
<tr>
<td>450-500</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 7:** The percentage of each rainfall synoptic type that overlaps with extreme wind for winter

6.2 Overlap days under future climate conditions

The characteristics of the coincident wind and rainfall days in the CC-Mk2 model are investigated for current and future climates. Figure 23 presents the frequency of occurrence of three of the five synoptic types identified for summer as well as the
frequency of unclassified days in the current, 2030 and 2070 climates for all extreme rainfall days and for rainfall days that overlap with extreme wind days. Types 4 and 5 occurred in insignificant numbers in CC-Mk2 and so are not shown. These data are stratified according to the modelled rainfall amount from the CC-Mk2 model.

**Figure 23:** (a) The percentage of rainfall synoptic types 1 to 3 for summer in CC-Mk2 for current, 2030 and 2070 climates. (b) the same as (a) except for events that are coincident with extreme wind. Each synoptic type is binned corresponding to the rainfall predicted by the model.

For all rainfall days (Figure 23a), Type 1 events show an increase in frequency from the current climate through to 2030 and 2070. For the events that coincided with extreme wind days, Figure 23b shows that their frequency increased from 6% in the current
climate to 11% by 2030 and 16% by 2070. Most of this increase in frequency is for the more extreme rainfall events. The total number of Type 2 events shows a decrease in frequency between the current and the 2070 climate, decreasing from 18% in the current climate to 13% by 2070. Decreases also occur in the number of Type 2 rain days that overlap with extreme winds. Similarly, decreases in Type 3 events occur in both the total rain days and the overlap days. Although they comprise a small number of extreme rainfall days, Type 3 events generally coincide with extreme wind days, as with the observed Type 3 events.

![Figure 24](image-url)

*Figure 24:* (a) The percentage of rainfall synoptic types 1 to 3 for winter in CC-Mk2 for current, 2030 and 2070 climates (b) the same as (a) except for events that overlap with extreme wind. Each synoptic type is binned corresponding to the rainfall predicted by the model.
For completeness, the equivalent pair of figures for winter is shown in Figure 24. However, it should be noted that owing to the smaller number of extreme rainfall events in winter and the larger percentages of un-typed events, the frequencies of different types and their future changes are much less reliable. The frequency of Type 1 events increases in total number from 40% under current climate conditions to 53% by 2030 and 2070. However, the percentage of days for which this synoptic type overlaps with extreme wind decreases from 18% under current conditions to 12% by 2030 and 9% by 2070.
7 Summary and Recommendations

In this study, an investigation into extreme rainfall and wind events over southeast Queensland has been undertaken. The implications of extreme rainfall events on riverine flooding are obvious. However, extreme winds, through the generation of storm surge or severe wave conditions, can exacerbate riverine flooding through backwater effects. Therefore, the frequency of extreme wind events that coincide with severe rainfall events must be understood in order to establish appropriate downstream boundary conditions for flood modelling. In addition to this, the development of long-term flood management plans must consider the possible impact of climate change.

This study has contributed to the above objectives. The nature of extreme rainfall events has been investigated in rainfall observations over southeast Queensland. Rainfall totals exceeding a threshold of 100 mm per day were used to identify extreme rainfall events over a 40-year observational record from 1961 to 2000. These events occur year round with the greatest frequency between January and March. A synoptic typing procedure was used to categorise the synoptic weather patterns associated with the extreme rainfall over the summer and winter half-years yielding five synoptic patterns associated with summer rainfall and two in winter. The most common weather pattern to bring extreme rainfall to southeast Queensland consisted of a ridge of high pressure in the southern Tasman Sea and a trough or depression in the Coral Sea producing onshore flow to the east coast. The remainder of events consisted of low-pressure systems of tropical or mid-latitude origins.

Three climate model simulations were assessed in terms of their ability to reproduce the climatology of extreme events that produce both extreme winds and rainfall. It was found that the regional climate model, CC-Mk2 was able to capture the climatology of extreme rainfall and extreme wind weather events affecting southeast Queensland. The results from the analysis also identified possible changes in frequency of these severe weather events, resulting from climate change.

The results show that the 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 events are characterised by a high-pressure system to the south east of the continent that acts to produce a large area of onshore northeasterly flow into the study region. There is also a weak offshore trough in the easterly flow. These events are generally associated with extreme rainfall in the coastal ranges of southeast Queensland. Between 20 and 50% of Type 1 rainfall days occur with extreme winds. Coincident wind and rainfall events associated with the Type 1 category show an 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 wind and rainfall events show a decrease in frequency under future climate conditions. These conclusions are based on the analysis of a single model, thus it is impossible to estimate the uncertainty associated with these conclusions. Ideally, outputs from other climate models should be examined to minimise the uncertainty associated with these results.

This study has shown that the CC-Mk2 model provides the best representation of the current climate extreme wind and extreme rainfall synoptic climatology. The CC-Mk3 model on the other hand, has an adequate representation of the most common summer
rainfall types, but it does not properly represent the summer Type 3 events or the climatology of winter events. A related project, funded by the Australian Greenhouse Office (AGO), is currently in progress. As part of that project, the extreme rainfall events identified in the CC-Mk3 model are to be downscaled over the southeast Queensland region with a high-resolution atmospheric model (RAMS). The outputs from that modelling study will provide a synthetic record of extreme rainfall events with a grid spacing of 4 km and a temporal spacing of 30 minutes.

Section 2.1 discusses the uncertainties associated with the development of climate change projections. One method for minimising this uncertainty is to consider results from multiple models. Results from the pilot study presented in Section 2.1 are currently available for detailed analysis over the region of interest and new results based on CC-Mk3 will become available at the completion of the AGO-funded project. Both of these studies were concerned with extreme rainfall events only, but it is expected that these simulations will also provide results related to coincident extreme rainfall and wind events.

The relevance of the coincident events in which both extreme rainfall and wind occur, lies in the fact that severe winds can elevate sea levels at the coast through storm surge and wave effects, which can worsen riverine flooding due to backwater effects. Hydrological or hydraulic modelling to assess flood risk must consider the possibility of combined effects through the appropriate specification of a downstream boundary condition to include an increase in the still water levels above that of the astronomical tide.

The fact that a range of wind conditions and hence sea levels can occur in conjunction with a particular rainfall intensity indicates that the risk of flooding must be addressed using stochastic processes such as Monte-Carlo techniques. Such techniques were used in McInnes et al. (2000) to evaluate storm tide return periods for the Broadwater with hydrodynamic models and a similar approach could be applied to flood modelling. For example, based on the information presented in Figures 11 and 21, a rainfall event in the range of 100-150 mm may be expected to coincide with elevated downstream water levels in approximately 20% of situations, whereas a 350-400 mm rainfall event may overlap with elevated sea levels in approximately 30% of situations. However, details of the range of wind intensities that could feasibly occur in conjunction with the rainfall events have not been determined in this study. This is because the gridded reanalysis data set used in this study was not considered to be of sufficient resolution to capture the wind speeds associated with extreme storm events. It is suggested that the dynamical downscaling be used to provide ranges and frequencies of wind speed and direction over coastal waters in a range of observed severe wind and rain events.

The following recommendations are made for future stages of this project. In Stage 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 downscale winds from current and future climate events to determine changes in frequency, magnitude and direction.

These recommendations allow the following tasks to be completed in Stage 2 of the project.

- Model the population of extreme rainfall and wind events identified in Stage 1 using the RAMS atmospheric model to derive high spatial and temporal resolution rainfall and wind information.
- Analyse the model output to derive estimates of the intensity-frequency curves for durations of 1, 3, 6, 12, 24, 48 and 72 hours.
- Analyse the model output to derive estimates of the depth-area curves for durations of 1, 3, 6, 12, 24, 48 and 72 hours.
- Analyse the model output to derive the temporal patterns for the severe rainfall events.
- Compare the statistics of the current climate simulations with the statistics derived from observed storms.
- Estimate the change in these quantities for the future climate.
- Use the model output to derive a refined analysis of the return periods of extreme rainfall and storm surge heights and their joint probability.

In Stage 3:

6. Increases in sea level due storm surge and wave set-up in the Broadwater, associated with the range of possible extreme wind events to be determined through hydrodynamic and wave modelling to provide a range of plausible tail water boundary conditions to apply to flood modelling.

8 References


