COASTAL STORM ACTIVITY ALONG THE EASTERN NORTH ISLAND OF NEW ZEALAND

– EAST CAPE TO WELLINGTON

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ABSTRACT

Coastal storm activity for the eastern North Island, between East Cape and Wellington, has been quantified from a meteorological perspective through the use of cyclone tracks and extreme winds and from an oceanographic perspective by using hindcast wave information. It has culminated in the production of a high quality, digital coastal storm database for the eastern North Island. Together, this information provides a new understanding of coastal storm behaviour for the eastern North Island.

A regional database of historical coastal storms along the eastern North Island between 1930 and 2005 (75 years) is now available in digital format. Coastal storms were identified as bouts of strong winds ($\geq$ 10.5 $m.s^{-1}$) from long-term local wind records from 1962 to 2005, and prior to this period, coastal storms were qualitatively recognised as any event leading to coastal shipping disruptions/delays, large wave conditions along the coast, episodes of coastal erosion and strong onshore wind periods. This digital database consists of five informative components that include storm meteorology, storm oceanography, impacts and damages, storm photo's and images, and data sources. It has identified a set of five storm types for the eastern North Island consisting of Trough/Ridges, East Coast Lows, Subtropical Lows, Tasman Sea Lows, and Cyclone-Anticyclone pair. The two dominant types are Trough/Ridge and East Coast Low, with the Trough pattern involving weather systems primarily from the southern ocean, whilst East Coast Lows involve large cyclones off the coast that can be distantly generated (from the Tasman Sea or subtropics) or locally generated around NZ from southern ocean troughs. The most intense coastal storms off the eastern North Island are East Coast Lows involving cyclones from the subtropics. These storm events reveal blocking-type anticyclones east of the Chatham Islands play a vital role in coastal storm activity by steering cyclones southward towards NZ and then blocking any eastward movements so that cyclones become slow-moving off the east coast. These factors increase the intensity of pressure gradients directly over eastern NZ.

The Gisborne region, for the 1962-1991 period (30 years), had an annual average of three coastal storms and displays peak activity in September. These storms are overwhelming from the south and southeast. A longer dataset of local winds at Wellington, spanning 1962-2005 (44 years), produced an annual average frequency

of 9 coastal storms per year. The monthly distribution revealed peak storm activity in June and heightened activity between May and August. Both short-lived, high intensity storms (winds ≥14.5 $m.s^{-1}$ for at least 12 hours) and long-lived, lower intensity storms (winds ≥ 10.5$m.s^{-1}$ for at least 24 hours) were identified for the Wellington region. Approximately 70% of these coastal storms persisted for up to two days duration and are predominately from the south and southwest. Furthermore, the more exposed nature and steep terrain surrounding Wellington means a greater likelihood of higher intensity coastal storms compared to the Gisborne region.

Strong cyclonic systems in the southwest Pacific cluster in the central Tasman Sea and east of the Chatham Islands in all seasons and are most frequent in winter. It is during winter that a clear frequency maximum is spotted over North Cape and appears to be related to the presence of slow-moving cyclones rather than high counts of discrete systems. Strong cyclones tend to form in the western Tasman Sea, in the subtropics near 22-23°S, and near North Cape. This local formation off North Cape could be related to the Tasman front and North Cape eddy which create warm sea surface temperature anomalies. The complete life cycle of all strong cyclones shows formation, intensification and maturity in the western-central Tasman Sea, and therefore, a large proportion of these cyclones approaching NZ are weakening systems. However, local generation and intensification near North Cape and the Chatham Islands ensures strong cyclones continue to influence eastern NZ, and further indicates weakened Tasman Sea cyclones can drive coastal storm events through interactions with ridges and high pressure systems. Strong cyclones are most frequent around NZ in August when an average of 4-5 systems per month occurs.

Extreme onshore winds off the eastern coast of NZ consist principally of winds from the southwest and south with a single high latitude frequency maximum near the dateline. These winds are generated from southern ocean cyclonic activity and their northward-extending troughs that pass over NZ, and their spread onto eastern NZ means they likely represent intense coastal storm events. Southeast, east and northeast winds rarely reach up to and beyond 20 $m.s^{-1}$ over the seas to the east of NZ and generally cluster north of 40-45°S indicating both subtropical and higher mid-latitude source mechanisms. Extreme southeast winds are generated by the eastern flanks of large anticyclones that occupy the western Tasman Sea or large anticyclones south of the Chatham Islands. The principal frequency maximum of east and northeast winds is remote from NZ appearing near 165°W, and represent distant generation areas for large swell events (rather than coastal storm activity). These winds that occur over northern NZ are associated with a Tasman Sea or subtropical cyclone off North Cape in combination with a large anticyclone or ridge over/or east of the South Island. In contrast, the distant core for eastward of NZ are generated off the backs of large anticyclones with a trough or cyclone on its northern flank.

The deep-water wave climate off the eastern North Island is dominated by waves from the south. Between 9 and 13 large wave events occur each year between East Cape and Wellington and are most likely in the months of May, June and July. In contrast, large storm waves from the southeast, east and northeast have annual average frequencies of 1-3 events. The Gisborne coast was found to be the most exposed with large deep-water waves (≥ 3m) coming from the northeast through to the southwest. However, waves from the south and southwest are the largest and most persistent. The meteorology creating these waves are southern ocean troughs whilst the less frequent waves from the easterly quarter involve low pressure systems east or northeast of NZ.

The different proxies for studying coastal storms all have shortfalls and arrive at different levels of coastal storm activity. It is suggested here that an optimal mix of these proxies can be used to identify damaging coastal storms along the eastern North Island.

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This thesis is dedicated, with much love, to my father Dick Dunn. This man is an amazing academic in his own right, possessing a wealth of general and specialised knowledge. As a father of twelve he has witnessed numerous degrees and trades achieved by his children across several academic disciplines, and it is with utmost pleasure that his baby daughter will present to him the first doctorate of the Dunn whanau – I know how proud you will be Dad!

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I was warmly welcomed and made ‘at home’ at Tairawhiti Library (Gisborne Public library) while searching through 75 years of newspapers, and wish to thank all the library staff who accommodated my many needs and lots more – in particular, my whanaunga aunty Mako Allen, Rangi Tangohau, and also Adrienne Simpson and Pene Walsh. I often delved into lengthy conversations about my research and sort advice from numerous colleagues within and outside NIWA. Vital and constructive advice was often received from Dr Mark Sinclair (Embry-Riddle Aeronautic University) who was so warmly supportive and openly helpful to a student on the other side of the world. I consider myself very fortunate to have received this advice that ultimately strengthened my research. Other people who shared their time include Georgina Griffiths, Ashmita Gosai, Mark Morrison, Rob Bell, Warren Gray, Meredith Lowe (all from NIWA), Gavin Fisher (Endpoint Solutions), and Ross Marsden (Metservice).

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TABLE OF CONTENTS

List of Figures

List of Tables

1 INTRODUCTION

A common meteorological hazard adversely affecting beaches and shorelines are coastal storms. The coupling of the extreme winds with the associated oceanographic components and processes of large storm waves, strong ocean currents, and elevated sea levels produce highly hazardous conditions for coastal residents, infrastructure and marine transportation.

Societal vulnerability to coastal storms is often judged by the public community based on local damages and leads to suggestions that the frequency of this type of extreme weather is increasing. This subjective judgment, however, fails to account for growing coastal populations and development in high risk areas (Balling & Cerveny, 2003; Karl & Easterling, 1999; Kunkel *et al.,* 1999; Easterling *et al.,* 1999; Dolan & Davis, 1992) which, in itself, acts to increase exposure and risk to damage. It therefore becomes essential to ascertain whether extreme weather events such as coastal storms are actually increasing in frequency (and intensity) to confirm public perceptions and link this to storm and oceanographic factors, or whether increasing damages are in fact related to increased exposure of coastal populations and property along coastal margins and high media coverage (Karl & Easterling, 1999). Furthermore, increases in storminess can be indicators of potential anthropogenically-forced or naturally occurring climate change (Bromirski *et al.,* 2003).

This assessment can only be performed with long term records of storm activity. In NZ it is not widely known whether such information is available. Comprehensive and high-quality compilations of storm events will not only provide storm frequency statistics but also a means from which to better understand overall storm dynamics (development, movement, intensity etc) and assist in avoiding areas at high risk to the associated hazards. Statutory responsibilities of regional and local government authorities require these organisations to formulate coastal plans and policies that will minimise, avoid, or mitigate the impacts of coastal hazards. However, for these policies to be effective they require detailed storm information.

1.1 Scope and Approach

This aim of this research is to examine and quantify coastal storm activity along the eastern North Island from meteorological and oceanographic perspectives. The spatial domain was selected on the basis that it is affected by large-scale weather systems capable of impacting the entire coastal region. The inclement weather associated with a large cyclone off the eastern coast of NZ is often felt from Wellington northward to East Cape.

The approach is to use observed local data (in-situ measurements) and global model and hindcast datasets to explore and quantify coastal storm activity. There appears to be no generally accepted single measure or proxy for exploring storm activity but rather a range of commonly used indicators. They include storm surges (tidal data), waves, cyclone frequencies, pressure, wind records, and damage assessments. Some of these represent direct indicators of storm activity, such as in-situ wind and pressure measurements, while others – waves and damage reports – represent secondary processes or effects. Instead of focussing on a single proxy, it was decided to utilise several storm indicators for which high-quality data was available. They are in-situ wind records, strong cyclone tracks, extreme onshore winds, and large storm-wave events. Cyclones and wind data provide a meteorological approach, while waves provide an oceanographic perspective. These datasets will help to reconstruct and analyse historical weather information in order to compile (as complete as possible) descriptions of past coastal storm events along the eastern North Island.

A storm can be defined as a meteorological disturbance producing a bout of weather consisting of strong winds, low atmospheric pressure, high rainfall, and often thunder and lightning. The strong winds are also generators of secondary storm processes such as large waves and elevated water levels. To be a “coastal” storm, additional conditions need to be applied such as a restriction to coastal margins (e.g. use of coastal weather stations), an onshore wind direction, or a focus on known processes or phenomena felt directly along the coast such as large waves, storm surges, erosion or coastal damage.

In this study coastal storms have several definitions depending on the dataset used and can be based on meteorological or oceanographic parameters. Here, a coastal storm event is defined three ways: a period of strong onshore winds (above a defined magnitude), large-storm waves impacting the coast (above a defined magnitude), and strong cyclonic weather systems through the NZ region.' As such, coastal storms are examined from meteorological and oceanographic perspectives, and will allow for an assessment of which indicator is most appropriate (or combination of indicators) for the eastern North Island. This research goes beyond identifying coastal storms to examining and describing the meteorology (weather systems, intensities, wind speeds, tracks), statistics (frequencies, durations, directions, and intensities), and coastal damages of past events.

1.2 Aims and Objectives

The specific objectives of this study are:

1. Identify the types of weather systems capable of generating coastal storms and their level of activity immediately surrounding NZ.
2. Compile a high-quality, digital coastal storm database for the eastern North Island (East Cape to Wellington) based on in-situ wind measurements;
3. Examine coastal storm activity using strong cyclones as a proxy of coastal storms
4. Explore coastal storm activity from a meteorological perspective by using extreme onshore gradient winds as a storm proxy
5. Analyse coastal storm activity from an oceanographic perspective by identifying large storm-wave events along the eastern North Island from a hindcast wave dataset

Objective One will establish the level of synoptic weather activity around NZ by reviewing the scientific literature. It will reveal the regions of high cyclone and anticyclone activity and their specific properties (e.g. formation, intensification, motion) immediately around NZ and applicable to the eastern North Island, and provide an overview on how stormy the NZ region is based on cyclone activity.

Objective Two creates a historical record of coastal storm events for use in coastal hazard panning, coastal studies and extreme weather research. It will quantify coastal storms from local data, and be as complete a record of storms as possible (1930-2005) by capturing the meteorological and oceanographic aspects of the storm, including their damages. It will also be in a format that is easily accessible to hazard analysts, regional and district councils, climate scientists, coastal planners and other interested users.

Objective Three examines the behaviour of strong cyclones around NZ. Cyclones are known to produce bouts of strong onshore winds along coastal margins and are a commonly used indicator of storminess. This analysis will identify, locally, where strong cyclones reside most frequently around NZ, and investigate their important properties of formation, intensification, trajectories, and frequencies.

Objective Four explores coastal storm activity from a meteorological perspective by using extreme onshore gradient winds as a storm proxy. This analyse will identify where extreme onshore winds occur off the eastern coast of NZ (spatial distributions), their dominant directions, and relative influence on the NZ region. The analysis will also reveal distant generation areas of large wave events along the eastern North Island.

Objective Five examines coastal storm activity from an oceanographic perspective by identifying large storm-wave events along the eastern North Island from a hindcast wave dataset. Large waves represent the most damaging aspect of storms at the coast, and therefore studying them is essential. Climatologies of large storm-wave events from SW, S, SE, E and NE will be compiled and will provide information pertaining to the coastal storm-wave climate. The meteorological situations that generate large wave events will also be investigated.

1.3 Previous Storm Activity Research

Existing information on storms in the NZ region fall into three categories: a) general information and individual storm reports; b) southerly changes and winds; and c) regional or local storm climatologies or databases. A brief review of these studies, with a particular focus on eastern NZ, will provide background information and a platform from which to investigate NZ storm events further.

Date of Storm	Storm Type	Region	Major Features	Author
11 March 1924	Flood, Rainstorm	Napier	Northeasterly conditions	Kidson (1930)
February 1936	Coastal storm (?)	North Island		Brenstrum (2000)
19 Feb 1938	Coastal Storm			Kerr (1974)
9-11 April 1938	Coastal Storm (?)	Eastern NZ		Kerr (1974), Revell & Gorman (2003)
October 1946	Coastal Storm	Christchurch	Beach erosion, large seas	Scott (1955)
March 1954	Coastal Storm	Christchurch	Very heavy seas, seawall destroyed	Scott (1955)
9-10 April 1968	Coastal Storm	Eastern NZ	"Wahine" storm – extreme winds and seas from ex-tropical cyclone Gisele	Revell & Gorman (2003); Carter *et al.,* (2002); Kerr (1974)
Feb to Aug 1971		NZ	Persistent northeasterly over NZ	Trenberth (1975)
30-31 May 1972	Coastal storm	Wellington	Overtopping of seawall, large waves	Chisholm (1976)
5-6 July 1972	Coastal storm	Wellington	Strong winds on south coast, southerlies	Revell (1978)
Feb to Aug 1972		NZ	Persistent south to southwest winds over NZ	Trenberth (1975)
March 1974	Coastal storm	Napier		Stanton (1974)
7-10 Oct 1974	Rainstorm	Wellington	Southerly, rainfall-based storms	Harmsworth & Page (1991)
11-13 Sept 1976	Distant storm	Eastern NZ	Wind and waves	Carter *et al*., (2002)
20 Dec 1976	Storm			Bishop (1977), Harmsworth & Page (1991)
18-21 July 1978	Coastal Storm	Coromandel, Northland		Reid (1979)
7 June 1984	Rainstorm	Gisborne	Lists major floods 1974-1983	Back *et al.,* (1984)
Feb 2002	Coastal Storm	Eastern North Island	Huge waves, marine disaster	Revell et al (2002), Carter *et al*., (2002)
June 2002	Coastal Storm	Coromandel	Northeasterly conditions, weather bomb	White (2003)

Table 1-1 A preliminary list of major storm events, in date order, from available scientific reports or articles.

Most information consists of reports on individual storm events that cover either the meteorology of the event, impacts or damages, and/or both. Thus, several discrete storm events have been well studied. Considerable work has also been undertaken on southerly winds and wind changes along eastern NZ to reveal generation mechanisms and their general characteristics. Comparatively, little research has been done on regional storm climatologies or coastal storm databases. This information is summarized in the following section.

1.3.1 General or Individual Storm Literature

A preliminary list of individual storm reports from around NZ is found in Table 1-1. The list is by no means exhaustive, and it is acknowledged that many storm events will have been missed. It is mostly confined to storm information gathered from easily-accessible sources and has not been built from a thorough literature review. Most of the reports contain information on floods, large rainstorms, snowstorms, anomalous weather periods, and coastal storm impacts. None of the reports regarding coastal storms are elaborated on here. Instead, the relevant information pertaining to the eastern North Island is included in detail in the coastal storm database (following chapter).

Some papers reveal general information on storms and their characteristics. For example, Reid & Page (2002) describe winter storms as being mostly of low intensity but long durations. Burrows & Greenland (1979) recognized tropical cyclones and slow-moving ex-tropical cyclones as generators of severe storms along the eastern North Island. Further, southwesterly storm events were associated with the passage of cold fronts over NZ, and easterly storms to southward-moving cyclones or slow-moving anticyclones to east of NZ. In the Gisborne region, Masters & Back (1986) noted major floods resulted from a quasi-stationary low pressure system east or northeast of East Cape, and conditions often deteriorate further if an anticyclone in the south Tasman Sea moved eastward.

In addition, weather patterns or cyclone tracks for particular months or seasons have been compiled (e.g. Revell, 1978; Crawford, 1977; Trenberth, 1973) as well as rainfall-based storm events (e.g. Harmsworth & Page, 1991; Eyles *et al.,* 1978).

1.3.2 Southerly Wind Events and Changes

1.3.2.1 Southerly Winds

In an early study on winds in the Wellington region Kerr (1942) identified the weather patterns responsible for southerly wind events. He classified the patterns into four main types: closed cyclones; meridional cold fronts; polar fronts; and east coast secondaries. From a short record of only six months, Kerr (1942) also suggested polar fronts crossing NZ that extend from low pressure systems near the Chatham Islands often generated southerly wind events of 2 to 5 days duration. Comparatively, meridional fronts (roughly north-south oriented cold fronts) produced shorter-lived southerlies of 1 to 3 days duration. With a longer dataset, Meldrum (1945) lists southerly winds of at least five days duration at Wellington from 1862 to June 1945. For winds of any intensity between W-SW and E-SE, annual frequencies were compiled as well as numbers of prolonged southerly events of at least 8 days duration. From this data, an annual average frequency of 4 southerly events of at least five days duration were found. Years that had twice as many southerly events as the annual average were 1864, 1876, 1881 and 1905. On a monthly basis, June and July experienced the greatest numbers of long southerly winds, and for events of at least 8 days duration, this peak shifted to May and June. Meldrum (1945) also provides details of all the southerly events of at least 12 days duration, as well as in-depth details of southerly winds of at least 8 days duration for the 1928 to 1945 period.

The nature and properties of southerly winds around the Wellington region and along the eastern coast of NZ have been intensively researched by Reid (1981, 1996, 1997, and 1998). In the first study, Reid (1981) used pressure differences of greater than 16hPa between coastal stations to identify extreme winds off eastern NZ for the 1962-78 time period. The largest pressure differences between the Gisborne and Kaitaia stations, representing strong northeasterly conditions, were found on 19 July 1978, 6 September 1976 and 19 September 1971. Strong onshore southeasterlies, represented by large Gisborne- Christchurch pressure differences, were found on 16 June 1974, 10 April 1968 and 3 February 1967. Reid (1981) further noticed the weather systems producing southerly conditions in the vicinity of Cook Strait were often less intense than those producing northeasterly conditions over the northern half of NZ (i.e. a stronger onshore pressure gradient in northern North Island than southern region). In later papers focussed around Cook Strait, Reid (1996, 1997, and 1998) identified a local acceleration of southerly winds along the Kaikoura coast, and a nonlinear relationship between wind speed and pressure gradients. That is, high wind speeds in the strait can occur with moderate pressure gradients, and vice versa, weaker winds with large pressure gradients. Further, the most severe southerlies in Wellington tend to have wind speeds around 20 to 30 m.s^{-1}.

1.3.2.2 Southerly Changes and Southerly Busters

A typical weather feature of the NZ region is a 'southerly change'. It is the local name given to the onset of southerly wind flows along eastern NZ that is often accompanied by strong gusty winds and large falls in temperature (Sturman, 1993). A 7-year climatology of southerly changes at Christchurch was produced by Ridley (1987). Winds between 160 to 260 degrees (inclusive) with speeds greater than 8.5 m.s^{-1} for 1 hour, or greater than 5.6 m.s^{-1} for 2 hours, were classified as southerly changes. The results showed these events were most (least) frequent in summer (winter), and had a predominance of northwesterly winds before the change. It was also noted that the 1982/83 El Nino event was accompanied by a 30% increase in the number of southerly changes. When these southerly changes are short-lived and generated purely by fronts (as opposed to troughs or depressions), they are termed 'significant events' and represented 35% of all southerly changes.

The general characteristics of southerly changes were revealed by Revell *et al.,* (1987) when they examined 10 southerly change events between 1973 and 1985. They found most events associated with cold fronts from the southern ocean that accompany upper-level short-wave troughs. These fronts can become somewhat distorted as they traverse NZ, and a splitting of the parent cloud system from the front is frequently observed. Furthermore, they recognized gusty, squally southerly changes occurred when high land temperatures from Foehn conditions precede the change.

From a study of four southerly change events along the eastern coast of NZ, Smith *et al.,* (1993) further revealed the southerly flow after the change to be shallow and the pre-frontal flow consistently a northwesterly. Further, the cold fronts accelerated across the coastline if large land-sea temperature differences existed. These authors concluded southerly changes are largely controlled by synoptic-scale processes such as approaching upper level troughs that are then modified by local orography and temperature differences. Similar features have been recognized by Sturman (1993), and have similar properties to southerly buster events of southeastern Australia.

Ridley (1990) investigated NZ southerly buster events occurring in the months of January and February. These events are essentially the same as the 'significant southerly changes' defined in Ridley (1987), being short-lived southerlies generated only by fronts. The average duration of 27 southerly busters was 6.5 hours and the depth of the southerly flow within hours of the change was generally shallow, being less than the mean height of the Southern Alps. By studying the synoptic patterns of five buster events, Ridley (1990) identified upper air (500hPa) features such as strong zonal flow south of the Tasman Sea and South Island before the change, a sharp trough crossing the Tasman Sea, and strong northwest winds over the South Island with the change. At sea level, a disturbed west-southwest flow in the South Tasman Sea before the change and a slow, eastward-moving anticyclone or ridge near or north of the North Island were the leading synoptic features.

With their relatively short durations and generation due strictly to fronts, southerly buster events are not recognized in this study as a major storm type (or coastal storm type). However, long-lived southerly changes generated by closed low pressure systems and sharp troughs form one of the leading types of storms along eastern NZ. These events will subsequently be called southerly storms.

1.3.3 Storm Climatologies or Databases

A search for storm databases or coastal storm climatologies around NZ revealed little information. Barnett (1938) investigated cyclone frequency for the northern half of the North Island between 1898 and 1936. A total of 255 cyclones said to be capable of producing winds to gale force strength were identified, and 50 of these were classified as severe cyclones. The annual average frequency was 6-7 cyclones per annum in the northern region, with only one of these being a severe system. Unfortunately, a definition of 'severe' was not given by Barnett (1938). The months of May, June, July had the highest cyclone numbers (and most severe cyclones), with a secondary peak in February and March. The wintertime frequency maximum has been attributed to cyclones entering the NZ sector from the regions to the west or northwest. Conversely, the peak of February-March is related to cyclones originating from tropical latitudes.

Several climatologies of major rainfall events, or rainstorms, for inland locations were located (e.g. Kasai et al., 2001; Marutani et al., 1999; Eden & Page, 1998; Page et al., 1994) and said to be accurate records of past storm frequency. In the work of Eden & Page (1998), the rainstorms were linked to the tracks of cyclones and it was found that 67% of cyclones had subtropical origins. Further, the positive phase of the Southern Oscillation Index, corresponding to La Nina events, produced more rainstorms. From a physical point of view, this feature makes sense as the La Nina phase brings increased winds from the easterly quarter over NZ, and eastern NZ gets the majority of its rainfall from easterly flows.

Only a few storm or coastal storm databases have been identified for the NZ region. They include a brief chronology of coastal storms for the Hawke's Bay as presented in Smith (1984), and the work of Hay (1991a, b) and de Lange & Gibb (2000) for the Bay of Plenty region. While investigating beach changes on the Napier coastline, Smith (1984) stated there was very little quantitative information on coastal storms in the region. To counter this, he compiled a list of coastal storms between1810 and 1980 from local history books, shipwreck reports, and local records from the harbour boards and local authorities. This 170-year record of storms, unfortunately, is limited to a date stamp and a single comment describing the wind or wave direction, and/or damages. There are several entries, also, that record visual wave heights that date back to the late 1800s.

For the Bay of Plenty region, Hay (1991a, b) compiled a coastal storm database for the time period 1873 to 1990. To qualify as a storm, local newspapers were searched and reports extracted if winds from the easterly quadrant (northeast to south) had speeds of at least 17 $m.s^{-1}$ (Beaufort Scale 8). In most cases, especially for the earlier part of the record, wind magnitude was estimated from the available information in the articles. A total of 153 storms were found, with 114 events being grade 8 and the remaining 39 storms being grade 9 and 10. Hay (1991a, b) determined a return period of a Beaufort scale 9 and 10 storm to be once every 3.4 years and 24 years, respectively. This database includes information on storm type and duration, pressure, winds and wind fetch, as well as oceanographic components such as mean sea level, tides, sea surface temperature, waves and storm surges.

More recently, de Lange & Gibb (2000) present a climatology of storm surge events for the Bay of Plenty. Using 38 years of measured tidal data, for the period 1960 to 1997, annual occurrences of storm surges (>0.1m above predicted high tide) were computed and showed considerable interannual variability. For example, a total of 48 surges were found in 1960 while only 5 appeared in 1978. On a monthly scale, two peaks in surge occurrence were found in March and August. Of the ten highest surge heights extracted, de Lange & Gibb (2000) discovered seven events occurred before 1973, and the largest surge of 0.88m was associated with the Wahine storm or Cyclone Gisele of April 1968. No relationship was found between surge height and the ENSO cycle, though a marked shift in surge frequency in the mid-1970s suggested a possible link with the Interdecadal Pacific Oscillation (IPO). In the 1960-77 period, surges were larger and more frequent in the Bay of Plenty region, and thus identified the IPO as an important decadal-scale cycle that can enhance or attenuate surge frequency.

Thus, only one section of the NZ coastline has a regional storm database – the Bay of Plenty. Unfortunately, this database only serves as a model for most coastal regions of eastern NZ since the findings can not be extrapolated, or said to also represent, say, the Gisborne coast or the southern coast of the Wellington region. The well-known Wahine disaster, the recent Waitangi Day storm, Matata debris flows, and the floods and gale force winds of 2004, are timely reminders that significant coastal storms regularly impact along the eastern coast of the North Island, yet regional or national databases of these meteorological hazards are still absent.

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2 SYNOPTIC WEATHER SYSTEMS

2.1 Introduction

It is well known that travelling or mobile cyclones and anticyclones dominate the weather in midlatitude regions (Sturman & Tapper, 1996). The movement of these synoptic-scale phenomena, and their associated fronts, troughs and ridges through the SW Pacific sector bring extremes in temperature, winds, rainfall and pressure. These meteorological situations are complemented by secondary hazards in the form of extreme wave conditions and elevated sea-level, and can have further destructive flow-on effects to marine transportation and coastal infrastructure. In some cases, the hazardous weather is the result of a lone intense low pressure system and at other times is generated by a combination of low and high pressure systems acting together. Thus, synoptic-scale features create periods of extreme weather such as droughts, strong winds and storm events.

The objectives of this chapter are to:

1. Explore the time-averaged behaviour of weather systems in the SW Pacific-New Zealand region by reviewing hemispheric and regional-scale studies on synoptic systems. (The process involves extracting the main features from these studies for the region generally bound by 150°E to 150°W);
2. Investigate cyclone and anticyclone frequencies, tracks, intensity, motion, and geographical formation, intensification, maturity and decay locations; including both Eulerian and Lagrangrian perspectives of extratropical systems; and
3. Review tropical cyclone activity in the South Pacific.

The properties of the datasets and different analyses need defining at this early stage as they represent a chief source of “variation” or discrepancy in the main findings between authors. They include different data sources (NCEP-NCAR, ECMWF, BOM), grid sizes (from 2x2, 2.5x2.5 to 5° cells), method or criteria for identification of cyclone systems (closed isobar, cyclonic vorticity, or satellite imagery), variable definitions of terms (e.g. cyclogenesis, system versus track density) and seasons. The spatial areas covered between the papers reviewed also varied. To combat these inconsistencies, an attempt is made to review the existing literature by grouping the main findings in “blocks” that contain similar methodologies, and then compare and condense all the findings.

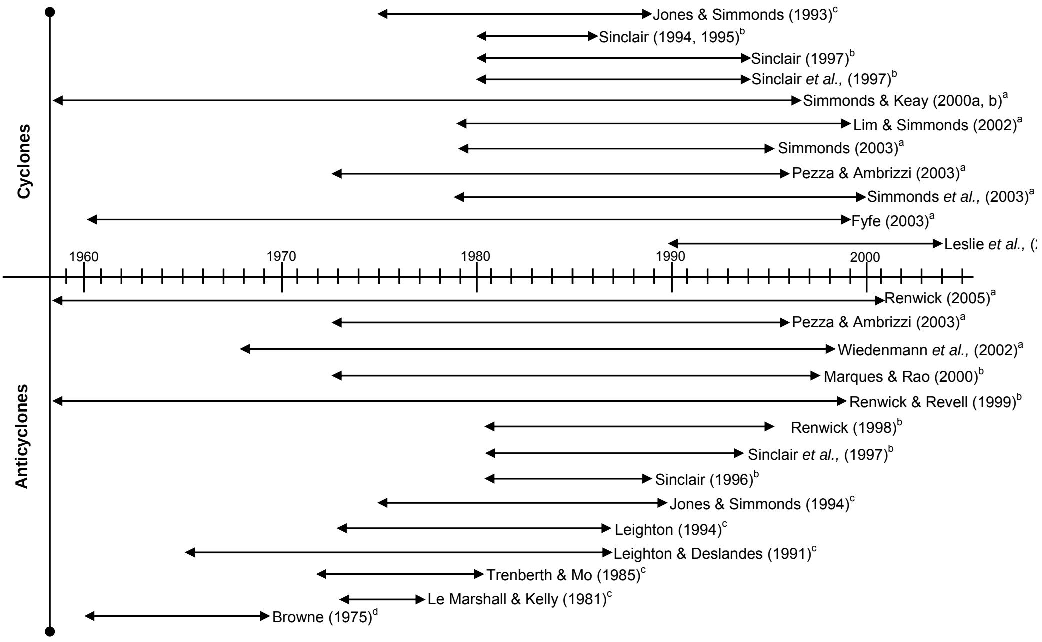

Figure 2-1 A timeline displaying all the literature reviewed in this study and the different time periods that each paper covered. Included are cyclones and anticyclone literature. The subscript letters represent the datasets used in these studies and include (a) NCEP-NCAR reanalyses; (b) European Center of Medium-range Weather Forecasting (ECMWF) reanalyses; (c) Australian Bureau of Meteorology analyses; and (d) NZ analyses.

2.2 Lagrangian Method

Identifying extratropical synoptic-scale activity is performed using Eulerian and Lagrangian methods. The Eulerian perspective, examines the temporal variances (or covariances) of time-filtered atmospheric fields such as mean sea level (MSL) or geopotential height to identify the regions of maximum variance. The Lagrangrian method involves using synoptic criteria to identify the individual surface weather systems (cyclones and anticyclones), tracking their geographical locations, and then calculating a variety of cyclone statistics. The main advantage of this approach is it provides information on specific cyclone properties such as frequency, intensity, and size, while its biggest drawbacks are its intensive process and restriction to surface analyses (Simmonds, 2003; Chang *et al.,* 2002). In terms of coastal storm activity, this method is fundamental as it allows the tracks and evolution of cyclones to be studied. On this basis, the following discussion focuses on the langrangian literature. A list of all literature reviewed here and used to generate the figures of this chapter are shown in Figure 2-1. Furthermore, regardless of how one chooses to define “storm tracks”, any shift in the geographical location of these maxima will lead to substantial regional climate anomalies (Chang, 2002).

2.3 Extratropical Cyclones: Lagrangrian Statistics

The two most common identification techniques use sea level pressure (SLP) criteria of a minimum pressure value with or without closed isobars (i.e. pressure minima without a closed isobar are included) or vorticity criteria. Sinclair (1994, 1995) introduced the use of vorticity criteria to compensate for the main drawbacks in SLP-based methods, in particular: the bias towards deeper and/or slower moving systems that obscure many mobile systems (e.g. latitude dependence), the inability to provide a measure of intensity, and genesis location displacements. By using a local minimum in geostrophic relative vorticity or a local maximum in cyclonic gradient wind vorticity, improved detection of migratory weather systems in the midlatitude band between 45-55°S occurs, together with early detection of cyclone formation. Vorticity measures also have shortcomings in that they are scale dependant and non-cyclonic features such as shear or curvature zones can be extracted as well. While these detection methods have their differences and limitations, both contribute towards a greater understanding of SH cyclones by providing complementary information.

Frequency statistics from Lagrangian methods appear in two categories of “cyclone/system density” or “track density”. Sinclair (1994, 1995, 1997) asserts that the use of system density introduces a bias towards slower-moving cyclones because an individual cyclone gets counted for every point along a track (i.e. uses all points along a cyclone track). This means high counts (or frequency maxima) may reflect slow-moving systems rather than a high frequency of discrete cyclones. As a result, maps of system density showing maxima in preferred geographical regions may represent either areas of slow-moving cyclones or of large numbers of discrete mobile centre’s, or both. The use of track density, with one count per cyclone track, can be used to remove areas of high cyclone counts generated by slow-moving systems and depict more accurately mobile systems. In the literature, the work of Jones & Simmonds (1993), Simmonds & Keay (2000a, b) and Simmonds (2000,

2003) provides cyclone information from a SLP-based detection scheme and look only at frequencies via system density. In contrast, Sinclair (1994, 1995, 1997) provides frequency statistics based on system *and* track density using a vorticity-based cyclone detection method.

This review extracts the main findings for the SW Pacific and Australian-NZ region from hemispheric and regional studies. A list of definitions of the terms that appears throughout the literature is required, as a lack of standardisation has meant that a variety of definitions appear for the same term, and hence, these irregularities need to be eliminated. They are presented in Table 2-1. The terms used in this study are as described in the property column of Table 2-1.

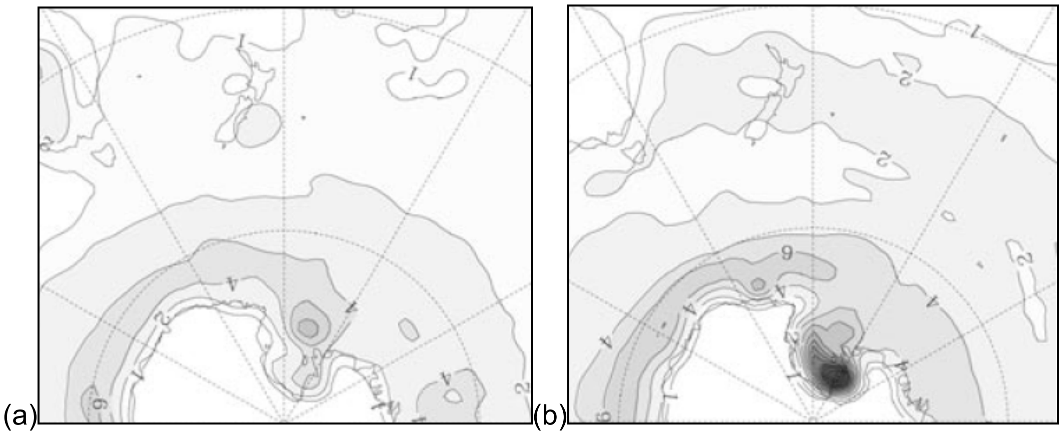

Figure 2-2 (a) Summer and (b) winter system densities for all cyclones (i.e. stationary, closed, mobile, and open cyclones) surrounding NZ. Contour interval is 2 x 10^{-3}(deg lat)$^{-2}$. Extracted from Simmonds & Keay (2000a).

2.3.1 Frequency

The summer distribution of cyclone densities (for both SLP- and vorticity-based schemes) shows most activity along and south of 60°S and over continental eastern Australia. A weaker subtropical band (~25°S) stretches from northeastern Australia to beyond the dateline, and a small area of high cyclone numbers also appears adjacent to the eastern South Island of NZ (Simmonds, 2003; Simmonds *et al.,* 2003; Fyfe; 2003; Simmonds & Keay, 2000; Sinclair, 1994; Jones & Simmonds, 1993). The latest studies, however, display an almost continuous high latitude band along and south of 60°S (Figure 2-2). Earlier studies based on less than six years of data reveal equivalent findings (e.g. Gibbs, 1953; Taljaard, 1967, 1972; Le Marshall & Kelly, 1981). For an exhaustive review of SH cyclones dating back to the early 1900s see Taljaard (1967, 1972) and Streten & Zillman (1984).

In winter, the circumpolar maximum remains around Antarctica and is joined by a mid-latitude maximum along 40°S across the Tasman Sea-NZ-SW Pacific sector (Figure 2-2). Australasian studies by Karelsky (1961) and Leighton & Deslandes (1991) also display a prominent subtropical band. In general, larger cyclone numbers are found in winter and the high latitude maximum is much enlarged and elongated. The use of vorticity exposes greater cyclone activity in the mid-latitudes of all ocean basins (especially the south Indian Ocean). This stems from vorticity-detection schemes identifying both closed systems with pressure minima and mobile open disturbances. This attribute indicates mobile disturbances are most common in the winter season in all mid-latitude ocean basins, and the subtropical maximum in the SW Pacific sector consists of both closed and open systems.

Sinclair (1994, 1995), using a 7-yr dataset, also produced cyclone density plots for near-stationary cyclones and migratory (mobile) systems by applying mobility criteria to the total cyclone count. The near-stationary cyclone distribution in summer and winter revealed the same continental maxima as seen in all cyclones and high numbers around Antarctica (but doesn’t account for all; i.e. some cyclones in circumpolar maxima are mobile). This led Sinclair (1994) to believe the majority of these cyclones represented orographic systems whose contribution to SH weather and climate is likely to be negligible. Furthermore, while a small trace of quasi-stationary systems is found in the Tasman Sea along 40°S, the subtropics and mid-latitudes generally contain few quasi-stationary cyclones. In the work of Leighton & Deslandes (1991), via immobility criterion, slow-moving cyclones in the Australasian region were found north of NZ in summer, while in winter small cores were evident in the Tasman Sea and east of NZ.

Property	**Terms in Use**	**Definition**	**Author**
Frequency or Occurrence	Cyclone or System Density	Simple count of all cyclones per unit area (or grid space)	Jones & Simmonds, 1993; Sinclair, 1994; Key & Chan, 1999; Simmonds & Keay, 2000a; Simmonds *et al,* 2003
	Track Density	Simple count of all tracks per unit area (or grid space); such that cyclones are counted only once per track	Sinclair (1994b, 1995a,b, 1997)
Cyclone Tracks	Cyclone Track	Path a cyclone takes over its entire life cycle from formation to decay	
Formation or Genesis	Cyclogenesis	Initiation or strengthening of cyclonic circulations	American Meteorological Society (2000)
		Initial position or appearance of a cyclone (i.e. the first tracked point)	Jones & Simmonds, 1993; Key & Chan, 1999; Simmonds & Keay, 2000a, Simmonds *et al.,* 2003
Intensification	Cyclogenesis	Intensification of a system *after* formation	Sinclair (1994, 1995, 1997)
Maturity	Maturity	Point of maximum development of cyclone	Sinclair (1994, 1995)
Decay/Lysis	Cyclolysis	Final (tracked) position of a cyclone, or its decay	Jones & Simmonds, 1993; Key & Chan, 1999; Simmonds & Keay, 2000a, and Simmonds *et al.,* 2003
Intense Cyclone	Intense Cyclones	Central vorticity value is $< -15 \times 10^{-5} s^{-1}$	Sinclair (1994, 1995)
Explosive Cyclones or Bombs	Bombs	24hr pressure fall of 24hPa at 60°S; also known as drop of 1 Bergeron (1B)	
		24hr *relative* pressure fall of 24hPa at 60°S	Lim & Simmonds (2002); Leslie *et al.* (2005)
	Rapidly Intensifying I	24hr central vorticity increase at rate > 4.5 or $7.8 \times 10^{-5} s^{-1}$	Sinclair (1994, 1995)
	Rapidly Intensifying II	Circulation* Increases at a rate of > 6 CUV.day^{-1} *Circulation is equivalent to the area enclosed by a curve times the mean vorticity over that area	Sinclair et al (1997)

Table 2-1 A list of definitions of cyclone statistic terms that appear in the literature.

After eliminating orographic systems, a different picture emerged for the remaining mobile systems (see also Sinclair, 1995a, b). In summer, mobile cyclones dominated the regions between 50 and 65°S so as to show a slight equatorward shift. In winter, two parallel maxima occur in the SW Pacific (Figure 2-3). The same high latitude maximum of summertime is seen but has shrunk to lie below 60°S, and is accompanied by a subtropical band along 40°S. This subtropical band of activity shows between 200-300 mobile systems across NZ per winter season, which is approximately twice that of summer. Thus, Sinclair (1994, 1995a, b) shows the preferred geographical regions for migratory cyclones are in the mid-latitude oceans (especially in winter), and near-stationary, orographic (and slower-moving) cyclones are found over the subtropical continents and around Antarctica.

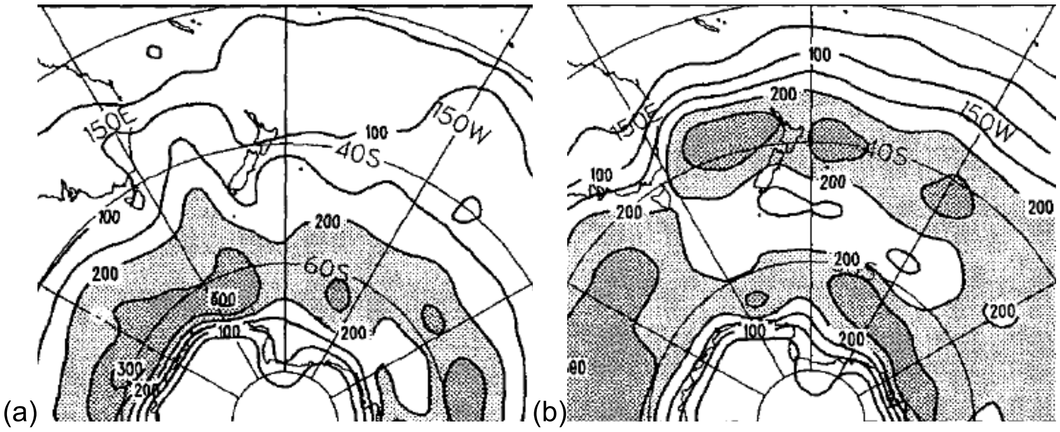

Figure 2-3 (a) Summer and (b) winter system densities for mobile cyclones surrounding NZ. Mobile cyclones are systems moving greater than 10° latitude and counted as the number of centres per 5° radius circles. Contour interval is 100. Adapted from Sinclair (1994)

All mobile centres were further subdivided into 'closed' mobile systems (i.e. those with a pressure minimum, Figure 2-4) and 'open' mobile disturbances (i.e. no pressure minima or closed isobar, by Sinclair (1994). Approximately 30% of summertime mobile systems consist of closed centre's that maximize in the 50-65°S latitude band (much like for all mobile centre's), though more activity occurs in the South Tasman Sea. Across NZ there are around 40 to 60 systems. The winter pattern, in comparison, shows two prominent bands – one along 40°S with 80-120 systems in the Tasman Sea and slightly fewer (80) to the east of NZ; and the other on and south of 60°S directly below which contains similar system numbers (Figure

2-4). Consequently, the majority of mobile systems are made of open disturbances (approximately 68%) and they cluster in the midlatitudes (Figure 2-5). A small summertime maxima in open disturbances was found SE of NZ near 50°S; otherwise, 50 to 100 systems are seen in the NZ region.

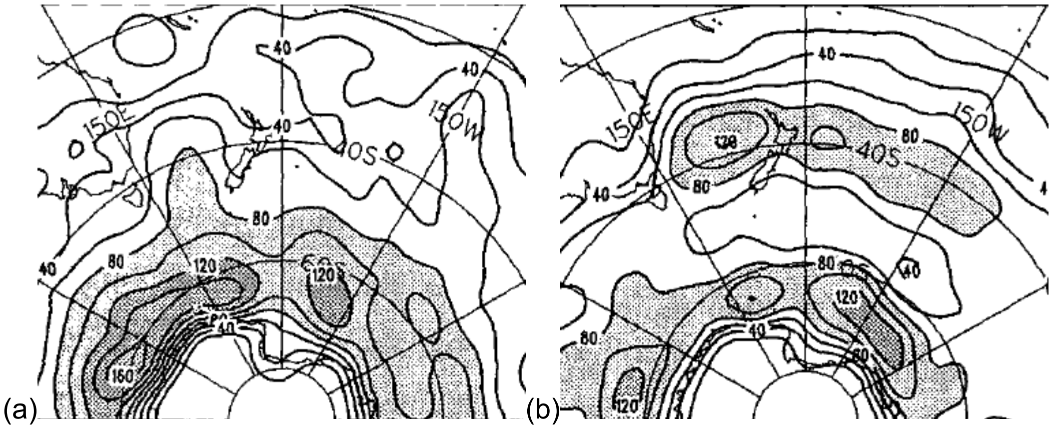

Figure 2-4 Summer (a) and (b) winter system densities for closed, mobile cyclones around NZ. These are cyclones with a closed isobaric centre & move more than 10° latitude. Contour interval is 20. Adapted from Sinclair (1994)

In winter, a single subtropical maximum is visible along 40°S that contains approximately 150 systems. These frequency statistics for the NZ region are listed in Table 2-2. Thus, of the mobile systems that traverse the SW Pacific region, we recognize the summer season as having the most (>80) closed centre's south of 50°S while across the NZ landmass there are more open disturbances than closed systems (see Table 2-2). Comparatively, the mobile systems of wintertime consist of both closed centres and mobile disturbances in the subtropical branch (with more open disturbances than closed centres), and essentially closed centres in the subpolar branch.

Cyclone frequency statistics for mobile cyclones, using track density, have also been investigated (Hoskins & Hodges, 2005; Sinclair *et al.,* 1997; Sinclair, 1997, 1995, 1994). These statistics are thought to eliminate the influence of slow-moving cyclones that potentially skew system density results. The summer distribution shows a single midlatitude band centred near 50-65°S, so as to lie equatorward of the system density maxima (i.e. the near-stationary cyclones within the circumpolar trough are less influential to the frequency statistics). There is similar structure in the SW Pacific sector, though there is less activity south of the Tasman Sea. In winter, the western Pacific sector displays two bands of track density maxima, much like with system density, but there is little activity in the Tasman Sea. Sinclair (1994) relates this attribute to the double-jet structure found in the same region, and by using track density finds a pattern that agrees well with the main SH baroclinic storm tracks (e.g. Trenberth, 1991; Nakamura & Shimpo, 2004).

System Type	Summer	Winter
All Cyclones	300-400	400
Quasi-stationary Cyclones	~200	~200
All Mobile Cyclones	100-150	200-300
Subtropical Band	n/a	200-300
High Latitude Band	200-300	200
Closed Mobile Systems	40-60	80-120
Subtropical Band	n/a	80-120
High Latitude Band	80-120	80-100
Open Mobile Disturbances	50-100	~150
Subtropical Band	n/a	150
High Latitude Band	n/a	n/a

Table 2-2 Approximate frequency statistics of cyclones across and immediately around the NZ landmass, and numbers of cyclones occurring in the subtropical and/or high latitude branches in the SW Pacific sector (150°E to 150°W) for the 1980-1988 period. These figures have been extracted from Sinclair (1994).

The other main discrepancy between SLP- and vorticity-based studies regards the locations of cyclone maxima. The inclusion of mobile disturbances (whether open or closed centre's) by means of vorticity-based studies, acts to generate an equatorward expansion of basic SLP-based patterns since mobile systems reside more in the mid-latitudes. Further, open mobile disturbances contribute more to the equatorward spread than closed mobile systems, and in effect, push the location of mobile centre maxima further north compared to SLP-based studies.

Together, system and track density frequencies reveal a wintertime split structure in the SW Pacific, and this implies a combination of both slow-moving and fast (mobile) cyclones in this region. When looking at these structures on a smaller scale, a system density winter maxima seen in the Tasman Sea sector is not as obvious in track density patterns. This suggests the Tasman Sea experiences higher proportions of slower-moving (or discrete) systems. Meanwhile, over and east of NZ there are maxima in both system and track densities so that a mixture of mobile and slow-moving cyclones exist.

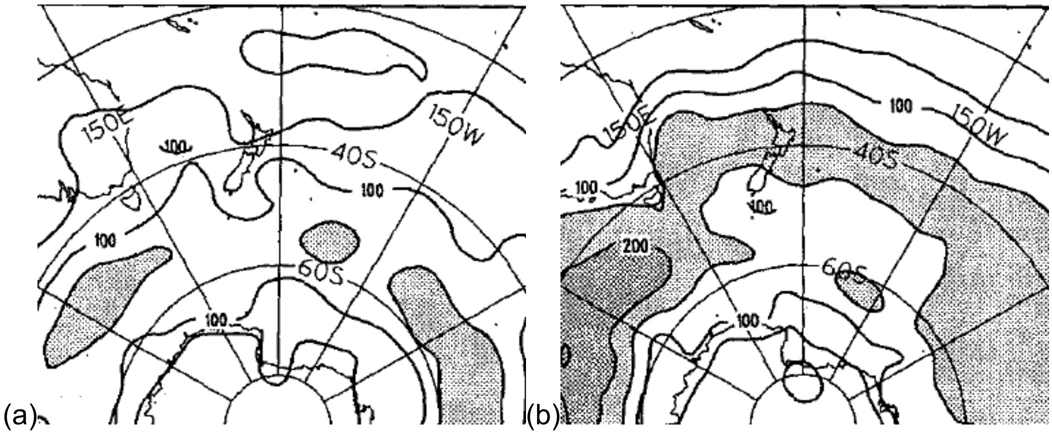

Figure 2-5 System densities of open mobile cyclones for (a) summer and (b) winter surrounding NZ (150°W - 150°E). Contour interval is 100. Adapted from Sinclair (1994).

2.3.2 Formation Regions

It is important to stress at the outset the advantages and disadvantages of SLP-based and vorticity-based detection methods when examining the geographical formation locations. Sinclair (1995a) claims the first track point identified with SLP-minima schemes may not be the initial formation point, as most newly-formed cyclones only attain closed isobaric centres at later stages of their life cycles. By using vorticity minima, cyclones are detected at earlier stages of development by identifying mobile disturbances long before they strengthen into a closed pressure centre. As a result, Sinclair (1995, 1997) prefers to call the point of initial development “cyclone genesis” or “cyclone formation”. This deviates from most other studies that define the initial point of formation or first track point as cyclogenesis (e.g. Taljaard, 1967; Jones & Simmonds, 1993; Simmonds *et al.,* 2003). Therefore, cyclogenesis in the work of Simmonds is synonymous with cyclone genesis by Sinclair. [This divergence is extremely important, for otherwise, one would be comparing formation regions from the work of Simmonds (and others) with intensification regions from the work of Sinclair]. For this review, the creation points of cyclones or first track points will be collectively referred to as “Formation Regions”.

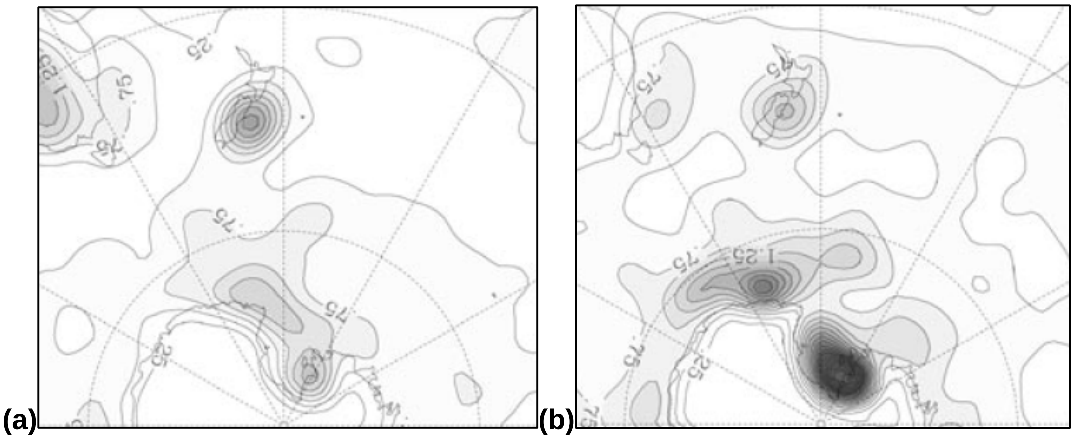

Figure 2-6 The main cyclone formation regions surrounding NZ in (a) summer and (b) winter. Contour interval is 0.25 x10^{-3} cyclones (deg lat)$^{-2}$day^{-1}. Taken from Simmonds & Keay (2000a).

In summer, clear formation regions are seen over eastern Australia and immediately off the east coast of the South Island (Simmonds *et al.,* 2003; Simmonds & Keay, 2000a; Jones & Simmonds, 1993) (Figure 2-6). These regions were not found using vorticity statistics (Sinclair, 1995b). In winter, the continental activity over eastern Australia moves eastward to sit of southeastern Australia and the eastern South Island activity reappears in a weaker state. Genesis also increases south of NZ in high latitudes. Thus, in both summer and winter, there are two genesis zones in the SW Pacific – east of NZ and directly south below 60°S. Further, there is better agreement in the winter pattern in the SW Pacific between SLP- and vorticity-based studies (unlike the summer pattern).

Using track density statistics, Sinclair *et al.,* (1997) show a slight variation to this winter pattern, whereby there is an equatorward spread of genesis in the high latitudes below eastern Australia and NZ. This core suggests an abundance of mobile systems are generated here (but not slower-moving centre’s as a corresponding core is not seen in system density). The concentrated activity east of the continents has been linked to baroclinic zones associated with warm ocean currents, strong SST gradients, and positions of the upper-tropospheric jetstreams (Sinclair, 1995a; 1997).

2.3.3 Intensification and Maturity Regions

The intensification or strengthening of pre-existing cyclones is called cyclogenesis in the work by Sinclair (1995a, b, 1997). To avoid confusion and inconsistencies in the literature, locations where cyclones intensify are here called “intensification regions”. The summer pattern reveals high cyclone densities off southeastern Australia and new the dateline along 40°S. In winter, the Tasman Sea becomes an active region for intensifying cyclones and this activity spreads westward across NZ along 30-40°S. A high latitude maximum also appears along 60°S (Figure 2-7). Thus, the winter pattern shows two bands where cyclones frequently intensify in the SW Pacific-NZ region: along 30-45°S and 55-70°S. These favoured locations are eastward and poleward of the main genesis locations. Also, winter intensification occurs over a broader region of the mid-latitudes compared to summer. Monthly track density plots for mobile systems show the same broad features (Sinclair, 1995a), particularly in winter.

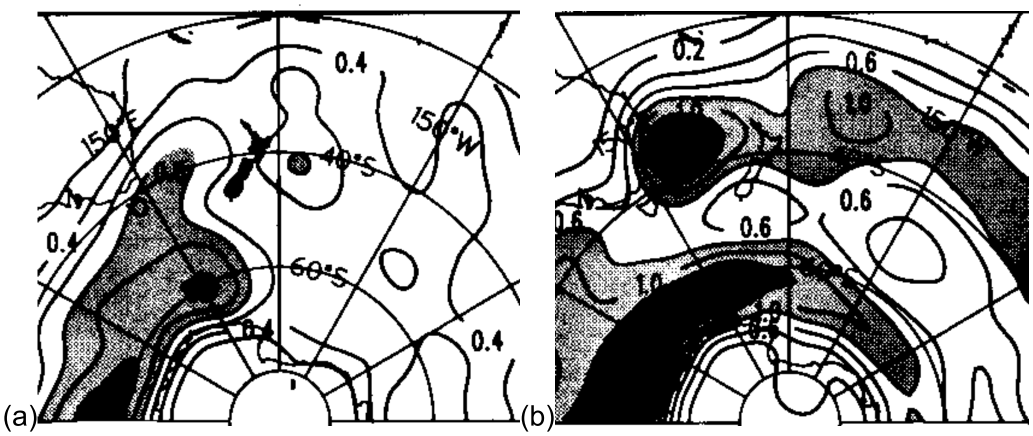

Figure 2-7 Intensifying mobile cyclones around NZ (150°W - 150°E) in (a) summer and (b) winter. Contour interval is 2 cyclones per 5° lat radius area per month. Taken from Sinclair (1995b)

Sinclair (1995a) also examined where migratory (mobile) cyclones reached their maximum intensity and development, which he termed “maturity”. Consistent with theory, the main locations were found downstream from formation and intensification regions. In summer-autumn, most activity occurs in the high latitudes (along 60S) below Australia and NZ. Mature cyclones surround NZ in winter-spring, when a subtropical band appears near 40°S in the SW-central Pacific, along with a subpolar band south of 60°S. This pattern is very similar to that of intensification, and the Tasman Sea-NZ sector is identified as a region where cyclones can both intensity and mature in winter. Thus, some cyclones can mature somewhat quickly after intensification.

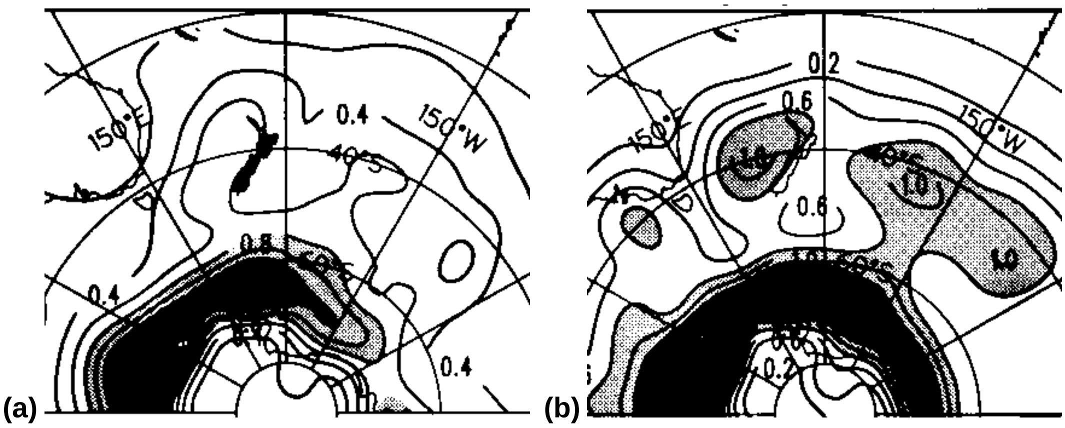

Figure 2-8 The main regions around NZ (150°W - 150°E) where decaying mobile cyclones are located in (a) summer and (b) winter. Contour interval is 2 cyclones per 5° lat radius area per month. Taken from Sinclair (1995b)

2.3.4 Decay Regions

The principal regions with high cyclone decay or lysis in summer is an almost continuous zonal band at or south of 60°S. SLP-based studies also show maxima over the continents. In winter, cyclone decay is largest poleward of 60°S surrounding Antarctica (Simmonds et al., 2003; Simmonds & Keay, 2000a; Sinclair, 1995b; Jones & Simmonds, 1993) (Figure 2-8). Vorticity-based studies, while showing similar patterns, also find high densities south of Australia, in the Tasman Sea and east of the dateline (Sinclair, 1995b). Monthly track density statistics for mobile systems show very similar patterns but wintertime activity spreads further northwards in the higher latitude branch. Thus, a double-maximum is recognised in wintertime cyclolysis in the SW and central Pacific Ocean in both system and track density plots (Sinclair, 1995a, b; 1997). This indicates large numbers of mobile and slow-moving decaying systems in these locations.

2.3.5 Intense and Rapidly Intensifying Cyclone Regions

Sinclair (1995a) partitioned mobile cyclones into two strength categories of intense and explosive types. Explosive cyclones are also called “rapidly intensifying”, “rapid deepeners”, and “bombs”. These alternate names are applied according to the intensity measure used. For example, pressure-based criteria are referred to as “rapid deepeners”, while vorticity-based criteria are termed “rapidly intensifying”. They are all defined in Table 2-1. It has been recognized that explosive cyclones based on a 24hr pressure fall (rapid deepeners) can provide misleading results. Sinclair (1994b, 1995a) shows the pressure fall can result from the rapid movement of cyclones across regions of lower background mean sea level pressure (MSLP), and not necessarily an increase in intensity. To correct for this, Lim & Simmonds (2002) define a “relative” central pressure fall or relative deepening rate as the central pressure minus the climatological pressure over the region. Sinclair (1995) formulated a measure based on increases in cyclonic vorticity that is independent of background pressures. However, in a later paper Sinclair (1997) found vorticity increases alone were also problematic and proposed the use of a circulation measure that accounts for both the size and rotation rate of cyclones. Thus, one will expect to find different spatial patterns to materialise from these intensity measures, as they either remove biases (e.g. background pressure with vorticity) or add new components (e.g. cyclone size with circulation).

There are no intense mobile cyclones (vorticity values $< -15\times10^{-5}.s^{-1}$) in the SW Pacific in summer (Figure 2-9). In winter, however, the Tasman Sea becomes a principal centre for intense cyclones, and to a lesser extent, east of the dateline.

Explosive cyclones or bombs, using central vorticity criteria, found localised centres of wintertime activity east of Australia, in the Tasman Sea, and east of the dateline (Sinclair *et al.,* 1997; Sinclair, 1995a,b) (Figure 2-10). The Bergeron and circulation criterion (see Table 2-1 for definition) found no significant activity around NZ (Sinclair *et al.,* 1997; Sinclair, 1995a, b).

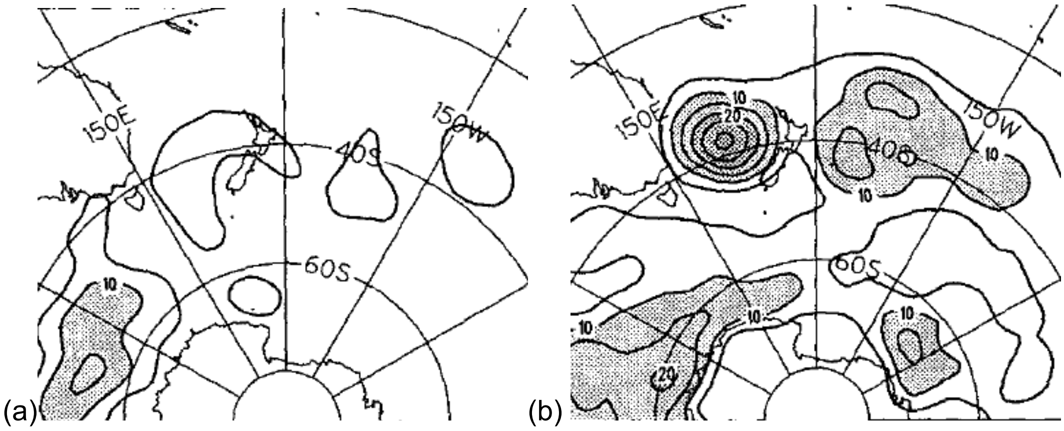

Figure 2-9 The distribution of intense cyclones ($\zeta_g < -15 \times 10^{-5} s^{-1}$) in the SW Pacific region and surround NZ for (a) summer, and (b) winter. The contour interval is 5 (from Sinclair 1994).

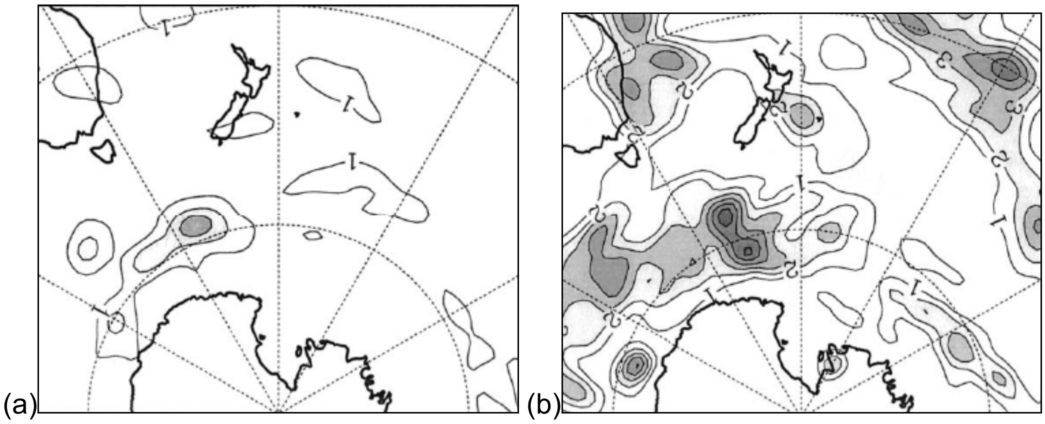

Figure 2-10 System densities of explosive cyclones or "bombs" around NZ (150°W - 150°E) in (a) summer and (b) winter. Contour interval is 1×10^{-5} cyclones per (deg lat)^2. Taken from Lim & Simmonds (2002) who define a 'bomb' as a 24 hPa pressure fall in 24 hours.

A comprehensive study of explosive cyclones (or bombs) was undertaken by Lim & Simmonds (2002) using a relative deepening rate of SLP cyclones. In this study, explosive cyclone activity is clearly weakest in summer but increases considerably in winter. Wintertime activity is clear in the SW Pacific, with centres of action off eastern Australia and east of Cook Strait near the dateline (Figure 2-10). Lim &

Simmonds (2002) partly link these distributions to baroclinic processes, latent heat fluxes and troughs in the subtropical easterly flow.

Lim & Simmonds (2002) also examined explosive cyclone motion, trends, and mean intensity, radius (size) and depth. Their tracks display east-southeast motions in low latitudes (and northeast motions south of 50°S in all seasons). The mean intensities around NZ are classified as weak to moderate systems based on a normalized deepening rate. The largest explosive systems are generally located south of NZ and have a mean radius of 5-6° latitude. Further, mean depths of explosive cyclones ≥ 9hPa tend to cluster around NZ.

More recently, Leslie et al (2005) provide a 15yr climatology (1990-2005) using the same criterion as Lim & Simmonds (2000) for the SE Tasman Sea – NZ sector. Explosive cyclone numbers ranged from 1 to 6 events in any one year with the most active years being 1990 and 1994. They were most frequent in June and July with a secondary peak in November-December, and have median central pressures of 980hPa. Another significant result was that 88% of the explosive cyclones identified were felt in the South Island of NZ, compared to only 42% striking the North Island.

2.3.6 Cyclone Motion and Duration

In general, cyclones travel along east-southeast paths in summer and winter (Sinclair *et al.,* 1997; Sinclair, 1995a, 1994; Jones & Simmonds, 1993). The mobility of these cyclones changes seasonally, such that much slower translation speeds occur north of NZ in summer (Sinclair, 1995a, 1994; Jones & Simmonds, 1993). Sinclair (1995a) was able to highlight the existence of slow-moving cyclones in the NZ region in winter through a comparison of system and track density structures. This is supported by an earlier Australasian study of Leighton & Deslandes (1991) who unveiled slow-moving cyclones in the Tasman Sea, over NZ and in the western Pacific in midwinter, autumn and spring.

Simmonds & Keay (2000a) also document the important cyclone property of track duration. They found SH cyclones exist, on average, for around 3 days, while a small percentage can persist for up to 10 days. Approximately 30% of these cyclones travelled distances of 500-1500km, and a moderate amount move in excess of 5000km. Winter tracks are, on average, more than 350km longer than summer tracks. No spatial distributions for these durations were presented.

2.3.7 Mean Cyclone Intensity, Radius, and Depth

A complete picture of SH cyclones can not be assembled by frequency statistics alone. Thus, Simmonds & Keay (2000a) explored whether regions that are host to large cyclone densities are affected by relatively weak or intense (or both) systems. That is, they established which regions contain high numbers of weak and/or intense cyclones. The cyclone properties of intensity, radius, and depth are all related through the Laplacian of the pressure field at the centre of the system, which is used as a direct measure of cyclone intensity. The depth is determined by calculating the pressure difference between the centre and the edge of the cyclone, and the radius represents the size or area.

Mean intensity values across or over NZ are 0.6-0.7hPa (deg lat)-2, 5°lat and 3-4hPa for intensity, radius and depth respectively. The largest cyclones occur right through the midlatitudes of the Pacific Ocean, with a centre of activity in the Tasman Sea. Across NZ, the mean intensities, radius and depths are 0.7-0.8hPa (deg lat)-2, 5.5-6°lat and 5hPa respectively. Thus, across NZ, cyclones are slightly largely and deeper in winter, though the intensities remain relatively the same as in summer. Simmonds *et al.,* (2003) reveal matching structures from an updated, later version of the NCEP-NCAR reanalyses.

Spatial and temporal trends in these properties have been evaluated by Simmonds & Keay (2000b) for the same dataset as above for the time period 1958 to 1997. Here, the focus is purely on the SW Pacific-Australasia sector. They found cyclone numbers have decreased south of NZ between 1958 to 1997 with few changes to the east and west. Most of these cyclones have become more intense between 30-45°S in the Australia Bight, Tasman Sea, and western Pacific. However, across the NZ and Australian landmasses these systems have become smaller, especially north of 50°S (and larger elsewhere i.e. in higher latitudes and east of 170°W in the Pacific). Also, south of 40°S below Australia and NZ into the western Pacific these cyclones have become deeper. Thus, reduced cyclone numbers doesn't necessary imply reduced damages or impacts as larger and deeper systems can compensate for this. In the NZ region while there has been little change in cyclone numbers, they have become more intense to the south and southwest, but are smaller systems. No changes were seen in cyclone depths.

2.3.8 The Complete Cyclone Life Cycle

From Sinclair (1995a), one begins to appreciate the full life cycle of SH cyclones by systematically looking at formation, intensification, maturity and decay regions. By viewing these properties together, "cross-over" zones appear and demonstrate, for example, where cyclones can form and decay, as well as gain a large-scale picture of their movements (particularly on an oceanic scale). An attempt has been made to expand upon the general consensus that cyclones intensity, mature and decay downstream from formation zones by probing the life cycle work of Sinclair (1995a). The following discussion applies to the winter season of the SW Pacific.

In the SW Pacific, Sinclair (1995a) shows cyclones form and intensify in the western Tasman Sea and mature and decay in the eastern Tasman, and across NZ into the central Pacific. There is one core region of genesis near 35°S off eastern Australia; however, a double-maximum is seen in intensification, maturity and decay plots. Given a single formation region, it is speculated that the set of intensifying and maturing cyclones along 60°S below NZ represent "foreign" systems moving into the SW Pacific from the eastern Indian Ocean. This notion is supported by the southward propagation of cyclones from the Tasman Sea region being negligible, and by the westerly wind belt through the midlatitudes carrying embedded cyclones eastward. Thus, it is suggested the subantarctic intensifying branch is generated by faster-moving cyclones from the eastern Indian Ocean. With this suspected flux of systems and their intensification in the SW Pacific, it follows that the same systems will mature and decay in similar latitudes to also show a subantarctic maximum.

Cyclones can form, intensify, mature *and* decay across NZ to indicate slow-moving systems and mostly eastward motions (i.e. small poleward component). The longitudinally stretched intensification and maturity regions (compared to formation) imply a considerable number of cyclones in this region also migrate rapidly across the SW Pacific.

2.3.9 Influence of El Nino Southern Oscillation (ENSO)

Relationships between cyclone frequency and ENSO have been investigated by Sinclair (1995b), Sinclair et al., (1997) and Pezza & Ambrizzi (2003). They discovered that El Nino events are associated with 10-20% fewer cyclones over Australia, in north Tasman Sea, and north of NZ, and more in the southern ocean below 40-50°S. Consequently, La Nina phases increase summer cyclonic activity by more than 50% north of NZ between 150°E and 150°W, with smaller increases over SE Australian.

2.4 Anticyclones and Blocking Systems

Anticyclones are a major feature of the weather in the Australian-NZ region (Sturman & Tapper, 1996). While significant storm events are not often associated with anticyclonic systems or blocking highs, these synoptic systems are capable of strong meridional and zonal wind events along their peripheries. When they become paired with low pressure centres, the airstream squashed between them can generate winds reaching or exceeding gale force strength for periods of several days. Consequently, studies of significant storm events need to take into account the presence and locations of anticyclones.

Climatologies of Southern Hemisphere anticyclones have been performed by numerous authors and extend back to the 1950s (Pezza & Ambrizzi, 2003; Sinclair, 1996; Jones & Simmonds, 1994; Leighton, 1994; Leighton & Deslandes, 1991; Le Marshall & Kelly, 1981; Taljaard; 1967; and Gibbs, 1953). Regional SW Pacific studies have also been completed by Wright (1974) and Browne (1975). These authors contribute the most knowledge on anticyclone frequency, genesis and decay locations, intensification, movement, and intensity. Further, several authors have investigated the influence of ENSO cycle and hemispheric atmospheric variability on anticyclones and will be discussed. The main studies used here are shown in Figure 2-1. The main features for the SW Pacific region are reviewed below.

2.4.1 Frequency Distribution

The maximum frequencies or densities are consistently found in dispersed cores between 25 and 45°S in the oceanic basins. In the SW Pacific, summer activity appears in the Tasman Sea, and east of the dateline into the central Pacific along 35-40°S (Sinclair, 1996; Jones & Simmonds, 1994; Leighton & Deslandes, 1991; Le Marshall & Kelly, 1981; Browne, 1975) (Figure 2-11). In the NZ sector, for the 1960-69 period, Browne (1975) found the largest numbers west of the North Island (Tasman Sea) in spring, summer and autumn.

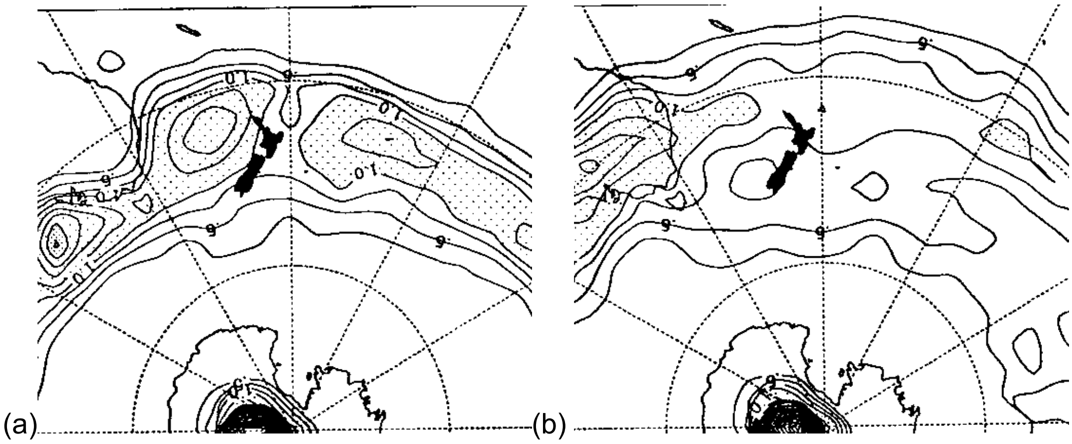

Figure 2-11 System densities of anticyclones in (a) summer and (b) winter surrounding NZ (150°E-150°W). Contour interval is 0.5 x 10^{-3} anticyclones per (degree latitude)^2. Adapted from Jones & Simmonds (1994).

The winter pattern fails to show the same structures across all authors, with some showing a prominent twin maximum in the SW Pacific (e.g. Le Marshall & Kelly, 1981; Taljaard, 1967), while others detect most activity over southern continental Australia and the North Tasman Sea (e.g. Sinclair, 1996; Jones & Simmonds, 1994; Leighton, 1994). This irregularity, as suggested by Sinclair (1996), could represent an interannual feature which is visible in some years but not in others. This indicates anticyclone numbers in the SW Pacific are extremely variable. With this in mind, one could speculate that the 1957-58 year of Taljaard (1967) and mid-1970s of Le Marshall & Kelly (1981) were dominated by years with twin maxima in the SW Pacific since the average shows the twin pattern. Accordingly, in the 1980s twin maxima in winter were less frequent as it fails to surface in the long-term average.

Trenberth (1976) noted that anticyclones prefer to cluster to the east or west of NZ, rather than across the landmass (much like Browne, 1975). He also found a trend of more anticyclones to the east of NZ since the 1940's and less in the Tasman Sea and over Australia. Further, Browne (1975) delineated consistently large anticyclone numbers east of the South Island in all seasons.

2.4.2 Formation and Intensification Regions

The principal latitude band where anticyclones form is between 25-40°S (Sinclair, 1996; Jones & Simmonds, 1994). In the SW Pacific, summertime centres appear east of Australia into the Tasman Sea, and east of NZ extending into the central-eastern Pacific (Figure 2-12). Sinclair (1996) found a pattern of genesis with maxima situated downstream from major mountain barriers prompting an orographic coastal ridging formation mechanism. In winter, anticyclone formation continues off SE Australia in the Tasman Sea but is less active (Sinclair, 1996; Jones & Simmonds, 1994).

After forming, summer anticyclones tend to intensify slightly southward or southeastward of genesis regions in the Tasman Sea and east of NZ. Intensifying anticyclones spread along 40°S off eastern NZ so as to cover a much larger area then genesis. Wintertime activity, comparably, is minimal around NZ.

2.4.3 Decay Regions

The main latitude band of decaying anticyclones is between 28 and 40°S, and is on average, approximately 2-4° equatorward of peak densities and genesis maxima (Sinclair, 1996; Jones & Simmonds, 1994). In the SW Pacific, anticyclones terminate north and east of their formation points in the Tasman Sea while east of NZ they decay further eastward. Thus, the Tasman Sea is a source and sink for summertime anticyclones. In winter, continental Queensland shows large numbers of decaying centres. Sinclair (1996) shows a slight variation to this winter pattern of Jones & Simmonds (1994), such that the SE Queensland maximum spreads northwards to cover NZ and the area north of NZ.

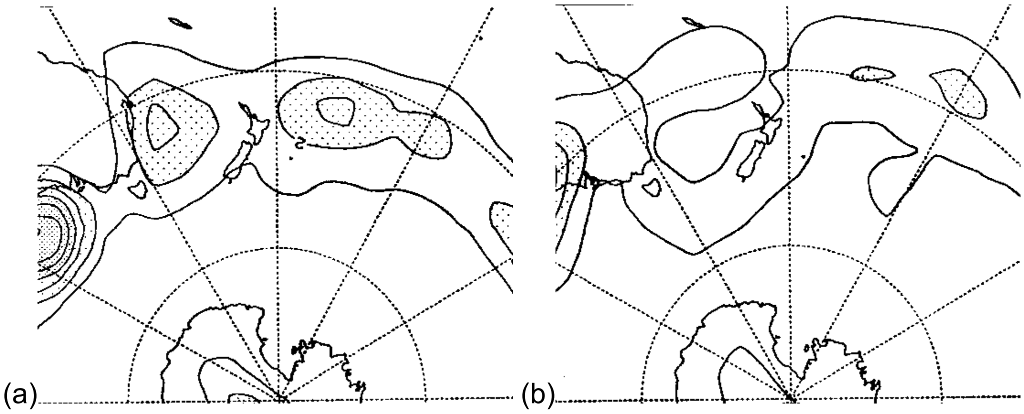

Figure 2-12 System densities of anticyclone formation regions in (a) summer and (b) winter surrounding NZ (150°E-150°W). Contour interval is 0.5 x 10^{-3} anticyclones per (degree latitude)^2. Adapted from Jones & Simmonds (1994).

2.4.4 Anticyclone Motions

In the SW Pacific, anticyclone movements are eastward with a slight equatorward component in both summer and winter (Sinclair, 1996; Jones & Simmonds, 1994; Taljaard, 1967). A slight seasonal variation in speed is seen across NZ whereby winter anticyclones in the north Tasman Sea travel faster and at a constant speed. Leighton & Deslandes (1991) and Leighton (1994) show the Tasman Sea-NZ sector favours slow-moving anticyclones for all midseason months, and is joined by further maxima near eastern NZ in mid-autumn and mid-winter. That is, slow-moving anticyclones to the east of NZ are most abundance in autumn and winter.

2.4.5 Intensity (Relative Mean Central Pressure)

Across the Australian and NZ landmasses, anticyclones are generally 10-15hPa above climatology year-round (Sinclair, 1996; Jones & Simmonds, 1994). Sinclair (1996) also explored the spatial distribution of anticyclones which contain central values greater than 1035hPa (and 1040hPa) and called these “intense” systems. They emerged either side of NZ between 40 and 45°S with speeds of around 5 m.s^{-1} (being much slower than the speed of all anticyclones, 8 m.s^{-1}). Those systems that exceeded 1040hPa also clustered around NZ.

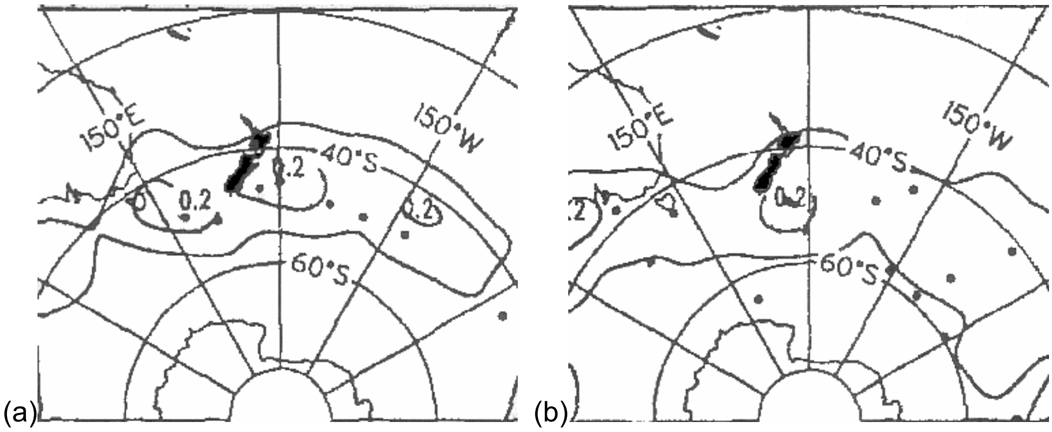

Figure 2-13 Track densities of rapidly intensifying anticyclones in (a) summer/autumn and (b) winter/spring surrounding NZ (150°E-150°W). Contour interval is 0.1 anticyclones per 5° latitude circle per month. Taken from Sinclair (1996).

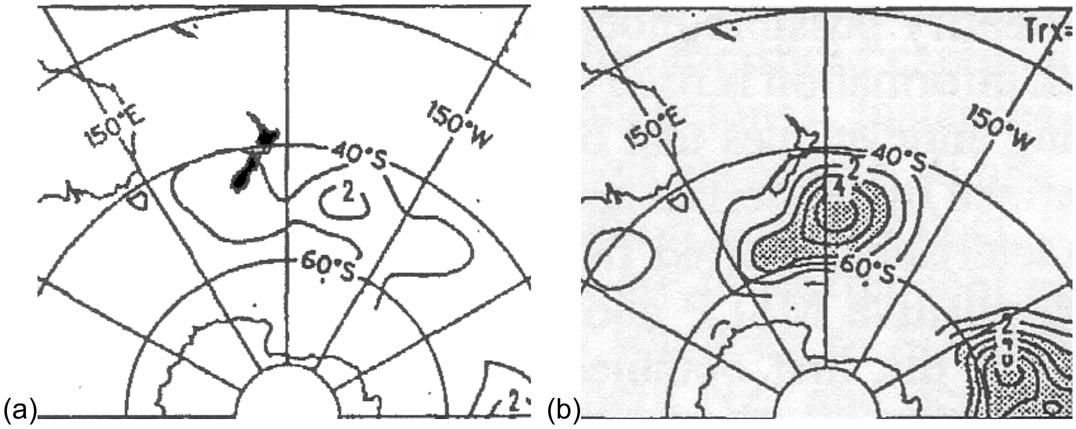

Figure 2-14 Total numbers of blocking anticyclones in (a) summer-autumn and (b) winter-spring surrounding NZ (150°E-150°W). Taken from Sinclair (1996) and identified as slow-moving and intense (see text).

Anticyclones that experienced a 24hr pressure increase greater than 5hPa (and 10hPa), termed “rapidly intensifying”, gathered slightly poleward of the intense systems on either side of NZ in summer (Sinclair, 1996). In winter, they accumulated in a single core just off southeastern NZ (Figure 2-13).

2.4.6 Complete Life Cycles

Sinclair (1996) also showed anticyclones can form, intensify, weaken and decay entirely in the Tasman Sea in summer, with a pattern of forming and intensifying in the western Tasman, weakening in the central sector and decaying in the eastern sector close to NZ. Winter activity, on the other hand, is centred over southern Australia.

2.4.7 Blocking Anticyclones

While the majority of anticyclones are mobile or slow-moving, there is another class known as blocking anticyclones (or “blocks”) that are characterised by a lack of motion sustained beyond the synoptic time-scale (Bluestein, 1993; Liu, 1994). These vertically coherent, quasi-stationary high-pressure systems disrupt or redirect eastward-travelling weather systems both upstream and downstream, as well as the midlatitude westerly belt in which they are embedded. In so doing, they become a significant meteorological feature that force the succession a weather systems along meridional paths in regions that usually experience strong west-east zonal flows. Unlike their cyclonic counterparts that cause destruction through strong winds, excessive rainfall and energetic seas, blocks generate meteorological events at the other end of the spectrum with light winds, lack of rainfall and incessant days of sunshine (e.g. droughts). However, around their peripheries can be strong meridional winds and accompanying slow-moving, and rapidly intensifying low pressure systems that are capable of producing foul weather.

A single, objective definition of what constitutes a “block” does not exist in the literature (Liu, 1994). Instead, a variety of techniques have been used including identification of a major split in the upper level flow over a week or more, significant positive geopotential anomalies, persistent positive MSLP anomalies above a specified threshold, or a combination of these (e.g. Renwick, 1998, 2005; Wiedenmann *et al.,* 2002; Marques & Rao, 2000; 2003; Renwick & Revell, 1999; Kiladis & Mo, 1998; Sinclair, 1996; Trenberth & Mo, 1985; Lejenas, 1984; Wright, 1974).

Until the paper of Sinclair (1996), a single principal centre for blocking in the Southern Hemisphere was found in the Australian-NZ region. This locality was most prominent in winter and appeared at sea level and in the mid-troposphere (Trenberth & Mo, 1985; Lejenas, 1984; Wright, 1974). The MSLP-based analysis by Sinclair (1996) defined blocking events in three ways: mobile highs with central pressures greater than 20hPa above time-mean climatology, persistent slow-moving blocks (move less than 20°latitude over at least 5 days), and as a combination (slow-moving and intense). The first definition extracted winter blocks in the 40-55°S band between NZ and 90°W (in South Pacific Ocean). Persistent slow-moving anticyclones show a mid-latitude SE Pacific extrema near 90°W and another in the eastern Atlantic in summer. In winter, these centres shrivel in size but remain in the same relative locations. When both of these properties are fulfilled (immobile and greater than 20hPa), a clear wintertime maximum appears east of NZ between 40 and 60°S (Figure 2-14).

Subsequent studies have also identified these principal centres of blocking activity or examined their blocking characteristics and differences (e.g. Wiedenmann *et al.,* 2002; Marques & Rao, 2000; Renwick, 1998, 2005; Renwick & Revell, 1999;). For example, Wiedenmann *et al.,* 2002 found from a 30-yr climatology that 81% of blocking events were confined to the Pacific Ocean and had an average duration of 6-8 days. Wright (1974) suggested an average duration of 11 days in the Australia-SW Pacific for the 1950-1971 time period. Further, Renwick (1998) discovered the SW Pacific centre experienced the most blocking activity in autumn and winter (whereas in the SE Pacific maximum activity was in winter and spring).

These preferred locations coincided with the core regions of the background quasi-stationary planetary waves or large-scale atmospheric variability modes. Blocking over the Australasian sector is said to be enhanced by the wave-3 pattern due to strong ridges south of 40°S or near NZ (Renwick, 2005; Trenberth & Mo, 1985; Coughlan, 1983). Trenberth & Mo (1985) indicate the summertime blocks are equally influenced by wave-1 which enhances split flow.

2.4.8 Influence of ENSO

The relationship between anticyclone frequency and spatial distributions with the phases of the ENSO cycle was examined by Jones & Simmonds (1994). They found El Nino events were associated with equatorward displacements of the main centres of large anticyclones numbers in the Tasman Sea and across northern NZ (western Pacific) in the summer season. However, the opposite was found in winter in the Australian region (poleward movements during El Nino). In the Australian region, they found no strong link between ENSO and system density in summer. More recently, Pezza & Ambrizzi (2003) show El Nino events are associated with increased anticyclones over SE Australia.

In the SW Pacific, a complex seasonal pattern was found for blocking anticyclones. Renwick (1998) and Renwick & Revell (1999) show El Nino phases increase blocking events during spring but is suppressed in winter, such that no net effect is observed over the full year. In addition, Sinclair *et al.,* (1997) suggested summer blocking anticyclones south and southeast of NZ were most frequent during La Nina phases.

2.5 Tropical Cyclones

Tropical cyclones (TC) are seasonal, synoptic-scale storms that form entirely over warm oceanic regions in tropical latitudes. The main energy source of these cyclones is provided by heat transfers from the warm ocean surfaces to the overlying atmosphere. The atmospheric response manifests as extreme surface winds which then supply momentum back to the oceans in the form of waves and surges (Lighthill, 1998). Consequently, TC development and intensification is extremely dependent on strong feedback mechanisms between the atmosphere and ocean. TC are described by a variety of names in different parts of the world and possess several unique and contrasting characteristics compared to extratropical systems. These aspects are listed in Table 2-3.

Unlike extratropical systems that can be studied from global datasets and on a hemispheric scale, TC data are compiled and examined according to individual ocean basins. In the SH, the Indian Ocean is usually divided into southwest (SW Indian, <100°E) and southeast (SE Indian, includes western Australian region, 100-

142°E) basins, and the Pacific Ocean into the SW Pacific (includes eastern Australian region, > 142°E) basin. However, it is common to find these convenient boundaries are ignored when regional-scale analyses are performed, such as those that cover the entire Australian region (e.g. Lourensz, 1981; Holland & Pan, 1981). Consequently, most Australian studies encompass the entire continent between 105°E to 165°E, and hence, combine statistics for the SE Indian and SW Pacific basins. Alternatively, as in the most recent 40-yr climatology (1963-2003) of Dare & Davidson (2004), the results are blended in the SE and SW Indian basins between 90-100°E. However, the overall impact appears to be small and results for the separate basins can generally be gauged and extracted from the graphics in these studies.

TC are defined as systems with 10-minute averaged maximum sustained surface winds in excess of 18 $m.s^{-1}$. Sub-categories of these cyclones include severe tropical cyclones (winds > $25 m.s^{-1}$), and intense TC or hurricanes (winds > 33 $m.s^{-1}$). However, both sub-categories are grouped together under the generic term of "tropical cyclone" (Neumann, 1993). A general review of the SE Indian-Australian basin and its tropical cyclone statistics and characteristics is provided below, before focusing on the SW Pacific sector.

2.5.1 Australian Regional Studies

The Australian sector is more often than not defined as the area bounded by 90-100°E to 160-165°E, and the TC season extends from November-December to April-May. In this sector, between 7 to 12 TC occur per season (Dare & Davidson, 2004; McDonnell & Holbrook, 2004; Lourensz, 1981), while studies covering smaller areas of the Australian sector (i.e. between 100-142°E) reveal smaller numbers of 3-6 events (Landsea, 2000; Neumann, 1993). These studies and others (e.g. Holland & Pan, 1981; Holland, 1984a, b; Frank, 1987; McBride, 1995), have revealed the following mean characteristics of tropical cyclones near and over Australia:

1. There are three main TC genesis regions: Gulf of Carpentaria; off the NW Australian Coast; and in the Coral Sea.

2. Tracks are predominantly westward-moving with average speeds of around 4 $m.s^{-1}$.
3. Mean intensities range from 967 hPa in western sector, 972 hPa in northern sector and 971 hPa in eastern sector. It has been advised by Dare & Davidson (2004) to use these mean features cautiously as there are significant variations between individual TC.
4. Long-term trends in TC activity (1969/70 to 1995/96) show a weak downward trend for weak (>990hPa) and moderate (≤990hPa) cyclones and a slight increase in intense events. However, these trends are partly artificial due to non-climatic factors, changes in the observational network and synoptic criteria (Buckley et al., 2003; Nicholls, 1998).

Interannual variations in TC numbers have been connected to the ENSO cycle by numerous researchers. The El Nino phase creates less TC numbers in the Australian region as a result of TC activity extending further eastward into the South Pacific, and there are fewer early season TC events (Kuleshov, 2003; Proh & Gourlay, 1997; Evans & Allan, 1992; Hastings, 1990). However, Evans & Allan (1992) note that this trend does not hold for the northern Australian sector where more TC develop and still occur close to the coast. In contrast, the La Nina phase exhibits increased TC frequencies, especially in the Gulf of Carpentaria, show tracks that penetrate further southward, and have higher tendency for early season genesis. Basher & Zheng (1995) suggested the preseason sea-surface temperature is responsible for changes in TC numbers in the Australian region, whilst Landsea (2000) indicates intensity and repositioning of the monsoon trough location alters TC activity. The modulation of Australian TC activity on intraseasonal timescales, as a result of the Madden-Julian Oscillation (MJO), has also been explored by Hall *et al.,* 2001 who describe more tropical cyclones in the active or strong phase of the MJO.

2.5.2 Southwest Pacific Basin

The SW Pacific basin extends from 142-150°E to 150°W (or to the international dateline in some studies) and encompasses eastern Australia, Tasman Sea and the New Zealand landmass. Consequently, there is a degree of overlap between the Australian sector just discussed and the greater SW Pacific basin. A TC database for the SW Pacific has been compiled from 1920 (Radford et al., 1996; Kerr, 1976), but is thought to be reliable only since the advent of satellite-derived data in the early 1970s. This dataset and others have been analysed for varying time periods and spatial domains to provide a good understanding of average TC statistics and properties (Dare & Davidson, 2004; McDonnell & Holbrook, 2004; Buckley *et al.,* 2003; Kuleshov, 2003; Sinclair, 2002a, b; Radford *et al.,* 1996; Thompson *et al.,* 1992; Revell, 1981; Kerr, 1976; Hutchings, 1953). Much like the Australian dataset, non-climatic jumps will also affect the SW Pacific TC data and act to contaminate long-term trends and frequency statistics (see Buckley et al., (2003)).

The SW Pacific TC season spans November-December through to April, and on average, around 9 TC occur per year with a marked peak in February-March. The smaller region of Dare & Davidson (2004) records 4 events per cyclone season while earlier pre-satellite records found an average of 3 to 6.5 events (Kerr, 1976; Hutchings, 1953). The main characteristics of SW Pacific TC are:

1. The core genesis region is the Coral Sea near 15-25° with other maxima near Fiji and the Cook Islands. Intraseasonal variations in origin points have been identified (Dare & Davidson, 2004; Thompson *et al.,* 1992; Revell, 1981) whereby genesis in more northern latitudes occurs from November-December and then shifts southward in the latter half of the season. As a result, TC activity increases in the Coral Sea between February and April, and the pattern is mirrored south of 30°S with frequency maxima shifting south into the North Tasman Sea. These latitudinal shifts in frequency and genesis locations have been linked to intra-seasonal movements of the monsoon trough and SPCZ, and sea-surface temperature (SST) anomalies.
2. TC motion exhibits different attributes depending on latitude and longitude. North of 10-12°S and west of the international dateline westward-moving tracks dominate, and this is consistent with the prevailing easterly tradewinds. However, south of around 15°S the majority of TC track eastward or southeastward with average speeds of 5-6 $m.s^{-1}$ (slighter faster than in Australian region).
3. Sinclair (2002a) found the most intense TC clustered in two maxima either side of the dateline (one in south Coral Sea and the other near 150°W) in the 20-25°S latitude band.
4. Unlike the Australian sector, no significant long-term trends have been found in SW Pacific TC activity (Landsea, 2000; Radford *et al.,* 1996).

Several authors have focussed their studies in smaller subregions of the SW Pacific basin and delineate TC attributes for the Tasman Sea and NZ areas. Sinclair (2002a) found significant differences in TC properties on opposite sides of the NZ landmass. On average, TC in Tasman Sea (western NZ) move slower on southward-directed paths, are stronger, and have peak frequencies in December. Dare & Davidson (2004) found mean lowest central pressures of 971hPa between 10 and 25°S, mean speeds of 4.7m.s^{-1}, and TC extend poleward of 35°S most often during December and March for the region 142°E to 165°E. The greater intensities west of NZ have been linked to the East Australian current and SST anomalies. In comparison, TC east of NZ track southeast-ward at twice the speed with a peak frequency in February and March. These differences were explained by Sinclair (2002a) as related to the background flow upon which the TC are embedded. For example, TC east of NZ encounter stronger westerly winds, forcing the cyclones to travel more rapidly eastward. Further, those TC that travel south of 35°S are most frequent in February and March and one event generally passes within 555 km of Northland and Auckland (Sinclair, 2002a; Revell, 1981).

The influence of ENSO on TC genesis region and frequency has been investigated by Deo (2004), Kuleshov (2003), Sinclair (2002a,b), Basher & Zheng (1995), Hastings (1990), and Revell & Goulter (1986). In general, genesis shifts further north and east to expand into the south Pacific east of the dateline during El Nino events and overall TC frequency increases. Deo (2004) states mean origin points of TC during El Nino are 174°E and 12°S, cyclone paths are longer and are more severe (i.e. 90% of TC exceed wind speeds of 148km/hr). Comparatively, the La Nina phase shows genesis clustering further west and south with frequencies being greatest in the south Coral Sea and New Caledonia area. According to Deo (2004), mean origin points are 171°E and 15°S. Further, Basher & Zheng (1995) noticed the mean cyclone frequency was 16% below average for neutral ENSO conditions. These location changes are consistent with movements of the SPCZ and warm water pool into the central South Pacific Ocean. These changes are listed in Table 2-4.

Properties	Tropical Cyclones	Extratropical Systems
Energy source	Warm ocean waters i.e. oceanic heat source	Frontal boundaries (or horizontal temperature gradients in the atmosphere) i.e. atmospheric heat source
Distinctive feature	Have a central "eye" and no fronts	Frontal structures
Occurrence	Summer-autumn only (Nov-April)	Year-round
Position of strongest winds	Surface	Near tropopause
Size	Relatively Small ~500km diameter	Big structures ≥ 500 km
Vertical structure	Vertically stacked such that the centre has little slope with altitude (the eye at surface and in troposphere is vertically aligned)	Slope strongly with altitude
Core temperature	Warm-cored	
Vertical wind shear	Small (require small changes in wind speed through the troposphere)	Large (develop where large changes in vertical wind speed occur)
Stratospheric influence	Stratosphere is not important	Fundamental component of structure of cyclone
Heat release from condensation	Important for formation	Not essential
Convective activity	Organised into circular rainbands around the centre	Asymmetric cloud formations, mostly on eastward and poleward sides
Relation to ocean	Only develop over warm oceanic surfaces (SST > 26°C), need surface-to-air heat (and moisture) fluxes	Develop and maintain themselves over land and ocean without underlying energy flux
Terminology	Also called hurricanes and typhoons	Also called storms

Table 2-3 The main properties of tropical and extratropical cyclones and their main differences.

Sinclair (2002) investigated the relation between ENSO and TC that propagate into the mid-latitudes (south of 30°S). The results for El Nino events show these TC occur most often east of the dateline where they travel at speeds exceeding 10m.s^{-1} on predominately zonal paths. The most intense TC occurred in two core regions – one in the Coral Sea and the other near 140-160°W in the 20-25°S latitude band. The opposite behaviour was observed during La Nina phases where most TC moving south of 35°S occur west of the dateline at average speeds of 7m.s^{-1} on south or south-southeast paths. These properties are summarised in Table 2-4. Sinclair (2002) also revealed that strong TC are most likely to reach NZ in the neutral phase of ENSO cycle (i.e. when SOI is near zero). To date, no research has been found that investigates interdecadal variations in TC activity due to the time series being to short.

2.6 NZ Weather Systems

The earliest analyses of weather patterns in NZ identified fronts or high pressure systems as the most common features influencing NZ weather (e.g. Watts, 1947; Kerr, 1944). A study of South Island weather reiterated these findings whereby anticyclonic SW conditions dominated in all four seasons and occurred approximately 48% of the year (Sturman *et al.,* 1984). In an earlier study by Trenberth (1975, 1976) for the larger Australasian sector, a dominance of anticyclonic conditions was also discovered, though easterly conditions were favoured and confined to the 25-45°S latitude belt. Although the differing analysis and classification methods are responsible for the divergences between these studies, the general picture suggests NZ experiences more anticyclonic, than cyclonic, weather. However, weather activity south of 50°S has not been captured in any of these studies and it is possible they exert some influence on NZ weather.

The first automated spatial analysis across NZ was performed by Kidson (1994) for the 1980-88 time period. Thirteen synoptic types were extracted from a combination of empirical orthogonal function analysis (EOF) and cluster analysis. The most persistent type involved a high pressure cell to the south of NZ (or off the Westland coast), and the next dominant pattern showed west to southwest flows over NZ from a low pressure system south of 60°S. These two patterns were most common in autumn and spring, respectively. A shortcoming of this early automated study, restricted to latitudes 25 to 55°S on a coarse grid, is the lack of synoptic types featuring low pressure systems. This misrepresentation of low pressure systems was acknowledged by Kidson (1994) who reasoned their small size didn’t register on a coarse grid, they had a lower frequency, and the selected domain boundaries obscured, smoothed or eliminated most depressions. Hence, Kidson (1997) performed a similar analysis using a smaller grid (2.5° squares) and extracted 4 patterns (out of seven) featuring low pressure cells. They were situated off the Otago coast, SE of NZ near 55°S, in the Tasman Sea near 40°S, and NE of East Cape.

ENSO Influences		El Nino	La Nina
Tropical cyclone property	*1. Core genesis region*	From eastern Australia (Coral Sea) eastward to 130°W (Central Pacific); [East of dateline]	In Coral Sea between 150°E and dateline; [West of dateline]
	2. Frequency	Increase (decrease) east (west) of the dateline, between 12-23°S	Increase in Coral Sea, maximise between 19°S and 30°S
	3. Average speed of motion	[> 10 m.s^{-1}]	[~ 7 m.s^{-1}]
	4. Paths/Track directions	[Zonal ESE motions]	[South or South-southeast]
	5. Intensity *[NB: Most intense across NZ in neutral phase]*	[Twin maxima near 20-25 in Coral Sea and east of dateline near 150°W]	[Single maxima in Coral Sea extending southward into Tasman Sea]
Background Environmental Conditions	*1. Winds*	[Stronger westerlies over and east of NZ]	[Weaker than normal westerlies]
	2. SST	[Warm anomaly north of 20°S, esp. east of dateline; cool anomaly south of 20°S all around NZ]	[Cool anomaly along equator (0-10°S), warm near 20-25°S east of 160°W]

Table 2-4 The influence of the El Nino-Southern Oscillation (ENSO) cycle on specific tropical cyclone characteristics and background environmental conditions. Text in [ ] brackets relate specifically to TC properties that move into the mid-latitude region of SW Pacific (i.e. south of 30°S).

With the availability of a new and longer dataset with better spatial resolution, Kidson (2000) updated his earlier studies. Using the NCEP-NCAR reanalysis dataset between 1958-97 on a 2.5 x 2.5° grid, a better representation of low pressure systems between 25° and 55°S was found, though the southern ocean cyclone activity remained outside the analysis domain. A set of 12 weather patterns were extracted (many being similar to his earlier studies) and split into trough, zonal or blocking regimes, with each regime containing 3 to 5 weather types (Figure 2-15).

The most frequent pattern fell within the blocking regime and comprised a high pressure cell to the east of Christchurch (HSE), occurring 13.7% of the time. This pattern was also found to be the most persistent, having a mean duration of just less than two days. The next dominant pattern (H), occurring 12.9% of the time, involves a high pressure cell in the Tasman Sea extending over NZ and westerlies south of 45°S. From the daily analyses, roughly equal numbers of trough and blocking situations were found (38% and 37%, respectively) while the zonal group accounted for only 25%. This research indicates anticyclonic conditions (H, HNW, W, HSE, HE, and HW; see Figure 2-15) influence NZ approximately 50% of the time, and cyclonic activity (T, SW, TNW, TSW and R) around 43% of the time (note: the NE pattern could not be classified as anticyclonic or cyclonic). Kidson (2000) also explored the sequence of synoptic types per regime, and shows the passage of troughs over NZ follow the pattern TNW – TSW – SW, and eastward moving anticyclones follow the pattern HNW – H – HSE – HE (Figure 2-15). In terms of duration, the zonal patterns of W and HNW are the most short-lived whereas HSE, H, T and TSW exist for up to half a day longer.

In both summer and autumn, the most frequent synoptic type is a high pressure cell to the SE of NZ (HSE). In winter, highs over NZ (H) dominate (followed closely by troughs) and then springtime experiences an abundance of troughs (T). For the individual types, a high east of NZ (HE) shows very little seasonal variation, whereas a high over NZ (H) doubles in frequency in autumn, winter and spring compared to summer. Furthermore, Kidson (2000) states more blocking occurs in summer and autumn while the lowest frequency of zonal weather types appeared in summer. A relationship with the ENSO cycle was also found, such that blocking (zonal flows) increases during La Nina (El Nino) events.

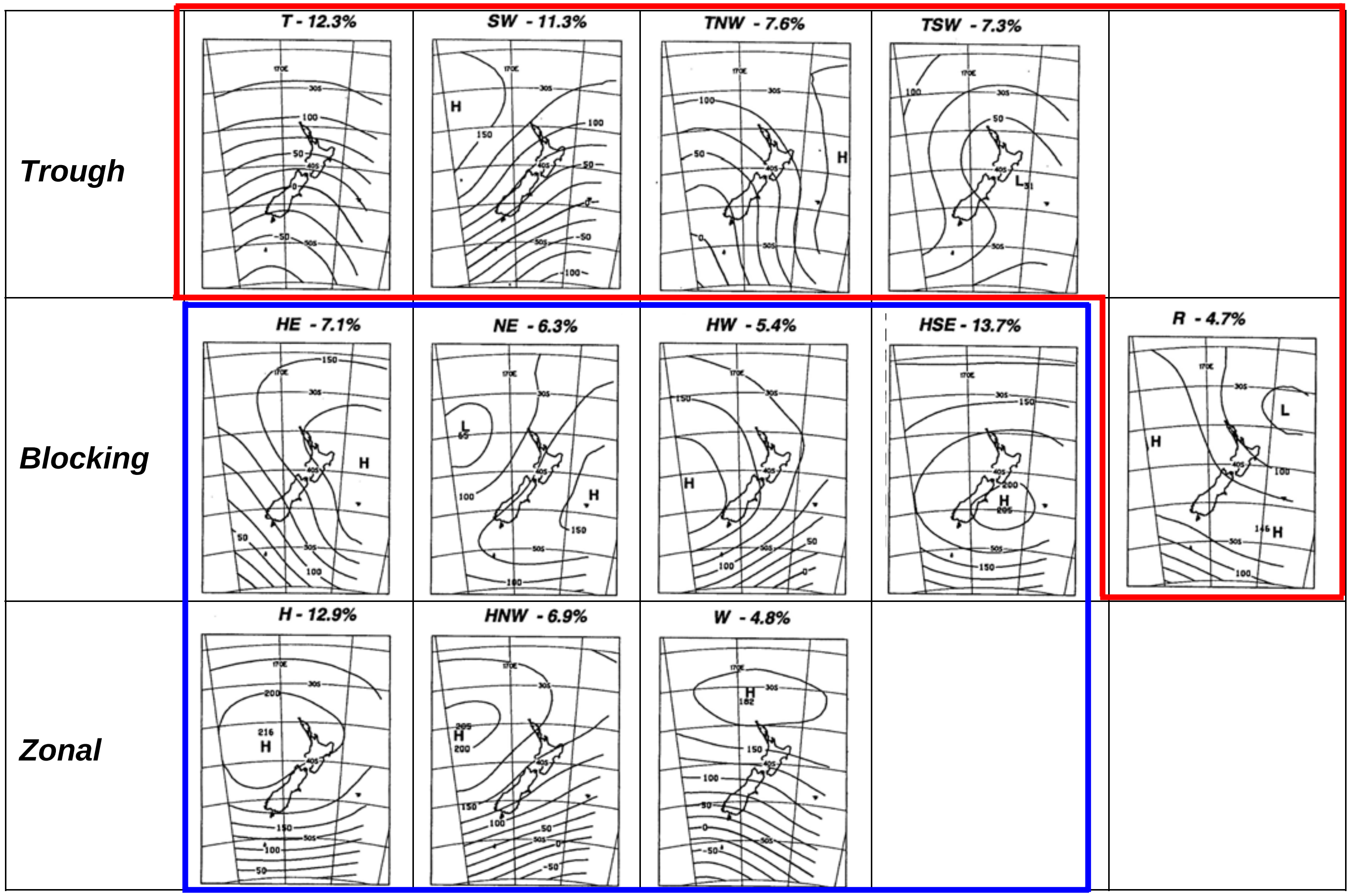

Figure 2-15 The twelve dominant synoptic weather patterns in the NZ region found by Kidson (2000). They are shown here in the three main groups of troughs, blocking and zonal types, and have also been grouped in the red box as cyclonic types and in the blue box as anticyclonic types.

Region	N to NW	N to NE	E to SE	S to SW
Gisborne	Ahead of cold fronts	High NE of East Cape with ridge over Chathams, and low NE of North Cape	Low E of N.Is and high in Tasman Sea (S or SE); Low off N N.Is and high east of NZ (SE)	Low E of N.Is and high in Tasman Sea (S or SE)
Napier		Large high to E of NZ and low to the W	Low over/E of N.Is and high south of NZ (E or SE); and Low E of Gisborne and high W (or over) of lower S.Is (SE); and Low over central N.Is and high SW of S.Is (SE)	High or ridge covers Tasman Sea and low E of NZ (SW); and High over lower S.Is (S)
Wairarapa	East-moving cold fronts with low SW or S of NZ High north of N.Is and low south of 50°S below NZ	Large high E of Wairarapa and low over central or N Tasman Sea	Low in NW Tasman Sea or tropics moves SE-ward over or just east of region	High in central Tasman Sea (SW) High over or south S.Is (S)
Wellington	Trough approaching or moving over S.Is from the west	Low (or trough) W of S.Is and high to E of N.Is (N) Low W of Northland (NE) High over or N of N.Is	Low W of Northland (E); Low near East Cape & high over S.Is (SE or ESE); High E of Canterbury (SE); Ridge over S.Is and lows over and E of N.Is (S); Ridge across seas SE of N.Is (SE)	Low east of NZ and large high over SE Australia (S or SW); Low SE of NZ (SW); Ridge across seas SE of NZ (S); High west of NZ (S or SW); Cold Fronts (S or SW)
Chathams	Belt high pressure N of NZ and lows to south (W or NW) Low S of NZ and high NE of N.Is (NW)	Large high to E of Chathams and low W of NZ (N or NE)	Large high south of Chathams (E) Low passing N or E of Chathams	High in central Tasman Sea and low to east of Chathams (SW) High S of NZ and low east of Chathams (S)

Table 2-5 Location of the main weather systems generating specific wind conditions for several different regions of NZ (N=north, S=south, W=west, E=east, N.Is=North Island, and S.Is= South Island.

The dominant pattern of a high to the south-east or east of NZ is found as the leading EOF by Kidson (1997, 2000) and Trenberth (1975) indicating consistency across authors, though the actual location of the centre varies slightly. This location of high pressure systems is also consistent with results from hemispheric analyses of blocking highs (e.g. Marques and Rao, 2000; Sinclair, 1996; Trenberth & Mo, 1985) suggesting this pattern could consist largely of blocking systems with only a small portion of travelling anticyclones. However, Kidson (2000) found the average persistence of the dominant pattern to be around 2 days, and one would expect blocking highs to have much longer durations. Therefore, this locality to the SE of NZ is most likely made up of quasi-stationary blocks and travelling anticyclones.

Most of this work indicates that highs situated over the northern Tasman Sea and northern NZ (i.e. in lower latitudes) generally bring westerly airstreams over NZ. In comparison, the most common weather type with slow-moving anticyclones and blocking systems east or southeast of NZ generate anticyclonic southeast, east and northeast conditions. In terms of cyclonic activity, 5 patterns have been found that describe low pressure systems affecting the NZ-Australian sector (see Figure 2-15). When the low is situated south of NZ it steers west, northwest or southwest winds across NZ. However, if the low is SE of NZ, southwest and southerly winds flow over NZ; while depressions in the Tasman Sea and NE of NZ create easterly conditions. Thus, the synoptic types capable of generating strong onshore flows (southerlies, northeasterlies and easterlies) along eastern NZ include HSE, NE, HW, R, TSW and SW.

Regional analyses of the weather and climate regimes around New Zealand were completed in the 1970s and 1980s and list the main weather systems and wind regimes affecting the regions (Thompson, 1987, 1983, 1982; Goulter, 1984; Quayle, 1984; NZMS, 1981; Hessell, 1980; de Lisle & Patterson, 1971). A summary of the reports covering the eastern North Island are presented in Table 2-5.

2.7 Summary

The movements and intensities of cyclones and anticyclones – and interactions between them – create extremes in wind and pressure which flow on to secondary forces at the coast of large storm waves and elevated sea levels (storm surges).

This review shows cyclones and anticyclones have preferred locations east of the North Island of NZ. The high cyclone activity is of direct interest to any study on coastal storms because they are often the leading cause of such events. Insights into cyclone behaviour, therefore, could help in understanding coastal storm activity. Year-round, large numbers of cyclones occur off the eastern coast of NZ. Mobile cyclones, however, display marked wintertime activity on both the eastern and western coasts of NZ. In addition, these cyclones consist of closed centres and open disturbances and it appears more open mobile disturbances traverse the NZ region (as opposed to closed centres). This indicates cyclonic weather is very common around NZ and cyclones can be two forms (closed and open). The eastern coast of NZ is also a preferred location for year-round cyclone formation while intensification of these cyclones occurs further downstream. The Tasman Sea is also a preferred area for cyclone formation and intensification, and a large majority of intensifying cyclones also decay in the Tasman Sea, and therefore, indicates that cyclones travelling eastward from the Tasman Sea are mostly weakened systems by time they impact NZ. The most intense and explosive cyclones are essentially wintertime phenomena which cluster eastward of NZ near the dateline. This location is such that eastern NZ will be directly impacted, and therefore, these systems could represent coastal storm events. Tropical cyclones are another type of weather system that can influence the eastern North Island. They show peak activity in February and March, and travel on southeast-ward paths.

Anticyclone behaviour also shows some features of interest to coastal storm activity. They show summertime frequency and formation maximums east of the dateline (and north of 40°S), suggesting a prominence of easterly flows off the eastern coast of NZ. Furthermore, rapidly intensifying and blocking anticyclones is also a feature around NZ though they occur in higher latitudes to the south and southeast of eastern NZ. Anticyclones situated in these locations will act to impede the movement of cyclones off the eastern coast of NZ so as to change their trajectories and propagation speeds.

Studies of local weather patterns around NZ indicate the most persistent weather pattern consists of an anticyclone off the South Island, being a blocking-type situation. Of a total of twelve dominant patterns, five displayed onshore wind flows over the North Island, being potential weather patterns associated with storm events.

However, these patterns represent the most common types and one wouldn't expect an extreme weather event such as a coastal storm to be represented. Furthermore, only one of the weather patterns portrays cyclones off eastern NZ.

These findings indicate coastal storms can result from cyclones that travel eastward from the frequency maximum in the Tasman Sea or can be locally generated immediately off the coast. The cyclones can have closed centre's or be open disturbances (e.g. troughs), and the most intense systems are most likely to occur in winter. Furthermore, decaying tropical cyclones are also a real threat for the eastern North Island. Anticyclones, on the other hand, suggest a predominance of easterly flows, and their preferred positions east and southeast of NZ indicate they will have a large influence through blocking and deflecting cyclone movements. That is, should a cyclone traverse the Tasman Sea and NZ and then meet an anticyclone east of the Chatham Islands, its progress will be halted or its trajectory changed immediately in the vicinity of the eastern North Island.

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3 COASTAL STORM DATABASE FOR THE EASTERN NORTH ISLAND

3.1 Introduction

Numerous damage-producing coastal storms have struck the eastern North Island of NZ and should be categorized as significant adverse weather phenomena. In some cases, these coastal storms have entered the natural disaster category (e.g. Wahine storm, 1968; Cyclone Bola, 1988). The damage potential of these storms can be primarily related to extreme wind speeds, and are then further compounded by the associated wind-driven oceanographic conditions of large waves, surge effects, and elevated tidal levels. Further complications can also be associated with extreme rainfall, antecedent environmental conditions, and level of coastal development.

Whilst our vulnerability to coastal storms is not disputed, large time intervals between such events can lead to complacency and a downplaying of the associated risks. Unfortunately, this mindset has led to a lack of interest in documenting and quantifying the coastal storm hazard for most of the NZ coastline. This lack of knowledge and information has had negative flow-on effects to society through allowing inappropriate coastal development, incorrectly defining coastal hazard boundaries, infrastructural (private and commercial) losses, badly chosen coastal management solutions, and disappearing beaches. These negative and unforeseen circumstances are evidence that coastal storms require considerable research emphasis.

This knowledge gap for one sector of the eastern North Island coastline from East Cape to Wellington is addressed here by constructing a database of historical coastal storms. It is hoped this resource, providing comprehensive and regularly updated assessments of past storm events, will assist emergency managers to better prepare and respond to coastal storms, improve (and maybe change) coastal management initiatives and policies, allow the community to better assess their risks and vulnerability, and kick-start the creation of new and advanced coastal hazard mitigation strategies.

The objectives of this chapter are to:

1. Construct a regional database of historical coastal storms along the eastern North Island for the 1962 – 2005 time period (instrumental record);

2. Examine the meteorological (synoptic) conditions associated with each storm event (e.g development and movement) and isolate the leading storm types;
3. Identify the major types of storm damages and impacts;
4. Reconstruct storm activity prior to the instrumental record through the use of readily-available data sources; and
5. Provide frequency statistics for major coastal storms.

3.2 Coastal Storms

There are numerous methodologies available for identifying storm events and they involve a variety of data sources. The types of data include storm surges and tides (e.g. Betts *et al.,* 2004; Bromirski *et al.,* 2003, Zhang *et al.,* 2002, 2000; de Lange & Gibb, 2000), waves (e.g. Davis *et al.,* 1993; Dolan *et al.,* 1988, 1992; Hayden, 1975), cyclone frequencies (e.g. Paciorek *et al.,* 2002; Angel & Isard, 1998; Lambert, 1996), pressure data (e.g. Alexander *et al.,* 2005; Barring & von Storch, 2004; Alexandersson *et al.,* 2000; Schmith *et al.,* 1998), wind records (e.g. Smits *et al.,* 2005; Forbes *et al.,* 2004; Lozano *et al.,* 2004; Hudak & Young, 2002; MacClenahan *et al.,* 2001; Schiesser *et al,* 1997; Hay, 1991; Danielsen *et al.,* 1957), damage assessments (e.g. Mathers *et al.,* 1964), and a combination of the above (e.g. Hirsch *et al.,* 2001).

For the purposes of a comprehensive coastal storm database, with which the prime focus is on storm meteorology (e.g. genesis and evolution), weather conditions and impacts, wind records represent an appropriate dataset to use. However, wind observations are often considered an unsuitable proxy because they can be compromised by inhomogeneities such as instrument and location changes and modifications to the surrounding area (Weisse *et al.,* 2005; Smits *et al.,* 2005; Barring *et al.,* 2004; WASA, 1998). This factor, however, becomes a major issue when the research objective involves detection of trend signals. Since this is not the case here, and a long-term dataset is readily available of adequate quality, the wind records are thought suitable for the purposes of a historical storm database.

Coastal storms are a type of extreme weather and their frequencies, generally, are low. It therefore is unreasonable to expect the meteorological patterns responsible for coastal storms to be a dominant (or average) synoptic type, such as the Kidson

(2000) weather types. These synoptic types do, however, show patterns that generate onshore flows along eastern NZ and the average locations of cyclones and anticyclones. This aspect implies the basic attributes of coastal storms may be captured in these types but the smoothing process removes the key features e.g. large low pressure systems. Furthermore, the averaging and smoothing process removes the ability to investigate intensities, see the variable locations of cyclones and anticyclones, and the true pressure gradients. When these features and properties are of interest, as they are here, it becomes apparent another class of weather types is needed.

History has demonstrated through events such as the “Wahine” storm (1968) and “Waitangi Day storm” (2002) that large, deep cyclones do indeed sit off the eastern coast of the North Island. These events indicate there is an upper limit to the use of the Kidson (2000) weather types in that they don’t adequately capture extreme weather patterns. To expand on Kidson (2000), and advance the knowledge on NZ weather patterns, a set of extreme weather patterns pertaining to coastal storms is needed and undertaken here. These patterns will better reflect low pressure systems east of NZ and identify their preferred locations during coastal storm events, and retain their intensities. In this light, these types will extend the work of Kidson (2000) such that the Kidson weather types represent average patterns, and the patterns here represent coastal storm patterns for the eastern North Island. Additionally, the new scheme will not identify weather patterns unrelated to coastal storms (e.g. weather types TNW, T, HE) and hence refine the set of patterns.

3.3 Methodology

3.3.1 Data Sources

The national climate database, administered by the National Institute of Water and Atmosphere (NIWA), holds digitized and quality-controlled measurements of hourly wind statistics for several weather stations around NZ. The complete hourly wind records and maximum wind gusts for the Gisborne and Wellington airports were extracted (A. Gosai, pers. comm.) as well as wind statistics for the Napier airport (though incomplete). The individual station histories for Gisborne, Wellington and Napier are provided in Table 3-1 . Additional station information for Gisborne and Wellington is contained in Fouhy *et al.,* (1992). The time period of instrumental wind records spans 1962 to 2005. However, only the Wellington site contains a continuous series of hourly wind statistics for this period. At Gisborne, complete hourly records exist between 1962 and 1991, and thereafter, are only recorded between 6am and 6pm. For the Napier site, the wind file is very irregular and fluctuates between synoptic (i.e. 3 hourly) and hourly readings over the entire 1962-2005 period. Furthermore, both the Gisborne and Napier sites have no wind records for 1993 and 1994 (corresponding to rearrangements in regulatory science organizations and responsibilities in NZ).

The complete Gisborne record between 1962 and 1991 (30 years) is used to identify coastal storms. The next available period of hourly wind data exists from 1999-2005 as taken from the Port of Napier wind anemometer, and is also used. We therefore have a period of incomplete (or no) wind data from 1992 to 1998. To address this problem an alternative method is applied (see below).

3.3.2 Coastal Storms – Definition

Two infamous coastal storms to strike the eastern coast of the North Island are the ex-tropical cyclones Gisele ("Wahine" storm, April 1968) and Bola (March 1988). The "Wahine" storm goes down in history as one of New Zealand's worse maritime disasters. The ferocious conditions at sea led to the sinking of the inter-island ferry Wahine in Wellington harbour and the loss of 51 lives (Brenstrum, 2003). The signature of this storm in the wind record, of 10hrs duration and a maximum hourly wind speed of 40.2 $m.s^{-1}$, means it represents a short-lived, extreme wind event. Cyclone Bola, on the other hand, that drenched the Gisborne region and battered the eastern North Island with strong winds represents a long-lived (sustained) high intensity wind event (winds exceeded 10 $m.s^{-1}$ for 34 hours).

In the mid-1980's, a wave meter deployed off the Gisborne coast captured a wave event on 6th June 1984 that measured waves up to a maximum of 5.5m (Mackey et al., 1987). Given that measured wave data is very sparse on this coast, this wave event most likely represents a significant coastal storm event. A search of the wind record verified this and identified 28 hours of winds exceeding 10.5 $m.s^{-1}$. Furthermore, a newspaper report in mid-August 2004 describes a storm event in Wellington that produced maximum wave heights of 14.4m at Baring Head (on

Wellington's south coast). Waves of this size are undoubtedly produced by coastal storms, and the wind record during this period confirmed a storm event of 79 hours duration (with winds exceeding 10.5 m.s^{-1}, including 9 hours over 22.5 m.s^{1}).

Gisborne Aero	
Station Agent No.	2807
Position (Lat –Long)	-38.661, 177.986E
Height Above MSL (m)	4m
Wind Instrument	Dines Anemograph (1962-1982), Munro Anemometer or Anemograph (1981-2005) at height of 18m
Rainfall Instrument	Automatic rain gauge (1937-2005)
Pressure Device	Barometer
Station History	1. Opened 1 May 1937; 2. Site change 1st May 1981 from airport to Oates St; 3. Synoptic and climate observations ceased from 31 Dec 1991; 4. Inspected on 6 June 1996 and no problems 5. Routine inspection on 19th Jan 2000
Napier Aero	
Station Agent No.	2977
Position (Lat –Long)	-39.468, 176.872E
Height Above MSL (m)	2m
Wind Instrument	Dines Anemograph (1962-1968), Munro Anemometer or Anemograph (1968-2005) at height of 10m
Rainfall Instrument	Manual 5" copper rain gauge
Pressure Device	Barometer
Station History	1. Opened 1st December 1948; 2. Station converted to synoptic/climate station; 3. Climate observations ceased from 20 March 1990; 4. Barometer, barograph and anemograph withdrawn; 5. Routine inspection between 1st June 1994 and 20th February 2006
Port of Napier (Wind and Waves)	
Station Agent No.	N/A
Position (Lat –Long)	-39°27.4606'S, 176°56.0673'E
Wave Buoy	TriAxys Directional Wave Buoy
Wind Instrument	Dines Anemograph (1962-1968), Munro Anemometer or Anemograph (1968-2005) at height of 10m
Wellington Aero	
Station Agent No.	3445
Position (Lat –Long)	-41.322, 174.804E
Height Above MSL (m)	43m
Wind Instrument	Munro Anemometer or Anemograph (1959-2005) at height of 11m
Rainfall Instrument	Automatic Daily Rain gauge (1960-May 1993), then Hydra Drop Gauge (10 Dec 1995 onwards)
Pressure Device	Barometer
Station History	1. Opened 1st December 1959; 2. Station moved 1.2km to the NW on 1st August 1994; 3. Routine inspection between 11th June 1996 and 22 February 2006

Table 3-1 Details of the weather stations and their instruments used in the coastal storm database as taken from the national climate database at NIWA.

The above-mentioned coastal storms provide a range of conditions that can be used to identify coastal storms for the eastern North Island. The other pre-requisite to be classified as a ‘coastal’ storm is an onshore wind component. Large damaging waves striking the eastern coast of the North Island can only come from strong winds that flow perpendicular to the coastline. For eastern New Zealand, this involves winds from the northeast through to southwest. Strong winds from these directions are often responsible for extreme sea conditions and have maximum force expended on the coastal margin, and therefore, represent ideal direction thresholds.

(A)	Wind Direction							
Speed (m/s)	SW	S	SE	E	NE	N	NW	W
0.5 - 2.4	0.3	0.9	0.4	0.3	1.8	1.5	0.1	0.1
2.5 - 4.9	1.5	5.0	1.0	0.4	3.4	6.4	0.3	0.2
5 - 8.4	1.3	10.7	1.0	0.1	3.8	17.3	0.6	0.1
8.5 - 10.4	0.2	4.6	0.2	–	0.6	10.3	0.3	–
10.5 - 14.4	0.3	5.7	0.1	–	0.2	11.3	0.4	–
>14.5	0.5	3.3	-	–	–	3.1	0.1	–
	4%	30%	3%	1%	10%	50%	2%	0%

(B)	Wind Direction							
Speed (m/s)	SW	S	SE	E	NE	N	NW	W
0.5 - 2.4	0.8	0.9	1.1	1.2	0.7	3.5	6.5	1.9
2.5 - 4.9	2.6	2.9	4.2	2.3	1.4	8.2	16.7	3.1
5 - 8.4	2.7	5.2	4.5	2.0	1.2	5.1	11.0	1.5
8.5 - 10.4	0.5	1.5	0.4	0.2	0.1	0.6	2.7	0.4
10.5 - 14.4	0.1	0.7	0.1	0.1	–	0.2	1.0	0.2
>14.5	–	0.1	–	–	–	–	0.1	–
	7%	11%	10%	6%	3%	17%	38%	7%

Table 3-2 A summary of hourly wind data (in percentages) per wind direction for (A) Wellington and (B) Gisborne. This data represents that of Wellington Aero from 1962-2005 and Gisborne Aero from 1962 – 1991.

The method employed here involves wind speed, direction and duration thresholds. Previous studies based on wind data have used a variety of threshold values, including speed magnitudes between 9 to 17 $m.s^{-1}$ and durations from 5 to 48 hours (Lozano *et al.,* 2004; Hudak & Young, 2002; Hirsch *et al.,* 2001; MacClenahan *et al.,* 2001; Schiesser *et al., 1997;* Hay *et al.,* 1991). These different values were selected with research objectives in mind, with some focusing on extreme events, long duration-high intensity storms, or potential damage-producing storms. The present study is aimed at a blend of the above, particularly intense and long-duration coastal storms that have a corresponding high damage potential.

The wind climates of Wellington and Gisborne are fundamentally different on several accounts (Table 3-2), and these differences mean separate wind magnitude and duration thresholds are warranted. Firstly, approximately 10% of Wellington hourly winds are greater than or equal 10.5 $m.s^{-1}$ from the NE through to SW. Comparatively, only 1.2% of Gisborne winds fulfil the same conditions (Table 3-2). Therefore, higher magnitude winds are more common in Wellington than Gisborne (from the onshore direction). And, secondly, the level of exposure and local weather effects strongly influence Wellington winds. In particular, the local topography of coastal Wellington leads to accelerations and deflections of the wind (see section 1.3.2).

The above mentioned information led to the following definitions of a coastal storm for the Gisborne region:

- Wind speeds ≥ 10.5 $m.s^{-1}$ for at least 6 consecutive hours; and
- Wind directions from the NE through to SW (i.e. 20 through to 240°).

For the Wellington site, a higher duration threshold was set as follows:

- Wind speeds ≥ 10.5 $m.s^{-1}$ for at least 24 consecutive hours;
- Wind speeds ≥ 14.5 $m.s^{-1}$ for at least 12 consecutive hours; and
- Wind speeds ≥22.5 $m.s^{-1}$ for at least 6 consecutive hours;
- Wind directions from the NE through to SW (i.e. 20 through to 240°).

The wind speed magnitude, a minimum of 10.5 $m.s^{-1}$, corresponds to a fresh breeze under the World Meteorological Organisation (WMO) wind standards (and Beaufort force 5). A similar magnitude was defined by Hirsch *et al.,* (2001) who recognized this value (or 10.3 $m.s^{-1}$) as a natural break between frequent lower wind magnitude storms and fewer higher intensity storms for the eastern United States coast. Furthermore, on the Irish coast, Carter & Stone (1989) define a wind speed of 12.86 $m.s^{-1}$ as a good measure for assessing potential foredune erosion (combined with a minimum duration and tidal heights). The above-mentioned known storms for Gisborne implied a duration threshold of 24-hours would be appropriate. However, when this duration criteria was applied (or minimum of 12-hours), only 13 (39) storm events were extracted. This small number prompted a rethink of the duration threshold, and a 6-hour duration window was selected.

Given the complete wind record at Wellington, and percentage of stronger winds, a longer duration threshold of at least 24-hours is used. Two further definitions of a "coastal storm" are created to target short-lived intense events such as the "Wahine" storm in the Wellington region. They are 1) minimum wind speed of 14.5 $m.s^{-1}$ for at least 12-hours; and 2) minimum wind speed of 20 $m.s^{-1}$ for at least 6 hours (both are for winds from the northeast through southwest).

This methodology focuses on long-lived (sustained), high intensity and short-lived, extreme intensity wind events, thought to be an adequate indicator of storm activity. It is possible that some coastal storms that will be missed from the above criteria, such as storms with fluctuating winds (e.g. Waitangi Day, 2002) and distant storms that significantly affect the NZ coastline but do not get registered in local wind records (e.g. Waitangi Day storm, 2002, in Gisborne). In such cases, these coastal storms have been included only in the database, for they created havoc, received massive media coverage, and have been labelled as major storm events. However, these storm events are not included in the coastal storm statistics (Section 4.4) which are based entirely on those events identified from the wind records.

3.3.3 Storm Event Identification

The Gisborne, Napier and Wellington wind records were filtered for the above conditions and a catalogue of coastal storms assembled. The filtering technique locates:

1. Start date and time - the first wind record (in any sequence of at least 6 readings) that exceeds the above threshold;
2. End date and time - the last wind record of a continuous sequence of readings;
3. Storm duration - the total time period (hours) between the start and end dates;
4. Average wind speed – the average speed over the storm duration; and
5. Average wind direction – the average direction over the storm duration.

If any of the identified coastal storms were closely connected in time (within 12 hours of each other), they are combined as one event. In such situations, the same principle applied to the large wave events is used whereby the storm parameters (e.g. duration, average speed and direction) are calculated based only on those data points that met the specified conditions. That is, should there be any two events spaced within 12 hours of each other, and during that 12 hour gap the wind speed falls below the 10.5 m.s^{-1} threshold, the calculated storm parameters are based solely on the data points for when the threshold is exceeded. This process is performed to eliminate the possible double-counting of events.

3.3.4 Storm Identification from Alternate Sources – Gisborne and Napier

During 1992 to 1998 reliable hourly wind data is not available for Gisborne and Napier. To address this problem, a 2-step selection process has been devised as follows:

1. Wellington hourly winds are used as a proxy to identify dates of strong wind events;
2. From these dates, daily local newspaper collections were searched for any weather-related news articles and storm impacts and damages along the coastal margin; then
3. Identify if the event struck the coastal areas of Gisborne and Napier.

This methodology is highly subjective and may not create an accurate representation of storm activity. To estimate the wind conditions during Gisborne storms when local data were not available, a regression analysis was undertaken using the *lm* function in R to assess whether Wellington data could be used as a proxy. Regressions were undertaken on all the available data, a subset of data consisting of storm conditions at Gisborne, and a final subset of data with storm conditions at both Gisborne and Wellington (Table 3-3). The results indicate that while there is considerable scatter in the data (low regression coefficients), for the storm conditions of interest (a storm affecting both Wellington and Gisborne) it is possible to utilise the Wellington data to provide an estimate of the Gisborne wind speeds. Hence, for the purpose of further analysis the Wellington data were used to fill gaps in the Gisborne record. However, given the low regression coefficient and high p value (Table 3-3), the calculated relationship was not used to adjust the Wellington data. This adjustment was considered unnecessary as no parameters are calculated from the wind speeds; they are used as a descriptor to characterise the storms.

It is of interest to also note that of the 91 storms in Gisborne, 58 coincided with storms in Wellington. Further, if the same coastal storm criteria for Gisborne is applied to Wellington (>10.5 $m.s^{-1}$ for more than 6hrs), a total of 76 storms concur. Therefore, only 15 storms in Gisborne were not registered in the Wellington winds (~16%). On this basis, this method is considered satisfactory (knowing that around 16% of storms will be missed).

Conditions	Samples	Intercept	Slope	Adj. r^2	p value
All available	8746	2.56±0.05	0.18±0.01	0.08	$<2.2\times10^{-16}$
Gisborne > 10.5 ms^{-1}	141	10.70±0.27	0.10±0.02	0.16	7.3×10^{-7}
Both Gisborne and Wellington > 10.5 ms^{-1}	79	9.88±0.80	0.15±0.05	0.11	0.0019

Table 3-3 Summary of linear regressions for predicting Gisborne wind speeds from measured Wellington wind speeds for a range of wind speed thresholds.

The dependence on the Wellington winds is also considered appropriate because the orientation of strong winds from the south and southwest indicate they are highly likely to penetrate coastal regions further northward (of Wellington). In other words, storm winds generated from the south will flow onto other eastern areas, and be they not extreme winds, then usually the stormy oceanographic conditions are felt.

Thus, two methods are used to identify storms for the Gisborne and Napier regions so that a long-term history of coastal storm activity is obtained. The first method, based on wind data, is used to calculate coastal storm statistics for the 1962-1991 (and 1999-2005) time period, considered the most reliable and accurate methodology. The second method (from 1992 to 1998) is used solely for input into the coastal storm database (i.e. storm frequencies are not computed). Documenting these coastal storms is still vital since they provide useful and essential knowledge on storm dynamics and damages, and hence, their inclusion in the storm database.

3.3.5 Coastal Storm Types and Origins

All coastal storms are assigned a storm type and origin based on 12-hourly weather maps and weather sequences. The weather map used to assign a storm type is that which corresponds closest in time to the peak or maximum wind speed per storm event. The process follows:

1. Identify the time of the peak/maximum wind speed per storm event ("time stamp");
2. Identify the weather map that corresponds closest in time to the "time stamp";
3. Identify and define positions of the weather features off eastern NZ (or northward) that generate the strong winds;
4. Group the storm events, based on (i) the position of the cyclone feature, (ii) absence of cyclones, and (iii) multiple weather systems, as follows:
   (a) Eastern NZ (cyclone east of NZ),
   (b) Tasman Sea (cyclone in Tasman Sea),
   (c) Subtropics (cyclone north of 35S);
   (d) Troughs/Ridges (no cyclones, but a trough or ridge is east of NZ); and
   (e) Cyclone-Anticyclone Pair (cyclone and anticyclone are east of NZ)
5. Identify and assign the origin of the leading cyclonic weather system (or trough/ridge) by viewing the 8-day weather sequence (see below in Meteorology section) – this identifies the location from which the closed cyclonic feature (or trough/ridge) first appeared and hence from where it has travelled;
6. Review each storm group to confirm similarity of patterns; if large differences are found within a group, a new group is formed.

While assigning the origin of eastern NZ cyclones, it became apparent that a significant proportion of east coast lows actually develop off eastern NZ. That is, not all of the cyclones off eastern NZ travel into the region from the subtropics, Tasman Sea or Southern Ocean. The origin of these cyclones, whilst they develop off eastern NZ, is linked to the origin of the trough from which they develop. The origin of the cyclones is required to gauge the true storm path trajectory. For example, a Tasman Sea low may not have travelled eastward from Australia but may actually have had an origin of the Coral Sea or tropics. Examination of the 8-day weather sequence (or animation) for each storm revealed 3 leading storm origins. These origins are illustrated in Figure 3-1 and include:

- *Subtropics* – the area north of 35°S between eastern Australia and 170°W.
- *Tasman Sea* – the area between 35° and ~48°S (i.e. south of Stewart Island) and eastern Tasmania (~147°E) to eastern NZ.
- *Southern Ocean* – the large high-latitude area spread across latitudes ~48° to 60°S and between longitudes 130°E to 170°W.

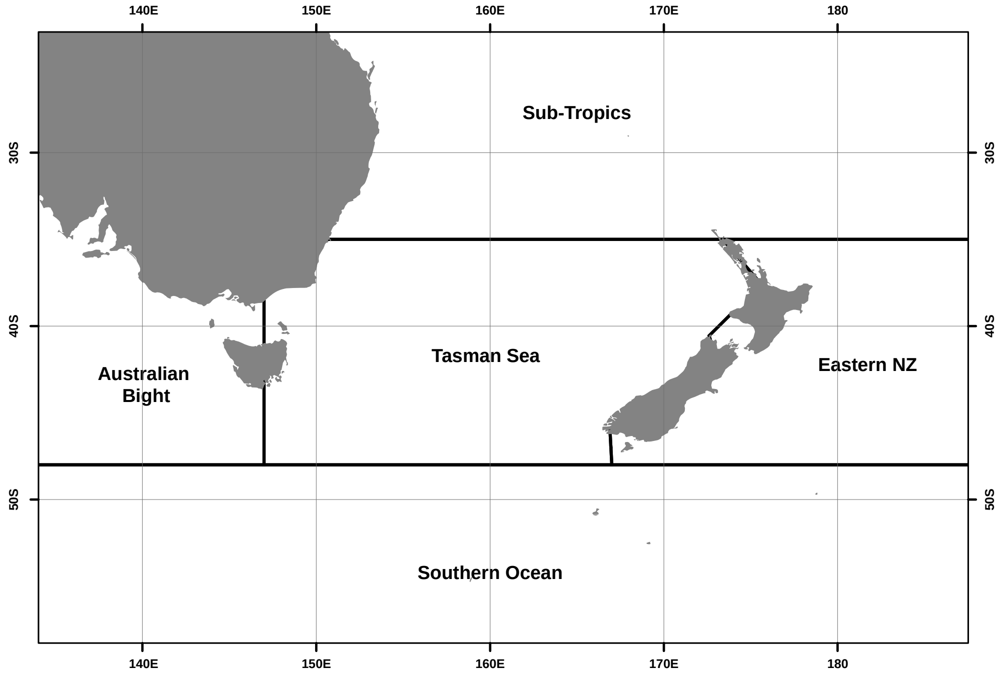

Figure 3-1 The five main origin points of weather systems responsible for generating coastal storms along the eastern coast of the North island (East Cape to Wellington).

This method has a high degree of subjectivity. Alternatively, a cluster analysis of the weather maps associated with each coastal storm could have been used to find the most commonly occurring patterns, though the smoothing associated with this method could lead to the loss of key features (as like with Kidson weather types). While the chosen, manual method is relatively straight-forward, some difficulties were experienced. Storm events with several peaks in the wind speed during a single event introduce several hourly maximum wind speed “time stamps”. In these situations, the time stamp of the first hourly maximum wind was used. It wasn’t always possible to pinpoint the cause of the strong winds for some short duration storms (≤ 12 hours) when using a 12-hour spacing of weather maps. This meant there were times whereby strong pressure gradients were missed on the weather maps, and therefore, the nearest 12-hourly weather map corresponding to the time stamp may not have represented the true cause of the strong winds. In the other respect, some long duration storms go through a sequence of storm types, and in these instances, a single storm type may not be the best representation of the storm. Rather, a sequence of storm types would have been appropriate.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1962						1	1		2			1	**5**
1963									1				**1**
1964					1								**1**
1965						2		1	1				**4**
1966					1		2	1					**4**
1967													**-**
1968				1	1		1				1	1	**5**
1969		1											**1**
1970		1						1	1				**3**
1971								1					**1**
1972		1		1			2		1			1	**6**
1973				1				1				1	**3**
1974			1	1		2			1				**5**
1975									1		1	1	**3**
1976		1		1		1			1			1	**5**
1977				1	1	2			2				**6**
1978					1		1						**2**
1979			1					1				1	**3**
1980													**-**
1981					1					1			**2**
1982				1	1	1							**3**
1983					1								**1**
1984				1	2	1		1		1			**6**
1985				1		1	1						**3**
1986			1		1		1		1				**4**
1987							1				1		**2**
1988			1						1				**2**
1989	1				1		1		2		1		**6**
1990			1				1		1				**3**
1991				1		1							**2**
Total	**2**	**4**	**5**	**10**	**12**	**11**	**12**	**7**	**16**	**2**	**4**	**7**	**92**
Ave	**0.1**	**0.1**	**0.2**	**0.3**	**0.4**	**0.4**	**0.4**	**0.2**	**0.5**	**0.1**	**0.1**	**0.2**	**3.1**

Table 3-4 Monthly and annual coastal storm frequencies for the Gisborne region. The total numbers and averages are also shown.

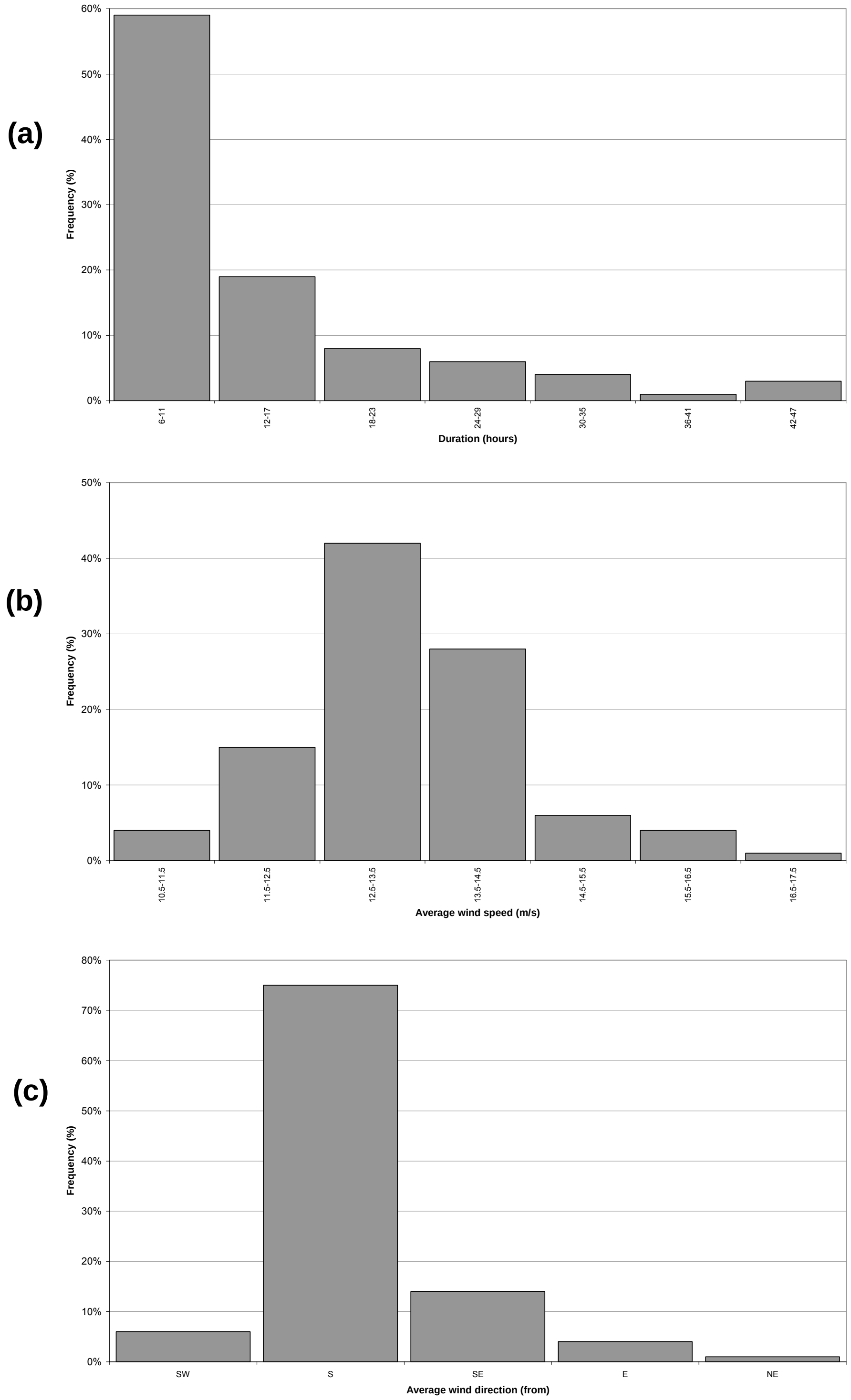

Figure 3-2 Frequency distributions of Gisborne coastal storm properties – (a) durations, (b) speeds and (c) directions.

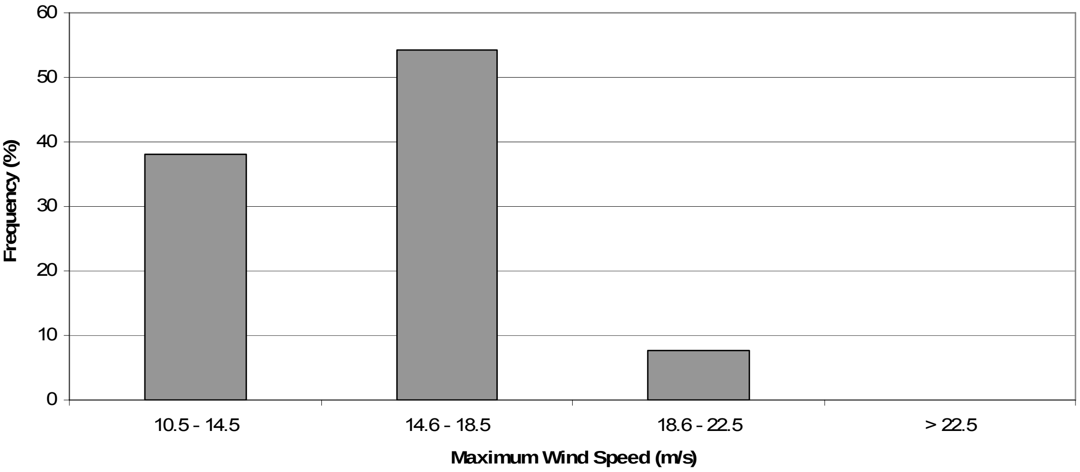

Figure 3-3 Frequency distribution of maximum wind speed for all Gisborne coastal storms (1962-1991).

The most difficulty was associated with classifying wave events which had no signature in the wind record, and hence no “time stamp”. In these instances, the weather map showing the strongest pressure gradients were selected. However, there were situations when the cause of the large wave events couldn’t be identified, and at these times, the weather map at the start of the wave event was used. Finally, complications were found with identifying the true origins of some storms due to the weather sequence not capturing the formation of the cyclone, or when two cyclones from difference origins merge (e.g. Tasman Sea Lows join up with a subtropical low or Southern Ocean lows).

3.4 Results

3.4.1 Gisborne Coastal Storms - Frequency

A total of 92 coastal storms have been found for Gisborne over the 30-year record (1962-1991) producing an annual average frequency of 3 coastal storms. Most of this storm activity clusters between April and July but the highest frequencies are in September (Table 3-4). Years with at least five coastal storms are seen in 1962, 1968, 1972, 1974, 1976-77, 1984 and 1989. There is a clear clustering of coastal storms in autumn and winter and they have been relatively rare in January-February and October-November. The average time interval or recovery period between these coastal storms is 114 days (just over 4 months).

3.4.2 Gisborne Coastal Storms – Storm Properties

Approximately three quarters of the coastal storms had durations of between 6 and 14 hours (Figure 3-2a). The remaining storms ranged from 15 up to 46 hours. Therefore, no coastal storms at Gisborne have persisted for more than 2 days. The average wind speeds (over the total duration) cluster in the 12.5 to 14.5 $m.s^{-1}$ range (Figure 3-2b). Several storms (11), however, have fallen into the near gale (>14.5 $m.s^{-1}$) category of the World Meteorological Organisation wind scale. The maximum hourly wind speed distribution (Figure 3-3) shows just under 10% of storms can reach speeds of up to 18.5-22.5 $m.s^{-1}$. These coastal storms are mostly from the south and southeast and represent more than 80% of all events. Southwest, east and northeast storms are rare (Figure 3-2c).

3.4.3 Wellington Coastal Storms - Frequency

A total of 392 coastal storms have been captured at Wellington from 1962 to 2005 (44-years) producing an annual average frequency of 9 per year. The monthly distribution (Figure 3-5) shows they occur mostly between May and August with a peak in June. The summer months have experienced at least a third less storms compared to the autumn-winter months. However, Figure 3-5 shows several years whereby this annual average has been greatly exceeded, including 1966, 1974, 1976-1977, 1989, and 1992, and several quiet years (e.g. 1971, 1987 etc). There is a higher degree of storm clustering seen at Wellington, as is expected given the higher number of storms. They show a tendency to cluster in the autumn and winter seasons (see Table 3-4), and there have been many separated by long quiescent periods (e.g. July 1987 to February 1988). Furthermore, the average time period between large coastal storms is 37.5 days.

3.4.4 Wellington Coastal Storms - Properties

Just under 70% of Wellington coastal storms have been between 24 and 48 hours long (Figure 3-4a). The first two columns of a represent the short-lived, high intensity storms, of which there have been at least 46 cases. The remaining storms therefore indicate that many coastal storms have persisted for more than 2 days and the longest storm has been up to 7 days long. A similar percentage (~72%) of storms have had average wind speeds that range between 13.5 and 16.5 m.s^{-1}, being shifted towards higher magnitude events compared to Gisborne (Figure 3-4b). More significantly, Wellington has experienced multiple coastal storms that have reached gale and strong gale force (or Beaufort scale 8 and 9) - these are intense coastal storms (Figure 3-4b). The frequency distribution of the maximum hourly wind speed per storm event shows nearly 20% of storms have reached speeds of over 22.5 m.s^{-1} (Figure 3-6). These storms are either from the south or southwest. Only 3 storms have been registered with winds from the southeast and northeast.

3.4.5 Storm Types and Origins

A set of 5 storm types were identified and are shown in Figure 3-7. They are:

(1) East Coast Lows

A cyclone is situated east of NZ between North Cape and Stewart Island and westward of the Chatham Islands (Figure 3-7a). These cyclones can originate from the subtropics (north of 35°S), Tasman Sea or Southern Ocean and represent cyclones that have formed elsewhere and propagated towards NZ as already established cyclones. Or, they can be cyclones that develop closed centres over or east of New Zealand from Tasman Sea, Southern Ocean or subtropical troughs. In most cases, east coast lows are accompanied by intense anticyclones on their westward sides, or have a ridge of high pressure spanning the lower South Island. This pattern represents cyclones immediately off the eastern coast of NZ.

(2) Tasman Sea Low

A cyclone is situated in the eastern Tasman Sea between 35S and 48S (Figure 3-7b) and covers the entire North Island. This cyclone combines with a ridge over or south of the South Island from an anticyclone in the South Tasman Sea, or an anticyclone south or east of NZ.

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1962						2	2		1				5
1963			1			3	4	1	2			1	12
1964				1	2	2	1		1				7
1965			2		1	4	2	1	1	1	1		13
1966				1	3	2	3	2	1	2	1	2	17
1967		1		1	2	2	1	1	1		1		10
1968				2	1	2	2		1				8
1969					3	2	3	1		1			10
1970	1	1	1		2	1	1	1			1		9
1971							1	1					2
1972		1		1		2			1	1		1	7
1973	1			1			1	2	1				6
1974		1	1	2	2	3	1	3	2	2			17
1975	1	2		1		2	3	2		1	1		13
1976		2	1	1		3	2	2	2	1	1	1	16
1977		2		2	5	1	1	2	4	1		1	19
1978		1			2	4	2		2	1			12
1979			1	1			2	2	3	2		2	13
1980	1					2	2	2			1	2	10
1981			1		1	2	2	1		2			9
1982			1	1	1	2	1	1		1			8
1983				2	2	1	2	2				1	10
1984					1		2			1			4
1985			2		1	1	1	2		1	1		9
1986			1			2	1	3	1				8
1987			1		1	1							3
1988		2	1	1		1	1			1			7
1989				1	3	3	2	1		2	1	1	14
1990			1			1	1	1	2	1	1		8
1991		1		2	1	4				2	1	1	12
1992		1		1	1	1	1	3	2	2	1	1	14
1993			1	2	1				2	1			7
1994			3		2		1						6
1995				2		1	1	2		1			7
1996						1	1	1					3
1997	1		2			2		2					7
1998	1				2								3
1999	1				2		2				1		6
2000						1	1		1	1			4
2001						1	1	1		1			4
2002		1		2	1		1	2			1		8
2003				2		1	2	1		1			7
2004	1	1	1		1	1	2	2			1	1	11
2005			1	1	1	1			1	1		1	7
Total	**8**	**17**	**23**	**31**	**45**	**65**	**60**	**48**	**32**	**32**	**15**	**16**	**392**
Ave	**0.2**	**0.4**	**0.5**	**0.7**	**1.0**	**1.5**	**1.4**	**1.1**	**0.7**	**0.7**	**0.3**	**0.4**	**8.9**

Table 3-5 Coastal storm frequencies by month and year for Wellington. The total numbers and averages are also shown.

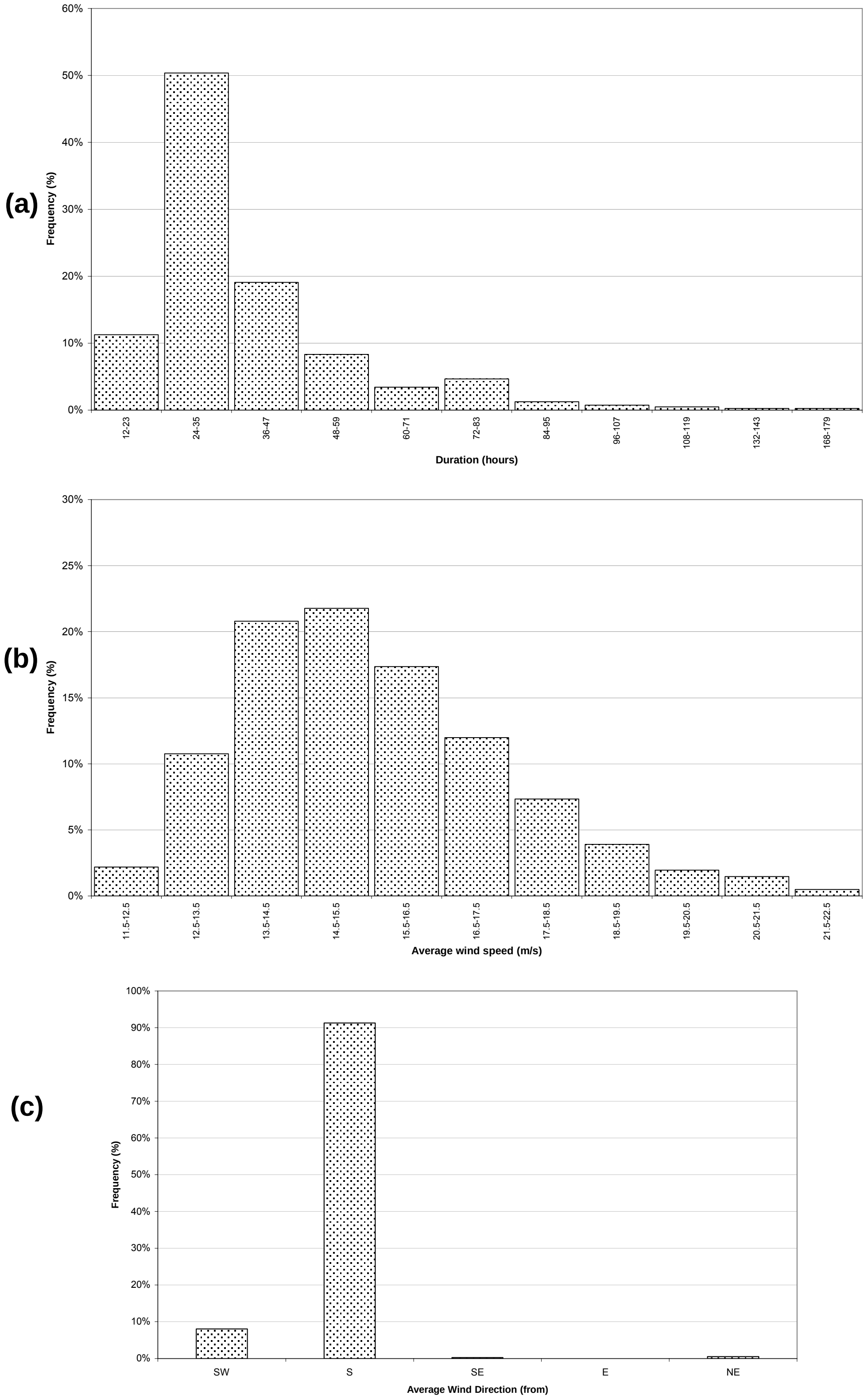

Figure 3-4 The frequency distributions of all Wellington coastal storm properties – (a) durations, (b) speeds and (c) wind directions.

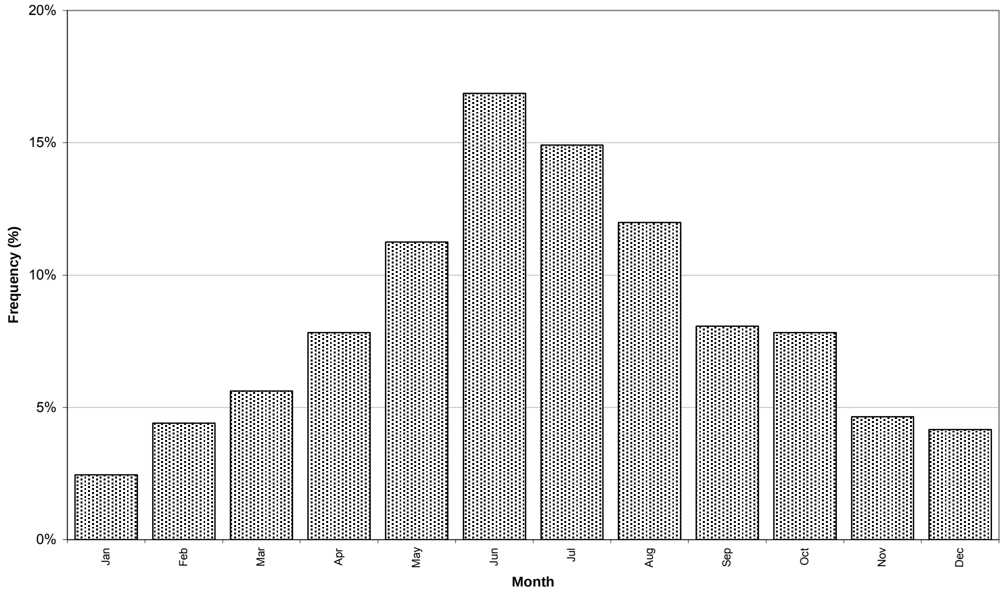

Figure 3-5 The monthly frequency distribution of all coastal storms at Wellington for 1962-2005.

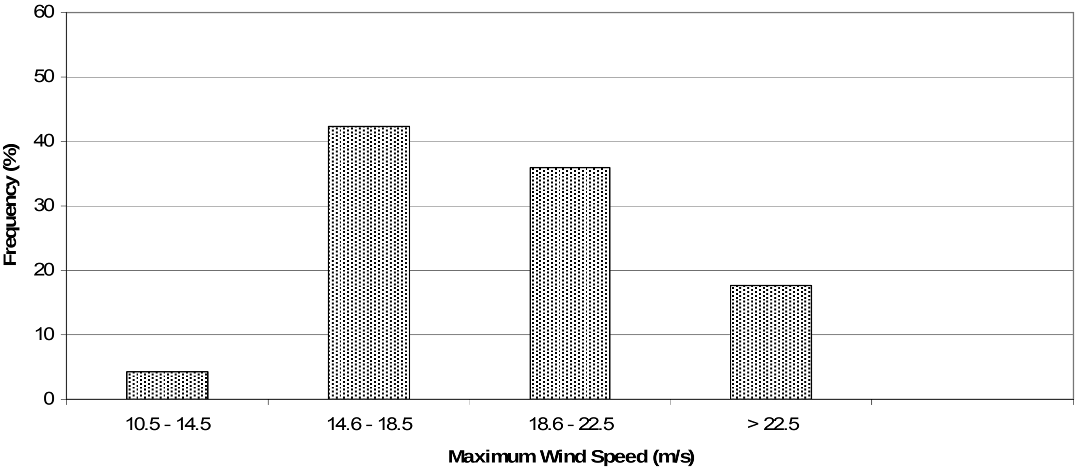

Figure 3-6 Frequency distribution of maximum wind speed for all Wellington coastal storms.

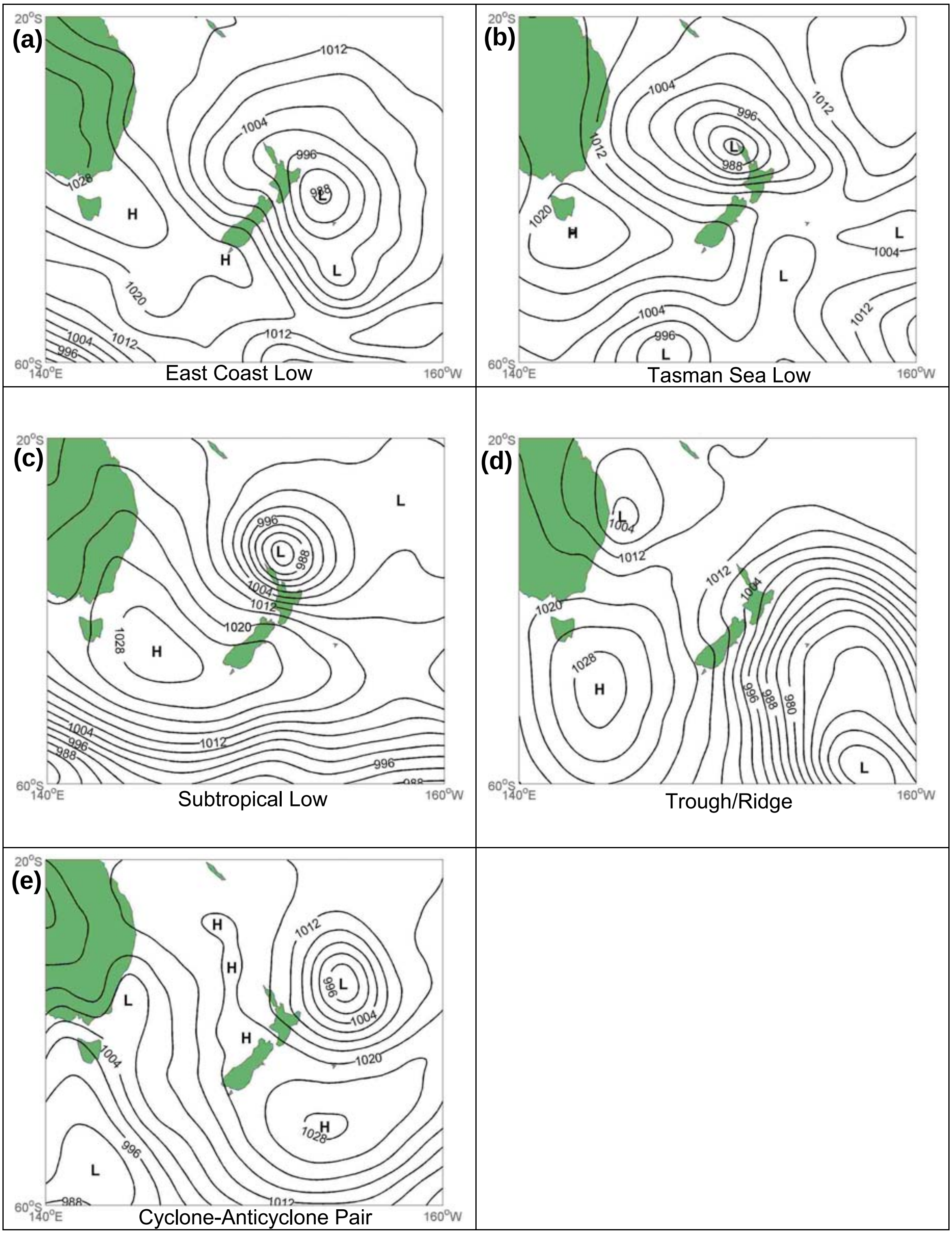

Figure 3-7 The five storm types identified in the coastal storm database – (a) East coast low, (b) Tasman sea low, (c) Subtropical low, (d) Trough/Ridge, and (e) cyclone-anticyclone pair.

(3) Subtropical Low

A cyclone is located north of 35°S in the subtropics and influences the top half of the North Island (approximately Gisborne-Napier northwards) (Figure 3-7c). They can represent ex-tropical cyclones or develop into strong systems as they move towards NZ, and be situated both east and west of North Cape. The pattern also has a ridge of high pressure over the South Island from a Tasman Sea anticyclone, or a large anticyclone to the east of the South Island.

(4) Troughs/Ridges

A trough of low pressure and/or ridge of high pressure stretch across New Zealand (Figure 3-7d) and occupy the area further eastward (e.g. Chatham Islands). These troughs can:

(a) extend from a parent cyclone in the southern ocean (south of 50°S);
(b) have formed from Tasman Sea or Subtropical lows that have dissipated into a trough structure off the east coast of NZ; and/or
(c) extend from cyclones that have moved south of Stewart Island, or east of the Chatham Islands.

Associated with the troughs are ridges of high pressure spreading onto NZ from Tasman Sea anticyclones. The combination of the ridge and trough are often responsible for the strong pressure gradients, and it is often difficult to identify which of the two weather systems is the generator of strong winds. The origin of Trough/Ridges refers only to the Trough.

(5) Cyclone-Anticyclone Pair.

A cyclone and anticyclone are both visible east of NZ and are positioned on or west of the Chatham Islands (Figure 3-7e). The entire anticyclone centre has to be east of NZ (i.e. not just a ridge). They can involve cyclones located in the subtropics or east of NZ that generally sit above a large anticyclone east or southeast of the South Island. Anticyclones south of the South Island are excluded (i.e. this is not classed as east of New Zealand). Therefore, these patterns can appear similar to Subtropical Lows and East Coast Lows, except they include an anticyclone east or southeast of NZ.

A total of 481 coastal storm events are contained in the coastal storm database between 1962 and 2005. This “total” means coastal storms identified from the instrumental record and all other coastal storms such as large wave events and significant events that aren’t captured by the winds (e.g. Waitangi Day storm 2002). Their coastal storm type frequencies and origins are shown in Figure 3-9. The two leading coastal storm types are Troughs/Ridges (47%) and East Coast Lows (43%). Tasman Sea Lows and Subtropical Lows are not common generators of coastal storms for the eastern North Island. The main source region of troughs is the southern ocean, while East Coast Lows are more likely to involve cyclones that have originated from the Tasman Sea. In the process of identifying the origin regions of the cyclones associated with East Coast Lows, it was found that only 16% of cyclones travel directly from the Southern Ocean as established or developed cyclones; the remaining 84% of cyclones are locally generated off the eastern coast of NZ from southern ocean troughs (i.e. develop closed cyclone structures, from southern ocean troughs, directly off NZ). It is due to this feature that the Southern Ocean becomes a dominant supplier of cyclones in the East Coast Low type. That is, the Southern Ocean influence on East Coast Lows is not through large, deep cyclones moving northward towards NZ but rather through secondary cyclones that develop locally from their troughs.

Of all the origin regions, the Southern Ocean has the largest influence on eastern North Island storm activity by way of Troughs and East Coast Lows. The Tasman Sea, whilst being the largest supplier of East Coast Low cyclones, is a source region for all the coastal storm type cyclones (e.g. cyclones in the Troughs, East Coast Lows, Tasman Sea Lows, Subtropical Lows, and Cyclone-Anticyclone Pairs storm types can come from the Tasman Sea).

Cyclonic weather systems from the subtropics affect eastern NZ the least (only 25% of time). They influence the eastern North Island as East Coast Lows (36%), Troughs (30%) and subtropical lows (12%). These statistics indicate that cyclones from the subtropics regularly travel south of 35S to become East Coast Lows (rather than sitting north of 35S and being subtropical lows) and of those that cause storms in NZ, they must have a strong southward trajectory to their movements. Furthermore, whilst cyclones travelling from the subtropics are outnumbered by those travelling from the Southern Ocean or Tasman Sea, three of the strongest coastal storms to affect the eastern North Island all had subtropical origins. That is, while fewer cyclones come from the subtropics, they have a greater impact on eastern North Island than cyclones from the Southern Ocean and Tasman Sea.

An in-depth analysis of the three strongest East Coast Low storms revealed many interesting features. The most important was the presence of a large anticyclone east, northeast or southeast of the Chatham Islands, and the role it plays in terms of storm activity for the eastern North Island. When this anticyclone is east or southeast of the Chatham Islands (i.e. similar position to the SW Pacific High position), it acts to “funnel” or deflect southeast-ward moving cyclones from the subtropics southward and down past the eastern coast of the North Island. If the Tasman Sea is occupied by a large anticyclone, the funnelling effect leads to the cyclones being enclosed by or squeezed between two large anticyclones in the NZ vicinity. Furthermore, the eastward anticyclone then acts as a “block” and causes the cyclone to become near stationary east of NZ (i.e. a blocking effect on cyclone movement). This immobility of the cyclone occurs while the Tasman Sea anticyclone continues to move eastward, and leads to increased pressure gradients directly over the NZ area. These factors could explain why cyclones from the subtropics generate the strongest winds for eastern NZ. In addition, when these cyclones move away from eastern NZ (east of the Chatham Islands), this same anticyclone maintains a large easterly flow over the seas east of NZ (i.e. fetch). Whilst this flow doesn’t directly impact NZ through strong winds, it becomes a wave-generating mechanism. Therefore, anticyclones to the east and southeast of the Chatham Islands strongly influence the storminess of the eastern North Island by firstly focussing cyclones towards NZ and then blocking their movements.

Hemispheric studies show a frequency maximum in summertime anticyclone activity north of the Chathams (near 40°S). It appears that this maximum could also flow into autumn. If this is the case it is speculated here that the position of this anticyclone maximum and the fact the summer and autumn seasons are when cyclone activity is strongest in the tropical and subtropical regions, could mean the summer and autumn months along the eastern North Island have the highest chances of experiencing intense storm activity from the subtropics.

The main features of each storm type – based on all the events in the coastal storm database – are described below.

3.4.5.1 East Coast Lows

A total of 138 storm events were categorised as East Coast Lows (~30%). Around half of these events had cyclones situated off the East Cape – Gisborne – Napier coast. The remainder of events showed preferred positions of cyclones off Cook Strait (approximately 20%) and the South Island (30%). The cyclones involved can be distantly generated, such that they are already fully developed systems as they travel towards and across NZ, or they can be locally generated off the eastern coast of NZ. The ratio of such cyclones is around 3 to 1. Those cyclones that are already developed with closed centres come primarily from the Tasman Sea (62%) and subtropics (30%). Only a small fraction travels northward from the Southern Ocean; of these, they either move northeast-ward through the South Tasman Sea and across New Zealand, or they move north- to northeast-ward up the eastern coast of the South Island. Comparatively, those cyclones that develop locally off eastern NZ (i.e. secondary centres) are overwhelmingly from the southern ocean (~80%). This local formation region off eastern NZ was also identified from hemispheric studies (see Figure 2-6, Chapter 2).

Those cyclones originating from the Tasman Sea developed closed centres in three main areas: off the Sydney-Melbourne coast (roughly near 155°E), west of North Cape-Auckland, and west of Cook Strait. The area off southeastern Australia matches that of Figure 2.6 (the main formation region of all cyclones from hemispheric studies). Furthermore, Figure 2-7 and Figure 2-8 (Chapter 2) show cyclones from the Tasman Sea intensify in the western Tasman Sea and have largely weakened by the time they get to the eastern Tasman Sea and off western NZ. This same pattern is seen here in the majority of East Coast Low storm sequences involving Tasman Sea cyclones. Only approximately 10-15% of Tasman Sea cyclones (and third of subtropical cyclones) intensify across and east of NZ. This finding indicates that weakened Tasman Sea cyclones (and subtropical cyclones) are still a large cause of storm conditions for the eastern North Island – not from local intensification as they cross NZ, but rather their interaction/collision with ridges and anticyclones in the NZ area. That is, the environment or meteorological situation the Tasman Sea (and subtropical) cyclone travels into becomes a critical determinant to the creation of storm conditions for the eastern North Island. This feature further implies that the local intensification region east of NZ, as found here for coastal storms and hemispheric studies (Figure 2-6, Chapter 2), is created largely by secondary cyclones from the southern ocean.

There were 65 East Coast Low storms with winds that exceeded 22.5 $m.s^{-1}$ (approximately 25%). The top three events – those with the highest maximum hourly wind – were all East Coast Lows from the subtropics. There were also 7 storms that had deep (≤ 980 hPa) low pressure systems associated with them; however, none of these corresponded to the strongest storms based on the maximum hourly wind speed. This suggests the use of strong cyclones as a measure of storminess may not be appropriate for the eastern North Island.

The three most intense East Coast Low storms, based on the maximum hourly wind speed, had the following properties:

- The cyclones are located immediately off Cook Strait or East Cape;
- Two of the three events had cyclones with central pressures < 990 hPa and intensified over or east of New Zealand;
- All had subtropical origins (from north of the North Island or the Coral Sea);
- In all three events, an anticyclone or ridge of high pressure east of the Chatham Islands had a “funnelling” effect on the East Coast Low and directed them southwards towards eastern New Zealand (instead of ESE or SE-ward).

3.4.5.2 Trough/Ridges

Nearly 50% of coastal storms off the eastern North Island are associated with a trough/ridge weather pattern. These troughs/ridges originate primarily from the southern ocean (65%) and Tasman Sea (21%). Southward-branching troughs from the subtropics are the least common (15%). Three main types of trough/ridge patterns were detected:

- a trough covers all of NZ and the area immediately eastward e.g. Kidson TSW type

- a ridge covers all of NZ and a trough or cyclone is immediately off eastern NZ and over the Chatham Islands e.g. Kidson HW type
- both a trough and ridge cover NZ e.g. Kidson TSW

Nearly half of the Trough/Ridge group had closed low pressure systems east of NZ (located east and south of the Chatham Islands and Stewart Island, respectively). Therefore, a large portion of the Trough/Ridge group shows a strong resemblance to the East Coast Low pattern, but their influence on eastern NZ is felt through their troughs of low pressure rather than from the cyclone itself.

3.4.5.3 Tasman Sea Lows

Tasman Sea Lows represent 5% of coastal storm events. They develop west of New Zealand from southern ocean troughs (i.e. in the Tasman Sea) or travel into the Tasman Sea from the subtropical region off northeastern Australia (i.e. near 25-30S, 155-165E). Those from the subtropics move southeast-ward through Tasman Sea and across NZ. The centres of these cyclones are predominately (82%) west of the Northland-Auckland region, while the rest are found slightly further southward. Two Tasman Sea Low events had wind speeds that exceeded 22.5 $m.s^{-1}$.

3.4.5.4 Subtropical Lows

Only 4% of coastal storms off the Eastern North Island are associated with subtropical lows. The preferred position of the cyclones is north or northeast of North Cape. The origins of these cyclones are subtropical, except on the rare occasion when a Tasman Sea Low travels northeast-ward into the subtropics north of New Zealand. The specific areas within the tropics that they spawn from are off northeast coast of eastern Australian (i.e. the Coral Sea, and off the Brisbane coast) and north of East Cape. They show two main pathways: from the Coral Sea and off Brisbane, they travel southeast-ward across the north Tasman Sea and across NZ; or, they descend southward from the subtropics north of East Cape. The influence of a blocking-type anticyclone east of the Chatham Islands is seen in nearly half of these storm events. None of these events created winds that exceeded 22.5 $m.s^{-1}$, and the minimum central pressure reached was 984hPa.

	Coastal Storm Types				
Max. Speeds (m/s)	**T/R**	**ECL**	**TSL**	**STL**	**CAP**
10.5 - 14.5	4	4	5	-	-
14.6 - 18.5	46	35	62	56	-
18.6 - 22.5	38	35	24	33	50
> 22.5	11	26	10	-	50
Origins					
Tasman Sea	21	44	62	11	50
Subtropics	13	25	38	89	50
Southern Ocean	66	30	-	-	-
% Freq. of Storms	**46**	**45**	**5**	**2**	**1**
Total No. of Storms	**182**	**178**	**21**	**9**	**2**

Figure 3-8 Coastal storm type frequencies and properties for Wellington.

3.4.5.5 Cyclone-Anticyclone Pair

There were only 11 storm events that are represented by the Cyclone-Anticyclone Pair weather pattern. These cyclones are positioned either north or northeast of East Cape (in the subtropics), or they are found off the North Island between East Cape and Cook Strait. In all but two events, the anticyclone covers the entire South Island and are always south of NZ (not off the South Island like in Kidson type HSE), and the cyclone generates a easterly airflow over the eastern North Island. In the other two cases, when the cyclone is off Cook Strait, the easterly flow is directed into the Cook Strait area rather than the whole of the east coast of the North Island, and the anticyclones are well south of NZ near 50S.

3.4.5.6 Wellington Region

The coastal storm types, origins and maximum wind speeds associated with the 382 storms to strike the Wellington region, as identified from the instrumental wind records (1962-2005), are summarised in Figure 3-8. There are roughly equal proportions of Trough/Ridge and East Coast Low storms (45-46%), and a small fraction associated with Tasman Sea Lows (5%). All three types are capable of generating winds that exceed 22.5 m.s^{-1}. However, they are mostly associated with East Coast Lows (just over 25%). These storm types show different source regions much like for all the coastal storms such that Troughs/ridges are predominately from the Southern Ocean, and East Coast Lows come principally from the Tasman Sea and subtropics (see Figure 3-9).

The three most intense storms to affect the Wellington region were all East Coast Lows from the subtropics (and are the same events described in section 3.4.5.1 East Coast Lows). They include the Wahine storm of April 1968, 27-28th April 1974, and 15th May 1985. The latter storm is described in detail in Chapter 4, section 1.6.4). The coastal damage related to these storms were:

(1) (1) 9-10th April 1968 (Wahine storm) – sinking of the inter-island ferry "Wahine" and lost of 51 lives, peak gusts recorded at 198 km/hr, roads to eastern bays blocked by high seas, disrupted rail-ferry- and air transport services (including closure of airport), houses lost roofs, seas tossed boulders up against retaining wall at Owhiro Bay

(2) 27 April 1974 – disruptions to rail, air and sea transport services, 137 km/hr gusts, ferry in Cook Strait described seas of 40 feet and the rough passage led to injuries to passengers and was unable to make Port, houses/buildings lost roofs at Lyall Bay.

(3) 15th May 1985 – airport shut-down, maximum gust of 144 km/hr, boated washed up on shore, debris over harbour-side roads from high seas, sea and rail services disrupted, houses evacuated at high tide, roofs torn from houses and garages, freighter forced back to Port by huge seas, huge waves ripped up roads between Houghton Bay and Island Bay, car shunted across road by waves, seawall damaged at Lyall Bay and waves reached some houses (flooding lower levels), Lyall Bay Surf Club doors smashed in by storm waves, tide line reached houses at Owhiro Bay and road eroded and car swept into the sea, several coastal roads closed, wooden accessway to Castlepoint Lighthouse destroyed.

3.4.5.7 Gisborne Region

The coastal storm types, origins and maximum wind speeds of the 91 coastal storms to strike Gisborne (1962-1991) are summarised in Figure 3-10. Nearly half of the coastal storms to impact the Gisborne region are associated with the Trough/Ridge type, and the other two dominant types are East Coast Low type (~40%) and Subtropical Lows (10%). While East Coast Lows aren't the most dominant storm type, they are more likely to create stronger winds in Gisborne. Troughs/ridges are predominately from the Southern Ocean, East Coast Lows from the Tasman Sea and subtropics, and subtropical lows from the subtropics.

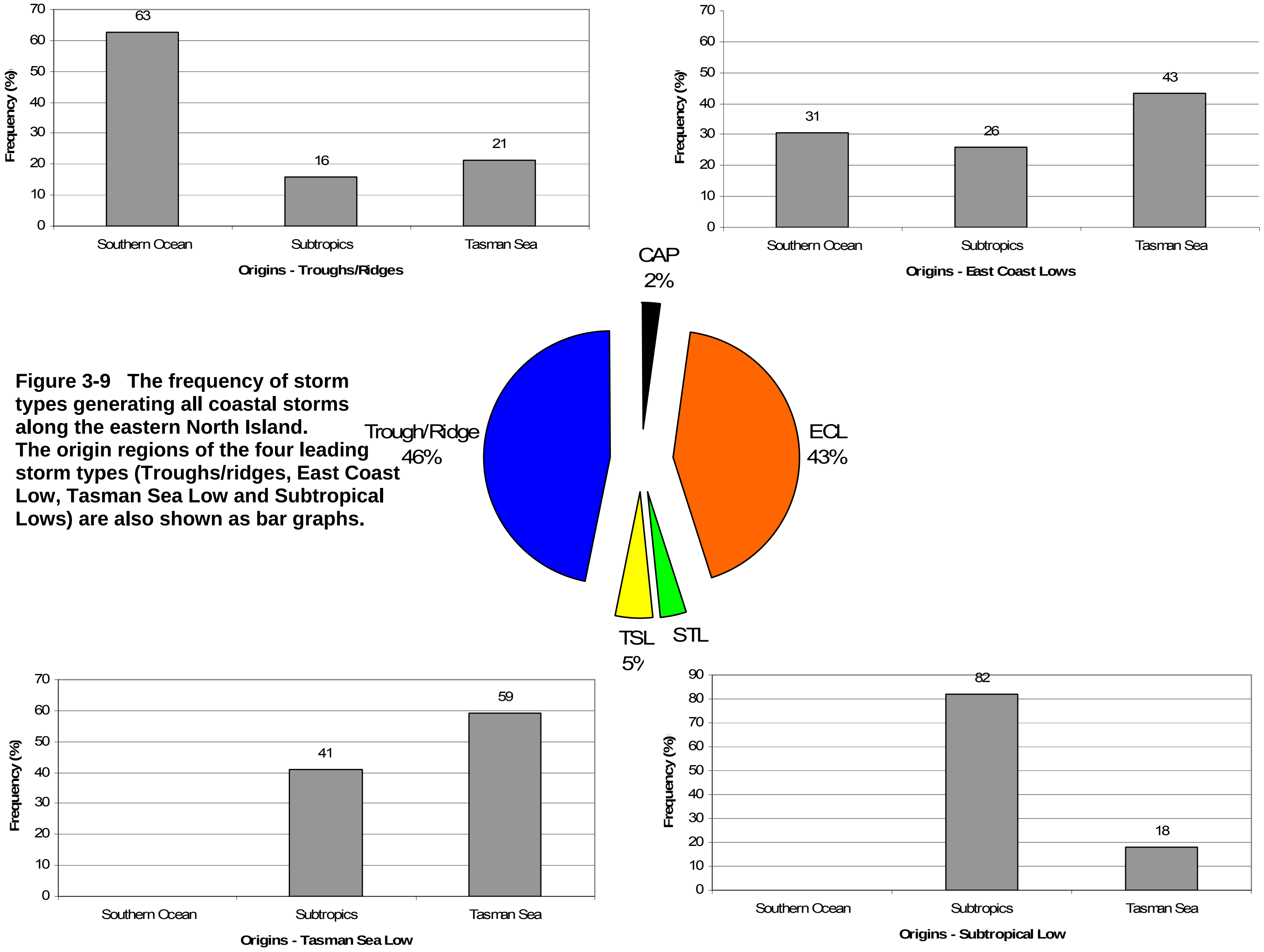

Figure 3-9 The frequency of storm types generating all coastal storms along the eastern North Island. The origin regions of the four leading storm types (Troughs/ridges, East Coast Low, Tasman Sea Low and Subtropical Lows) are also shown as bar graphs.

	Coastal Storm Types				
Max. Speeds (m/s)	**T/R**	**ECL**	**TSL**	**STL**	**CAP**
10.5 - 14.5	34	34	-	63	100
14.6 - 18.5	64	54	100	13	-
18.6 - 22.5	2	11	-	25	-
> 22.5	-	-	-	-	-
Origins					
Tasman Sea	23	37	50	13	-
Subtropics	27	37	50	88	100
Southern Ocean	50	26	0	0	-
% Freq. of Storms	**48**	**38**	**2**	**9**	**3**
Total No. of Storms	**44**	**35**	**2**	**8**	**3**

Figure 3-10 Frequency of Coastal Storm Types and their properties for the Gisborne region.

There is a difference in the dominant storm types between Wellington and Gisborne, such that East Coast Lows are more prevalent in Wellington and Tasman Sea Lows impact Wellington weather more than Gisborne. This attribute links to the strong pressure gradient being positioned in Cook Strait when cyclones are positioned west of the Northland-Auckland region.

The three most intense storms to affect Gisborne – based on the maximum hourly wind speed – all fall into the East Coast Low category and involved cyclones from the subtropics (9th April 1982, 18th March 1974 and 9 April 1968). Two of these storms involved ex-tropical cyclones (Bernie, 1982 and Gisele, 1968) that formed in the Coral Sea near the Solomon Islands. In all three storms, a blocking-type anticyclone is seen eastward of the Chatham Islands and acts to either deflect the cyclones southward towards eastern North Island or slows the eastward progress of the cyclone whilst it is off the North Island. The April 1982 storm event (ex-TC Bernie) intensified down the eastern coast of the upper North Island and was most intense off East Cape, while ex-TC Gisele intensified over the North Island near Wellington. The March 1974 storm involved a cyclone from off the Brisbane coast combining with a subtropical low north of NZ. This cyclone progressed very slowly down the eastern coast of the upper North Island due anticyclonic activity east of NZ, and during its passage from East Cape to the Chatham Islands intensified and covered eastern North Island with very strong southerly airstream. This cyclone came as close to East Cape as the April 1982 event, but was a weaker system.

The coastal damage associated with these storms were numerous, and included:

(1) 9th April 1982 - transportation disruptions to coastal roads due to flooding and slips; airport shut down; extreme wind gusts at East Cape recorded at 167 km/hr uprooted tree's and blew roofs off houses; and destruction of seawall at Tokomaru Bay from storm waves.

(2) 9th March 1974 storm - yachts ripped from moorings, century-old church flattened and large seas destroy a bach at Hicks Bay, retaining wall at Port Gisborne damaged; East Cape lighthouse keeper forced to crawl to lighthouse due to extreme winds, erosion at Tokomaru Bay, and wind gusts recorded at 130 km/hr in Gisborne and at East Cape.

(3) 9th April 1968 – wind gusts up to 138 km/hr (from northeast), caravan at Makorori Beach tipped over by winds, aerial ripped house at Wainui Beach, barometric pressure reading by Meteorological Service reached as low as 976 hPa, baches deroofed at Mahia, car and caravan swept out to sea at Lottin Point, and ship sailing from Napier estimated to have encountered waves of 50 feet.

3.4.6 Storm Types – Relationship to Kidson Weather Types

A comparison was made between the leading coastal storm types (T/R, ECL, TSL, STL and CAP) and the synoptic types of Kidson (2000). The Trough/Ridge coastal storm type effectively merges the weather types of SW, HW, TSW, and HNW into one group. The East Coast Low storm type could be represented by the R weather type, but this more closely resembles the Subtropical Low (which also has a strong resemblance to NE weather type). The subtropical low pattern here depicts the location of the cyclone closer to NZ than in the NE weather type pattern. The Tasman Sea Low pattern resembles that of the NE weather type, though the patterns here do not have large anticyclones east of New Zealand and the cyclonic feature is immediately off the west coast of the North Island (i.e. the cyclones are found much closer to the NZ landmass).

The cyclone-anticyclone pair coastal storm type has a resemblance to that of the Kidson HSE weather type (Kidson 2000), which was found to be a dominant pattern. The pattern suggested it could bring easterly winds onto the eastern North Island and possibly be strongly associated with storm events. However, the classification undertaken here has not found this to be the case. It appears an anticyclone sitting off the South Island is too far northward to spread easterly flows onto the eastern North Island. When the anticyclones are found in more southern locations (i.e. south of NZ and near and 50S), easterly flows affect the eastern North Island.

3.4.6.1 Wellington Storms and Kidson Synoptic Types

The leading synoptic types linked to coastal storms at Wellington are R, SW and HW which range between 15 to 18% (Figure 3-11) and are associated with southerly and southwest pressure gradients over NZ. The R synoptic type (18%) depicts a cyclone northeast of NZ in subtropical latitudes and is near identical to the Subtropical Low storm type. This type is also the nearest equivalent to the East Coast Low pattern. The frequencies found here for either subtropical lows (2%) or east coast lows (45%), however, do not correlate with Kidson weather type frequencies. The SW and HW types match the Trough/Ridge storm type identified here as the leading storm type. When the SW, TSW, HW and HNW types are merged into one group, to represent the Trough/Ridge storm type, they represent 55% of coastal storms, and these frequencies show excellent correlation. Thus, the leading types, using Kidson (2000) and the coastal storms identified here, agree well though their frequencies vary (especially for the R type).

Several of the other synoptic types have been linked to coastal storms, and some of these do not correlate with the criteria of a coastal storm as defined in this study. For example, the synoptic types T, HE, and W are linked to a few storms and these display northwest airflows over NZ. These airflows do not represent onshore wind directions for eastern NZ and therefore shouldn't be linked to storms. Furthermore, the HSE weather type is linked to around 10% of coastal storms, but the position of the anticyclone in this pattern implies light winds (calm conditions) rather than storm conditions. These anomalies could partly be an error connected with using 12-hour spacing of weather maps which can lead to missing the true cause of the winds.

A further anomaly of the Kidson weather type is the second dominant type, SW, which displays southwest airflows over NZ while the majority of Wellington storms are from the south (Figure 3-4c) and only a tiny portion (4%) of measured winds are southwesterly (Table 3-2). Wellington winds, clearly, are deflected from southwest to south due to strong topographic influences, such that measured winds don’t’ always align with synoptic weather map pressure gradients.

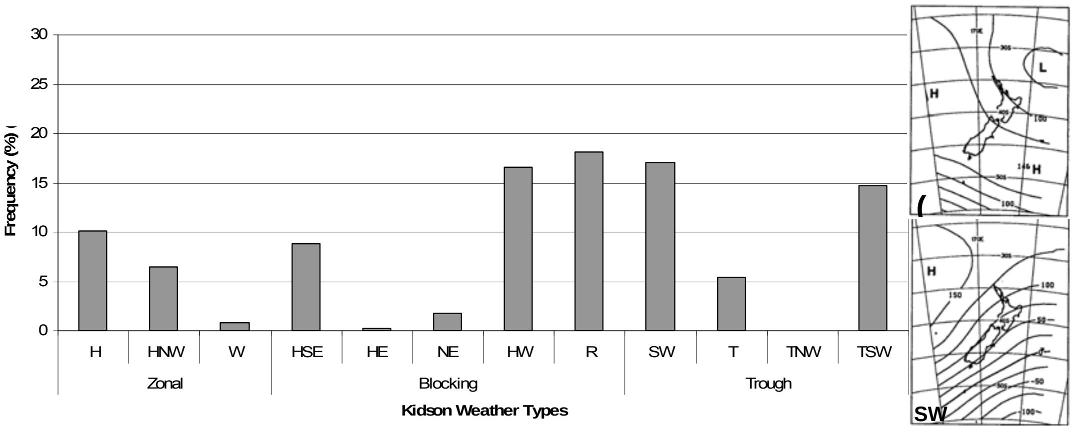

Figure 3-11 The principal Kidson synoptic types associated with coastal storms at Wellington.

3.4.6.2 Gisborne Storms and Kidson Synoptic Types

The Kidson classification scheme (Kidson, 2000) identifies the leading weather type as R and represents around a quarter of Gisborne coastal storms. This weather type matches the subtropical low storm type (or the East Coast Low type) but their frequencies do not compare with those found here. The next most frequent weather type is HW (Figure 3-12, bottom right) and relates to the Trough/Ridge storm type. When the SW, TSW, HW and HNW types are merged into one group, to represent the Trough/Ridge storm type, they represent 43% of the coastal storms, and this correlates well with the frequencies found here (48%). Therefore, the Kidson scheme finds cyclones northeast of NZ as the leading storm types while the coastal storm types here find troughs as the leading pattern.

These results suggest the Kidson scheme could be used to classify coastal storms. However, (like with Wellington), it is interesting that a considerable number of coastal storms in Gisborne are linked to the HSE type. This result indicates that any weather pattern involving an anticyclone east of NZ will be classed as HSE (regardless if they also have cyclonic systems to the north). This pattern was not seen in any of the coastal storms identified in the database, though the nearest match is to the cyclone-anticyclone pair which has an anticyclone east of NZ (though in more southern latitudes, and in conjunction with a cyclone to the north) and they are very uncommon. The Kidson scheme also links some Gisborne coastal storms to unacceptable weather types of TNW and W which are northwest airflows in Gisborne.

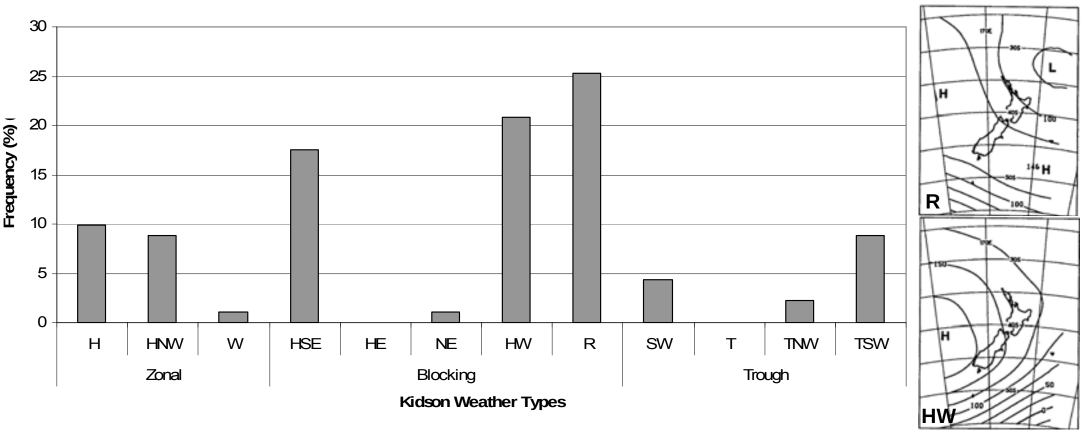

Figure 3-12 The principal Kidson synoptic types associated with coastal storms at Gisborne. The two leading synoptic types are displayed on the right-hand side and represent average patterns generated from a long-term dataset.

3.4.6.3 Usefulness of the Kidson (2000) Weather Types for Coastal Storms

The Kidson (2000) weather types have near-equivalent patterns for three of the five coastal storm types. It is less than ideal, however, that the second leading coastal storm type of East Coast Lows is absent from the Kidson types. This storm type is responsible for approximately one quarter of the strongest winds to affect eastern NZ, and clearly depict the causative meteorological structure that brings extreme weather (or stormy weather) to eastern New Zealand. It is also discouraging that the inclusion of weather patterns unrelated to coastal storms in Kidson (2000) scheme have been picked out as storm patterns (e.g. 15% of Gisborne storms were related to the weather type HSE, but were not identified in such proportions in the coastal storm database). Furthermore, the Kidson (2000) weather types, while showing equivalent patterns to the coastal storm types here, don’t portray storm conditions (e.g strong pressure gradients) or depict cyclones adequately.

These shortfalls of the Kidson (2000) scheme indicate the weather types aren’t appropriate for representing coastal storm patterns. The scheme identified here, of 5 coastal storm types, provide accurate representations of coastal storm weather and refines the set of patterns to only encompass those patterns linked to coastal storms. Other advantages of this scheme include:

(1) the weather pattern responsible for 25% of the most intense storms (based on the maximum wind speed) is captured (ECL);

(2) the cause of the strong winds is visible (e.g. strong pressure gradients);

(3) the locations of cyclones is defined to show where they are most troublesome to the eastern North Island; and

(4) Cyclonic weather systems are represented and appropriately linked to coastal storms.

The Trough/Ridge storm type merges four of the Kidson types into one group. In the same light, it is possible that the Kidson weather type R merges the coastal storm types East Coast Lows, Subtropical Lows, Tasman Sea Lows and Cyclone-Anticyclone Pairs into one group. Should this be the case, it is unfavourable in terms of understanding storm weather.

3.5 Coastal Storm Activity – 1930-1961

There is no doubt that major coastal storms occurred prior to the instrumental period, and these should be included in any storm database if a true long-term picture or understanding of coastal storm activity is desired. This long-term element is, however, often limited to the use of few, and often subjective, data sources. Nonetheless, these data sources may be the only records of past storms and subsequently become a vital resource. For most places around NZ, the most accessible information is contained in newspapers. Consequently, collections of local newspapers are the main building block for exploring past storm activity for the period prior to 1962.

3.5.1 Data Sources

The primary data sources are local newspapers from the Gisborne and Wellington regions. The available and easily accessible sources were the *Poverty Bay Herald*, *Gisborne Herald*, *Dominion* and *Evening Post*. A local newspaper for the Napier region could not be sourced outside of Napier itself. However, the *Dominion* and *Evening Post* were regional newspapers and included information pertaining to the Napier region (as does the *Gisborne Herald*).

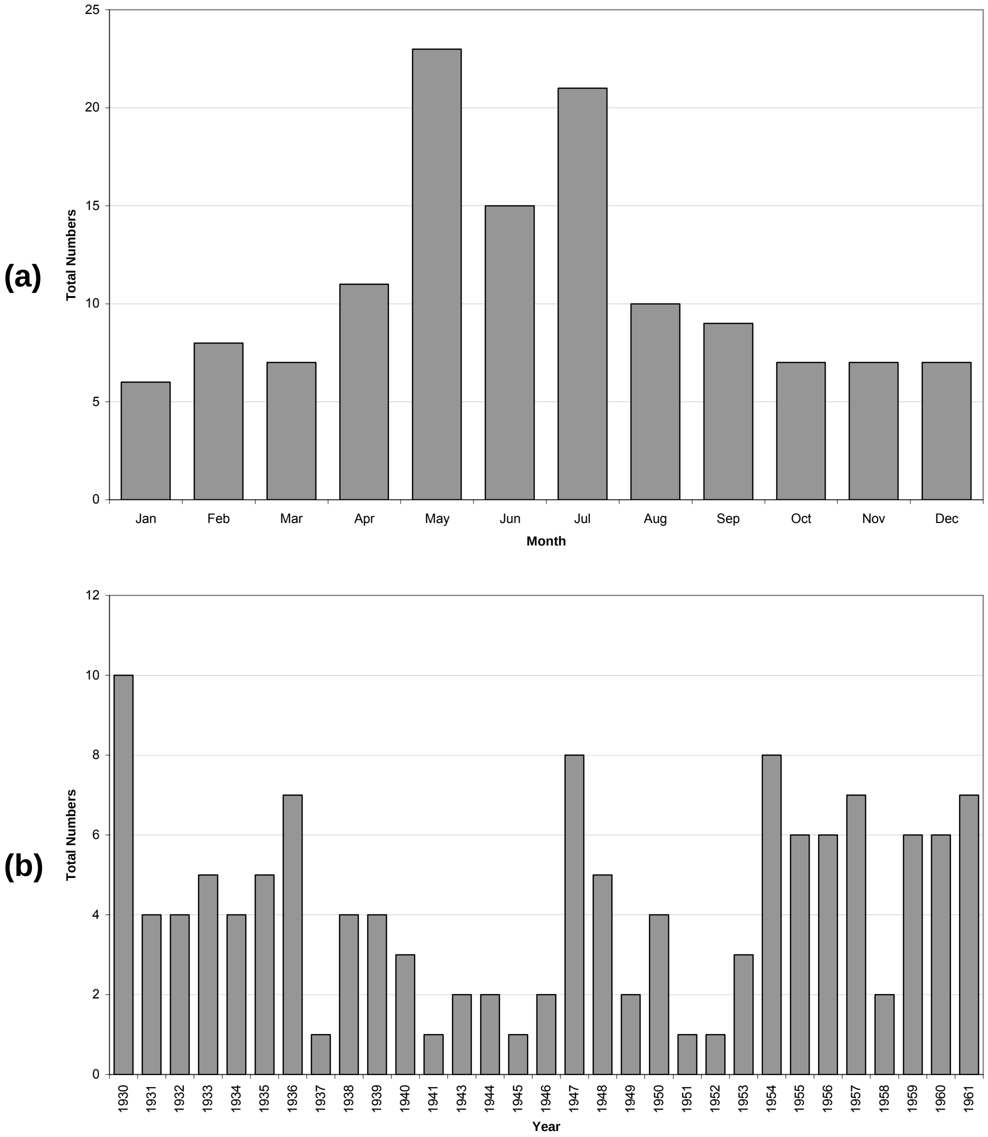

Figure 3-13 (a) Monthly and (b) annual frequencies of coastal storms between 1930 and 1961 (pre-instrumental record).

3.5.2 Storm Identification

These newspapers were searched on a daily basis from 1961 back to 1930 and all significant coastal-related weather events recorded (extracted). After identification of possible coastal storms, all available weather information was copied – meteorology, winds, tides and pressure details. Although the methodology follows no strict guidelines, the storms were essentially selected based on the damage assessments of the main newspaper headlines, verified as major coastal storms by reviewing the available weather information, and particular emphasis on these three categories:

1. Coastal shipping disruptions and delays;
2. Descriptions of large waves or bad ocean conditions along the eastern coast;
3. Articles on coastal erosion or shoreline damages; and
4. Any wind events whereby quantitative data on average wind speeds is provided (excludes storms whereby only the maximum gust is given).

As a result, the 1930-1962 period should be viewed as pertaining only to major damage-producing coastal storm activity.

3.5.3 Format of Information in Storm Database

Where possible, the storms for this earlier period are in the same format as described in Section 3.1 (i.e. synoptics, weather conditions, oceanography). However, the level of detail is significantly reduced and limited to that which is provided in the weather columns and related articles. Where additional data sources are available, they were utilized. They include:

- Animated GIF images of synoptic conditions from 1950 to 1961 using the NCEP-NCAR reanalysis dataset;
- Measured rainfall values for Gisborne, Napier, Wellington
- Unpublished and published reports and journals

Furthermore, very little synoptic weather information was obtainable during the war years (1939-1945) when publishing of weather information was poor or non-existent. Therefore, meteorological and oceanographic conditions between 1939 and 1945 are sparse.

3.5.4 Coastal Storm Statistics (1930-1961)

A total of 131 coastal storms were found between 1930 and 1961 (32 years). This equates to an annual average of 4 coastal storms per year and is very similar to that found from the instrumental record between 1962-1991 (3 per year). The monthly and annual frequencies of these storm events are shown in Figure 3-13. A different monthly distribution to the pre-1962 period appears such that peak monthly activity clusters in May and a secondary peak in July. However, seasonal activity still occurs in late autumn and early winter. Unfortunately, coastal storm activity during World War II hasn't been captured due to the absence of weather information and through media emphasis focusing on war stories rather than local issues.

3.6 The Database - Components

A database was constructed using Microsoft Office Access (2003). It consists of five essential components: meteorology (synoptic conditions and weather statistics), oceanography, impacts and damages, storm photos and images, and data sources. All the information is in NZ standard time. A variety of data was used to compile this information and includes amalgamating some of the information contained in the previous chapter (i.e. hindcast waves). Each component is discussed in some detail below.

This database is essential for a number of reasons. One of the first steps to reducing the impacts of coastal storms is understanding the characteristics of the hazard itself, and this database achieves this in a number of ways. It records all past storm events in one central location to give so that we can understanding historical events (and are needed to make predictions into the future i.e. we need to understand the past before we can predict into the future). The meteorology component describes the evolution and movement of leading weather systems, identifies the areas where cyclones and anticyclones are most damaging for the eastern North Island. The history of adverse effects and major damages will enable better assessments of our risks along the coast, and can link into coastal planning initiatives and assist with improved management strategies.

Several limitations affected the production of this database. First and foremost was incomplete wind datasets for Gisborne and Napier, followed by access to commercially sensitive data (winds and waves), and a lack of freely-available database software that is graphics-enhanced. This latter factor leads to slow upload times and low resolution of images.

3.6.1 Meteorology

An overview of the storm event is presented in the meteorology section. It provides the storm date, location, wind direction, wind duration, together with the coastal storm type and its origin. The weather map linked to the storm type is displayed and a brief summary of the synoptic conditions.

A subsection titled 'Weather Conditions' appears and links through to plots (or graphs) of the specific weather conditions of the storm event. They include:

- Wind speed and direction – units: meters per second ($m.s^{-1}$) and degrees (clockwise from North);
- Maximum wind gust and direction – units: kilometres per hour ($km.hr^{-1}$) and degrees (clockwise from North)
- Barograph – units: hectoPascals (hPa);
- Daily rainfall totals – units: millimetres (mm)

The following wind information is used:

- Hourly wind speed (and direction) and maximum wind gust (and direction) from Gisborne airport from 1962 to 2005 excluding the 1992-1998 period (Source: National climate database, NIWA);
- Hourly wind speed (and direction) and maximum wind gust (and direction) from the Port of Gisborne weather monitoring site from 2004 to 2005 (Source: Eastland Infrastructure and Port of Gisborne, pers comm. Deane Crawe, Murray Carman, and Wayne Turner, 2005);
- Hourly wind speed (and direction) and maximum wind gust (and direction) from Port of Napier from 1999 to 2005 (Source: Port of Napier; pers comm. Peter Frizzel, 2005);
- Hourly wind speed (and direction) and maximum wind gust (and direction) from Wellington airport from 1962 to 2005 (Source: NIWA Climate database);

Wind speed and direction for the Napier region is only available from 1999 onward by using the high-quality hourly wind information from the Port of Napier. Synoptic (i.e. 3-hourly) pressure readings and daily rainfall totals were obtained from the national climate database (pers comm. A. Gosai, NIWA) for the weather stations from Gisborne, Napier and Wellington airports. However, total rainfall values for Gisborne are from the Gisborne Harbour (Port) station.

There is also a subsection titled ‘Weather Maps’ that links through to an 8-day sequence of synoptic weather patterns that is viewed as an animation. The animations were made from NCEP-NCAR reanalysis mean sea-level pressure fields and plotted using a Matlab contouring program from 1958 to 2005. Between 1950 and 1957 weather sequences were created using images from the Climate Diagnostics Center website. The sequence covers the 4 days preceding the start date of the coastal storm, days of the storm, and 1-2 days after. This format allows one to track the movement and evolution (e.g. cyclone development, intensification) of leading weather systems as they travel towards and over NZ and determine the point of origin. Sequencing is a preferred method when a thorough explanation of the relationship between synoptic conditions and the surface environment is sought (e.g. Yarnal & Frakes, 1997; Yarnal, 1993), as is the case here.

To maintain consistency, we use the same date range of the 8-day weather sequence for all other components of the coastal storm. That is, the meteorological and oceanographic properties presented for each individual storm event covers the same 7-9 day sequence as the weather patterns. For example, if a storm occurred on 7th February 1962, the weather sequence duration is from 3rd to 9th February. Consequently, the corresponding weather conditions (e.g. daily rainfall totals) are presented for 3-9th February, and all parameters are in NZ standard time.

3.6.2 Oceanographic Information

This section discusses all information obtained on wave and tidal conditions. Measured (quantitative) wave data is sparse for the eastern coastline of NZ between East Cape and Wellington up until 1999. Consequently, from 1962 to 1978, the data consists entirely of single statements of wave conditions as extracted from newspaper articles (*Gisborne Herald*, *Dominion*, and *Evening Post*). From 1979, the text listing of wave conditions continue and are accompanied by plots of hindcast deep-water wave heights and directions. For details on the hindcast wave data see Chapter Three, Section 3.5. Furthermore, plots of real-time measured wave data from 1996 are available for the south Wellington coast and from 1999 at Napier. Also contained in this section is a plot of the predicted tide heights over the 8-day period.

3.6.3 Impacts and Damages

Major storm impacts and damages are displayed in a text field and describe all the negative effects felt between East Cape and Wellington, and also cover significant coastal damages for other coastal locations along the eastern coast of NZ. The damages can range from rainfall based impacts (e.g. torrential rain, flooding), persons affected, physical impacts (e.g. infrastructural damage, erosion, houses unroofed etc) and service or utility interruptions (e.g. telephones and electricity cut, shipping halted, ferries stopped etc). Most of this material was gathered and extracted from newspaper articles (*Gisborne Herald*, *Dominion*, *Evening Post*). Depending on the magnitude of the coastal storm, additional sources are included. These include general articles, journal articles, and published and unpublished reports.

3.6.4 Storm Photo's and Images

Photo's or images showing major damages and impacts relating to each coastal storm are included and can be viewed at low resolution. A maximum of four images are available per storm event. However, in a majority of events, no such images are found. These images were sourced from newspaper articles, journal articles, published and unpublished reports, and personal photo collections.

3.6.5 Data Sources and References

The data sources used to describe the individual coastal storms are listed here as a simple text field. This will enable viewers to go back to the original sources and obtain any further information pertaining to the storm event, if required. It also allows for easy verification of the information provided in the database.

3.7 Summary

A digital, high-quality coastal storm database for the eastern North Island has been compiled from 1962 to 2005 (44 years). Coastal storm activity has been extended back to 1930 but is thought most accurate and representative from a statistical point of view for the instrumental period (1962-2005). Each coastal storm is explained in great detail - meteorologically, oceanographically and damage-wise – by merging numerous data sources. Furthermore, it is the first such database for eastern NZ and in a format that is easily maintained, accessed and updatable. As more information becomes easily available, it would be highly advantageous to include components such as water levels (e.g. storm surge), real-time wave data, storm track graphics, and empirical wave parameters such as wave run-up levels.

There are five weather types or patterns associated with coastal storms on the eastern coast of the North Island – Trough/Ridges, East Coast Lows, Subtropical Lows, Tasman Sea Lows, and Cyclone-Anticyclone Pair. This set of coastal storm types provide accurate descriptions of storm weather, define the location of cyclones that are troublesome for the eastern North Island, and appropriately link coastal storms to cyclonic weather systems. Every type, (obviously) excluding Trough/Ridge, contains a cyclonic weather system and differ based on the location of the cyclone.

Troughs and Ridges (Trough/Ridge storm type) are the leading storm type for eastern North Island coastal storm events. They involve a large trough that encompasses the whole of NZ, a ridge of high pressure extending from a Tasman Sea anticyclone over most of NZ, or a combination of both. They originate primarily from the Southern Ocean, and can often have a strong resemblance to the East Coast Low type when cyclones have travelled west and south of Chatham and Stewart Islands, respectively.

East Coast Lows involve cyclones immediately off the eastern coast of NZ and show preferred positions off the Gisborne-Napier coast and off Cook Strait. Using the peak (maximum) wind speed as a measure of intensity, East Coast Lows are responsible for the most number of intense storm events. Approximately 25% of East Coast Low storm events produce winds that exceed 22.5 $m.s^{-1}$. In addition, the three strongest coastal storms were all East Coast Lows (with subtropical origins). East Coast Lows consist of two types of cyclones: fully developed systems that are distantly generated (just over 90% from the Tasman Sea and subtropics), or cyclones that are locally generated (e.g. develop closed centres) immediately off NZ. This cyclone formation region off eastern NZ has been captured in previous research on southern hemisphere cyclones. This study shows a large majority of the cyclones generated off eastern NZ develop from troughs extending from the Southern Ocean (e.g. secondary cyclone centres). Furthermore, the main influence of the Southern Ocean on East Coast Lows (and eastern NZ storm activity) is from secondary cyclones (not large, deep southern ocean cyclones).

Tasman Sea Lows and Subtropical Lows are only associated with 5% of coastal storms. Tasman Sea Lows have the largest impact on the eastern North Island when they are located west of the Northland-Auckland region, and subtropical lows when they are north or northeast of North Cape. Those cyclones with subtropical origins are generated in the Coral Sea region and off Brisbane.

Eastern North Island coastal storm activity is also affected by blocking-type anticyclones to the east and southeast of the Chatham Islands, which act to funnel (or focus) cyclones from the subtropics down the eastern coast of the North Island (i.e. deflect cyclones onto southward pathways) and then block their movements to cause stationarity. This blocking effect relates mostly to cyclones from the subtropics, and helps explain why the three strongest coastal storms involved cyclones from the subtropics.

Gisborne has, on average, experienced three coastal storms per year from 1962 to 1991 and September is the most favoured. Trough/ridge and east coast low storm types represent nearly 90% of all storm events. Wellington has, on average, experienced 9 coastal storms per year (1962 to 2005) and these are most likely to strike in June. The Wellington region experiences longer-duration and higher magnitude coastal storms compared to Gisborne (e.g. 68 storm events in Wellington reached wind speed in excess of 22.5 m.s^{-1}, Gisborne had none). These storms are equally represented by East Coast Lows and Trough/Ridge storm types. However, stronger winds are likely to be generated by East Coast Lows than troughs.

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4 EASTERN NZ STORM ACTIVITY AND ONSHORE WIND PATTERNS

4.1 Introduction

It has been shown from hemispheric and basin-scale studies that the eastern coast of New Zealand is home to large numbers of cyclones and anticyclones. These systems include intensifying, strong and explosive cyclones, and rapidly intensifying, intense and blocking anticyclones. Be they discrete systems, or occurring in combination, cyclones and anticyclones are capable of generating stormy weather conditions that impact on the eastern coastline of the North Island. To evaluate and understand such events one needs to study regional and/or local-scale information in their various forms.

There is no single commonly used or accepted measure of storm activity. On this basis, this chapter examines coastal storm activity by using other high quality, readily available data sources of strong cyclone tracks, extreme onshore winds, and large wave events which will provide a clearer picture of offshore coastal storm activity. These are all commonly used measures for exploring storminess, with the latter two being directly related to “coastal” storms. The inclusion of cyclonic weather systems is warranted as the coastal storm database identified low pressure systems as a leading generator of strong winds and negative impacts to the eastern North Island coastal regions. The three proxies chosen (strong cyclones, extreme onshore winds and large waves) will provide further understanding of coastal storm activity and complement the information gained from in-situ measurements (i.e. the coastal storm database). As with the instrument wind records, there are advantages and disadvantages associated with each proxy and they are described in Table 4.1. In general, the positives outweigh the negatives, especially in the case of nonexistent oceanographic data that can be filled by predicted (or hindcast) information.

The objectives of this chapter are to:

1. Quantify and describe the behaviour of strong cyclones in the NZ region;
2. Examine the spatial patterns of strong onshore winds over the seas off eastern NZ;
3. Produce a climatology of large wave events along the eastern North Island using a 20-year hindcast wave dataset; and
4. Investigate the relationships between cyclone tracks, strong onshore winds, and large wave events.

Objective One will reveal the frequencies and spatial distributions of strong cyclones through the NZ and identify any local centre's of storm activity pertaining to formation or intensification, and discuss their movements and intensities.

Objective Two will identify where extreme onshore winds from the SW through E to NE dominate off the eastern coast of NZ and discuss their relative influence on the coastal regions of the eastern North Island. The frequencies of these events will be quantified to illustrate their preferred monthly and seasonal regimes, and the weather patterns responsible for generating the extreme winds will be isolated and described.

Objective Three will determine the frequency of large wave events and isolate their important properties of maximum wave heights, directions and average wave heights. The weather patterns linked to these large wave events will be identified, and comparisons made between these patterns and the coastal storm types. Furthermore, the clustering of storm events in time will be quantified to reveal the variability and average time interval between large waves at the coast.

Objective Four will explore the linkages, if any, between cyclone tracks, strong winds, and large wave events through frequency analyses, and individual case studies associated with known coastal storms. Theoretically, the relationship is expected to be strong since strong cyclones bring strong winds and the strong winds generate waves.

4.2 Strong Cyclones Around NZ – 1950-2005

4.2.1 Introduction

Most damaging storms are related to the presence of low pressure systems directly off the affected coastline. This connection indicates coastal storm activity can be assessed through studying cyclone behaviour. The presence of a cyclonic system off any coast does not, however, automatically lead to storm conditions. Many other factors or features come into play that determine whether strong winds and rainfall will occur, such as the strength (and direction) of the pressure gradient, wind direction, and location and speed of movement of the system. As a result, cyclone activity will only provide part of the picture towards understanding any regional coastal storm hazard by revealing the principal locations of genesis and intensification, average movements, and monthly and seasonal variations.

Proxy for Coastal Storms	Strengths	Weaknesses
Strong Cyclones (generator of storms)	∗ Commonly used measure ∗ Storms are “cyclonic” weather systems ∗ Cyclones been linked to some extremes in weather ∗ Identify locations of high frequencies, genesis, intensification and movement ∗ Link cyclone location to other storm parameters (e.g. erosion potential, storm surge etc)	∗ Single cyclones not always cause of storm conditions or strong winds (often need other features) ∗ Don’t capture winds associated with cyclones ∗ Paths usually more important than numbers ∗ Effects vary as they develop and with their trajectories
Extreme Winds over the Sea (generator of storms)	∗ Most common measure of storms ∗ Storms characterised by strong winds ∗ Captures storm events from multiple generation mechanisms (lows, highs, ridges etc) ∗ Not affected by inhomogeneities as in in-situ data ∗ Damage producing from direct force or indirectly from waves and surges etc ∗ Generating force for large waves	∗ Coarse resolution of model data leads to missing events over smaller regions ∗ Not representative of winds at surface (need adjustments to reflect surface conditions) ∗ Capture distant events that won’t influence eastern North Island (if spatial domain too expansive)
Large Wave Events (Coastal Impact of storm)	∗ Oceanographic feature of storms ∗ Large waves are a product of storms ∗ Most destructive force at the coast ∗ Damages at coast primarily from waves ∗ Represent most serious hazard at coast ∗ Generated by wind fields (regardless of weather system type) ∗ Capture distant storms (unrelated to wind records)	∗ Hindcast data (not real-time) of limited time period ∗ Hindcast data known to over-estimate wave heights ∗ Exaggeration of storm frequency due to distantly generated wave events

Table 4-1 Strengths and Weaknesses associated with the three storm proxies used to explore coastal storm activity

4.2.2 Methodology

4.2.2.1 Data Source

A database of cyclone tracks for the Southern Hemisphere (SH) is being maintained by Dr Mark Sinclair (Embry-Riddle Aeronautical University, Arizona) and was recently updated. An interface program called TRAX can be used to filter from the entire database desired cyclone properties and output the results as contour maps, histograms or text listings. The TRAX program also contains temporal and geographical filters so one can assess cyclone activity for specific locations. Subsequently, a text listing of all strong cyclones in the NZ region bound by 150E-150°W, 30-50°S was obtained for the time period 1950 to September 2005 following the methodology as outlined in Sinclair (1994, 1997) and using the NCEP-NCAR reanalysis dataset (Dr M. Sinclair, personal communication) . This file contains information on central pressure, central vorticity, circulation, translation vectors, position and time. This methodology is discussed in detail in the following section.

The NCEP-NCAR Reanalysis Method is discussed in great detail in Kalnay *et al.,* (1996) and Kistler *et al.,* (2001), and as such, is briefly touched on here. This reanalysis makes use of the NCEP atmospheric (spectral) model and statistical interpolation scheme and is run with a large array of assimilated global atmospheric observations. The main outputs consist of gridded values of numerous atmospheric variables four-times daily for multiple vertical levels of the atmosphere.

The 50-year NCEP-1 dataset, unfortunately, is not without errors (Bromwich & Fogt, 2004; Kistler *et al.,* 2001; Hines *et al.,* 2000; Kalnay *et al.,* 1996). Although the reanalysis data assimilation system remains constant, the same does not apply to the observational network, which has faced two major changes associated with rawinsonde data (from 1958), and the introduction of satellites (1979 onwards). Human errors were also recognized, and include a problem with Southern Hemisphere surface pressure input data between 1979 and 1992 (known as PAOBS error). The area most affected by incorrect longitude coordinates, was south of 40-45°S and relates to synoptic-scale features (Kistler et al., 2001) rather than monthly means. Luckily, the impact of the PAOBS error is small in the NZ-SW Pacific sector investigated here (150°E to 150°W, 30-50°S) due to plentiful physical observations negating the use of PAOBS data. That is, the area examined in this study is considered to be data-rich and use of PAOBS data was reserved for data-poor regions. Therefore, the main impacts of the PAOBS data can safely be assumed to fall or lie outside the immediate area of Australia and NZ. These errors have since been corrected for as part of the updated NCEP-NCAR dataset now known as NCEP-DOE Reanalysis (NCEP-2) that covers the time period from 1979 to the present.

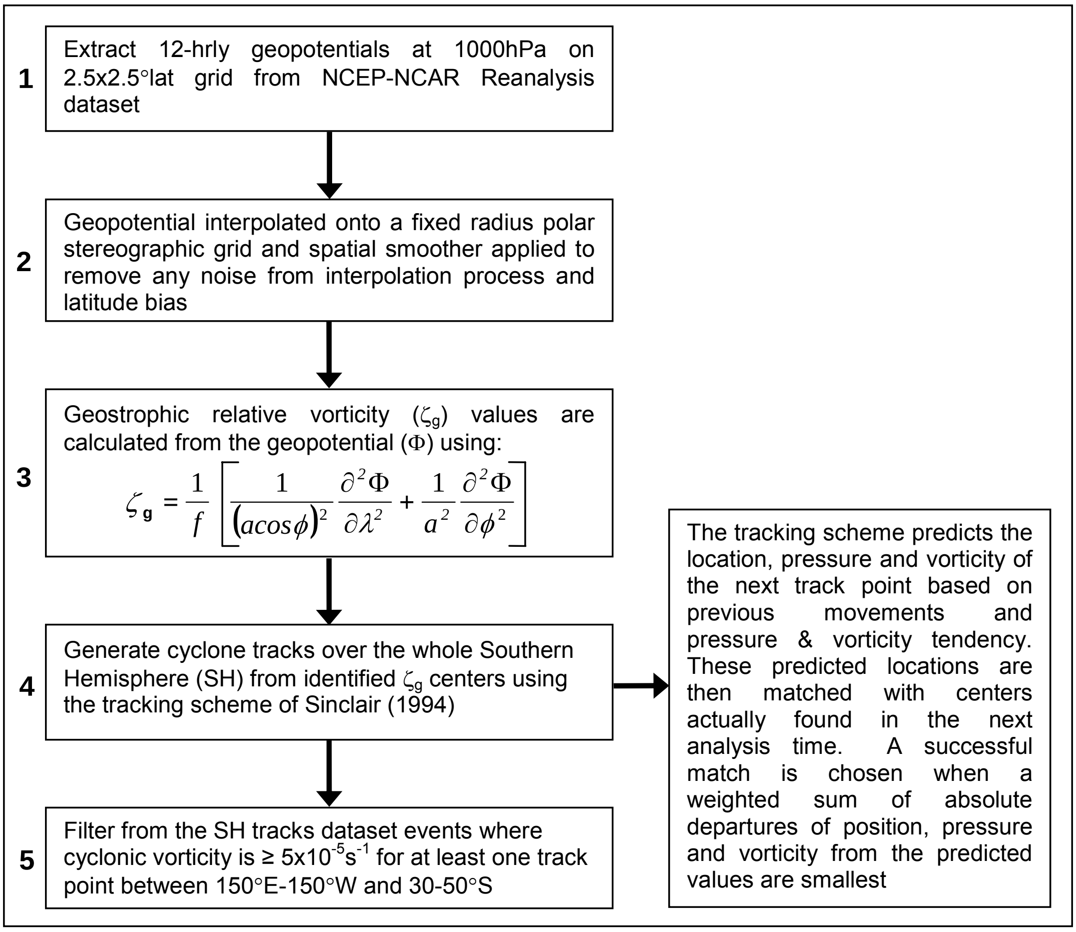
4.2.2.2 Cyclone Identification and Tracking

The objective automated scheme, as described in Sinclair (1994), was applied to twice daily (0000 and 1200 UTC) 1000-hPa geopotential analyses to generate cyclone statistics for the region bound by 150°E-150°W and 30-50°S (Dr Mark Sinclair, pers comm. 2005). This methodology is outlined here in detail. Cyclones are identified as local maxima in cyclonic geostropic relative vorticity, ζ_g (i.e. clockwise rotating systems) as calculated from geopotential fields. All cyclonic disturbances where ζ_g at the centre is greater than (i.e. more cyclonic) $5 \times 10^{-5}\ s^{-1}$ at some point in the cyclone track are retained. From a statistical viewpoint, this value coincides with approximately the top 10% of all cyclones (1934 tracks of 17109 total, of any intensity) to give the strongest 2-3 cyclones per month. Cyclones are always passing over the NZ region, and not all pose a threat. It is assumed that strong cyclones have a higher damage potential.

The position, time, central vorticity, mean SLP and whether the system is open or closed are subsequently obtained. The overall process is summarized in Figure 4-1 as described in Sinclair (1994, 1997) and from which greater detail can be found. Once these minima have been located, they are generated into individual cyclone tracks. The tracking scheme predicts the next track point location (and pressure and vorticity values), after identification, based on previous movements, and pressure and vorticity tendencies (Sinclair, 1994). These predicted locations are then matched with actual centres found in the next time step as described in Figure 4-1. A successful match is chosen as the minimum of a weighted sum of absolute departures of position, pressure and vorticity from the predicted locations.

It is also possible to identify geographical regions where cyclones develop, intensify, mature and decay by defining thresholds for these different stages in the cyclone life cycle. The same criteria as Sinclair (1994) have been adopted:

- Cyclone = point where value is > 5 x 10^{-5}.s^{-1}
- Genesis/formation - the first point of the track, or first value where cyclonic ζ_g is less than 5 x 10^{-5} s^{-1} ;
- Intensification – track points where cyclonic ζ_g is increasing faster than 2x 10^{-5} s^{-1} per day;
- Maturity – track points of maxima in cyclonic ζ_g (i.e. point of maximum development); and
- Decay – track points where cyclonic ζ_g is decreasing faster than 2 x 10^{-5} s^{-1} per day.



1 Extract 12-hrly geopotentials at 1000hPa on 2.5x2.5°lat grid from NCEP-NCAR Reanalysis dataset

2 Geopotential interpolated onto a fixed radius polar stereographic grid and spatial smoother applied to remove any noise from interpolation process and latitude bias

3 Geostrophic relative vorticity (ζ_g) values are calculated from the geopotential (Φ) using:

$$\zeta_g = \frac{1}{f}\left[\frac{1}{(a\cos\phi)^2}\frac{\partial^2\Phi}{\partial\lambda^2} + \frac{1}{a^2}\frac{\partial^2\Phi}{\partial\phi^2}\right]$$

4 Generate cyclone tracks over the whole Southern Hemisphere (SH) from identified ζ_g centers using the tracking scheme of Sinclair (1994)

The tracking scheme predicts the location, pressure and vorticity of the next track point based on previous movements and pressure & vorticity tendency. These predicted locations are then matched with centers actually found in the next analysis time. A successful match is chosen when a weighted sum of absolute departures of position, pressure and vorticity from the predicted values are smallest

5 Filter from the SH tracks dataset events where cyclonic vorticity is ≥ 5x$10^{-5}$$s^{-1}$ for at least one track point between 150°E-150°W and 30-50°S

Figure 4-1 The methodology applied and performed by Sinclair (1994) for extracting cyclone tracks (pers. comm. Dr Mark Sinclair, 2005).

Furthermore, cyclone motion can be obtained by computing mean vector velocities between track points. The velocities are calculated by applying a centred time differencing scheme to the track point coordinates (Sinclair, 1994). Cyclone intensity is here defined as the track point containing the minimum pressure value and maximum vorticity value. The frequency distributions of pressure and vorticity values will also be analysed for the cyclone life stages.

The spatial distributions of these properties were calculated and plotted using ArcGIS^{TM} Spatial Analyst software. Point densities were calculated with a circular search radius of 5° centred on each grid cell. Circular geometry avoids the problem associated with counting cyclones in rectangular latitude-longitude grids which change dimensions with latitude (Sinclair, 1994, 1995). In a simple density calculation, points that fall within the search area are summed and then divided by the search area size to get each cell's density value (McCoy and Johnston, 2001). However, in order to get smoother distributions a kernel density calculation was used here. This process is much the same except points lying near the centre of the cell's search area are weighted more heavily than those lying near the search radius edge (McCoy and Johnston, 2001). These density distributions were then displayed as contour plots. Unfortunately, there was no method available in ArcGIS^{TM} Spatial Analyst for calculating track densities, and hence, the spatial frequencies are expressed as system densities. In addition, nearly 8000 data points were located outside of the 150°E to 150°W and 30-50°S spatial domain. This means partial cyclone tracks that pass through the boundaries of the defined area were included in the analysis, and may generate dubious behaviour along the edges of the contour plots.

This methodology was chosen on the basis of its many strengths and ability to suit the requirements of this study. Firstly, the method has been endorsed or approved by the scientific community through the numerous research papers of Sinclair (1994, 1995, 1996, and 1997). It is known to have improved detection capacity for migratory weather systems (with closed and open structures) in the 45-55S latitude band for which NZ falls within. Furthermore, because this methodology includes a measure of intensity, it was possible to demarcate only the cyclones of interest (e.g. strong cyclones). Given the approved nature of this tracking scheme, the properties relative to NZ and the intensity measure, together with the fact a database of cyclone tracks already exists for the NZ region (i.e. no need to “reinvent the wheel”), it was sensible to utilise this dataset and method. The only significant drawback of the methodology is the possible extraction of non-cyclonic features (such as shear and curvature zones), and inability to display track densities due to software limitations.

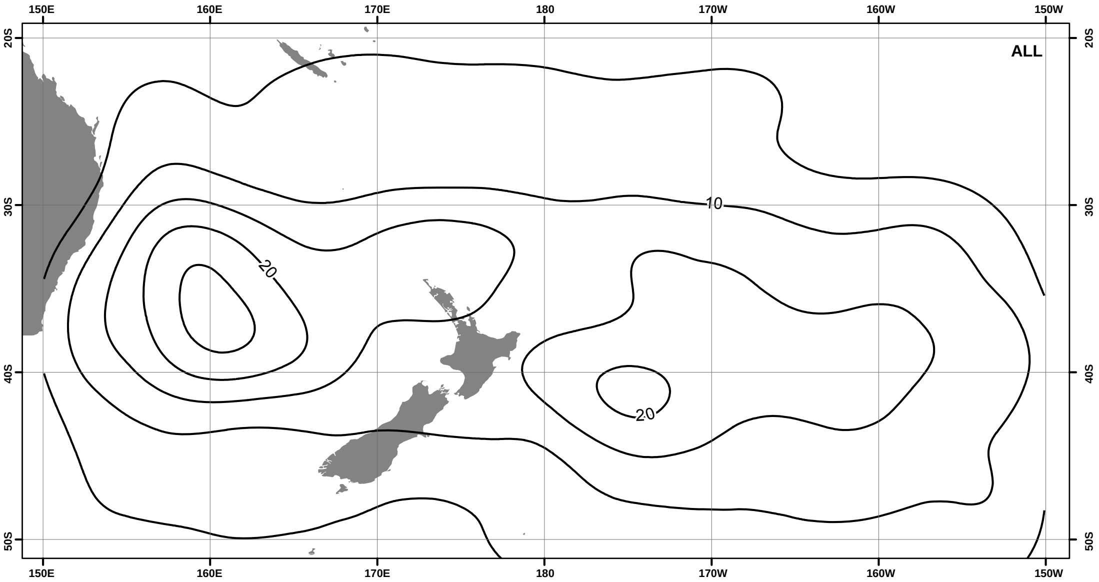


Figure 4-2 The spatial distribution of all strong cyclone tracks through the SW Pacific between 1950 and September 2005. Frequencies are given as the number of systems per 5° circle and the contour interval is 5.

4.2.2.3 Cyclone Frequency

The frequency of strong cyclone tracks were computed for the entire region, called the SW Pacific, as defined by the spatial limits of 150°E-150°W, 30-50°S on monthly, seasonal and yearly timescales. Based on the spatial patterns – showing two regions of high frequency – it was decided to present separate statistics for two sub-regions within the SW Pacific. The two frequency maximum sit either side of the international dateline and hence the dateline is used to define two sub-regions. The zone west of the dateline (150°-180°, 30-50°S), which encompasses the Tasman Sea maximum seen in the spatial patterns (and NZ), is called the Tasman Sea-NZ sector. The other sub-region is east of the dateline (180°-150°W, 30-50°S) and covers the frequency maximum near the Chatham Islands. This division will allow the frequency distribution of cyclones to be studied in greater detail and identify any differences between them (e.g. large number of cyclone tracks vs. region of slow-moving cyclones).

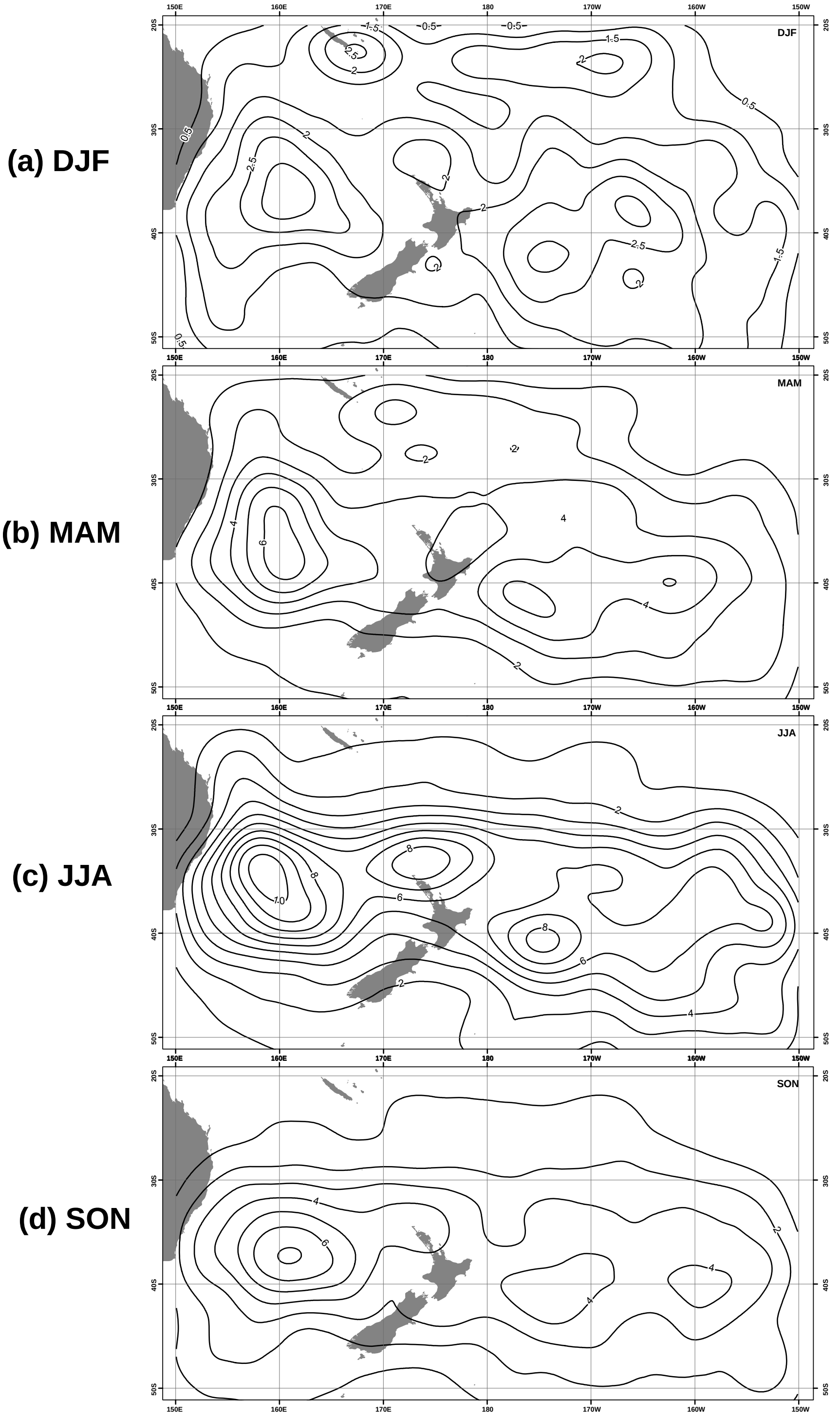
The spatial domains of these sub-regions were defined as 150°-180°, 30-50°S and 180°-150°W, 30-50°S. The cyclone tracks were then partitioned into these regions based on their coordinates. Unfortunately, a degree of overlap will occur since some cyclone tracks could start in the Tasman Sea and travel eastward of the dateline.

4.2.3 Results - Spatial Distribution

4.2.3.1 Frequency

Two prominent maxima in cyclone density are found on either side of NZ (Figure 4-2). The central Tasman Sea is regularly traversed by strong cyclones, as is the area northeast of the Chatham Islands near 175°W. The annual cycle, depicted by seasonal averages, is shown in Figure 4-3. In all seasons, two density maxima are prominent on either side of NZ – one in the western-central Tasman Sea and the other east of the dateline. The centre east of the dateline is spread between 180° and 160°W along 40°S, whereas the Tasman Sea centre has a tightly packed structure near 160°E.

The lowest incidences of strong cyclones through the study region occur in summer. The pattern shows density maxima in the tropics near New Caledonia and a secondary region near 170°W, 24°S, as well as in the subtropics on either side of NZ (Figure 4-3a). Small maxima are also visible near northern NZ and northeast of Christchurch. During autumn, activity increases two-fold in the western-central Tasman Sea, and the tropical maximum near New Caledonia is shifted southeastward. The small centre near northern NZ has enlarged and now covers most the North Island (Figure 4-3b). East of the dateline, most activity is along 40°S and is slightly increased from summer.


(a) DJF

(b) MAM

(c) JJA

(d) SON

Figure 4-3 Seasonal distributions of strong cyclone activity for the time period 1950 to September 2005. Frequencies are given as number of track points per 5° area and the contour interval is 1. The seasons are (a) DJF = summer; (b) MAM = autumn; (c) JJA = winter; and (d) SON = spring.

The winter pattern clearly shows the highest frequencies with clusters in three regions: off eastern Australia (western-central Tasman Sea), near northern NZ and near 175°W, 40°S (north of the Chatham Islands). The centres near northern NZ and north of the Chatham Islands contain the same cyclone densities, while the Tasman Sea region has slightly higher numbers (Figure 4-3c). Furthermore, there is very little activity north of 25°S (i.e. in the tropics), and this seasonal distribution shows the most activity over NZ (especially the upper North Island). In spring, the Tasman Sea maximum displays similar numbers to autumn. However, the centre is stretched zonally and extends across northern NZ (Figure 4-3d). Strong cyclones east of NZ are dispersed along 40°S as far east as 165°W (much like autumn and winter).

Overall, several features can be described:

1. Most activity occurs in the western-central Tasman Sea in all seasons; however, the shape of maxima changes from being meriodinally-oriented in autumn to being stretched zonally in spring.
2. Cyclone activity north of 30°S (in the tropics) is restricted to summer and autumn months, and most likely represents a significant tropical cyclone component;
3. The most activity directly over NZ occurs in winter, and is highest over the North Island;
4. In all seasons, a frequency maximum consistently appears near 175°W, 40-42°S (north or northeast of the Chatham Islands);
5. East of NZ, cyclone activity is generally spread along 40°S between 180°E and 155°W.; and
6. Seasonal variations show slight movements in the Tasman Sea frequency maxima, such that most cyclones appear slightly further north and east in winter.

4.2.3.2 Formation, Intensification, Maturity and Decay Regions

The preferred formation regions are in the western Tasman Sea (or off the eastern Australian coast) and along 22-23°S between 170°E and 170°W in the tropics. Further maxima are apparent just north of NZ and in the Cook Strait area (Figure

4-4a). The pattern essentially shows the majority of cyclones tracking through the NZ area come from the north and west, and only a tiny fraction possibly comes from southern latitudes. The formation of cyclones near Eastern Australia has previously been linked to the warm East Australia current, strong sea-surface temperature gradients, and the subtropical upper-tropospheric jet (Sinclair, 1995). Sinclair (1994) states wintertime cyclone maxima are located approximately 10° south of the subtropical jet or associated with poleward shifts in its position.

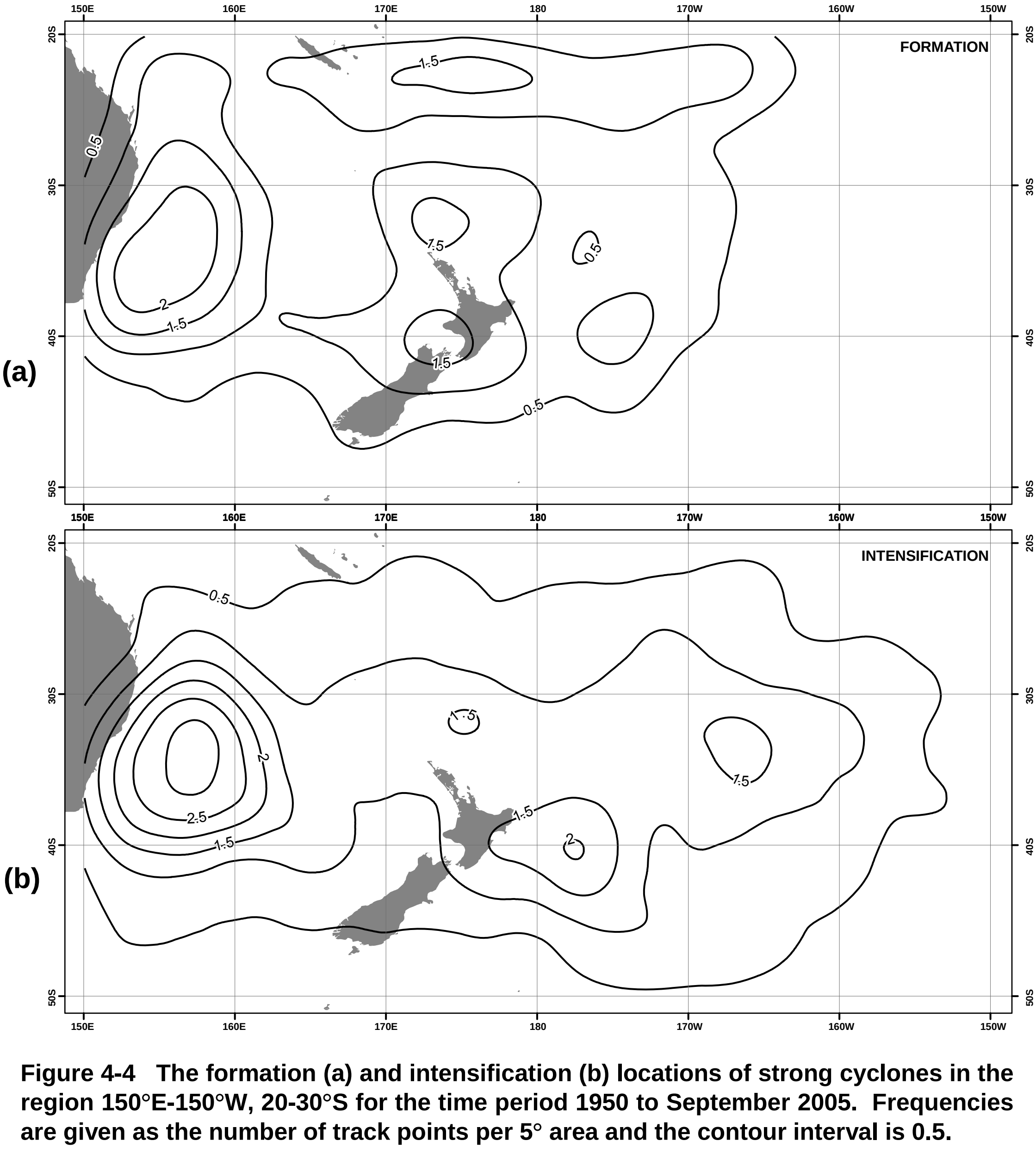


Figure 4-4 The formation (a) and intensification (b) locations of strong cyclones in the region 150°E-150°W, 20-30°S for the time period 1950 to September 2005. Frequencies are given as the number of track points per 5° area and the contour interval is 0.5.

The formation of cyclones near northern NZ could be linked to the Tasman front which represents a meandering zonal flow (or jet) that travels across the Tasman Sea from near Sydney towards northern NZ between 33° and 35°S (Ridgway & Dunn, 2003; Tilburg *et al.*, 2001). This thermal front sheds a large warm-core eddy near Norfolk Island and is also linked to the near-stationary and warm cored North Cape eddy (Ridgway & Dunn, 2003; Tilburg *et al*, 2001; Roemmich & Sutton, 1998; Denham & Crook, 1976). These warm anomalies drive convective activity and should lead to intensification of cyclones as the pass across them.

The most favoured location for intensifying cyclones appears in the western Tasman Sea. This indicates the western Tasman Sea is a region where a large portion of cyclones develop *and* intensify. Other maxima (>2) occur northeast of North Cape, over eastern North Island stretching eastward to 175°W, and near 165°W, 35°S (Figure 4-4b). The activity near North Cape coincides with the location of the North Cape eddy (Tilburg *et al*., 2001; Roemmich & Sutton, 1998) and supports the assumption that cyclones moving across warm anomalies near northern NZ leads to cyclone intensification. The maximum east of the North Island partially coincides with the location of the Wairarapa Eddy (Roemmich & Sutton, 1998), which is another quasi-stationary feature that presents warm anomalies. Thus, there is considerable activity immediately surrounding eastern NZ. Furthermore, while cyclone formation is high in the tropics, the same can not be said for intensification. Like cyclone genesis, intensification zones have been linked to positions of the subtropical jet and sea-surface temperature gradients (Sinclair, 1995, see Figure 6b).

The central Tasman Sea is the home to large numbers of cyclones that have reached maturity, or maximum development (Figure 4-5a). A broader centre is also visible spread along 40°S east of NZ. Decaying cyclones are seen occupying the regions slightly eastward of intensifying and maturing zones with maxima in the eastern Tasman Sea and east of NZ along and south of 40°S (Figure 4-5b).

Putting all this information together, the pattern shows the western and central Tasman Sea is a region where cyclones form, intensify and mature, and therefore, travel only short distances between these phases of development. The pattern also shows a large proportion of cyclones approaching NZ from the west are weakening.

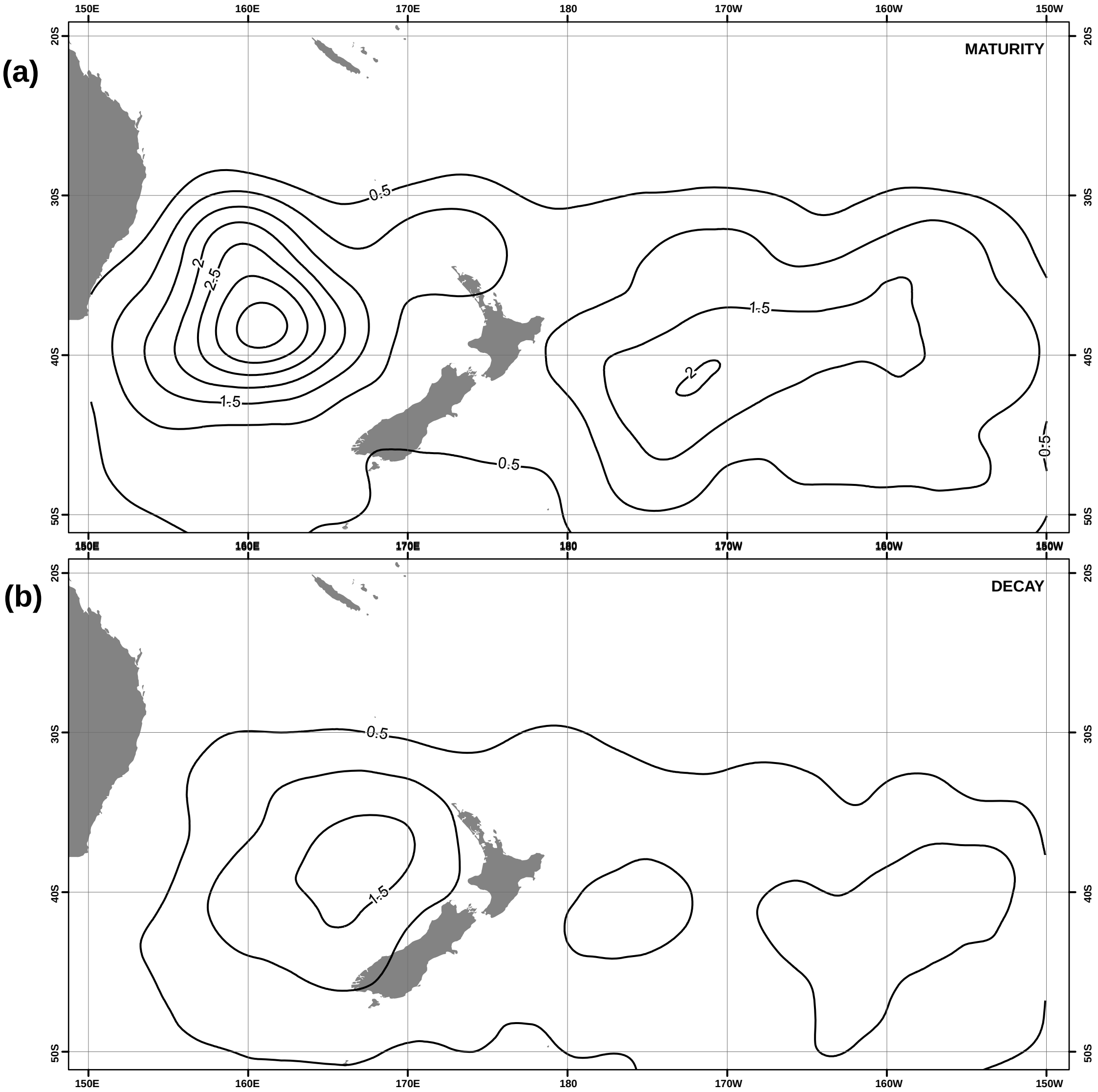


Figure 4-5 The maturity (a) and decay (b) locations of strong cyclones in the SW Pacific – NZ sector, for the time period 1950 to September 2005. Frequencies are number of track points per 5° area and the contour interval is 0.5.

Another sub-region showing a similar, though weaker, sequence is near 40°S, 175°W. Focussing on the area immediately around NZ, we see genesis and intensification centres north of the North Island, while over the NZ landmass itself the pattern shows genesis in the western Cook Strait and intensification over the eastern coast. Thus, although a proportion of eastward-travelling cyclones from near Australia are weakening as they approach NZ, this is slightly offset by generation and intensification of cyclones from immediately around NZ. That is, considerable cyclone activity occurs around NZ itself, as well as from those that travel into the region from the west and north.

An intriguing feature for the eastern coast of NZ is the absence of cyclone activity immediately to the south. This indicates very few cyclones impacting the region come from southern latitudes; that is, strong southern ocean low pressure systems very rarely reach NZ latitudes. This absence in cyclonic activity south of NZ between 45 and 55°S lies between the upper-tropospheric jets (i.e. between the subtropical and polar jetstreams) and is also seen in previous studies (e.g. Simmonds *et al.,* 2003; Simmonds & Keay, 2000; Sinclair, 1995). With no upper-level jet and associated upper-level divergence, the principal ingredients for cyclone formation and intensification are not available to drive significant cyclonic activity in this region.

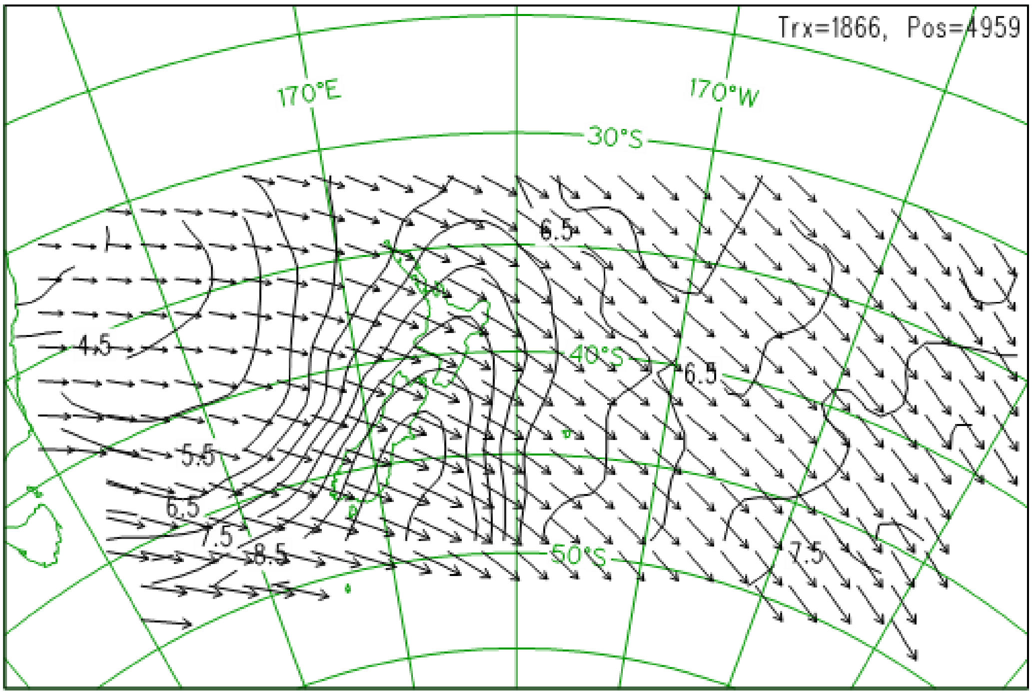


Figure 4-6 Spatial distribution of average cyclone motion vectors (in m.s^{-1}) for the region 150°E-150°W, 30-50°S between 1950 and September 2005 (kindly supplied by Dr Mark Sinclair, Meteorology Department, Embry-Riddle Aeronautical University, Arizona).

4.2.3.3 Cyclone Motion

Most cyclones follow ESE pathways in the Tasman Sea sector and then become more meridionally-oriented over and east of NZ to travel on southeast-ward paths. The fastest travelling cyclones are immediately off the eastern South Island where speeds of around 8.5-9 m.s^{-1} are apparent (Figure 4-6). The pattern also shows cyclones speed up west and east of NZ and then slow down east of the dateline. Furthermore, cyclones north of NZ travel slower (~6.5 m.s^{-1}) than those to the south (~ 8.5-9 m.s^{-1}). Eastern Australia is where the slowest (4.5 m.s^{-1}) cyclones occur, and therefore, it is no surprise that a frequency maximum is also found in this region (see Figure 4.2) since the use of system density involves high counts for slow-moving cyclones (i.e. more than one count per system). In accordance, the high speed of cyclones over the South Island counteracts the formation of a frequency maximum.

Looking specifically at the region directly off the eastern coast of NZ, defined as the area bounded by 35-47°S, 170°E-175°W, plots of the frequency distribution of individual track point speeds shows just over 60% have speeds between 5 and 12.5 m.s^{-1} (Figure 4-7) and a comparable number are moving towards the E, ESE and SE (80-140°) (Figure 4-8).

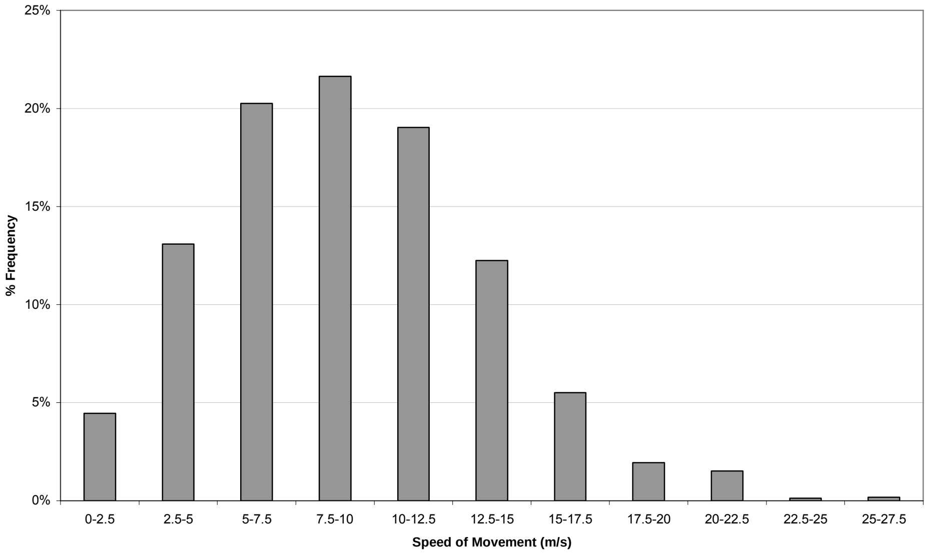


Figure 4-7 Frequency distribution of the speed of movement of individual track points of strong cyclones that pass into the region off eastern NZ, as defined by 35-47°S, 170°E-175°W.

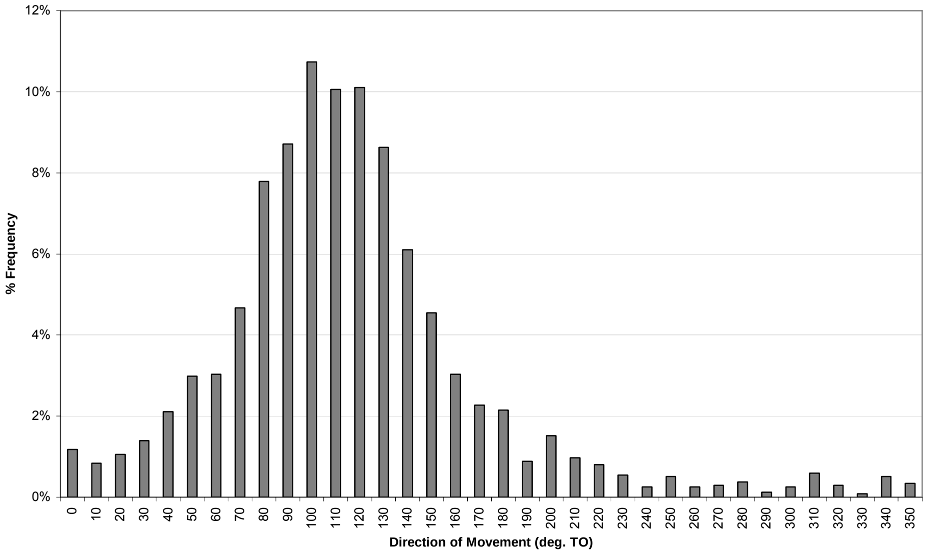


Figure 4-8 Frequency distribution of the direction of movement of all track points in the region off eastern NZ (35-47°S, 170°E-175°W)

An effort was made to separate cyclones into fast and slow-moving systems for the same domain. Within this domain, 907 cyclone tracks were identified and the mean speed of movement (and standard deviation) of all the individual track points was calculated. Fast-moving (slow-moving) cyclones were then defined as those cyclone tracks whose average speed in the defined region off eastern NZ were greater than (less than) one standard deviation from the mean. This resulted in 214 cyclones being classified as fast and only 43 cyclones as slow-moving (and the remaining as average). For these two samples, the frequency distributions of the direction of movement, central pressure and central vorticity were examined (Figure 4-9) and averages calculated.

Cyclone Property	Fast Cyclones	Slow Cyclones
Average Pressure (hPa)	997	1003
Average Vorticity (CVU)	4.1	3.6
Average Direction of Movement	109° (E)	147° (SE)
Average Number of Track Points	1.5	3

Table 4-2 Properties of fast and slow moving cyclones directly off eastern NZ (defined as the box bound by 35-47°S, 170°E-175°W).

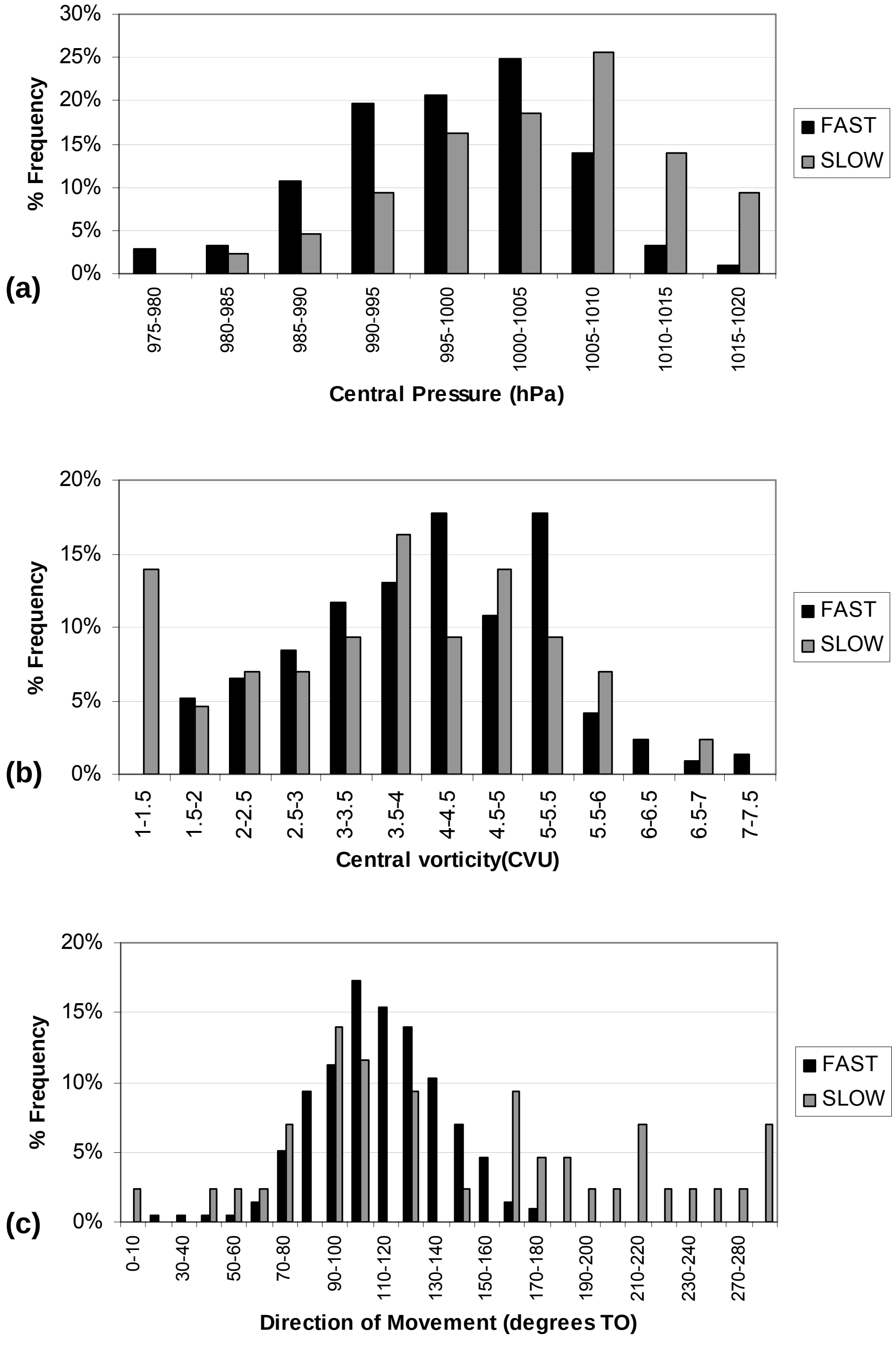


Figure 4-9 The distributions of (a) average pressure, (b) vorticity and (c) direction of movement of all fast- and slow-moving cyclones that track through the region off eastern NZ (35-47°S, 170°E-175°W). Vorticity units of CVU are x10^{-5}s^{-1}.

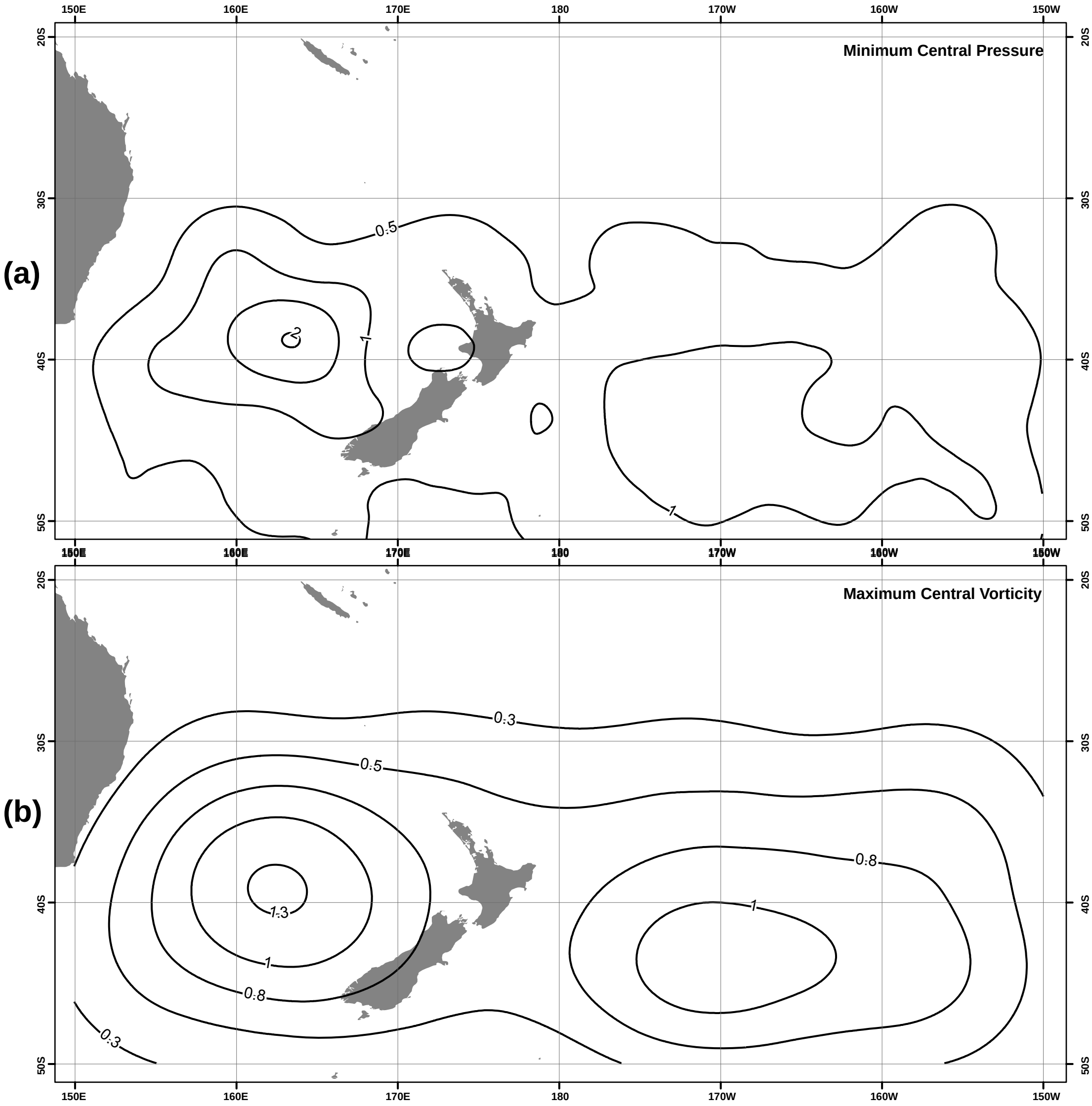


Figure 4-10 Distribution of cyclone intensity, being the points with (a) the lowest pressure values and (b) strongest central vorticity values (bottom) per storm track.

The results appear in Figure 4-2 and displays large differences in the average direction of movement, pressure, and vorticity of fast- versus slow-moving cyclones off eastern NZ. Unfortunately, a test for statistical significance could not be applied as the underlying assumption of normality was not satisfied (especially for slow-moving cyclones, see Figure 4-9). Regardless, fast-moving cyclones that travel past eastern NZ generally move eastward, have lower central pressures and stronger cyclonic circulations. Comparatively, slow-moving cyclones have higher central pressures, less cyclonic rotation, and paths containing a stronger southward component. Furthermore, Figure 4-9c shows slow-moving cyclones have a greater range of path trajectories, with a third having moved southward through to westward. A mechanism for slow-moving cyclones off eastern NZ is through the presence of an intense anticyclone east of NZ or a strong ridge over the South Island extending eastward, both acting to retard the eastward and/or southward movement of cyclones.

4.2.3.4 Intensity

The density plot of cyclone intensity, using pressure values, shows maximum activity in the central Tasman Sea near 40°S (Figure 4-10a). A weaker, enlarged centre is also seen between 40 and 50°S east of the dateline. Thus, approximately twice as many cyclones reach their maximum intensity, or strongest phase, west of NZ than eastward. Maximum vorticity shows the same general patterns (Figure 4-10b).

4.2.4 Frequency Statistics

4.2.4.1 SW Pacific Sector

The peak month for strong cyclones is August which experiences, on average, 4-5 per year. There is a clear maximum in the winter months of June-July-August (Figure 4-11) and this activity is reduced over the summer months. Across all the years (1950-2005), we can always expect at least one strong cyclone in May, June, July and August; that is, between 1950 and 2005, strong cyclones featured in all of these months. Several anomalous months, being either stormy (active) or quiescent (inactive), were identified from the monthly distributions. Stormy or active periods include February 2004 (8 strong events, against a mean of ~2), May 1956 (9 strong cyclones, mean of ~3), and June 2002 (12 strong cyclones, mean of ~4). Quiet periods, defined as those featuring significantly less strong cyclone numbers than the average, are seen in July 1950, August 1971/1972/1994, and June 1993 (Figure 4-11).

On a seasonal scale, the lowest number of strong cyclones occurs in summer, which experiences on average 6 events per year, though they can range from one to 15 in any one season. A peak of 15 strong cyclones occurred in summer 2003/04. Autumn frequencies range from 3 to 16 events with a mean of 8 per month (Figure

4-11). The autumn of 1996 was particularly stormy, having experienced twice the average number of strong cyclones. The peak season for strong cyclones is clearly in winter (Figure 4-11) when an average of 13 events per season is seen. However, wintertime frequencies can range up to as many as 22-23 cyclones as was seen in winter 1996 and 2002. Springtime frequencies are very similar to autumn with around 8 strong cyclones per year. In the spring of 2003, there was a maximum frequency of 15 strong cyclones, being almost double the annual mean value (Figure 4-11). Furthermore, the standard deviations for summer, autumn, and spring were all very similar (~3 events). Yearly variations range from a minimum of 24 strong events to a maximum of 60 in 1996. This maximum is the result of increased storminess in the autumn and winter seasons, which nearly doubled their respective annual means. The annual mean frequency is approximately 34 strong cyclones through this region (Figure 4-11).

4.2.4.2 Tasman Sea-NZ Sector vs. East of the Dateline

The lowest numbers of strong cyclones occur in the summer months (Dec-Jan-Feb) in both the Tasman Sea-NZ sector and east of the dateline. In these months, only one strong event occurs on average per year. Much like the entire SW Pacific domain, the peak in strong cyclone numbers both east and west of the dateline occurs in August when approximately 3-4 events traverse the region (Figure 4-12). The winter months (June-July-August) are by the far the most active. Furthermore, there is very little difference in annual monthly mean cyclone numbers east of the dateline in July and August (3.4 and 3.6, respectively). While no major differences can be seen between the two sub-regions,

Figure 4-12 suggests there is slightly more cyclonic activity east of the dateline in the winter months and early autumn (March-April) than in the Tasman Sea-NZ sector, and the reverse pattern occurs in late spring-early summer (slightly more activity in the Tasman Sea-NZ sector compared to east of the dateline). Interestingly, the month of May has the same annual monthly mean for both sub-regions. When viewing the monthly statistics across all the years (1950-2005), the following periods showed more strong cyclones east of the dateline than in the Tasman-Sea-NZ sector: March 1996, June 2002 and August 1951 (Figure 4-12).

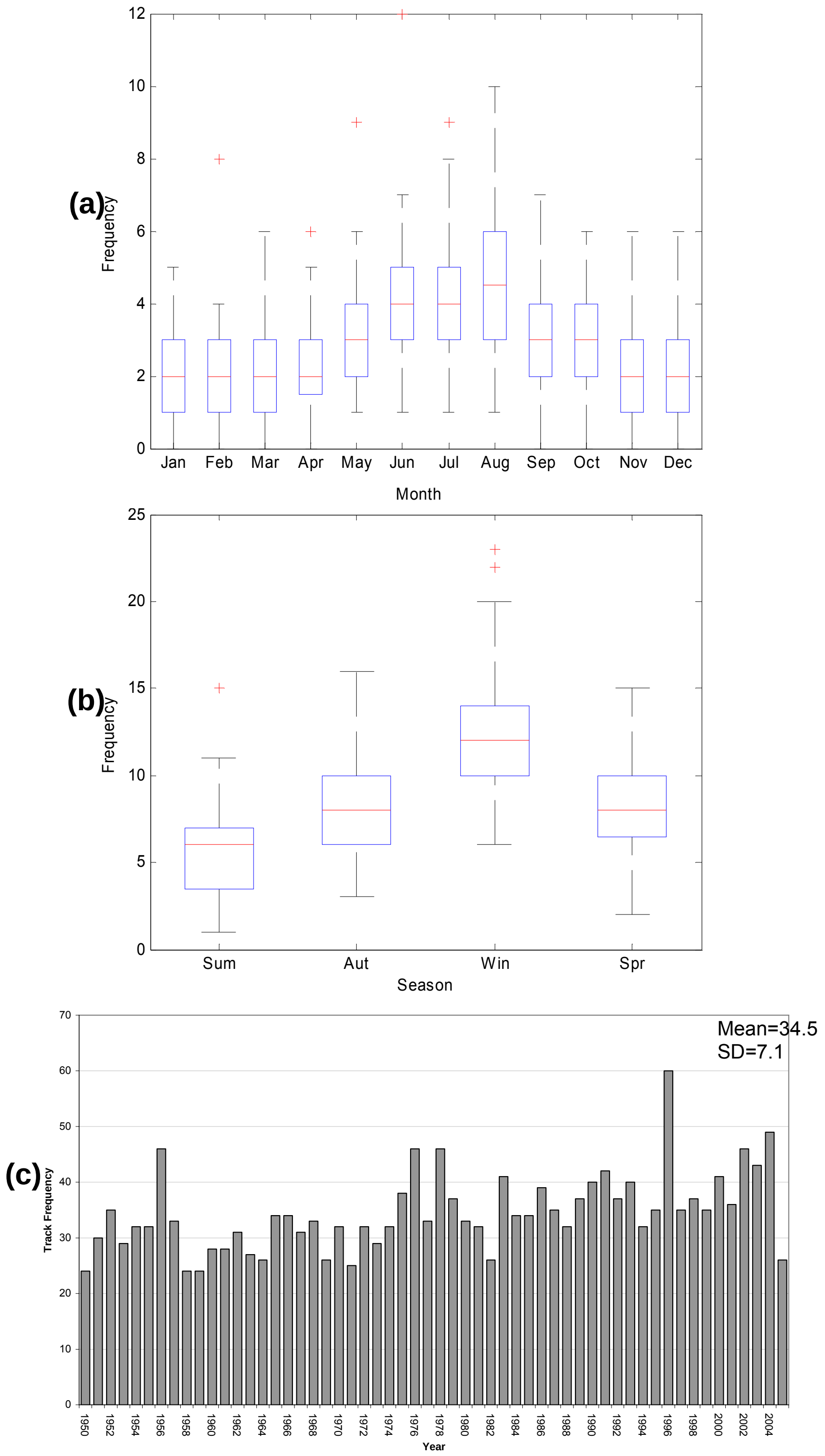


Figure 4-11 (a) Monthly and (b) seasonal mean strong cyclone frequencies in the SW Pacific (150°E-150°W, 30-50°S) for 1950 to September 2005. Annual variations (c) and their annual mean frequency (inset) are also included.

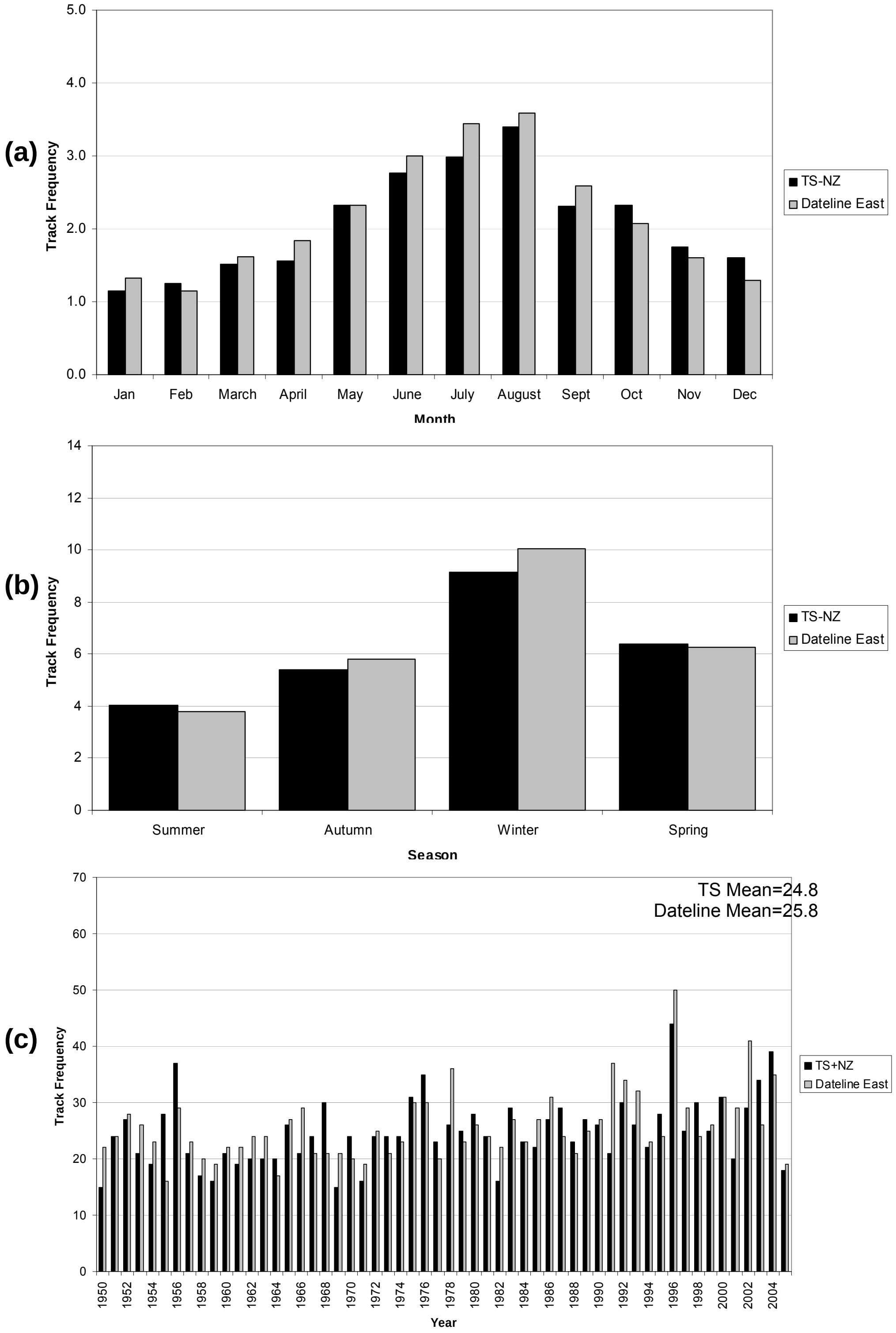


Figure 4-12 (a) Monthly and (b) seasonal mean cyclone frequencies in the Tasman Sea-NZ sector (150°E-180°E, 30-50°S) and east of the dateline (180°E-150°W, 30-50°S) for 1950 to September 2005. Annual variations (c) and their annual mean frequency (inset) are also included.

	Month												Season				YEAR
Direction	1	2	3	4	5	6	7	8	9	10	11	12	Summer	Autumn	Winter	Spring	
SW Pacific (150E - 150W)	1.9	1.8	2.3	2.4	3.2	3.9	4.1	4.6	3.2	2.8	2.2	2.0	5.7	8.0	12.6	8.2	**34.5**
Tasman Sea (150E - 180E)	1.1	1.3	1.5	1.6	2.3	2.8	3.0	3.4	2.3	2.3	1.7	1.6	4.0	5.4	9.1	6.3	**24.8**
Dateline East (180E - 150W)	1.3	1.1	1.6	1.8	2.3	3.0	3.4	3.6	2.6	2.0	1.6	1.3	3.7	5.8	10.0	6.2	**25.8**

Table 4-3 Summary statistics (average frequencies) of strong cyclone activity in the Southwest Pacific and smaller subregions of Tasman Sea-NZ sector and east of the dateline for 1950 to September 2005.

The seasonal frequency distribution was much the same as for the SW Pacific, with an abundance of strong cyclones in the winter season both east and west of the dateline. On average, there are similar numbers of 9 strong cyclones in the Tasman Sea-NZ sector and 10 east of the dateline in winter (Figure 4-12). There was more than double the average in winter 2002 east of the dateline when 22 strong cyclones influenced the sub-region (compared to only 14 in the Tasman Sea-NZ). The next most active season was spring, with an annual seasonal average of around 6 events in both the eastern and western sub-regions (Figure 4-12). A large anomaly between these sub-regions was identified in 2003 when there was high numbers in the Tasman Sea-NZ sector (~13) compared to eastern sector (~8). The autumnal annual mean is slightly less than in spring (just under 6 events) while the least active season was summer (~4 strong cyclones per season). Overall, there are no major differences between the eastern and western sub-regions for all the seasons or annual mean frequencies (25 and 26 strong events, respectively). The summary statistics or average monthly, seasonal and annual frequencies for the Southwest Pacific, Tasman Sea-NZ, and east of dateline regions are shown in Table 4-3.

4.2.4.3 Cyclone Intensity Distributions

The frequency distribution of lowest central pressure (per cyclone track) is presented in Figure 4-13. Approximately 30% of the cyclones had minimum central pressure values between 990 and 1000hPa, and a further 30% had values less than 980hPa. The general distribution shows an abundance of cyclones at the higher end of the spectrum between 980 and 1005 hPa. One cyclone from the entire record (1934 cyclone tracks) reached a lowest central pressure of 929hPa, but this excluded due its location being near Antarctica.

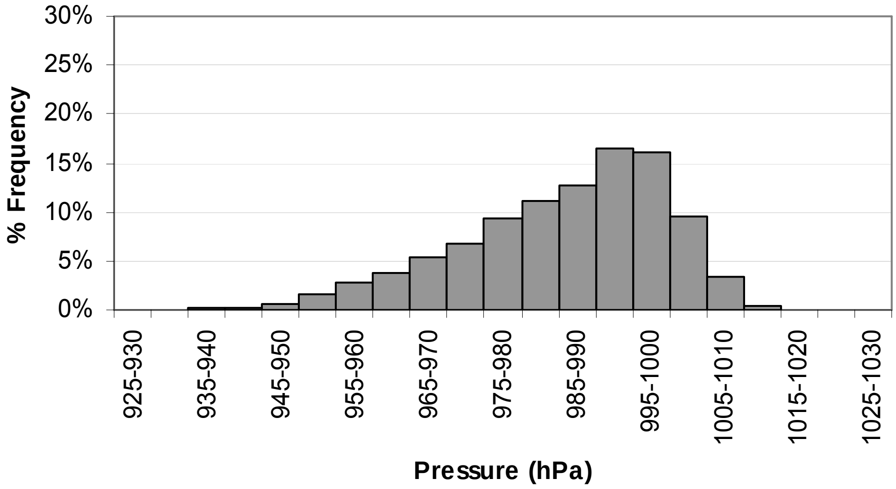


Figure 4-13 The frequency distribution of the lowest pressure values per cyclone track between 1950 and September 2005.

A similar analysis of pressure values at each stage of the cyclone lifecycle was performed. At the generation stage, just over 50% of the cyclones had central pressure values between 1005 and 1015 hPa and as expected, indicates cyclones are weakest at genesis (Figure 4-14a). However, the left tail of Figure 4.14a shows a small proportion of cyclones were relatively strong at the first track point and therefore shouldn’t be classified as ‘new’ systems. This factor is attributed to prematurely ending cyclone tracks (Sinclair, 1995) that are subsequently identified as a ‘new’ cyclone in the next (or same) analysis time step. At the point of intensification, the pressure distribution shifts to much lower pressure values with half of the points falling in the 970 to 980 hPa range (Figure 4-14b), and has a long left tail (i.e. higher proportion of cyclones with low pressures). Those cyclones that have reached maturity mostly range between 990 and 1005 hPa (Figure 4-14c) and show the largest fraction of cyclones with pressures below 980 hPa (~ 16%). This is as expected, since maturity defines the point of maximum development.

Decaying cyclones cluster mostly in the 995 to 1010 pressure range (Figure 4-14d). The highest central vorticity values, being another measure of cyclone intensity, revealed the same features (Figure 4-15). Furthermore, there are a few cyclones that appear below the $5x10^{-5}s^{-1}$ threshold at maturity. This results from some cyclones reaching their maximum intensity at a different phase of the cyclone life cycle (i.e. intensification).

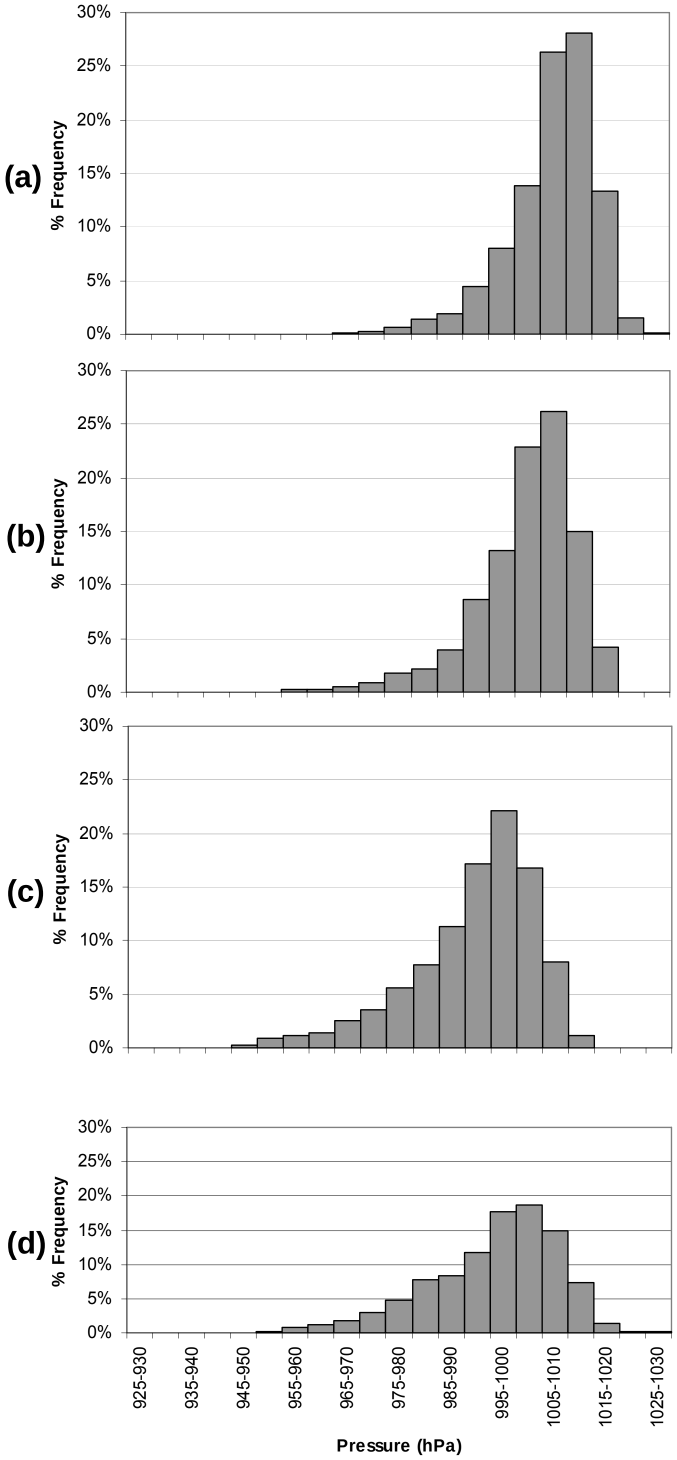


Figure 4-14 Frequency distributions of cyclone pressure at (a) generation, (b) intensification, (c) maturity, and (d) decay.

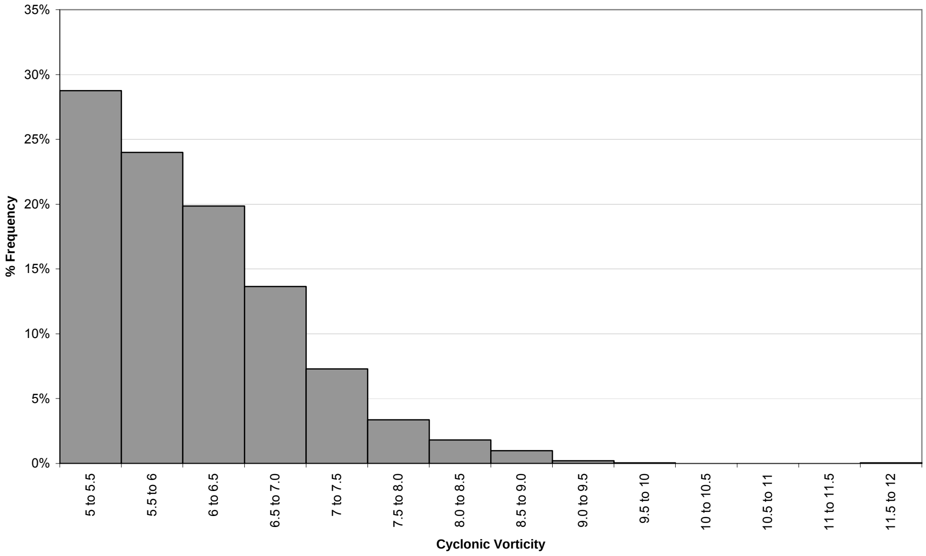


Figure 4-15 Frequency distribution of the highest central vorticity values per cyclone track between 1950 and September 2005. Cyclonic vorticity units are x $10^{-5}s^{-1}$.

4.2.5 Coastal Storms and Strong Cyclones

Frequency statistics show that around 24 (34) strong cyclones pass through the Tasman Sea – NZ (SW Pacific) region per year. It is of interest to know how many of these strong cyclones are linked to or is a cause of coastal storms on the eastern North Island. To quantify this link, the storm track data was searched for the dates of known coastal storms. If the dates of coastal storms (as identified in the coastal storm database) were found in the storm track dataset, the coordinates of the track were inspected for the day(s) of the event. A positive association between the cyclone track and coastal storm event was made if the coordinates of the track were between 35-50°S and westward of 175°W (i.e. the cyclone was immediately off eastern NZ). Furthermore, if the storm event was of the type Tasman Sea Low or Subtropical Low, the storm track was also accepted if the coordinates were eastward of 165°W and between 30-45°S.

The results of this basic analysis indicate, on average, that only 6-7 (~25%) of the 25 cyclone through the Tasman Sea-NZ region per year result in coastal storms on the east coast of the North Island. When the coastal storm events were partitioned into their respective storm types, between 65 and 70% of East Coast Lows, Tasman Sea

Lows, Subtropical Lows and Cyclone-Anticyclone Pair storms were linked to strong cyclones. Comparatively, the Trough/Ridge type had a much lower association (42%). Therefore, we are more likely to find a strong cyclone associated with the former coastal storm types than with the trough/ridge group. These results show that a large majority of coastal storms do not involve strong cyclonic weather systems.

4.2.6 Discussion

The behaviour of strong cyclones in the NZ region display several different characteristics to that of all southern hemisphere cyclones. They are:

1. A prominent wintertime frequency maximum occurs immediately off North Cape. This activity – though slightly weaker – also flows over into spring. This indicates strong cyclones frequently traverse northern NZ (or the upper North Island). These cyclones can be potential generators of coastal storm events.
2. Clear summertime frequency maxima are captured near New Caledonia and 170W (along 22-24S).
3. Peak cyclone activity in the SW Pacific occurs in the winter months, with August being the most preferred and showing an annual average of 4-5 strong cyclones per month per year.
4. Strong cyclones can be generated in the tropics along 22-24S directly north of NZ. This feature represents tropical cyclone activity, and indicates ex-tropical cyclones impacting NZ are essentially propagating from the Coral Sea area or north of New Zealand (i.e. Fiji area). This is consistent with the coastal storms identified from the instrumental record (Chapter 3), though the cyclone track data better defines the specific areas from which they originate. These formation regions likely arise from strong sea-surface temperature gradients and the presence of the monsoon trough and South Pacific convergence zone.
5. Strong cyclones are also generated off North Cape, and the formation region over Cook Strait is in a more northern location than that found in hemispheric studies (see Figure 2.6, Chapter 2).
6. These cyclones speed up on approaching and crossing NZ, and then slow down over the dateline. Furthermore, cyclones travel much faster off the

South Island compared to those near northern NZ, and faster-moving cyclones are usually stronger and have zonal paths.

The pattern of strong cyclones forming, intensifying, and decaying in the Tasman Sea, as seen in hemispheric studies for cyclones of all intensities, is also found here. However, whilst this indicates that a large majority of cyclones approaching NZ from the west (Tasman Sea) or northwest (subtropics) are weakened systems, local formation and intensification over and east of NZ partially offsets this. These local formation and intensification areas are located such that these cyclones will directly impact the eastern coast of the North Island, and therefore, influence (and generate) coastal storm activity.

Several features show excellent agreement with hemispheric studies (e.g. Sinclair, 1994; 1995; Simmonds & Keay, 2000). They include wintertime activity clustering in the 30-40S band (including peaks in the Tasman Sea and east of the dateline – see Chapter 2, Figures 2.2-2.5), the main formation zones in the Tasman Sea and tropics, and the general pattern of cyclones forming, intensifying and decaying across the Tasman Sea.

Hemispheric studies identified a high latitude circumpolar maximum in cyclone activity. It is very rare, however, for these cyclones to be directly responsible for coastal storms along the eastern North Island (i.e. to move far enough northward to directly impact eastern NZ). Instead, it is the troughs of these cyclones that have a large influence on coastal storm activity. Comparatively, strong cyclone activity in the tropical and subtropical regions north of NZ can travel directly towards NZ, and be a direct source of coastal storm activity should they travel near northern NZ (North Cape). Furthermore, the strongest coastal storms to affect the eastern North Island had subtropical origins. In this respect, it is very important to study cyclone behaviour north of NZ in terms of understanding coastal storm activity, even though activity here is relatively small compared to that at higher latitudes.

Annually, around 34 strong cyclones traverse the region surrounding NZ. Seasonally, winter is the most active with around 12 events per season, which doubles that of summer, while autumn and spring display similar activity (approximately 8 per season).

4.3 Extreme Winds over the Seas off Eastern NZ

4.3.1 Introduction

The distribution of prolonged strong or extreme winds near a coastal region can be used as an alternative proxy for exploring storm activity. As mentioned earlier, the presence of a single cyclonic system does not automatically guarantee a spell of strong winds. Extreme winds can also be associated with intense or intensifying anticyclones, frontal systems, or a combination of these features. Therefore, additional insight into coastal storm activity can be gained by examining extreme onshore wind events over the oceans adjacent to coastal areas and can be responsible for damaging waves that come from afar.

4.3.2 Data and Methodology

4.3.2.1 Data Source

A list of extreme onshore wind events with speeds greater than 20 m.s^{-1} for the region bound by 160°E-160°W and 30-50°S was provided by Dr M. Sinclair (personal communication, 2005). This dataset was produced using 1000hPa geopotential fields from the NCEP-NCAR reanalysis dataset (NCEP-1) for the period 1950 to 2005. See section 3.3.1.1 above (Cyclone Tracks Across NZ – 1950-2005, Data Source) for information on this dataset. The methodology of extracting and identifying extreme wind events was performed entirely by Dr Mark Sinclair following the method set down in Sinclair (1997), and is described in the next section (Dr M. Sinclair, personal communication, 2005).

4.3.2.2 Extreme Onshore Wind Event Identification

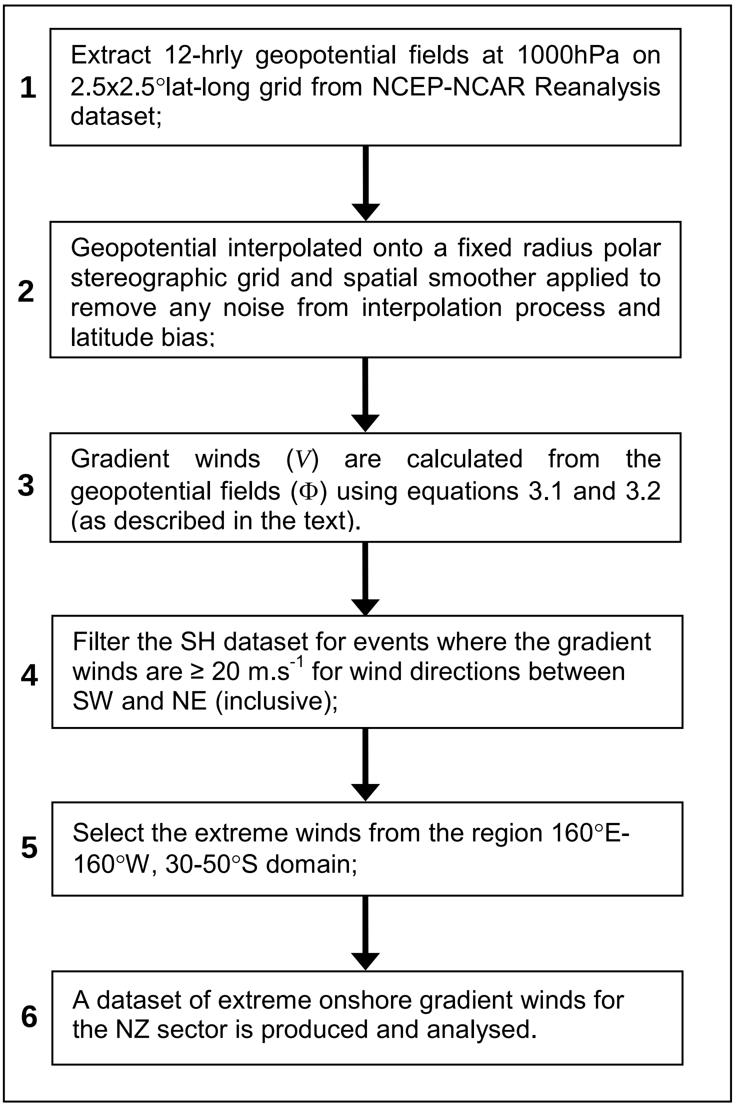
The gradient wind, V, is calculated directly from the 1000hPa geopotential fields on a 2.5x2.5°lat-long grid using:

$$fV_g = KV^2 + fV \qquad (3.1)$$

where f = Coriolis parameter, V_g is the geostropic wind, and K is the curvature of the parcel trajectory. K is approximated by the isobar curvature and computed as described in the Appendix of Sinclair (1997) as:

$$\frac{\partial^2\Phi/\partial x^2\left(\partial\Phi/\partial y\right)^2 - 2\left(\partial\Phi/\partial x\right)\left(\partial\Phi/\partial y\right)\partial^2\Phi/\partial x\partial y + \partial^2\Phi/\partial y^2\left(\partial\Phi/\partial x\right)^2}{\left[\left(\partial\Phi/\partial x\right)^2 + \left(\partial\Phi/\partial y\right)^2\right]^{3/2}} \tag{3.2}$$

where Φ is the geopotential, $\partial/\partial y$ is $\partial/a\,\partial\phi$ (ϕ, λ are latitude, longitude in radians, and a is the mean earth radius). Cyclonic curvature is negative in the Southern Hemisphere and has units of per meter. The solution process for equation (3.1) uses an iterative technique (Sinclair, 1997).



1 Extract 12-hrly geopotential fields at 1000hPa on 2.5x2.5°lat-long grid from NCEP-NCAR Reanalysis dataset;

2 Geopotential interpolated onto a fixed radius polar stereographic grid and spatial smoother applied to remove any noise from interpolation process and latitude bias;

3 Gradient winds (*V*) are calculated from the geopotential fields (Φ) using equations 3.1 and 3.2 (as described in the text).

4 Filter the SH dataset for events where the gradient winds are ≥ 20 m.s^{-1} for wind directions between SW and NE (inclusive);

5 Select the extreme winds from the region 160°E-160°W, 30-50°S domain;

6 A dataset of extreme onshore gradient winds for the NZ sector is produced and analysed.

Figure 4-16 The process for calculating and extracting extreme gradient winds for the greater NZ sector as performed by Dr Mark Sinclair (pers. comm. Dr Mark Sinclair, Embry-Riddle Aeronautical University, 2005).

The gradient wind is that which flows parallel to curved isobars above the atmospheric boundary layer (i.e. above the level of frictional effects) and represents the flow associated with a balanced of coriolis, centripetal and pressure gradient forces. Surface winds, as approximated from the gradient flow, are therefore affected by surface friction to show slightly reduced speeds (approximately 70% of gradient speed) and are rotated clockwise by approximately 30° on average (pers comm. Dr Mark Sinclair).

Extreme onshore winds, in the region bounded by 160°E to 170°W, 30-50°S (i.e. surrounding NZ), are defined as those events when the gradient wind direction is from NE through E to SW with speeds greater than or equal to $20 \mathrm{m.s}^{-1}$. The cut-off at 170°E was chosen to ensure the analysis focused on extreme onshore winds that affected eastern NZ. In addition, the inclusion of SW winds which do not blow directly onshore along eastern NZ, are based on the fact that large swell conditions are often felt along the east coast from extreme SW winds. All such events between 1950 and September 2005 were extracted, following the process as shown in Figure 4-16.

The extreme winds for the NZ sector were split into directional bins of:

- Southwest winds – between 210 and 250° (230°±20°)
- Southerly winds – between 160 and 200° (180°±20°)
- Southeast winds – between 110 and 150 (135°±20°)
- Easterly winds – between 70 and 110° (90°±20°)
- Northeast winds – between 25 and 65° (45°±20°)

The spatial distributions were calculated as kernel point densities using a 5° search radius with ArcGIS™ Spatial Analyst software. With the kernel technique, density is greatest at the point location and diminishes to zero with increasing distance from the point (i.e. weighted spatial averaging). This option produces a smoothly curved surface, and the units are points per unit of area i.e. number of points per 5° radius (McCoy & Johnston, 2001). The densities are then presented as contour plots.

4.3.2.3 Frequency of Extreme Onshore Wind Events

An attempt has been made to compute discrete or individual extreme wind events. To achieve this requires overcoming the following difficulties:

1. Defining the start and end date of wind events - every date stamp in the dataset has multiple readings that are closely-spaced or span distances of up to 10° latitude or longitude. It is highly likely that these individual points collectively represent a discrete wind event (i.e. one wind event).
2. Isolating discrete wind events - basing them purely on latitude or longitude thresholds is deficient in that the weather systems producing the winds are moving (and hence the latitude and longitude values will move). For example, for an extreme wind event from the south, the winds will span several degrees of latitude, while an easterly wind spans several degrees of longitude.

Taking all this in to mind, an alternate process has been designed to isolate discrete wind events. It contains several assumptions and is as follows:

1. Two spatial domains are defined – the eastern North Island (175°E-175°W, 35-42.5°S) and eastern South Island (170-180°E, 42.5-50°S) – to quantify frequencies and isolate any differences in frequencies between North and South Island;
2. All the extreme wind events in these two spatial domains are extracted from the main dataset (winds ≥ 20 m.s^{-1} from SW through E to NE);
3. It is assumed that each time (date) stamp represents an individual wind event, *unless* the next time step has the same date, or is the next consecutive date stamp; in this case, the date stamps are combined (grouped) together as one continuous wind event. Major swings in wind direction were checked for my assessing the standard deviation within wind events (occurred less than 1% of time). Table 4-4 below describes this process, and the $*$ symbol signifies a discrete wind event;
4. Groups of dates that belong to a continuous sequence were isolated (see shaded data in Table 4-4). From each group the average wind direction and speed are calculated, and these values are tagged to the first date at the beginning of the sequence;

5. Steps 1 to 4 are repeated for the complete time series of extreme wind events from 1 January 1950 to mid-September 2005;
6. The first date, or time stamp (∗), of the identified groups are retrieved and they are labelled as discrete wind events;
7. The discrete wind events are then partitioned into directional bins of southwesterlies, southerlies, southeasterlies, easterlies and northeasterlies, based on the average wind direction;
8. Monthly and annual totals are computed for each wind direction.

		Date Stamp	Wind Dir	Speed	Ave Dir	Ave Speed
Event 1	∗	24-May-1995	210	21	216	21.7
		24-May-1995	210	21		
		24-May-1995	220	23		
		24-May-1995	220	25		
		24-May-1995	230	21		
		25-May-1995	220	20		
		25-May-1995	210	20		
		25-May-1995	210	24		
		25-May-1995	210	21		
		26-May-1995	220	21		
		26-May-1995	220	22		
Event 2	∗	31-May-1995	90	25	87	25
		31-May-1995	80	25		
		31-May-1995	90	25		
		…				

Table 4-4 Example of the process for isolating individual or discrete extreme wind events from a sequence of date stamps. A discrete event is symbolized by ∗.

4.3.2.4 Meteorological Situations - Cluster Analysis

Using the start dates of extreme wind events, a cluster analysis is performed to search for commonly-occurring weather patterns responsible for generating extreme winds. The NCEP-NCAR dataset comprising 00Z-hour analyses between 1958 and 2005 is the primary data source and the specified area extends from latitudes 20° to 60°S and longitudes 140°E to 160°W. The clustering technique is based on that of Kidson (1997, 2000) and is based on the k-means procedure that starts with a set of randomly-generated seeds, each of which represents the initial clusters. Every initial state is then assigned to the cluster that it best matches. Pattern matching is based on the minimisation of the roots-mean-squared (RMS) distance between the input data points and the initial seed cluster. At each step, the two clusters with the highest pattern correlation are merged and an iterative procedure continues to assign the states into the most compact clusters (Kidson, 2000).

The choice of number of clusters to retain is determined by comparing the patterns obtained from a number of runs with different seeds (or cluster values). As the number of clusters is reduced, the patterns eventually converge to a set of stable patterns or clusters (Kidson, 1997, 2000). For the dataset used here, the input data consists of sea level pressure values at 2.5° spatial resolution that pertain to the dates of the extreme wind events. Five consecutive runs with an initial 50 seed clusters were generated and only the top eight clusters returned and analysed. The final number of clusters retained was that for which identical patterns were identified across all five runs.

4.3.3 Results

4.3.3.1 Spatial Distribution

The spatial patterns for the five directional bins (SW, S, SE, E and NE) are presented in Figure 4-17. For winds from the SW direction, a single high density maximum is visible just north of 50°S near 177°W (i.e. southeast of Christchurch). These winds are, by far, the most frequent in the oceanic area surrounding NZ (Figure 4-17a). Although the highest densities at the centre of this maximum are unlikely to directly influence NZ due to the orientation of the wind, we also see a considerable proportion (approximately one third) immediately off the eastern South Island of NZ. Thus, extreme southwesterly gradient winds are indeed a common occurrence east of southern NZ. This maximum is most likely generated by the eastward passage of deep southern ocean cyclones (or troughs) south of NZ.

The main centre of activity for extreme southerly winds (Figure 4-17b) lies over the international dateline (180°) near 45°S. This is slightly west and north of the maximum seen for extreme southwesterly winds. This maximum contains significantly less southerly events (approximately one quarter) compared to southwesterly winds. These winds, however, through the orientation of the wind, will have a greater impact on eastern NZ. This pattern also shows a local source of southerly storm events and local generator of extreme oceanographic conditions along the eastern NZ coastline. This high-latitude maximum is most likely generated by southern ocean cyclone's and troughs while the northward expansion over the North Island suggests extreme southerly winds are also associated with Tasman Sea and subtropical lows (i.e. cyclonic activity north of 40°S). Furthermore, large intense anticyclones in the south Tasman Sea that collide with cyclones or troughs east of NZ could also generate strong southerly wind flows over NZ.

Extreme southeasterly winds show maximum activity east of the dateline between 30-40°S (Figure 4-17c). A small centre is also visible east of Christchurch, and represents an area of extremely strong winds immediately east of NZ. Furthermore, the pattern shows signatures of subtropical southeasterlies to the east and north of NZ, and higher mid-latitude activity near southern NZ. That is, southeasterlies may be generated by southward or southeast-ward propagating low pressure systems from lower latitudes, and from westward moving low pressure centres (or secondary lows) from Tasman Sea.

Extreme easterly winds show two maxima in subtropical latitudes (Figure 4-18a). One centre appears north of East Cape, and could indicate a local source of strong easterly winds capable of generating stormy conditions for the upper North Island of NZ. A distant high-density centre is also visible further eastward near 165°W, 36°S. This feature will be a distant source of easterly swells (waves) for the eastern North Island, and is incapable of producing bad weather over NZ. That is, this zone is recognized as a distant wave generator for the eastern coastline, but the associated extreme winds and rainfall properties will not be felt near NZ. These easterly winds are confined mostly to latitudes north of 40°S and suggests subtropical generation mechanisms (e.g. subtropical lows and Tasman Sea cyclones). Anticyclonic easterlies are another possible cause, whereby large anticyclones over or south of the South Island or east of the dateline near 45°S have strong easterly winds on their northern sides. The presence of a subtropical low north of anticyclones can further intensify the flow. Furthermore, the maximum near 165°W could be forced by the same weather systems that generate strong easterlies north of NZ, but a few days later after propagating eastward (and colliding with anticyclones).

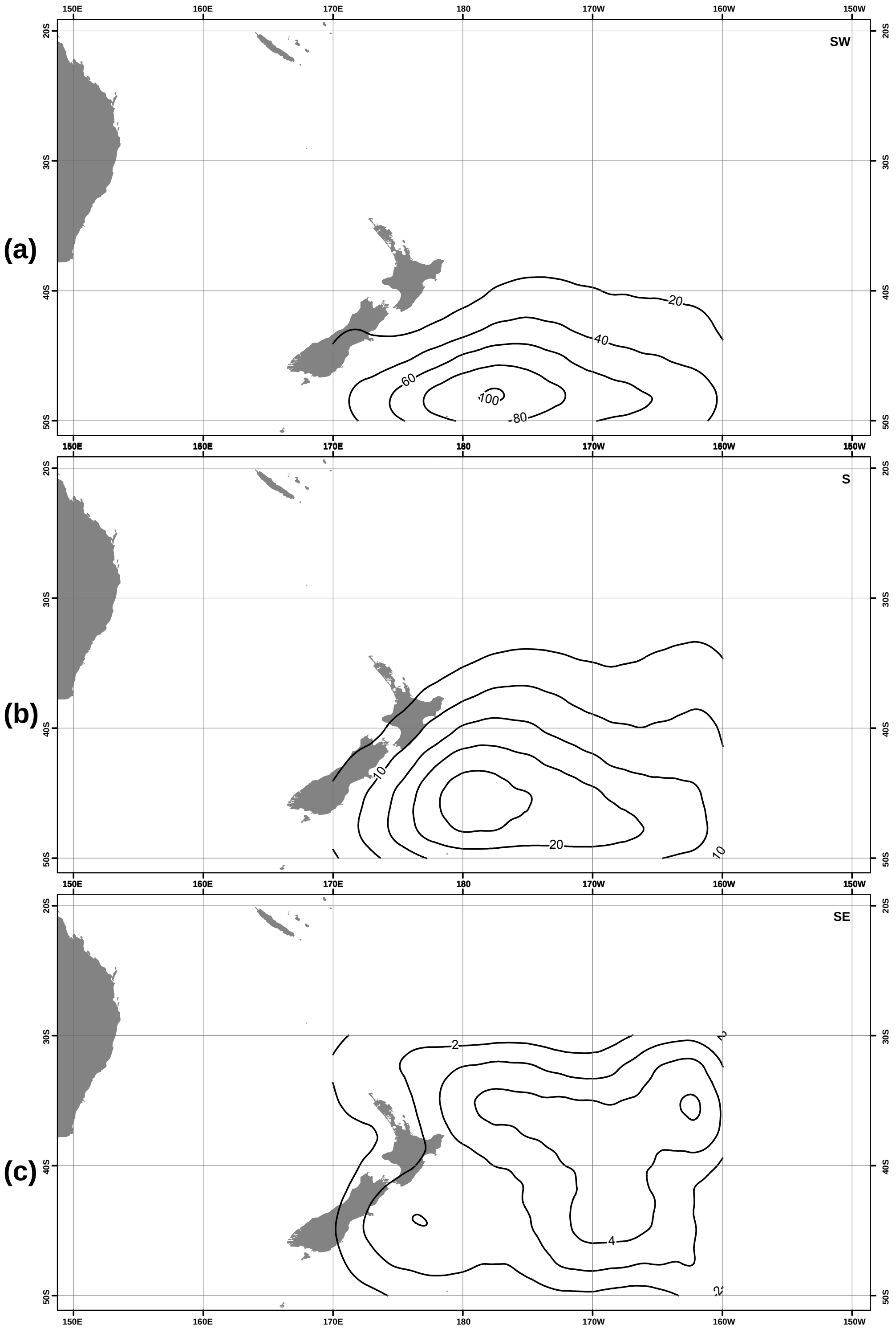


Figure 4-17 Spatial distribution of extreme gradient winds around NZ from the (a) southwest, (b) south and (c) southeast. Frequencies are given as the number per 5° area and the contour intervals are (a) 20, (b) 5, and (c) 1.

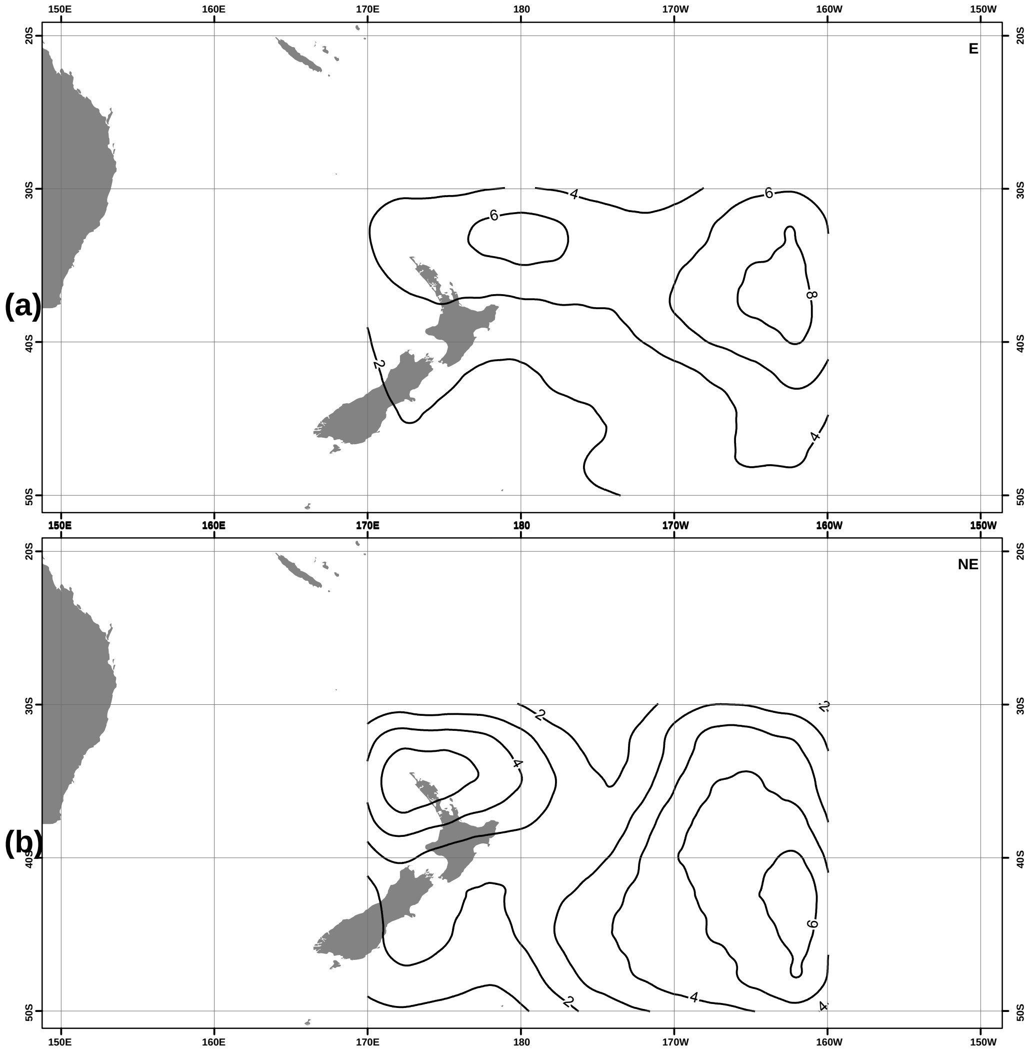


Figure 4-18 Spatial distribution of extreme gradient winds around NZ from the (a) east and (b) northeast. Frequencies are given as the number per 5° area and the contour intervals are (a) 2 and (b) 1.

Two prominent maxima in extreme northeasterly winds are identified, with one covering the North Island of NZ (Figure 4-18b). This feature is interpreted as a ‘local’ source of stormy northeasterly conditions that directly impact on NZ in the form of large waves, heightened sea levels at the coast, clouds, rain and gusty winds. A large, elongated maximum also appears between 160-170°W east of NZ. This area will have little influence on eastern NZ due to the orientation of the winds. The distinct separation of these centres suggests two unrelated forcing mechanisms. Examination of the weather charts found this to indeed be the case. Strong northeast winds over northern NZ were overwhelmingly associated with Tasman Sea or subtropical low pressure systems off North Cape and often in combination with a large anticyclone or ridge over or east of the South Island. The maximum near 165°W was often generated from the western side of anticyclones that were east of 160°W and had cyclones on their northwestern edges. Therefore, the dearth of extreme northeasterly winds near 175°W between the two maximum relates to the preferred location of cyclonic centres.

Across all wind directions, the most frequent extreme winds across NZ are from the southwest. The winds from the southerly quadrant, particularly southwesterlies and southerlies, show maxima in the southern ocean (i.e. at higher latitudes). Extreme southeasterly winds, however, show considerable activity on either side of 40°S east of NZ. In contrast, winds with a large easterly component (east and northeast winds) cluster strongly in subtropical latitudes (i.e. north of 40°S) over or just north of NZ. Between 160-170°W, eastward from NZ, extreme southeast, east and northeast winds are always more frequent than those near or over NZ. These centres, however, represent distant winds beyond the limit of NZ, and their main influences will be swell waves along eastern NZ, rather than large coastal storm events. Thus, prominent maxima near NZ, representing local sources of extreme winds, have been found for all onshore wind types examined. Southwest, south, and southeasterly conditions are mostly confined to regions near or south of 45°S, whereas east and northeasterlies winds cluster near 35°S.

It was thought prudent to compare the locations of these extreme wind maxima with those of strong cyclone activity. The most pronounced match is between extreme northeast winds over the North Island and a corresponding maximum in wintertime cyclone frequency. The other NE wind maxima between 160-170°W, however, does not have a similar counterpart in winter cyclone densities, and instead could be linked to the eastward movement of cyclones from the northern NZ cyclone maximum. Instead, strong cyclones are found further westward between 180°E and 170°W, although weak activity does spread as far as 160°W (see Figure 4-2). Extreme southeast and east winds between 160 and 170°W show most activity downstream (i.e. south and east) of a maximum in cyclone intensification zones.

This combination of extreme winds and strong cyclone densities indicates the cyclone frequency maximum between 180°E and 170°W is not always accompanied by extreme winds, whereas those cyclones that track further eastward consistently generate extreme winds (> 20 $m.s^{-1}$). Alternately, the strong winds from the easterly quarter (southeast, east and northeast) are generated from the northern and western sides of high pressure systems or blocking highs in this zone (most likely in conjunction with a lower latitude low pressure system). Furthermore, it may be the case that while fewer cyclones occur through the 160-170°W sector, they may be of greater intensity and capable of generating extreme winds. Therefore, it is not simply the number of cyclones but rather their intensity that is important for strong winds.

4.3.3.2 Frequency Statistics

Monthly, seasonal and annual frequencies are summarised in Table 4-5. Across all months (excluding January), the highest counts of extreme onshore winds off the eastern North Island are from the southwest. Peak SW activity occurs in June, and similar frequencies are found in late autumn and late winter. In January, however, extreme onshore winds switch from the SW to southerly and easterly (Figure 4-19a). There is a large increase in the number of events from March to April in extreme SW winds off the North Island, whereas a gradual decline occurs in spring months. That is, Figure 4-19 exhibits a sharp rise in the number of extreme southwest events in autumn, unlike springtime where a gradual decline in events occurs. Furthermore, there is a definite summertime minimum in extreme southwest winds.

Southerlies are the next most dominant type of extreme onshore winds. They are most prevalent between May and September with a clear peak in May–June. Southeast, east, and northeast wind events are uncommon over the 20 $m.s^{-1}$ threshold off the North Island. However, southeasterlies have tended to occur mostly from May to July, easterlies in January, March and July and northeasterlies in July-August. In addition, southeast and easterly events mostly cluster in the first half of the year (January through July). Figure 4-19 also shows December-January-February as the calmest months, in the sense of extreme winds.

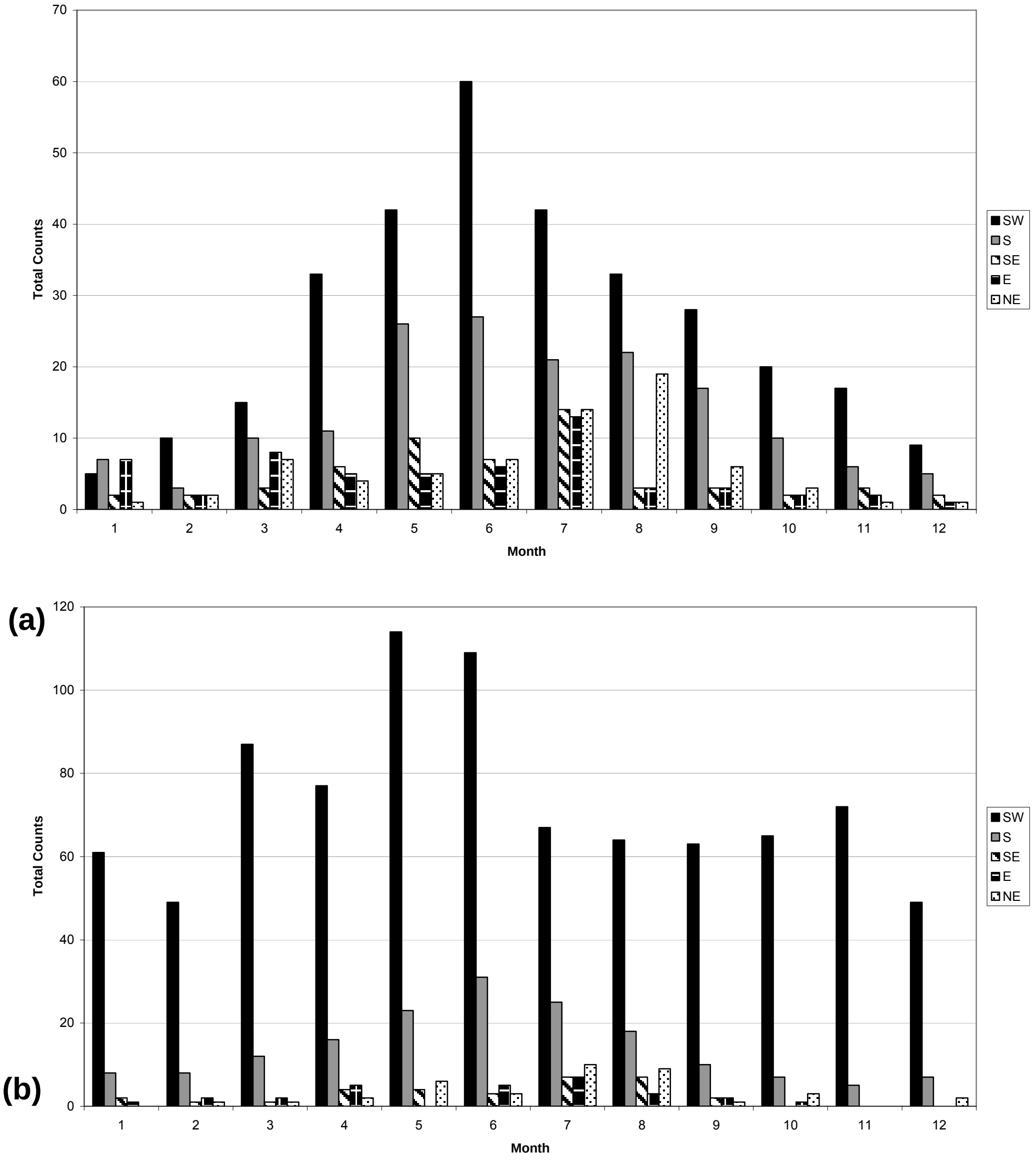


Figure 4-19 Total monthly frequencies of extreme winds per month for the (A) eastern North Island and (B) eastern South Island.

Off the South Island of NZ, extreme southwest winds are common for all months (Figure 4-19b). In general, there will be 5 to 20 times more wind events from the southwest compared to any other wind type. However, the spatial distributions imply that a large majority of these events will not directly impact eastern NZ due to the orientation of the wind. Interestingly, there are more extreme southwesterly winds in late autumn (March, April) than in late winter (July, August) (Figure 4-19b). Additionally, peak activity occurs in May and June, and the minimum in December and February (summer). Extreme winds from the south are the next most frequent wind type with peak activity in June (Figure 4-19). Extreme winds from the easterly quadrant are exceptionally rare from September through to March. The highest numbers are most likely to occur in July and August for southeast, east and northeast winds. These extreme events are least likely to occur in November and December.

		Month												Season				YEAR
Spatial Domain	Direction	1	2	3	4	5	6	7	8	9	10	11	12	Summer	Autumn	Winter	Spring	
Eastern NI	SW	0.1	0.2	0.3	0.6	0.8	1.1	0.8	0.6	0.5	0.4	0.3	0.2	0.4	1.6	2.4	1.2	**5.6**
	S	0.1	0.1	0.2	0.2	0.5	0.5	0.4	0.4	0.3	0.2	0.1	0.1	0.3	0.8	1.3	0.6	**2.9**
	SE	-	-	0.1	0.1	0.2	0.1	0.3	0.1	0.1	-	0.1	-	0.1	0.3	0.4	0.1	**1.0**
	E	0.1	-	0.1	0.1	0.1	0.1	0.2	0.1	0.1	-	-	-	0.2	0.3	0.4	0.1	**1.0**
	NE	-	-	0.1	0.1	0.1	0.1	0.3	0.3	0.1	0.1	-	-	0.1	0.3	0.7	0.2	**1.3**
Eastern NI Total		**0.4**	**0.3**	**0.8**	**1.1**	**1.6**	**1.9**	**1.9**	**1.4**	**1.0**	**0.7**	**0.5**	**0.3**	**1.1**	**3.4**	**5.2**	**2.2**	**11.8**
Eastern SI	SW	1.1	0.9	1.6	1.4	2.0	1.9	1.2	1.1	1.1	1.2	1.3	0.9	2.8	5.0	4.3	3.6	**15.7**
	S	0.1	0.1	0.2	0.3	0.4	0.6	0.4	0.3	0.2	0.1	0.1	0.1	0.4	0.9	1.3	0.4	**3.0**
	SE	-	-	-	0.1	0.1	0.1	0.1	0.1	-	-	-	-	0.1	0.2	0.3	-	**0.6**
	E	-	-	-	0.1	-	0.1	0.1	0.1	-	-	-	-	0.1	0.1	0.3	0.1	**0.5**
	NE	-	-	-	-	0.1	0.1	0.2	0.2	-	0.1	-	-	0.1	0.2	0.4	0.1	**0.7**
Eastern SI Total		**1.3**	**1.1**	**1.8**	**1.9**	**2.6**	**2.7**	**2.1**	**1.8**	**1.4**	**1.4**	**1.4**	**1.0**	**3.4**	**6.3**	**6.6**	**4.1**	**20.4**
Entire Area	SW	1.4	1.5	2.1	1.9	2.4	2.3	1.7	1.5	1.7	1.8	1.8	1.2	4.1	6.4	5.5	5.2	**21.2**
	S	0.4	0.3	0.5	0.6	0.8	0.8	0.8	0.6	0.5	0.2	0.3	0.3	1.0	1.9	2.3	1.0	**6.1**
	SE	0.2	0.2	0.2	0.3	0.5	0.3	0.4	0.3	0.2	0.2	0.1	0.1	0.5	1.0	1.0	0.5	**3.0**
	E	0.2	0.2	0.4	0.3	0.2	0.3	0.5	0.5	0.2	0.1	-	0.1	0.6	0.9	1.4	0.4	**3.2**
	NE	0.1	0.2	0.3	0.2	0.2	0.2	0.3	0.6	0.3	0.2	0.1	0.2	0.5	0.6	1.1	0.6	**2.8**
Entire Area Total		**2.3**	**2.4**	**3.5**	**3.1**	**4.2**	**3.9**	**3.7**	**3.6**	**2.8**	**2.5**	**2.3**	**1.9**	**6.6**	**10.8**	**11.2**	**7.6**	**36.2**

Table 4-5 Average frequency statistics of all extreme wind events for the entire spatial domain off eastern NZ (30-50°S, 170°E-160°W), Eastern North Island (35-42.5°S, 175°E-175°W) and the eastern South Island (42.5-50°S, 170°E-180°E) per month, season and year.

The eastern North Island experience around five to six extreme wind events from the southwest per year between 1950 and 2005 (Figure 4-19, Table 4-5). Southerly events have a slightly lower frequency of around 3 per year while those from the easterly quadrant number just one event per year. Off the South Island of NZ, there are around 15 extreme southwesterly events per year, outnumbering those of southerly events (3) and easterly quarter winds (<1).

When comparing the North and South Islands (Figure 4-20), we see little difference in the annual frequencies of extreme southerly winds and a slightly higher incidence of extreme winds from the easterly quadrant off the North Island. These features suggest a large majority of extreme southerly winds influence both islands at the same time, and could indeed be the same events. Furthermore, the processes or mechanisms driving these extreme winds could be such that the winds influence both the North and South Island, and this is consistent with the orientation of the winds. The same cannot be said for southwesterly winds. Instead, the higher count off the South Island most likely results from capturing a large number of extreme winds associated with deep low pressure systems propagating eastward well south and east of NZ that sweep only the southern limits of NZ. The spatial distribution of extreme southwesterly winds indicates this scenario is indeed the case, and therefore, a large majority of southwesterly events could be discarded since they are incapable of significantly impacting eastern NZ.

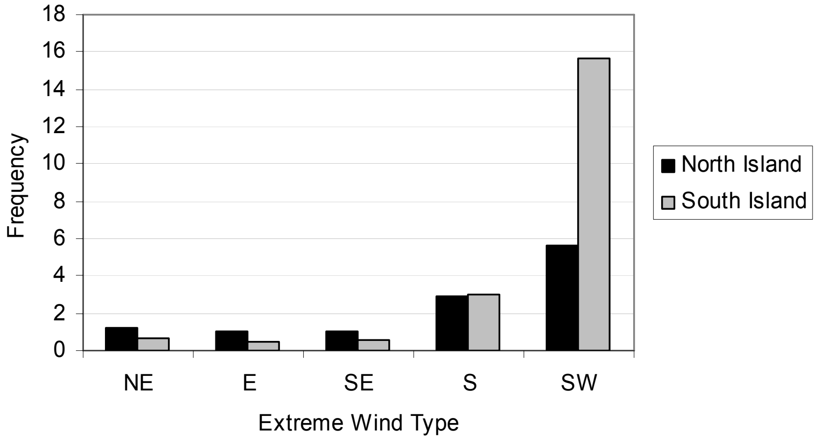


Figure 4-20 Annual mean frequencies of extreme wind types for the eastern North and South Islands of NZ for the period 1950 to September 2005.

In addition, these winds fail to reach the North Island, partly due to the orientation of the winds and because of the rapid mobility of low pressure systems south of NZ (see cyclone motion, Figure 4.6). An interesting feature also seen in Figure 4-20, pertaining only to southerly winds, is a tendency for more events in autumn off the South Island compared to the North Island, and a reverse situation in spring (more off the North Island). That is, southerlies are most prevalent from mid-autumn to winter in the South Island and most likely in late autumn, winter and early spring off the North Island.

For winds from the easterly quadrant, the spatial distribution indicates the weather systems producing the extreme winds have tropical or subtropical origins, and therefore, have a higher potential of striking the North Island than the South Island (particularly in summer). Furthermore, the paths of these weather systems are such that they propagate on southeast or east-southeast paths east of NZ rather than southward (see Figure 4-6), and hence are less likely to reach the South Island.

4.3.3.3 Associated Meteorological Situations

The average cluster patterns for all extreme wind types are shown in Figure 4-21. Generally, sets of 2 to 4 clusters returned stable weather patterns. Four clusters were found for extreme SW winds with each showing varying positions of southern ocean troughs and varying strengths of a ridge of high pressure over or north of the North Island. The strong SW winds are always associated with the western sector of the trough, and are seen in clusters 1 through to 4 southeast-ward or over the Chatham Islands or south of NZ. In addition, the consistent location near or southeast of the Chatham Islands correlates with the frequency maxima of Figure 4-17. Furthermore, cluster 3 shows the extreme winds are closest to NZ when the southern low reaches 60°S (i.e. southern ocean is in most northern position).

Three stable patterns were found associated with extreme southerly winds and are very similar to that of SW winds. They are generated by southern ocean troughs over NZ or the Chatham Islands that have south to south-southwest airstreams on their western flanks (see cluster one and two, Figure 4.20) and large Tasman Sea anticyclones with no ridges. These patterns indicate more southerly flows affect NZ when the Tasman Sea anticyclone contains no ridges. Consequently, the area of strong southerly winds is over southern NZ and the area immediately eastward being consistent with the maximum in Figure 4-17. Cluster three shows the weakest airflow west of the Chatham Islands (Figure 4-21). Two stable patterns were returned for extreme southeast winds and are shown to be generated from a ridge of high pressure over the South Island extending from the Tasman Sea or from a subtropical trough of low pressure east of NZ combining with an anticyclone south of the Chatham Islands (Figure 4-21). Thus, cluster 1 displays SE winds over NZ while cluster two shows SE winds over and east of the Chatham Islands.

Extreme easterly winds were related to three dominant clusters. Two patterns (cluster 1 and 3) display easterly flows east and north of the North Island from the northern sectors of anticyclones that occupy the NZ and Chatham Islands region. The regions showing easterly flows are consistent with the maximum in extreme easterly winds in Figure 4-18. The other cluster shows easterly winds being generated by a cyclone east of the North Island and an associated ridge in the southern ocean. Stable and identical cluster patterns for extreme winds were not found across all five runs from a set of eight clusters down to two clusters. The spatial distribution of extreme northeast winds (Figure 4-18) suggests two separate generation mechanisms are involved given that the two prominent maximum (one north of NZ and the other near 165°W) are spatially distinct and appear unrelated. This situation is not ideal for cluster analysis as the blurring or smoothing of rather different patterns results and stable clusters are hard to achieve.

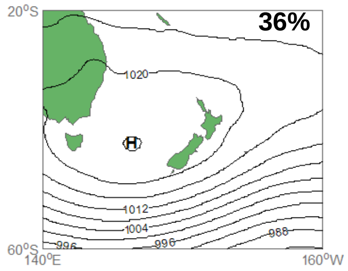
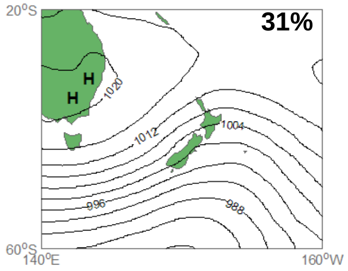
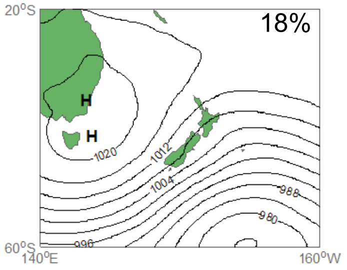
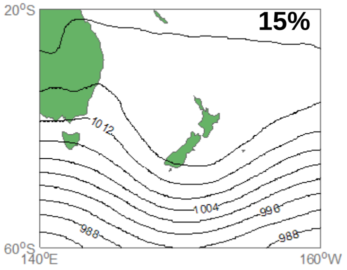
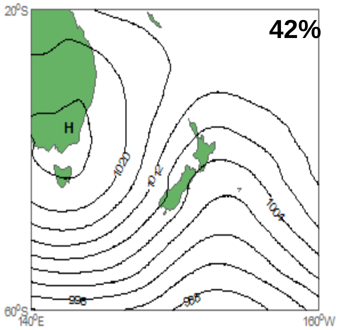
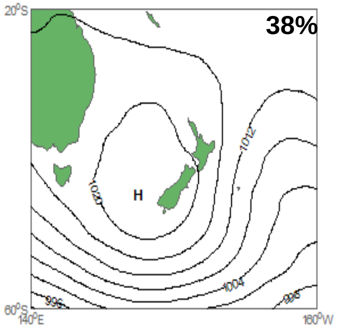
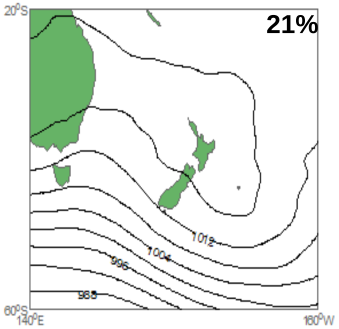
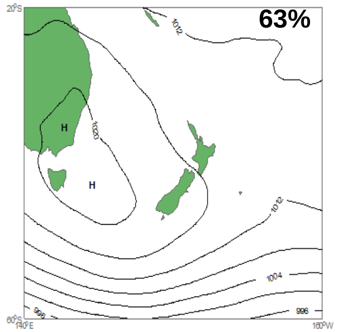
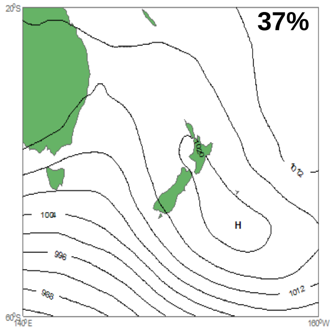
To test this hypothesis, individual weather maps were generated for all northeast wind events and separated into winds directly affecting NZ (and therefore associated with the maximum near NZ) versus those winds eastward of the Chatham Islands by eyeballing the maps. Cluster analysis was then applied to the 'NZ maximum of NE winds' and '165°W maximum'. This separation enabled four stable clusters to be found for both the NZ maximum and 165°W maximum (Figure 4-21), and they are indeed generated by different mechanisms. The local maximum in extreme northeast winds over and north of NZ involve a cyclone-anticyclone pair or subtropical trough-anticyclone pair. The anticyclone is either south, east or over the Chatham Islands while the cyclone or trough is north of NZ or in the north Tasman Sea west of Northland. On the other hand, extreme northeast winds near 165°W are associated with subtropical troughs northeast of NZ combining with a ridge of high pressure east of the Chatham Islands (cluster 1 and 3) or southern ocean cyclonic activity colliding with a ridge of high pressure near 165°W (cluster 2 and 4). Furthermore, when a subtropical trough is involved the northeast winds are confined to the area north of 40°S while southern ocean cyclones or troughs generate strong northeast winds south of 40°S.

4.3.4 Discussion

The most frequent extreme winds over the oceans east of NZ are from the southwest and cluster in the high latitudes with maximum activity east of 175°E where they are generated by southern ocean troughs. While maximum activity is well away from eastern NZ, the distribution still shows large numbers of southwest winds over and east of the lower South Island. Extreme southerly winds also show a high latitude maximum centred near the dateline, however they spread further northward and cover the entire eastern North Island. Southeast, east and northeast extreme winds, in contrast, have maximum activity in the midlatitudes between 30 and 45°S and cluster off the North Island. Both east and northeast winds cluster in two distinct areas, with one immediately north of the North Island, and the other east of 170°W. The centre of activity near the North Island is located such that the eastern North Island will be largely unaffected – the easterly wind maximum is too far northward, and northeast wind maximum is too far westward. Nonetheless, the widespread distribution of the winds shows that extreme east and northeast winds still affect the eastern North Island and will generate coastal storms. And, furthermore, the other centre of activity near 170°W acts as a distant wave generator.

The synoptic situations associated with extreme southwest winds show southern ocean troughs and ridges of high pressure over and north of the North Island (extending from Tasman Sea anticyclones). The strongest pressure gradients off eastern NZ occur when the trough extends from a southern low that is situated near 60°S (i.e. the parent cyclone is in a more northern position). In contrast, extreme southerly winds involve southern ocean troughs that extend further northward due to the absence of ridges of high pressure over the North Island. In other words, the anticyclone in the Tasman Sea appears to determine whether the trough has a south or southwesterly flow – if the Tasman Sea anticyclone has an eastward branching ridge, southwest flows will develop; if there is no ridge, southerly flows develop. These synoptic patterns are identical to the Trough/Ridge coastal storm type. Extreme southeast winds affecting the eastern North Island are created by a Tasman Sea anticyclone that is aligned on a NW-SE axis and a trough over or north of the North Island.

The synoptic patterns associated with extreme winds from the easterly quadrant involve large anticyclones to the east of NZ with troughs directly northward (easterly winds) or troughs and low pressure systems to the west or northwest of the North Island. These patterns strongly resemble the coastal storm type's cyclone-anticyclone pair, subtropical low and Tasman Sea Low.

Wind	Cluster 1	Cluster 2	Cluster 3	Cluster 4
SW				
S				**Figure 4-21** **The leading cluster patterns for extreme wind events from the SW, S, SE, E and NE off eastern NZ.**
SE				

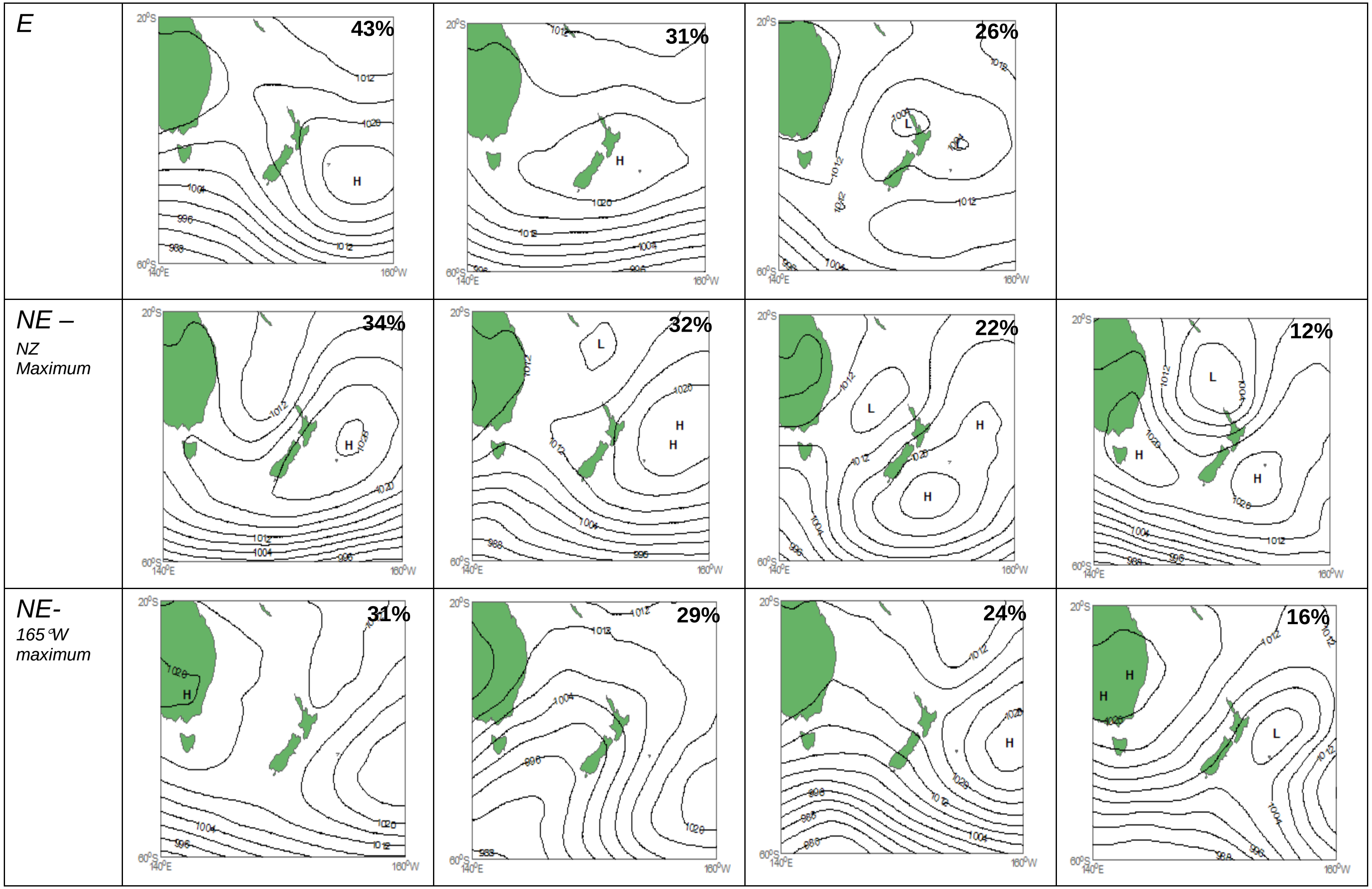


Figure 4-21 (cont.) The leading cluster patterns for extreme wind events from the SW, S, SE, E and NE off eastern NZ.

Rough estimates of the annual average frequencies of these extreme winds have been made. The area off the eastern South Island experiences around 15 extreme southwest wind events per year, greatly exceeding that of the eastern North Island (5 per year, on average). This greater frequency off the South Island is attributed to its close proximity to the source region. Extreme southerly wind events off the eastern North and South Islands, however, have the same annual average of 3 events, while those winds from the easterly quarter are more likely to affect the eastern North Island and occur only once a year.

4.4 Climatology of Large Wave Events

4.4.1 Introduction

The strong wind fields generated from cyclonic weather systems or storms are rarely the most serious hazard affecting coastal margins and occupants (Davis & Dolan, 1993). More often than not the highest damage potential is associated with secondary processes such as storm waves, currents and indirect effects such as erosion and flooding. This realisation means storm activity should also be assessed through studying the occurrences of large wave events along coastal margins.

A 20-yr record of hindcast deep-water wave conditions for the NZ region has recently become available and can be used as another index or proxy of storm activity for the eastern North Island. The generation mechanisms of extreme wave events involve large and powerful weather systems, often of cyclonic form, that we classify as ‘storms’. Both real-time or hindcast wave information have been used to develop coastal storm climatologies or databases and understand storm activity in Australia and the United States (e.g Moodie et al., 2005; You & Lord, 2005; Kemp et al., 2003; Allen & Callaghan, 1999; Feren, 1990; Dolan and Davis, 1992; Dolan *et al.,* 1988). The significant wave height thresholds from these studies vary between 1.5 m to 5 m, and as a rule represent conditions conducive to some degree of coastal erosion or damage to coastal infrastructure and transportation.

The 20-year hindcast record produced by Gorman & Stephens (2003) is one of the best datasets on the coastal wave climate around NZ. It also lends itself easily to investigations of extreme wave events or storm wave conditions, and hence, coastal storm activity. As a result, this dataset is used to produce statistics of large wave events along eastern NZ following a methodology similar to that of eastern and southern Australia (e.g. Moodie et al., 2005; Kemp et al., 2003; Allen & Callaghan, 1999; Feren, 1990).

4.4.2 Methodology

4.4.2.1 Data Source

Gorman & Stephens (2003) and Gorman *et al.,* 2003 performed a 20-yr simulation of deep-water wave conditions around NZ with the numerical WAM wave model. The model is driven by wind fields derived from the European Centre for Medium-range Weather Forecasts (ECMWF) for the time period 1979 to 1993. These analyses provide 10m winds on a 1.125x1.125° latitude-longitude grid at 6 hourly intervals. This wind data has been supplemented with operational analyses for the five years 1994-1998. These wind fields were then interpolated to the spatial grid used by the wave model. At each grid point, the wind field was entered and the model calculated (for each time step) a spectrum of wave energy distributed between 16 different frequency bins and 25 propagation directions (Gorman & Stephens, 2003; Gorman *et al.,* 2003; Laing & Gorman, 2000; Laing et al., 1997). A separate wave spectrum was calculated at each grid point and output wave statistics at 3-hourly intervals.

For the 1979 to 1998 time period, three hourly wave spectra for five sites along eastern NZ were obtained from Dr Richard Gorman (National Institute of Water & Atmospheric Research, Hamilton). The selected sites were chosen near the 100m depth contour, and include East Cape (178.67°E, 37.78°S), Gisborne (178.25°E, 39.85°S), Napier (177.45°E, 39.47°S), Castlepoint (176.35°E, 40.9°S), and Wellington (175.33°E, 41.63°S).

4.4.2.2 Large Deep-water Wave Events

Large wave events are identified when the significant wave height, H_s, is greater than or equal to 3 m within any 3-hour interval for directions between northeast (22.5-67.5˚) and SW (202.5-247.5˚). The 3 m criterion, while being arbitrary, was selected in order to focus on the more extreme wave events and to ensure those waves propagating into shallow water closer to the coast still possess large heights. The duration of the event is also calculated as the length of time during which H_s

persists on or above the 3 m threshold. In order to completely isolate individual large wave events, a further condition was applied such that any pair of large wave events that occur within 12 hours of each another are merged into a single event. For a given large wave event, the following parameters were extracted:

1. Total duration of exceedance ≥ 3 m;
2. Peak (maximum) significant wave height and its corresponding direction;
3. Average wave direction and height over the total event duration;
4. Average wave period for the total event duration; and
5. The time step (or gap) between individual wave events.

This process was applied to all the coastal wave sites and monthly, seasonal and annual frequencies computed. These large events are also converted into time series according to the wave direction. Therefore, climatologies of large wave events are available for waves from the southwest, south, southeast, east and northeast.

4.4.2.3 Storm (or Large Wave Event) Clustering

The temporal intervals or periods between the end of one wave event and the beginning of the next event were quantified. This was performed on all large wave events, regardless of wave direction, for all wave sites along eastern NZ on a monthly scale. The monthly scale was further subdivided into 5-day blocks (e.g. 1-5, 6-10, etc) in order to assess the variability within the 30 day (month) period. The frequency distributions of the time intervals were then computed.

4.4.2.4 Weather Systems Conducive to Large Wave Events

A cluster analysis is performed to assess the leading weather systems associated with large wave events for the Gisborne wave site. The Gisborne coast was chosen because it encounters large waves from all the dominant onshore wave directions and has experienced the largest number of wave events. Furthermore, it is considered highly likely that the identified weather patterns will also be representative of the other sites along the eastern North Island coast.

Wave Site	Direction	Total Events	Mean Annual Frequency	Mean Seasonal Frequency				Mean Monnthly Frequency											
				Sum	Aut	Win	Spr	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
East Cape	SW	1	0.1			0.1									0.1				
	S	215	10.8	0.7	3.7	4.8	1.7	0.4	0.1	1.1	1.0	1.7	2.0	1.9	1.0	0.9	0.5	0.4	0.3
	SE	49	2.5	0.3	0.8	0.8	0.7	0.1	0.1	0.1	0.3	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.1
	E	44	2.2	0.4	0.7	0.9	0.2	0.1	0.3	0.3	0.2	0.3	0.1	0.5	0.4	0.2	0.1		0.1
	NE	45	2.3	0.3	0.3	1.2	0.5	0.1	0.1	0.1	0.1	0.2	0.6	0.4	0.3	0.3	0.1	0.2	0.2
East Cape Total		**354**	**17.7**	**1.6**	**5.5**	**7.7**	**3.0**	**0.5**	**0.6**	**1.5**	**1.6**	**2.4**	**3.1**	**2.9**	**1.8**	**1.4**	**0.8**	**0.8**	**0.6**
Gisborne	SW	89	4.5	0.6	1.5	1.6	0.8	0.2	0.1	0.3	0.5	0.7	0.4	0.7	0.6	0.4	0.2	0.2	0.3
	S	245	12.3	1.1	3.8	4.9	2.6	0.6	0.1	1.2	1.1	1.6	2.0	1.6	1.4	1.4	0.7	0.5	0.5
	SE	41	2.1	0.2	0.9	0.7	0.3	0.1	0.1	0.2	0.3	0.4	0.3	0.2	0.2	0.1	0.1	0.1	0.1
	E	39	2.0	0.2	0.5	1.0	0.3	0.1	0.2	0.2	0.2	0.2	0.3	0.5	0.3	0.2	0.1	0.1	
	NE	42	2.1	0.5	0.3	1.1	0.3	0.1	0.2	0.1	0.1	0.2	0.4	0.2	0.5	0.2		0.2	0.2
Gisborne Total		**456**	**22.8**	**2.6**	**6.9**	**9.2**	**4.2**	**1.0**	**0.6**	**1.9**	**2.1**	**3.0**	**3.2**	**3.1**	**2.9**	**2.2**	**1.1**	**1.0**	**1.0**
Napier	S	186	9.3	0.6	3.3	4.2	1.3	0.4	0.1	0.9	0.9	1.6	1.6	1.5	1.1	0.6	0.5	0.2	0.1
	SE	36	1.8	0.2	0.6	0.7	0.4	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.1	0.1	0.1
	E	34	1.7	0.2	0.5	0.8	0.2		0.2	0.1	0.2	0.3	0.3	0.4	0.2	0.1		0.1	0.1
Napier Total		**256**	**12.8**	**1.0**	**4.4**	**5.7**	**1.9**	**0.5**	**0.3**	**1.1**	**1.3**	**2.0**	**2.1**	**2.2**	**1.4**	**0.9**	**0.6**	**0.4**	**0.2**
Wairarapa	SW	6	0.3	0.1	0.1	0.2		0.1				0.1		0.1	0.1				0.1
	S	267	13.4	1.1	4.6	5.5	2.2	0.6	0.2	1.3	1.5	1.9	2.2	1.7	1.6	1.4	0.5	0.4	0.4
	SE	28	1.4	0.1	0.4	0.8	0.2	0.1		0.2	0.2	0.1	0.3	0.4	0.2	0.1	0.1	0.1	
	E	35	1.8	0.1	0.6	0.8	0.3		0.1	0.2	0.3	0.2	0.2	0.4	0.2	0.2		0.1	
	NE	2	0.1	0.1															0.1
Wairarapa Total		**338**	**16.9**	**1.5**	**5.7**	**7.2**	**2.7**	**0.7**	**0.3**	**1.6**	**2.0**	**2.2**	**2.7**	**2.5**	**2.1**	**1.6**	**0.5**	**0.6**	**0.6**
Wellington	SW	36	1.8	0.3	0.6	0.7	0.3	0.1		0.2	0.2	0.3	0.3	0.3	0.1	0.2	0.1		0.2
	S	197	9.9	0.9	3.5	4.0	1.5	0.5	0.2	0.9	1.3	1.4	1.8	1.1	1.2	1.0	0.3	0.2	0.2
	SE	24	1.2		0.3	0.7	0.3			0.1	0.1	0.1	0.3	0.3	0.1	0.2	0.1	0.1	
	E	34	1.7	0.1	0.6	0.8	0.2	0.1	0.1	0.2	0.3	0.2	0.3	0.3	0.3	0.2		0.1	
	NE	10	0.5	0.1	0.1	0.2	0.2			0.1		0.1		0.1	0.2	0.1		0.1	0.1
Wellington Total		**301**	**15.1**	**1.3**	**5.1**	**6.3**	**2.4**	**0.7**	**0.2**	**1.4**	**1.8**	**2.0**	**2.6**	**2.0**	**1.8**	**1.6**	**0.4**	**0.4**	**0.5**

Table 4-6 Summary frequency statistics of large wave events at East Cape, Gisborne, Napier, Wairarapa and Wellington.

Wave Site	Direction	Total Events	Avg Wave Height (m)			Avg Period (s)			Max Wave Height (m)				Event Duration (hours)									Kidson Types
			3-4	4-5	5-6	6-8	8-10	>10	3-4	4-5	5-6	>6	<6	6-11	12-17	18-23	24-29	30-35	36-41	42-48	>48	
East Cape	SW	1	1			1			1					1								TSW
	S	215	179	35	1	115	85	15	142	45	17	11	13	39	33	28	23	24	14	16	25	SW,HW,HNW
	SE	49	45	3	1	37	11	1	31	12	4	2	3	3	6	9	4	6	2	6	10	HSE,R,TSW
	E	44	34	9	1	26	17	1	25	12	4	3	2	3	3	6	4	2	7	3	14	HSE,R,NE
	NE	45	36	9		41	4		28	11	4	2	12	8	6	3	4	2	1	5	4	NE,TNW,TSW
East Cape Total		**354**	**295**	**56**	**3**	**220**	**117**	**17**	**227**	**80**	**29**	**18**	**30**	**54**	**48**	**46**	**35**	**34**	**24**	**30**	**53**	**SW,HW,HSE**
Gisborne	SW	89	73	16		60	28	1	52	19	13	5	4	17	21	7	7	7	9	8	9	SW,HNW,T
	S	245	197	42	6	152	81	12	149	52	24	20	11	34	30	29	30	21	16	25	49	SW,HW,HNW
	SE	41	38	2	1	25	14	2	26	11	3	1	5	2	4	8	4	2	4	3	9	R,HSE/TSW
	E	39	32	7		18	19	2	21	12	5	1	2		7	4	4	7	2	6	7	R,NE,TSW
	NE	42	38	4		37	5		28	10	3	1	8	7	10	6	2	3	2	1	3	TNW,NE,HE
Gisborne Total		**456**	**378**	**71**	**7**	**292**	**147**	**17**	**276**	**104**	**48**	**28**	**30**	**60**	**72**	**54**	**47**	**40**	**33**	**43**	**77**	**SW,HNW,HW**
Napier	S	186	164	20	2	91	80	15	127	41	13	5	17	24	28	27	25	21	9	12	23	SW,HNW,HW
	SE	36	32	3	1	25	10	1	24	9	1	2	4	5	6	1	4		4	5	7	R,HSE,TSW
	E	34	31	3		13	18	3	21	11	1	1	1	6	4	4	6	1	6	2	4	R,NE,HSE/TSW
Napier Total		**256**	**227**	**26**	**3**	**129**	**108**	**19**	**172**	**61**	**15**	**8**	**22**	**35**	**38**	**32**	**35**	**22**	**19**	**19**	**34**	**SW,HNW,HWR**
Wairarapa	SW	6	5	1			4	2	5			1	1	2		1		1	1			SW
	S	267	225	38	4	146	98	23	176	59	18	14	18	41	41	35	36	21	19	30	26	SW,HNW,HW
	SE	28	24	4		15	11	2	20	4	2	2	2	3	5	4	2	3	2	2	5	TSW,R,HSE
	E	35	32	3		8	25	2	26	7	2		2	4	7	4	6	3	1	5	3	R,NE,TNW
	NE	2	2				2		2					2								TSW
Wairarapa Total		**338**	**288**	**46**	**4**	**169**	**140**	**29**	**229**	**70**	**22**	**17**	**23**	**52**	**53**	**44**	**44**	**28**	**23**	**37**	**34**	**SW,HNW,HW**
Wellington	SW	36	33	2	1	15	21		30	3	1	2	6	8	9	3	3	2	1	2	2	SW,HNW,HWT
	S	197	168	26	3	115	62	20	128	46	15	8	20	28	32	26	17	17	18	19	20	SW,HNW,HW
	SE	24	21	3		14	9	1	16	5	2	1	2	4	3	3	4	3	1		4	TSW,HSER
	E	34	31	3		14	17	3	26	7	1		3	8	7		7	1	1	4	3	NE/R,TNW
	NE	10	10			9	1		9	1				5	4	1						HE/NE/TNW
Wellington Total		**301**	**263**	**34**	**4**	**167**	**110**	**24**	**209**	**62**	**19**	**11**	**31**	**53**	**55**	**33**	**31**	**23**	**21**	**25**	**29**	**SW,HNW,TSW**

Table 4-7 Summary statistics of specific wave properties of large wave events at East Cape, Gisborne, Napier, Wairarapa and Wellington. Also included is the total duration of large waves and three leading Kidson synoptic weather types.

From the date stamps of large wave events, the 00Z-hour sea level pressure distributions from the NCEP-NCAR dataset (1979-1998) for the area extending from latitudes 20°-60°S and longitudes 140°E-160°W were input to a cluster analysis. The clustering technique is based on that of Kidson (1997, 2000) and is the same as that described in section 3.4.2.4. Five consecutive runs with an initial 50 seed clusters were generated and only the top eight clusters returned and analysed. The final number of clusters retained was that for which identical patterns were identified across all five runs. For SE, E and NE wave events that have less than 100 counts, the initial seed value was set to 20 seeds.

4.4.3 Results

The frequency of LWE from specific directions are presented in Table 4-6 and specific wave properties in Table 4-7 for East Cape, Gisborne, Napier, Wairarapa and Wellington. The results for the different regions are discussed in some detail below. The details of the longest duration storms are provided in Table 4-8 and the degree of storm clustering in Figure 4.25. Also, a plot showing large wave events for all the wave sites per wave direction appears in Figure 4-22.

4.4.3.1 East Cape

The most common LWE at East Cape come from the south (180±22.5°) in all months except February. Peak activity is mostly restricted to May-June-July when these southerly events more than triple that of the other wave directions (Table 4-6). In the month of February, southerly events are greatly suppressed, as are the other summer months (December and January). Furthermore, there is a massive increase in activity from February to March and slightly more events in mid-to-late autumn months compared to early spring (Table 4-6). Therefore, large southerly wave events dominate the autumn and winter seasons.

LWEs from the southeast (total of 49) have been relatively infrequent over the 20-year period investigated. They cluster between April and June, and have a secondary peak in November (Table 4-6). Easterly wave events are also infrequent near East Cape (total of 44). They show a bi-modal distribution with a peak in February-March and again in July-August. The former peak most likely represents tropical cyclone or ex-tropical cyclone activity. Easterly storms are least likely from October to January, and then show a large jump in February (Table 4-6). The winter season experiences the largest number of events, followed closely by autumn. Therefore, both east and southeast wave events have two peaks in monthly frequency.

Most storm events generating large northeast waves occur between June and September (and a minimum between January and April) though they have not been common events (total = 45). The peak month is June (Table 4-6), making extreme northeast waves the leading storm events after southerlies (in June). Consequently, the winter season shows the most activity. Of all the wave types, these northeasterly events have the shortest duration with approximately 71% of events being 3 and 24 hours in length (and of these, 27% are only 3 hours long).

The gap between LWE (regardless of onshore wave direction) is rarely more than 90 days. Approximately 96% of the time, the interval between events is between 0 and 90 days i.e. less than 3 months (Figure 4-25). On only 10 occasions was the interval between large wave episodes greater than 90 days, and the longest quiescent period was 172 days. The average time interval, or ‘recovery’ period, between LWE is 20 days. The largest waves come from the south and these persist most often for longer than 2 days (Table 4-7).

4.4.3.2 Gisborne

Gisborne experiences more LWE from the southwest compared to any other location (total of 89). Peak frequencies occur in May, though most activity is spread across April through August (Table 4-6). This corresponds to a wintertime maximum that slightly exceeds that of autumn. These seasons experience more than double the number of large SW wave events observed in summer and spring (Table 4-6). LWE from the south are the most frequent type on the Gisborne coastline (total of 245). In some months (e.g. June), they more than double the frequency of any other wave type. Peak activity is in June, although large numbers are also seen from March through September. This activity is greatly suppressed in February, but strengthens significantly in March. Thus, a wintertime peak is seen on a seasonal timescale, as well as more activity in autumn compared to spring.

Southeast events have not been a common occurrence offshore from Gisborne during the 20 year record (41 events). Most activity has been captured in the autumn months with a peak in May, and is relatively rare between October and February. The seasonal distribution (Table 4-6) exhibits a peak in autumn (followed by winter) and a summertime minimum. The number of easterly storms (39 events) has been much the same as that of southeasterlies, being relatively infrequent. They show most activity between June and August (with a peak in July) and rarely occur from October through January. A small total of 42 large northeast wave events were also found and they show preferred monthly activity in August. In February, the most common LWE come from the northeast (and east), though they have been very infrequent (over the 20 period, there have been only 3 such events). Seasonally, we can expect large waves from the northeast most often in winter (Table 4-6).

Approximately 99% of the intervals between large wave episodes are less than or equal to 90 days at Gisborne. Only 5 storms have been spaced more than 90 days apart, with the largest gap being 121 days. When the monthly time scale is broken down into 5 day intervals in order to investigate intra-month variability, it was found that more than 50% of events are separated by no more than 10 days (Figure 4-25). To further confirm a high degree of storm clustering, the average time interval or 'recovery' period is 13 days. Across all wave types, there appears to be no consistent peak months such that activity spreads from May through to August. Furthermore, the largest waves come from the south and highest number of events with durations longer than 2 days (Table 4-7)

4.4.3.3 Napier

LWE offshore from Napier are restricted to the south, southeast and easterly directions. No events were captured from the southwest or northeast, and this has been put down to sheltering (topographic) effects from Cape Kidnappers and Mahia Peninsula. Offshore from Napier, the wave climate is dominated by southerly storms with a total of 186 events found. Peak activity occurs between May and July whereas in December and February these events are infrequent (Table 4-6). As has been seen for East Cape and Gisborne, there is also a large jump in activity from

February to March for southerly wave events. Subsequently, we find most activity in winter and autumn, which have more than double the number of events of spring or summer.

LWE from the southeast are relatively infrequent at Napier. A total of 36 events were attained mostly between April and July, while little activity occurs between October and February (Table 4-6). Thus, winter and autumn seasons experience the most events. Easterly wave events are also infrequent, with only 34 events retained. Maximum monthly activity occurs in July, or between April and July, and a large proportion in February. Winter and autumn, therefore, display the largest numbers of events (and is seen in all wave directions).

Approximately 90% of large deep-water wave events occur within one month of the previous event on the Napier coast. Intra-monthly variability revealed around 56% of these events were within 15 days of each other (Figure 4-25). In addition, there were 19 occasions whereby the interval between LWE has exceeded 90 days. This is the most “quiescent” periods of all the sites, and most likely relates to the reduced directional window of LWE on this coast; that is, the absence of large waves from the SW and NE could be responsible for the large gaps between some events. Furthermore, the average time interval (recovery period) between large deep-water wave events is 27 days, the largest waves and longest events come from the south (Table 4-6).

4.4.3.4 Wairarapa

LWE from the southwest are rare off the Wairarapa coast, with only 6 events extracted from the 20 year hindcast dataset. They were spread across several months so that there was no clear maximum (Table 4-6). The deep-water wave climate off the Wairarapa coast is dominated by large wave events from the south (total = 267). They are numerous between March and September and show a clear peak in June (Table 4-6). As like all other wave sites, there is a large increase in activity from February to March. This corresponds to a wintertime maximum, closely followed by autumn and a summertime minimum.

Only 28 LWE from the southeast were obtained, making southeasterly storms infrequent off the Wairarapa coast. Peak activity was reserved for the months of June, July and August. Comparatively, they are completely absent in October, December and February. We therefore see a wintertime maximum on a seasonal scale. A total of 35 easterly storms were captured between 1979 and 1998. The peak month is July, though a secondary peak also appears in April. Very few events occur between October and February. Only two northeasterly wave events were found off the Wairarapa coast and both in the month of December.

Around 96% of LWE on the Wairarapa coast are spaced between 1 and 90 days apart. Of these events, just over 70% are followed by another within 20 days. Thus, large deep-water wave events for any onshore direction (NE through to SW) are closely spaced in time (Figure 4-25) with the average period being only 19 days. Furthermore, all large wave types show maximum activity in the winter season, and largest and longest duration events come from the south (Table 4-7).

4.4.3.5 Wellington

The majority of southwest wave events (a total of 36) appear between March and September with a peak in July. There is little activity in October-November and January-February. This corresponds to the winter and autumn seasons showing most activity. By far the most common large wave events on the Wellington coast are from the south (total of 197) and show maximum activity between March and September with a peak in June (Table 4-6). Southerly events in October to December and also February are suppressed compared to the other months. We therefore see a winter and autumn peak in seasonal activity and least activity in summer.

Only 24 LWE from the southeast were found. They are spread between March and November with a peak in June. No large southeasterlies have occurred in December through to February (Table 4-6). This means maximum activity occurs in winter and autumn and a complete absence in summer. Similar numbers (total of 34) of easterly wave events were retained with most activity in March-April and June to August (peak in July), and are relatively infrequent between October through February, making the winter season most active. Only 10 extreme wave events from the northeast were extracted from the total time series. They are spread through March, May, July-September and November-December.

Off the Wellington south coast, approximately 95% of time intervals between LWE are less than (or equal to) 90 days apart. Of these events, 60% occur between 1 and 15 days of the previous event (Figure 4-25). Only 15 events (5%) have been separated by time periods greater than 90 days, and the longest gap was 238 days (just under 8 months). The average time period between all LWE is 21 days. Furthermore, all large wave types have peak activity in June or July, and largest and most persistent waves come from the south (Table 4-7).

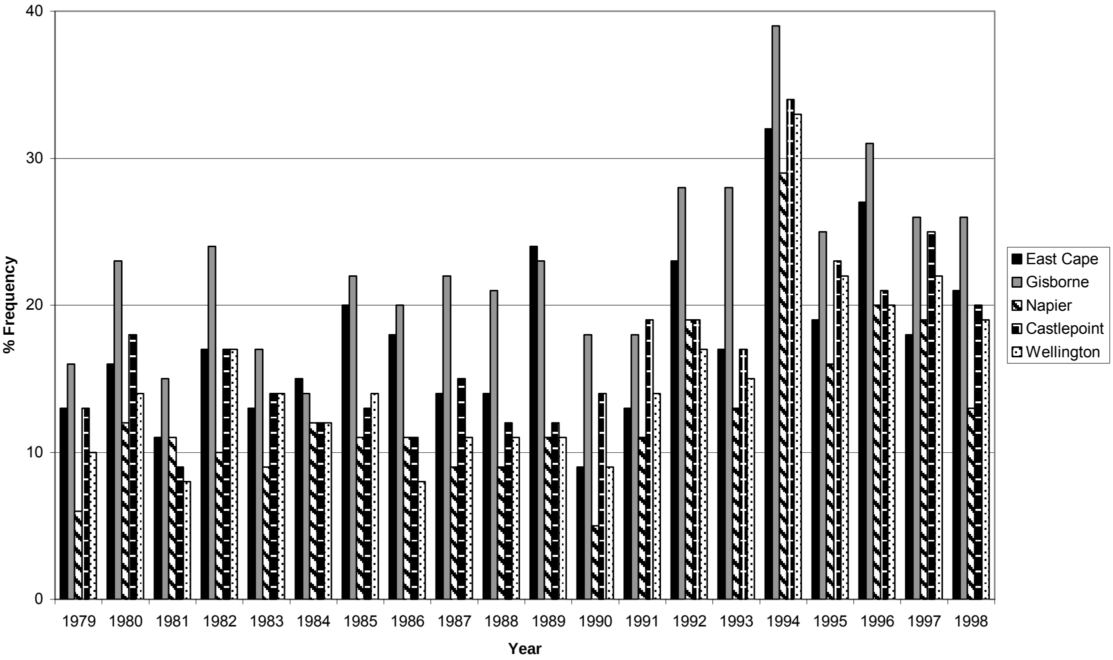


Figure 4-22 The total number of large wave events per year for all of the wave sites between 1979 and 1998. Only wave events with directions from NE through to SW (inclusive) are calculated.

4.4.3.6 All Wave Events

The total number of LWE per year for all the wave sites is shown in Figure 4-22. It includes all wave events from all onshore directions (NE through to SW). The year 1994 stands out with maximum wave activity for all sites. It is not clear whether this peak is real or an artefact of the introduction of a new data source (operational analyses). However, the picture that emerges is increased large wave activity from the early 90s at all wave sites; that is, the increased activity appears to have started before the operational analyses were utilized and therefore the peak of 1994 could indeed be real. Furthermore, all wave sites except Wellington show the next peak in 1996, and this coincides with a corresponding peak in strong cyclones through the NZ region (see Figure 4-11 and Figure 4-12), unlike 1994.

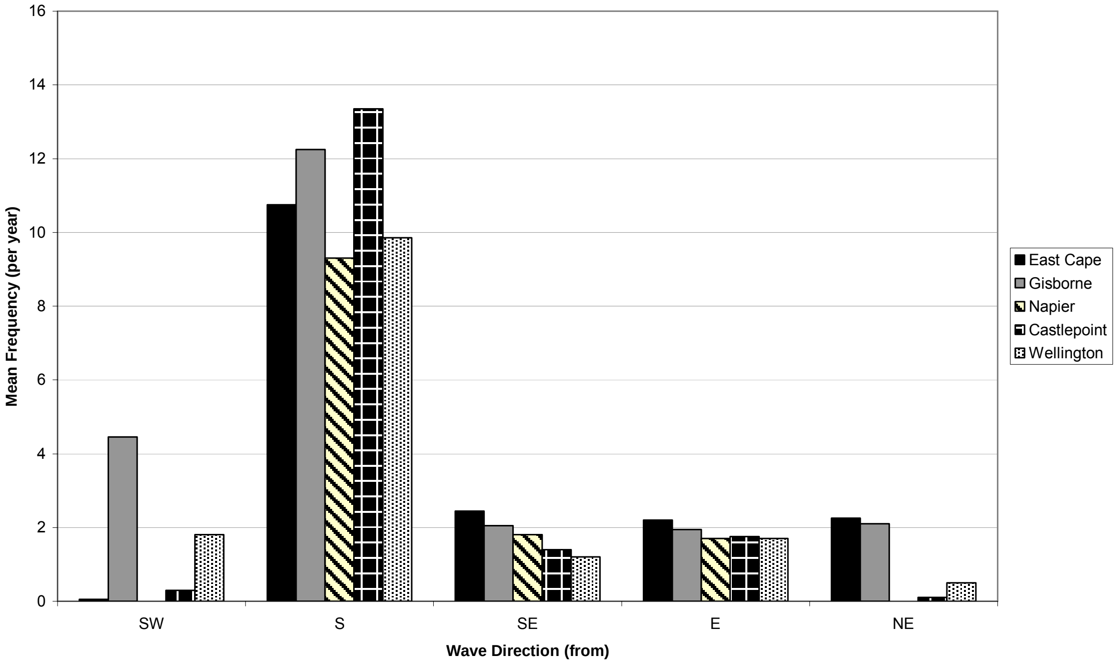


Figure 4-23 The mean annual frequencies of large wave events from the SW, S, SE, E and NE for the individual wave sites.

The mean frequencies of LWE per year were also calculated according to wave direction (Figure 4-23). Wave events from the south dwarf those of any other direction with mean frequencies ranging from 9 to 13 and being most numerous off the Wairarapa coast. Southwest wave events dominate off Gisborne and occur around 5 times per year. Southeast, east and northeast waves occur on average only twice per year at East Cape and Gisborne and decline slightly further southward (Figure 4-23).

A search was also made for all LWE that occurred across all sites. A total of 92 southerly events were found whereby 3 meter waves were generated at East Cape, Gisborne, Napier, Wairarapa and Wellington. The general pattern consists of the large waves appearing at Wellington and Wairarapa (mostly within 3 hours of each other), and then spreading northward to Gisborne, Napier and East Cape. This pattern of Wellington-Wairarapa-Gisborne-Napier-East Cape was found for 50% of southerly wave events and the time lag computed between each location and between Wellington and East Cape. The average time lags are:

- Wellington to Wairarapa: 1.7 hours (maximum of 6 hours);
- Wairarapa to Gisborne: 3.3 hours (maximum of 12 hours);
- Gisborne to Napier: 2.9 hours (maximum of 9 hours);
- Napier to East Cape: 2.6 hours (maximum of 18 hours); and
- Wellington to East Cape: 10 hours (maximum of 24 hours).

Ten occasions were found whereby all wave sites experienced large waves (>3m) from the east. The general pattern is almost directly opposite to that of southerlies, consisting of large waves first appearing at East Cape, then Gisborne, and spreading southward to Napier, Wairarapa and lastly Wellington. This pattern indicates a subtropical or northern origin of the responsible weather system and subsequent southward movement. The average time lags were computed for each of these sites:

- East Cape to Gisborne: 9 hours (maximum of 21 hours);
- Gisborne to Napier: 5.1 hours (maximum of 12 hours);
- Napier to Wairarapa: 7.8 hours (maximum of 21 hours);
- Wairarapa to Wellington: 4.2 hours (maximum of 12 hours); and
- East Cape to Wellington: 26 hours (maximum of 45 hours).

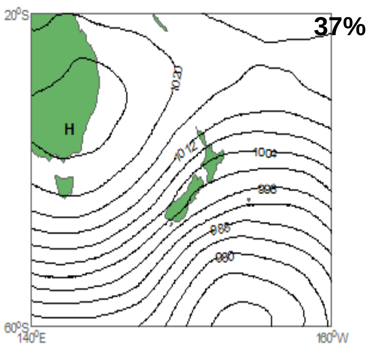
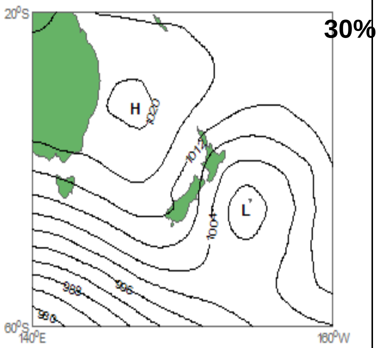
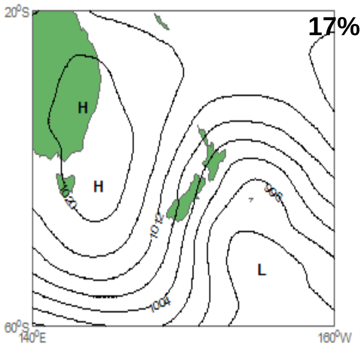
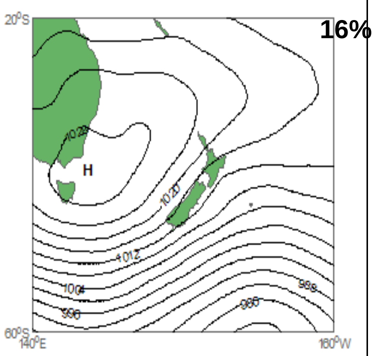
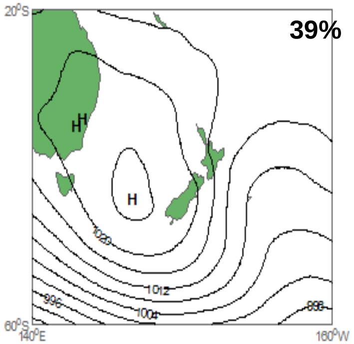
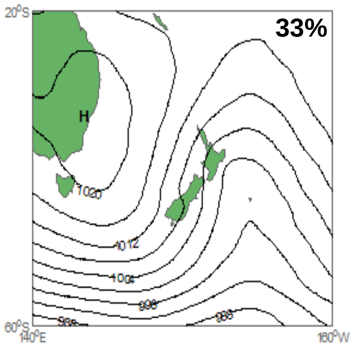
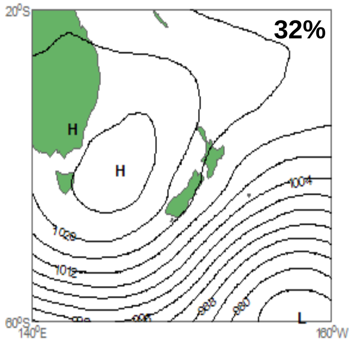
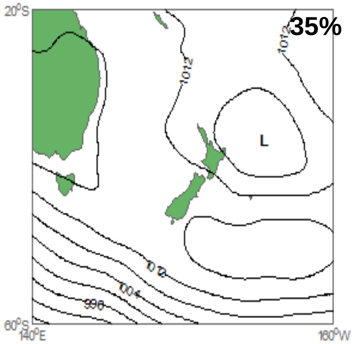
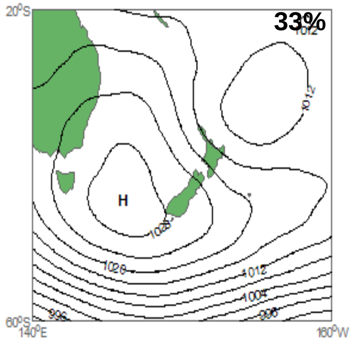
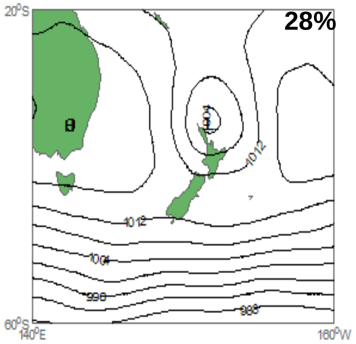
Southerly wave events, therefore spread relatively quickly up the east coast of NZ from Wellington to East Cape whereas easterlies travel only slowly southward. This suggests the weather systems generating southerlies are often fast-moving or of large-scales. The slow southward spread of easterly waves suggests there is often an anticyclone or ridge over and east of southern NZ that retards the southward movement of subtropical cyclones.

4.4.3.7 Weather Systems Associated with LWE on the Gisborne Coast

Of a total of 89 southwest wave events four leading weather patterns have been identified. The dominant pattern involves a trough of low pressure extending from a deep southern ocean low with a strong southwest flow on its western side covering NZ (Figure 4-24). The second dominant pattern has a closed low pressure centre over the Chatham Islands with a southerly flow on its western side. Both of these patterns display anticyclones in the north Tasman Sea. The remaining patterns show weaker troughs over or east of NZ. (Figure 4-24). The leading patterns for large southerly wave events are nearly identical to those for southwest wave events, except the Tasman Sea anticyclone occupies the south Tasman Sea or have weak southward-directed ridges. In cluster three (Figure 4-24), however, a strong southwest airstream dominates the area southeast of NZ and therefore Ekman turning, whereby the water flow is to the left of the wind direction (in the southern hemisphere) acts to redirect the waves to a more southerly direction. All of these patterns compare well the coastal storm types of trough/ridge and east coast low.

Three leading clusters were found for large southeast waves and all involve low pressure systems off the North Island combined with anticyclones in varying positions (Figure 4-24). The most dominant pattern has the anticyclone south of the Chatham Islands (east of NZ), while the second cluster has the anticyclone in the south Tasman Sea extending a ridge eastward. Large easterly waves show patterns with large anticyclones east of NZ combined with subtropical cyclones or troughs over the North Island (Figure 4-24). These patterns have strong similarities to the coastal storm type's subtropical low and cyclone-anticyclone pair. Furthermore, these patterns display east-northeast airstreams rather than direct easterly flows. Not surprisingly, the two leading patterns for large northeast wave conditions are very similar to that for easterly waves, differing only in the position of the low pressure systems which occupy the Tasman Sea (with large and intense anticyclones east of NZ). These patterns show north to northeast flows, and resemble that of coastal storm type Tasman Sea Low.

A comparison of these leading weather patterns with those for extreme winds show good agreement for winds and waves from the south (the two leading patterns are very similar), while east and northeast have some common clusters. This demonstrates that coasts with a wave climate that is dominated by distantly generated waves will experience some degree of difficulty when trying to isolate the cause (generation) of the waves because they will not be represented by local weather conditions.

	Cluster1	Cluster 2	Cluster 3	Cluster 4
SW	 37%	 30%	 17%	 16%
S	 39%	 33%	 32%	**Figure 4-24** **The leading cluster patterns for large wave events from the SW, S, SE, E and NE at the time of onset of waves greater than 3m for the Gisborne site.**
SE	 35%	 33%	 28%	

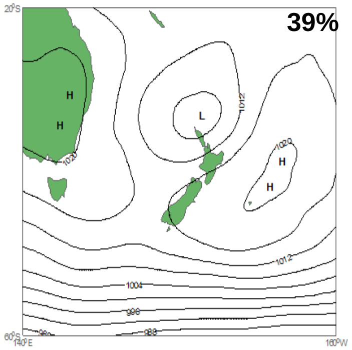
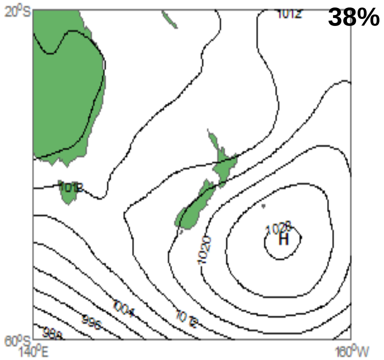
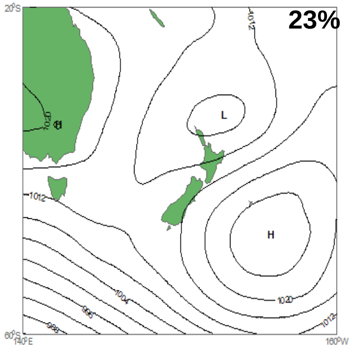
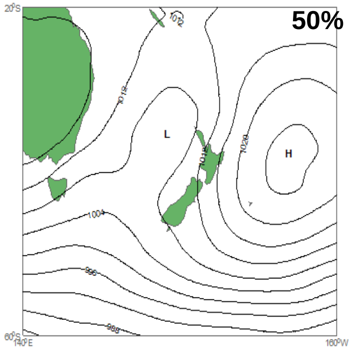
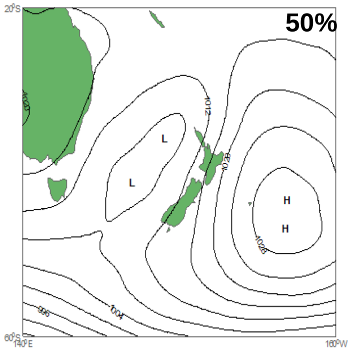
E				
NE				

Figure 4-24 The leading cluster patterns for large wave events from the SW, S, SE, E and NE at the time of onset of waves greater than 3m for the Gisborne site.

Wave Site	Wave Dir	Date	Duration (hrs)	Ave Height (m)	Ave Period (s)	Max Height (m)
East Cape	SW	10 Aug 1996	6	3.2	7	3.2
	S	17-22 Aug 1998	111	3.6	8	4.5
	SE	17-23 Sept 1993	138	3.5	9	3.9
	E	6-13 Sept 1989	156	4.3	9	6
	NE	21-25 June 1996	102	4.6	9	7.4
Gisborne	SW	15-19 Oct 1994	81	3.7	9	4.9
	S	3-9 June 1995	159	4.0	9	6.4
	SE	27Apr-3May 1995	123	3.7	8	4.4
	E	7-13 Sept 1989	153	4.3	9	5
	NE	2-5 Aug 1989	75	3.6	7	4.2
Napier	SW	-	-	-	-	-
	S	7-11 June 1990	90	3.4	8	4.6
	SE	19-22 April 1984	69	3.3	9	3.7
	E	7-13 Sept 1989	138	3.9	9	4.6
	NE	-	-	-	-	-
Wairarapa	SW	15-17 July1982	36	3.3	9	3.4
	S	20-24 May 1990	102	3.6	11	4.5
	SE	25-28 July 1985	78	4.7	9	6.7
	E	7-13 Sept 1989	135	3.8	9	4.3
	NE	23-24 Dec1995	9	3.1	8	3.2
Wellington	SW	5-7 Aug 1992 15-17 July 1982	51 51	3.9 3.4	8 8	4.5 3.5
	S	3-8 June 1995	114	3.9	9	4.8
	SE	25-29 July 1985	75	4.8	9	6.7
	E	7-13 Sept 1989	138	3.6	8	4.3
	NE	13-14 Aug 1984	18	3.4	7	3.7

Table 4-8 A list of the longest duration wave events from the southwest, south, southeast, east and northeast for the five wave sites along the eastern North Island.

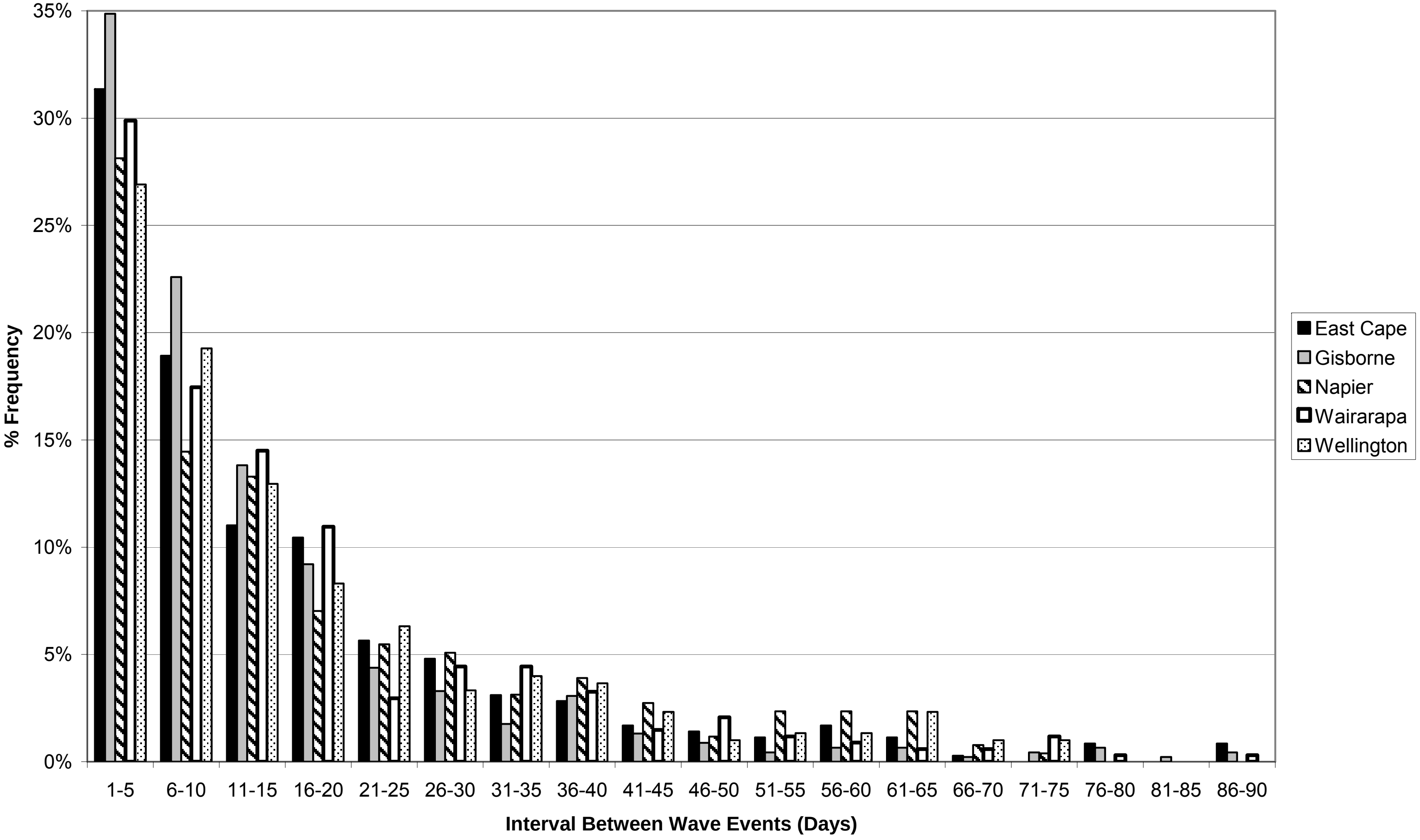


Figure 4-25 **The time interval between large wave events for East Cape, Gisborne, Napier, Wairarapa and Wellington. Intervals or gaps greater than 90 days are not shown as they represent less than 7% of all events.**

4.4.4 Discussion

At all sites, the extreme deep-water wave climate off eastern NZ consists of waves from the south. The Wairarapa coast has experienced the most southerly events, followed closely by Gisborne, which has also registered a considerable amount of (and most) activity from the southwest (Figure 4-22 and Figure 4-23). The Napier coast has only received LWE from the south, southeast and east. This is due to the sheltering or blocking effect of Mahia Peninsula for waves propagating from the northeast and Cape Kidnappers for waves from the southwest. Large deep water waves from the easterly quadrant are uncommon along the eastern North Island. Waves from the southeast and east show a gradual decline in total numbers from East Cape to Wellington (from north to south) even though overall numbers are very similar. This suggests East Cape (and Gisborne) is closer to the source region that generates these waves (i.e. the subtropics), and this is supported by the spatial patterns of extreme southeast and east winds (Figure 4-17 and Figure 4-18). Northeast wave events cluster mostly off East Cape and Gisborne.

At East Cape, the largest waves (5-5.5 meters) and periods (11 seconds) come from the south, southeast and east. Maximum wave heights have reached as high as 8.5-9m from the south, whereas the longest duration events have come from the southeast and east (5 to 7 days). Offshore from Gisborne, a similar pattern appears for the largest wave heights and periods (mostly from the south and southeast) though less activity is found for waves from the east. The maximum wave heights are from the south (8-9.5m) and the most persistent events are from the south, southeast and east (4-7 days). At Napier, southerly wave events have the largest heights, longest periods, and are also the longest (durations between 3 and 6 days). In more southern locations, the Wairarapa coast experiences the largest waves from the south (5-6m) and these have periods of 12-13 seconds. However, the longest wave events are from the east and can be up to 5-6 days duration. Off the south coast of Wellington, the largest waves are from the south and southwest, and the southerlies also have the longest periods (12-13 seconds). Much like the Wairarapa coast, the longest events are reserved for the infrequent easterly events (5-6 days).

Cluster analysis has shown that the meteorological conditions leading to large south and southwest waves are nearly identical. The leading patterns show southwest waves are more likely when the Tasman Sea anticyclone occupies the northern

Tasman Sea area, and the flows are directed more southward when this anticyclone expands into the south Tasman Sea. Meteorological similarities are also seen for large southeast and east wave events. Southeast waves are generated when the northern cyclone is northeast and east of East Cape, but if the cyclones are near North Cape the waves will have more eastward trajectories. These conditions are totally reliant on the presence a large ridge of high pressure or anticyclone in the south Tasman Sea or east of NZ. And, large waves from the northeast involve cyclones that occupy the Tasman Sea. Furthermore, it has been shown that some weather patterns (clusters) show flows that don't match the wave direction (east and northeast). This suggests a large majority of wave events from east and northeast were distantly generated, and the use of cluster analysis based on the day of onset of LWE as they will not represent the generating meteorological conditions. This suggestion is supported by the extreme wind distributions for east and northeast waves, which show most activity well east of NZ (i.e. distant wave generation areas for the eastern North Island).

It appears the 3-meter criterion that defines a LWE over-estimates coastal storm activity given the number of events found from a short 20-year hindcast dataset, and given the contamination by distantly generated waves that probably aren't of a damaging nature. It is suggested that heights above 4-meters will be more representative of coastal storm activity as this threshold returns similar numbers of coastal storms to that identified in the coastal storm database for Gisborne (based on measured winds). Furthermore, on coasts such as Gisborne that has a swell-dominated wave climate, the use of wave data as a proxy for coastal storms means some degree of filtering is needed to remove distantly generated waves that have a low damage potential.

4.5 Relationships between Strong Cyclones, Extreme Winds and Large Wave Events

No association between the spatial patterns of strong cyclone activity east of 170°E and extreme winds were found except for wintertime northeasterly winds. This is to be expected for two reasons: strong winds associated with cyclonic weather systems are not found at cyclone centres; and, the presence of a single cyclonic system does not necessarily initiate strong winds. Additional factors such as troughs, intense or intensifying anticyclones and quasi-stationary weather systems often come into play for generating extreme winds. These components were revealed by assessing the meteorological conditions associated with large waves off the Gisborne coast.

Given that large waves are produced from high winds, or moderate winds over long time periods, and high winds are often associated with cyclonic systems, a cross reference of wind, wave and cyclone track dates was performed to assess the connection between these three storm indicators. Firstly, to gauge if large wave events were related to extreme winds, all events were extracted whereby the onset of large waves (i.e. start date of large waves) occurred during the period of extreme wind event and for a further 24-hours after the winds. That is, from the duration of extreme winds (i.e. between the start and end date) plus 24 hours, all wave events were selected that feel within this time period and had similar wind and wave directions. Once this association was met, a search was then made for a corresponding storm track for which at least one track point related to the wind event dates.

This assessment extracted a total of 194 wind-wave-cyclone track events for the Gisborne site. Of the total number of large wave events (456), a wind-wave-cyclone relationship was found for 38% of events. For all other sites, the relationship varied between 27% (East Cape) and 34% (Napier). It was observed that multiple wave events could be related to the same extreme wind events. Thus, a large majority of wave events are either correlated with longer-lived, lower magnitude winds, lower magnitude cyclonic systems, relate to distant storms whose outgoing swell waves propagate towards NZ taking several days to arrive on NZ shores, or combinations of high and low pressure systems. A longer lag period of up to 48 hours after the end of the strong winds could potentially lead to a higher ratio of wind-wave-cyclone pairs.

The lack of association between strong cyclones and extreme winds is not surprising. It has already been mentioned that the presence of a single cyclonic weather system does not automatically initiate strong winds. Instead, the above results indicate that additional features come into play for generating strong wind events. They include troughs, intense and intensifying high pressure systems and quasi-stationary weather systems. These components were revealed by assessing the meteorological conditions associated with large waves off the Gisborne coast. However, the study of strong cyclonic systems still serves as a good proxy of storm activity.

The lack of connection between the extreme wind climatology and large wave events is more surprising. This could be a result of the two analyses using different data sources (winds from NCEP-NCAR reanalyses, and waves from ECMWF analyses), not correcting the extreme gradient winds to mean sea level, and taking into account that the extreme winds are predominately from the southwest, while waves come mostly from the south (i.e. most extreme southwest winds don't generate large waves for the eastern North Island). Furthermore, perhaps more emphasis on extreme wind duration and fetch criteria (or speed and duration) would make for better relationships with large wave events off the coast.

Consequently, the three storm proxies should be viewed separately as representing different aspects of coastal storm activity. The strong cyclone activity can be viewed as a measure of the number of cyclonic systems that travel through the SW Pacific-NZ sector. The extreme wind climatology represents the occurrence of strong onshore winds over the seas off eastern NZ (i.e. where and how often winds greater than 20 $m.s^{-1}$ occur offshore from eastern NZ). And lastly, the large wave events are a measure of extreme deep-water wave conditions.

4.6 Relationships between Strong Cyclones, Extreme Winds and Large Wave Events – Case Studies with Coastal Storms

4.6.1 Introduction

It is generally assumed that strong cyclones will generate high winds (most often in association with other synoptic features), and winds over the open ocean will transfer energy into the water and will result in waves along the coast. The previous section found this relationship to be weak went simply linking the date values of strong cyclones, extreme winds and large wave events. This method appears insufficient to capture the true inter-relationships between these storm proxies.

An improved method to explore – in greater depth – the connection between strong cyclones, extreme onshore winds and LWE, off the eastern North Island is case study analyses. Subsequently, a case study is presented for each coastal storm type (Trough/Ridge, East Coast Low, Subtropical Low, Tasman Sea Low, and Cyclone-Anticyclone Pair).

4.6.2 Methodology

The LWE dataset spans the 1979 to 1998 time period. A representative from each coastal storm type was selected within these years and became an individual case study. For each coastal storm (Trough/Ridge, East Coast Low, Subtropical Low, Tasman Sea Low, and Cyclone-Anticyclone Pair), the weather sequence in the database was analysed and a causative cyclone identified. This cyclone track was then extracted from the cyclone tracks dataset and plotted. From the dates of this cyclone track (and the dates of the coastal storm), the extreme winds dataset was searched for corresponding dates, extracted and plotted along side the storm track. The large wave dataset was then searched to see if waves greater than 3 meters in height were generated during the period of the coastal storm. Therefore, each case study investigates cyclone behaviour, the distribution of extreme winds, and presence of large waves. Also included in these analyses are the measured winds and pressure at Wellington and/or Gisborne, and the damage caused at the coast. Each case study is split into three sections: meteorology, oceanography, and damages.

4.6.3 Case Study One – Trough/Ridge (17-18th July 1981)

This coastal storm was characterised by an intense trough with a long fetch created on its western side. This fetch was a source region for large waves. The case study is focussed mainly on the Wellington region as continuous data wasn't collected in Gisborne during this time.

4.6.3.1 Meteorology

(a) Synoptic Environment (Weather Sequence and Cyclone Track)

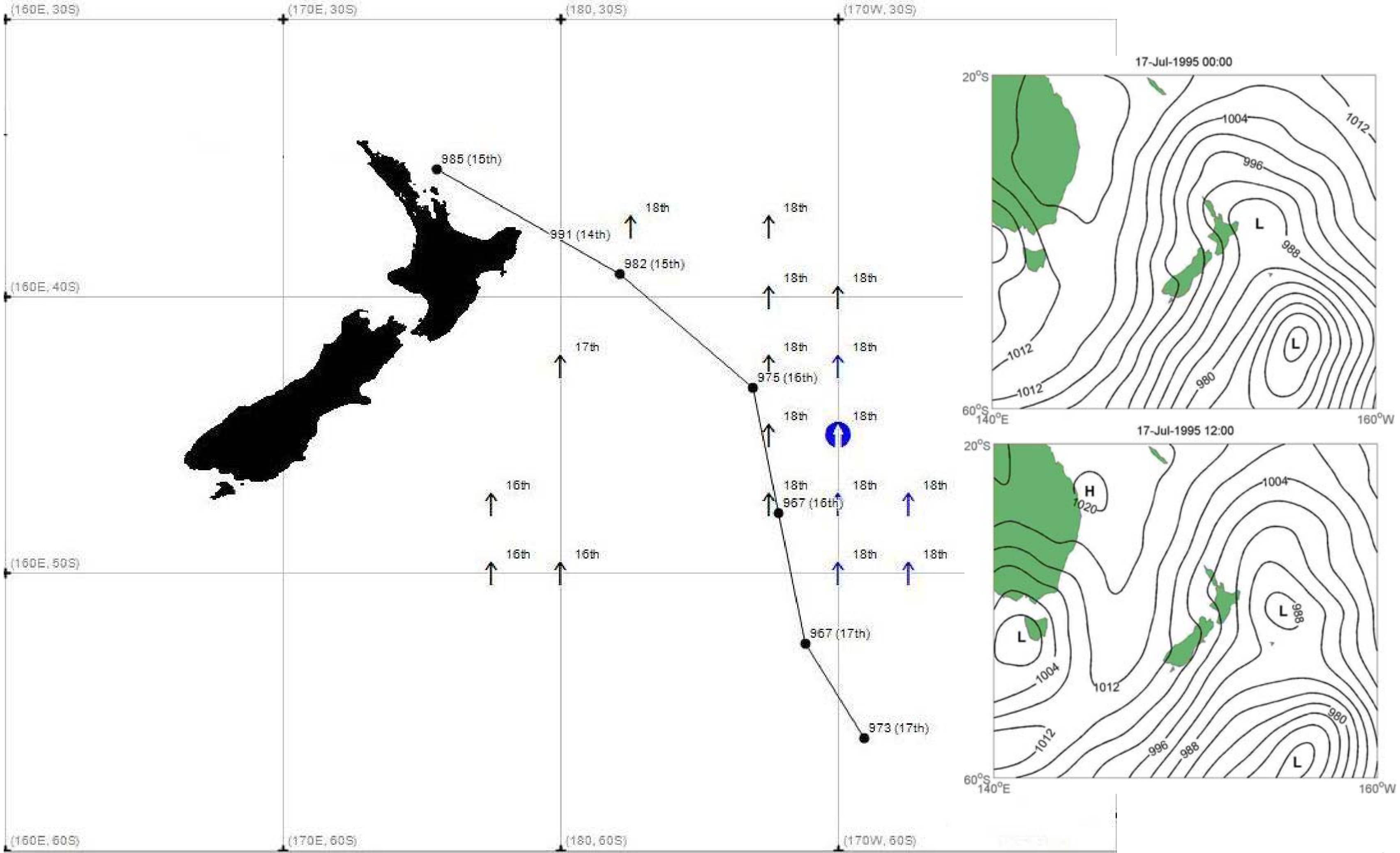
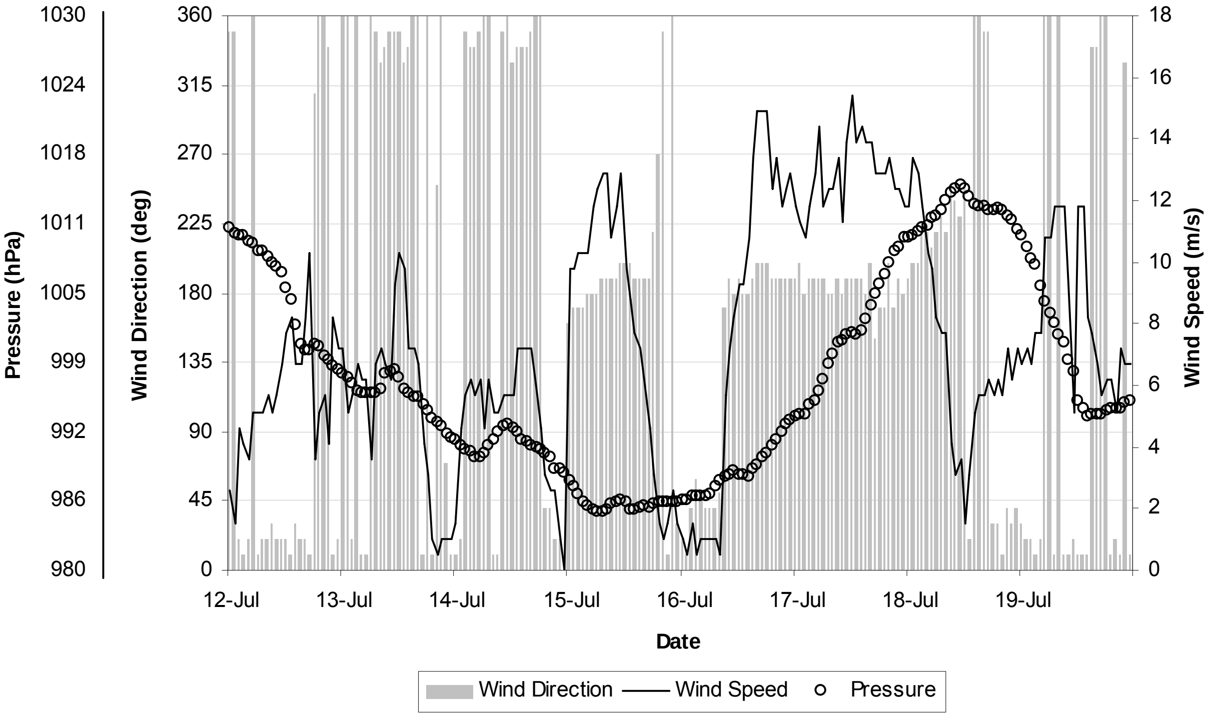


Figure 4-26 Cyclone track and distribution of extreme onshore winds for a typical trough/ridge type coastal storm, as occurred on 17th July 1995). Also shown is the associated weather map for the day of the coastal storm and time of maximum winds (17th July). The key to the coloured arrows are: black (one 12-hr time step), blue (two 12-hr time step i.e. 24 hours), orange (three 12-hr time steps), and red (≥four 12-hr time steps); and the bold arrow defines the area of maximum wind speed.



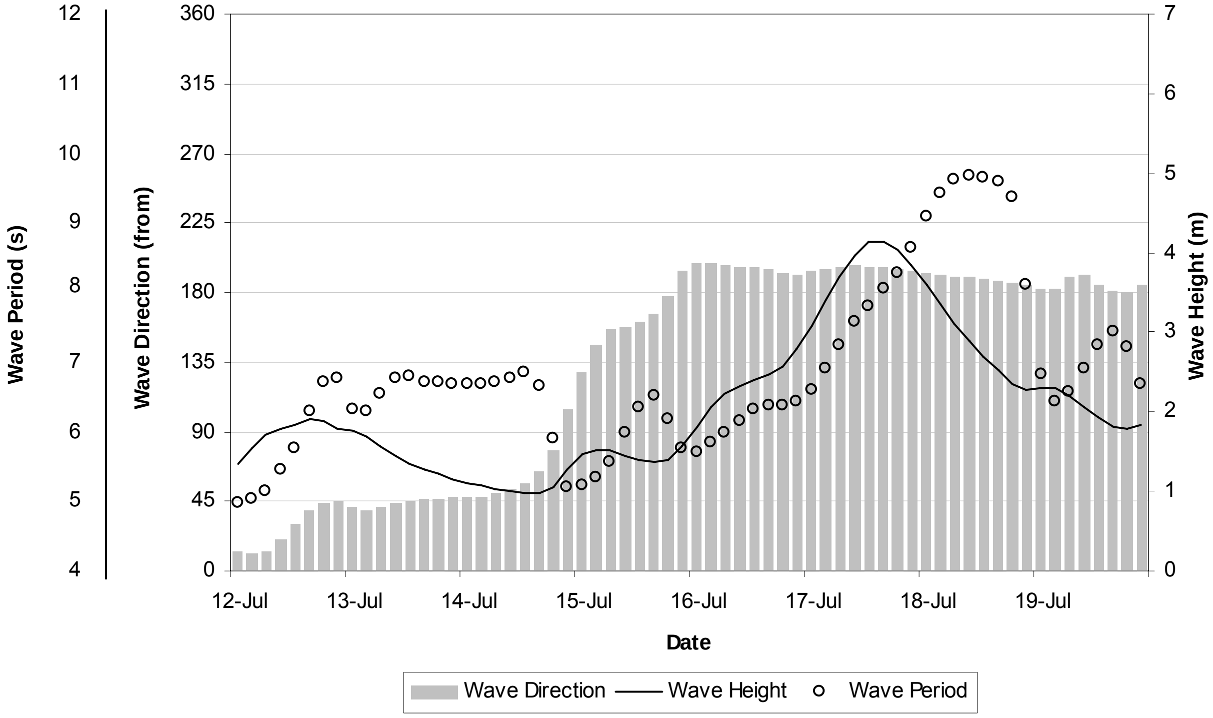


Figure 4-27 (a) Measured wind speed, wind direction and pressure at Wellington for the trough/ridge coastal storm of 17th July 1995, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (12 –20th July 1995).

A cyclone developed in the east Tasman Sea west of North Cape, and during the 15th and 16th it intensified and moved rapidly southeast-ward across NZ and past the Chatham Islands (Figure 4-26). On the 16th this cyclone was situated south of the Chatham Islands as a very deep system (<970 hPa) and a large trough extended over NZ from which a second low pressure centre developed over the North Island. On the 17th, this second cyclone was positioned directly north of the first cyclone that was now in the southern ocean near 60S. The western side of these two cyclones contained a strong pressure gradient and southwest flow that stretched from 60S up to 40S (being a very large fetch). As the second cyclone moved away to southeast (on the same path as the first cyclone) on the 18th and 19th a second burst of strong southerly winds developed but were well eastward of the Chatham Islands. The rapid southeast-ward movement of the first cyclone is captured by the cyclone track in Figure 4.26 and the pressure readings show this was indeed a deep system (982 hPa) even when it was east of the upper North Island on the 15th July. The track of the second cyclone (dashed line) followed that of the first cyclone but was further north and slightly weaker.

Thus, two cyclones formed in the space of two days in the same area west of North Cape and both followed similar tracks southeast-ward across the North Island and past the Chatham Islands. The first cyclone that went past the eastern North Island (15th-16th July) was a very intense system, whilst the second cyclone was slightly weaker and passed eastern North Island on 16th and 17th (Figure 4-26).

(b) Extreme Gradient Winds over the Sea (winds > 20 m.s^{-1})

This cyclone generated short-lived extreme winds in the area bound by 175-180°E, 45-50°S and east of Christchurch near the dateline (Figure 4-26), associated with the strong pressure gradient on the western side of the first cyclone to track past eastern NZ. The strongest oceanic winds were generated east of the Chatham Islands (over a large fetch), and were generated by the second cyclone. These winds, however, had little impact on coastal eastern NZ.

(c) Measured Winds & Pressure - Wellington

Strong winds from the south struck Wellington just before midnight on the 16th July. Over a five hour period, winds went from calm to greater than 10.5 m.s^{-1} and remained above this threshold for the next two days (Figure 4-27). The average wind speed associated with this coastal storm was 12.9 $m.s^{-1}$ with a maximum of 15.4 $m.s^{-1}$. The timing of these winds coincided with the formation of the second cyclone off the Taranaki coast, and its gradual southeast-ward movement across NZ. Given that the extreme gradient winds were remote from NZ (>175°E), there is little correlation between measured and oceanic (gradient) wind speeds. Furthermore, the extreme oceanic winds east of NZ on 16th July were associated with the first cyclone, whilst the measured winds in Wellington were associated with the crossing of the second cyclone over (and east) of the North Island.

The pressure in Wellington dropped from 1010hPa on the 12th to 985hPa on the 15th, and remained low (<990hPa) for the next 24 hours or so. This prolonged drop in pressure was caused by the passage of two cyclones in close succession over the North Island.

4.6.3.2 Oceanography – Hindcast Waves

Figure 4.27 shows that wave heights started to build significantly shortly after the rapid rise in wind speed. Waves from the south persisted above 3 meters for approximately 18 hours (short duration, like the extreme winds over the sea), peaked at 3.5 meters (average wave height was 3.3 meters), and dropped off as quickly as they had risen (i.e. very peaked distribution). The wave period distribution shows this storm was dominated by large “sea” waves, even when the largest heights were reached; that is, the swell waves of this event were smaller and arrived after the peak in height.

It was anticipated that large waves would be generated as a result of the large fetch and strong pressure gradient of this storm. However, the hindcast wave heights don’t support this assumption and therefore the duration of the extreme winds and/or pressure gradient limited wave growth. The rapid movement of the cyclones away to the southeast, and the short duration of extreme winds, supports the duration of the winds as limiting the wave generation potential for this coastal storm.

4.6.3.3 Coastal Damage

The damage potential of this storm was minor. The only recorded damage relate to a yacht being pushed up against rocks by high winds in Wellington Harbour, and power outages.

4.6.3.4 Discussion

The passage of two relatively fast-moving cyclones through the NZ region, and past the eastern North Island, generated ephemeral onshore winds both over the ocean and on land in Wellington. This short-lived nature of the winds is also mirrored in the wave pattern, with waves from the south reaching over 3 meters in height for less than 24 hours. Whilst the weather pattern displayed a large fetch with a strong southwest pressure gradient, the duration of these winds were insufficient to generate persistently high waves along the coast. Therefore, this case study that while an intense cyclone passing the eastern North Island generates strong winds offshore and a large wave event, the impact at the coast is not severe.

4.6.4 Case Study Two – East Coast Low (13-17th May 1985)

This coastal storm, identified between 13th and 17th May 1985, was described at the time (by the then Meteorological Service) as having weather conditions very similar to that of the 1968 Wahine storm. It was on this basis that this storm was selected as a case study.

4.6.4.1 Meteorology

(a) Synoptic Environment (Weather Sequence and Cyclone Track)

A cyclone formed to the northeast of East Cape (near 25S, 175W) on 9th May, and travelled southeast-ward (Figure 4-28). Through the 11th to 13th the cyclone moved southwest-ward and deepened until it was positioned over the Chatham Islands on the 14th with a central pressure of 988hPa. This westward trajectory can be attributed to a ridge of high pressure downstream of the Chatham Islands having a ‘steering’ effect on cyclone motion that deflected it back towards eastern NZ. At the same time of this retrograde movement of the cyclone, an intense Tasman Sea anticyclone was moving east- to southeast-ward (i.e. the cyclone and anticyclone were heading towards each other). On the 14th-15th this culminated in the cyclone moving up against the anticyclone (and its developing ridge extending to the southeast) and a steep pressure gradient developing between them with a strong east-southeast to southeast flow. The steepest pressure gradient occurred on the 14th-15th when the cyclone – now situated off Cook Strait (Figure 4.28) – moved westward into the eastern edge of the Tasman Sea anticyclone. During the 15th and 16th May this intense pressure gradient swung around to the south and spread up the eastern coast of the North Island as a result of the cyclone moving away to the northeast. Figure 4.28 clearly shows the strong southward trajectory and sharp turn to the west off Cook Strait.

(b) Extreme Gradient Winds over the Sea (winds > 20 m.s^{-1})

Figure 4-28 shows a large wave fetch bounded by 170-180°E and 40-50°S, corresponding to the western side of the cyclone that experienced winds greater than 20m.s^{-1} from the southeast and south during the 14th and 15th May. Immediately off the South Island, these winds persisted for up to 2 days from the southeast (14th and 15th), while the strongest winds (25 m.s^{-1}) were off Wellington's south coast and from a southerly direction (and blew for around 24 hours). These extreme winds spread as far northward as 40°S immediately off southern Hawke's Bay.

(c) Measured Wind Speeds and Pressure

In Wellington, wind speeds increased rapidly from the south on the 13th (Figure 4-29) and exceeded the threshold value of 10.5 m.s^{-1} for more than three days. Figure 4-29(a) shows a second jump in wind speeds approximately 24 hours later, with speeds rising from 18-19 m.s^{-1} to 28-29 m.s^{-1}.

For approximately 20 hours, winds exceeded 25 m.s^{-1} and had an average speed of 28 m.s^{-1}. These are intense wind speeds, and coincide with the westward movement of the cyclone from near the Chatham Islands back towards Cook Strait, which had the effect of intensifying the pressure gradient. Both the first and second jumps in wind speed occurred as pressure was dropping (Figure 4.28(b)), and the minimum pressure (997 hPa) was reached during the period of intense winds (over 28 m.s^{-1}). While the winds in Gisborne switched to the south and southwest on 16th and 17th May (shortly after the lowest pressure was reached), they didn't persist above 10.5 m.s^{-1} (Figure 4-30).

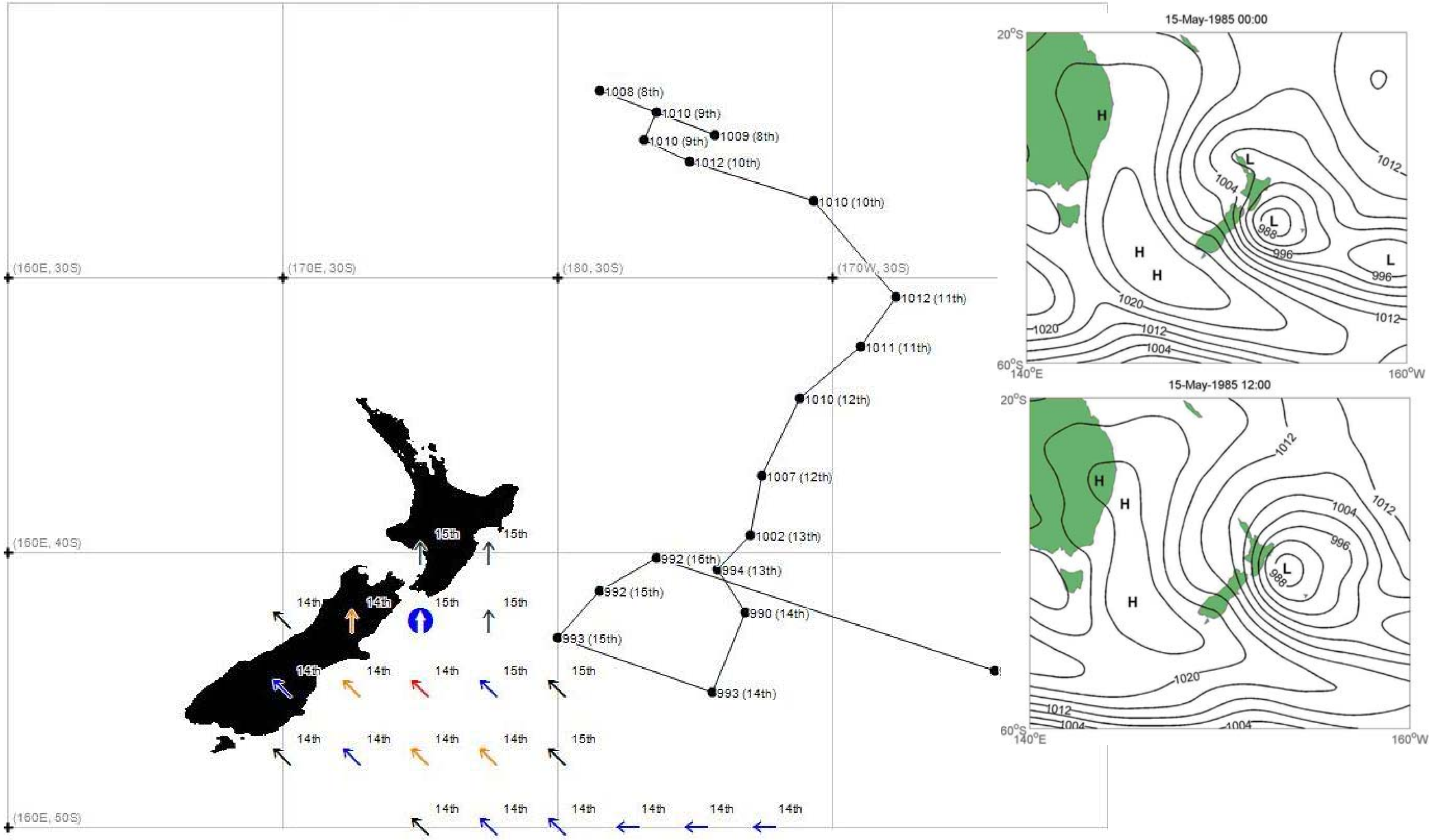


Figure 4-28 Cyclone track and distribution of extreme winds over the ocean east of NZ for the coastal storm of 13 to 17th May 1985. Inset is the weather maps for the 15th May when the strongest pressure gradient was immediately off the eastern coast of North Island. See Figure 4-26 for key to coloured arrows.

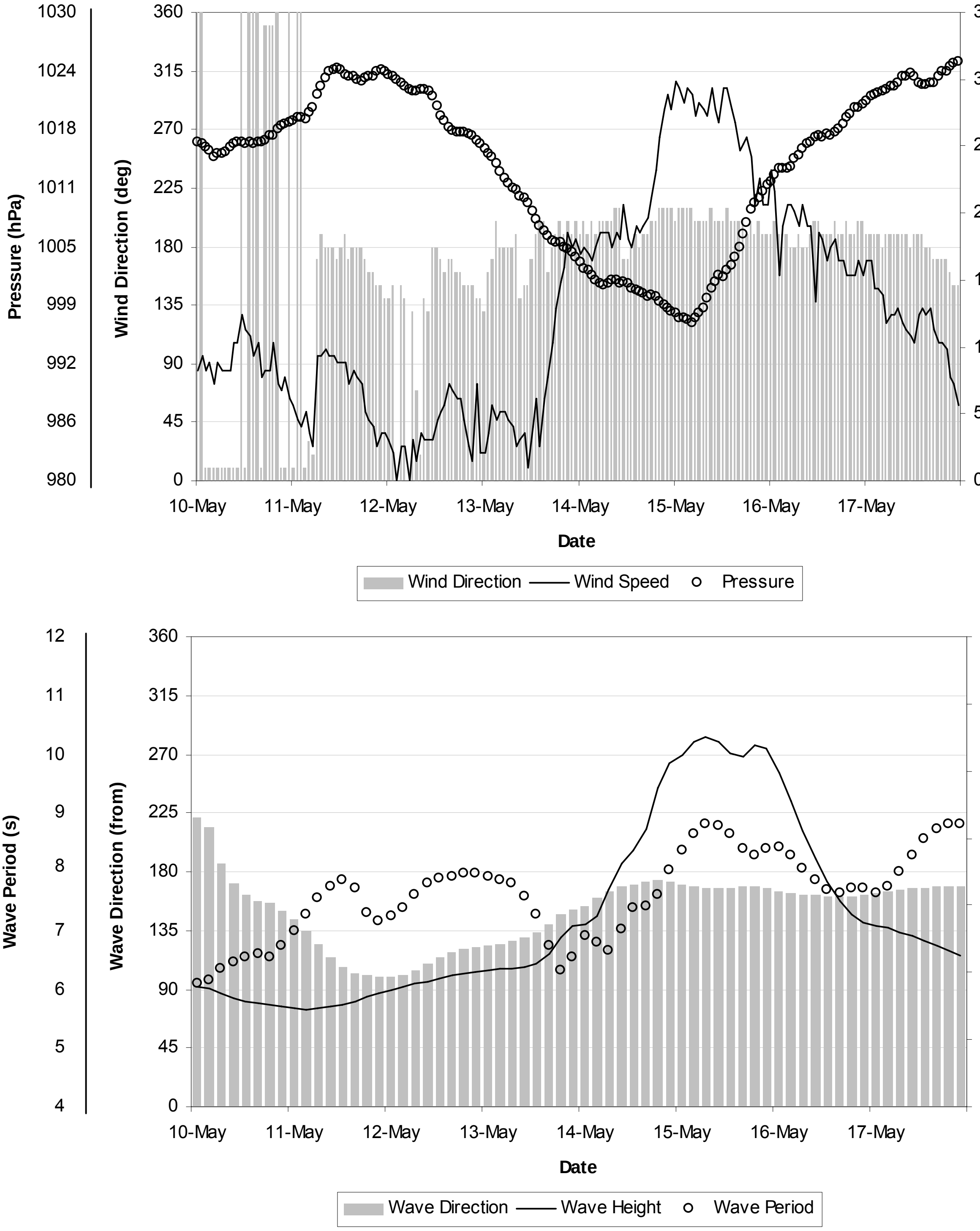


Figure 4-29 (a) Measured wind speed, wind direction and pressure in Wellington for the East Coast Low coastal storm of 15-16th May 1985, and (b) Hindcast wave height, direction, and period during the 8-day sequence of the coastal storm (10-18th Mary 1985).

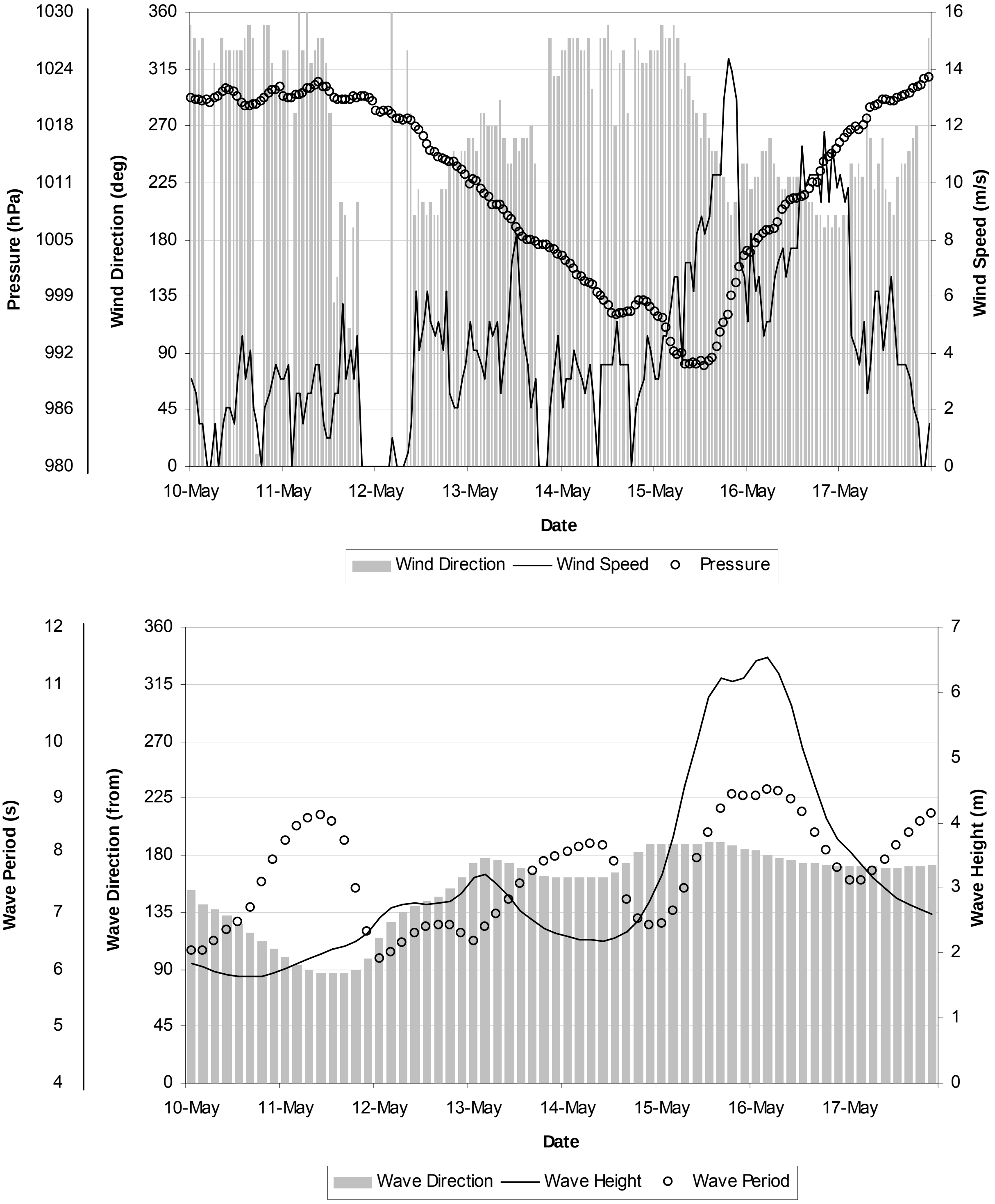


Figure 4-30 (a) Measured wind speed, wind direction and pressure in Gisborne for the East Coast Low coastal storm of 15-16th May 1985, and (b) Hindcast wave height, direction, and period for the 8-day sequence of the storm (10 – 18th May 1985).

There is excellent agreement between the extreme gradient winds and measured winds. The extreme gradient winds revealed a peak wind speed of 25 $m.s^{-1}$ off Wellington's south coast, and these magnitudes (and higher) were recorded in the Wellington region.

4.6.4.2 Oceanography – Hindcast Waves

Wave heights started to increase from the south to southeast early on the 14th May in Wellington and exceeded 3 meters for just over two days, and peaked at 5.5 meters. A weaker second peak also occurred around 12 hours later reflecting the two-step jump in wind speeds and, therefore, two pulses of wave energy. Interestingly, the hindcast waves at Gisborne peaked 24 hours after Wellington and reached as high as 6.5 meters from the south. The smaller peaks were generated by the storm as it tracked southward, and hence arrived at Gisborne first. The large and more damaging waves were generated as the storm intensified and moved back towards the coast, hence they travelled northwards up the east coast of the North Island, arriving at Wellington first. This storm also shows the longest wave periods coincide with the largest waves (Figure 4-29 and 4-30), and therefore the majority of this storm consisted of large powerful swell waves (unlike that seen in case study one) at both Gisborne and Wellington.

4.6.4.3 Coastal Damage

The damage along the coast was extensive from this coastal storm, and included:

1. Disruption to all forms of transportation (road, sea, air and rail): Wellington airport was closed and flights cancelled; roads were closed around Wellington Harbour due to waves surging over them; ferry crossings were cancelled; freighters returned to port; and railway tracks were overwashed by waves around the harbour;
2. Large storm waves destroyed the wooden accessway to Castlepoint Lighthouse, destroyed the concrete seawall at Lyall Bay and smashed the doors of the Lyall Bay Surf Club, sand was deposited to a thickness of 1 meter in Island Bay Surf Club, the storm surge lead to some houses being evacuated, and boats were ripped from moorings in Port Gisborne;

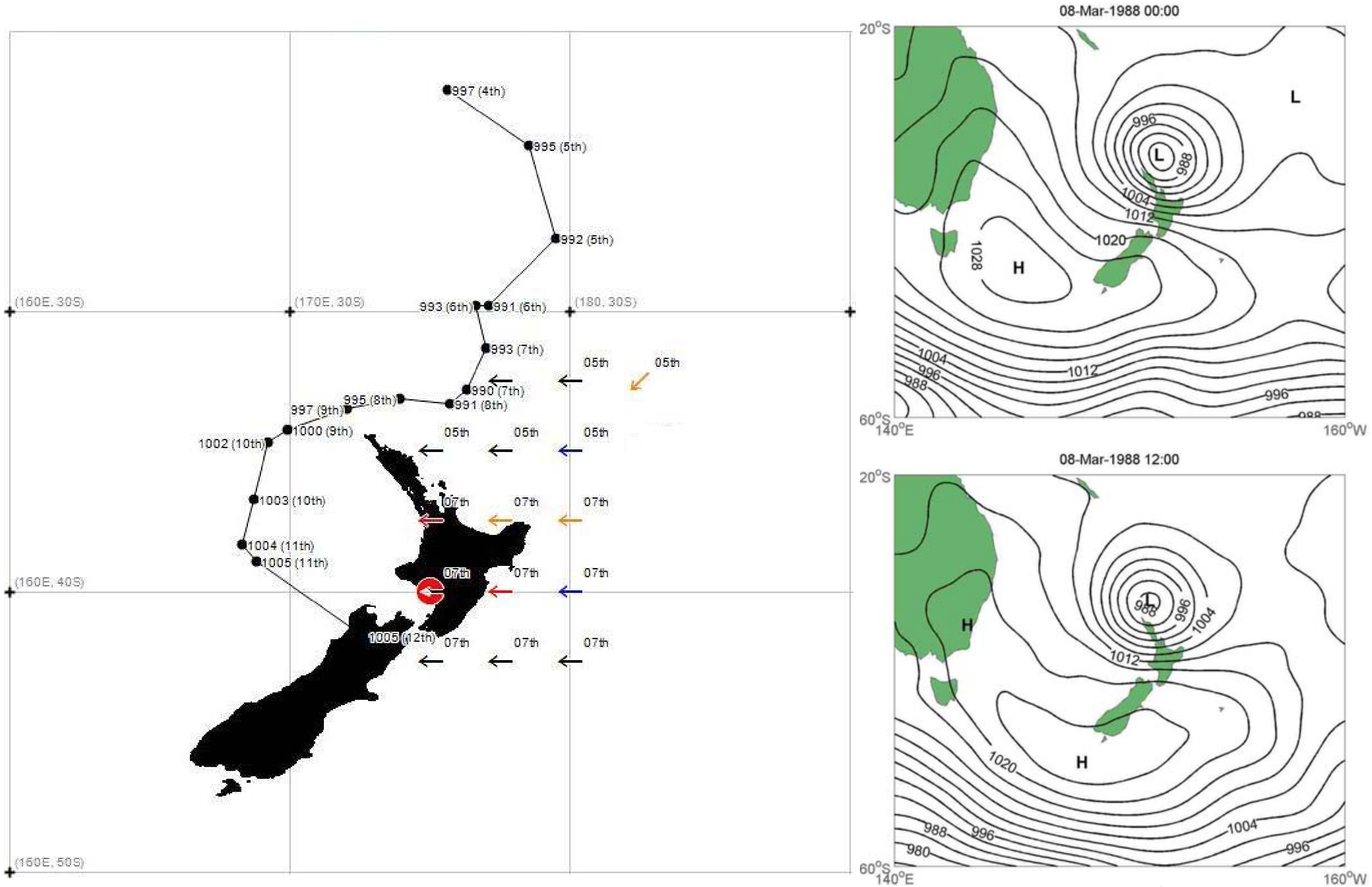


Figure 4-31 Cyclone track and distribution of extreme winds over the ocean east of NZ for the coastal storm of 7-8th March 1988. The key to the coloured arrows are: black (one 12-hr time step), blue (two 12-hr time step i.e. 24 hours), orange (three 12-hr time steps), and red (≥four 12-hr time steps); and the bold arrow defines the area of maximum wind speed. Inset is the weather maps for the 8th March when the strongest pressure gradient was immediately off the eastern coast of North Island.

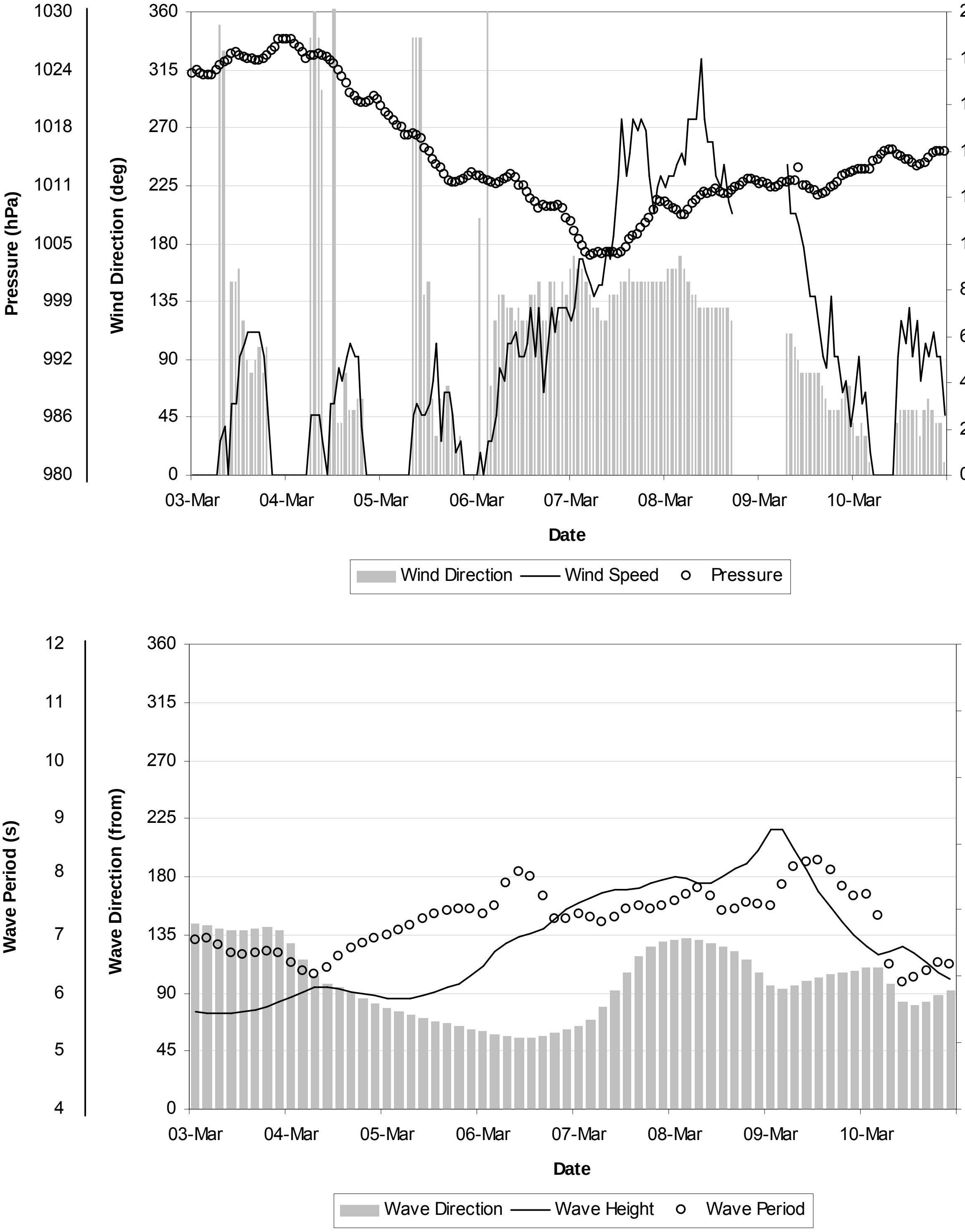


Figure 4-32 (a) Measured wind speed, wind direction and pressure in Gisborne for the subtropical low type coastal storm of 7-8th March 1988, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (3 – 11th March 1988).

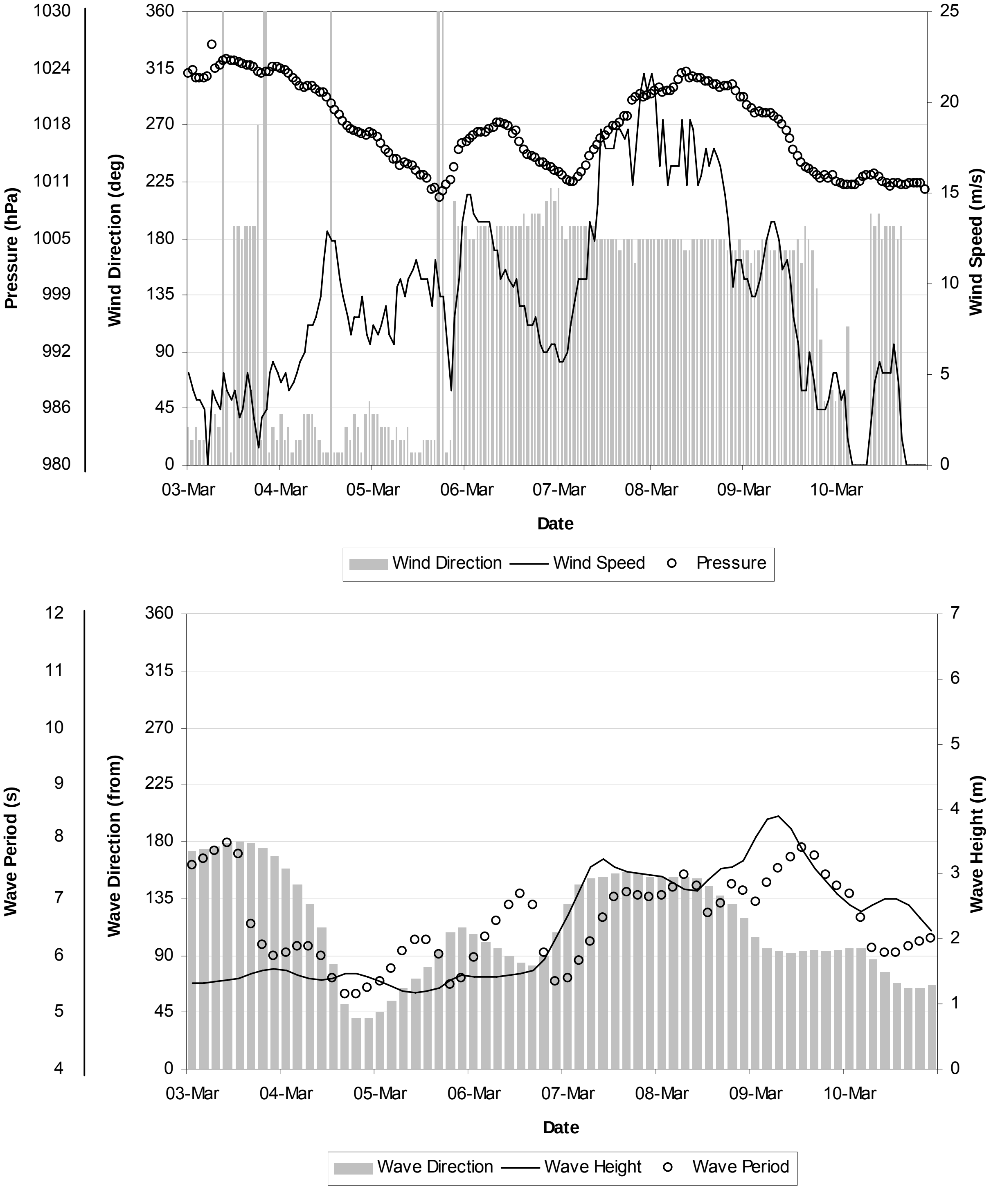


Figure 4-33 (a) Measured wind speed, wind direction and pressure in Wellington for the subtropical low type coastal storm of 7-8th March 1988, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (3 – 11th March 1988).

3. Houses lost roofs and there were widespread power failures.

4.6.4.4 Discussion

This intense coastal storm is an excellent example of the storm type East Coast Low, and shows very close agreement between cyclone track, extreme gradient winds, measured winds, and hindcast waves. The magnitudes of the winds, both over the sea and on land, and the large waves they generated, combined to make this a severe and damaging coastal storm in both Wellington and Gisborne.

4.6.5 Case Study Three – Subtropical Low (7-8th March 1988)

This case study covers ex-tropical cyclone Bola that has gone down in NZ history as one of the worst storms to affect the eastern North Island. It was a devastating event in the Gisborne region and led to a state of emergency situation due to extreme flooding. This storm has been well studied from a flooding perspective (e.g. Sinclair, 1993), but little as a potentially damaging coastal storm.

4.6.5.1 Meteorology

(a) Synoptic Environment (Weather Sequence and Cyclone Track)

This cyclone formed north of Fiji on the 24th February and travelled southwest-ward to Vanuatu (see Sinclair, 1993 for full track). During 2-5th March, tropical cyclone Bola headed southward toward NZ, transitioned into an extratropical cyclone, and began intensifying again. On the 5th and 6th March, this intensifying cyclone moved slowly towards the North Island (Figure 4-31), which had large anticyclones both to the west (Tasman Sea) and east.

During 7th and 8th March, this cyclone hovered around North Cape (near stationary) whilst the Tasman Sea anticyclone strengthened and extended a ridge eastward to cover the South Island. This ridge effectively blocked any southward movement of the cyclone, and deflected it westward into the Tasman Sea. These two features – strong cyclone over the North Island and intense anticyclone over the South Island – created a steep pressure gradient and strong easterly flow over the North Island on the 7th and 8th March.

The cyclone track is shown in Figure 4-31 from the 4th March heading southward to northern NZ, then southwest-ward past North Cape into the Tasman Sea. It clearly captures the slow motion of the cyclone near North Cape on 7th and 8th March by the clustering of track points.

(b) Extreme Gradient Winds over the Sea (winds > 20 m.s^{-1})

A well-defined area of extreme (onshore) easterly winds is shown in Figure 4-31 off the eastern North Island. Over the upper eastern North Island (East Cape to Napier) these winds persisted for more than 24 hours on the 7th March and reached speeds of up to 24 m.s^{-1}. These winds correspond to the eastern and southern side of the cyclone when it was situated north and east of North Cape. It should be noted that extreme winds also occurred off the west coast of the North Island but are not shown here as they have no relevance to the east coast. Furthermore, the most persistent and strongest winds occurred in the southern Taranaki region.

(c) Measured Winds & Pressure

Winds from the southeast started affecting the Gisborne region on the 6th March and reached the threshold value for a coastal storm (> 10.5 m.s^{-1}) around noon on the 7th (Figure 4-32). They continued for the next 34 hours with an average speed of 13.6 m.s^{-1} and reaching up to a maximum of 18 m.s^{-1}. However, these values are not true reflections of the wind strength as the anemometer failed for a limited period during this coastal storm (most likely from extreme wind speeds).

The winds from Wellington, interestingly, were all from the south during this storm (Figure 4-33) and averaged 17.3 m.s^{-1} (maximum of 21.6 m.s^{-1}). Both weather sequences and extreme winds display a strong easterly flow while measured winds in Wellington were clearly southerly. This storm, therefore, provides an excellent example of the winds in Wellington being deflected by topographic influences. Furthermore, wind speeds in Wellington reached above 20 m.s^{-1} to attain magnitudes similar to those occurring offshore (extreme gradient winds).

Gisborne pressure fell from 1028 hPa on the 4th to 1003 hPa on the 7th as the anticyclone influencing the North Island moved away eastward and the northern cyclone stretched onto northern NZ. Pressure hovered around the 1004 hPa mark for approximately 10 hours and then began to increase. It was during this time the wind speed doubled in strength.

4.6.5.2 Oceanography – Hindcast Waves

Waves started to increase in height on the 5th March and initially came from the northeast. These waves then shifted around to the east and southeast on the 7th, and then back again to the east on the 9th March (Figure 4-32). Waves greater than 3 meters occurred early on the 7th and hovered around 3 to 3.5 meters until midday on the 8th, and then increased further (as waves arrived from the east) i.e. bi-modal. Wave height peaked at 4.3 meters and then rapidly decreased (i.e. gradual rise with two peaks, rapid fall). Wave periods indicate this storm was dominated by sea waves, and the longest periods weren't associated with maximum wave heights.

Waves in Wellington also show the twin peaks in height, the first from the southeast and the second from the east (Figure 4-33). However, the waves weren't maintained above the 3 meter mark between these peaks. Wave heights peaked at 3.9 meters, and like off the Gisborne coast, began to drop off rapidly, and wave periods indicate "sea" waves dominated.

4.6.5.3 Coastal Damage

This coastal storm created widespread flooding throughout the Gisborne region, including along the coast north of Gisborne. Most media covers the damages associated with the flooding which lead to a state of emergency being declared. The only other coastal damages found within newspaper reports were the cancellation of Cook Strait ferries.

4.6.5.4 Discussion

Ex-tropical cyclone Bola tracked towards NZ, and during its slow progress to the north of NZ generated extreme onshore winds over the seas east of the North Island. These winds created a prolonged period of large waves along the east coast of the North Island. The true damage potential at the coast is difficult to assess because the widespread devastation associated with flooding dominated the media coverage.

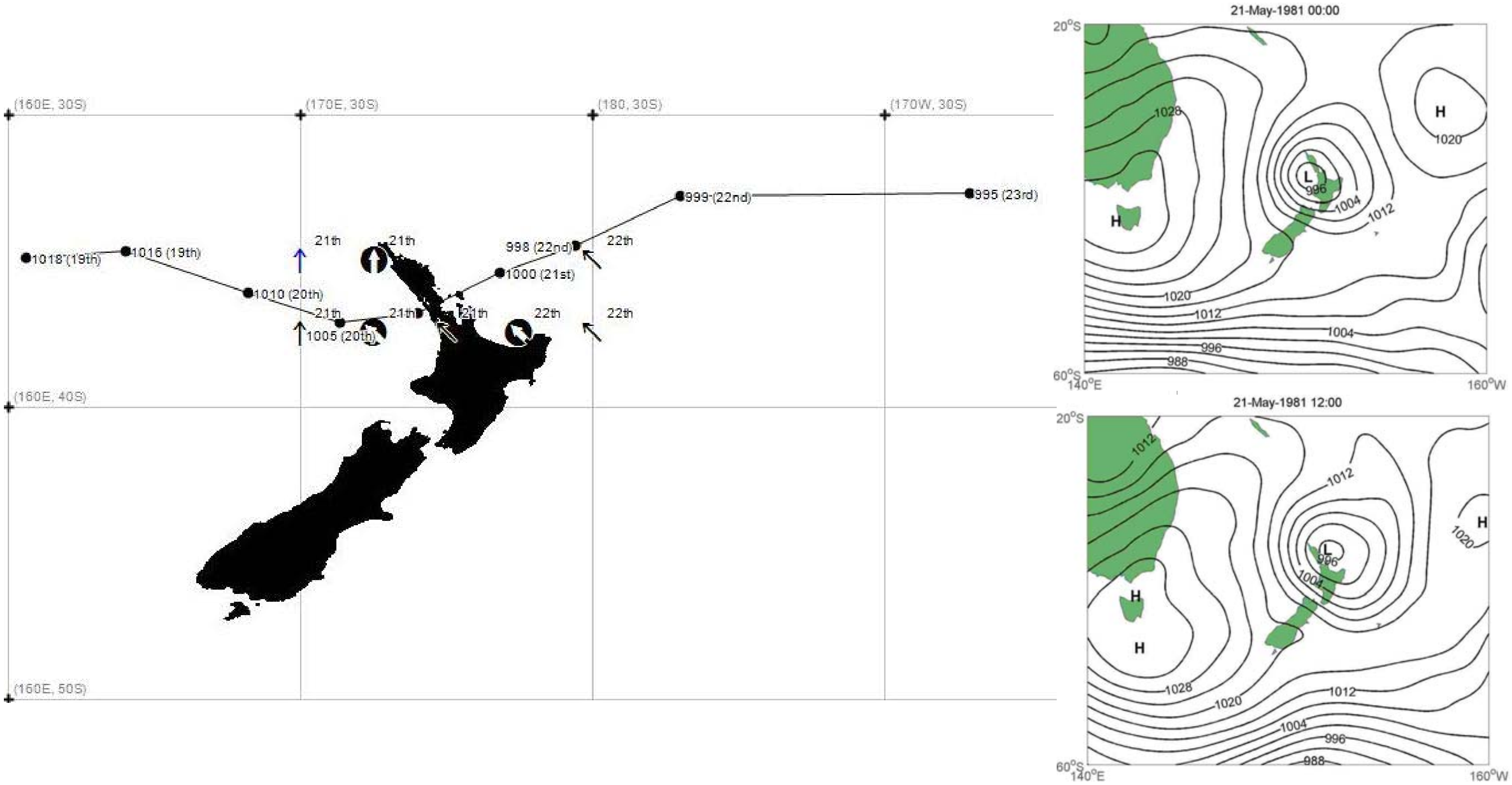


Figure 4-34 Cyclone track and distribution of extreme winds over the ocean east of NZ for the coastal storm of 20-21st May 1981. The key to the coloured arrows are: black (one 12-hr time step), blue (two 12-hr time step i.e. 24 hours), orange (three 12-hr time steps), and red (≥four 12-hr time steps); and the bold arrow defines the area of maximum wind speed. Inset is the weather maps for the 21st May when the strongest pressure gradient was immediately off the eastern coast of North Island.

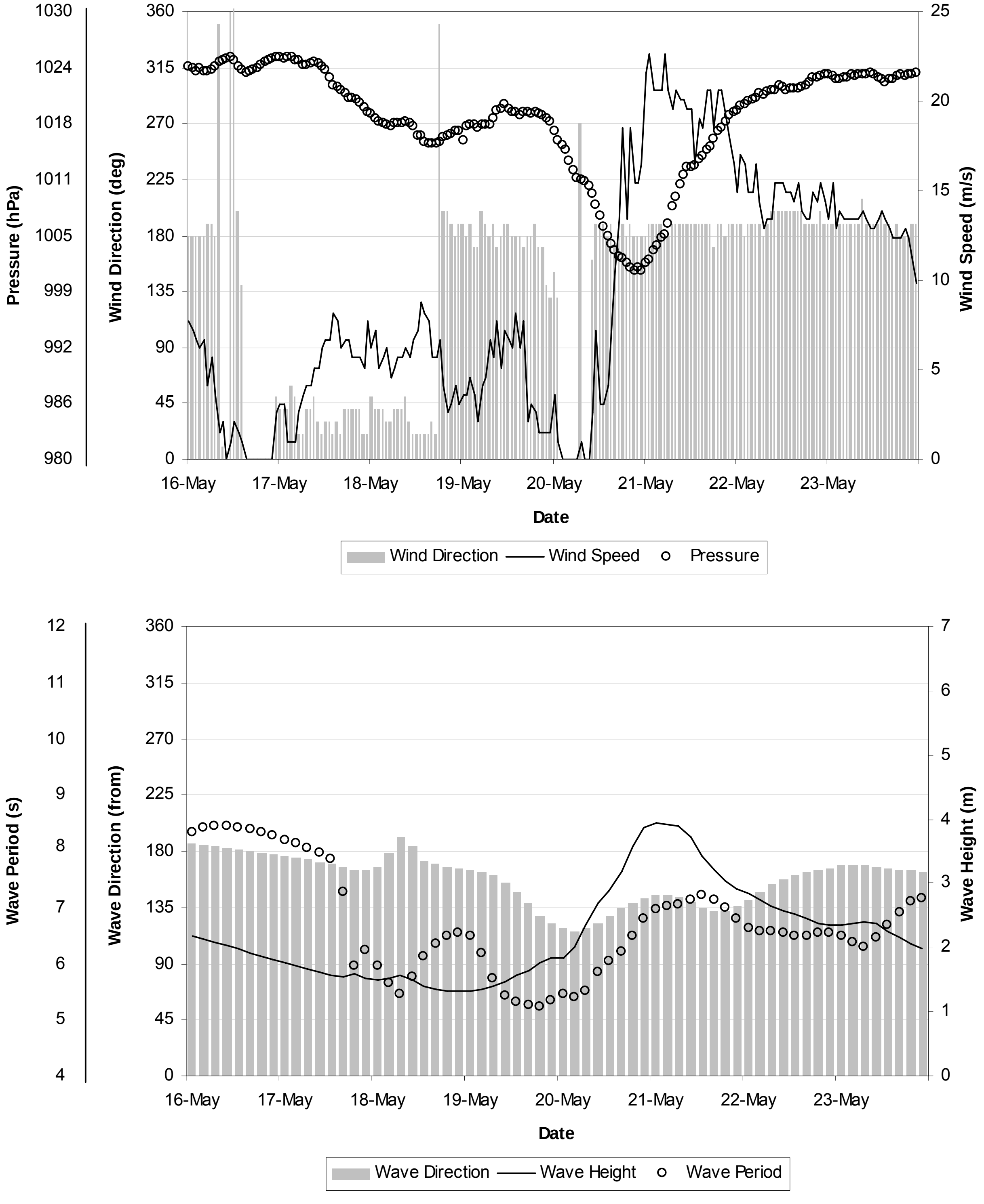
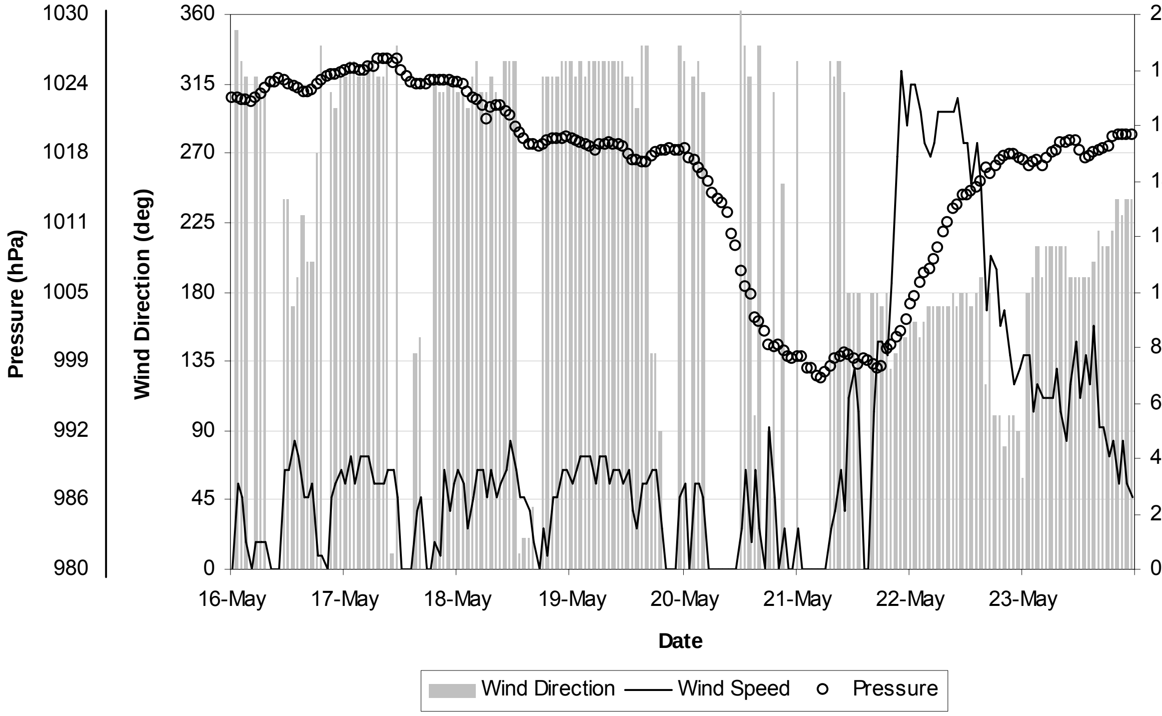


Figure 4-35 (a) Measured wind speed, wind direction and pressure in Wellington for the Taman Sea Low coastal storm type of 20-21st May 1981, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (16 – 24th May 1981).



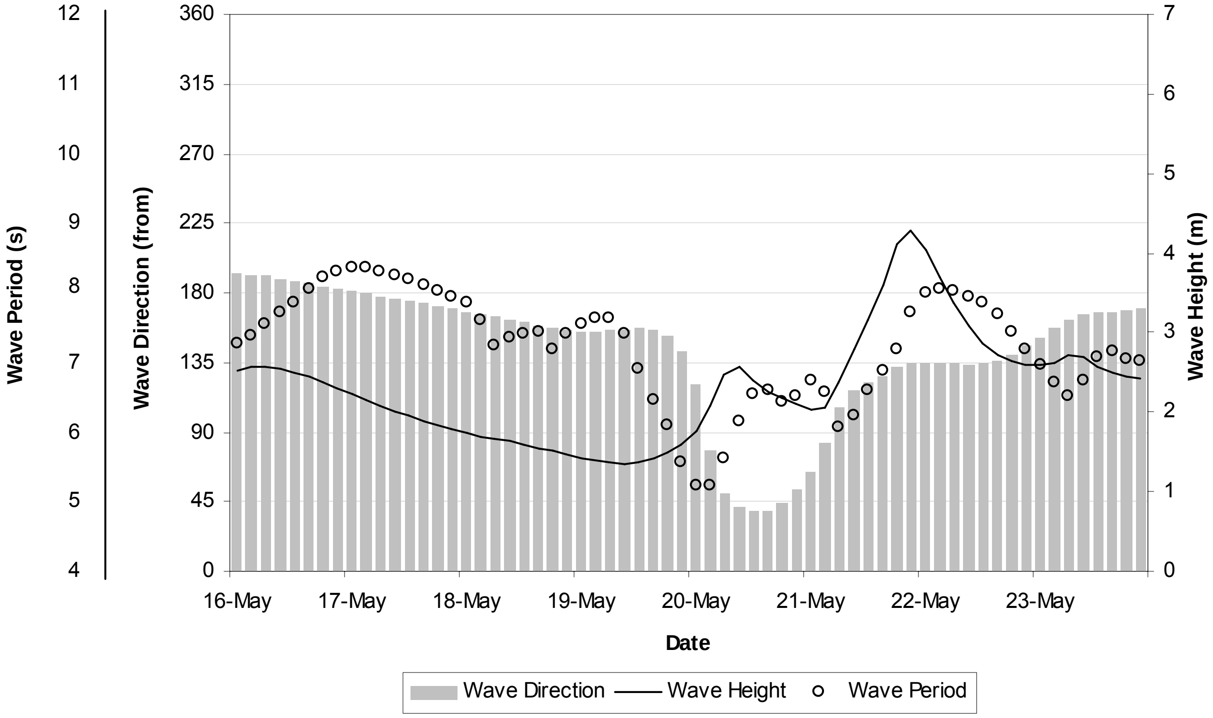


Figure 4-36 (a) Measured wind speed, wind direction and pressure in Gisborne for the Taman Sea Low coastal storm type of 20-21st May 1981, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (16 – 24th May 1981).

4.6.6 Case Study Four – Tasman Sea Low (20-21st May 1981)

This storm is representative of the type Tasman Sea Low.

4.6.6.1 Meteorology

(a) Synoptic Environment (Weather Sequence and Cyclone Track)

A cyclone developed in the central Tasman Sea on the 19th and travelled eastward to sit off the Taranaki coast during the 20th (Figure 4-34). During this period, the cyclone deepened slightly and had an anticyclone both upstream and downstream of it. The eastward progress of the Tasman Sea cyclone was impeded by the downstream anticyclone, whilst the intense upstream anticyclone was progressing across the south Tasman Sea and spreading a ridge over the South Island. This situation of a slow-moving cyclone and moving anticyclone upstream created a strong pressure gradient and east to southeast flow through the Cook Strait region. This strong flow affected the Wellington region throughout the 21st as the cyclone moved slowly northeast-ward and eventually spread up the eastern North Island (Figure 4-33). The storm track shows the initial eastward movement, the slow progress during the 20th, and the northeast-ward motion across and away from NZ (Figure 4-34).

(b) Extreme Gradient Winds over the Sea (winds > 20 m.s^{-1})

Extreme winds from this cyclone were of short duration (occurring in only one time step) and mostly concentrated off the western coast of the upper North Island (Figure 4-34). These winds correspond with the western side of the cyclone which contained the strongest pressure gradient. While a steep pressure gradient is also seen in the Cook Strait area (Figure 4-33), no extreme winds were found here. This situation indicates the strongest winds are located in the region where the edges of cyclones and anticyclones converge. However, southeast winds above 20 m.s^{-1} were generated over and off East Cape on the 22nd when the cyclone moved away northeast-ward.

(c) Measured Winds & Pressure - Wellington

The wind in Wellington swung around to the south at midday on 20th May and had exceeded the 10.5 m.s^{-1} threshold approximately 6 hours later. These southerly winds were sustained for the next three and half days, and over which the average speed was 16 m.s^{-1} and peaked at 22.6 m.s^{-1} (Figure 4-35). Figure 4-35 shows measured winds in Wellington exceeded 20 $m.s^{-1}$ and coincided with the time of extreme pressure gradients through Cook Strait. Thus, while no extreme gradient winds were identified offshore, they were measured over land. This anomaly is likely linked to local wind accelerations due to orography. In Gisborne, southerly winds above 10.5 $m.s^{-1}$ began just before midnight on the 22nd and persisted for up to 19 hours with an average speed of 16 $m.s^{-1}$ and maximum of 18 $m.s^{-1}$ (Figure 4-36). Unlike Wellington, these winds were initially from the southeast before turning south.

Since this was not a deep cyclone, the minimum pressure at Wellington reached 1001 hPa (998hPa at Gisborne). However pressure hovered around the 1000hPa mark on the 21st during which the cyclone crossed the North Island (Figure 4-35). The pressure distribution at Wellington shows the onset of strong winds preceded the lowest central pressure by approximately 6 hours.

4.6.6.2 Oceanography – Hindcast Waves

On the Wellington coast, waves from the southeast started increasing in height from the 20th May and exceeded the 3m threshold just over 24 hours later (Figure 4-35). They were maintained for 24 hours and peaked at 3.5 meters (average height of 3.4 meters). In Gisborne, two peaks in wave height appear. The first peak was on the 21st May when a 2-2.5 meter easterly swell arrived. The waves then shifted to the southeast and the wave heights rapidly increased again from 2m to over 4m in around 12 hours (maximum height was 4.3 m) (Figure 4-36). This is a short duration of large waves on the Gisborne coast, with heights decreasing as rapidly as they grew. This transient nature of the waves is linked to the rapid departure of the cyclone to the northeast once it had crossed the North Island. Furthermore, for both Wellington and Gisborne this storm was dominated by “sea” waves (not large, powerful swells).

4.6.6.3 Coastal Damage

There were no coastal related storm damages in either Wellington or Gisborne. It is a surprise that the intense winds experience in Wellington created few damages, given that similar magnitudes during the East Coast Low coastal storm wreaked havoc. These results suggest coastal storms with east and southeast winds (and waves) have a lower damage potential, and this relates to waves arriving obliquely on the Wellington coast rather than directly into Wellington Harbour. This obliquity of the waves will also lead to a weaker storm surge effect.

4.6.6.4 Discussion

The passage of a relatively weak cyclone past NZ created short-lived extreme winds over the oceanic region off the eastern North Island, and generated waves over 3 meters in height. And, while the wind magnitudes recorded at Wellington closely matched those of the extreme gradient winds offshore (> 20 $m.s^{-1}$), no serious coastal damages were linked to this storm.

4.6.7 Case Study Five– Cyclone-Anticyclone Pair (15-16th July 1987)

This case study was selected due to the long wave fetch and persistent easterly pressure gradient east of the North Island, being a characteristic pattern associated with the cyclone-anticyclone pair coastal storm type. This storm is studied for the Gisborne region only.

4.6.7.1 Meteorology

(a) Synoptic Environment (Weather Sequence and Cyclone Track)

During the 12 and 13th July a weak low pressure system moved northeast-ward through the Tasman Sea to the area off North Cape (Figure 4-37). On the 14th, this cyclone was just off North Cape and a large anticyclone had become established east of the South Island (with a ridge extending to the northeast and lay downstream of the northern cyclone). With an anticyclone over eastern Australia spreading over the south Tasman Sea, this cyclone became surrounded by areas of high pressure. This situation led to the cyclone becoming near-stationary off North Cape. Between the cyclone and anticyclone off the South Island a northeast airstream developed and covered the eastern North Island. During the 15th July, the anticyclone strengthened and maintained its strong ridge to the northeast that impeded any eastward motion of the cyclone. However, the cyclone extended a trough eastward and this intensified the pressure gradient immediately off East Cape.

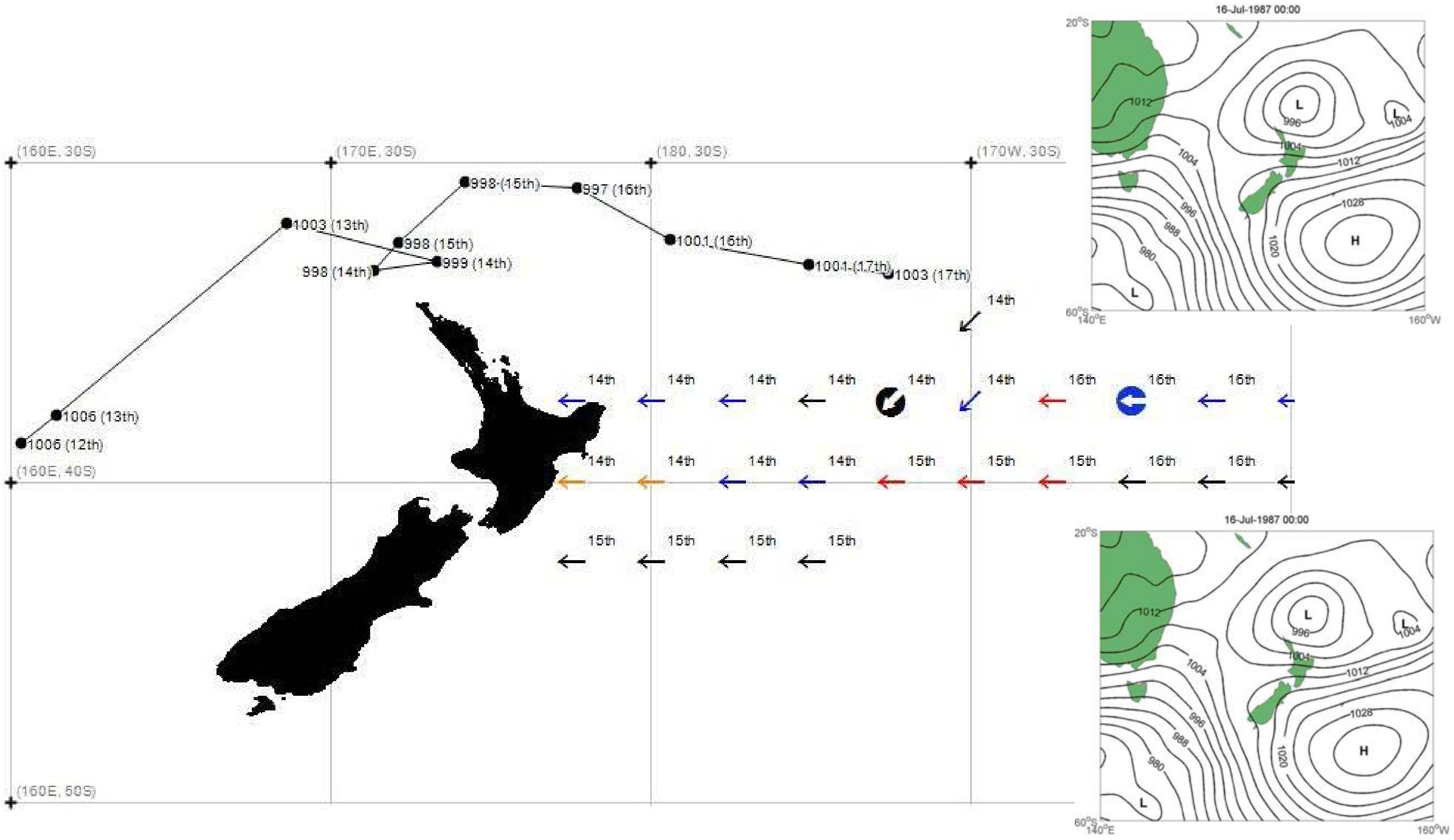


Figure 4-37 **Cyclone track and distribution of extreme winds over the ocean east of NZ for the coastal storm of 15-16th July 1987. The key to the coloured arrows are: black (one 12-hr time step), blue (two 12-hr time step i.e. 24 hours), orange (three 12-hr time steps), and red (≥four 12-hr time steps); and the bold arrow defines the area of maximum wind speed. Inset is the weather maps for the 15-16th July when the strongest pressure gradient was immediately off the eastern coast of North Island.**

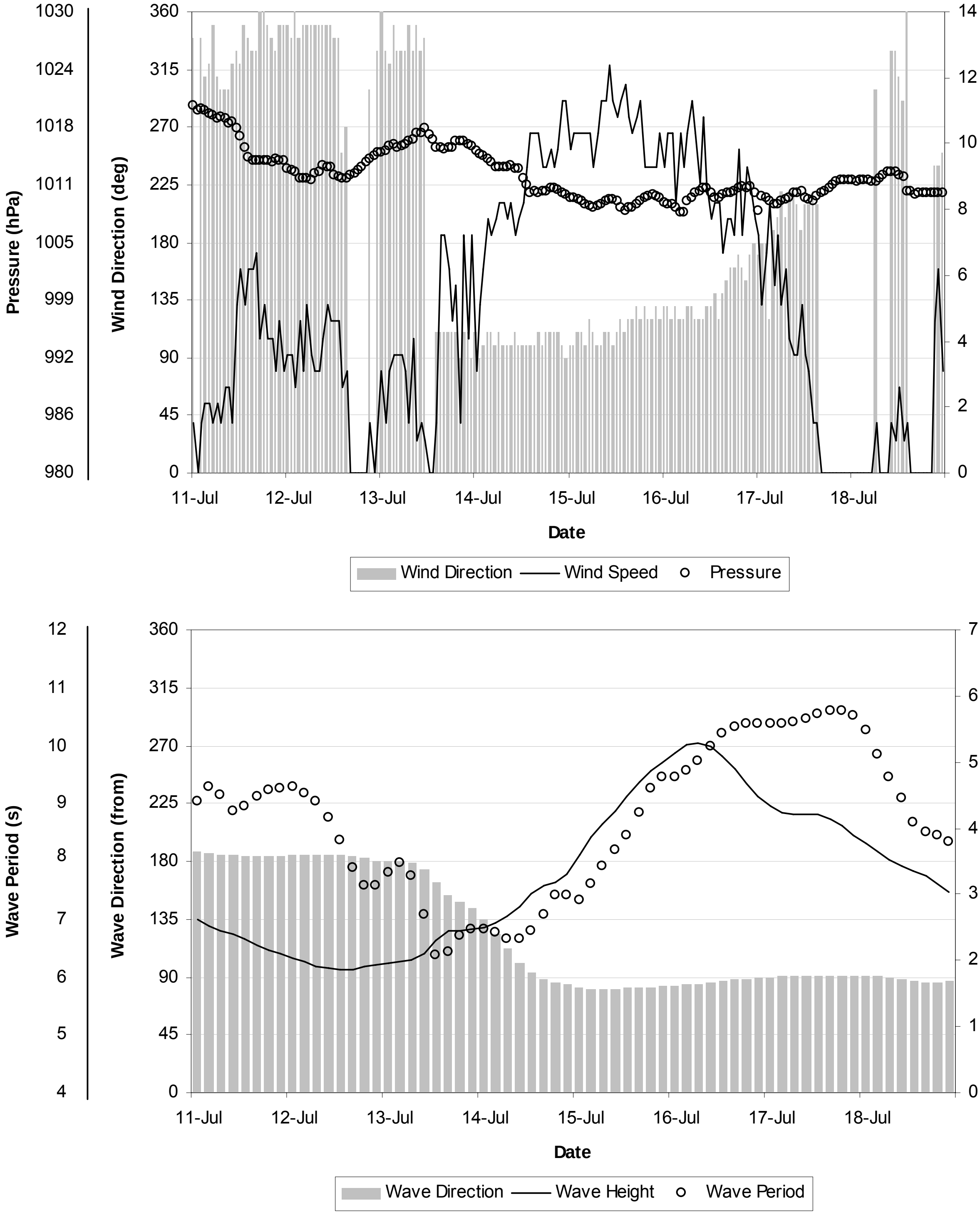


Figure 4-38 (a) Measured wind speed, wind direction and pressure in Gisborne for the cyclone-anticyclone pair coastal storm type of 15-16th July 1987, and (b) Hindcast wave height, direction and period for the 8-day sequence of the storm (11 – 19th July 1987).

With both the northern cyclone and southern anticyclone (off the South Island) being slow-moving, the strong pressure gradient and easterly flow was maintained east of the North Island through till the 17th July and spanned around 30 latitude degrees (e.g. ~160°W to eastern North Island) (Figure 4-37). It would be assumed that this large fetch and intense pressure gradient would generate large waves on the eastern North Island.

(b) Extreme Gradient Winds over the Sea (winds > 20 $m.s^{-1}$)

Figure 4-36 shows strong easterly winds over the seas off the eastern North Island between 160°W and 175°E. These winds were sustained for up to 36 hours immediately off the eastern North Island and reached speeds of 23 $m.s^{-1}$. However, the strongest and most prolonged winds occurred well east of NZ, and would result in considerable wave generation rather than strong winds over land.

(c) Measured Winds & Pressure – Gisborne

Gisborne winds fluctuated around the 10 $m.s^{-1}$ value from the east during the 15th and 16th and were consistently above 10.5 $m.s^{-1}$ for a very short period (8 hours) on the 15th (Figure 4-38a). The maximum wind speed reached was 12.4 $m.s^{-1}$. Stronger winds were anticipated given the distribution of extreme winds offshore from Gisborne. However, no such winds materialised.

The pressure started to fall late on the 13th July and from the 15th fluctuated around the 1010 hPa mark until midday on the 17th before it began to rise slowly (Figure 4-38). Since the northern cyclone was not an intense system, low pressures were not experienced in Gisborne.

4.6.7.2 Oceanography – Hindcast Waves

Waves started to build in height from the southeast but had shifted around to direct east when they exceeded 3 meters (Figure 4-38). Waves beyond 3 meters were maintained for over 36 hours and climbed to a peak of 5.3 meters. Even after the maximum wave height of 5.3 meters was reached, the waves continued to persist above 3 meters for a further 60 hours (i.e. a very gradual decline in height, long-tailed distribution). Furthermore, wave periods ranged up to 11 seconds and remained around 10-11 seconds well after the maximum heights were reached, indicating a large distantly generated (or “ground”) swell event (i.e. the waves were large, powerful swells). These distantly generated waves (from a prolonged wind event) show a more rounded height distribution and prominent long tail, unseen in any of the wave height distributions from the other coastal storms.

4.6.7.3 Coastal Damage

This coastal storm was responsible for erosion at Wainui Beach, and the large waves generated from it were noteworthy (so as to be noted in media reports). The only property damages pertain to power outages and flooding. Much like the Tasman Sea Low coastal storms, the cyclone-anticyclone pair storm type creates winds and waves that are strongly oblique to coastal Wellington and therefore won’t impact areas such as inside Wellington Harbour.

4.6.7.4 Discussion

The combination of two slow-moving systems – a large intense anticyclone east of the South Island and a northern cyclone northeast of the North Island – created a strong and persistent easterly pressure gradient over a large fetch. This strong pressure gradient created extreme offshore winds that then generated a large distantly generated swell off the eastern North Island. Furthermore, the persistence of the extreme offshore winds was mirrored in the wave data so that waves above 3 meters in height impacted the Gisborne coast for a remarkable 5 day period, and an associated gradual fall in height after the peak.

4.7 Coastal Storms and Large Wave Events

This analysis has shown that waves above 3 meters in height from the southwest through east to northeast (“large wave events”) are common phenomenon along the east coast of the North Island (annual average of 15 to 22 large wave events per year). For a short time period of only 20 years, this proxy leads to the conclusion that coastal storms are ever frequent along the eastern North Island, painting a very different picture to that of the measured wind record (Chapter 3, coastal storm database). It is possible the 3 meter criterion is too low and captures a large number of non-damaging (and distantly generated) large wave events and therefore over-estimates coastal storm activity.

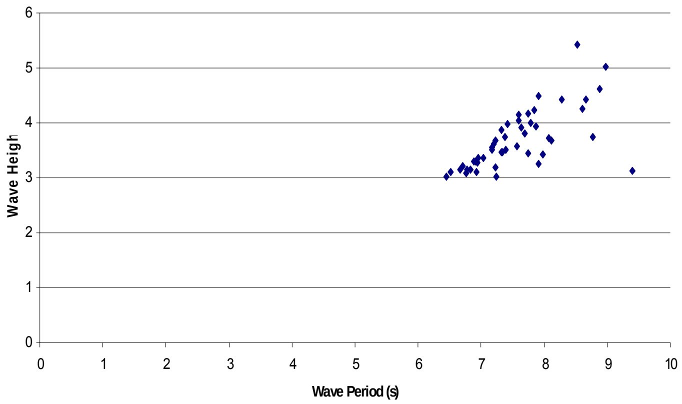
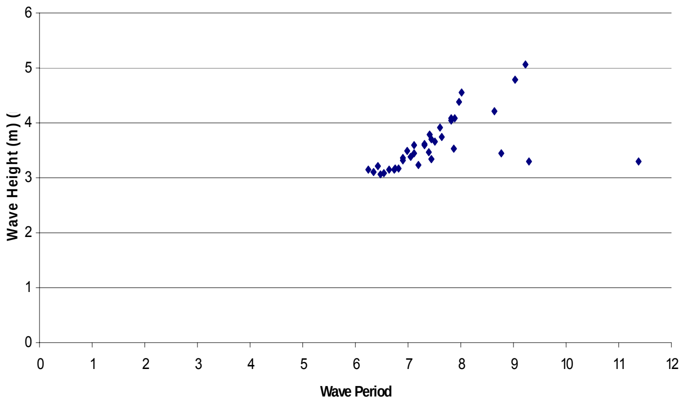
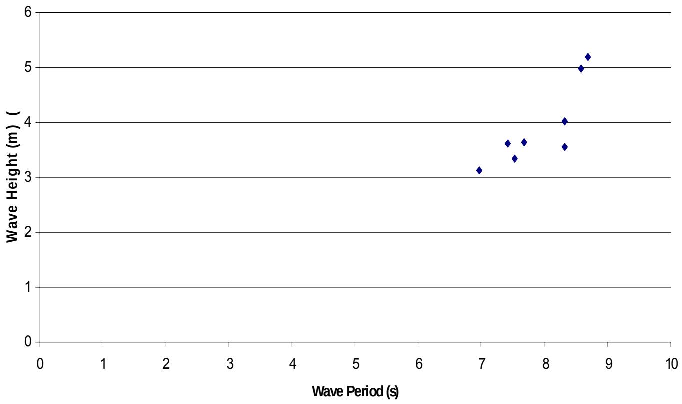
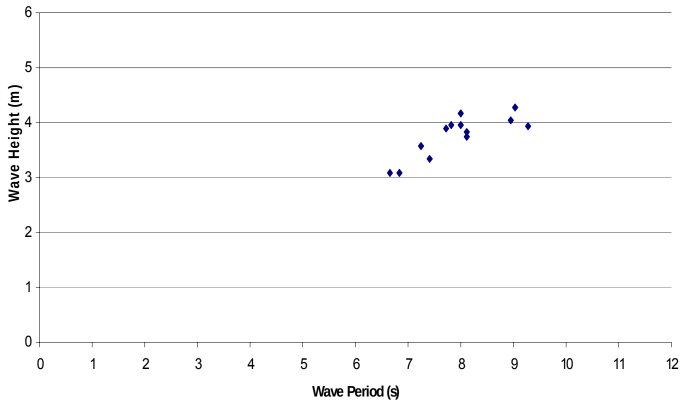
Location	Trough/Ridge	East Coast Low
Wellington		
Gisborne		

Table 4-9 Scatterplots of significant wave height and period for all LWE categorised as Trough/Ridge and East Coast Low storm types for Wellington (1979 to 1998) and Gisborne (1979 to 1991).

(a)		**Coastal Storm Type**	
Wave Property		**ECL**	**Trough/Ridge**
Max Height (m)	Average	4.1	4.3
	Max	7.1	7.4
	St.Dev	0.96	1.07
Ave. Height (m)	Average	3.6	3.7
	St.Dev	0.49	0.55
Wave Period (s)	Average	7.5	7.6
	Max	11.4	9.4
	St.Dev	1.01	0.69
Directions (from)	S	79%	90%
	SE	13%	8%
	SW	8%	2%

(b)		**Coastal Storm Type**	
Wave Property		**ECL**	**Trough/Ridge**
Max Height (m)	Average	4.4	4.85
	Max	5.39	8.3
	St.Dev	0.77	2.17
Ave. Height (m)	Average	3.76	3.93
	St.Dev	0.38	0.75
Wave Period (s)	Average	7.9	7.9
	Max	9.3	8.7
	St.Dev	0.8	0.62
Directions (from)	S	38%	63%
	SE	31%	12%
	NE	8%	25%
	E	23%	0%

Table 4-10 Summary statistics of large wave events for all the coastal storms at (a) Wellington and (b) Gisborne as associated with the coastal storm types East Coast Lows and Trough/Ridges.

On this basis, it was decided to link the large wave events with the coastal storms identified in the coastal storm database – based on measured winds in Gisborne and Wellington – to understand the degree of association and identify which coastal storms generate the largest waves. This was achieved by extracting the dates of the coastal storms at Gisborne and Wellington for the 1979 to 1998 period (the period of hindcast wave data), and searching the large wave event dataset for identical dates (or dates either side of the coastal storm). Once a match was made, the wave information was retained, and the coastal storms separated into their respective types (e.g. East Coast Low, subtropical low etc). Therefore, those coastal storms with a match to a large wave event will have information pertaining to (hindcast) wave heights, periods and directions. Their statistics of average and maximum wave heights, periods and directions were calculated and presented below.

For the Wellington coast, a total of 162 coastal storms were extracted between 1979 and 1998. Large wave events were matched to 92 of these coastal storms (57%). Of these storms, 38 were East Coast Low, 48 trough/ridge, and only 3 each of subtropical low and Tasman Sea Low. On this basis, wave statistics pertaining only to ECL and Trough/Ridge were calculated. The results are shown in Table 4-9 and Table 4-10. Based on a small sample set (86 events), it appears slightly larger waves (both average and maximum heights) are associated with the coastal storm type Trough/Ridge for the Wellington region, and these are overwhelmingly from the south. The wave periods associated with maximum wave heights are mostly less than 8 seconds (Table 4-9), indicating that troughs produce an abundance of "sea" waves rather than large swell. East Coast Lows show slighter lower maximum wave heights from the south and southeast, and the larger range of wave periods indicates a mix of sea and swell waves.

For the Gisborne coast, an even smaller dataset is used as the coastal storms were only recorded up to 1991. Therefore, for the period of overlap between Gisborne coastal storms and hindcast waves (1979 to 1991), there were 37 coastal storms and 26 were matched to large wave events (70%). Of these, 13 were East Coast Lows, 8 Trough/Ridges, 2 subtropical lows and cyclone-anticyclone pairs, and one Tasman Sea Low. Based on this very small sample set, the trough/ridge coastal storm type generates higher maximum wave heights mostly from south, southeast and northeast (Table 4-10), and the wave periods indicate a dominance of sea waves. East Coast Lows have lower maximum wave heights but a large directional spread (northeast through east to southwest), and the scatterplot (Table 1-8) shows a mix of sea and swell waves.

4.8 Usefulness of Different Storm Proxies – Strong Cyclones, Extreme Winds, Measured Winds and LWE

The use of the three different methods to explore coastal storm activity raises the question as to which proxy is most appropriate. Each proxy explored here contains deficiencies. The measured wind speed and duration thresholds (greater than 10.5 m.s^{-1} for at least 6 or 24 hours) identifies several coastal storms with low or no coastal damages, and are limited to the time period of measured wind records. The use of strong cyclones through the region has shown that a considerable amount of coastal storm activity can be linked to cyclones of any strength. The spatial domain of extreme winds was too broad and collected an abundance of winds with no direct relevance to the eastern coast of the North Island. Large storm waves (waves greater than 3 meters in height) appear to over-estimate storm activity due to the large number of events extracted from a short record and capturing of remotely generated wave events that most likely are non-damaging.

These results suggest an optimal mix or combination of the above proxies could be used to focus on and identify damaging coastal storms. To achieve this, the properties of damaging storms in the database were investigated. In this context, damaging coastal storms refers to those coastal storms that contain excerpts pertaining to beach closures, waves surging over roads, large measured or estimated waves, ferry crossing cancellations, and beach/coastal erosion. The storm type, measured wind speeds and duration, and hindcast wave conditions of these coastal storms were examined. Of the 30 coastal storms that matched the above conditions, approximately 75% involved large low pressure systems east of NZ (East Coast Low, Subtropical Low) or near North Cape (Tasman Sea Lows) and had hindcast wave heights above 3 meters for more than 24 hours. Furthermore, average wind speeds exceeded 14.5 $m.s^{-1}$ for at least 48 hours (or average speeds greater than 16.5 $m.s^{-1}$ for at least 24 hours). Based on these properties, an "optimal" proxy for identifying damaging coastal storms along the eastern North Island is suggested and contains four factors:

(1) A closed low pressure system east of the North Island and west of the Chatham Islands (e.g. between 30-50°S, 173-175°W); and
(2) Measured winds greater than 14.5 $m.s^{-1}$ for at least 48 hours (or exceeding 16.5 $m.s^{-1}$ for at least 24 hours); and
(3) Waves exceeding 3 meters for at least 24 hours; and
(4) Wind and wave directions from the southwest through east to northeast.

4.9 Summary

The North Cape area experiences large numbers of strong cyclones, especially in winter and autumn, and is favourable to cyclone formation. Oceanographic properties supporting cyclone genesis include the meandering Tasman Front and quasi-stationary (warm-cored) North Cape Eddy. These features provide sea-surface temperature gradients (warm anomalies) that can drive convection. Furthermore, cyclones that pass over these warm anomalies could undergo intensification, and this assertion is supported by a small intensification maximum in the vicinity of the warm-cored North Cape Eddy. Cyclones positioned near northern NZ are known to cause coastal storms along the eastern North Island as shown in the coastal storm type's subtropical low, Tasman Sea Low and cyclone-anticyclone pair. Therefore, the large numbers of cyclones that track past northern NZ directly influence coastal storm activity along the eastern North Island.

Considerable cyclone activity also occurs in the subtropics to the north and northwest of NZ, and contains another prominent formation zone for strong cyclones. Cyclones emanating from this area on southward and southeast-ward trajectories will impact the eastern North Island and become potential coastal storms. In fact, the most destructive coastal storms to affect the eastern North Island, to date, have all had subtropical origins. Furthermore, cyclone activity to the north of NZ spreads southward in the form of closed low pressure systems and troughs to influence NZ weather, unlike high latitude cyclone activity that is felt mainly through troughs.

Extremely important to coastal storm activity is the area of intensifying cyclones east of the North Island. These deepening systems will directly affect the eastern North Island, and whose damage potential will be greatest when the western sides of these cyclones develop strong pressure gradients.

On average, around 25 strong cyclones occur per year around NZ and are most likely in August. However, only around 25% of these cyclones are likely to generate coastal storms along the eastern North Island, meaning strong cyclones off the eastern North Island are not a pre-requisite for coastal storms. This finding indicates the paths of cyclones and their interaction with surrounding areas of high pressure are important drivers of coastal storm activity, and coastal storms can be generated by cyclones of any strength. This suggests that cyclones alone (strong or weak) may not be a good measure of coastal storm activity (especially for the eastern North Island) and that the synoptic environment these cyclones move into becomes an extremely important factor in terms of coastal storms.

Extreme onshore winds over the ocean off eastern NZ are very common from the southwest. However, they cluster in high latitudes east of the dateline and therefore the large majority of these winds have no direct relevance to eastern NZ. This feature aside, intense southwesterly winds are present off the South Island where they can cause coastal storm activity. Extreme southerly winds on the other hand, that also concentrate in the high latitudes but with lower frequencies, spread northward far enough to cover the eastern North Island. The orientation of these intense winds means they will have a large influence on eastern NZ and generate coastal storm events. These intense southwest and southerly winds develop on the western margins of southern ocean troughs that extend over NZ in combination with a Tasman Sea anticyclone. Furthermore, this Tasman Sea anticyclone determines whether the flow will be south or southwest through ridging. If the anticyclone has a ridge over or north of NZ, southwest flows develop, and if ridge is absent the flow becomes strongly meridional (i.e. southerly). These synoptic patterns strongly resemble the coastal storm type Trough/Ridge.

Southeast, east and northeast extreme winds over the ocean are largely suppressed compared to southwest and southerly winds with maximum activity remote from eastern NZ (i.e. eastward of 170°W). These remote centres of intense southeast, east and northeast winds represent distant wave generation zones rather than drivers of coastal storm activity. However, some of these intense winds do spread over the eastern North Island to show potential for coastal storm events. The synoptic patterns associated with these winds involve large intense anticyclones east of NZ with troughs or cyclones to the north or northwest so as to resemble several of the coastal storm types (Cyclone-anticyclone pair, Subtropical Low and Tasman Sea Low). Furthermore, southeasterly winds can also involve a Tasman Sea anticyclone with ridges extending to the southeast over the South Island.

Large, deep-water wave events off the eastern coast of the North Island are overwhelming from the south, and the Gisborne region experiences more LWE than any other location on the eastern North Island. This is linked to its greater exposure, being one of the eastern-most locations in NZ. This feature means the Gisborne wave climate has a large directional spread, and will experience waves from the southwest right through to the north. Furthermore, there is a distinct difference between the LWE directions (southerly-dominated) and extreme onshore winds (southwest dominance). This divergence indicates or proves that a large majority of the extreme southwest winds to the south of NZ have little influence on the eastern North Island while those from the south have a direct impact.

For the Gisborne region, the largest and most persistent waves come from the south, and long duration wave events are also common from the southeast and east. The large proportion of these latter events (southeast and east LWE) consist of distantly generated swell waves derived from extreme winds downstream of eastern NZ, and this is verified through the spatial patterns of extreme onshore winds that show maximums east of 170°W. An annual average of 23 LWE were found for the 1979-1998 period (from southwest through east to northeast directions). At least half of these come from the south whilst those from the southeast, east and northeast have an annual average frequency of only 2 events. This annual average matches that of strong cyclone activity. Approximately 75% of all LWE are from the south and southwest, and they display the following characteristics:

1. There are 12 LWE from the south per year (5 per year from southwest), and are most likely in May, June and July;
2. Peak frequencies occur in autumn and winter, where they double the activity of both summer and spring;
3. Around 20% reached heights that exceeded 5 meters;
4. Around 20% persisted for more that two days (i.e. long durations); and
5. The Gisborne coast is the most exposed to southwest waves.

LWE in the Wellington region have lower frequencies than off Gisborne but are also dominated by southerly events (approximately 80% of LWE are from south and southwest). They have an annual average frequency of 15 events and two-thirds will come from the south and cluster in autumn and winter. Furthermore, only 10% of LWE from the south and southwest have reached heights exceeding 5 meters (being half that of the Gisborne coast).

The meteorological conditions leading to LWE from the south and southwest are nearly identical and show large southern ocean troughs over or east of NZ and a large anticyclone occupying the Tasman Sea. In contrast, LWE from the southeast have low pressure centres to the east and northeast of the North Island (i.e. involve subtropical or Tasman Sea weather systems as opposed to southern ocean features). These southeasterly pressure gradients are created by the presence of an anticyclone that is located in the south Tasman Sea or south of the Chatham Islands. The patterns associated with east and northeast LWE failed to some meteorological conditions with east and northeast pressure gradients. This anomaly appears related to a large majority of these LWE being remotely generated, and for which the use of local weather patterns at the onset of LWE will be inappropriate as they will not contain the forcing mechanism.

The relationship between all three storm proxies – strong cyclone tracks, extreme onshore winds, and LWE – is strong on an individual coastal storm basis (i.e. case-by-case basis). Such case studies suggest that the coastal storm type East Coast Low generates the largest (and most powerful) swell waves and therefore have the highest damage potential. This is particularly true when the cyclone east of NZ intensifies and is slow-moving. Furthermore, the wave characteristics of Troughs, Tasman Sea Lows, and Subtropical Lows indicate they produce predominantly “sea” waves rather than powerful swells.

Coastal storm activity has been explored three ways: high winds, strong cyclones and large wave events. It appears that each proxy has drawbacks. The results suggest the least favourable proxy is strong cyclones since a large majority of coastal storms identified from wind thresholds weren’t linked to strong cyclones. However, the selection of coastal storms based on wind speed and direction thresholds is subjective itself, and renders many non-damaging coastal storms. Furthermore, the main drawback of using large wave events, based solely on wave height, is the capturing of distantly generated wave events that have a low damage potential. These drawbacks suggest that a refined definition of a coastal storm could be found by using an optimal mix of the three proxies. For example, to select only those coastal storms with a high damage potential, a coastal storm definition should include the minimal requirements of (a) an area of low pressure with a closed circulation located off the east coast of NZ (but west of the Chatham Islands; (b) the area east of NZ (but west of Chatham Islands) contains extreme onshore winds above 20 m.s^{-1}, and (c) in-situ winds of at least 10.5 m.s^{-1} (or 14.5 m.s-1) for at least 12 hours.

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5 CONCLUSIONS

A high quality digital coastal storm database has been produced for the eastern North Island for the period 1930 to 2005. It visually displays storm meteorology through an 8-day animation of weather maps, and graphics pertaining to measured wind speeds, pressure, rainfall and hindcast wave data. A list of all the damages and impacts (some of which include images) associated with the storms completes the database. As data becomes more readily available, it would be beneficial to other storm components including a storm track graphic, storm surge values, and real-time wave data.

This database has defined a set of coastal storm types for the eastern North Island. The five coastal storm types are Trough/Ridges, East Coast Low, Tasman Sea Low, Subtropical Low, and Cyclone-Anticyclone Pair. Trough/ridge and East coast low types are the dominant patterns, while Tasman Sea Lows, subtropical lows, and cyclone-anticyclone pair types represent between 2 and 5% of all coastal storms. The Gisborne region experiences around 3 coastal storms year, whilst the Wellington region gets 8 coastal storms per year.

The Trough/Ridge storm type contains large troughs, primarily from the southern ocean, over or east of NZ (no closed isobars). They interact with Tasman Sea anticyclones to create high winds in the NZ area. They often have long fetches, at times stretching from 40-55°S, and this feature means this storm type is capable of generating large waves along the eastern North Island coast. The Trough/Ridge storm type represents 47% of all coastal storms that have affected the Gisborne and Wellington region.

East Coast Lows represent 43% of coastal storms and involve large low pressure systems off the eastern coast of New Zealand. The cyclones involved are of two types: already established low pressure systems that have travelled into the NZ region, or they develop closed structures immediately off eastern NZ primarily from southern ocean troughs. Those cyclones that are distantly generated are derived from three main areas in the Tasman Sea (off the Sydney-Melbourne coast, west of North Cape-Auckland and west of Cook Strait) or two zones in the subtropics (near New Caledonia, and north of NZ). Using the peak wind speed as a measure of intensity, East Coast Lows generate the largest number of intense storms since one quarter of East Coast Low storm events registered wind speeds that exceeded 22.5 $m.s^{-1}$. Furthermore, the three most intense storms off eastern NZ were East Coast Lows from the subtropics.

The Tasman Sea is a large supplier of cyclones to the NZ area. However, the general pattern revealed from the storm meteorology analyses shows these cyclones have largely weakened by time they arrive near NZ and this pattern was also revealed by hemispheric studies and analyses of strong cyclones around NZ. Since only around 10-15% of Tasman Sea cyclones intensified over or east of NZ, this indicates weakened Tasman Sea cyclones are a major contributor to storm conditions for the eastern North Island mainly through their interactions with ridges or anticyclones. In other words, the meteorological situation or environment the Tasman Sea (or subtropical) cyclone travels into becomes a critical determinant to storm conditions in the NZ region.

Eastern North Island coastal storm activity is related to the presence of blocking type anticyclones east of the Chatham Islands. These anticyclones, especially in autumn months when they are north of 40°S and near-stationary, funnel or deflect cyclones from the subtropics southward towards NZ and then block eastward cyclone movement leading to stationarity. This blocking effect occurs as anticyclones on the western side of the cyclone are moving towards NZ, and the combined effect is steep pressure gradients directly over NZ.

Strong cyclones around NZ show a preference for the North Cape area. Large numbers of cyclones were found here as well as a formation maximum and minor intensification zone. Sea surface temperature gradients associated with the warm-cored North Cape Eddy and Tasman Front provide local conditions to support generation and intensification. Cyclones positioned near North Cape can be associated with coastal storms on the eastern North Island, though intense coastal storms involve cyclones situated off the east coast. Large numbers of strong cyclones also develop in the subtropics north (and northwest of NZ), and those on southward and southeast-ward paths will reach NZ. Detailed analyses of past coastal storms indicate the most intense events had subtropical origins, such that cyclonic activity north of NZ affects coastal storm activity for the eastern North Island. Furthermore, intensification of strong cyclones clusters east of NZ. Cyclones in these locations have a high damage potential for the eastern North Island if their western sides cover the NZ area. However, the link between known coastal storms and strong cyclones was weak, suggesting strong cyclones are not a pre-requisite for coastal storms but rather cyclones of any intensity.

Extreme onshore winds over the ocean off eastern NZ are overwhelmingly from the southwest and south, and there clustering in the southern ocean is caused by southern ocean troughs. The determining factor of southwest versus southerly winds appears linked to the presence of a ridge of high pressure to the north of NZ. These weather patterns show a strong resemblance to the coastal storm type Trough/Ridge. Whilst southwest winds occur more frequently, the orientation of southerly winds are more influential to the eastern North Island. It is believed the activity immediately off the eastern coast of NZ (i.e. west of 180°E) would show equal amounts of both south and southwest winds. Comparatively, winds above 20 $m.s^{-1}$ from the southeast, east and northeast have most activity remote from NZ (i.e. east of 170°W) to represent distant wave generation zones.

Large, deep-water storm waves over 3 meters in height have been common off the eastern coast of NZ over a 20-year period and consist primarily of wave from the south and southwest. Along the Gisborne coast, approximately 23 large wave events occur per year from the southwest through east to northeast, though half of them will be from direct south. Furthermore, waves from the south and southwest are more likely to bring the largest and persistent waves to the coast. The less exposed deep-water wave climate at Wellington experiences around 15 large wave events per year on average and two-thirds will be from the south. The meteorological situations creating large south and southwest wave events are southern ocean troughs, whilst the less frequent waves from the easterly quarter (mostly southeasterly) have a low pressure cyclone east or northeast of NZ as a forcing mechanism.

It is believed that a refined indicator of coastal storms for the eastern coast of the North Island could be devised based on an optimal mix of the three proxies investigated here.

5.1 Future Research Initiatives and Directions

Time constraints prevented the inclusion of several meteorological and oceanographic components in the coastal storm database. These include:

- empirical wave run-up, wave set-up and erosion/accretion calculations
- cyclone track graphics, and
- pressure tendencies and pressure differences between weather stations

Furthermore, ways to increase the upload speeds of the weather animations and weather statistic charts in the coastal storm database need to be explored and implemented. It is hoped that this be overcome by placing the database on the web where it can be easily accessed by coastal managers and users of natural hazard information.

This study suggests that cyclone formation and intensification near northern and western NZ could be related to the Tasman front (and its associated eddies) and the subtropical front further southward. Future research could focus on assessing this connection. These oceanographic features provide sea-surface temperature gradients that are an important ingredient to cyclone formation and intensification.