The Impact of Climate Change on Coastal New South Wales

Final Report

Report on research undertaken for the National Greenhouse Advisory Committee

CSIRO
Atmospheric Research

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Glossary

1×CO₂ Describes a climate simulation using a global climate model under conditions of ‘present-day’ atmospheric concentration of carbon dioxide. The CSIRO model uses a 1×CO₂ carbon dioxide concentration of 330 ppm (approximate global average concentration around 1975) and its 1×CO₂ climate is thus applicable to the last thirty years.

2×CO₂ Describes a climate simulation by a global climate model in which the atmospheric concentration of carbon dioxide is instantaneously doubled from the equivalent of a present-day concentration, and the atmosphere has been allowed to come to equilibrium after responding to the increase in carbon dioxide. Such simulations are often referred to as ‘equilibrium’ experiments. The CSIRO model uses a 2×CO₂ atmospheric concentration of 660 ppm.

Coupled model Term used to describe a global climate model which uses a full ocean model ‘coupled’ to an atmospheric model (cf. ‘slab ocean’). A coupled model is able to represent ocean currents, the exchange of heat between surface and deep layers of the ocean, and how these processes may change under enhanced greenhouse conditions (see also Transient experiment).

DARLAM Division of Atmospheric Research Limited-Area Model.

ENSO El Niño – Southern Oscillation.

ECMWF European Centre for Medium-range Weather Forecasting. The source of observational analyses used for verification of model performance.


GCM Global Climate Model.

IPCC Intergovernmental Panel on Climate Change.

La Niña Wet phase of the El Niño – Southern Oscillation variability in Australia.

LAM Limited-area model. An atmospheric model that is run over a limited (i.e. non-global) geographical region or domain.

NCEP National Centre for Environmental Prediction. The source of observational analyses used for verification of model performance.

RCM Regional climate model. A limited-area model that uses GCM model output as boundary conditions and produces a higher resolution climate simulation over a region of interest.

Slab ocean model Term used to describe global climate models that use a simplified ocean model in which there is no deep ocean (cf. ‘coupled’).
**SOI**  
Southern Oscillation Index. A measure of the phase and strength of the ENSO phenomenon. It is defined as the Tahiti minus Darwin surface pressure and is positive during La Niña events and negative during El Niño events.

**SPCZ**  
South Pacific Convergence Zone. A band of cloud and rain that generally extends from Papua New Guinea southeastwards towards South America.

**SST**  
Sea surface temperature.

**Transient experiment**  
The type of enhanced greenhouse experiment performed using a coupled GCM. CO$_2$ levels are increased at a rate of 1% per annum rather than being instantaneously doubled at the start of the experiment as is done with ‘slab ocean’ GCMs.

**UTC**  
Universal Time Constant. Equivalent to Greenwich Mean Time which is ten hours behind Australian Eastern Standard Time and eleven hours behind Eastern Daylight Savings Time.
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The work presented in this report draws upon research carried out by other colleagues within the Division of Atmospheric Research. Martin Dix and Ian Watterson ran the CSIRO Mark 2 GCM that was developed by members of the Climate Modelling Group within the Division. John McGregor, Jack Katzfey and Kim Nguyen carried out the limited area modelling experiments.

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Executive Summary

1. Introduction

The New South Wales coast spans the sub-tropics in the north to the mid-latitudes in the south and is therefore affected by weather systems of both origins. To the north are tropical cyclones during the summer months and depressions developing in easterly troughs. Further south, low pressure systems such as cut-off lows, migratory lows and east coast lows are a major source of severe weather, particularly in the colder months. These systems are all capable of generating storm surges and severe wave conditions along the coast. Less severe weather conditions can also impact on the wave climatology of the region. For example, anticyclones can be a major source of wind-generated waves from the northeast, as can sea-breezes during the warmer months of the year.

Beach and nearshore physical processes, such as flooding, erosion, sedimentation and littoral transport, are affected primarily by waves and storm surges acting in conjunction with normal tidal motions. Under conditions of climate change due to the enhanced greenhouse effect, the atmospheric conditions which drive ocean waves and storm surges may change in frequency and intensity and thereby alter the balance attained at the coastal boundary. In addition to this, rising sea levels will further increase the capacity for waves and storm surges to impact on the coastal zone.

The purpose of this report is to augment a study entitled, “Coastal vulnerability and greenhouse induced environmental change - formulation of a methodology for use in coastal management and planning”, by Professor Thom and Dr Cowell (University of Sydney) and Dr Tainsh (Public Works Department), under the Dedicated Greenhouse Research Grant Scheme. A number of specific objectives were identified under the agreement for the present study as outlined below:

1. A specialised modelling study of sea-breezes under normal and increased sea surface temperature conditions.
2. An additional set of storm surge simulations under present and enhanced sea surface temperature conditions were to be carried out to determine the possible impact of enhanced greenhouse effect on storm surge intensity.
3. An analysis of changes in surface winds over the Tasman Sea to be examined using available simulated climate data and implications of these changes on the wave climate of NSW discussed.
4. Seasonal and daily rainfall changes under enhanced greenhouse conditions to be examined.
5. Best current estimates of the possible mean sea level rises along the NSW coast to be provided.
6. Changes to the frequency, intensity and location of east coast lows and tropical cyclones to be provided.
7. The relationship between mid-latitude lows and ENSO to be examined.

In addition to addressing these specific objectives, a review of other relevant research is undertaken and areas where further research is needed or alternative methodologies or data sets are available, are also discussed.

2. Regional Model Simulations

An investigation of wind speed and direction changes is undertaken using 10 m winds from a Regional Climate Model (RCM) under 1×CO₂ and 2×CO₂ conditions. Regions in the Tasman Sea to the northeast, east and southeast of Sydney were examined. The wind directions likely to contribute to the wave climate of the east coast were the main focus. Generally 1×CO₂ winds verified well against observed winds although there was a tendency for the frequency of westerlies in the midlatitude locations to be overestimated and the easterlies to be underestimated. The most notable change between the 1×CO₂ and 2×CO₂ climate likely to affect the east coast was a shift to less frequent north-easterly winds and more frequent south-easterly winds during the winter months. In autumn, there was a general
reduction in winds from all key directions impinging upon the coast. However, for the most part, changes between the 1×CO$_2$ and 2×CO$_2$ climates were not statistically significant and in many cases, were smaller than the differences between the observations and the control climate. The results presented here were obtained from an RCM nested within a ‘slab ocean’ GCM which utilises a simplistic representation of the ocean. More recent RCM simulations have been nested in coupled GCM models that employ complex ocean circulation models. Comparisons between these model simulations indicate marked differences in the sign and magnitude of the wind changes between the 1×CO$_2$ and 2×CO$_2$ climates. These results suggest that a range of models should be considered before reliable changes in wind directions can be made for the NSW coastal regions. Furthermore, whilst examination of wind changes can give broad guidance as to the possible changes in wave climate of the NSW coast, quantitative guidance can only be obtained by running sophisticated wave models over the region of interest using wind forcing derived from climate models.

3. Cut-off lows and their impacts

Cut-off lows under present and doubled CO$_2$ conditions were analysed in a ‘slab’ ocean GCM over the east coast and Tasman Sea regions. This study showed that despite the relatively low resolution of the GCM, many features associated with their development were well captured. The frequency of systems was considerably underestimated however. Under a doubling of CO$_2$, even fewer systems occurred and this reduction was attributed to a reduction in atmospheric circulation caused by relatively greater warming in the high latitude regions. It should be noted that more recent coupled GCM simulations do not show such a pronounced warming in high latitudes and it is necessary to repeat such a study using a coupled GCM. Furthermore, an RCM nested within a coupled GCM may provide a better representation of the frequency of systems due to its higher resolution.

4. Tropical cyclones

An RCM nested in a ‘slab ocean’ GCM climate simulation was used as a basis for a study into tropical cyclones under enhanced greenhouse conditions. Since the higher resolution of the RCM is still not sufficient to capture the detail of these systems, a technique was employed whereby a higher resolution Limited Area Model (DARLAM) was nested within the RCM for each individual tropical cyclone-like vortex that was identified. This technique ensured that more realistic cyclone intensities were obtained. Under a doubling of CO$_2$, a moderate increase in the average and maximum tropical cyclone intensities was found. There was no significant change in the frequency of tropical cyclones, however, those that developed were found to persist further south. This result has two important implications for NSW. Firstly, there may be an increase in the number of tropical cyclones affecting the northern coastal regions and secondly, there may be a greater incidence of tropical cyclones undergoing redevelopment and producing severe extratropical lows further south. However, further investigation is required to determine if indeed this would be the case.

5. Sea-breeze and local circulation

A study of the impact of warmer surface temperatures on the strength and fetch of the sea-breeze circulation over the ocean on three consecutive days was conducted using DARLAM. Results showed onshore wind strengths over the ocean were up to 10% stronger. The fetch of the onshore flow however, was unaffected by increases in surface temperature, suggesting that the broader-scale synoptic patterns govern the seaward boundary of the sea-breeze circulation. Examination of mean temperature changes between 1×CO$_2$ and 2×CO$_2$ simulations in recent RCM simulations indicated relatively greater warming over the land surface compared with the ocean along the east coast. Even though there was no enhancement made to the thermal contrast across the east coast in the experiments described here, it is likely that this effect would further enhance the sea-breeze circulations. The sea-breeze circulations modelled in the present study all developed within a synoptic pattern consisting of two anticyclones, one
in the Great Australian Bight and one in the central Tasman Sea with a region of weak pressure gradients located over the east coast. This suggests that a more detailed investigation of the frequency of sea-breezes under present and enhanced CO$_2$ conditions could be conducted by identifying occurrence of similar broader-scale synoptic patterns.

6. Mid-latitude cyclones and anticyclones

The behaviour of mid-latitude cyclones and anticyclones in relation to El Niño – Southern Oscillation (ENSO) was investigated using automated tracking software applied to twenty-three years of daily observational analyses. In the vicinity of the east coast of Australia, it was found that cyclones were more frequent and had lower central pressures during La Niña events. They also tended to occur slightly further northwards in a band extending east to the South Pacific Convergence Zone and then followed a more southeastward track as they crossed the Pacific. Over eastern Australia, anticyclones tended to be located slightly further polewards during La Niña summers and El Niño winters.

A recent study of high rain-bearing east-coast lows indicates that there is a strong tendency for these systems to occur between transitions from strong El Niño to strong La Niña events. A separate study examined mid-latitude cyclone and anticyclone behaviour under enhanced greenhouse conditions using similar automated tracking software as used here. It was found that both cyclones and anticyclones decreased in frequency with cyclones decreasing by 10 to 15%. This result is attributed to the reduced circulation caused by relatively greater warming at high latitudes. However, that study makes use of model output from a slab ocean GCM simulation and different results may be found if coupled GCM model output is analysed, since coupled GCMs produce less warming at higher latitudes.

7. Rainfall changes under $2\times$CO$_2$ conditions

Changes in rainfall intensity may lead to significant changes in flood frequency in coastal regions that could also affect sedimentation rates within estuaries and river outflow regions. Changes in flood frequency due to rainfall changes are best determined by running catchment models since the conversion of rainfall to runoff is governed by various factors that are specific to each drainage basin. Previous catchment modelling studies for NSW and northern Victorian catchments have highlighted the fact that under enhanced greenhouse conditions, moderate increases or even small decreases in average rainfall can still produce marked increases in flood frequency. Recent RCM simulations for NSW have been used to create scenarios of precipitation change under a doubling of CO$_2$. Average increases in spring and summer rainfall of up to 5% are accompanied by a shortening of return periods between extreme rainfall events, whereas average decreases of winter rainfall of up to 10% are accompanied by a lengthening of return period between extreme rainfall events. However, in autumn, despite a 5% decrease in average rainfall, there is an increase in extreme rainfall events that is offset by a reduction in lighter rainfall events. Based on these results and earlier catchment modelling studies, it is possible that the coastal catchments of NSW could experience an increase in run-off from spring through to autumn under enhanced greenhouse conditions.

8. Sea-level rise

Average sea-level rise due to the enhanced greenhouse effect is a serious threat to coastal regions. Although the magnitudes of future sea-level rise may be relatively small (approximately 3 - 18 cm by 2020 and 10 - 60 cm by 2070), in combination with a severe storm, it may be enough to expose more vulnerable regions of the coastline to attack by storm surge and waves. Sea-level rise is caused by a number of processes that operate on different spatial scales. On the global scale, contributions to sea-level are expected due to the thermal expansion of oceans, melting of glaciers and ice sheets and changes in the accumulation rates of snow and ice. Regionally, sea levels may be further affected by changes in ocean currents and atmospheric wind regimes, although for the NSW coast, regional
contributions are expected to be negligible under enhanced greenhouse conditions. It is also worth noting that sea-level variations can also occur due to other factors such as geological movements and local effects such as sediment compaction and groundwater removal.

9. Storm surge and its impacts

A study into the weather conditions associated with sea-level anomalies along the NSW coast, indicate that cut-off low events are a major cause. The sea-level anomalies were typically no greater than half a metre and, because of the relatively narrow continental shelf, were likely to consist of a storm surge and wave set-up component. Despite the low amplitudes of the anomalies, their typically long duration, combined with the fact that the accompanying weather system is often responsible for intense rainfall, suggests that the elevated sea levels and run-off could combine to exacerbate coastal flooding. Three events were chosen for more detailed investigation using an atmospheric model and a storm surge model. Storm surge simulations were found to underestimate the amplitude of the measured sea level increase by up to 50%, although wave set-up at the coast could easily account for the remainder of the anomaly. The timing of the modelled peak sea-level anomaly was found to be in relatively poor agreement with observations. Further investigation suggested that the timing errors were most likely related to differences between the modelled atmospheric conditions used to force the storm-surge model and observed atmospheric conditions.

Generally, it was found that the greatest precipitation occurred in the region of onshore winds to the south of the low, whereas the storm surge was found to coincide with the region of southerly or coast parallel winds in both the model and the observations. The impact of elevated sea-surface temperatures (SSTs) on the intensity of the atmospheric storm and the associated coastal impacts due to rainfall and storm surge intensity changes were investigated. An increase in storm surge from zero to almost 50% was found depending on case and coastal location. The greatest wind speed and hence storm surge increases were found to occur to the north of about 33°S whereas the greatest rainfall increases due to the warmer SSTs were found to occur south of about 31°S. This result suggests that there may be an increased likelihood of overlap between storm surge and extreme rainfall run-off in central NSW coastal regions as a result of greenhouse warming, with an associated increased threat of coastal flooding events. Future investigation of this issue could be carried out directly by analysing the rainfall and wind field patterns under 1×CO₂ and 2×CO₂ conditions simulated by a higher resolution RCM.
1. Introduction

This is the final report of a consultancy carried out by the Climate Impacts Group of the CSIRO Division of Atmospheric Research for The National Greenhouse Advisory Committee (NGAC). The purpose of this report is to augment a study entitled: “Coastal vulnerability and greenhouse induced environmental change - formulation of a methodology for use in coastal management and planning”, conducted by Professor Thom and Dr Cowell (University of Sydney) and Dr Tainsh (Public Works Department), under the Dedicated Greenhouse Research Grant Scheme.

The aims of the Thom et al. study are:

1. To provide a system taking climatic and sea-level projections from NGAC Core Projects and applying them to risk assessment in the coastal zone, for use in determining practical planning matters such as set-back limits for development and land-use zonings.
2. To investigate factors involved in producing various types of vulnerability in coastal NSW, assuming that vulnerability is enhanced by rises in sea level and increased storminess over the next 50 years.
3. To evaluate the impact of the different management practices on the overall vulnerability of these environments to climate change in order to determine management practices most appropriate to particular environments.

To achieve these objectives, a Geographic Information Systems technique combining stochastic and descriptive logic procedures for routine risk analysis was developed.

The purpose of this report is to identify the dominant weather systems and discuss their influence on coastal processes along the New South Wales (NSW) coast. The influence of climate variability and the possible effects of anthropogenic climate change on the NSW coast, based on a combination of specific modelling studies and analysis and literature review, are discussed. The report also identifies areas where future research is desirable and outlines, where appropriate, methodologies that could be applied, based on either new techniques for analysis, or new model data sets.

Several specific objectives were identified under the agreement:
1. A specialised modelling study of sea-breezes under present and elevated sea surface temperature conditions.
2. A set of storm surge simulations under present and enhanced SST conditions were to be carried out to determine the possible impact of enhanced greenhouse effect on storm surge intensity.
3. An analysis of changes in surface winds over the Tasman Sea to be examined using available simulated climate data and implications of these changes on the wave climate of NSW discussed.
4. Seasonal and daily rainfall changes under enhanced greenhouse conditions to be examined.
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1.1 The New South Wales Coast

Beach and nearshore physical processes are largely governed by the movement of the sea and consequent erosion and transport of sand and sediments in the coastal zone. These movements are caused by winds, waves, tides, currents, storm surges and tsunamis. In relation to climate variability and climate change due to the enhanced greenhouse effect, storm surges, wave climates, and currents have the greatest potential to vary over time as atmospheric and oceanic conditions vary. The capacity for
these processes to affect the coastal zone will also increase as sea-level rises due to the enhanced greenhouse effect.

Coastal processes are affected by weather systems over two distinct time scales. On temporal scales operating over several days are the destructive consequences of extreme sea-level events that are driven by severe atmospheric storms. In such events, it is the combination of storm surge and wind driven waves that produce elevated sea levels at the coast and possible coastal flooding. High rainfall associated with the storm may also contribute to flooding in river systems and estuaries. Wind and wave action accelerates erosion, and coastal currents facilitate littoral transport. On longer time scales extending to years and decades, the cumulative effect of all weather events determines the wave climate of the region and its subsequent influences on the coastal zone.

The NSW coastline extends from the sub-tropics in the north to the mid-latitudes in the south and as such experiences severe weather from a range of meteorological conditions. In the north, depressions that form in easterly troughs on the coast are a major source of severe weather as are tropical cyclones in the warmer months. The southern coastal regions are affected by low pressure systems including cut-off lows which develop in the Tasman Sea to the north of a blocking high (McInnes et al., 1992) and migratory lows which may originate over the continent or the Great Australian Bight and travel eastwards. They often intensify when they reach the east coast. East coast lows can form within a larger migratory depression to produce severe weather conditions along the NSW coast (Holland et al., 1987).

In addition to depressions are wind changes associated with the eastward movement of cold fronts. In the warmer months when the cold fronts are generally shallower, the orography of the east coast blocks and channels the cold air behind the front to produce severe squally winds along the east coast at the leading edge of the front. These events are known as southerly busters (McInnes, 1993) and whilst responsible for severe coastal weather conditions, are usually short-lived so as to not have a major effect on the wave climate of the region.

The central coastal regions experience an overlap in the weather systems that occur in the northern and southern regions. All regions experience the effects of the eastward movement and intensification of anticyclones that can produce north-easterly winds on the coast. They generally cross the NSW coast at around 37ºS in winter and about 29ºS in summer. When the centre of the sub-tropical high moves eastward of about 150ºE, atmospheric conditions on the coast are relatively calm and during the summer months, differential heating and cooling of the land surface occurs relative to the ocean and causes sea and land breezes. Cold fronts often occupy the region between two successive high pressure systems and their passage generally brings about a change in wind direction in the Sydney region from south easterly winds which become progressively easterly as the high moves further to the east.

1.2 The Outline of this Report

With regards to the key atmospheric phenomena identified as influencing sea-level fluctuations and wave climate on the NSW coast, the remainder of the report attempts to summarise the current knowledge of the possible effect of climate change. Chapter 2 examines the wind climate at selected locations off the NSW coast in high resolution climate simulations of current and doubled CO₂ conditions. The need for further work in this area, as simulations from improved climate models become available, is also discussed.

Chapter 3 examines east coast lows in a GCM simulation and compares the number and intensity of systems under doubled CO₂ conditions. Chapter 4 summarises recent progress in quantifying the effects of climate change on tropical cyclones. Chapter 5 examines the typical synoptic situations conducive to
sea-breeze occurrence. High resolution sea-breeze simulations on the NSW coast are also presented in which surface temperatures are elevated by an amount consistent with a doubling of CO$_2$.

Chapter 6 examines the influences of cyclones and anticyclones on NSW climate from 1973 to 1996. The results are correlated with the Southern Oscillation Index to determine the way in which storm tracks vary with extremes of ENSO. The impact of climate change on storm tracks is then addressed based on results from other studies.

The impact of climate change on seasonal and daily rainfall over NSW is summarised in Chapter 7 based on the results of recent nested climate simulations under present and doubled CO$_2$ conditions. The implications of the findings in view of recent catchment modelling studies are also discussed. Chapter 8 discusses factors influencing sea-level rise and presents scenarios for sea-level rise under enhanced greenhouse conditions for the NSW coast.

A study of storm surges on the NSW coast is presented in Chapter 9. A review of the weather systems most conducive to storm surge generation is carried out and it is found that east-coast lows and intense mid-latitude lows situated in the Tasman are the most common cause. Three storm surge events are modelled and the impact of a sea-surface temperature increase on the storm surge height is investigated.
2. Wind Climatology

2.1 Introduction

The largest contribution of energy from the sea to the nearshore and beach region which drives erosion and transport of sand and sediment is from wind-generated waves. The wave climate is governed by the climatological average of all weather situations, which affect a particular coastal region. The four components of the wind field that affect the wave climate are the wind direction, strength, duration and fetch. In this Section, changes to the wind climate of the east coast, due to the enhanced greenhouse effect, are examined using Regional Climate Model (RCM) simulations. The main components that will be examined are wind strength and direction changes, although duration of events will be briefly examined also.

For the Sydney region of the east coast, the total annual wave climate is made up of waves that originate from the north-east (17%), east (42%) and south-east (41%), (Short and Trenaman, 1992). Northeast waves occur predominantly in summer, are of relatively low amplitude (1.25 m) and have relatively short wave periods (7-8 s). Easterly waves occur year round with peaks in March and November and amplitudes predominantly 1.5 m high (but reaching 3 m on occasion) with a 9 s period. SE waves have a broader spectrum of wave heights reaching summer and winter maxima of 4 m. The winds responsible for wave generation are caused by five dominant meteorological systems; tropical cyclones, east coast lows, mid-latitude cyclones, zonal anticyclonic highs and sea-breezes.

2.2 Methodology

The limited area model DARLAM (CSIRO Division of Atmospheric Research Limited Area Climate Model) was nested at 125 km within the CSIRO Mark II simulation and run for ten years under 1×CO₂ and 2×CO₂ conditions to produce regional climate simulations. Ten years of once daily 10 m winds have been averaged over three rectangular regions that broadly represent the genesis region of tropical cyclones (TC region), east coast lows (EC region) and mid-latitude lows (ML region); (Figure 2.1). Over each of these regions, information from 9 grid-points has been used. In terms of broad-scale synoptic features, the TC region will also sample characteristics of the trade winds which are most pronounced in this region during the summer months. Easterlies from the EC region during summer may be associated with anticyclonic activity over the Tasman Sea. During the winter half-year, they may be associated with depressions located offshore. Southerlies and south-easterlies from the mid-latitude region will generally be caused by mid-latitude depressions or their associated cold fronts.

Changes in wind frequencies have also been considered at locations closer to Sydney. These inner locations, denoted the northern inner (NI), eastern inner (EI) and southern inner (SI) regions, are shown on Figure 2.1 and represent a single model grid-point at each location. North-easterly winds, especially those of weaker strength, from the NI region are most likely to be caused by anticyclones located in the central Tasman. North-easterlies of greater intensity may be associated with tropical depressions located further north in the Coral Sea, particularly during the summer months. Weaker easterly winds from the EI region may also be associated with anticyclones located in the Tasman during the warmer months, while stronger easterlies particularly from autumn to spring are likely to be associated with depressions such as east coast lows in the Tasman Sea. South-easterly winds from the SI region are likely to be associated with depressions further south in the Tasman Sea, cold front activity or east coast lows.

All modelled winds are compared to observational winds derived from the European Centre for Medium-range Weather Forecasting (ECMWF). These analyses were available for six years from 1985 to 1990.
Figure 2.1: Diagram indicating the location where winds from the 125 km Regional Climate Model winds were analysed. The three curved boundaries denote the source regions for tropical cyclones, east coast lows and mid-latitude lows based on Short and Trenaman (1992). Modelled and observed winds are averaged and compared over the rectangular regions TC, EC and ML. Winds are also compared at the northern, eastern and southern inner points labelled NI, EI and SI respectively.

2.3 Analysis of Outer Wind Changes

Figures 2.2, 2.3 and 2.4 compare the wind frequencies at the three outer locations shown in Figure 2.1 for each season from the 1xCO$_2$ and 2xCO$_2$ simulations with equivalent observational data derived from ECMWF analyses. In the northern-most region bounded by 160ºE-165ºE and 23ºS-28ºS and referred to as the tropical or TC region, winds are predominantly from the east to south-east particularly in the summer and autumn. During the spring, summer and autumn, the 1xCO$_2$ simulation tends to underestimate the frequency of south-easterly winds and overestimates the frequency of the north-easterlies. During winter however, good agreement exists between analyses and the 1xCO$_2$ simulation.

In the 2xCO$_2$ simulation, north-easterly and easterly winds undergo a general reduction in frequency, which is most pronounced in autumn and winter. South-easterly winds on the other hand increase in all seasons. The south-easterly trade winds are a dominant feature of the wind climate of the TC regions. Winds from other directions may be caused by tropical storms or cyclones. Therefore, an increase in the frequency of south-easterly winds in the warmer months of the 2xCO$_2$ climate may indicate fewer instances of tropical storms. In further support of this is the fact that the frequency of north-easterly and north-easterly winds, which are most likely to occur if a low is located in the Coral Sea, tend to decrease in the 2xCO$_2$ simulation, and the most pronounced decrease is in the higher wind-speed categories.
Figure 2.2: Histogram representing the frequency of occurrence of wind direction for the four seasons for the TC (tropical cyclone) region indicated in Figure 2.1 for observed and simulated conditions.

Figure 2.3 compares wind frequencies for each season over the eastern region bounded by 155ºE-160ºE and 34ºS-39ºS. Winds in this region are fairly uniformly distributed among all directions during summer and autumn. During winter and spring, there is a greater frequency of winds from the southwest and west. In general, the 1xCO₂ simulation produces more westerly wind days and less easterly wind days than observations suggest and this is likely to be caused by too few low pressure systems occurring in the region in the model simulation. Differences between the 1xCO₂ and 2xCO₂ wind frequencies are relatively small but are generally suggestive of a further increase in westerlies and decrease in easterlies. A reduction in the incidence of low pressure systems in this region is likely to be a contributing factor, and indeed was found by Katzfey and McInnes (1996) (see Chapter 3), for the CSIRO R21 model simulation which was used to provide boundary conditions for the RCM simulation used in the present study.
Figure 2.3: Histogram representing the frequency of occurrence of wind direction for the four seasons for the EC (east coast) region indicated in Figure 2.1 for observed and simulated conditions.

The mid-latitude region (Figure 2.4) is dominated by winds with a large westerly component all year round. The model in this region overestimates the frequency of wind days that have winds with a westerly component and underestimates the frequency of wind days in the other five wind direction categories. In the 2xCO₂ climate, there is little change in the wind climate in summer, autumn and spring. Winter however, exhibits an overall reduction in winds consisting of a westerly component and a corresponding increase in winds from all other directions.
In terms of the contribution of winds to the wave climate in Sydney, the most relevant wind directions for analysis are north-easterly winds in the tropical region, easterly winds in the east coast region and south and south-easterly winds in the mid-latitude region. Southerly winds are included in the latter category since the directional frequency is reasonably homogeneous with longitude in this region and southerly winds originating from a location slightly further west may also influence the wave climate on the east coast. It is noteworthy that the wind directions in each region which are likely to have the greatest impact on the wave climate on the east coast are not the dominant winds in the region and in some cases provide the smallest contribution to the overall wind climatology. Table 2.1 summarises the changes in frequency of winds from these directions between the 1×CO₂ and 2×CO₂ simulations and indicates where the changes are statistically significant.

In the summer months, there are slight increases in the frequency of winds from the EC and ML regions. The increase in easterly winds in the EC region is related to a movement further south of the
trade easterlies in the 2×CO$_2$ simulation at this time of the year. During the autumn months however, there is an overall reduction in winds from all three quadrants.

During the winter months, there is a decrease in winds from the TC region and an increase in winds from the ML region. Both these changes are statistically significant at the 90% confidence interval although it should be noted that these wind direction categories represent a small percentage of the total. The winds from the TC region fall predominantly into the weakest wind speed category while those from the ML region also include increases in the frequency of winds in the 8-16 m s$^{-1}$ category. Changes during spring in the 2×CO$_2$ climate consist of a reduction of winds from the TC and EC regions and a slight increase in winds from the ML region.

The persistence of wind events was also examined for the three outer regions. For the wind direction classes considered in the three regions, at least 50% of all events of a given wind direction were found to persist for only a day and fewer than 1% were found to persist for more than 4 days. Table 2.2 summarises the main results. The east coast region during the summer months experiences a shift to longer duration easterly wind events under 2×CO$_2$ conditions. In all seasons, the ML region undergoes a shift to events of longer duration in the 2×CO$_2$ climate. However, only in JJA is the longer duration of events also combined with a greater frequency of events in the 2×CO$_2$.

Table 2.1: The frequency of days per season (expressed as a percentage) which experience winds from the directions indicated. For each of the three regions, TC (tropical cyclone), EC (east coast) and ML (mid-latitude) which are indicated in Figure 2.1, only the wind direction likely to influence the wave climate at Sydney, is considered. The total frequencies are also broken down into wind speed categories of less than 8 m s$^{-1}$, 8-16 m s$^{-1}$, and greater than 16 m s$^{-1}$. Changes between the 1×CO$_2$ and 2×CO$_2$ that are statistically significant at the 90% confidence level, based on a standard t-test, are indicated in bold typeface.

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<th>Season</th>
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<th>1 × CO$_2$</th>
<th>2 × CO$_2$</th>
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<td>8-16 m s$^{-1}$</td>
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</table>
Table 2.2: The frequency of days per season (expressed as a percentage) for which the winds persist for one day or greater than one. Note that for each of the three regions, TC (tropical cyclone), EC (east coast) and ML (mid-latitude) indicated in Figure 2.1, only the wind direction likely to influence the wave climate at Sydney is considered.

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<td>SE&amp;S</td>
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2.4 Analysis of Inner Wind Changes

Comparison of winds at grid-points closer to Sydney is made with ECMWF analyses in Figures 2.5-2.7. The inner northern location during summer is dominated by northerlies through to south-easterlies and southerlies while during winter, southerlies and south-westerlies are dominant. A striking feature in the 1×CO₂ simulation, is the degree to which it has captured the shift in directional frequencies with the seasons. In summer, the main difference is an underestimation in southerlies and an overestimation in the north-westerlies. In autumn and winter, there is an overestimation in the frequency of southerlies and south-westerlies. During spring, the model tends to underestimate northerlies and overestimate north-westerlies.

The most consistent change between the 1×CO₂ and 2×CO₂ simulations is an increase in northerlies and a decrease in southerlies and south-westerlies during summer, autumn and spring. However in winter, the direction of change in these wind categories is reversed.

At the inner eastern location, the model again captures the overall pattern of distribution of winds reasonably well. In summer, northerlies and north-easterlies occur too frequently in the model at the expense of winds from almost all other directions. In autumn and winter, northerlies through to easterlies in the model tend to be underestimated in frequency while winds with a westerly component are generally overestimated.

At the inner southern location, the model again captures the overall seasonal wind frequencies. Again, however, there is a tendency for northerlies, north-easterlies and easterlies to be underestimated while
south-westerlies, westerlies and north-westerlies tend to be overestimated. This is most pronounced in autumn.

![Histograms](image)

**Figure 2.5:** Histogram representing the frequency of occurrence of wind direction for the four seasons for the NI (inner northern) location indicated in Figure 2.1 for observed and simulated conditions.

At each of the inner locations, winds that influence waves in the Sydney region are; north-easterlies from the northern-most location, easterlies from the eastern location and south-easterlies from the southern-most location. The changes in frequency of winds from these directions between the $1\times CO_2$ and $2\times CO_2$ simulations are summarised in Table 2.3. Also included is a breakdown of frequencies of the various wind-speed categories. North-easterly winds are most frequent in summer and spring where they are predominantly of the lowest wind speed category. This is consistent with the results for the TC region. In the $2\times CO_2$ climate there is an overall reduction in north-easterlies at all times of the year, although only the wintertime reduction is statistically significant.
Easterly winds from the EI location are most pronounced during summer, although as previously noted, easterlies are generally underestimated at other times of the year. In the $2\times\text{CO}_2$ climate, their occurrence increases slightly in spring and summer and reduces in autumn and winter, the latter of which is statistically significant and is likely to be related to the reduced east coast low-type activity under a doubling of \text{CO}_2, as found in Katzfey and McInnes (1996).

The incidence of south-easterly winds from the SI location is generally lower from summer through winter and almost unchanged in spring. South-easterly winds at this location are likely to be associated with east coast low activity also, particularly during the colder months. Cold fronts and mid-latitude depressions located in the southern Tasman sea are also likely to contribute to the incidence of south-easterly winds. The reduction of east coast low-type activity reported in Katzfey and McInnes (1996)
under doubled CO$_2$ conditions is likely to extend to mid-latitude lows in general. This will be discussed further in Chapters 3 and 6.

![Histogram representing the frequency of occurrence of wind direction for the four seasons for the SI (inner southern) location indicated in Figure 2.1 for observed and simulated conditions.](image)

**Figure 2.7:** Histogram representing the frequency of occurrence of wind direction for the four seasons for the SI (inner southern) location indicated in Figure 2.1 for observed and simulated conditions.

The duration of wind events was examined also, and results are summarised in Table 2.4. In general, wind events tended to be of shorter duration over the three locations considered. Wind events that lasted for more than one day, occurred most frequently (i.e. in more than 30% of events) from the north-east in the summer and from the east and south-east in autumn and winter in the 1×CO$_2$ climate. Under doubled CO$_2$ conditions, the frequency of these longer wind events was reduced however, except for easterly wind events during winter.
Table 2.3: The frequency of days per season (expressed as a percentage) which experience winds from the directions indicated. Note that for each of the three regions, NI (inner northern), EI (inner eastern) and SI (inner southern) indicated in Figure 2.1, only the wind direction likely to influence the wave climate at Sydney, is considered. The total frequencies are also broken down into wind speed categories of less than 8 m s\(^{-1}\), 8-16 m s\(^{-1}\), and greater than 16 m s\(^{-1}\). Changes between the 1\(\times\)CO\(_2\) and 2\(\times\)CO\(_2\) that are statistically significant at the 90% confidence level are indicated in bold typeface.

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<td>Freq. %</td>
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Table 2.4: The frequency of days per season (expressed as a percentage) for which the winds persist for one day or more than one day. Note that for each of the three regions, NI (inner northern), EI (inner eastern) and SI (inner southern) indicated in Figure 2.1, only the wind direction likely to influence the wave climate at Sydney is considered.

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</table>
2.5 Discussion

In this Section, an analysis of wind climate changes between the 1×CO$_2$ and 2×CO$_2$ climates in a Regional Climate Model simulation has been performed for the NSW coastal region. Each of the climate simulations was carried out for ten years with boundary conditions taken from the CSIRO R21 Mark II slab ocean GCM simulation. Ten metre wind data was available once daily at 0000 UTC. The approach adopted in this study was to examine firstly, the wind climate based on an average of nine grid-points located in the north-central, central and south-central Tasman Sea. The rationale behind this choice is that these locations are representative of regions where tropical cyclones, east coast lows, and mid-latitude cyclones occur respectively, and these weather systems are a major contributor to the wave climate along the east coast. Winds at three individual grid-points closer to the east coast were also examined. The main results are summarised in Figure 2.8.

There is little overall change in winds from the key directions considered during summer. The only notable change is a 3% overall reduction in north-easterlies from the inner northern location.

In autumn, winds from all of the locations indicated undergo a reduction in frequency. This reduction is most pronounced at the outer east location and may reflect the occurrence of fewer east coast low-type depressions occurring in the Tasman, as found in Katzfey and McInnes (1996). It should be noted however, that these changes are not statistically significant.

Winter exhibits the most pronounced changes with statistically significant reductions in north-easterly winds at both the outer and inner northern locations. The outer southern region on the other hand, undergoes an increase in southerlies and south-easterlies that are also statistically significant. The other three locations undergo slight reductions in wind frequencies under 2×CO$_2$ conditions. In spring, small increases in the frequency of winds occur from the east and south, while a slight reduction occurs in north-easterly winds at the outer-most northerly location.

The overall tendency is for increases (or in autumn, more minor decreases) in winds from the south central Tasman compared with the north central Tasman and inner north location which generally experiences reductions. In the autumn months, these reductions are more pronounced than those in the south-central Tasman. Such a change could produce a shift in the directional distribution of the wave energy resulting in more swell from the south compared with waves from the north and this could have an impact on littoral processes on beaches along the east coast.

Winds at both eastern locations and the inner southern location underwent a reduction in frequency in summer, autumn and winter although slight increases occurred in spring. This result is likely to be related to the tendency for slab ocean GCM’s (such as the one used to provide the boundary conditions for the RCM analysed here) to produce fewer mid-latitude cyclones in doubled CO$_2$ climates. In particular, this was found for the east coast region by Katzfey and McInnes (1996) for the east coast region (see Section 3 for details). In that study, a smaller reduction in the numbers of lows in spring was also found in the enhanced greenhouse climate although the reasons why this occurred are uncertain.

It is worth re-iterating that while changes were seen in the wind frequencies in the Tasman Sea, they were, for the most part, not statistically significant and therefore, may simply represent natural variations and not constitute a systematic response of the model. Furthermore, the results presented in this study are based on an older style of GCM that utilises a slab ocean where only the upper 50 m of the ocean is represented. Clearly, such models are unable to represent the deep ocean circulation and changes to it resulting from increased greenhouse gases. This constitutes a major limitation on the results derived from such models.
Preliminary results obtained from GCMs that are coupled to dynamic ocean models reveal considerably different results to the mixed-layer ocean GCMs. In particular, the relatively high level of warming that occurs in high southern latitudes in mixed-layer GCMs, is not seen in fully coupled GCMs. This is because the southern ocean in coupled GCMs absorbs some of the heat from the atmosphere at these latitudes and transports it down into the deeper ocean.

As an illustration of the general differences between the two classes of model, we briefly examine some results from four GCMs. They are the CSIRO R21 9-level Mark 1 (Watterson et al., 1995) and Mark 2 (Watterson et al., 1997) slab ocean GCM models and two versions of the CSIRO coupled GCM (Hirst et al., 1996; Gordon and O’Farrell, 1997). The differences between the coupled GCMs relate to the diffusion schemes used in the ocean model. The first uses a horizontal diffusion scheme (Gordon and
O’Farrell, 1997) and will be referred to as the HD model. The second uses a more realistic scheme where diffusion takes place along constant density surfaces and is referred to as the GM model (Hirst et al., 1996). In the 2×CO$_2$ experiments using the slab ocean GCMs, levels of CO$_2$ are doubled and the model integrated forward in time until equilibrium in global mean temperature is reached. Enhanced greenhouse simulations in the coupled models are performed by increasing the CO$_2$ levels at a rate of 1% per year. The model output is stored over a time interval coinciding approximately with a doubling of present day CO$_2$ levels. For convenience, these transient experiments are also referred to as 2×CO$_2$ experiments.

The differences between 2×CO$_2$ and 1×CO$_2$ zonally averaged zonal winds from the four models at the lowest model level (about 200 m above the surface) are shown in Figure 2.9. Westerly winds are dominant south of about 30ºS (not shown). During DJF, the two coupled models indicate no changes in the westerly wind regime under a doubling of CO$_2$ while the two mixed-layer GCMs indicate changes of opposite sign to each other. In MAM, all models exhibit a negative anomaly in this region indicating a weakening of westerlies under doubled CO$_2$ conditions.

In JJA and SON, both slab ocean GCMs agree on an increase in average westerlies of the order of 0.5 m s$^{-1}$. This result is related to the pattern of warming which occurs in this type of model under enhanced greenhouse conditions. More warming takes place in polar regions relative to equatorial regions, thereby reducing the north-south temperature gradient and hence the baroclinicity of the region. Accompanying the weakening of the zonal wind maximum at 50ºS is a general broadening of the band of westerlies (not shown). It is this feature which leads to positive westerly wind anomalies in the southern Australian latitudes under enhanced greenhouse conditions.

The coupled models in JJA and SON, on the other hand indicate a change of the opposite sign in southern Australian latitudes. A strengthening of the zonal wind maximum occurs further south and is accompanied by a narrowing in the westerly wind belt and hence a weakening of average westerlies over southern Australian latitudes. The strengthening of the westerly wind maximum around 50-60ºS is likely to be related to the pronounced heat uptake by the dynamic ocean model at these latitudes which helps maintain a strong north-south temperature gradient in the southern hemisphere.

These results illustrate that, wind climatologies for the NSW coast could be strongly influenced by the type of GCM simulation used, particularly in relation to winds originating from the southern ocean. This point has also been made by Whetton et al. (1996) in relation to rainfall results from coupled and mixed-layer ocean models in the Australian region. In principle, the coupled experiments are likely to be most representative of future changes since coupled GCM is a more physically based representation of the whole climate system.
Figure 2.9: Enhanced greenhouse change in zonal wind (m s\(^{-1}\)) based on model winds at 920 hPa for the CSIRO Mark I and Mark II mixed-layer ocean GCMs and fully coupled HM and GM GCMs. Note that a westerly wind anomaly is positive.
3. East Coast Lows and Climate Change

3.1 Introduction

The east coast of Australia is a favoured location for the development of intense surface low pressure systems often responsible for severe rainfall and winds. These systems often develop in association with a blocking anticyclone that forms at latitudes higher than the normal location of the subtropical ridge. Such depressions generally become ‘cut-off’ from the westerly airflow and may persist in the region for several days. Cut-off lows can also provide the synoptic environment for the severe and rapid cyclogenesis often associated with the development of east coast lows. While east coast lows are generally too small in scale to be represented by the typical resolution of GCMs, the larger scale cut-off lows are simulated. In this Chapter, the representation of cut-off lows over the east coast of Australia in the CSIRO Mark I GCM slab ocean simulation is investigated. A detailed account of this study can be found in Katzfey and McInnes (1996) and only a brief summary of the main findings are presented here.

3.2 Representation of East Coast Lows in a GCM

A detailed comparison of a GCM generated cut-off low with an observed cut-off low shows that even at the R21 (500 km × 500 km) horizontal resolution, the CSIRO 9 Mark I slab ocean GCM simulation can capture many of the observed features of these systems. One of the main differences is a tendency in the GCM for the surface low to develop further east of the upper-level low. In this configuration, the lows are usually more mobile. Consistent with this finding is the fact that cut-off lows in the GCM tend to travel more rapidly from west to east than the observed lows, as indicated in Figure 3.1. In observed cut-off lows, the surface low development is often preceded by the development of an upper level cut-off low and latent heat release plays an important role in intensifying the surface low. These characteristics were also seen in the development of the GCM cut-off low and this provides confidence in the ability of the GCM to adequately represent the development of these systems.

However, the GCM was found to under-simulate the frequency of cut-off lows in the east coast region by about 45% in the ×CO₂ simulation and this was most pronounced in autumn and winter (Figure 3.2). Model resolution and differences in sampling intervals may be an overall contributing factor in this result. Furthermore, in the summer months, the heat low over northwest Australia was more intense in the GCM simulation than in the observational data, and this may have contributed to a relatively higher incidence of lows which became mobile and moved eastwards and intensified during spring and summer months. From autumn to spring, on the other hand, the subtropical ridge in the GCM extended further east into the Tasman than observations indicate and this is consistent with the incidence of fewer lows developing in this region.
3.3 The Impact of Climate Change

The incidence of cut-off lows was also examined in the $2\times$CO$_2$ simulation and it was found that even fewer cut-off lows occurred over eastern Australia (Figure 3.2). This result is likely to be related to the pattern of warming which occurs in the GCM. In general, polar regions warm relatively more than the tropics resulting in a weaker zonal temperature gradient and hence decreased baroclinicity. As a result of this, fewer mid-latitude systems develop. A similar result has been found in other studies which examine extratropical cyclones in slab ocean GCMs (König et al., 1993; Bates and Meehl, 1986).

While fewer systems are found in the doubled CO$_2$ climate, there is a tendency for the cut-off lows that developed in the Australian region to be more intense (Figure 3.3) than those found in the present climate simulation. This result suggests a greater role played by latent heat effects once development has been initiated.
3.4 Conclusions

This study has shown that the GCM captures many of the important features associated with the
development of cut-off lows. However, the underestimation of cut-off low numbers suggests that low
model resolution may be the primary cause. An analysis of higher resolution GCMs or even RCMs that
are nested within lower resolution GCMs may yield more realistic frequencies and intensities of cut-off
lows under present climate conditions.

The GCM used in this study was a slab ocean GCM and, as discussed in Chapter 2, such models tend to
produce relatively greater warming in the high mid-latitudes than coupled model GCM simulations under
enhanced greenhouse conditions. It is possible therefore that a different result could be obtained by
examining a transient coupled ocean GCM.

Figure 3.3: The relative frequency distribution of the lowest central pressure attained by each of the
cut-off lows while located within the east coast region for the ECMWF analyses and the two GCM
simulations.
4. Tropical Cyclones and Climate Change

4.1 Introduction

This Section reviews recent developments addressing the issue of tropical cyclones under enhanced greenhouse conditions. A recent review of this topic is contained in Henderson-Sellers et al. (1998). Tropical cyclones can directly affect the northern coastal regions of NSW although their frequency is fairly low with only about 10 cyclones occurring since 1960. Cyclones of tropical origin can also degenerate into extratropical depressions as they track south, bringing rain and severe weather to more southern coastal regions. Therefore, the effect of the enhanced greenhouse effect on tropical cyclones could influence not only the frequency and intensity of cyclones affecting the northern coast of NSW but also the future incidence of mid-latitude depressions occurring further south.

The numbers of tropical cyclones approaching the east coast of Australia is strongly affected by the state of the ENSO (e.g. Basher and Zheng, 1995). While significant advances have been made recently in our understanding of the effects of climate change on El Niño (Tett, 1995; Roeckner et al., 1996), it is still fair to say that this issue is uncertain. If the characteristics of El Niño were to change in any significant way, it could affect tropical cyclone numbers off the east coast of Australia, either decreasing or increasing them.

There are additional large uncertainties associated with tropical cyclone behaviour under enhanced greenhouse conditions because tropical cyclones are not adequately resolved by the relatively low grid resolution of the GCMs used in climate studies. The development of RCMs in which a higher resolution atmospheric model is nested within a GCM over a geographical region of interest comprised a significant step towards representing tropical cyclones more realistically in climate simulations (see for example Walsh and Watterson, 1997).

In general, climate change could affect the following characteristics of tropical cyclones in the NSW region:
- Numbers
- Intensities
- Regions of Formation
- Regions of Occurrence i.e. what happens to tropical cyclones after they form and leave the tropics.

Each of these factors will be discussed in turn.

4.1.1 Tropical Cyclone Numbers

At present, there is no entirely satisfactory way of estimating the effect of climate change on tropical cyclone numbers. Two main approaches have been used in the past. Climate models have been used to generate low pressure systems which have some of the structural characteristics of observed tropical cyclones, and their numbers simulated under the current climate and under enhanced greenhouse conditions have been counted. A recent example is the GCM study of Bengtsson et al. (1996). Studies of this kind have been hampered by concerns about the reliability of the response of the climate model to enhanced greenhouse conditions when simulating a combination of several important atmospheric parameters such as those that are needed to model tropical cyclones. For instance, Bengtsson et al. (1996) found that under enhanced greenhouse conditions the number of tropical cyclones generated by their model in the Southern Hemisphere more than halved. This is an extreme response compared with observed natural variability in the Southern Hemisphere and therefore raises questions about the quality of the model’s response to climate change. In contrast, climate change simulations using a regional
climate model (Walsh and Katzfey, 1998) suggested slight increases in tropical cyclone numbers, at least in the Australian region.

Another approach has been to derive parameters from combinations of atmospheric and oceanic variables that are known to be important for tropical cyclone formation, and to apply these parameters to the output of GCM simulations of current and enhanced greenhouse climates. Unfortunately, the best known of these, the seasonal genesis parameter of Gray (1975, 1979), is clearly tuned to the current climate (Ryan et al., 1992). When it is applied to enhanced greenhouse simulations, the number of cyclones it predicts is typically double that of the current climate because of the seasonal genesis parameter’s extreme sensitivity to sea surface temperatures, which naturally increase as a result of global warming. This sensitivity is not observed in nature. More recent attempts to update and modify the seasonal genesis parameter in order to remove this sensitivity have yet to be validated thoroughly (Royer et al., 1998).

Note that tropical cyclone numbers in the Australian region are strongly influenced by the state of ENSO, as mentioned above, whose exact characteristics in a warmer world are currently uncertain.

4.1.2 Intensities

In contrast to numbers, more can be said about tropical cyclone intensities in a warmer world. As is the case for numbers, both direct model simulation of intensities and theoretically-derived parameters have been used to estimate this effect. Unlike techniques used to estimate cyclone numbers, however, those used to predict intensity changes have been much more thoroughly validated.

A recent study by Knutson et al. (1998) is perhaps most relevant. In that study, an established tropical cyclone weather forecasting system was modified to simulate a number of tropical cyclone-like vortices (TCLVs) in both the current climate and under enhanced greenhouse conditions. The design of the experiment was as follows. Weak TCLVs were detected in a coarse-resolution GCM simulation, and their positions noted. At these positions, a high-resolution limited-area forecast model was nested within the GCM, and an artificial TCLV of a specified intensity was inserted in the mesoscale model at this point. The subsequent intensity evolution of the TCLV was then followed over a period of several days. This procedure was repeated 50 times at various locations in the north-west Pacific ocean basin, for both the current and enhanced greenhouse climates.

The results suggest that both mean and maximum tropical cyclone intensities are likely to increase slightly in a warmer world. A study for the Australian region based on a similar technique (Walsh and Ryan, 1998) reaches the same conclusion, although the fact that the Australian region has less open ocean than the north-west Pacific makes it more difficult for the storms to intensify. As a result, the intensity increases under enhanced greenhouse conditions in the Australian region tend to be less than in the Knutson et al. (1998) study.

A second approach involves formulating a parameter that can analyse the output of a GCM to derive typical maximum cyclone intensities at various locations, depending upon the average atmospheric and oceanic conditions that are encountered. It is suggested that the maximum potential intensity that a tropical cyclone can reach in any one location depends on the energy available in the atmosphere at that location. Such parameters (Emanuel, 1987, 1991; Holland, 1997) suggest modest to moderate increases (10-20%) in maximum tropical cyclone intensities in a warmer world. Unfortunately, as with most climate modelling estimates, the uncertainties in this technique are fairly large, as the errors in a GCM simulation of the maximum potential intensity in the current climate are typically larger than the forecast change in intensity.
Thus, a number of recent studies suggest some increase of mean and maximum tropical cyclone intensities as a result of climate change.

4.1.3 Regions of Formation

It is now realised that there is no *a priori* reason why the regions of formation of tropical cyclones would necessarily increase as a result of global warming. Under the current climate, tropical cyclones only form where sea surface temperatures are at least 26°C. While it is true that the area likely to experience such temperatures will increase as a result of global warming, there are good theoretical reasons to believe that the sea surface temperature threshold for cyclone generation is actually a function of a number of different atmospheric conditions. Tropical cyclone formation itself is better related to a threshold for particular rainfall conditions than it is to sea surface temperatures directly. Under enhanced greenhouse conditions, it is therefore considered likely that a new, higher sea surface temperature threshold would be established for tropical cyclone formation, since the atmospheric conditions would also change (Holland, 1997). The net result would be little change in the regions of cyclone formation. The results of Walsh and Katzfey (1998) show a statistically insignificant southward shift in formation and therefore tend to support this conclusion. This is discussed in more detail in the next Section.

4.1.4 Regions of occurrence

Tropical cyclones form in tropical regions of the globe, but they often travel far poleward of their regions of formation while retaining destructive winds and intense rainfall. Since the mechanisms of formation and dissipation are not entirely similar, it is reasonable to speculate that regions of occurrence could be influenced by changes in sea surface temperatures, since higher sea temperatures could give a cyclone more energy to retain its intensity and characteristics for a longer time. It has been suggested (Henderson-Sellers et al., 1998) that changes in the way cyclones dissipate could occur as a result of global warming.

Little work has been performed on this issue. One of the first studies to examine it is that of Walsh and Katzfey (1998). This work is examined in detail below.

4.2 Tropical Cyclone-Like Vortices in an RCM

In the study reported upon here, 20 years of seasonally varying RCM simulations at 125 km horizontal resolution, nested in a slab ocean GCM under 1x and 2xCO₂ conditions have been analysed to determine the ability of the nested RCM to simulate TCLVs.

The first task was to determine an appropriate threshold for TCLV detection. A threshold is needed because observed tropical cyclones are defined to occur when a low pressure system in the tropics has a cyclonic low-level circulation and near-surface wind speeds greater than 17 m s⁻¹. This observed threshold is probably not appropriate for an RCM simulation of 125 km horizontal resolution, however, as it is well known that simulated TCLV intensities increase with finer horizontal resolution (e.g. Krishnamurti and Oosterhof, 1989; see also Figure 4.1). In Walsh and Waterson (1997), a lower threshold for TCLV detection was established based upon the Outer Core Wind Strength (OCS, Weatherford and Gray, 1988), which is the mean tangential (i.e. around the cyclone centre) wind speed in the region of radius 110-270 km from the cyclone centre. This measure was considered more appropriate than maximum wind speed because the inner core region of a tropical cyclone, where the observed maximum wind speed occurs, is typically less than 100 km from the storm centre and thus not resolved at all by an RCM with a horizontal resolution of 125 km. In Walsh and Waterson (1997), a
threshold OCS value of 10 m s$^{-1}$ was chosen based upon some analysis of observations performed by Weatherford and Gray (1988).

In Walsh and Katzfey (1998), a slightly different approach has been used. TCLVs were first detected in the 125 km horizontal resolution RCM simulation, and were then inserted into a finer-resolution mesoscale model implemented around the detected position of the cyclone; the finer-resolution domain has a horizontal resolution of 30 km and a vertical resolution of 18 levels. A number of different TCLVs were simulated to see whether they would “spin up” or intensify until they reached the observed tropical cyclone threshold of 17 m s$^{-1}$. Tests using initial vortices of varying strengths showed a range of probability of spin-up (Table 4.1). For very weak systems ($2 \text{ m s}^{-1} < \text{OCS} < 4 \text{ m s}^{-1}$), the percentage of storms which spin up is low, whereas a much higher percentage spin up when the initial systems are stronger, as expected. Based upon the figures in Table 4.1, a lower threshold for TCLV behaviour was chosen as being only those storms that have an OCS of at least 5 m s$^{-1}$ in the 125 km resolution simulation. This ensures that around 80% of storms will spin up.

![Simulated mean sea-level pressure](image-url)

**Figure 4.1:** Simulated mean sea-level pressure associated with a tropical cyclone-like vortices at (a) 125 km simulation; and (b) the same storm at 30 km horizontal resolution. Contour interval is 2 hPa.
Figure 4.2: Seasonal variation of cyclone numbers over all regions simulated by DARLAM, for (solid line) observations over the period 1967-1986; and the DARLAM simulation under 1x (dotted line) and 2xCO₂ (dashed line). The numbers are based on an OCS > 5 m s⁻¹.

Table 4.1: Percentage of TCLVs generated in the base simulation (125 km horizontal resolution) which spin up to greater than tropical storm intensity when simulated at 30 km resolution, for varying initial vortex strengths, as measured by the OCS.

<table>
<thead>
<tr>
<th>Number</th>
<th>Strength Interval (OCS in m s⁻¹)</th>
<th>Percentage Spin up</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2 – 4</td>
<td>30%</td>
</tr>
<tr>
<td>20</td>
<td>4 – 6</td>
<td>70%</td>
</tr>
<tr>
<td>20</td>
<td>6 – 10</td>
<td>90%</td>
</tr>
</tbody>
</table>

Once this detection threshold was established (OCS > 5 m s⁻¹), the numbers of TCLVs simulated by the RCM in the current climate could be examined. Figure 4.2 shows the simulated seasonal variation of TCLV numbers. The representation of the observed variation in the model is quite good, although numbers are slightly underestimated. We have also examined regions of TCLV formation (or “cyclogenesis”) and compared them to observations. Figure 4.3 shows the observed and modelled formation regions for tropical cyclones for the months of January, February and March (JFM). This is the period of most frequent tropical cyclone formation in the Australian region.

Comparing observed and simulated cyclogenesis, a number of similarities and differences can be seen. Regions of formation in the model simulation and the observations are similar. Cyclogenesis is suppressed in the model simulation near the boundaries of the domain, where the simulation falls under the influence of the larger-scale forcing of the GCM. The observations (Figure 4.3a) show that there is a broad band of cyclone formation off the northeast and northwest coasts of Australia and in the Gulf of Carpentaria. While the model results (Figure 4.3b) show that the RCM can generate cyclones in the same general areas, numbers are generally smaller than observed, except in some regions off the northeast coast.
Figure 4.3: Observed and simulated tropical cyclone formation, for (a) observed JFM; (b) simulated JFM. Units are numbers cyclones per 20 year period per 5 degree grid square, and results have been interpolated to a 2.5 degree grid for clarity. The observations are taken from NOAA (1988).

4.3 Tropical Cyclones under Enhanced Greenhouse Conditions

Under 2×CO₂ conditions, a similar pattern of seasonal variation is seen (Figure 4.2). Slightly more cyclogenesis is seen in the warmer months compared with the control simulation and slightly less in the colder half year.

In terms of cyclone formation, there is a tendency for cyclones to form slightly further south in the 2×CO₂ simulation, although this change was not statistically significant. An analysis of the climatology of the RCM suggests this may be the result of a number of factors. Tropical cyclogenesis typically occurs in regions of low vertical wind shear, low-level cyclonic vorticity and high mid-tropospheric relative humidity (Gray, 1995, 1979) and convergence (Molinari et al., 1997) and sea surface temperatures higher than about 26°C. These conditions typically promote formation on the poleward side of the monsoon trough. In the 2×CO₂ simulation, the region of low climatological wind shear associated with the monsoon trough has shifted about 300 km south of its position in the current climate simulation.

Cyclone tracks in the 2×CO₂ climate also have shifted further south as can be seen in Figure 4.4, with a statistically significant increase occurring south of 20°S. Investigation of the various factors that may contribute to the persistence of cyclones into more southern regions indicates that increases in SSTs in the 2×CO₂ climate may be a major cause.

There are several other important uncertainties in climate change research which affect the reliability of any conclusions drawn above. The formation regions and numbers of tropical cyclones vary from year to year as a result of variations in the ENSO phenomenon (Basher and Zheng 1995; Evans and Allan 1992), and the state of El Niño in a changed climate is currently unknown (Pittock et al. 1996) although it is
widely believed that El Niño and La Niña events will continue to occur (Tett, 1995). Foremost among all uncertainties, however, is the question of how confident we are about the reliability of our estimates of regional climate change using GCMs. Before any firm conclusions can be made about the regional impacts of climate change on tropical cyclone behaviour in northern NSW, a significant amount of further work needs to be performed on improving confidence in the model predictions upon which possible impacts are based. In particular, the nesting of the RCM in more advanced GCMs needs to be performed.

4.4 Summary

The results presented here indicate that tropical cyclones under enhanced greenhouse conditions may persist further south. This could have a number of consequences for northern NSW. Firstly, tropical cyclones, which only occasionally affect this region in the current climate, may become more frequent. Secondly, there may be a greater incidence of cyclones of tropical origin undergoing redevelopment as extratropical lows which can bring severe weather to more southern coastal regions. Such a result could increase the frequency of severe mid-latitude lows occurring during the warmer months and possibly offset the reductions found during winter that was found for mid-latitude cut-off lows in the previous Chapter. Further investigation would be necessary to determine if this is indeed a consequence of the results presented here. Finally, the wind and wave climate of the region may be altered by a greater frequency of wind waves from the northeast impinging on NSW coastal regions during the warmer months of the year.
Figure 4.4. Simulated cyclone tracks for the months of January, February and March, for (top) 1×CO$_2$ conditions; and (bottom) 2×CO$_2$. Crosses indicate formation locations, while circles represent positions once a day. Tropical cyclone-like vortices are identified as having an OCS $> 5$ m s$^{-1}$ in observed and simulated conditions.
5. Sea-breezes

5.1 Introduction

Sea-breezes are thermally driven circulations caused by the greater heating of the land surface relative to the adjacent ocean. They have a long-term impact on the coastal zone, through their contribution to the wave climate during the warmer months of the year. In the Sydney region, they contribute mostly to low amplitude and short period ocean waves (Short and Trenaman, 1992).

Sea-breezes are a mesoscale phenomena which require model resolution of between 10 and 100 km for adequate representation. GCMs such as the CSIRO R21 model, with a horizontal resolution of around 500 km, cannot resolve the details of such events. Regional climate model simulations conducted at sufficiently high resolution may be able to resolve sea-breezes but storage of model output would be required at sufficiently high temporal resolution to capture the diurnal variation of such events. As such, climate models are a prohibitively costly and impractical alternative for examining the possible effects of climate change on sea-breeze circulations.

In the present study, a more cursory approach is taken to determine how global warming may influence sea-breeze circulations with particular focus on the changes occurring over the sea where wave generation is occurring. This is achieved by running a limited area atmospheric model for known sea-breeze days under control conditions and with surface temperatures increased by amounts consistent with climate model simulations for the region of interest. It should be noted that no change is made to the land sea temperature contrast other than the normal diurnal variations. The effect of the surface warming on wind strength and fetch of the sea-breeze events over the ocean and the nearshore region is examined.

5.2 Synoptic Background

Chosen for the study is a four-day interval during January 1994 when sea-breezes developed in the afternoons of the latter three days. Simulations are conducted using the limited area model, DARLAM, under control and elevated surface temperature conditions. An increase in temperature of 3°C is used and is based on the approximate surface warming over the ocean to the east of Australia produced by the CSIRO R21 GCM simulations under doubled CO₂ conditions.

The model is initialised at 2300 UTC 15 January 1994 using the Australian Bureau of Meteorology’s regional objective analyses. Initially, an anticyclone is located in the central Tasman and a cold front is moving eastwards across south-eastern Australia. A day later, the front has crossed the east coast of Australia (Figure 5.1a). In the following twenty-four hours, it slips away to the south (Figure 5.1b). Anticyclones are located over the south coast of the continent and the central Pacific, leaving a col over the east coast which persists for the next 48 hours (Figures 5.1c,d). The weak pressure gradients in the vicinity of the east coast associated with this synoptic pattern are favourable for sea-breeze development. This suggests that a possible approach to determining changes to sea-breeze occurrence under climate change conditions would be to objectively identify and count occurrences of the broader synoptic scale patterns in a GCM.

5.3 Model Simulations

Figure 5.2 shows the lowest model level temperature in the control simulation. The times of the simulations have been converted to Local Standard Time to facilitate interpretation of the results and are shown at 1300 LST (1 p.m.) and 1900 LST (7 p.m.) on January 17-19. On each of the three days, the
temperature at 1300 shows a well-pronounced temperature gradient located along the coast separating the warmer land from the cooler ocean. By about this time, a low-level onshore flow has developed and continues to strengthen and deepen throughout the afternoon. Figure 5.3 shows a vertical cross-section of the wind perpendicular to the coast and intersecting Sydney at 1300 and 1900 on January 18 (see Figure 5.2a for the location of the cross section). This is typical of the development seen during each of the three afternoons, although the vertical extent of the onshore flow is greater on the 17th, no doubt due to the recent cold front passage which may have influenced the onshore development on that particular day. By 1900 local time, the persistent onshore flow during the afternoon has eroded the long shore temperature gradient bringing air, cooler by up to 10ºC, to inland areas (Figure 5.2b).

The impact of warmer surface temperatures on the wind field, in the model simulation, is illustrated for 1600 January 18 in Figure 5.4. It is indicative of the differences exhibited between the two simulations on the other two days as well as at the times 1300 and 1900 local time. The effect of the warmer surface temperatures is to increase the strength of the onshore flow over the ocean by up to 10% of the wind strength in the control simulation with the greatest increase observed later in the afternoon. This strengthening of flow is consistent with results reported in McInnes and McBride (1993) for model simulations of southerly busters. In that study, simulations in which surface heating was switched off in the model produced weaker low-level winds in the cooler post-frontal air and weaker updrafts in the warm air ahead of the front. As a consequence of this, the frontal speed was lower in the run without surface heating. Reeder et al. (1991) reported similar findings in idealised simulations of cold fronts. They found that the effect of increased surface heating was to enhance the low-level convergence (i.e. flow towards the leading edge of the front) in response to the lower static stability in the surface mixed layer.

The inland penetration of the sea-breeze in the results presented here is largely unaffected by the warmer temperatures. This result may be due to the fact that there has been no change in the thermal contrast between the two simulations and also because the east coast orography may act as a barrier to the inland penetration of the flow.

The aerial extent of the onshore flow associated with the sea-breeze circulation appears to be unaffected by the increase in surface temperatures in the model. This is illustrated in Figure 5.4 but is also the case for the other days and times. This result suggests that the sea-breeze circulation may be constrained by the circulation pattern associated with the anticyclone in the central Tasman. This larger scale synoptic pattern appears to have been relatively unchanged by the imposed increase in surface temperature.

5.4 Discussion and Conclusions

This brief study of sea-breezes using a limited area model has yielded several interesting results. The first pertains to the synoptic scale circulation associated with sea-breeze development on the east coast. Sea-breezes are thermally direct circulations established by land-sea thermal contrasts in the absence of strong synoptic-scale circulation. The three successive sea-breeze days that were examined, were characterised by slow moving anticyclones; one located in the Australian Bight and the other in central Tasman, with a region of weak gradients located between them in the vicinity of the east coast. This suggests that one way to determine the impact of the enhanced greenhouse effect on sea-breeze occurrence in low resolution GCM simulations would be to identify and analyse changes in the incidence of the large scale synoptic patterns that create favourable conditions for sea-breeze circulations.
Figure 5.1: Mean Sea Level Pressure for the modelled sea-breeze days at 2300 UTC on (a) 16 January, (b) 17 January, (c) 18 January and (d) 19 January, 1994.
Figure 5.2: Temperature at lowest model level produced by DARLAM for (a) 16 January at 1300 local time (left) and 1900 local time (right), (b) 17 January and (c) 18 January. The line XY marks the location of cross-section diagrams shown in Figure 5.3.
Figure 5.3: Vertical cross-section of wind for at (a) 1300 local time (0200 UTC) 17 January 1994 and (b) 1900 local time (0800 UTC) 17 January 1994. The location of the cross-section is indicated in Figure 3-2 (a).
Figure 5.4: The model generated vectors and contours of wind speed at the lowest model level corresponding to about 50 m above the surface in (a) the control experiment at 1600 local time on 18 January 1994 and (b) the increased surface temperature experiment at 1600 local time on 18 January 1994. The contour interval is 2 m s$^{-1}$. 
A uniform 3°C rise in surface temperature in the limited area model simulation was found to increase the strength of the onshore winds associated with the sea-breeze by up to 10%. This is an important result in that it shows that even in the absence of changes in the land/sea-temperature gradient, an increase in surface temperature may act to increase the sea-breeze over the ocean. This result was consistent with other simulations that examine the relative effects of surface heating on the winds associated with cold fronts. The inland penetration of the flow was unaffected by the surface warming and this may have been due to the presence of the orography which blocks the flow of the cold air. The fetch of the onshore flow over the adjacent water was relatively unaffected by changes in surface temperature suggesting that the sea-breeze extent is confined by the broader synoptic scale patterns and is less sensitive to increases in surface warming. It is possible that the enhanced, thermally direct circulation, associated with the warmer surface temperatures could also trigger local convective activity in the coastal zone more frequently although this would need to be examined in more detail before any conclusions could be drawn.

It should be noted that only uniform surface warmings were considered in this study and while these produced some strengthening of flow over the ocean, it is likely that an enhancement of the land sea contrast would further increase the sea-breeze circulation. The simulated difference in average maximum daily temperature between 1×CO₂ and 2×CO₂ climates have been examined in the high resolution DARLAM simulations (Whetton et al., 1997) and these indicate greater warmings over land compared with the adjacent ocean regions (Figure 5.5). This suggests that further enhancement of the sea-breeze circulation may be expected under doubled CO₂ conditions.

Figure 5.5: Simulated difference in average daily maximum temperature between the 1×CO₂ and 2×CO₂ DARLAM simulation for summer (left) and winter (right).
6. Extratropical Weather Systems, ENSO and Climate Change

6.1 Introduction

Severe weather events such as cold fronts and east coast lows are associated with the passage of high and low pressure systems and all contribute to the overall wave climate of the east coast. Slight directional changes in the wind regime associated with changes in the movement, frequency or intensity of these events could reorient the wave energy impacting the shore and affect nearshore processes such as littoral transport. Cowell and Thom (1994) argue that shoreline recession is far more sensitive to imbalances in the longshore sediment balance than to rises in mean sea level. They demonstrate that an imbalance amounting to 0.1% of the annual sediment budget can produce shoreline recession over a 5 year period of a similar magnitude to a 0.5 m mean sea-level rise, which they note would take at least 50 years under a severe greenhouse scenario. Furthermore, there is evidence to suggest that natural climate variability such as ENSO can cause reorientation of beaches along the NSW coast (Cowell, private communication).

As a first step towards estimating future changes to severe weather events due to the enhanced greenhouse effect, it is necessary to establish an appropriate way of quantifying their occurrence in present climates as well as their relationship to variations in climate such as the El Niño Southern Oscillation (ENSO). In this Chapter, the objective technique of Murray and Simmonds (1991a, b) is used to identify, count and track low and high pressure anomalies in twenty-three years of observational analyses and quantities that represent the frequency, intensity and movement of the weather systems are presented and discussed.

The relationship between ENSO and the movement and intensity of mid-latitude weather systems is then examined by correlating the derived characteristics of the cyclones and anticyclones with the Southern Oscillation Index (SOI). Finally, the possible impact of the enhanced greenhouse effect on these systems is addressed through a review of other studies employing similar methodologies.

6.2 Results

The automated tracking software is applied to daily-reanalysed gridded data produced by the National Centre for Environmental Prediction. The data is available on a $2.5^\circ \times 2.5^\circ$ latitude/longitude global grid and spans the years from 1973 to 1996. Several diagnostic fields are examined and these include the system density (the number of systems counted per degree latitude square), which indicates the frequency of occurrence of the systems, the mean central pressure of the systems indicating their average intensity and their average speed and direction of movement.

6.2.1 Cyclones

Figure 6.1 shows the area-normalised system density, (the number of systems per degree latitude square) for the summer and winter seasons. This quantity is a maximum in the circumpolar trough at around $60^\circ$ S. In the summer months, enhanced cyclone density associated with the heat trough occurs over the northwest of the Australian continent. A region of elevated system density extends eastwards from southeastern Australia into the south central Pacific and merges with the circumpolar trough. In the winter months, the secondary maximum off the east coast of Australia is stronger and located further north. It should be noted that the high values in the vicinity of the high South American topography are a result of the interpolation of surface pressure to mean sea level over the high topography.

The mean central pressure (Figure 6.2) is zonally symmetric with a minimum coinciding with the circumpolar trough and a maximum in the vicinity of the subtropical ridge. The most pronounced shift in
the mean central pressure with the seasons can be seen in the Pacific Ocean where a deepening in systems of up to 5 hPa can be seen in the winter months.

Figure 6.1: The system density for cyclones in summer and winter. The contour interval is $0.5 \times 10^{-4}$ cyclones.day$^{-1}$(deg.lat)$^{-2}$.

Figure 6.2: The mean central pressure of cyclones for summer and winter. Contour interval is 2.5 hPa.

The average speed and direction of cyclones lasting for at least two days is shown in Figure 6.3 and indicates that the systems travel in an east to ESE direction in the mid-latitudes. The easterly component diminishes on average for systems occurring further northwards, this being particularly evident in the summer season. Peak cyclone speeds are found between latitudes $45^\circ$S and $50^\circ$S in the Indian and Atlantic Oceans.
Figure 6.3: Wind vectors and contours of wind speed for cyclone tracks in summer and winter. Contour interval is 1 m s$^{-1}$.

6.2.2 Anticyclones

Figure 6.4 shows the 26 year average of normalised system density for summer and winter. In summer, the preferred location of anticyclones is in the subtropical band from 30°S to 45°S. Local maxima in this quantity can be seen in the Great Australian Bight and Tasman Sea. During winter, the maxima weaken over the ocean regions while there is more pronounced anticyclone activity over the Australian continent.

The MCP of the anticyclones in summer and winter are shown in Figure 6.5. These indicate a maximum in the subtropical ridge located at about 45°S in summer and about 40°S in winter. There is also some longitudinal variation evident with a minimum situated between the Great Australian Bight and the Tasman Sea during the summer season and maxima in the eastern Pacific in both seasons.

The mean anticyclone velocity is shown in Figure 6.6. In general, anticyclones travel in an easterly direction with a slight equatorward migration. Near the western coasts of Australia and South America, a slight southward deflection in the vectors during summer can be seen, indicating a tendency of highs to skirt around the continents during these seasons.
Figure 6.4: The system density for anticyclones in summer and winter. The contour interval is $0.25 \times 10^{-4}$ cyclones day$^{-1}$ (deg.lat)$^{-2}$.

Figure 6.5: The mean central pressure of anticyclones for summer and winter. The contour interval is 2.5 hPa.
6.3 The Relationship between Weather Systems and ENSO

In the Southern Hemisphere, the most significant contribution to climate variability is the ENSO phenomenon. In Australia, ENSO is strongly correlated to rainfall amount with greater rainfall tending to occur during La Niña events. Tropical cyclones are also affected with a greater frequency of events occurring during La Niña events. Linkages between ENSO and mid-latitude cyclones and anticyclones are less obvious. However, establishing the general relationship is an important first step in determining how the NSW coast is likely to be affected by climate variability. Previous studies such as Jones and Simmonds (1993a, b) have also addressed this topic. The present study differs from that study by using a different data set over a longer time interval and higher horizontal resolution. The relationship between the weather systems described in the previous section and ENSO is investigated by correlating the various storm track characteristics with the SOI.

6.3.1 Correlation between SOI and cyclones.

Figure 6.7 shows the correlation between system density and SOI in summer and winter for cyclones. In the summer, a positive (though not statistically significant) region of correlation can be seen off the northwest coast of Australia and off the east coast extending eastwards into the Tasman Sea. Negative correlations well to the south of Australia are consistent with systems in the circumpolar trough being located further equatorward during La Niñas. In winter, there is a large band of positive correlation around Australia that extends southeast. East of the dateline in both seasons the correlations are negative in a band aligned east-southeast, consistent with the eastward movement of the South Pacific Convergence Zone (SPCZ) during El Niño.

The correlation between mean central pressure and SOI (Figure 6.8) shows strong negative values over Australia implying a tendency for deeper systems to occur in both summer and winter during La Niñas. In the central and eastern Pacific and south of about 45ºS in Australian longitudes, the correlations are of the opposite sign and are statistically significant.
Figure 6.7: Simultaneous correlations between SOI and system density (cyclones) for summer and winter. Darker shading represents areas of positive correlation above 0.1 and lighter shading represents areas of negative correlation less than –0.1.

Figure 6.8: Simultaneous correlations between SOI and mean central pressure (cyclones) for summer and winter. Darker shading represents areas of positive correlation above 0.1 and lighter shading represents areas of negative correlation less than –0.1.
Correlations between SOI and system velocity (not shown) are noisy and for the most part, not statistically significant. In winter, there is a general tendency for cyclone velocities over eastern Australia to be slower during La Niña.

### 6.3.2 Correlation between SOI and anticyclones.

The correlation between SOI and anticyclone system density is shown in Figure 6.9 for summer and winter. There appears to be a southward shift in the location of highs during La Niñas over eastern Australia in summer. This result is consistent with Hopkins and Holland (1997) who have examined the location of the sub-tropical anticyclone in relation to east coast low events. The band of positive correlations extending in an ENE direction from 140°E into the central and eastern Pacific suggests that anticyclones follow a more northeastward path as they cross the Pacific during La Niñas, while during El Niños, the paths are more zonal. During winter, correlations are positive over much of Australia and the southern ocean well to the south. The small band of negative correlations over southern Australia is indicative of a poleward displacement of the sub-tropical ridge during El Niño episodes. The correlation between SOI and mean central pressure for anticyclones (not shown) exhibits a similar relationship to that for cyclones with lower pressures over Australia occurring during La Niñas. The corresponding diagram for anticyclone speed (not shown) is noisy and for the most part, not statistically significant.

![Figure 6.9: Simultaneous correlations between SOI and system density (anticyclones) for summer and winter. Darker shading represents areas of positive correlation above 0.1 and lighter shading represents areas of negative correlation less than −0.1.](image)

### 6.4 The Impact of Climate Change

In a recent study by Sinclair and Watterson (1998), automated tracking software was used to examine changes in cyclones between the control and 2xCO₂ climates of the CSIRO Mark II slab ocean GCM. In agreement with other studies (e.g. König et al., 1993; Lambert, 1995) that have examined the climatology of the two climates, they found a reduction in the mid-latitude westerlies under 2xCO₂ conditions.
Changes in weather system frequency are consistent with the reduction in baroclinicity and indicate that mid-latitude extratropical cyclone numbers decrease by 10-15%. In the southern hemisphere, the most marked decreases in cyclone frequency were found east of Africa and in the southeast Pacific. However, it should be noted that the difference in cyclone numbers between the two climates is smaller than the difference between the control climate and observed cyclone climatology. Anticyclone numbers were also found to decrease under 2×CO$_2$ conditions. Anticyclone frequencies in the southern hemisphere were found to decrease also (although less markedly than cyclones) particularly at around 40ºS although in Australian longitudes and extending to the central Tasman, there is zero change or a very weak increase indicated.

The intensities of mid-latitude cyclones were found to weaken under enhanced greenhouse conditions. This result is in contrast to a number of similar studies where a decrease in numbers of cyclones but an increase in their intensity is found (eg. Katzfey and McInnes, 1996; Lambert, 1995). The likely reason for the different result is that in earlier studies, intensities were measured in terms of the minimum central pressure attained by the cyclone, which, as noted by Sinclair and Watterson (1998) may have been influenced by changes in the background pressure climatology. They measured intensity in terms of maximum cyclonic vorticity (derived from wind velocities) which they argue is a more sound measure of storm intensity. Despite the overall weakening of storms in the 2×CO$_2$ climate, they do note an increase in very intense storms occurring between 40-60ºS in the South Pacific. These storms occur in late summer, implying that increased latent heating might be an underlying cause. However, due to the relatively low frequency of these storms, a longer GCM simulation would be needed to determine whether this is a robust feature of the GCM’s enhanced greenhouse climate.

6.5 Conclusions

This Chapter has examined the frequency and movement of extratropical weather systems in twenty-three years of global objective analyses through the use of automated tracking techniques. The relationship between the weather systems and ENSO was also briefly investigated.

It was found that during La Niña, there was a tendency for cyclones to be more frequent, have lower central pressures and be located further to the north over the Australian region, extending across the Tasman to the approximate location of the South Pacific Convergence Zone. Beyond that, the cyclones followed a more southeastward track over the central and eastern Pacific and tended to be weaker. During El Niño, cyclones tend to be slightly less frequent to the south of Australia, were weaker and travelled more zonally as they crossed the Pacific.

Anticyclones tended to be situated slightly further to the south during La Niña summers and El Niño winters. They tended to track slightly more to the northeast as they crossed the Pacific during La Niña while during El Niño, their paths were more zonal, the same as for the cyclones. Over Australia, anticyclones had lower pressures during La Niña and higher pressures during El Niño. The converse situation was found for the central and eastern Pacific.

These results suggest that the east coast wave climate could be affected by climate variability. For example, during La Niña, the northeasterly winds associated with anticyclones may be less frequent or weaker during the summer months although a positive correlation between tropical cyclones and SOI may counter this effect. On the other hand the southeasterly waves associated with mid-latitude cyclones in the southern Tasman Sea during the winter months may become more frequent and intense. However, a far more detailed study presumably involving the running of a numerical wave model, would be required to establish such linkages and determine more quantitatively the net effect on the wave climate and processes in the nearshore region.
It is noteworthy, that in a recent study of high rainfall bearing east coast lows by Hopkins and Holland (1997), it is found that there is a strong tendency for east coast cyclones to occur after El Niño years. This tendency is most pronounced between transitions from large negative to large positive values of the SOI.

A review of a recent study into the impact of the enhanced greenhouse effect on mid-latitude weather systems, applying similar automated tracking techniques to the CSIRO Mark 2 GCM simulation, revealed a number of interesting results. In particular, cyclone numbers were found to decrease by 10-15% under 2×CO$_2$ conditions and anticyclones were found to decrease also. This result is in broad agreement with a number of other storm track studies. There was an overall weakening of the intensity of mid-latitude cyclones under doubled CO$_2$ conditions with the exception of a small region in the South Pacific that showed a slight increase in intense systems. This finding was different to a number of earlier studies that have looked at cyclone intensity under doubled CO$_2$ conditions and is attributed to the use of a more robust indicator of cyclone intensity that relates to the cyclone winds rather than central pressure. There still remains a need to ascertain for the Australian region, the impact of the enhanced greenhouse effect on mid-latitude storm tracks in a fully coupled GCM model.
7. Rainfall and run-off changes under enhanced greenhouse conditions

7.1 Introduction

Changes in rainfall patterns may lead to significant changes in the flood frequency in coastal regions. Related to such changes are issues of sedimentation within estuaries and river outflow regions, temporary changes in salinity and turbidity and the possible consequences of this on biological processes.

The conversion of rainfall to run-off within a drainage basin involves a complex set of processes that are dependent on the characteristics of the catchment basin. These include terrain shape, soil type, vegetation cover and seasonal growth patterns of the vegetation. Determining the impact of the enhanced greenhouse-induced rainfall changes on river flood frequency therefore requires detailed catchment modelling, which is beyond the scope of the present study for the catchments along the NSW coast.

Several studies to date have examined the impact of rainfall changes due to the enhanced greenhouse effect on specific catchments in eastern Australia. A brief review of these studies and their key findings will be presented in the following section. This will be followed by some recent results on precipitation change under enhanced greenhouse conditions, undertaken as part of a three year project to provide fine resolution climate change scenarios for NSW. The research is based upon simulations with the DARLAM run at a model resolution of 60 km centred over NSW. The finer resolution enables more detailed regional representation of climatic features that are not adequately resolved by the GCM. Lateral boundary conditions for these simulations are derived from the CSIRO Mark II slab ocean global climate model (GCM) for present levels of carbon dioxide ($1\times CO_2$) and double present levels ($2\times CO_2$). The possible implications of these results in the context of previous catchment studies are then discussed.

7.2 Catchment Modelling Studies

Catchment modelling studies, conducted under present and changed climate conditions, have served to illustrate how moderate increases, and even in some cases decreases, in monthly average rainfall can still produce moderate to large increases in the incidence of riverine flooding events. One such study was carried out by Bates et al. (1995). In their study, a stochastic weather generator based on the present climate was used to generate daily weather conditions as input to two different catchment models calibrated for specific catchments. To simulate the impact of enhanced greenhouse conditions, the catchment model parameters were adjusted in a manner consistent with the changes in monthly statistics between the control and doubled CO$_2$ conditions of the CSIRO Mark I GCM.

Results from the two catchment models were qualitatively similar. For example, for the Styx River catchment on the east of the Great Dividing Range in northern NSW, both models reproduced the maximum median run-off in late autumn and early winter under present climate conditions. Under enhanced greenhouse conditions, an increase in late summer and autumn median run-off occurred, dramatically reducing the return period between extreme run-off events. Average summer rainfall increases in the doubled CO$_2$ simulation for this location were about 10% higher than in the control climate.

Schreider et al. (1996) applied a catchment model to the Ovens and Goulburn basins in northeastern Victoria. Using the ‘most wet’ and ‘most dry’ scenarios of climate change that are based on a number of climate model simulations, they examined the impact on flood and drought frequency. Under the ‘most wet’ scenario, flood frequency was found to increase by 50% at 2030 and 100% at 2070. Under the ‘most dry’ scenario, flood frequency diminished to zero by 2070 while drought frequency increased by 80%. A similar study conducted for the Macquarie River basin also yielded large changes in the
frequency of floods and droughts despite small changes in average climate (Hassall and Associates, 1997).

7.3 Rainfall changes in recent DARLAM simulations

The DARLAM simulation conducted under current climate conditions was found to represent well many features of the observed patterns of average seasonal rainfall over the State although there was a tendency for summer rainfall to be too high particularly along the Great Divide. The northern portion of the range in winter also exhibited higher than observed rainfall values (Whetton et al., 1997).

Under 2xCO₂ conditions, rainfall is simulated to decrease in summer. However the changes are not statistically significant and are mostly less than 15%. Some small increases are simulated in coastal areas. Rainfall decreases also prevail in autumn, and are strongest in southern inland areas where they reach 30% and are statistically significant. Rainfall is simulated to decrease throughout the State in winter, with highly statistically significant decreases of 30-40% prevailing in all but coastal and southernmost areas. In coastal regions under enhanced greenhouse conditions, changes in average rainfall are largely negative except in spring when increases occur in the southern coastal regions. The changes are not statistically significant however. Seasonal variability in the model is weaker in the model compared to observations, particularly in summer in inland areas and in winter in the southern coastal regions. This is likely to be due in part to the fact that the GCM in which DARLAM is nested does not simulate ENSO variability.

7.4 Daily Extremes

The previous Section dealt with year-to-year rainfall variability and the occurrence of very wet or very dry years. A different insight is gained into rainfall variability by examining the occurrence of extreme daily totals. Such events are important in regard to flood occurrence, particularly in the smaller, coastal catchments of NSW. Furthermore, previous studies based on daily data from CSIRO and other GCMs have indicated marked increases in the magnitude of extreme daily rainfall events under enhanced greenhouse conditions for the Australian region, and corresponding marked decreases in the return period of extremes of a given magnitude (Whetton et al., 1993; Fowler and Hennessy, 1995; Hennessy, et al., 1995).

The daily rainfall totals in the twenty years of data from the 1xCO₂ and 2xCO₂ simulations were analysed for each of the DARLAM grid points over NSW. Figure 7.1 shows the annual results averaged over all NSW grid points for the simulated return periods for extreme daily rainfall. Under 1xCO₂ conditions, the one in twenty year daily rainfall total averages 95 mm and the one in ten year event 83 mm. These values are much higher, and closer to the values observed in the real world at points, than the values obtained in previous GCM-based studies for NSW (see Fowler et al. 1992 ). Under 2xCO₂ conditions the magnitude of these events increase to 124 mm and 102 mm respectively (increases of 20-30%). The magnitude of the increase becomes smaller as shorter return period events are examined. The results may also be expressed as change in return period for an event of a given magnitude. The figure shows quite marked decreases in return period. For example, the one in ten-year annual event under 1xCO₂ conditions is simulated to become the one in five year event under 2xCO₂ conditions. These increases in the magnitude of extreme rainfall events are particularly notable considering that average annual rainfall has decreased and are likely to be reflecting the greater moisture holding capacity of a warmer atmosphere. When the results are broken down season by season (Figure 7.2), it becomes apparent that the increase in intensity of heavy events is greatest in summer and spring where changes in statewide total rainfall are small (decreases of 4% and 2%, respectively), only just apparent in autumn where total rainfall decreases by 12%, and absent in winter where total rainfall decreases by 20%.
7.5 Discussion

The current DARLAM simulation reproduces many features of the observed patterns of average seasonal rainfall over NSW. However, the rainfall simulations also have some significant shortcomings, the most notable being a tendency for summer rainfall to be too high over the mountains in the east of State. Under 2×CO$_2$ conditions, statewide decreases in rainfall occur in summer, autumn and winter with the autumn and winter decreases being statistically significant. In spring, increases in rainfall occur but these are not statistically significant.

Scenarios of precipitation change for the NSW coastal regions have been prepared for 2030 and 2070 based on the latest DARLAM enhanced greenhouse results and represent changes from 1990 levels. High and low estimates are given to allow for major uncertainties in estimating the extent of global warming as determined by the IPCC (Houghton et al., 1996). The scenarios for 2030 that represent changes from 1990 levels can be summarised as follows:

- Increases in summer precipitation of 0–5%.
- Decreases in autumn of 0–5%.
- Decreases in winter precipitation of 0–10%.
- Increases in spring precipitation of 0–4%.

Changes are larger in 2070 than they are in 2030, and for the high case assumptions, are around twice as large.
Precipitation variability in the DARLAM simulation is well captured when model biases in average rainfall are taken into consideration. Major limitations in the model simulations of precipitation variability can be attributed to the model’s lack of an ENSO signal which, in the real world, causes considerable variability in rainfall on interannual timescales. However, this study has shown that even when climate variability does not change significantly under enhanced greenhouse conditions, a change in the average will cause large changes in the frequency of extremes.

Under 2xCO₂ conditions, DARLAM simulates an increase in rainfall variability which is associated with decreases in the average rainfall. These results strongly support earlier studies using GCMs that indicate marked increases in daily rainfall intensity and in the magnitude of extreme daily rainfall events, even when average rainfall doesn’t change. Changes in the return periods of daily rainfall extremes are pronounced and have highlighted the possibility of increases in the frequency of both dry years and high rainfall events. These scenarios indicate that significant increases in flood frequency could occur under enhanced greenhouse conditions. However, more detailed catchment scale studies would need to be undertaken for specific coastal catchments to quantitatively determine the possible changes in flood frequency.
The DARLAM-based scenarios are dependent upon the simulated climate changes of the host GCM. Different, but equally plausible, high-resolution scenarios for climate change over NSW could be obtained by nesting DARLAM in a different GCM. In particular, comparisons suggest that simulated rainfall change in summer would be sensitive to the choice of host GCM. Thus, it is recommended that a high priority for future research should be to nest DARLAM in the latest CSIRO coupled ocean-atmosphere GCM. Current uncertainties in estimating regional enhanced greenhouse climate would be better represented by this provision of another high resolution scenario for NSW. Also the CSIRO coupled GCM represents some aspects of ENSO variability.
8. Sea Level Rise on the NSW Coast

Sea-level rise as a consequence of the enhanced greenhouse effect is one of the more confident results of climate change research (IPCC 1996). The amount of sea-level rise at any given location is a function not only of sea-level rise at the global scale but also regional and local considerations. Accordingly, there are a number of significant issues that should be addressed before precise estimates of sea-level rise can be made.

8.1 Global Sea level Rise

Global sea level rise over the next few decades is expected from several sources. These include thermal expansion of the oceans, melting of glaciers and small ice sheets, and changes in the accumulation of snow and ice in Antarctica and Greenland. Estimates of changes to these components are made using predictions of future warming from climate models. These models are complex numerical representations of the Earth’s ocean and atmosphere and depending on how the physical processes in the models are represented, they predict a range of different warmings for a specified increase in greenhouse gases. Furthermore, there is considerable uncertainty regarding the future emissions of greenhouse gases and associated aerosols, as the amount of these emissions depends upon the character and scale of future economic activity, which is difficult to predict. Therefore predictions of mean global sea-level rise are usually given as a range over several different scenarios (see Table 8.1), depending upon the amount of future emissions assumed.

Table 8.1: Low, mid and high estimates of global mean sea level rise (in cm) for the years 2020 and 2050 (IPCC 1996), relative to 1990.

<table>
<thead>
<tr>
<th>Year</th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
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<tbody>
<tr>
<td>2020</td>
<td>5</td>
<td>10</td>
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<tr>
<td>2050</td>
<td>10</td>
<td>20</td>
<td>40</td>
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</tbody>
</table>

8.2 Regional Sea Level Rise

At the regional scale, sea levels can be influenced by pressure variations in the ocean associated with ocean currents, and in the atmosphere due to different wind regimes. These variations could be of similar magnitude to the possible global sea level fluctuations (Pittock et al., 1996). Recent estimates (MacDougall and Jackett, personal communication) suggest that local variations along the NSW coast from this effect are approximately the global average, although this result has yet to be more precisely quantified. Climatic variations associated with ENSO can also produce regional variations in sea level due to the changes in atmospheric and oceanic conditions, although this effect is small on the coast of NSW.

Geological movements of land masses can also influence relative sea levels. For example, in the Australian region, the rise in sea level since the end of the last Ice Age has flooded continental shelf areas. The resulting extra weight of water has pushed these regions down, and to compensate for this subsidence, adjacent land areas have been pushed up. This is known as hydro-isostatic uplift. Estimates of this effect along the NSW coast vary. Lambeck and Johnston (1995) suggest that the coast of NSW is currently rising at about 0.4 mm yr$^{-1}$ from this effect alone. Compared to the predicted magnitudes of the global mean sea-level rise, though, this is a relatively small contribution.

8.3 Local Sea-Level Variations
On the local scale, sea-level variations may be caused by subsidence of land due to sediment compaction or groundwater removal (e.g., Bird, 1993). This effect can be large, dwarfing the predicted effects of climate change. Any estimate of sea-level rise at a specific site would have to include the magnitude of these processes.

9. Storm Surges

9.1 Introduction

Storm surges are temporary elevations in sea-surface height driven by surface winds and changes in atmospheric pressure. Their severity depends on the strength and duration of the atmospheric disturbance, and the structure of the coastal terrain. Severe storm surges can cause inundation of low lying coastal plains and flooding of river systems, and in combination with wind-generated wave action, can cause estuarine erosion. In cases where the atmospheric storm also produces extreme rainfall and flooding of coastal regions, there is the potential for storm surges to prolong and exacerbate the existing floods, by elevating sea levels in the vicinity of river outflows and thereby reducing the drainage rates of the flooded river systems.

In this study, the relationship between storm surges and intense mid-latitude atmospheric depressions occurring on the east coast of Australia, is investigated. These severe weather events known variously as cut-off lows (McInnes et al., 1992), east coast cyclones (Holland et al., 1987; Lynch, 1987; Hopkins and Holland, 1997), east coast lows (Hess, 1990; McInnes and Hess, 1992) and coastal lows (McInnes et al., 1992), tend to occur along Australia’s east coast most commonly between autumn and spring, producing heavy precipitation and strong winds. They often form within a synoptic-scale blocking pattern consisting of a low pressure system which is “cut-off” from the mid-latitude westerlies by a ridge of high pressure to the south, and which tracks parallel to the coast for some part of its life.

While the overall development of these systems takes place on the synoptic scale, a number of modelling studies over recent years, suggest that the storms may be modified by local factors. For example Leslie et al. (1987) and Lynch (1987) have demonstrated the importance of accurate SST's for obtaining realistic storm tracks and precipitation amounts. McInnes and Hess (1992) showed that accurate resolution of the east coast orography was also important in obtaining accurate spatial representation of rainfall over land. McInnes et al. (1992) found that sea surface temperature increases in model simulations of east coast lows, could dramatically increase the intensity of the storms, resulting in more extensive areas of stronger surface winds and heavier rainfall. This result has clear implications for storm surge intensity in circumstances when SST's off the east coast of Australia are higher than usual, a situation which is most likely to be the case if greenhouse warming occurs.

This study aims to investigate the impact of cut-off lows on storm surge generation. Storm surge and meteorological data are examined to ascertain the role of these lows in generating elevated sea levels along the NSW coast. Numerical simulations of three cut-off low events are carried out using the three dimensional atmospheric model described in McInnes and Hess (1992) and McInnes et al. (1992). The low level winds and atmospheric pressure fields from this model are then used to drive a storm surge model based on Hubbert et al. (1990) with more recent modifications described in Hubbert and McInnes (1999). The modelled cases are analysed to determine the nature of the interaction of the atmospheric disturbance with the coastal waters. The sensitivity of the storm surges to increases in SST’s is also studied. This is achieved by re-running the atmospheric model with elevated SST’s following the methodology of McInnes et al. (1992). The altered fields from the atmospheric model are then applied to the storm surge model.

The remainder of the Chapter is set out as follows. In Section 9.2, a limited climatology of the types of atmospheric disturbances contributing to storm surges along the NSW coast is presented. In Section 9.3,
the models employed in this study and the methodology used in carrying out the experiments are described. The synoptic features of the particular events chosen for this study are described in Section 9.4 while modelling results are presented and discussed in Section 9.5. Sensitivity experiments are presented in Section 9.6 and finally, conclusions are presented in Section 9.7.

9.2 Storm Surges along the East Coast

There are several processes other than astronomical tides that can cause sea level variations at the coast. Two major contributors are storm surges, caused by severe atmospheric storms, and wave set-up, due to the cumulative effect of breaking waves in the surf-zone. Wave run-up and storm water run-off into estuaries can also contribute to local sea levels. Storm surges are caused by barometric effects and surface wind stresses. Coastal bathymetry is also an important determinant in the height of the storm surge with shallow wide continental shelves tending to amplify their effect. The NSW coast features a relatively narrow continental shelf which limits storm surge heights to typically less than half a metre.

Tidal records have been maintained routinely along the NSW coast over the last century by a network of tide gauges and wave-rider buoys deployed by the New South Wales Public Works Department and the Maritime Services Board MSB (Public Works Dept. NSW, 1991). From this data, tidal residuals, representing the contribution from storm surges and wave set-up, are calculated by subtracting out the predicted astronomical tide heights.

Table 9.1 and 9.2 show the highest ranked storm surges recorded at Sydney between 1966 and 1990 and Coffs Harbour between 1971 and 1990 respectively (Public Works Dept. NSW, 1991). While the amplitudes of these surges are relatively low compared with the storm surges sometimes produced by tropical cyclones, their duration is of the order of a day or more with the longest event lasting over 9 days. Clearly, events of such duration will encounter tidal maxima, which will further elevate sea-levels by up to a metre depending on the coastal location. Also the long duration could potentially increase the likelihood of elevated sea levels coinciding with floods produced by the excessive run-off, particularly if the peak surge occurs in the vicinity of the flooded river system.

Tables 9.1 and 9.2 also indicate the type of meteorological system influencing the east coast of Australia at the time the surge was recorded. At Sydney, the majority of surge events coincided with cut-off low in the Tasman Sea while at Coffs Harbour, cut-off lows appear to be responsible for the surges in about half of the cases.

Table 9.1: Ranked tidal anomalies at Sydney 1966-1990. In cases where the synoptic situation consists of a cut-off low, column 6 gives the approximate location of the cut-off low centre at the time of the peak surge based on daily manual weather charts from the Australian Bureau of Meteorology. Column 7 indicates the meteorological conditions reported during the surge event. Definitions of wind conditions are as follows; strong breeze, 11-14 m s\(^{-1}\); gale force wind, 17-20 m s\(^{-1}\); and storm force wind, 24-28 m s\(^{-1}\). Finally, (F) indicates whether floods were reported during the event.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Peak (m)</th>
<th>Time and Date of peak surge (EST)</th>
<th>Duration (hours)</th>
<th>Synoptic Situation</th>
<th>Location of Low Centre</th>
<th>Wind Strength Floods reported (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.59</td>
<td>02:00 26-May-1974</td>
<td>93</td>
<td>Cut-off low</td>
<td>157°E 32°S</td>
<td>Strong to gale force, (F)</td>
</tr>
<tr>
<td>2</td>
<td>0.54</td>
<td>04:00 02-Jun-1978</td>
<td>48</td>
<td>Cut-off low</td>
<td>150°E 35°S</td>
<td>Gale force, (F)</td>
</tr>
<tr>
<td>3</td>
<td>0.52</td>
<td>18:00 10-Jun-1974</td>
<td>75</td>
<td>Cut-off low</td>
<td>162°E 35°S</td>
<td>Gale force, (F)</td>
</tr>
<tr>
<td>4</td>
<td>0.51</td>
<td>12:00 13-Jun-1966</td>
<td>80</td>
<td>Cut-off low</td>
<td>-</td>
<td>Gale force, (F)</td>
</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>23:00 27-Apr-1990</td>
<td>212</td>
<td>Cut-off low</td>
<td>Not identifiable</td>
<td>Gale force, (F)</td>
</tr>
<tr>
<td>6</td>
<td>0.44</td>
<td>06:00 21-Jun-1975</td>
<td>29</td>
<td>Cut-off low</td>
<td>154°E 34°S</td>
<td>Gale to storm force, (F)</td>
</tr>
<tr>
<td>7</td>
<td>0.43</td>
<td>11:00 15-Jun-1978</td>
<td>42</td>
<td>Cut-off low</td>
<td>161°E 33°S</td>
<td>Gale force</td>
</tr>
<tr>
<td>8</td>
<td>0.40</td>
<td>08:00 01-May-1966</td>
<td>73</td>
<td>Front</td>
<td></td>
<td>Gale force</td>
</tr>
<tr>
<td>9</td>
<td>0.38</td>
<td>11:00 03-Aug-1990</td>
<td>18</td>
<td>Cut-off low</td>
<td>158°E 33°S</td>
<td>Gale force, (F)</td>
</tr>
</tbody>
</table>
Table 2: As for Table 1 except for tidal anomalies at Coffs Harbour 1971-1990.

<table>
<thead>
<tr>
<th>Rank</th>
<th>Peak</th>
<th>Time and Date of peak surge (EST)</th>
<th>Duration (hours)</th>
<th>Synoptic Situation</th>
<th>Location of Low Centre</th>
<th>Wind Strength</th>
<th>Floods reported (F)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.69</td>
<td>01:00 11-Jun- 1974</td>
<td>70</td>
<td>Cut-off low</td>
<td>165°E 35°S</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.63</td>
<td>11:00 20-Aug- 1973</td>
<td>17</td>
<td>Front</td>
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<td>Strong</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.57</td>
<td>16:00 28-May- 1974</td>
<td>48</td>
<td>Cut-off low</td>
<td>170°E 40°S</td>
<td>Strong to Gale force (F)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.49</td>
<td>22:00 18-May- 1977</td>
<td>70</td>
<td>Cut-off low</td>
<td>159°E 29°S</td>
<td>Gale force</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.48</td>
<td>23:00 01-Feb- 1973</td>
<td>29</td>
<td>Front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.44</td>
<td>16:00 15-Jun- 1978</td>
<td>21</td>
<td>Cut-off low</td>
<td>162°E 33°S</td>
<td>Gale force (F)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.43</td>
<td>01:00 10-Jul- 1985</td>
<td>56</td>
<td>Cut-off low</td>
<td>158°E 34°S</td>
<td>Gale force (F)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.42</td>
<td>15:00 13-Jun- 1974</td>
<td>21</td>
<td>Cut-off low</td>
<td>165°E 35°S</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>0.42</td>
<td>18:00 01-Jun- 1978</td>
<td>21</td>
<td>Cut-off low</td>
<td>153°E 32°S</td>
<td>Strong to Gale force (F)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.40</td>
<td>10:00 28-Jun- 1977</td>
<td>34</td>
<td>Low</td>
<td></td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0.39</td>
<td>20:00 08-Mar- 1990</td>
<td>54</td>
<td>Cut-off low</td>
<td>160°E 33°S</td>
<td>Strong</td>
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<tr>
<td>12</td>
<td>0.37</td>
<td>11:00 21-May- 1985</td>
<td>45</td>
<td>Cut-off low</td>
<td>165°E 32°S</td>
<td>Strong to Gale force</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>0.37</td>
<td>06:00 08-Aug- 1986</td>
<td>18</td>
<td>Cut-off low</td>
<td>166°E 37°S</td>
<td>Gale force (F)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0.35</td>
<td>09:00 27-Mar- 1976</td>
<td>35</td>
<td>Cut-off low</td>
<td>164°E 38°S</td>
<td>Strong to Gale force</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.34</td>
<td>09:00 25-Jul- 1971</td>
<td>51</td>
<td>Cut-off low</td>
<td>162°E 36°S</td>
<td>Strong to Gale force</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.34</td>
<td>09:00 02-Jul- 1980</td>
<td>49</td>
<td>Front</td>
<td></td>
<td>Gale force</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.34</td>
<td>13:00 05-Jul- 1984</td>
<td>29</td>
<td>Low</td>
<td></td>
<td>Gale force</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.34</td>
<td>14:00 15-Dec- 1984</td>
<td>42</td>
<td>Benign</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.32</td>
<td>09:00 21-May- 1974</td>
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</tr>
<tr>
<td>20</td>
<td>0.32</td>
<td>21:00 09-Aug- 1976</td>
<td>20</td>
<td>Cut-off low</td>
<td>162°E 35°S</td>
<td>Strong</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.32</td>
<td>22:00 18-Mar- 1977</td>
<td>20</td>
<td>Cold front</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0.32</td>
<td>05:00 27-Sep- 1981</td>
<td>48</td>
<td>Low</td>
<td></td>
<td>Gale to Storm force</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0.32</td>
<td>03:00 10-Aug- 1988</td>
<td>19</td>
<td>Front</td>
<td></td>
<td>Strong to Gale force</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.31</td>
<td>12:00 30-May- 1979</td>
<td>31</td>
<td>Anticyclone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0.31</td>
<td>14:00 01-May- 1981</td>
<td>30</td>
<td>Low</td>
<td></td>
<td>Strong</td>
<td></td>
</tr>
</tbody>
</table>

In all cut-off low events, wind speeds at the location of the surge were recorded as strong to gale force. The approximate location of the low pressure centre relative to the peak surge for the cases where a cut-off low was the principle meteorological system in the area is estimated from 0000 UTC manual analyses produced by the Australian Bureau of Meteorology. In the majority of cases, the low pressure centre is located offshore placing the east coast under a southerly wind regime.

In over half of the cases where surges at either Sydney or Coffs Harbour coincided with a cut-off low in the Tasman, flooding was also reported in various river systems along the coast. However, due to the limited data available, it is not possible to ascertain whether the flooding coincides with the elevated sea levels.

9.3 Model Description and Experimental Design

The storm surge model used in this study is a depth-integrated, ocean-current model developed specifically to simulate currents and sea surface elevations on continental shelves. An earlier version of the model is described in Hubbert et al. (1990) and more recent changes are documented in Hubbert and McInnes (1998). In the present study, storm surge simulations were conducted at 2 km resolution over the region illustrated in Figure 9.1.
High resolution winds and surface pressure, needed to drive the storm surge model, were obtained by running a limited area atmospheric model based on McInnes and Hess (1992) over the regions shown in Figure 9.1. Fifteen vertical levels were used with the lowest model level located at approximately 10 m above the surface. The atmospheric analyses used to initialize and provide boundary conditions for this model were obtained from 12-hourly analyses. The source of the analyses varied according to availability. Case 1 used analyses from the National Center for Environmental Prediction, case 2 used analyses from ECMWF and case 3 used the Australian Bureau of Meteorology regional analyses (Mills and Seaman, 1990). Output from the atmospheric model was stored every six hours. Surface pressure and 10 m winds were then interpolated spatially to the storm surge model grid and also temporally to provide the surface boundary condition for the storm surge model.

For each of the three cases modelled in this study, a control and an elevated sea-surface temperature (SST) experiment is performed. SSTs are elevated by 3°C which is based on the average increase in SST for the east coast region simulated in recent doubled CO₂ climate simulations. The atmospheric model simulations are carried out at 20 km horizontal resolution over the regions indicated in Figure 9.1.

Figure 9.1: (a) The various regions over which model simulations are conducted. Topographic contours are shown at 100 m intervals. (b) The storm surge model domain showing relevant coastal locations and bathymetric contours at 10 m increments to 100 m and at 500 m intervals thereafter.

9.4 Synoptic Overview and Atmospheric Modelling Results

The three cases that have been selected for detailed investigation in this study each produced elevated sea-levels at one or more of the NSW tidal recording stations. A brief meteorological description of each of the cases is given and atmospheric model simulations are presented and discussed.

9.4.1 Case 1. 1200 UTC 8 May 1997

This event occurred over a five day interval commencing at 1200 UTC 8 May 1997 and the development of the surface low off the east coast of Australia is shown in Figure 9.2. The system reached its peak
intensity in the 24 hours up to 9 am local time on May 11 producing isolated heavy rainfall of up to 131 mm around Sydney and 124 mm at Norah Head. Wind gusts during the event reached 30 m s\(^{-1}\) at Newcastle.

**Figure 9.2:** Sequence of daily analyses of sea level pressure showing the development of the low on the east coast at the times indicated for case 1.

Figure 9.3 compares observed and modelled wind speed, direction and pressure at Sydney and Coffs Harbour over the five days. Sydney shows a rise in wind speeds to a peak of around 20 m s\(^{-1}\) between 48 and 60 hours. Wind gusts are shown also and exceed 25 m s\(^{-1}\) at these times. The modelled winds reach a peak some 12 hours earlier and are generally over-estimated by between 10 and 20\%. At Coffs Harbour, the overestimation by the model is even more pronounced. Wind direction which is uniformly from the south at Sydney and southwest at Coffs Harbour is well captured by the model (Figures 9.3b). The modelled surface pressure at Sydney (Figure 9.3c) is also well captured by the model and indicates a fall of 10 hPa.

**9.4.2 Case 2. 0000 UTC 6 March 1990**

At the commencement of this event, a weak trough associated with a cold front to the south of the continent extended from the NW to SE along the NSW coast (Figure 9.4a). Thunderstorms and hail occurred along the coast at this time with 13 and 31 mm of rain recorded at Sydney and Coffs Harbour respectively. Tropical cyclone Hilda was located off the Queensland coast at around 19°S, 155°E. On the 7th, a low developed in the trough off the NSW coast producing further rainfall (Figure 9.4b). On the 8th, the cyclone moved into the Tasman Sea as an extra-tropical depression bringing further showers to the northern NSW coast. It remained well offshore at longitudes of around 160°E as it tracked south producing southerly winds on the east coast for much of the four day interval (Figures 9.4c-d).
Figure 9.3: Observed (thin lines) and modelled (thick lines) time series of (a) wind speed, (b) wind direction and (c) pressure at Sydney and Coffs Harbour over a five day interval commencing 1200 UTC 8 May 1997. Note that observed wind gusts are also shown in (a).
Figure 9.4: Sequency of daily analyses of sea level pressure showing the low developing on the east coast for case 2.

Figure 9.5: Observed (thin lines) and modelled (thick lines) time series of (a) wind speed and (b) wind direction for Sydney and Coffs Harbour over a four day interval commencing at 0000 UTC 6 March 1990.
Modelled wind speed and direction at Sydney and Coffs Harbour (surface pressure data observations were not available) are compared with three-hourly observations in Figure 9.5. As for case 1, southerlies were maintained for most of the four day period at both locations. At Sydney, the strongest winds which at times, exceeded 12 m s$^{-1}$, occurred over a 48 hour interval from about 6 to 54 hours after the commencement of the event. At Coffs Harbour, the southerly wind magnitudes were similar but occurred from around 24 to 72 hours.

9.4.3 Case 3. 2300 UTC 30 July 1990

Case 3 commenced with a low that deepened near the NSW coast during July 31, 1990 (Figure 9.6a). The low then tracked southwards along the coast producing rainfall totals of 108 mm in Sydney in the 24 hours leading up to 2300 UTC 31 July 1990 (Figure 9.6b). Heavy rainfall also occurred in the mountain and coastal regions to the south of the State. On August 1, 1990, the low moved inland and weakened while a second low developed on the coast near Sydney (Figure 9.6c). Rainfall totals of 49 mm were recorded in Sydney in the 24 hour period leading up to 2300 UTC 1 August 1990. In the following 24 hours, the second low intensified producing gale to hurricane force winds in Sydney and the surrounding coastal regions (Figure 9.6d), although rainfall totals dropped to 24 mm during this time.

Observed and modelled wind speed, direction and surface pressure for Sydney are shown in Figure 9.7. In the first 48 hours during the development of the primary low, easterly winds occurred consistent with the depression lying to the north. At 66 hours, the secondary low undergoes rapid intensification to the east of Sydney producing southerly winds exceeding 17 m s$^{-1}$ for over six hours. This development coincides with a 15 hPa fall in surface pressure.
**Figure 9.6:** Sequence of daily analyses of sea level pressure for case 3 commencing at 2300 UTC 30 July 1990.

### 9.5 Storm Surge Model Results

Modelled storm surges are now compared to sea level residuals in each of the three cases. In case 1 (Figure 9.8), the modelled sea levels peak about 24 hours earlier than the observed, coinciding with the modelled wind speed maximum which also occurred earlier. Generally modelled storm surge heights are lower than the observed residuals and, since modelled winds were overestimated, the storm surge component may have been lower still. In case 2 (Figure 9.9), the timing of the surge corresponds well with the observed sea-level anomaly although again, the amplitude of the modelled surge is underestimated.

In case 3, the maximum sea level anomaly recorded at Sydney and Port Stephens occurs at around 74 hours and is of shorter duration (about 16 hours) compared with the previous two events (Figure 9.10). The elevated sea levels coincide approximately with the shift to southerly winds in the atmospheric model however, because this wind shift occurred some 12 hours later than observations indicate, the modelled surge also exhibits a similar delay. Storm surge amplitudes are again underestimated at Sydney and Port Stephens.
Further investigation of this event was undertaken in view of the relatively poor agreement between modelled and observed winds. This particular event was also poorly simulated by all real-time atmospheric models available to forecasters at the Australian Bureau of Meteorology, including the RASP model which produced the data assimilated analyses used in this study (J. Ferren, private communication). Two simple experiments were carried out using the atmospheric and storm surge models. In these, the earth’s atmosphere was moved 2° to the east and west relative to the land surface. It was found that this shift in location altered the onset time of the storm surge by about plus or minus 10 hours. When the earth’s surface was shifted to the west relative to the atmosphere, the onset time of the southerly winds was earlier and so the surge coincided more closely with the observed surge. However, the amplitude of the surge decreased because the band of southerly winds occupied a broader region between the low and the coast and consequently were less intense. These experiments demonstrate that the timing of the surges is extremely sensitive to the location and movement of the depression. Manually drawn analyses for this event were also examined (J. Colquoun, private communication), and these depicted a different situation with a more intense cyclone that was centred on the coast to the north of Sydney at the time that the peak water levels occurred. Clearly, one reason for the poor agreement between the observed and modelled storm sea level anomaly is a difference in the intensity and movement of the observed and modelled surface low.
Storm surge model results from all three cases did not account for the full sea level anomaly recorded at the coast. The reasons for this and other possible contributions to the measured sea level anomalies are now considered. As discussed previously, errors in positioning, intensity and movement of lows can have a profound impact on the timing of the storm surges at the coast. Without comprehensive observational data over the adjacent ocean regions, it is not possible to adequately verify the model wind and pressure fields and these may be a major source of error in the storm surge model results.

**Figure 9.8:** Observed (thin lines) and modelled (thick lines) sea level heights for the locations indicated over 120 hours commencing 1200 UTC 8 May 1997.

**Figure 9.9:** Observed (thin lines) and modelled (thick lines) sea level heights for the locations indicated over 96 hours commencing 0000 UTC 6 Mar 1990.
Wave set-up at the coast may also explain part of the difference in sea level height between the observations and storm surge simulations. Accurate determination of wave set-up requires the running of complex wave models which is beyond the scope of the present study. However, empirical relationships can be used to estimate the contributions from such processes. Generally wave set up is between 15 and 20% (WMO, 1998) of the deepwater significant wave height, $H_s$, where $H_s$ is defined as the average height of the highest one third of all waves and is a function of wind speed, duration and fetch. For case 1, a broad region of south-easterly winds with a coast normal component of around 12 m s$^{-1}$ occur over a band between 32° and 35°S for a 24 hour time interval and fetch of over 500 km. The corresponding maximum wave height would be around 3.5 m and so the wave set-up could be between 0.5 and 0.7 m which is generally larger than the discrepancy found in the present study. On the other hand, the tide gauges used in this study are all located in relatively protected embayments and are not likely to experience the same degree of wave set-up that would be expected to occur at more exposed coastal locations. In any case, it is possible that wave set-up which is not modelled in the present study could account for the shortfall in modelled sea-level heights.

Figure 9.10: Observed (fine) and modelled (bold) sea level heights for the locations indicated over 120 hours commencing 2300 UTC 30 July 1990.
9.7 The Impact of elevated Sea Surface Temperatures

The study of McInnes et al. (1992) showed that an increase in SST of 3°C in model simulations of cut-off low events could increase the near-surface winds by the order of 10% as well as increase the rainfall totals and aerial extent of the rainfall. The choice of 3°C in that study was based on temperature increases in climate model simulations under doubled CO₂ experiments (Whetton and Pittock, 1991). More recent climate model simulations indicate a similar increase in SST in this region (Whetton et al., 1997). In this section, the impact of such changes on storm surges is investigated. In each of the three cases the atmospheric model was run with SSTs elevated by 3°C and the resulting surface pressure and wind field used to drive the storm surge model. Figure 9.11 shows the difference between wind fields in the control and enhanced SST simulation for each event at a time close to that of the peak surge. Each event shows a marked difference in the spatial pattern of wind changes, although there are also a number of distinct similarities. In general, all simulations show an increase in strength in southerly winds along the continental shelf although the strongest increases are seen further north. The increase varied at Coffs Harbour from about 1 m s⁻¹ in case 1 to 5 m s⁻¹ in Case 2.

Figure 9.11: Vectors and contours of the difference between modelled winds in the control and enhanced SST simulation for (a) case 1 at 60 hours into the simulation, (b) case 2 at 48 hours into the simulation and (c) case 3 at 84 hours into the simulation. The times shown correspond to the approximate time of the peak surge. The contours are shown every 1 m s⁻¹.
The rainfall changes in the three events are illustrated in Figure 9.12 and again these indicate considerable spatial variation and variation between events. Generally, the coastal zone receives small to moderate increases in rainfall amounts, although some areas receive more rainfall and others, less. For example, the Sydney region experiences a slight decrease in rainfall amounts in Cases 1 and 3 with increases occurring to the north and south whereas Case 2 has 30 mm increases over the Sydney region. It is noteworthy that in Cases 1 and 3 which indicated reduced rainfall totals around the Sydney region in the enhanced SST simulation, the sign of these changes was reversed at about 48 hours into each simulation. In other words, the higher SSTs appeared to produce greater rainfall intensities earlier in the simulation and the rainfall rate diminishes more rapidly as the simulation progressed. In all three events, Coffs Harbour did not experience strong rainfall increases and Case 2 experienced marked decreases because much of the increased rainfall fell further to the south.

**Figure 9.12:** The difference between the modelled precipitation in the control and enhanced SST simulation for (a) case 1 at 60 hours into the simulation, (b) case 2 at 48 hours into the simulation and (c) case 3 at 84 hours into the simulation. The times shown correspond to the approximate time of the peak surge.

The results from the storm surge model run with atmospheric forcing from the enhanced SST simulation are summarised in Table 9.3. In accordance with the wind field changes, there is considerable variation in the sea level changes between events and locations. The relatively larger increases occurred further to the north at Coffs Harbour while the smallest increases were seen at Sydney. Case 2 produced a
Table 9.3: Peak storm surge heights from the control and enhanced SST experiments and percent change between the two runs.

<table>
<thead>
<tr>
<th></th>
<th>Sydney</th>
<th></th>
<th>Port Stephens</th>
<th></th>
<th>Coffs Harbour</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>SST+3</td>
<td>%</td>
<td>Control</td>
<td>SST+3</td>
<td>%</td>
</tr>
<tr>
<td>Case 1</td>
<td>0.19</td>
<td>0.19</td>
<td>0</td>
<td>0.29</td>
<td>0.30</td>
<td>3</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.12</td>
<td>0.15</td>
<td>25</td>
<td>0.14</td>
<td>0.20</td>
<td>43</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.14</td>
<td>0.15</td>
<td>7</td>
<td>0.19</td>
<td>0.22</td>
<td>16</td>
</tr>
</tbody>
</table>

sensitivity to SSTs while Case 1 produced almost no change in storm surge heights due to the insignificant changes in wind speed in the coastal zone. In general, the relative increases in sea level were about twice the changes in windspeed. For example, at Coffs Harbour, a 23% increase in coast parallel winds in Case 2 resulted in almost a 46% increase in sea level height. This is due to the quadratic nature of the wind stress term in the equations governing the ocean movement in response to surface wind forcing.

Despite the limited number of cases examined here and the large variations between events, a number of important insights can be derived of the relationship between elevated sea levels and rainfall patterns along coastal NSW due to low pressure systems in the Tasman Sea. Firstly, there is a general tendency for the highest rainfall amounts to occur in the moist onshore winds to the south of the low centre. The high coastal orography also helps to amplify the rainfall amounts along the coastal plains. The largest sea level anomalies in the simulations performed here on the other hand, occur further northward in the region of the strongest coast parallel winds. Increasing the SSTs had the effect of increasing rainfall over a large portion of the NSW coast with most of the increases occurring between 31°S and 36°S. However, there was also a large variation in amounts and some regions of the coast also experienced decreases. Increases in coast parallel winds on the other hand were most pronounced between around 29° and 33° S. This suggests that the greatest threat of increased coastal flooding events due to the combined action of rainfall and storm surge may occur along the more northern parts of the NSW coast under a scenario of warmer SSTs. This region has the greatest overlap between stronger coastal winds and increased precipitation. Figure 9.13 presents a schematic illustration of the interaction between the low, winds, and the precipitation. It is possible that an increase in the northward coastal currents generated on the continental shelf during such events could also affect coastal erosion by increasing the net northward transfer of sediment. In addition to this, the stronger winds that occurred further offshore, particularly in Cases 1 and 2 would presumably generate higher significant wave heights so that wave set-up at the coast could be expected to increase also.
Figure 9.13: Schematic diagram illustrating the relationship between the low, winds, rainfall and storm surge on the east coast of Australia.

9.8 Conclusions

This study has examined the causes and nature of sea level anomalies along the NSW coast. A review of previous studies and a limited study of the synoptic conditions associated with elevated sea levels indicate that low pressure systems which form and intensify in the Tasman Sea are the major cause. Whilst the elevated sea levels which occur during these events rarely exceed half a metre, their duration can extend to a day or more. This, together with the fact that the depressions often bring high rainfalls to the eastern coastal regions suggest that coastal flooding events due to the combination of severe run-off and sea levels is a major hazard associated with these events.

A storm surge model together with a limited area atmospheric model were used to investigate three events on the NSW coast. It was found that in two of the cases, the timing of the highest sea levels was not well simulated by the storm surge model although the duration of the events was reasonably well captured. Comparison between atmospheric model fields and manually drawn analyses revealed large differences in location and intensity of the low pressure system suggesting that the main source of error was contained in the atmospheric fields used to force the storm surge model. Further sensitivity experiments in which the centre of the low was moved to the east or west relative to the coast produced large differences in the timing of the peak surge and this was related to the time of onset of the sustained coast parallel flow associated with the low pressure system.

In all storm surge model simulations, the sea levels modelled at the coast explained only about 50-80% of the sea level anomaly that was observed. Crude estimates of the possible contribution by wave set-up in each of the cases suggested that it could explain most of the remainder of the observed sea level anomaly.

Comparison of the timing and location of peak rainfall produced by the atmospheric model with the modelled storm surge indicated that in general, the most pronounced rainfall was located in the onshore winds to the south of the low centre during the development phase of the storm. The storm surge on the other hand was found usually further northward in the region of coast parallel flow, often at the time when the storm was reaching maturity.
Finally, an investigation into the possible impact on storm surge heights of warmer ocean temperatures off the east coast of Australia was carried out. In each of the atmospheric model simulations, the sea surface temperatures were increased by 3°C, an amount consistent with climate model estimates under a doubling of pre-industrial levels of atmospheric carbon dioxide. The stronger winds and pressure gradients associated with the storms were found to increase the storm surge by up to 46% depending on event and coastal location although there was a large degree of sensitivity in the response of the atmospheric model to the SST increases. An obvious limitation of the experiments conducted here is that an increase in SST alone can reduce the static stability of the lower troposphere. This may not be indicative of the deeper and longer term heating of the troposphere that occurs due to trace gas radiation absorption in GCM model simulations under enhanced greenhouse conditions. However, the experiments presented here to serve to illustrate the spatial interactions between rainfall and wind speed changes that may occur if more intense systems were to be a characteristic of a greenhouse warmed world. The simulations indicated that the coastal region north of about 33°S experienced the greatest increases in winds, whereas the coastal rainfall totals were found to increase more strongly south of about 31°S in the enhanced SST simulation. This suggests that there is an increased likelihood of overlap between storm surge and extreme rainfall run-off, and hence coastal flooding events, in the mid-NSW coastal region, under a scenario of warmer SSTs. However, this result is based on a small number of cases. It would be of interest to examine in detail, the wind and precipitation characteristics of cut-off lows in the control and enhanced greenhouse climate of a higher resolution RCM simulation. The results could be analysed directly to determine the changes in storm surge and extreme runoff events at locations along the east coast.
10. Recommended Future Work

In this report, dominant weather conditions that affect coastal processes along the NSW coast have been identified. The likely impacts of climate change on these weather conditions, based on recent research using GCMs as well as some specific modelling studies have been presented and discussed. This report has identified a number of key areas where further research is required. In addition to this, methodologies that could be applied, based on new techniques for analysis or new model data sets, have been outlined where appropriate. This section summarises these recommendations.

The output from GCM model simulations has been used to determine the likely impact of climate change on winds (Chapter 2), east coast lows (Chapter 3), tropical cyclones (Chapter 4), mid-latitude cyclones and anticyclones (Chapter 6) and rainfall (Chapter 7). In all cases, the older slab ocean GCMs have been used or the higher resolution RCMs nested within slab ocean GCMs. Now, with the availability of coupled GCM climate simulations for analysis, as well as RCMs that have been nested within coupled GCMs, much of the work presented in this report needs to be re-evaluated. This includes results relating to wind and rainfall changes, and the frequency and intensity of tropical cyclones.

The frequency of cut-off lows on the east coast of Australia were examined in a slab ocean GCM and the results used to infer the likely impact of enhanced greenhouse conditions on the more intense, smaller scale east coast lows. With the availability of climate simulations from higher resolution RCMs, the numbers and intensities of low pressure systems developing off the east coast may be more realistically represented and this needs to be assessed.

Other small scale phenomena such as sea-breezes are not likely to be well represented by even the higher resolution RCMs. Sea-breezes are most likely to develop on days when there are strong land-sea temperature gradients and weak pressure gradients in the vicinity of the coast. On the east coast of Australia, these conditions are often associated with an anticyclone located in the central Tasman. This suggests that a method could be developed for diagnosing likely sea-breeze events in GCM or RCM simulations. This would involve objectively identifying the broader scale anticyclone pattern in daily surface pressure fields as well as calculating the thermal gradient at the coast in the daily fields of surface temperature. In this way, an indicator for sea-breeze occurrence could be constructed.

Further work is needed to examine the role of severe weather events, such as low pressure systems in the Tasman, on elevated sea level conditions at the coast. In particular, the contribution of wind waves in the form of wave setup at the coast needs to be established through detailed modelling of the wave field. The impact of climate change on these events also requires further investigation, particularly in relation to the spatial patterns of rainfall and wind. This could be achieved by identifying and analysing such events in the control and enhanced conditions of an RCM simulation. Storm surge simulations could be conducted using the surface wind and pressure fields from the identified RCM events to establish climatologies of the extreme sea level events in both climates. Rainfall amounts and spatial patterns could be analysed also, to determine the degree of overlap between the storm surge events and the rainfall.
11. References


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