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NSW COASTAL INUNDATION HAZARD STUDY: COASTAL STORMS AND EXTREME WAVES

by

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Technical Report 2010/16
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Technical Report No	2010/16
Report Status	Final
Date of Issue	January 2011
WRL Project No.	09095
Project Manager	T D Shand

Title	NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves
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Client Reference	EX-6541-V00250

The work reported herein was carried out at the Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, acting on behalf of the client.

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EXECUTIVE SUMMARY

The NSW coast is subject to a generally moderate wave climate periodically affected by large wave events originating from offshore storm systems. Such events, particularly when they occur coincidently with high water levels, may cause coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety. Accurate estimation of the likelihood and magnitude of large wave events is essential for the quantification of extreme beach erosion and inundation levels, design of nearshore structures, and long-term coastal management.

Following a series of intense and damaging storms in 1974, a network of wave buoys has been incrementally established along the NSW coast by the NSW Department of Public Works. Data from this wave buoy network is presently collected by Manly Hydraulics Laboratory (MHL) for the NSW Department of Environment, Climate Change & Water (DECCW). This study, undertaken for DECCW under the Natural Disaster Mitigation Program (NDMP), has used state-wide wave buoy data collected by DECCW, Sydney Ports Corp and Queensland DERM, together with numerical hindcast and nowcast wave data from the US Oceanic and Atmospheric Administration (NOAA) and European Centre of Medium-Range Forecasting (ECMRF) to:

- Critically review the NSW coastal storm types that affect the NSW coast,
- Determine the spatial distribution and seasonal variation of these classified storm types
- Determine the statistical distribution of extreme wave height and storm duration using wave buoy data from nine locations along the NSW and southern Queensland coast spanning the years 1971 to 2009, and
- Derive extreme wave height with different return periods along the NSW coast.

Results show the mean significant wave height (H_{sig}) along the NSW coast to be relatively consistent, ranging from 1.43 m at Batemans Bay to 1.63 m at Sydney, although seasonal variation is evident in the north with larger waves occurring during autumn and smaller waves occurring during spring and summer. Storm wave data has been classified into one of the following six synoptic types: Tropical Cyclone; Easterly Trough Low; Continental Low; Southern Tasman Low; Southern Secondary Low; Inland Trough Low; Anticyclone Intensification; Tropical Low. Major storm events (H_{sig} > 6 m) in the north are a mixture of tropical cyclones, tropical lows and easterly trough lows while in the mid coast, major storm events also include inland trough lows and southern secondary lows. In the south, tropical cyclones and lows do not contribute to major storm events which are instead a combination of easterly trough lows, inland and continental lows and southern secondary lows, with a number of southerly trough (Southern Tasman) lows causing waves in excess of 5 m but not reaching 6 m. A seasonal analysis of storminess (i.e. storm frequency) shows March, July and October

to be the stormiest months, with November, December and January being the least stormy. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August.

Extreme statistics were evaluated using standard extreme values analysis techniques with a Weibull probability distribution function was found to provide the best fit to data. Based on approximately 20-30 years of data, 100 year design values can now be estimated with a 90% confidence interval of +/-10%. Results showed the mid NSW coast to exhibit the highest extreme wave climate with a 100 year ARI, one hour exceedance height of 9.0 m at Sydney and 9.1 m at Botany Bay. Extreme height decreases to the north and south reaching 8.0 m at Brisbane and 8.5 m at Eden. Both Batemans Bay and Byron Bay exhibit the lowest extreme heights of 7.7 and 7.6 m respectively. Inclusion of notable missing storm events at Byron Bay and Batemans Bay by interpolation from adjacent buoys were found to increase the extreme statistics slightly, however, the values remained within the 90% confidence limits. Wave direction was found to influence extreme values. The extreme values of wave events arriving from north of 90° were found to be approximately 25% lower of the *'all direction'* values, wave events from the east to southeast were approximately 5% lower than the *'all direction'* values and waves arriving from south of south-east were typically equivalent to the 'all direction' values and would be adopted as the design direction.

Extreme values derived using buoy measurements were compared with those derived using numerical wave datasets (NOAA WW3 and ECMRF ERA-40). Overall, the NWW3 numerical model resulted in over prediction of extreme vales in the north and under prediction in the south, while the ERA-40 dataset resulted in general under prediction of extreme values across all regions. Apart from a limited number of locations, differences were generally outside the evaluated 90% confidence limits. This result indicates that numerical models should not be used to derive extreme wave climates on the NSW coast. The ERA-40 under prediction is of key concern to coastal engineers using this data for design in other regions.

Summary of Spatial Variation in One Hour Exceedance H_{sig} along the NSW Coast

	H_{sig} (m) ± 90% CI			
Buoy	**1 yr ARI**	**10 yr ARI**	**50 yr ARI**	**100 yr ARI**
Brisbane	5.1 (± 0.2)	6.6 (± 0.3)	7.6 (± 0.4)	8.0 (± 0.4)
Byron Bay	5.2 (± 0.2)	6.4 (± 0.2)	7.2 (± 0.3)	7.6 (± 0.3)
Coffs Harbour	5.2 (± 0.2)	6.7 (± 0.3)	7.7 (± 0.4)	8.1 (± 0.4)
Crowdy Head	5.4 (± 0.2)	7.0 (± 0.4)	8.0 (± 0.5)	8.5 (± 0.5)
Sydney	5.9 (± 0.2)	7.5 (± 0.4)	8.6 (± 0.5)	9.0 (± 0.5)
Botany Bay	5.7 (± 0.2)	7.4 (± 0.3)	8.6 (± 0.4)	9.1 (± 0.4)
Port Kembla	5.4 (± 0.2)	7.1 (± 0.3)	8.3 (± 0.4)	8.8 (± 0.5)
Batemans Bay	4.9 (± 0.2)	6.3 (± 0.4)	7.3 (± 0.5)	7.7 (± 0.5)
Eden	5.4 (± 0.2)	7.0 (± 0.3)	8.1 (± 0.4)	8.5 (± 0.5)

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1. INTRODUCTION

The NSW coast is subject to a generally moderate wave climate predominantly from the south to south-east. Previous studies have found an average offshore significant wave height of 1.5 to 1.6 m and average peak period of 9.4 to 9.7 s (Lord and Kulmar, 2000). This generally moderate wave climate is periodically affected by large wave events originating from offshore storm systems. These storms vary both spatially and temporally in their genesis, intensity and track. Storm types which affect the NSW coast include tropical cyclones, easterly trough lows (east coast lows) and southern secondary lows. Full descriptions of NSW coastal storm types including genesis, characteristics and typical coastal effects are provided within Chapter 2.

Very large storm events such as those which occurred in 1974 (*'Sygna Storm'*) , 1997 (the *'Mothers Day Storm'*), 2001 and 2008 (the *'Pasha Bulker Storm'*) occasionally impact the coastline and, particularly when they are co-incident with high water levels, may cause widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety (Figure 1.1). Accurate estimation of the likelihood and magnitude of large wave events is essential for the quantification of extreme beach erosion and inundation levels, design of nearshore structures, and long-term coastal management.

Following a series of intense and damaging storms in 1974, a network of wave buoys was incrementally established along the NSW coast by the NSW Department of Public Works. Data from these buoys is collected by Manly Hydraulics Laboratory for the Department of Environment and Climate Change. Analysis of wave records, collected over a sufficient time period, allows quantification of extreme wave heights and, using appropriate extreme value analysis, characterisation of large, low probability wave events. These low probability events are generally described by either their average recurrence interval (ARI) or return period (RP), both of which describe the average time interval between events exceeding a particular magnitude, or by their annual exceedance probability (AEP). The AEP describes the probability of an event which exceeds a particular magnitude occurring in any given year. The relationship between average recurrence interval and annual exceedance probability is near reciprocal, and given by Eqn. 1-1.

$$AEP = 1 - \exp\left(\frac{-1}{ARI}\right) \qquad (1\text{-}1)$$

While the use of particular terminology to describe extreme events is interchangeable and somewhat arbitrary, the use of average recurrence interval and return period has been criticised for being "*sometimes misinterpreted as implying that the associated magnitude is only exceeded at regular intervals, and that they are referring to the elapsed time to the next exceedance*" (Australian Rainfall and Runoff Guidelines, IE Aust., 1987). The probability of an event of particular magnitude (AEP/ARI) occurring within a specified timeframe (TL) is given by Eqn. 1-2 and presented within Table 1.1.

$$P(Z) = 1 - (1 - AEP)^{T_L} \qquad (1\text{-}2)$$

Table 1.1
Probability of Event Occurrence within a Specified Timeframe

Event Average Recurrence Interval (ARI; Years)		Probability of event occurrence within					
		1 year	**5 years**	**10 years**	**20 years**	**50 years**	**100 years**
	1	1.00	1.00	1.00	1.00	1.00	1.00
	5	0.20	0.67	0.89	0.99	1.00	1.00
	10	0.10	0.41	0.65	0.88	0.99	1.00
	50	0.05	0.23	0.40	0.64	0.92	0.99
	100	0.01	0.05	0.10	0.18	0.39	0.63
	1000	0.001	0.005	0.01	0.02	0.05	0.10

Previous evaluations of extreme wave heights along the NSW coast include:

- Lawson and Abernethy (1974) evaluated three years of wave data collected by the Maritime Services Board of New South Wales at Botany Bay, Sydney to derive exceedance statistics. Due to the short record length, ARI type statistics were not derived.
- Blain, Bremner and Williams Pty Ltd and Lawson and Treloar Pty Ltd (PWD, 1985; 1986) evaluated historical storm events between 1880 to 1985. Proxy wave heights were assigned on the basis of historical charts, weather bulletins and reports, newspapers and other studies and theses and extreme wave heights derived for the north, mid-north, central and south coast sector. Derived extreme wave heights generally increased from south to north, with the derived 100 year ARI significant wave height on the north coast estimated at between 12.27 and 12.55 m depending on the selection of extreme value distribution.
- Lord and Kulmar (2000) presented an analysis of wave buoy data at all buoys up until 1999 including evaluation of extreme wave heights for Byron Bay, Sydney and Eden for events of between one and 24 hour duration. The 100 year ARI significant wave height with a 1 hr duration for Byron Bay was estimated at 7.8 m, for Sydney at 8.6 m

and for Eden at 9.3 m. This indicates a reverse spatial trend from the PWD (1985; 1986) studies.

- You (2007) examined the fit of nine extreme value distributions to long term wave data (1988 to 2006) for the Sydney wave buoy and found the 100 year ARI significant wave height to vary between 7.04 m and 9.63 m depending on selection of extreme value distribution. You (2007) found the FT-1 (or Gumbel) and Weibull distributions provided the best fit, with derived 100 year ARI significant wave heights of 8.62 and 8.61 m respectively.

Confidence in predicted extreme values depends primarily on the length and quality of recorded data. Pugh (1987) suggested that extrapolation of extreme value distributions should be limited to three to four times the record length. Analysis undertaken within this present study shows that the 90% confidence limits for design waves along the NSW coast for the 100 year storm are now less than 10%.

A key assumption of this present study and of previous studies is that of statistical stability which is related to stationarity in the long-term climate. Present climate assessments (IPCC, 2007) indicate, however, the intensification of storm events under global warming scenarios (DCC, 2009).

1.1 Scope of Works and Report Structure

The Department of Environment, Climate Change and Water (DECCW) is presently undertaking a state-wide study of Coastal Inundation Hazard under the Natural Disaster Mitigation Program (NDMP), with the study split into *Coastal Storms and Extreme Waves* and *Elevated Coastal Water Levels* components. The Water Research Laboratory, UNSW (WRL), Climate Futures at Macquarie, and Access Macquarie (Macquarie University) were commissioned to investigate the characteristics and impacts of NSW coastal storms and to determine the statistical distribution of extreme storm wave heights along the NSW coast.

A full description of NSW coastal storm climatology is provided within Section 2. This includes a review of the generation mechanisms, typical storm track and coastal impacts of the various storm types known to affect the NSW coast, with specific examples provided for particular types. Section 3 presents sources of wave data including wave buoys and numerical sources. Details of the locations, attributes and completeness of each dataset are presented. Section 4 presents the analysis of wave data sets. Wave data statistics for each of the analysed wave buoy data sets are presented and individual storm events located and assigned storm types. An extreme value analysis using appropriate probability distribution functions was undertaken for each wave buoy with results compared to those derived from numerical sources. The spatial and temporal variation of the different storm types and of the derived extreme values is discussed, along with the effect of storm duration and direction. Section 5 presents conclusions and recommendations based on the study results.

1.2 Significance of Study

This study has reviewed characteristics of storms which impact the NSW coastline using data collected over the past 38 years. Trends in the spatial and temporal distribution of coastal storms causing large wave events are presented and discussed. The study has derived extreme wave heights corresponding to low annual exceedance probability events for a range of storm durations and evaluated the effect of storm direction and spatial variation throughout NSW. Results of this study will have useful and highly practical application in a number of important areas including:

- Evaluation of the contribution of extreme waves to elevated coastal water levels;
- Design of offshore and nearshore structures and infrastructure;
- Providing boundary conditions for study of beach response to extreme wave events;
- Improved understanding of extreme storm climatology leading to large wave events on the NSW coast.

Collaroy-Narrabeen Beach, Sydney. March, 1976. Photograph: A. Short

Jonson St, Byron Bay, 1973. Photograph: K. Dunstone c\ Byron Shire Council.

WRL Report No. 2010/16	SIGNIFICANT STORM EVENTS LEADING TO SEVERE COASTAL EROSION AND INUNDATION.	Figure 1.1

2. NSW COASTAL STORM CLIMATOLOGY AND IMPACTS

The NSW coast spans the southern Coral Sea to the Southern Tasman Sea across the sub-tropical to mid-latitude zone. Extreme wave energy is mainly generated within the Coral Sea and Tasman Sea window, but can also be generated from outside this zone: in the South – West Pacific tropics; and, in the Southern Ocean in the extra-tropics. Aspects of the wave climate for the NSW coast have been previously described by Short and Trenaman (1992), Kulmar *et al.* (2005), numerous NSW PWD and MHL reports, including an annual wave climate summary, the NSW Coastline Management Manual (NSW Govt., 1990) and Hemer *et al.* (2007). The relationship between the SE Queensland and NSW modal wave climate and hemispheric climate variability modes has been explored by Phinn and Hastings (1999), Ranasinghe *et al.* (2004), Goodwin (2005) and Harley *et al.* (2009). Comprehensive, long-term storm wave climatologies for NSW have been reconstructed from historical records by PWD (1985) and Helman (2007). These studies have estimated quantitative storm parameters and provided information on the impact and effects of particular storm events.

Statistical evaluations of storm wave climates have been undertaken by Lawson and Treloar/PWD (1986), Webb and Kulmar (1990), Lord and Kulmar (2000), You and Lord (2008) and Speer *et al.* (2009), with a specific focus on extreme waves generated by East Coast Cyclones. Extreme storm impacts, including: beach and dune erosion, dune overtopping and inundation, storm surge, and estuarine inlet breakthrough and/or migration are outlined in the Coastline Management Manual (NSW Govt., 1990) and have been reported for individual storm events (e.g. Lord and Kulmar, 2000, Watson *et al.* 2008) and for individual beaches and estuaries.

Due in part to their rapid intensification and complexity, East Coast Cyclones have proven difficult to both forecast and categorise. The Australian Bureau of Meteorology (BOM) used seven different storm categories to compile their NSW maritime low database, while the PWD report used a different six categories. Holland *et al.*(1987) discussed three types of East Coast Cyclone events and Hopkins and Holland (1997) used a different eight classifications. As there is no broad consensus on what constitutes an East Coast Cyclone, discrepancies exist between these reports. The following definition proposed by Hopkins and Holland (1997) is similar to that used by the BOM.

"Any system with closed cyclonic circulation at sea level, which forms in a maritime environment between 20° and 40°S and within 500km of the coast. The Low pressure

system must exhibit at some stage of its lifetime a component of movement parallel to the coastline and have a pressure gradient of at least 4 hPa (100km)$^{-1}$."

Storms which fit this description can be divided into four types based on their origin, namely: East Coast Lows (ECL), Southern Secondary Lows (SSL), Inland Troughs (IT) and Tropical Cyclones (TC). The following definitions have been used to classify storms in this study and are based on the classifications used in PWD (1985) and Hopkins and Holland (1997) .

- East Coast Low (ECL) or Easterly Trough Low (ETL) storms are the primary type of ECC; they initially form as a trough in the easterly flow along the Queensland / Northern NSW coast. These storms move parallel to the coast and often intensify rapidly causing significant damage.
- Southern Secondary Low (SSL) storms form as a cut off low in the wake of a cold front in the mid-latitude westerly circulation.
- Inland Troughs (IT) form as troughs in the tropical heat low regions of Queensland and West Australia and move overland to the East Coast, often re-intensifying in the coastal environment. These storms occur mostly in the warmer months but in the right conditions, can occur at any time of the year.
- Tropical Cyclones (TC) tend to form north of 20°S in a homogeneous atmosphere that is warm and moist and they may sometimes move into higher latitude and re-intensify. TCs are rare in the winter months.

Although ECL, SSL, IT and TC storms all fit the Hopkins and Holland (1997) classification of an East Coast Cyclone, they are different weather systems often occurring under contrasting climatic conditions. ITs and TCs are both warm season weather systems and are rare in winter. The primary winter East Coast Cyclones are SSLs and ECLs; in both cases intensification at the surface is accompanied by an upper atmospheric trough or cut off low.

The storm climatology in this study is based on a synoptic typing approach that has expanded upon that used in the PWD (1985) study. A classification of the storm wave data into one of the following eight synoptic types was made: TC – Tropical Cyclone; TL – Tropical Low; AI – Anticyclone Intensification; ETL – Easterly Trough Low; CL – Continental Low; ITL – Inland Trough Low; STL – Southern Tasman Low and SSL – Southern Secondary Low. Figure 2.1 presents examples of these synoptic types and detailed descriptions of specific storm events are presented in Appendix A.

Between December and March, intense low pressure synoptic systems form in the Coral Sea and track south or south-east. These systems are classified by the BOM (1978) as Tropical Cyclones if the maximum winds occur near the centre of the system and the 10 minute mean winds are at least 17.5 m/s (34 knots) or Tropical Lows (TL) if wind speeds are lower. Tropical cyclones (TCs) are identified in the Australian region either by the BOM, the Fiji Meteorological Service in Nadi, or the NIWA Tropical Cyclone Warning Centre in Wellington, New Zealand. TCs produce extreme waves along the NSW coast with a wave direction from the eastern quadrant. Peak significant wave heights of up to 7.4 m have been observed in the buoy records and total storm duration can be very long as the systems move slowly along the coast or become stationary. Such events have a history of causing severe erosion and inundation along the NSW coastline due to their extreme wave height which often arrives from the easterly quadrant and the large storm surge often reported during such events. A storm surge of 0.68 m was reported to have occurred during Tropical Cyclone Pam in 1974 (Helman, 2007). This storm surge combined with a spring tide and lead to flooding of low lying areas of Brisbane and the Gold Coast and severe erosion on the Gold Coast, Sunshine Coast and Belongil Spit (Gordon *et al.* 1978) which had already been severely eroded by an earlier cyclone (TC Wanda, 24-27 Jan, 1974).

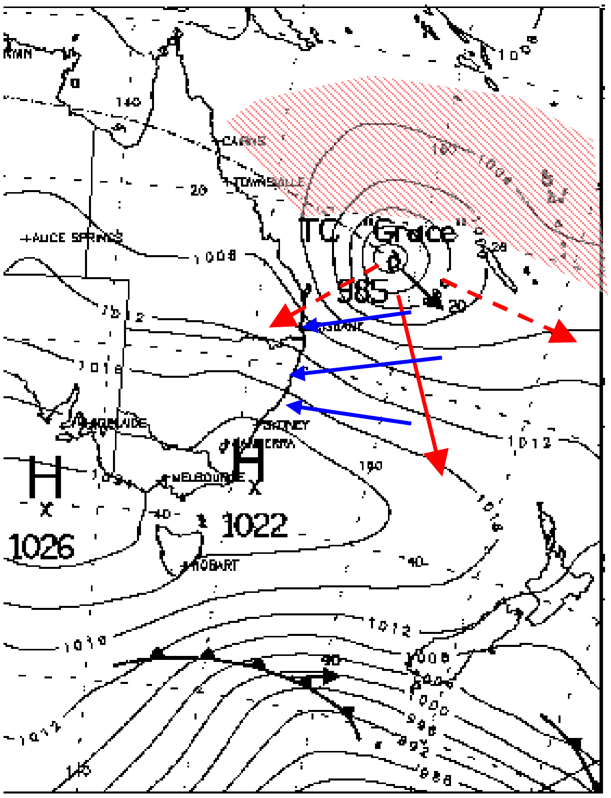
Extreme waves may also develop when the pressure gradient on the northward limb of the subtropical anticyclone (high pressure system) intensifies, which is termed Anticyclone Intensification (AI). Strong east or south-east winds develop across the Tasman Sea and often persist for over 100 hours due to the blocking of the anticyclone. While peak significant wave height induced by these systems rarely exceeds 5 m, the long duration of such events can still result in severe beach erosion.

Easterly Trough Lows (ETLs) are complex cold season meso to synoptic scale (50-500 km) weather systems. They form over the southern Coral Sea and northern to central Tasman Sea, bordering the east coast of Australia, and affect coastal regions from southern Queensland to Victoria. Their intense form and close proximity to the coast means that ETLs are responsible for some of the largest waves on record with a peak wave height of 8.9 m recorded at Botany Bay in May, 1997, but are also relatively confined spatially. ETLs can cause significant storm damage through storm winds, heavy rainfall leading to flooding, heavy seas, storm surge, wave setup and beach erosion. ETLs form on average several times per year, mostly in Autumn and Winter, with a maximum occurrence in June (Holland *et al.* 1987). Events can be as short as 16 hours or last for several days (Hopkins and Holland, 1997) and tend to be clustered over successive weeks when conditions are favourable (Allen and Callaghan, 2001). This tendency for clustering amplifies associated erosion by precluding substantial beach recovery between events.

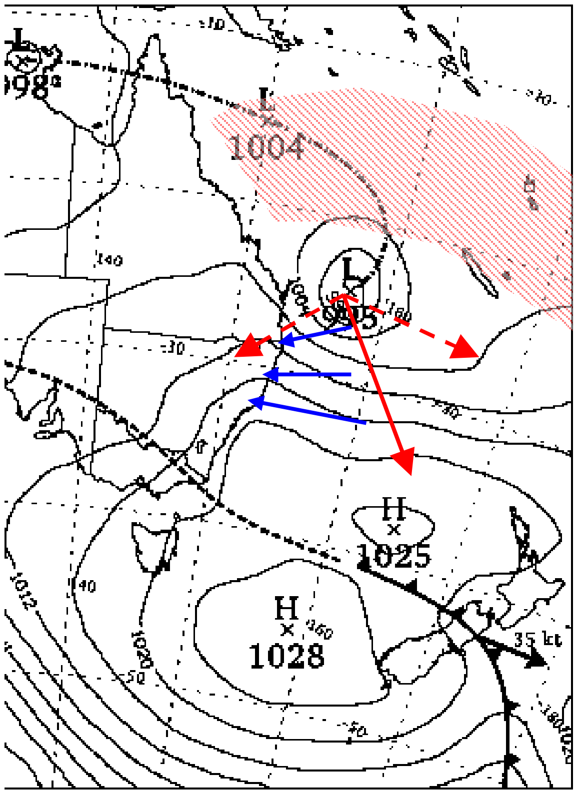
Continental lows form in the westerly airstream over southern Australia and travel eastwards over the continent. As the lows cross the eastern coastline of Australia, they can intensify and produce storm wave erosion. They are often associated with a strengthened subtropical anticyclone centred in the Great Australian Bight. The associated strong south-east wind field in the Southern Tasman, combines with the CL to extend the duration of peak waves. Inland Trough Lows (ITLs) originate in the quasi-permanent low pressure trough over inland Queensland. Their movement to the east coast is often associated with the interaction with a Southern Tasman Low (STL). Hence, the synoptic pattern of the ITL after crossing the east coast, can resemble the pattern associated with the Southern Secondary Lows (SSLs).

Large extra-tropical low pressure systems develop in the atmospheric longwave trough in the southern ocean south of 38°S, and extend northwards into the central Tasman Sea. These systems are classified as STLs and can produce extreme waves along the NSW and Victorian coasts. However, due to the distance from the coast and southerly wave direction, resultant erosion is not typically as severe as for the more local ETL and TC events. SSLs form in association with STL and evolve into a secondary or cut off low in the Tasman Sea region, adjacent to a subtropical anticyclone. These SSL synoptic types produce more extreme wave energy, comparable to the ETL type with peak significant wave heights of over 7 m occurring on occasion. The most notable Southern Secondary Low event was the May, 1974 "Sygna Storm" which caused significant erosion on the central, Sydney and Illawarra coasts and was responsible for the shipwrecking of the Norwegian coal carrier, the *Sygna*, in Stockton Bight north of Newcastle.

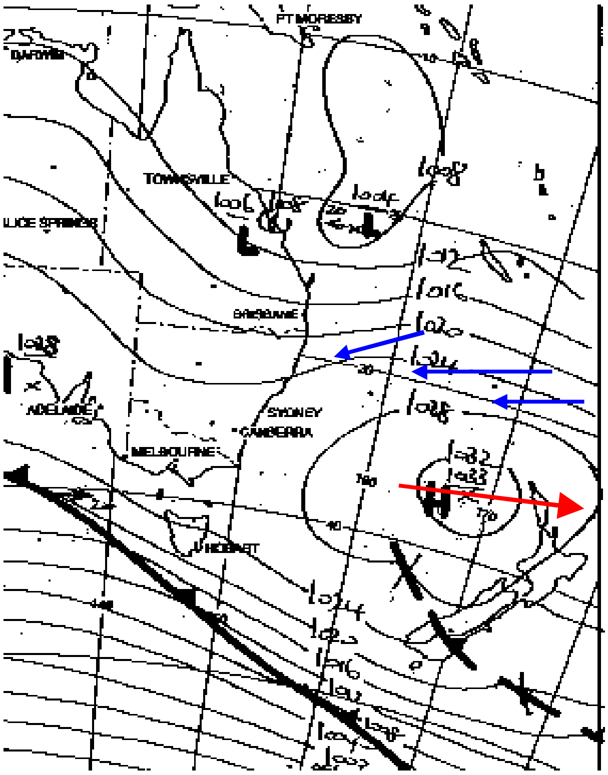
Further examples of specific storm events affecting the NSW coast, their associated synoptic type, storm characteristics and impacts on the coastline where reported are provided within Appendix A.



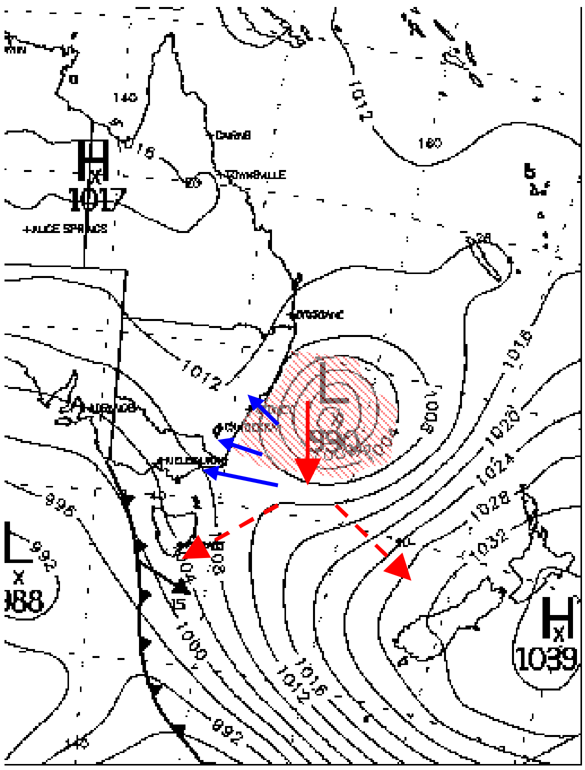
Tropical Cyclone (TC)



Tropical Low (TL)



Anti-cyclone Intensification (AI)

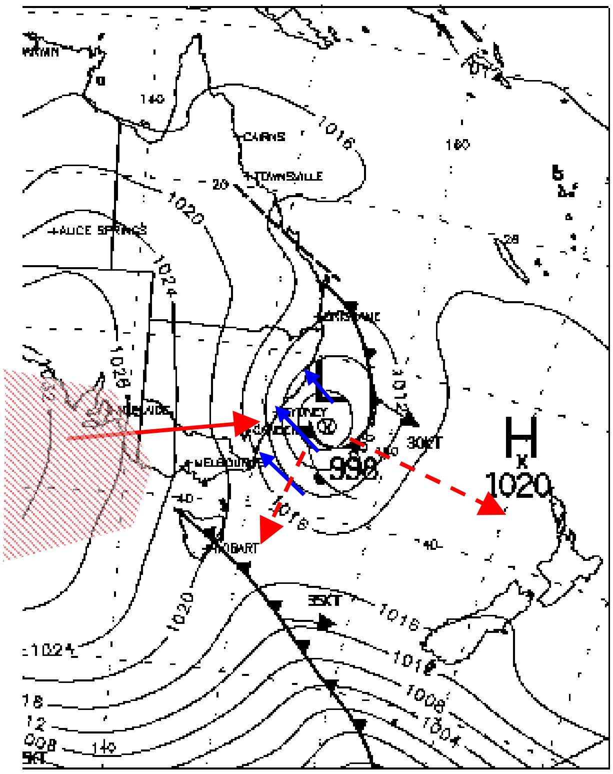


Easterly Trough Low (ETL)

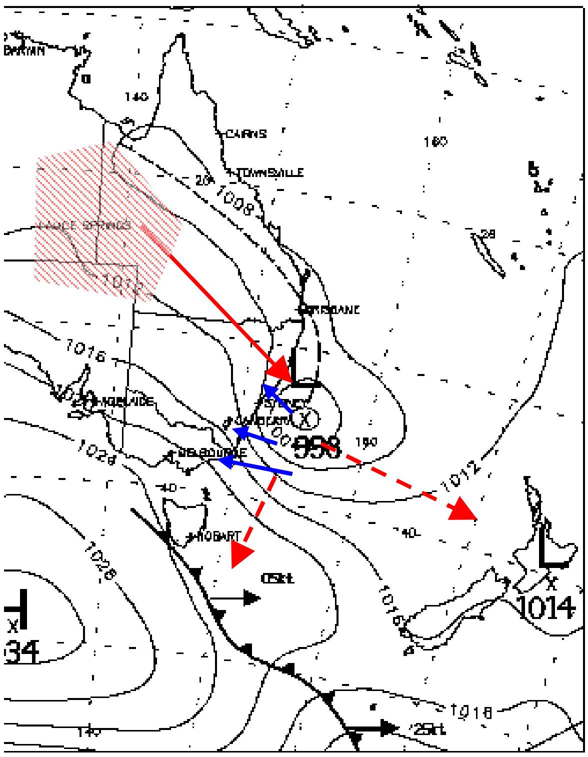
All Charts: Bureau of Meteorology

Storm genesis region — General storm path — Typical Wave Direction

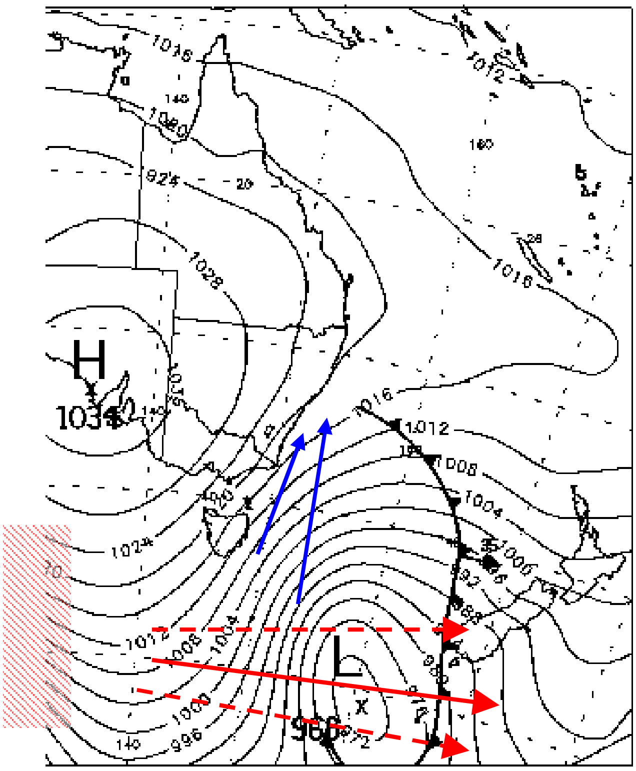
WRL Report No. 2010/16	EXAMPLE SEA LEVEL PRESSURE SYNOPTIC CHARTS FOR SYSTEMS CAUSING STORM WAVES ON THE NSW COAST	Figure 2.1A



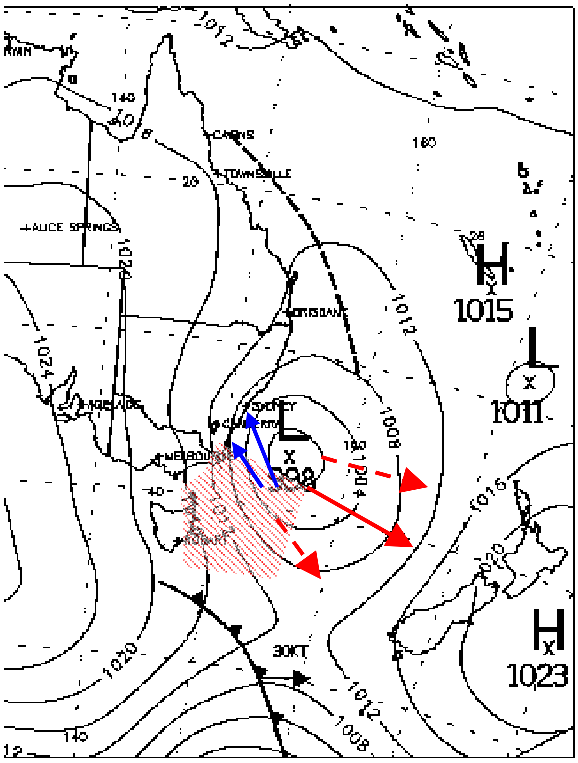
Continental Low (CL)



Inland Trough Low (ITL)



Southern Tasman Low (STL)



Southern Secondary Low (SSL)

All Charts: Bureau of Meteorology

Storm genesis region General storm path Typical Wave Direction

WRL Report No. 2010/16	EXAMPLE SEA LEVEL PRESSURE SYNOPTIC CHARTS FOR SYSTEMS CAUSING STORM WAVES ON THE NSW COAST	Figure 2.1B

3. DATA SOURCES

Sources of data which provided quantitative information on wave heights along the NSW coast include:

- Wave buoys (1971 to present);
- The (US) Oceanic and Atmospheric Administration (NOAA) Wavewatch III Numerical Hindcast (1997 to present);
- The European Centre of Medium-Range Forecasting (ECMRF) WAM-cycle 3 ERA-40 Hindcast (1957 to present).

3.1 Wave Buoys

Just prior to a series of large storms in 1974, (including the “Sygna storm”) which caused extensive damage along the NSW East Coast, the then NSW Department of Public Works (PWD) initiated a program of wave data collection. This began with the installation of a wave buoy at Port Kembla in February 1974. The large storms of 1974 provided further impetus to extend the wave buoy network, which has been expanded to seven sites along the NSW coast, maintained by Manly Hydraulics Laboratory (MHL) and supported by the NSW Department of Climate Change and Water (DECCW). Wave buoys are presently located off Byron Bay (directional), Coffs Harbour, Crowdy Head, Sydney (directional), Port Kembla, Batemans Bay (directional) and Eden.

Sydney Ports Corporation has maintained a wave buoy offshore of Botany Bay since 1971 to provide real-time oceanographic data to commercial port users and the public. The Queensland Department of Environment and Resource Management (DERM) maintains a network of 12 wave buoys along the Queensland coastline. A wave buoy located offshore of Brisbane (Point Lookout on North Stradbroke Island) since 1976 is also incorporated within this study to improve evaluation of wave height and storm trends in far north NSW.

3.1.1 Locations

The locations of wave buoys have varied through time as wave buoys were lost, removed and replaced during routine maintenance, or repositioned to improve data capture. The present locations of the seven MHL/DECCW, one Sydney Ports Corporation and one Queensland DERM buoy are shown in Table 3.1 and within Figure 3.1. The location history of all MHL/DECCW wave buoys as defined within the NSW Wave Climate and

Coastal Air Pressure Annual Summary 2008-2009 (MHL, 2009) is presented within Appendix G.

Table 3.1
List of Wave Buoys and Locations used within the Present Study

Site	Present Location	Water Depth (m)	Maintained by	Buoy Type	Date Range
Brisbane	153° 37.5' E 27° 28.1' S	76	Queensland DERM	Directional Waverider	Oct 1976 – Dec 2009
Byron Bay	153° 42.1' E 28° 51.2' S	62	MHL/DECCW	Directional Waverider	Oct 1976 – Dec 2009
Coffs Harbour	153° 16.1' E 30° 21.4' S	72	MHL/DECCW	Waverider	May 1976 – Dec 2009
Crowdy Head	152° 51.6' E 31° 49.5' S	79	MHL/DECCW	Waverider	Oct 1985 – Dec 2009
Sydney	151° 25.0' E 33° 46.3' S	92	MHL/DECCW	Directional Waverider	Aug 1987 – Dec 2009
Botany Bay	151° 15.1' E 34° 02.3' S	73	Sydney Ports Corporation	Waverider	Apr 1971 – Dec 2009
Port Kembla	151° 01.6' E 34° 28.5' S	80	MHL/DECCW	Waverider	Feb 1974 – Dec 2009
Batemans Bay	150° 20.6' E 35° 42.2' S	73	MHL/DECCW	Directional Waverider	May 1986 – Dec 2009
Eden	150° 11.1' E 37° 18.1' S	100	MHL/DECCW	Waverider	Feb 1978 – Dec 2009

3.1.2 Instrumentation

Deep water wave buoys maintained by MHL are based on the Waverider system developed by the Dutch company, Datawell. The non-directional Datawell Waverider system uses an accelerometer mounted within a buoy to measure vertical accelerations as the buoy moves with the water surface. Datawell Directional Waverider buoys measure accelerations in the horizontal and vertical directions. These accelerations are integrated twice to obtain displacements. The use of accelerations instead of buoy slope renders measurement insensitive to buoy roll and allows the use of smaller buoys. Measurement range in the directional Waverider buoys is given at ±20 m elevation and 1.6 to 30 s period. Buoy resolution is 1 cm and post-calibration errors are given at 0.5% to 1.0% (www.datawell.nl). Directional resolution is given at 1.4° with error of 0.4 to 2° depending on latitude.

Buoys are tethered to 15 metre rubber shock cords and PVC coated galvanised steel wire rope which is attached to anchor blocks of between 300 and 800 kg. Mooring lines are normally 2.5 times the water depth (Wyllie and Kulmar, 1995). To ensure waves are observed in close to deepwater conditions, buoys are moored in water depths of 60 to 100 m. This is equivalent to theoretical *deepwater* (> $L_0/2$) for waves of less than 9 to

11.3 s period respectively (or around 75% of waves on the NSW coast; Lord and Kulmar, 2000).

3.1.3 Data Capture and Analysis

Data has been captured by the wave buoy network at intervals of 12, 6 and 1 hour, although from 1984 all MHL wave buoys captured data at 1 hour intervals. Table 3.2 shows the date ranges for the various sampling intervals, the total data capture (%) for each buoy, the total record length (years) and the effective record length (years). The effective length is the product of the total record length and the total data capture and is important in calculating extreme values and confidence intervals (refer Section 4). The spatial completeness of the wave buoy record is also presented within Figure 3.3. It is evident within Figure 3.3 that the Byron Bay wave buoy has the highest occurrence of data breaks. This is reflected by the total capture rate of 73.1%. The Batemans Bay buoy has the highest capture rate of 89.7%.

Table 3.2
Details of Wave Buoy Sampling Intervals and Data Capture

Buoy Location	Sampling Interval (hrs)			Total Capture (%)	Total Record Length (yrs)	Effective Record Length (yrs)
	12	6	1			
Brisbane (ND)[1]	31/10/1976 – 13/05/1982	17/06/1982 – 25/10/1991	26/10/1991 – 21/11/1996	85.9	33.2	28.5
Brisbane (D)[2]	-	-	21/11/1996 – 31/12/2009			
Byron Bay (ND)	-	14/10/1976 – 27/06/1984	28/06/1984 – 25/10/1999	73.1	33.2	24.3
Byron Bay (D)	-	-	26/10/1999 – 31/12/2009			
Coffs Harbour	-	26/05/1976 – 05/05/1984	27/06/1984 – 31/12/2009	84.7	33.6	28.5
Crowdy Head	-	-	10/10/1985 – 31/12/2009	85.6	24.2	20.7
Sydney (ND)	-	-	17/07/1987 – 04/10/2000	84.5	22.5	19.0
Sydney (D)	-	-	03/03/1992 – 31/12/2009			
Botany Bay	-	08/04/1971 – 17/06/1980	17/06/1980 – 31/12/2009	87.7	38.8	34.0
Port Kembla	-	07/02/1974 – 14/06/1984	14/06/1984 – 31/12/2009	85.1	35.9	30.6
Batemans Bay (ND)	-	-	27/05/1986 – 21/02/2001	89.7	23.6	21.2
Batemans Bay (D)	-	-	23/02/2001 – 31/12/2009			
Eden	-	08/02/1978 – 22/10/1984	27/03/1985 – 31/12/2009	83.5	31.9	26.6

[1] Non-directional
[2] Directional

Data is captured for 34 minutes every sampling interval, transmitted to shore and logged. Erroneous sample points are removed before processing by zero-crossing and spectral analysis (Figure 3.4). This process extracts a range of wave height, period and direction statistics which are described within Table 3.3 and Figure 3.4 (MHL, 2009).

Table 3.3
Wave Buoy Statistics (MHL, 2009)

Zero Crossing Statistics		
Statistic	**Unit**	**Description**
HMEAN	metres	Mean wave height
HRMS	metres	Root mean square wave height
HSIG	metres	Significant wave height
H10	metres	Average top 10% wave height
HMAX	metres	Maximum wave height
TC	seconds	Crest wave period
TZ	seconds	Zero up-crossing wave period
TSIG	seconds	Significant wave period
Spectral Analysis Statistics		
F0	Hertz	Frequency at first spectral estimate
YRMS	metres	Root mean square sea surface displacement
SPECT_DENS	m^2/Hz	Maximum spectral density
TP1	seconds	Wave period at spectral peak
TP2	seconds	Wave period at second spectral peak
P2ONP1		Ratio 2nd peak spect estimate to 1st
M0 – M3		First to fourth spectral moment
Wave Direction Statistics (relative to True North)		
WDIR	degrees	Best available principal wave direction
WDIR_BUOY	degrees	Mean direction at spectral peak
WDIR_TP1	degrees	Wave direction at spectral peak
WDIR_TP2	degrees	Wave direction at 2nd spectral peak
Miscellaneous Statistics		
DEPTH	metres	Average water depth at instrument
POWER	Watts/m	Wave power per length of wave crest
GROUPI		Wave groupiness factor

Waverider buoys are known to suffer damage due to spinning (Wyllie and Kulmar, 1995). This spinning is most often caused by vessel impact or mooring and may result in corrupt data. Buoy moorings may also fail due to either vessel collision or extreme storms. Other contributors to missing data include receiving station component failure, radio interference, telemetry faults and the loss of shore station power due to extended mains power failure (Wyllie and Kulmar, 1995). Other possible sources of error within wave buoy data include submergence at wave crests (Bettington and Wilkinson, 1997) and due to strong currents leading to underestimation of wave height and increased linearity in observed waveforms due to loose buoy tether lines (Tucker, 1994).

3.2 Numerical Data

3.2.1 Models

Data generated by two deepwater, numerical wave models were also used for comparative analysis. These numerical models included the Wave Watch III (WW3) model, maintained by the United States National Oceanic and Atmospheric Administration *(*NOAA; NWW3) and the Wave Analysis Model (WAM) maintained by the European Centre of Medium-Range Weather Forecasting (ECMWF).

Wave Watch III is a third generation, phase-averaging spectral wave model which, like other third generation wave models, solves the action balance equation in spherical co-ordinates for the two-dimensional action density ocean wave spectrum $F(\omega,\theta,\phi,\lambda,t)$ with respect to wave frequency (ω) and direction (θ), as a function of latitude (ϕ), longitude (λ) and time (t).

$$\frac{\partial F}{\partial t} + (\cos\phi)^{-1}\frac{\partial}{\partial\phi}(\dot{\phi}\cos\phi F) + \frac{\partial}{\partial\lambda}(\dot{\lambda}F) + \frac{\partial}{\partial\omega}(\dot{\omega}F) + \frac{\partial}{\partial\theta}(\dot{\theta}F) = S \qquad (2\text{-}1)$$

where:

- $\dot{\phi}$: component of group velocity with respect to latitude
- $\dot{\lambda}$: component of group velocity with respect to longitude
- $\dot{\omega}$: rate of change of the dispersion relation
- $\dot{\theta}$: rate of change of direction (due to great circle propagation)
- S: net source function describing the change of energy of a propagating wave group as shown in Equation 2.2

$$S = S_{in} + S_{nl} + S_{ds} + S_{bot} \qquad (2\text{-}2)$$

where:

- S_{in}: atmospheric input from the wind
- S_{nl}: non-linear interactions between spectral components
- S_{ds}: dissipation due to “white capping”
- S_{bot}: dissipation due to interaction with the bottom

A global Wave Watch III model has been operated by NOAA (NWW3) since 1997 and provides freely available wave data on a 1.0° (latitude) by 1.25° (longitude) model grid (~110 × 90 km in NSW) at 3 hour intervals.

The WAM model was used by the ECMWF to generate the ERA-40 hindcast dataset. This global wave hindcast was run between September 1957 and August 2002 (Sterl and Caires,

2005) at a spatial resolution of 2.5°× 2.5° (275 × 225 km in NSW) and temporal resolution of 6 hours.

Validation of modelled wave heights from the ERA-40 dataset against buoy and global satellite altimeter measurements in the northern hemisphere indicated generally good agreement (Caires and Sterl, 2005), although the ERA-40 wave heights were found to systematically overestimate wave heights during calm conditions and underestimate peak wave conditions. Wave heights were also found to contain synthetic biases and trends resulting from assimilation to different altimeter datasets throughout the 45-year period.

Harley *et al.* (2009) compared ECMWF ERA-40 and corrected ERA-40 (C-ERA-40) reanalysis data with wave measurements collected by the Sydney wave buoy. Results show that the numerical datasets represented the Sydney wave climate reasonably well, although westerly waves were significantly over-predicted in the model. Removing these values was found to strengthen correlations between predicted and measured wave heights.

The *skill* of these two models was assessed by Hemer *et al.* (2007) around the Australian coast by comparing the predictions to measurements from 27 wave buoys. The C-ERA-40 model dataset had a Root-Mean-Square-Error (*RMSE*) for significant wave height (H_{sig}) of 0.59 m. The Wave Watch III dataset had an *RMSE* of 0.63 m for H_{sig}. Coghlan (2009), compared a high-resolution WAM model (Hi-WAM) developed by the Australian Bureau of Meteorology (BoM) against wave buoy measurements from 18 locations around Australia over an 11 year period (1997 to 2008) and against a NWW3 dataset at Sydney. Coghlan (2009) noted that wave energy was over predicted by Hi-WAM for extreme wave heights at Sydney, but was under predicted at sites exposed to mid-latitude cyclone (roaring forties) swell in Victoria, Tasmania, South Australia and Western Australia. Coghlan also found the NWW3 model to have slightly superior performance over Hi-WAM when compared to wave buoy data at Sydney.

3.2.2 Locations

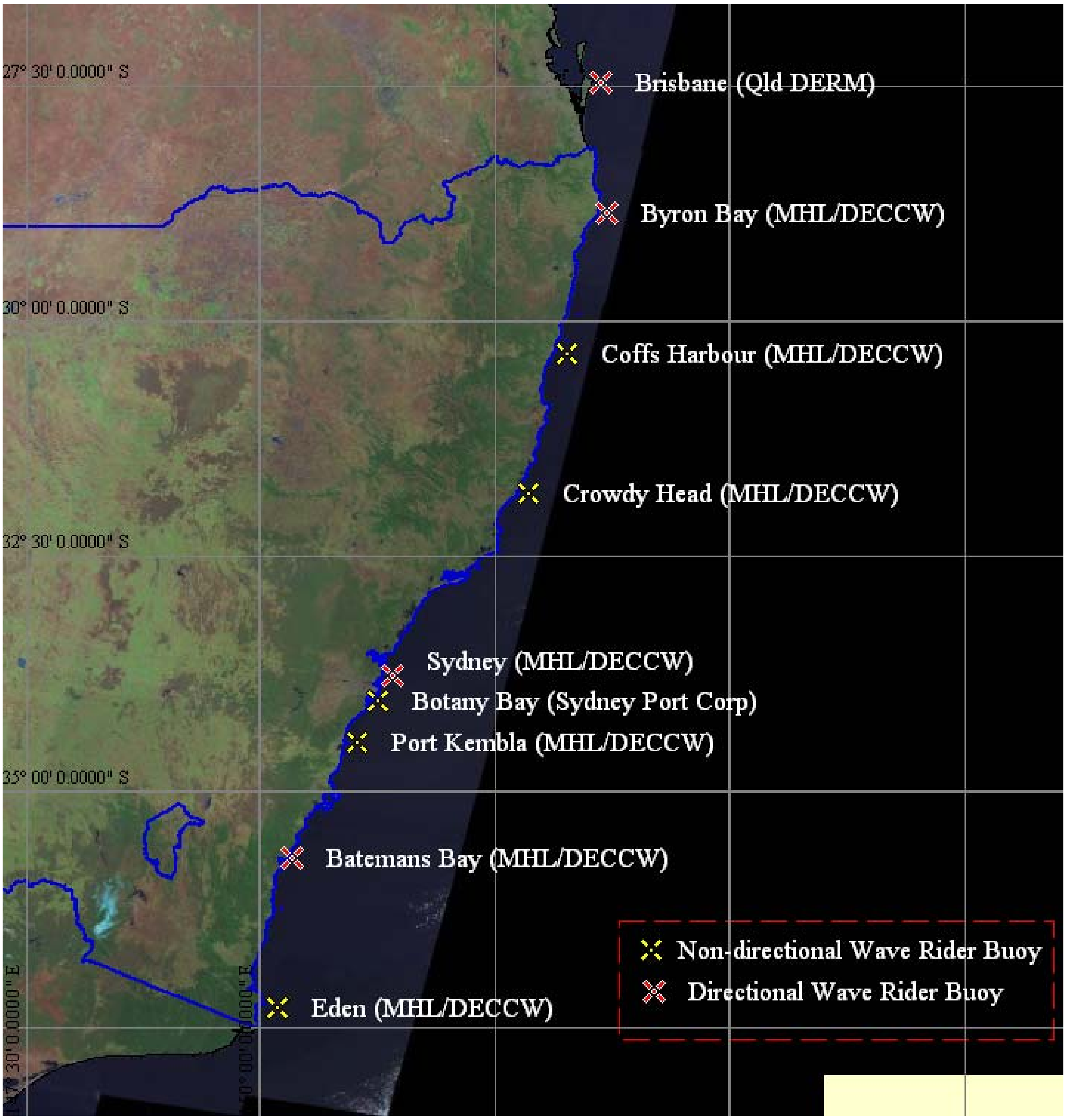
Numerical data was extracted from grid cell locations along the NSW coast most closely representing the wave buoy locations (Figure 3.5). In total, seven NWW3 numerical datasets were extracted. Each corresponding to one wave buoy, except in the vicinity of Sydney, where the numerical grid cell was representative of the Sydney, Botany Bay and Port Kembla wave buoys. In total, five ERA-40 numerical datasets were extracted. These datasets encompassed the entire NSW coast and southeast Queensland. The Queensland cell was noted to be bounded by a ‘land’ cell immediately to the south. This was expected to result in a significantly reduced southerly component at this buoy location.

3.2.3 Data Capture and Analysis

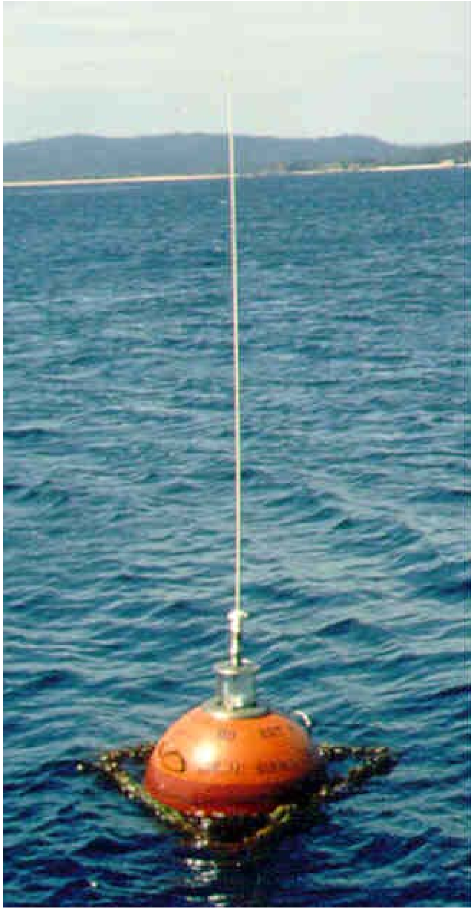
Data from the NOAA NWW3 model was available for the period January 1997 to August 2009. The data was sampled at 3 hourly intervals, with no irregularities or missing data. The ECMWF ERA-40 dataset extends from September 1957 to September 2002. The data is sampled at 6 hourly intervals with no irregularities. A summary of available data is presented within Table 3.4 and Figure 3.3.

Table 3.4
Details of Numerical Wave Data

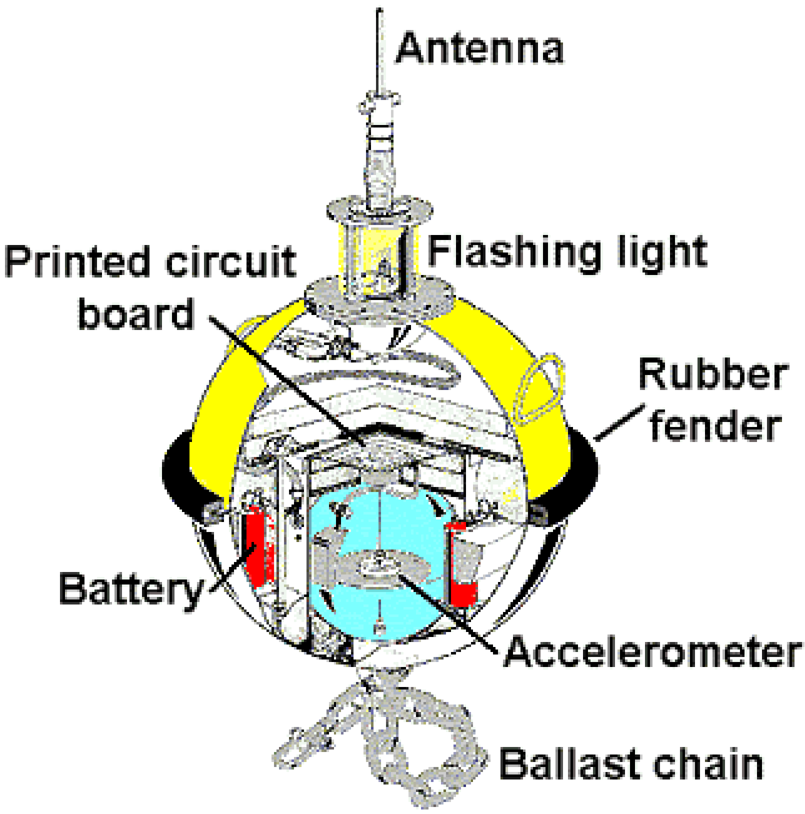
Dataset	Location			Date Range	Sampling Interval	Complete (%)	Effective record length (yrs)
	Nearest Buoy	Lat	Long				
NOAA Wave Watch III	Brisbane	-27.0	153.75	30/01/97 - 01/08/09	3 hr	100	12.6
	Byron Bay	-29.0	153.75	30/01/97 - 01/08/09	3 hr	100	12.6
	Coffs Harbour	-30.0	153.75	30/01/97 - 01/08/09	3 hr	100	12.6
	Crowdy Head	-32.0	153.75	30/01/97 - 01/08/09	3 hr	100	12.6
	Sydney/Port Kembla	-34.0	151.25	30/01/97 - 01/08/09	3 hr	100	12.6
	Batemans Bay	-36.0	151.25	30/01/97 - 01/08/09	3 hr	100	12.6
	Eden	-37.0	150.00	30/01/97 - 01/08/09	3 hr	100	12.6
ECMWF ERA-40	Brisbane	-27.5	152.50	01/09/57 - 01/09/02	6 hr	100	45
	Byron/Coffs	-30.0	155.00	01/09/57 - 01/09/02	6 hr	100	45
	Crowdy Head	-32.5	152.50	01/09/57 - 01/09/02	6 hr	100	45
	Sydney/PK/ Batemans	-35.0	152.50	01/09/57 - 01/09/02	6 hr	100	45
	Eden	-37.5	150.00	01/09/57 - 01/09/02	6 hr	100	45



WRL Report No. 2010/16	WAVE BUOY LOCATIONS ALONG THE NEW SOUTH WALES COAST AND OFFSHORE OF BRISBANE	Figure 3.1

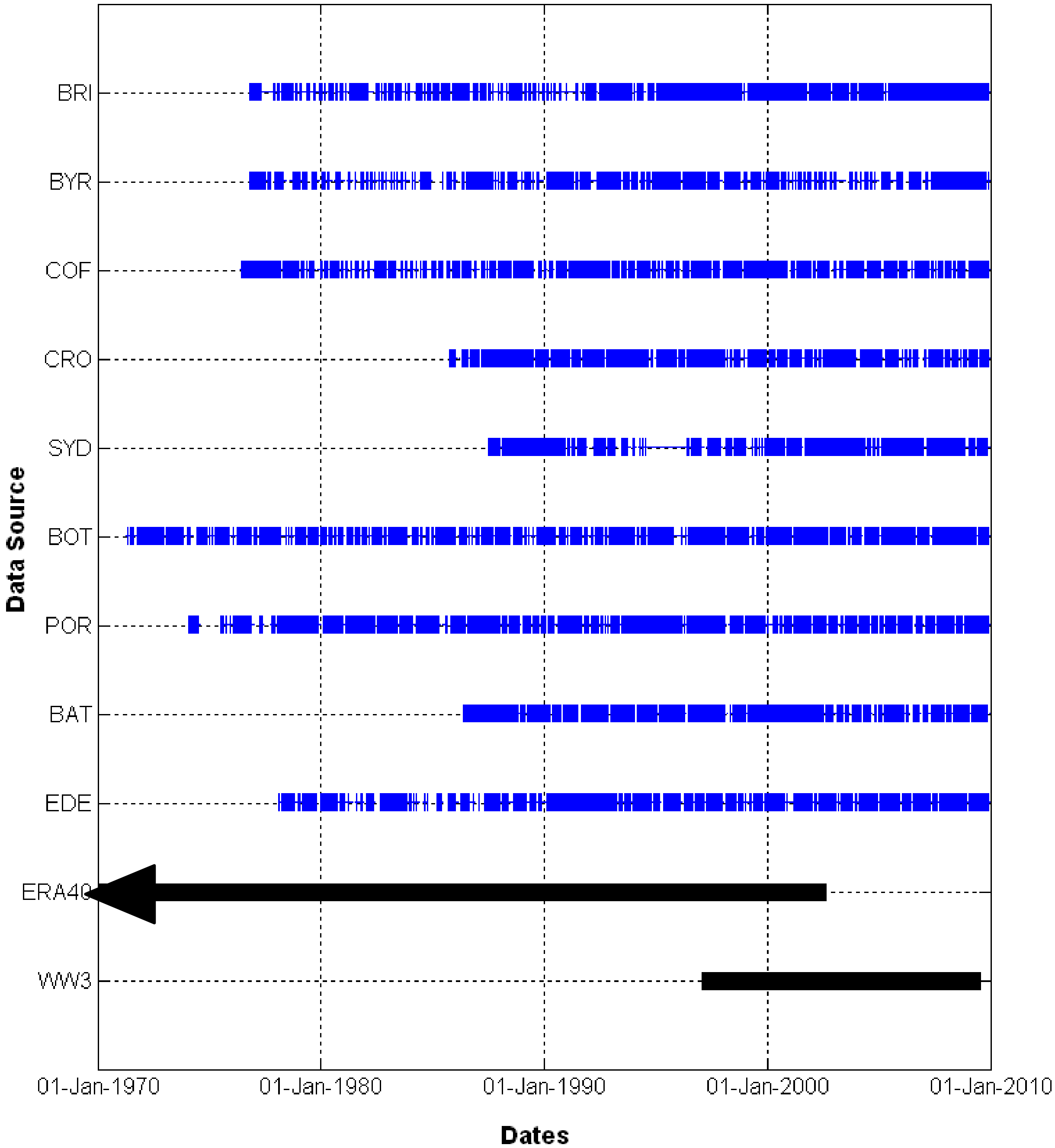


WWW.DATAWELL.NL **Manly Hydraulics Laboratory**



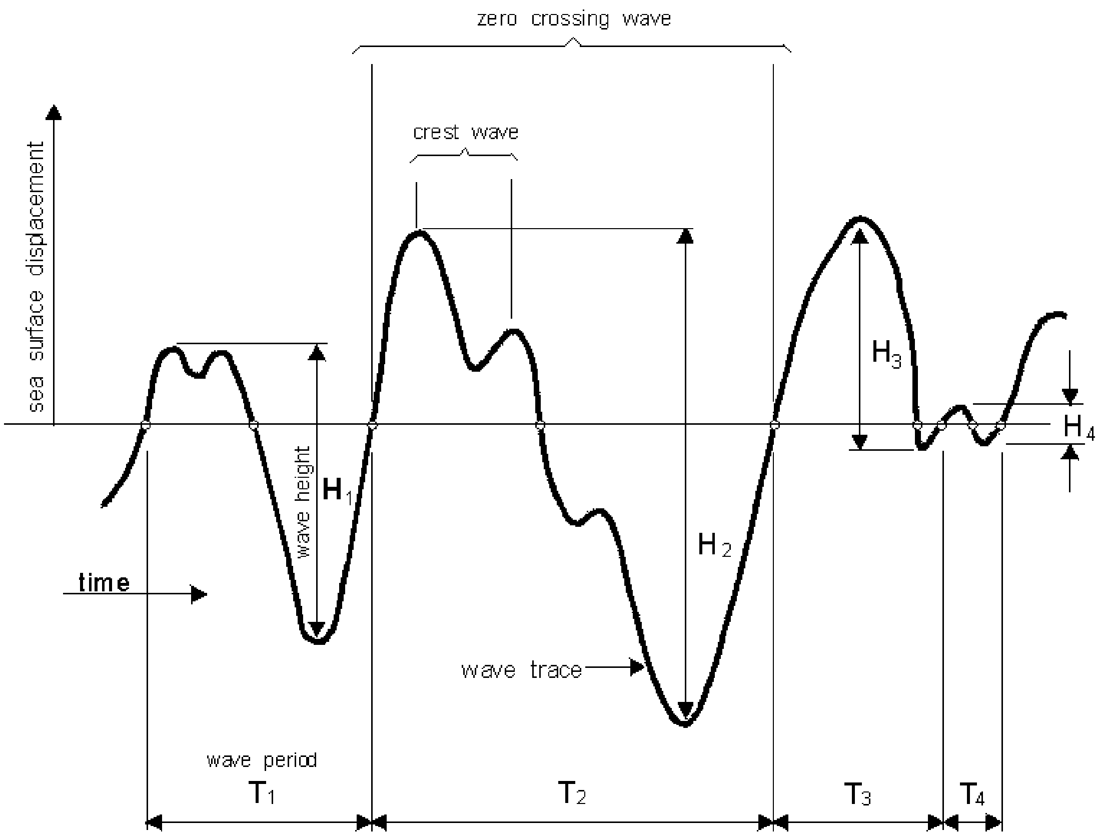
QUEENSLAND DERM

WRL Report No. 2010/16	EXAMPLE IMAGES AND SCHEMATIC DIAGRAM OF A DATAWELL WAVE RIDER BUOY USED BY MHL/DECCW AND QUEENSLAND DERM	Figure 3.2



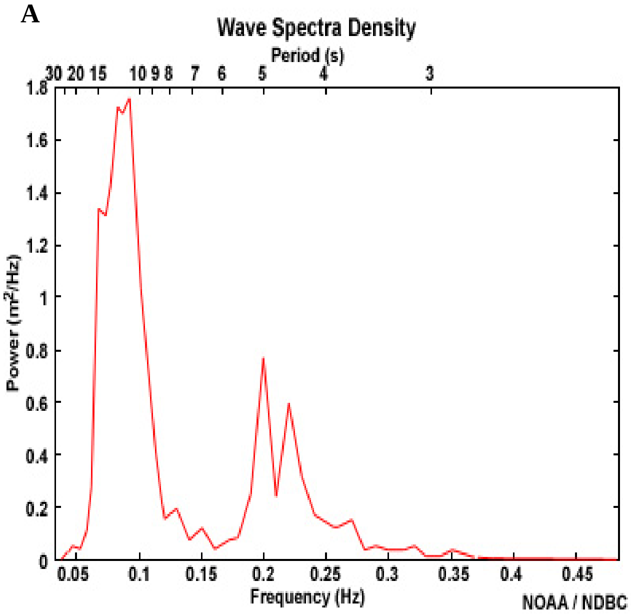
WAVE BUOY AND NUMERICAL DATA RECORD

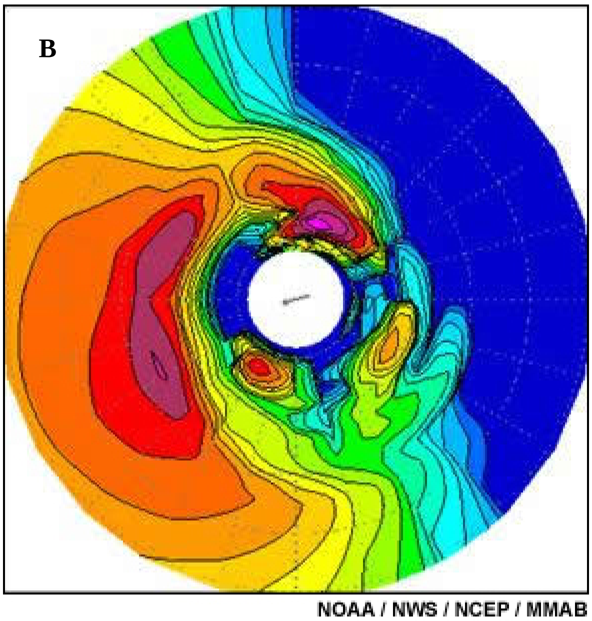
Figure 3.3



Example of wavy water surface and definitions of wave parameters (source: Manly Hydraulics Laboratory)

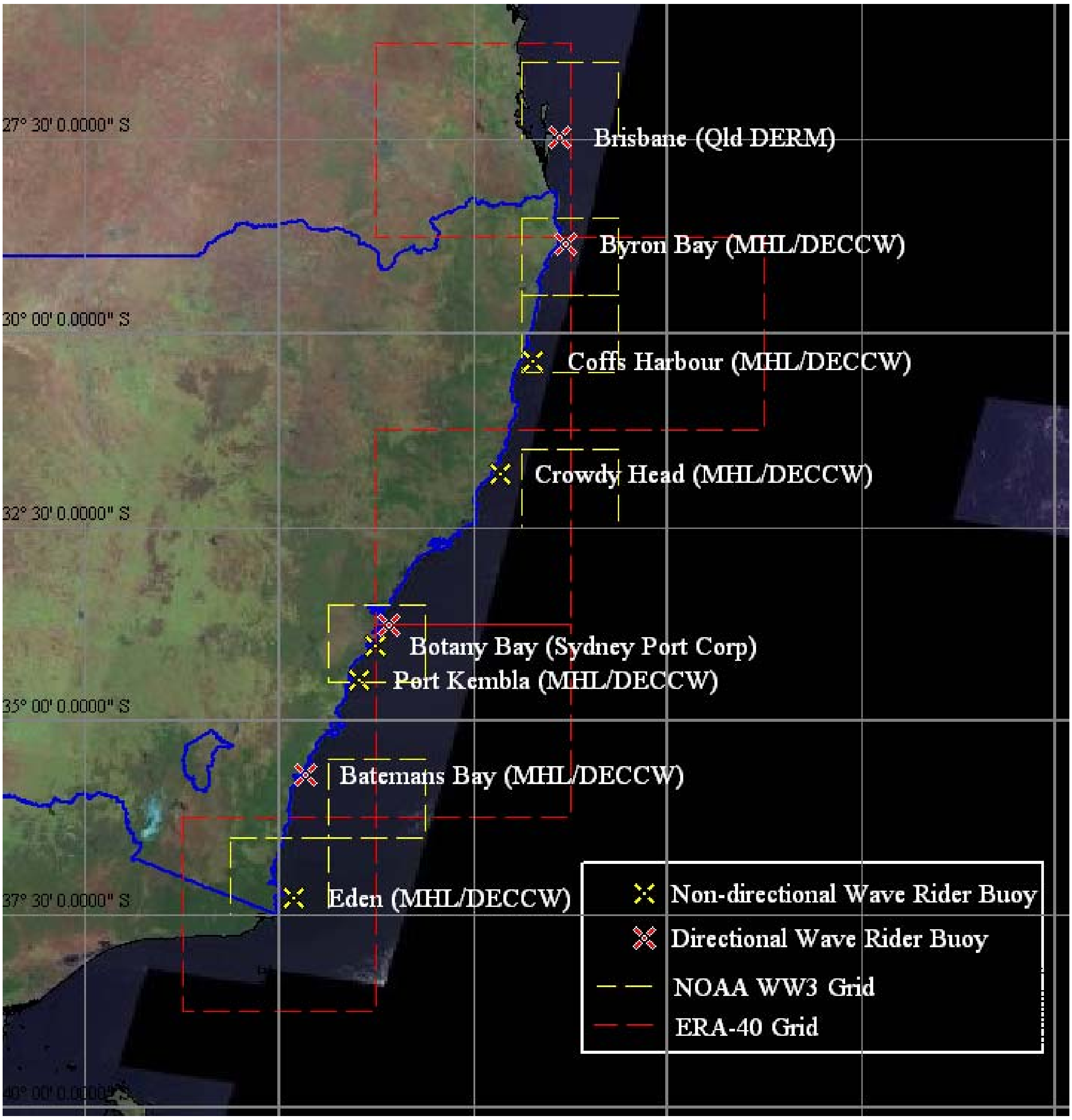
A





Example of two (A) and three-dimensional (B) wave spectra (source: NOAA)

WRL Report No. 2010/16	WAVE PARAMETER AND SPECTRA DEFINITIONS	Figure 3.4



WRL Report No. 2010/16	LOCATION OF EXTRACTED NUMERICAL DATA COMPARED TO WAVE BUOY LOCATIONS	Figure 3.5

4. DATA ANALYSIS

4.1 Descriptive Statistics

Wave buoy characteristics including monthly mean H_{sig} and wave power, the relationship between H_{sig} and T_p, wave height exceedance and directional data (where applicable) is provided for all buoys within Appendix C. Significant wave height (H_{sig}) exceedance and peak wave period (T_p) occurrence tables for each wave buoy are presented within Table 4.1 and 4.2 respectively along with mean statistics. A combined plot of wave height exceedance for all buoys is presented within Figure 4.1. Figure 4.2 presents seasonal and mean significant wave height (A), peak spectral period (B) and peak spectral direction (C) and Figure 4.3 presents a combined wave rose plot for Brisbane (A), Byron Bay (B), Sydney (C) and Batemans Bay (D).

Figure 4.2 and Table 4.1 show that the median (50% exceedance) significant wave height ranges from 1.30 m at Batemans Bay to 1.52 m at Eden, although, with the exception of Batemans Bay, all buoys are relatively uniform. Mean H_{sig} is similarly lowest at Batemans Bay (1.43 m) and largest at Sydney (1.63 m). The 1% exceedance and maximum observed H_{sig} are highest at Sydney and Botany Bay, with a maximum H_{sig} of 8.86 m observed at Botany Bay, followed by Sydney and Port Kembla at 8.43 m. More notable along-coast variation in mean H_{sig} is observed seasonally (Figure 4.2), with larger waves occurring in the north during autumn and lower waves occurring during spring and summer. Wave height in the south is more uniform year-round.

Mean peak wave period (T_p) ranges from 9.27 s at Botany Bay to 9.72 s at Sydney. This difference may indicate minor differences in data processing techniques between the two collecting organisations. Wave period is otherwise largely uniform along the coast although it displays significant seasonal variation, increasing at all buoy locations during autumn and winter and decreasing during spring and summer (Figure 4.2). This change is representative of the seasonal changes in wave generation systems further discussed in Section 4.2.2. From Appendix C, it can be seen that during very large wave events, peak period ranges between 11.0 and 13.0 s. The 1% exceedance T_p ranges from 14.7 and 15.1 s.

Table 4.1
Significant Wave Height Exceedance (%) Table

H_{sig} (m)	Brisbane	Byron Bay	Coffs Harbour	Crowdy Head	Sydney	Botany Bay	Port Kembla	Batemans Bay	Eden
0.5	99.900	99.873	99.888	99.931	99.828	99.533	99.792	99.188	99.802
1.0	84.717	86.024	83.532	85.203	83.785	81.590	83.006	75.961	89.250
1.5	49.644	49.865	44.934	46.717	46.916	45.282	45.048	35.953	51.426
2.0	25.520	25.132	20.685	21.774	22.855	21.901	20.853	14.787	21.641
2.5	11.499	11.627	9.054	9.692	10.811	10.533	9.635	6.167	8.943
3.0	4.927	4.968	4.009	4.422	5.438	5.148	4.369	2.586	3.931
3.5	2.132	2.132	1.815	2.135	2.642	2.587	1.992	1.113	1.869
4.0	0.992	0.878	0.777	0.981	1.299	1.264	0.914	0.497	0.903
4.5	0.406	0.300	0.334	0.472	0.656	0.596	0.438	0.197	0.452
5.0	0.191	0.0896	0.129	0.207	0.311	0.303	0.213	0.0744	0.202
5.5	0.104	0.0369	0.0514	0.0851	0.153	0.135	0.0958	0.0270	0.0790
6.0	0.0676	0.0102	0.0235	0.0337	0.0634	0.0578	0.0432	0.0103	0.0201
6.5	0.0260	0.0051	0.0075	0.0055	0.0193	0.0245	0.0152	0.0038	0.0036
7.0	0.0074	0.0023	0.0010	0.0017	0.0079	0.0104	0.0066	0.0011	0.0010
7.5	0.0000	0.0006	0.0000	0.0000	0.0030	0.0042	0.0024	0.0000	0.0000
8.0	0.0000	0.0000	0.0000	0.0000	0.0024	0.0021	0.0019	0.0000	0.0000
8.5	0.0000	0.0000	0.0000	0.0000	0.0000	0.0008	0.0000	0.0000	0.0000
Descriptive Statistics (H_{sig}, m)									
Mean H_{sig}	1.63	1.66	1.58	1.61	1.63	1.60	1.58	1.43	1.64
Median H_{sig}	1.47	1.50	1.43	1.46	1.46	1.43	1.43	1.30	1.52
10% Exceed	2.57	2.59	2.44	2.48	2.55	2.54	2.47	2.22	2.43
1% Exceed	4.04	3.93	3.85	3.94	4.19	4.17	3.94	3.57	3.93
Maximum	7.36	7.64	7.37	7.35	8.43	8.86	8.43	7.19	7.14
Variance	0.51	0.48	0.44	0.46	0.54	0.55	0.48	0.39	0.42
Effective record length (yrs)	28.5	24.3	28.5	20.7	19	34	30.6	21.2	26.6

Table 4.2
Peak Wave Period Occurrence (%) Table

T_{P1} (s)	Brisbane	Byron Bay	Coffs Harbour	Crowdy Head	Sydney	Botany Bay	Port Kembla	Batemans Bay	Eden
2 – 3.99	0.41	0.36	0.41	0.28	0.44	0.17	0.91	0.36	0.24
4 – 5.99	6.71	5.42	5.78	5.05	6.23	5.62	6.05	6.95	7.46
6 – 7.99	19.82	16.05	15.55	15.43	16.07	19.49	17.22	20.61	19.49
8 – 9.99	37.72	33.65	33.85	33.12	27.70	41.20	31.76	30.74	31.38
10 – 11.99	24.55	28.10	27.73	27.75	31.29	26.06	25.50	25.40	24.28
12 – 13.99	9.17	14.24	14.56	15.66	14.95	6.68	16.00	14.38	15.11
14 – 15.99	1.50	1.95	1.87	2.30	2.73	0.66	2.23	1.35	1.83
16 – 17.99	0.092	0.22	0.24	0.40	0.54	0.057	0.31	0.20	0.21
18 – 19.99	0.001	0.010	0.011	0.022	0.042	0.003	0.022	0.008	0.013
20 – 21.99	0.000	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000
Descriptive Statistics (T_{p1}, s)									
Mean T_{p1}	9.32	9.59	9.58	9.71	9.72	9.27	9.57	9.36	9.41
Median T_{p1}	9.31	9.50	9.50	9.50	9.77	9.38	9.50	9.50	9.50
10% Exceed	12.14	12.20	12.20	12.20	12.50	11.98	12.23	12.20	12.20
1% Exceed	14.67	15.10	15.10	15.10	15.10	14.38	15.10	15.10	15.10
Maximum	19.17	19.70	19.79	19.79	20.00	23.65	19.70	19.70	19.69
Variance	4.75	4.92	4.99	5.12	5.57	5.24	5.60	5.17	5.46
Effective record length (yrs)	28.5	24.3	28.5	20.7	19	34	30.6	21.2	26.6

Mean peak wave direction is more east at the northerly buoys (123° at Byron Bay) and becomes slightly more southerly in the southern buoys (135° in Sydney). Seasonal variation of 10 to 20° is observed, with more a southerly mean peak wave direction in winter and more easterly direction in summer. Waves of greater than 5 m occur more commonly from the east to east-south-east in the northern buoys (Appendix C) and from the south-south-east to south-east in the southern buoys. This is reflective of the storm systems responsible for generation of large waves discussed further in the following sections.

4.2 Storm Event History

There are various methods of defining data for extreme value analysis. These include analysis of the entire series (the total sample method), analysis of the largest event per year (annual maxima method), and analysis of values identified using a peaks over threshold (PoT) method, whereby once waves exceed a defined threshold, an event is defined.

Requirements for the statistical sample include independency, whereby one event is not correlated to the prior or next event and homogeneity, where all samples belong to the same population (Goda, 2000). The total sample method does not satisfy the first statistical requirement for wave analysis as storm events typically persist for hours to days, meaning subsequent samples are likely highly correlated. This leaves either the annual maxima method or peaks over threshold method as valid candidates. For relatively short data sets, the peaks over threshold method is generally favoured as it provides a larger sample size and thus reduces the confidence interval (Goda, 2000).

4.2.1 Event Detection

A key component of this present study is evaluating the distribution of extreme, long-duration storm events rather than simply the yearly maxima. The peaks over threshold (PoT) method was therefore used to analyse the wave data and define storm events. An initial PoT analysis was undertaken for $H_{sig} > 2.0$ m with a minimum exceedance duration of three days. A second PoT analysis was then undertaken with a higher threshold of $H_{sig} > 3.0$ m. Thus storms with $H_{sig} > 2.0$ m and duration greater than three days were identified, as well as storms of any duration with $H_{sig} > 3.0$ m. This ensures that enough long duration storm events were captured for extrapolation of extreme wave heights and avoids generation of an excessive number of small and short duration events. You (2007) found the estimated extreme wave height to be largely insensitive to variation in the adopted threshold of between 3.0 and 4.5 m.

A minimum interval between storms was set at one day. This prevents single storms being split into two or more events if wave height temporarily drops below the threshold (i.e. Figure 4.4) as this would violate the assumption of sample independency.

Each detected event was manually checked against the original time series record for that buoy and against adjacent buoys to ensure:

1. erroneous spikes (where present) were removed;
2. single storms that were detected as separate events were combined;
3. multiple storms which may have been detected as a single event were separated.

While missing data within a storm event has been noted, no new data was synthesised as this would introduce a somewhat subjected component to the dataset. Only data missing during the largest events is expected to significantly influence the evaluated extreme wave statistics. This may have occurred at the Batemans Bay buoy where the May 1997 storm was missing and at Byron Bay where a number of large events may have been excluded, supposedly due to buoy submergence.

A summary of detected storm events for each of the NSW wave buoys is presented within Table 4.3 and Figure 4.5. The largest 10 storm events for each wave buoy based on peak H_{sig} are presented within Table 4.4. A complete *Storm History Table* detailing storm characteristics for each storm event detected on the NSW Coast by wave buoys between 1971 and 2009 is presented within Appendix D. For each storm, the table provides detailed wave characteristics (H_{sig}, T_p, duration, total storm energy) observed at the buoy which experienced the largest peak H_{sig}. Additionally, the peak H_{sig} observed at every buoy during that event is provided for comparison. Locations which did not observe a storm event (i.e. H_{sig} remained below the threshold height) are left blank and period where the buoys were not operational during a storm event are noted.

Table 4.3 and Figure 4.5 show the central NSW coast to be subject to the highest number of storm events per year as well as the largest mean and maximum storm peak height. The largest storm on record is the *'Mother's Day'* storm which occurred in May 1997. The storm peaked during the night of the 10^{th}-11^{th} May, with H_{sig} reaching 8.43 m at both Sydney and Port Kembla and 8.86 m at Botany Bay. Peak H_{sig} decreased to the north and south, reaching 5.9 m at Eden and 5.6 m at Coffs Harbour. The Batemans Bay buoy did not log data between 11pm on 8^{th} May and 2 pm on 14^{th} May, 1997. The largest storm event by total storm power was the 'Pasha Bulker Storm' which occurred in June 2007. This storm reached a peak H_{sig} of 6.9 m in Sydney but remained elevated over 3 m for 8 days and over 5 m for nearly 2 days.

Storms observed at the northern buoys tend to exhibit longer durations, with a mean storm duration at Brisbane of 90 hours and mean durations of over 70 hours for Byron Bay, Coffs Harbour and Crowdy Head. Buoys south of this exhibit mean durations under 70 hours, with Batemans Bay having a mean storm duration of 57 hours. This is attributed to the characteristics of the responsible storm systems, further discussed in the following section.

Mean storm direction is slightly more southerly at Sydney (153°) compared with Brisbane (137°), Byron Bay (149°) and Batemans Bay (142°), although the spread of storm directions is also greatest at Sydney (Figure 4.5). Very large storms at Sydney and Batemans Bay (Table 4.4) occur from the south-east to east-south-east, while at Brisbane and Byron Bay very large storms may also occur from the east to east-south-east.

Table 4.3
Summary of Storm Events Detected at Each Wave Buoy

Data source	Number of detected storm events	Effective Record length (years)	Average number of storms/ year	Maximum storm peak wave height $(H_{sig})_{peak}$	Mean storm peak wave height $(H_{sig})_{peak}$	Mean storm duration (hours)	Mean total storm power (kW/m)
Brisbane	456	28.5	16.0	7.36	3.69	90	-
Byron Bay	495	24.3	20.4	7.64	3.75	74	2800
Coffs Harbour	454	28.5	15.9	7.37	3.78	72	2910
Crowdy Head	390	20.7	18.8	7.35	3.84	73	3130
Sydney	451	19	23.7	8.43	3.98	64	2830
Botany Bay	751	34	22.1	8.87	3.91	63	-
Port Kembla	594	30.6	19.4	8.43	3.80	64	2340
Batemans Bay	318	21.2	15.0	7.19	3.71	57	2310
Eden	441	26.6	16.5	7.14	3.87	68	2590

Table 4.4
Largest 10 Storm Events Ranked by Peak H_{sig} for Each Wave Buoy

Brisbane												
	Duration			Storm Peak				Storm Mean			Total	Storm
Rank	Peak	Hours	Storm Type	Hsig	Hmax	Tp	Dirn	Hsig	Tp	Dirn	Power (MW/m)	rms H_{sig}
1	17/03/93	319	TC	7.4	12.9	12.3		3.5	9.7			3.8
2	4/03/06	144	ETL	7.2	11.5	12.2	100	4.1	9.5	116		4.4
3	5/03/04	154	ETL	7.0	14.3	12.1	72	3.2	9.6	110		3.4
4	2/05/96	263	ETL	6.9	10.1	11.9		3.5	9.5			3.8
5	15/02/95	226	TL	6.4	10.8	11.2		3.1	9.3			3.2
6	23/08/08	67	SSL	6.4	9.6	11.5	160	3.4	12.5	153		3.6
7	31/12/07	233	TL	6.3	9.0	13.4	91	3.8	11.0	98		3.9
8	15/02/96	123	TC	6.2	11.9	12.9		3.2	10.7			3.3
9	25/04/89	126	ETL	6.1	9.1	10.6		3.5	9.4			3.7
10	26/03/98	67	TC	6.0	9.5	13.1	77	3.6	10.4	113		3.8

Byron Bay

	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	**Peak**	**Hours**	**Type**	**Hsig**	**Hmax**	**Tp**	**Dirn**	**Hsig**	**Tp**	**Dirn**		
1	21/05/09	186	ETL	7.6	12.1	13.0	99	4.0	11.0	100	18.2	4.2
2	14/02/09	107	IT	6.6	10.5	10.9	101	2.8	9.4	126	4.6	2.9
3	11/05/97	284	ETL	6.0	10.2	15.1		2.9	11.0		14.0	3.0
4	15/09/88	90	ETL	6.0	9.2	11.1		3.3	10.0		5.3	3.5
5	4/09/03	38	STL	5.9	10.7	13.5	159	3.5	13.0	155	3.7	3.7
6	26/04/89	147	ETL	5.9	10.0	10.2		3.6	10.0		10.8	3.8
7	15/02/95	291	TL	5.8	8.4	10.2		2.7	9.1		10.5	2.8
8	7/03/95	160	TC	5.8	10.7	12.2		3.4	11.1		10.5	3.5
9	8/05/80	144	ETL	5.8	9.8	10.8		3.2	11.1			3.4
10	8/03/90	74	TC	5.7	9.5	12.2		3.7	11.7		6.3	3.8

Coffs Harbour

	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	**Peak**	**Hours**	**Type**	**Hsig**	**Hmax**	**Tp**	**Dirn**	**Hsig**	**Tp**	**Dirn**		
1	22/06/89	299	ETL	7.4	13.5	11.1		3.3	10.3		18.7	3.5
2	14/07/99	107	ETL	6.8	9.8	12.2		3.7	11.4		9.2	3.9
3	9/07/85	25	ETL	6.6	9.7	11.1		4.0	9.6		2.3	4.2
4	22/05/09	200	ETL	6.5	10.2	12.2		3.5	11.1		16.9	3.8
5	25/02/04	182	IT	6.5	10.8	11.1		3.1	10.2		10.1	3.3
6	8/08/86	174	ETL	6.4	11.1	13.5		3.4	12.4		13.9	3.6
7	9/02/88	83	IT	6.4	9.8	15.1		3.4	11.6		6.7	3.6
8	9/04/84	96	TC	6.2	8.6	11.7		3.8	10.1		1.4	3.9
9	7/03/95	139	TC	6.2	9.8	13.5		3.6	11.5		10.8	3.8
10	16/11/05	64	IT	6.0	8.6	13.5		3.7	10.8		5.0	3.8

Crowdy Head

	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	**Peak**	**Hours**	**Type**	**Hsig**	**Hmax**	**Tp**	**Dirn**	**Hsig**	**Tp**	**Dirn**		
1	4/03/95	206	TC	7.4	11.0	13.5		3.7	10.9		17.8	3.9
2	15/07/99	104	ETL	6.8	11.2	12.2		4.2	11.6		11.8	4.4
3	29/05/90	70	ETL	6.7	9.3	12.2		3.4	9.7		4.6	3.6
4	9/02/88	93	IT	6.5	10.4	15.1		3.7	11.3		8.5	3.9
5	23/04/99	110	SSL	6.5	10.4	15.1		3.7	11.9		10.4	3.9
6	13/10/90	103	CL	6.4	9.7	15.1		3.5	12.2		8.8	3.7
7	29/07/01	35	ETL	6.3	9.3	15.1		3.4	11.6		3.2	3.7
8	30/06/02	98	SSL	6.3	11.2	15.1		3.9	13.1		11.1	4.1
9	11/05/97	225	ETL	6.3	10.6	15.1		2.9	11.1		11.9	3.1
10	7/03/90	84	TC	6.3	12.9	12.2		3.9	11.4		8.0	4.1

Sydney

	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	**Peak**	**Hours**	**Type**	**Hsig**	**Hmax**	**Tp**	**Dirn**	**Hsig**	**Tp**	**Dirn**		
1	11/05/97	303	ETL	8.4	13.7	12.8	151	3.1	11.6	138	21.2	3.5
2	3/08/90	157	ETL	7.2	11.8	10.2		2.9	10.2		7.2	3.0
3	28/07/01	29	ETL	7.0	11.7	13.5	169	5.2	12.3	161	5.5	5.4
4	9/06/07	491	ETL	6.9	14.1	10.8	135	3.2	11.2	153	29.5	3.3
5	12/11/87	78	IT	6.8	10.2	11.1		3.9	9.2		6.1	4.1
6	18/07/04	66	SSL	6.7	8.1	12.2	167	4.0	10.6	159	6.2	4.1
7	23/03/05	285	IT	6.6	11.2	12.2	139	2.8	9.7	157	12.2	3.0
8	19/07/07	73	SSL	6.5	12.3	12.9	158	3.8	11.6	158	6.9	4.0
9	3/06/06	89	SSL	6.5	9.9	13.5	173	3.7	11.1	168	8.1	4.0
10	26/08/90	124	SSL	6.3	11.6	12.2		3.4	11.5		9.1	3.6

Botany Bay												
	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	Peak	Hours	Type	Hsig	Hmax	Tp	Dirn	Hsig	Tp	Dirn		
1	10/05/97	275	ETL	8.9	13.7	13.1		3.3	10.6			3.7
2	28/07/01	99	ETL	8.1	12.7	12.5		4.4	10.7			4.7
3	21/06/75	162	IT	7.4	13.1			3.2	10.3			3.5
4	25/09/95	133	SSL	7.2	10.4	11.7		3.6	10.3			3.9
5	25/10/85	14	IT	7.0	9.5	11.3		5.3	11.4			5.4
6	23/03/05	266	IT	6.9	11.0	12.1		2.8	9.6			3.0
7	1/06/78	90	ETL	6.9	11.5			3.9	11.5			4.1
8	5/08/86	134	ETL	6.8	10.3	10.8		4.5	10.5			4.7
9	28/04/99	254	STL	6.7	10.9	11.8		3.4	10.2			3.6
10	10/07/05	68	IT	6.6	9.3	12.6		3.7	11.5			4.0

Port Kembla												
	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	Peak	Hours	Type	Hsig	Hmax	Tp	Dirn	Hsig	Tp	Dirn		
1	11/05/97	101	ETL	8.4	13.7	12.8		4.4	10.9		6.7	4.7
2	31/08/96	119	IT	7.4	10.5	13.5		3.2	10.3		7.4	3.5
3	19/03/78	102	ETL	6.9	10.4	11.7		4.6	10.7		2.1	4.9
4	6/08/86	248	ETL	6.8	10.8	12.2		3.7	11.7		21.8	3.9
5	2/06/78	120	ETL	6.7	11.1	11.7		4.1	11.0		2.3	4.3
6	26/08/90	140	SSL	6.7	11.9	13.5		3.6	11.5		11.6	3.7
7	25/09/95	120	SSL	6.6	9.5	12.2		3.2	10.4		7.2	3.4
8	13/10/90	66	CL	6.5	10.4	13.5		3.9	12.1		6.5	4.1
9	28/07/01	88	ETL	6.3	9.3	12.2		3.8	11.0		2.0	4.0
10	20/05/78	132	CL	6.3	10.6	12.2		3.5	11.8			3.7

Batemans Bay												
	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	Peak	Hours	Type	Hsig	Hmax	Tp	Dirn	Hsig	Tp	Dirn		
1	31/08/96	107	IT	7.2	10.1	12.2		3.6	10.8		8.9	3.9
2	28/11/05	79	IT	6.6	10.7	12.2	153	3.2	10.2	156	4.9	3.4
3	24/10/99	62	IT	6.6	10.4	12.2		3.8	10.1		5.3	4.1
4	13/10/90	71	CL	6.0	9.9	13.5		3.8	12.2		7.0	4.0
5	19/11/86	72	IT	6.0	7.8	10.2		4.4	11.0		8.7	4.6
6	20/06/07	242	ETL	5.7	10.2	11.5	148	2.8	10.7	138	10.7	2.9
7	6/08/86	242	ETL	5.6	10.3	12.2		3.2	11.2		15.7	3.4
8	28/07/01	87	ETL	5.4	8.4	11.1	146	3.3	10.4	133	5.4	3.5
9	23/06/05	59	SSL	5.4	9.8	11.1	164	2.8	9.8	127	2.3	2.9
10	28/06/07	77	ETL	5.4	9.5	12.9	149	3.2	11.6	137	4.9	3.3

Eden												
	Duration			Storm Peak				Storm Mean			Total Power (MW/m)	Storm rms H_{sig}
Rank	Peak	Hours	Type	Hsig	Hmax	Tp	Dirn	Hsig	Tp	Dirn		
1	29/06/02	78	SSL	7.1	13.1	12.2		3.5	11.0		6.1	3.8
2	28/06/07	84	ETL	7.1	10.8	12.2		4.0	11.3		8.4	4.2
3	1/09/96	116	IT	6.8	10.5	13.5		3.4	10.9		8.5	3.6
4	13/03/94	209	IT	6.7	11.0	13.5		3.5	10.8		16.0	3.7
5	11/07/89	100	SSL	6.7	10.1	11.2		3.8	11.8		9.0	4.0
6	2/06/78	90	ETL	6.5	10.9	14.9		4.0	12.2		0.0	4.3
7	23/06/98	96	SSL	6.4	11.8	10.2		3.6	10.6		7.0	3.8
8	12/10/90	110	CL	6.4	10.1	12.2		3.5	11.2		7.9	3.7
9	10/07/05	86	IT	6.3	10.2	11.1		3.6	10.8		6.4	3.9
10	25/10/85	58	IT	6.1	10.4	12.2		4.0	10.1		5.1	4.1

4.2.2 Storm Type

The synoptic type was assigned to each storm event based on the storm classification described in Section 2, using the NCEP-NCAR Reanalysis (NCEP) pressure dataset from 1948 to 2009 (Kalnay *et al.* 1996). These types are provided, in brief, within Table 4.5 and for each observed storm event within the *storm history table* in Appendix D. The types were determined using the 1000 hPa (surface) and 500 hPa pressure field data. The assigned type for each storm event was based on the synoptic genesis of the storm and the synoptic pattern at the time of the observed peak wave climate. We also determined a secondary storm type which produced storm waves during the duration of the observed peak wave conditions. The storm types often are transformed as they move eastwards or southwards in the Tasman Sea region. Whilst most synoptic type classifications were unambiguous, some classifications were difficult due to factors such as change in storm type during wave generation, multiple simultaneous swell generating weather systems.

The total number of storms observed yearly by storm type is presented within Figure 4.6 with the year of wave buoy commission indicated. Storms observed only at the Botany Bay buoy were not assigned types within this study. Total yearly storm numbers since all wave buoys were commissioned (1987) has remained largely constant at around 32 storms per year, with a slight increase observed during the late 1990s. This may be related to the change in phase of the Interdecadal Pacific Oscillation (IPO) (Goodwin and Browning, in prep) from El Niño-like to La Niña-like in the early to mid 2000s. The relationship between storm frequency and the El Niño-Southern Oscillation (ENSO) was examined by You and Lord (2008), who found correlation between average yearly storm intensity and Southern Oscillation Index (SOI) indicating more severe storm events during La Niña years. The Sydney wave buoy was found to detect an average of 23.7 storms per year (Table 4.3) meaning that the Sydney coastline is affected, based on the adopted H_{sig} threshold, by around 75% of all storm wave events on the NSW coast. However, it is important to note that the available buoy data only span the El Niño-like phase of the IPO together with a few recent years of the La Niña-like phase. Hence, it is probable that any trends and relationships between storm type, frequency and severity, ENSO and the IPO are biased towards the El Niño-like phase, where interannual El Niño events are stronger and more persistent over multi-years, and La Niña events weaker and less persistent. Goodwin and Blackmore (in prep) will report the results of hindcasting NSW wave climate over the La Niña-like phase of the IPO prior to the buoy measurement period.

Appendix E provides, for each wave buoy, a time series of storm peak H_{sig} and type. Major storm events (> 6 m) on the northern NSW coast are a mixture of tropical cyclones, tropical lows and easterly trough lows while on the central NSW coast, major storm events also include inland trough lows and southern secondary lows. Along the southern NSW coast, major storm events are mainly associated with a combination of easterly trough lows, inland and continental lows and southern secondary lows, with a number of Southern Tasman lows causing waves in excess of 5 m but not reaching 6 m. The latter produce long period oblique swell along the central and northern NSW coasts.

Storm types are presented by percentage for each wave buoy within Figure 4.7. This figure shows a similar spatial variation in the occurrence of particular storm types. A decrease in the occurrence of anticyclone intensification induced events and tropical lows and cyclones to the south and a corresponding increase in southerly trough lows can be observed for all storms. For storms exhibiting peak H_{sig} > 5 m, the reduction in anticyclone intensification induced events and tropical lows and cyclones is more pronounced. An increase in inland trough and continental lows is observed at the southern buoys. Easterly trough lows are largely constant north to south, although reduce in the central coast from Sydney to Port Kembla, where there is a corresponding increase in the occurrence of southern secondary lows.

Seasonal changes in the occurrence of various storm type are shown within Figure 4.8 which provides the total number of storms observed for each month. March, July and October are the stormiest months, with November, December and January being the least stormy. Inland trough lows and southern secondary lows exhibit strong negative-correlation, with greater numbers of southern secondary lows occurring between April and October and larger numbers of inland trough lows occurring between October and March. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August. Both anticyclone intensifications and Southern Tasman lows occur throughout the year, although anticyclone intensification events tend to be more concentrated and produce larger wave events between January and June and Southern Tasman lows are concentrated and produce larger wave events between July and December.

Table 4.5
Storm Type Definitions

Number	Abbreviation	Full Name	Description
1	TC	Tropical Cyclone	Swell related to named Tropical Cyclones forming in the Coral Sea between 5-10° latitude.
2	ETL	Easterly Trough Low	Cyclonic depressions generated primarily along the central NSW coast between 25 and 40° latitude
3	CL	Continental Low	Storms originating in Western Australia of the Great Australian Bight and moving overland, often re-intensify upon crossing the east coast
4	STL	Southern Tasman Low	Major lows in the southern ocean south of 38S
5	SSL	Southern Secondary Low	Form in association with STL as a secondary cut off low in the Tasman sea
6	ITL	Inland Trough Low	Originate in the quasi-permanent low pressure trough over inland Qld, their movement to the east coast is often associated with STL
7	AI	Anti-Cyclone Intensification	Form when a high across the Tasman Sea directs onshore E to SE winds to the coast
8	TL	Tropical Low	Low pressure systems forming in the Coral Sea but not reaching the low pressure intensity of a named tropical cyclone

4.2.3 Duration of Wave Height Exceedance

Extreme value analysis of wave data is generally undertaken for the peak significant wave height only. This provides extreme wave heights corresponding to the sampling interval, which is typically one or three hours. However, for many applications such as evaluating beach erosion and coastal inundation, the combination of both wave height and elevated water levels are critical. In these cases, evaluation of extreme wave height over a longer duration is required (Lord and Kulmar, 2000; Carley and Cox, 2003). Thus, an extreme value analysis should also be undertaken for wave height exceedance values over longer durations.

This has been undertaken by assessing the exceedance significant wave height for varying durations from the sampling interval (1 hour) to 144 hours (6 days) for each defined storm event. If a particular storm event does not extend beyond the duration of interest, that storm event does not contribute to the record for extreme value analysis. A reduced number of storm events is therefore noted for longer durations. An example of the change in number and magnitude of detected events as a function of duration is presented in Figure

4.9 for the Sydney wave buoy. It is evident from this figure that while a threshold storm height of 3 m may have been appropriate for assessing storm durations up to 24 hours, the lower 2 m threshold is required for assessing longer duration events.

4.3 Extreme Value Analysis

4.3.1 Background

Large, low probability wave events are generally defined in terms of a return period (RP) or average recurrence interval (ARI). The commonly used approach to derive extreme wave height for a particular ARI is to fit a theoretical distribution to historical storm wave data. If the record is of insufficient length to provide the event magnitude for the return period of interest, the distribution is extrapolated. The reliability of such extrapolation is dependent on selection of an appropriate distribution to best fit the available data and the length of extrapolation relative to data record length.

As described previously, an important requisite of the samples used for extreme value analysis is statistical independence (Goda, 2000). This means that the correlation between successive data should be near zero. While care is taken when defining storm events to ensure each meteorological event produces only one sample, clustering of storms and generation of wave-inducing meteorological events by other wave-inducing meteorological events, i.e. an anticyclone intensification induced by a tropical low, may result in slight dependence. Another important requisite is that of homogeneity where all samples are of the same *population* and belong to a common parent distribution. While all wave events are generally treated as belonging to the same population, generation by differing meteorological events, i.e. southerly trough lows compared with tropical cyclones, will mean that this requirement is not completely satisfied. This is partially addressed by the proxy of storm wave direction. The effect of direction on extreme events is further discussed within Section 4.3.6. The data used within extreme values analysis is also assumed to be statistically stable, i.e. long term change is negligible.

You (2007) describes five steps in calculating extreme wave height: analysing raw wave data to obtain statistically independent storm wave heights; estimating an empirical probability distribution function (pdf); fitting candidate functions to the observed data to obtain the best fit; extrapolating the best fit pdf to the required return value (H_R) and estimating the confidence intervals of the resultant height.

4.3.2 Fitting Probability Distribution Functions

You (2007) examined the fit of nine extreme value distributions to long term wave data (1988 to 2006) for the Sydney wave buoy. These included Exponential, Lognormal, Weibull, Fisher-Tippett type 1 (FT-I or Gumbel), type 2 (FT-II), type 3 (FT-III), Generalised Pareto type 1 (GPD-I), type 2 (GPD-II) and type 3 (GPD-III) distributions. All but two (FT-III and GPD-III) are unbounded at the upper end. You (2007) suggested that use of upper bounded distributions is inappropriate for extreme value analysis of wave heights as they as they tend to underestimate extreme wave height.

You (2007) found both the FT-I (Gumbel) and Weibull distributions to best fit the observed data and suggested the FT-1 as most appropriate due to its simplicity as a two-parameter distribution rather than the three-parameter Weibull. Goda (1988) similarly suggested the FT-I (Gumbel) and Weibull distributions as most appropriate for evaluation of extreme waves. These candidate distributions, presented within Eqns. 4.1 and 4.2, are therefore adopted for consideration within the present study.

FT-1
$$F_{(x)} = \exp\left[-\exp\left(-\frac{x-B}{A}\right)\right] \tag{4.1}$$

Weibull
$$F_{(x)} = 1-\exp\left[-\left(\frac{x-B}{A}\right)^{k}\right] \tag{4.2}$$

Where $F_{(x)}$ is the distribution function and *A*, *B* and *k* are scale, location and shape parameters.

As can be observed, the FT-1 or Gumbel distribution (4.1) is a function of only the scale and location parameter while the Weibull distribution (4.2) contains an additional shape parameter.

4.3.3 Evaluating Goodness of Fit

The *expected* probability ($F_{(m)}$) of the observed data or variates is evaluated using an appropriate plotting position formula. The simplest plotting position formula is the Weibull formula (Eqn. 4.3). However, this formula has been found to produce a positive bias, particularly in small data sets (Goda, 1988). More appropriate plotting position formula producing minimal bias are the Gringorten plotting position formula (Gringorten, 1963) for the FT-1 distribution and the modified Petruaskas and Aagaard formula proposed by Goda (1988) for the Weibull distribution (Eqn. 4.4).

$$F_{(m)} = 1 - \left(\frac{m}{N+1} \right) \tag{4.3}$$

$$F_{(m)} = 1 - \left(\frac{m-\alpha}{N+\beta} \right) \tag{4.4}$$

Where $F_{(m)}$ is the expected probability of the m^{th} ordered variates, N is the number of samples and α and β are constants given as 0.44 and 0.12 for the FT-1 distribution (Gringorten, 1965) and ($0.2 + 0.27/k^{0.5}$) and ($0.2 + 0.23/k^{0.5}$) where *k* is the distribution shape parameter (Goda, 1988).

By plotting observed height (H) of each data against a reduced variate (X), calculated according to Eqns. 4.5 (FT-1) and 4.6 (Weibull), scale, location and shape parameters (A, B and *k*) may be estimated for Eqns. 4.1 and 4.2 using a fitting method.

$$X = -\ln(-\ln F_{(m)}) \tag{4.5}$$

$$X = \left[-\ln(1 - F_{(m)}) \right]^{1/k} \tag{4.6}$$

There are a variety of methods available including the graphical fitting method, least squares method, method of moments and maximum likelihood method. Goda (2003) advocates the use of the least squares method with appropriate plotting position formula over the other methods on the basis of bias and efficiency. This least-squares method was similarly used by You (2007). Scale and location parameters are determined based on the relation shown within Eqn. 4.7. The goodness of fit may be evaluated by a variety of tests. In this case, the coefficient of regression, R^2, the sum of the squares of the error (SSE), evaluated according to Eqn. 4.8, and a visual assessment of goodness of fit are used. This visual assessment is important as the goodness of fit compared to the data extremes is very important and may not be adequately assessed by evaluation of the R^2 and SSE only.

$$H = AX + B \tag{4.7}$$

$$SSE(H) = \sum_{i=1}^{m} (H_i - H)^2 \tag{4.8}$$

Where H_i is the i[th] peak storm wave height and H is the equivalent value evaluated according to (4.7).

While the parameter assessment is relatively simple for the FT-1 method, the shape parameter, k, in the Weibull distribution influences both the plotting position formula and reduced variates and is not assessed implicitly. The shape parameter k is therefore estimated using the optimisation method described in You (2007), where k is incrementally varied until $|W-1|^{0.5}$ is ≈ 0 where W is evaluated by Eqn. 4.9. This optimisation is shown within Figure 4.10A.

$$W = \frac{\sum_{i=1}^{m}(H_i - \overline{H})(X_i - \overline{X})}{\sum_{i=1}^{m}(X_i - \overline{X})} \times \frac{\sum_{i=1}^{m}(X_i^{*} - \overline{X^{*}})(X_i - \overline{X})}{\sum_{i=1}^{m}(X_i^{*} - \overline{X}^{*})(H_i - \overline{H})} \qquad (4.9)$$

Where H_i is the i^{th} peak storm wave height, X_i is given by (4.6) and $X_i^{*} = X[-ln(1-F_{(m)}]$.

Table 4.6 compares the SSE and R^2 obtained using the FT-1 distribution and Weibull distribution with individually optimised shape parameters for a range of storm durations observed at the Sydney wave buoy. While the R^2 value is high for both distributions, the SSE value is substantially lower for the Weibull distribution. This distribution is also visually the most appropriate across the range of exceedance durations due to the greater flexibility afforded by the three parameter fit. The Weibull distribution with a shape parameter optimised for each data set has therefore been adopted within this study.

Table 4.6
Evaluation of Goodness of Fit for FT-1 and Weibull distributions for Sydney

Coefficient of Regression (R^2)

Distribution	Shape parameter	1 hr	3 hr	6 hr	12 hr	24 hr	48 hr	96 hr	144 hr
FT-1	-	0.981	0.981	0.988	0.994	0.992	0.979	0.949	0.899
Weibull	Variable: k = 0.76 to 1.24	0.991	0.989	0.995	0.997	0.995	0.989	0.974	0.967

Sum of Squares of the Error (SSE)

Distribution	Threshold	1 hr	3 hr	6 hr	12 hr	24 hr	48 hr	96 hr	144 hr
FT-1	-	6.66	6.07	3.66	1.76	1.43	1.60	0.55	0.30
Weibull	Variable: k = 0.76 to 1.24	1.59	2.01	0.78	0.49	0.52	0.73	0.25	0.08

4.3.4 Evaluating Annual Recurrence Interval and Confidence Interval

Once the appropriate probability distribution function and function coefficients have been determined, the annual recurrence interval (ARI) and return value (H_R) can be assessed by Eqn. 4.9 and 4.10 respectively

$$ARI = \frac{1}{\lambda[1 - F(x_u)]} \tag{4.9}$$

$$H_R = F^{-1}\left(1 - \frac{1}{\lambda ARI}\right) \tag{4.10}$$

Where $F(x_u)$ probability of non-exceedance of a variate (x_u) and λ is the average number of events per year.

Confidence intervals are assessed based on the standard deviation for each return value (Eqn. 4.11),

$$\sigma(x_R) = \sigma_z \times \sigma_x \tag{4.11}$$

Where σ_x is the sample standard deviation and σ_z is the standard deviation of the reduced variate given by Eqn. 4.12 (Goda, 1988) as:

$$\sigma_z = \left[1.0 + a(y_R - c + \alpha \ln v)^2\right]^{1/2} / \sqrt{N} \tag{4.12}$$

With *a* being:

$$a = a_{1\exp}\left[a_2 N^{-1.3} + \kappa(-\ln v)^2\right] \tag{4.13}$$

and the constants within Eqns. 4.12 and 4.13 interpolated from empirical values derived by Monte Carlo simulation in Goda (1988) and presented in Table 4.7.

Table 4.7
Constants for the Standard Deviation of the Return Value (Goda, 1988)

Distribution	a_1	a_2	κ	c	α
Weibull (k = 0.75)	1.65	11.4	-0.63	0.0	1.15
Weibull (k = 1.0)	1.92	11.4	0.00	0.3	0.90
Weibull (k = 1.4)	2.05	11.4	0.69	0.4	0.72
Weibull (k = 2.0)	2.24	11.4	1.34	0.5	0.54

A 90% confidence interval as suggested by Goda (2000) has been adopted within the present study. Alternative methods of defining confidence intervals were considered including assessment of the confidence in the least squares slope. The derived confidence intervals were, however, insensitive to such alternatives.

Extreme waves with average recurrence intervals of between 1 and 100 years and durations between 1 hour and 144 hours (6 days) are presented for each wave buoy within Appendix F along with numerical results for the 3 hourly NWW3 data and 6 hourly ERA-40 data.

4.3.5 Spatial Variation

The 1 hour exceedance H_{sig} for all buoys for average recurrence intervals of between 1 and 100 years is shown in Figure 4.11 and summarised for the 1, 10, 50 and 100 year ARI along with 90% confidence intervals in Table 4.8. The mid NSW coast exhibits the highest extreme wave climate, with both Sydney and Botany Bay showing similar extreme statistics with 100 year ARI H_{sig} values of 9.0 and 9.1 m respectively. Port Kembla exhibits slightly lower 100 year ARI H_{sig} of 8.8 m, although this is within the confidence intervals of Sydney. Both Eden and Crowdy Head have 100 year ARI H_{sig} of 8.5 ±0.5 m. The difference between this value and Sydney is at, or outside, the confidence limits, indicating a statistically valid spatial difference.

Table 4.8
Summary of Spatial Variation in One Hour Exceedance H_{sig} along the NSW Coast

	H_{sig} (m) ± 90% CI			
Buoy	**1 yr ARI**	**10 yr ARI**	**50 yr ARI**	**100 yr ARI**
Brisbane	5.1 (± 0.2)	6.6 (± 0.3)	7.6 (± 0.4)	8.0 (± 0.4)
Byron Bay	5.2 (± 0.2)	6.4 (± 0.2)	7.2 (± 0.3)	7.6 (± 0.3)
Coffs Harbour	5.2 (± 0.2)	6.7 (± 0.3)	7.7 (± 0.4)	8.1 (± 0.4)
Crowdy Head	5.4 (± 0.2)	7.0 (± 0.4)	8.0 (± 0.5)	8.5 (± 0.5)
Sydney	5.9 (± 0.2)	7.5 (± 0.4)	8.6 (± 0.5)	9.0 (± 0.5)
Botany Bay	5.7 (± 0.2)	7.4 (± 0.3)	8.6 (± 0.4)	9.1 (± 0.4)
Port Kembla	5.4 (± 0.2)	7.1 (± 0.3)	8.3 (± 0.4)	8.8 (± 0.5)
Batemans Bay	4.9 (± 0.2)	6.3 (± 0.4)	7.3 (± 0.5)	7.7 (± 0.5)
Eden	5.4 (± 0.2)	7.0 (± 0.3)	8.1 (± 0.4)	8.5 (± 0.5)

Batemans Bay is substantially lower at 7.7 m ±0.5 m. While Batemans Bay is known to have missed a number of large events including the May 1997 event, the mean and 50% exceedance value at Batemans Bay are also lowest indicating a more systematic difference. Calculated extreme wave heights to the north of Crowdy Head decrease with Coffs Harbour, Byron Bay and Brisbane exhibiting 8.1, 7.6 and 8.0 ±0.5 m respectively. Again, Byron Bay is known to have missed a number of large events, although its two largest events of 7.6 m and 6.6 m on 21st May and 14th February 2009 were captured. The effect of missing data is addressed within Section 4.4 but interpolation of major missing storms from adjacent buoys is not found to substantially change extreme statistics (i.e. values remain within the assessed confidence limits).

4.3.6 Storm Duration

As discussed earlier, many applications requiring extreme wave height (i.e. assessment of coastal inundation) are also influenced by elevated water levels. In these cases, the height exceedance for longer durations is important. However, as less data is available for storms of long duration, confidence intervals are proportionally larger. Appendix F presents wave height exceedance for events of duration up to 144 hours (6 days). The change in exceeded wave height as a function of duration for the Sydney buoy is presented within Figure 4.12. This figure shows that for all ARI events, height drops by around 20% from the 1 hour height at 12 hours and by 50 % at 72 hours (3 days), before asymptoting to between 35% and 40% of the 1 hour height at 6 days.

Comparison of the 100 year ARI values for all buoys within Figure 4.12 shows the wave height at the northern buoys of Brisbane and Byron Bay to drop more slowly and the southern buoy at Eden to drop more quickly. This is, again, a function of the type and track of storms causing the wave events with longer duration events such as anticyclone intensification and slow moving tropical cyclones and lows affecting the northern coast to a greater extent. Extreme wave height does not decrease to 50% of the one hour height until after 132 hours (5.5 days) at Brisbane and 108 hours (4.5 days) at Byron Bay.

4.3.7 Numerical Comparisons

Comparison of the extreme wave heights derived using buoy measurements and those derived using NOAA's Wavewatch III (NWW3) numerical wave model and the ERA-40 numerical hindcast dataset are presented within Figure 4.13 for the one hour exceedance event and for the 10 and 100 year ARI events within Table 4.9.

The NWW3 model provides very good agreement with the Brisbane buoy and Port Kembla buoy. The model over predicts extreme wave height at Byron Bay, Coffs Harbour, Crowdy Head and Batemans Bay. In all cases, the over prediction is outside the wave buoy confidence limits and the over prediction is severe at Crowdy Head (1.5 m over prediction). The NWW3 model under predicts extreme wave height at Sydney, Botany Bay and Eden, although the under prediction at Sydney and Botany Bay is at the confidence limit level. Confidence limits for the NWW3 predictions are higher than for the buoys due to the shorter record length (±0.9 to 1.2 m for the 100 year ARI height cf. ±0.3 to 0.5 m for the buoys). It should be noted that the numerical output from the grid cell containing the wave buoy location was used rather than the weighted average from a number of adjacent cells.

The ERA-40 hindcast dataset under predicts wave height in most locations except Byron Bay, Batemans Bay and Coffs Harbour where agreement with buoy values is reasonable. At Byron and Batemans Bay, the over prediction is at around the buoy confidence limit. Severe under prediction occurs at Brisbane and Eden. This under prediction is likely due to adjacent land cells limiting the input of wave energy from particular directions. It should be noted that, due to the large size of the ERA-40 spatial domain, the same numerical output is used at Byron Bay and Coffs Harbour, and at Sydney, Botany Bay, Port Kembla and Batemans Bay.

Table 4.9
One Hour Exceedance 50 and 100 year ARI H_{sig} For Wave Buoys and Numerical

	10 year ARI			100 year ARI		
Buoy	**Wave Buoy**	**NWW3**	**ERA-40**	**Wave Buoy**	**NWW3**	**ERA-40**
Brisbane	6.6 (± 0.3)	6.6 (± 0.5)	4.3 (± 0.3)	8.0 (± 0.4)	8.0 (± 0.8)	5.3 (± 0.5)
Byron Bay	6.4 (± 0.2)	7.0 (± 0.6)	6.7 (± 0.3)	7.6 (± 0.3)	8.4 (± 0.8)	8.2 (± 0.5)
Coffs Harbour	6.7 (± 0.3)	7.4 (± 0.6)	6.7 (± 0.3)	8.1 (± 0.4)	8.9 (± 0.9)	8.2 (± 0.5)
Crowdy Head	7.0 (± 0.4)	8.3 (± 0.8)	6.5 (± 0.3)	8.5 (± 0.5)	10.0 (± 1.2)	8.1 (± 0.5)
Sydney	7.5 (± 0.4)	7.0 (± 0.6)	6.7 (± 0.3)	9.0 (± 0.5)	8.6 (± 0.9)	8.2 (± 0.5)
Botany Bay	7.4 (± 0.3)	7.0 (± 0.6)	6.7 (± 0.3)	9.1 (± 0.4)	8.6 (± 0.9)	8.2 (± 0.5)
Port Kembla	7.1 (± 0.3)	7.0 (± 0.6)	6.7 (± 0.3)	8.8 (± 0.5)	8.6 (± 0.9)	8.2 (± 0.5)
Batemans Bay	6.3 (± 0.4)	7.5 (± 0.6)	6.7 (± 0.3)	7.7 (± 0.5)	8.8 (± 0.9)	8.2 (± 0.5)
Eden	7.0 (± 0.3)	5.9 (± 0.4)	5.2 (± 0.2)	8.5 (± 0.5)	6.8 (± 0.5)	6.1 (± 0.2)

Selection of an appropriate buoy duration to compare with the numerical data sets is also problematic as the numerical datasets are provided at three hour (NWW3) and six hour (ERA-40) intervals, yet are instantaneous samples rather than three or six hour averages. While the peak of an event could be missed by the numerical model run, the fact that they are '*instantaneous*' values rather than averages meant it was deemed appropriate to compare the numerical outputs to the one hour (or peak) buoy values. Overall, the NWW3 numerical model resulted in over prediction of extreme vales in the north and under prediction in the south, while the ERA-40 dataset resulted in general under prediction of extreme values across all regions.

4.3.8 Storm Direction

The effect of storm direction on extreme wave height is shown within Figure 4.13. In all cases, extreme waves arriving from north of 90° are predicted to be lowest. Brisbane and Byron Bay predict extreme waves from between east and south-east (90 to 135°) to be largest, while Sydney and Batemans Bay predict extreme waves from south of 135° to be largest. Due to the short length of directional record at Byron Bay, the extrapolated extreme values from the east and south-east (90 to 135°) are predicted to exceed the '*all directions*' values. This is inappropriate and should converge to agreement with the '*all directions*' value once the record length increases. In practice, the '*all directions*' value should be adopted as an upper limit.

Table 4.10 shows the extreme directional statistics for the 10 year ARI events. Confidence limits increase markedly for directions where a limited number of storm are available for analysis. Only five storms with a direction north of 90° were available at Byron Bay resulting in 90% confidence limits of ± 2.1 m. This indicates very low statistical confidence, although the extreme distribution fits the data well.

Table 4.10
One Hour Exceedance 10 year ARI H_{sig} For Directional Wave Buoys

	H_{sig} (m) ± 90% CI			
Buoy	**All**	**0 - 90°**	**90 - 135°**	**135 - 225°**
Brisbane	6.6 (± 0.3)	4.6 (± 1.2)	6.8 (± 0.6)	5.7 (± 0.4)
Byron Bay	6.4 (± 0.2)	4.3 (± 2.1)	7.1 (± 1.6)	6.1 (± 0.4)
Sydney	7.5 (± 0.4)	4.5 (± 0.7)	6.2 (± 0.7)	7.5 (± 0.5)
Batemans Bay	6.3 (± 0.4)	4.5 (± 1.4)	5.6 (± 1.2)	6.1 (± 0.7)

4.4 Study Uncertainties and Limitations

Uncertainties in extreme value analysis may arise from several sources. Most influential are in the accuracy and completeness of original data and in the appropriateness of the fitted extreme value distribution.

4.4.1 Data Accuracy and Completeness

The accuracy of Datawell Waverider Buoys is indicated by the manufacturer at ±0.5 to 1 %. Translating this to the derived 100 year ARI 1 hour H_{sig} values of 7.6 to 9.1 m gives uncertainties of 0.05 to 0.1 m. These uncertainties are well within confidence limits.

The most serious uncertainty is related to data censoring, where major storm events are excluded due to instrument damage or other factors. Data capture has improved over time and the only real solution to this problem is to continue to collect data including large events. An example of this is the May and February 2009 events captured at Byron Bay where H_{sig} reached 7.6 and 6.6 m respectively. The previous maximum measured wave height was 6.0 m. Calculation of extreme height excluding these recent events would have resulted in underestimation of extreme values by up to 0.5 m (100 year ARI, 1 hr H_{sig} of 7.1 m excluding events cf. 7.6 m including). Table 4.11 presents a list of notable storm events, i.e. an event ranking in the top 10 for a particular buoy, where data from an adjacent buoy was missing (excludes events which occurred before a buoy was commissioned). This table interpolates a peak significant wave height for the missing buoy based on adjacent values and indicates the ranking which that interpolated event would have for the respective buoy record.

Results show that the Byron Bay buoy was missing data during a number of large adjacent events. However, the interpolated values would not have been within the 10 largest for the Byron buoy and therefore do not change the extreme statistics markedly with the 100 yr ARI, 1 hr H_{sig} increasing from 7.60 m to 7.65 m, a change which is well within the 90% confidence limits. While there is a possibility that the storm peak may have affected Byron Bay more than the adjacent sites due to the relatively small-scale nature of storm systems on the NSW coast, this specific detail cannot be resolved using the data analysis methods of this study.

Similarly, values interpolated from adjacent buoys for missing events at Coffs Harbour, Crowdy Head and Eden were outside the 10 largest events at each buoy and, as such, are not expected to change the extreme statistics notably. The notable missing storm at Batemans Bay is more significant, constituting the equal largest event on record. Inclusion of this record increased the 100 yr ARI, 1 hr H_{sig} from 7.7 m to 8.0 m, although this increase is still within the 90% confidence limits of ± 0.5 m. As previously described, the wave height during a particular event is highly dependent on the specific storm track and fetch orientation with large variation observed between the peak storm height observed at Port Kembla (8.4 m) and Eden (5.9 m). The exact height experienced at Batemans Bay is unknown, although the smaller wave heights typically observed at Batemans Bay indicates that a linear interpolation is likely conservative.

Table 4.11
Notable Missing Storm Data in Wave Buoy Record

Date	Peak H_{sig} (m)									Missing Buoy	Interpolated	Would be xth largest
	BRI	BYR	COF	CRO	SYD	BOT	PK	BAT	EDE			
9/04/1984	5.2	-	6.2	-	-	4.0	3.6	-	< 2	Byron	5.7	10
4/03/2006	7.2	-	4.1	3.1	< 2	< 2	< 2	< 2	< 2	Byron	5.7	10
5/03/2004	7.0	-	4.1	-	3.1	3.1		< 2	< 2	Byron	5.6	14
7/03/1990	3.3	5.7	-	6.3	4.7	5.0	4.8	3.3	3.1	Coffs	6.0	11
7/03/1990	3.3	5.7	-	6.3	4.7	5.0	4.8	3.3	3.1	Coffs	6.0	11
25/02/2004	3.7	-	6.5	-	5.5	4.7	5.1	3.5	3.9	Crowdy	6.0	13
10/05/1997	4.3	6.0	5.6	6.3	8.4	8.9	8.4	-	5.9	Batemans	7.2	1 or 2
20/11/1986	3.2		3.9	4.2	-	6.3	4.9	6.0	-	Eden	6.0	12

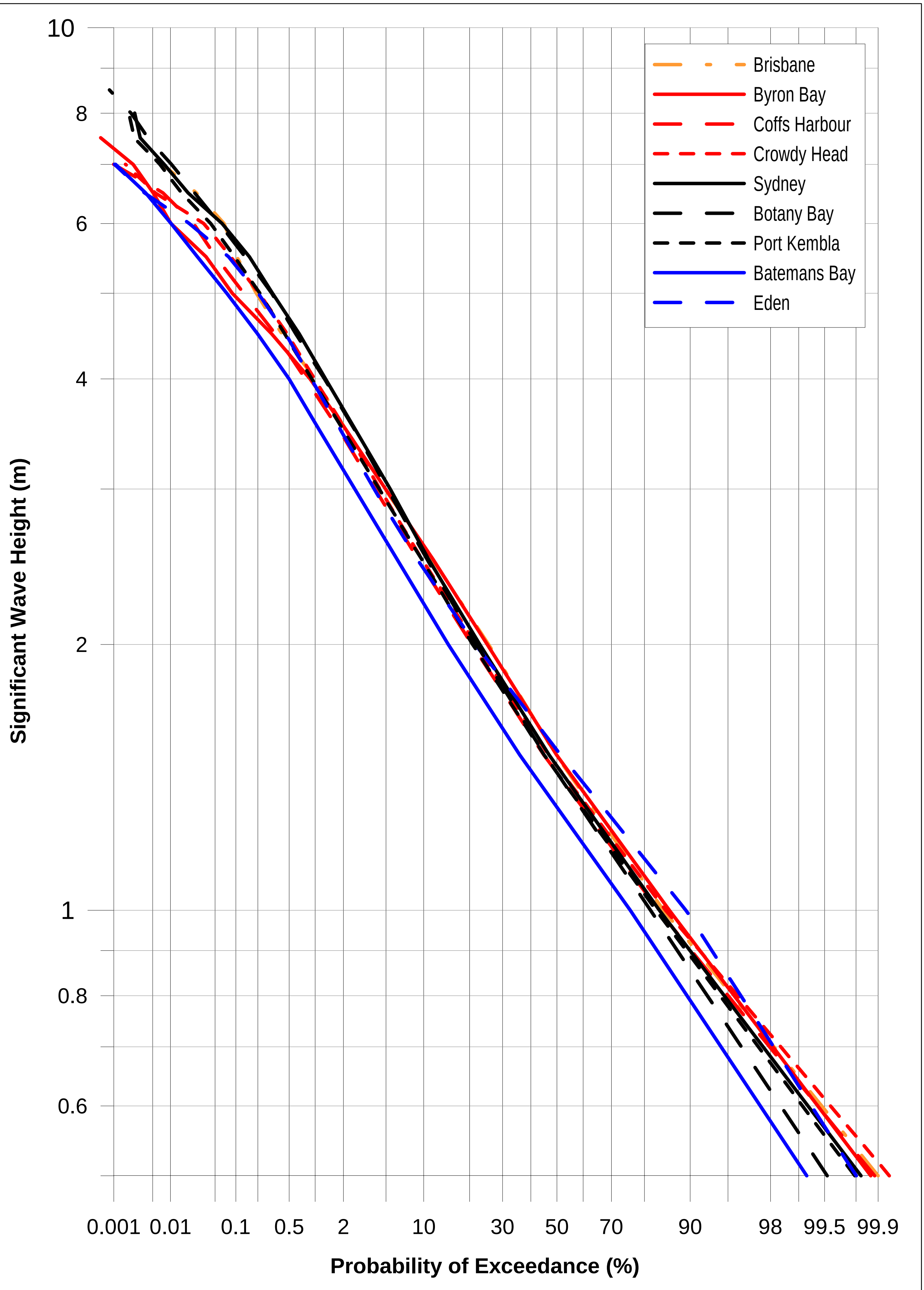
Note: missing storm data denoted by –
shaded cells indicate most significant missing event

The length of reliable extrapolation is a function of effective record length. As previously stated, Pugh (2004) suggests that reliable extrapolation can be undertaken up to three to four times the record length. All buoy records are now of sufficient length that 50 year ARI values may be considered reliable and 100 year ARI events nearly so. This is, however, less true for long duration events and for specific storm wave directions where a low number of storm events have been recorded to date. The reliability of such statistical analysis will improve in the future as more data is collected.

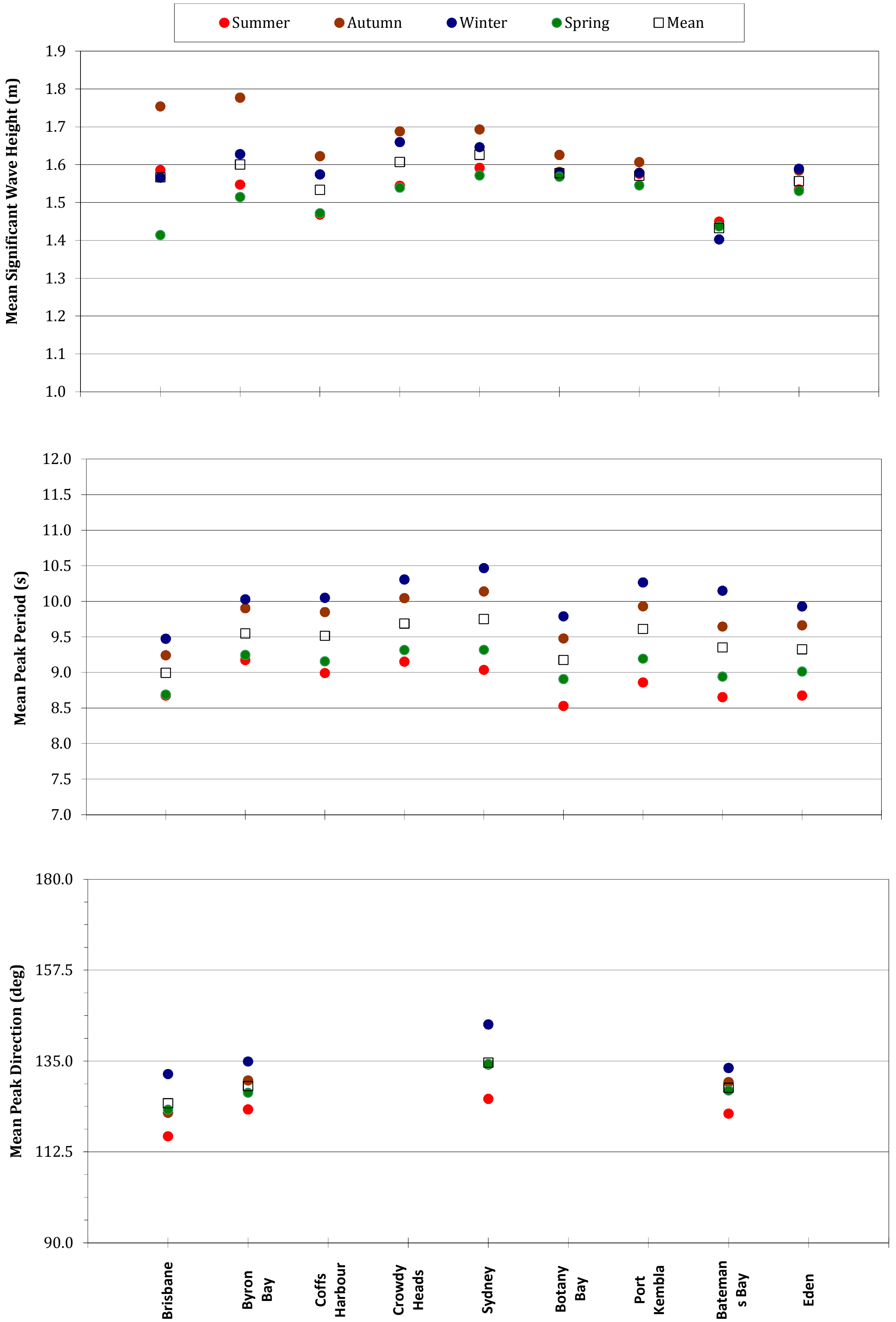
4.4.2 Extreme Value Analysis

The extreme value distributions employed in this study are those recommended as most generically appropriate by Goda (2000; 1988) and for Sydney by You (2007) who undertook comparative analysis using nine candidate functions. The confidence limits provide some measure of statistical certainty and sensitivity assessment using the upper confidence limit values as well as the best-fit values is recommended in practice.

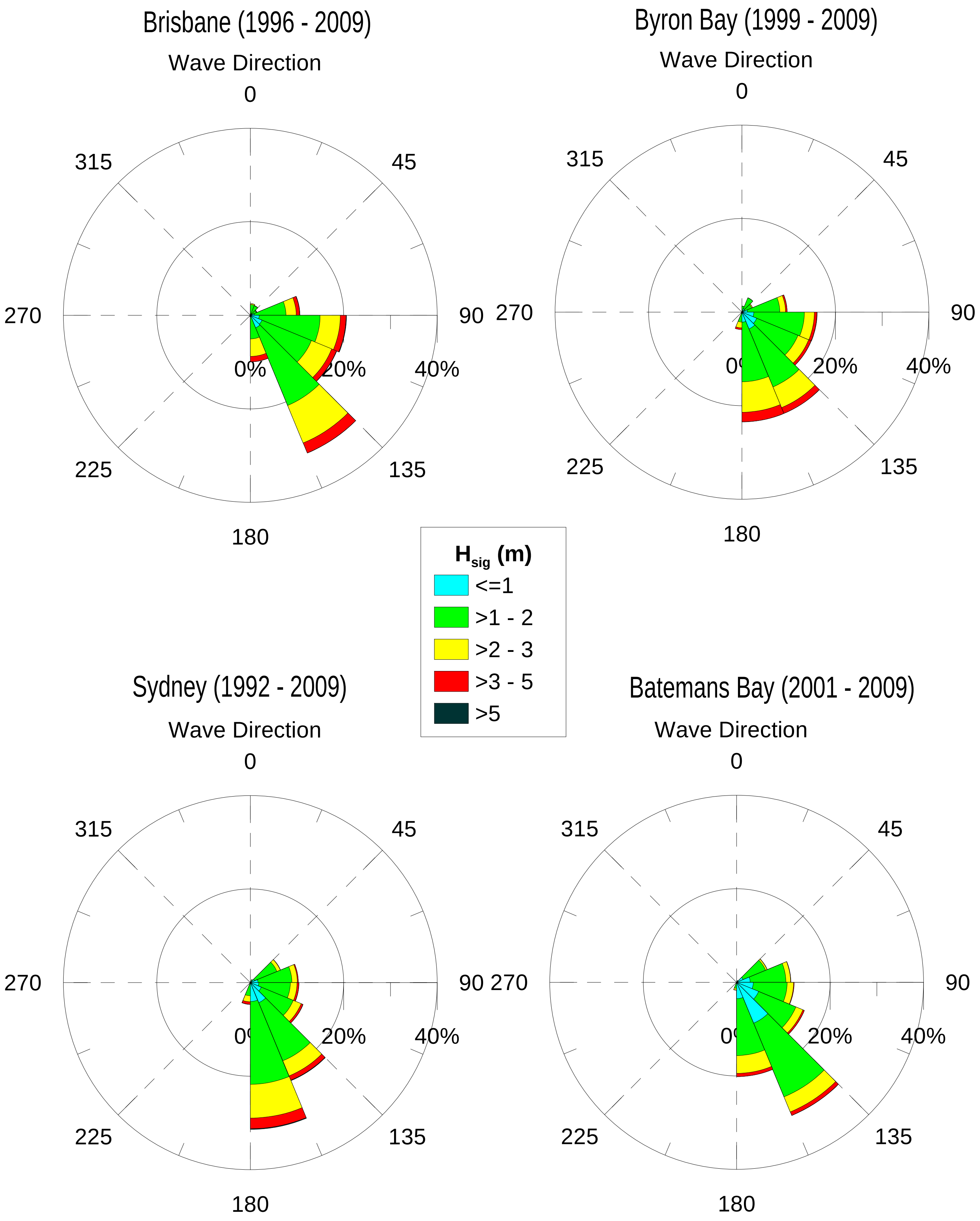
As previously discussed, a key assumption in this study is that the data is statistically stable. Any future increase in storm intensity and corresponding wave heights as suggested by DCC (2009) would likely result in larger return values than estimated within this study. Examination of changes in mean or storm wave height over time have not been undertaken within this study. Such an examination should be undertaken for the NSW wave data along with a sensitivity assessment on effects of an increasing storm wave climate on derived extreme wave height.



WRL Report No. 2010/16	SIGNIFICANT WAVE HEIGHT EXCEEDANCE FOR NEW SOUTH WALES WAVE BUOYS AND BRISBANE	Figure 4.1 4.1 EXCEEDANCE.grf

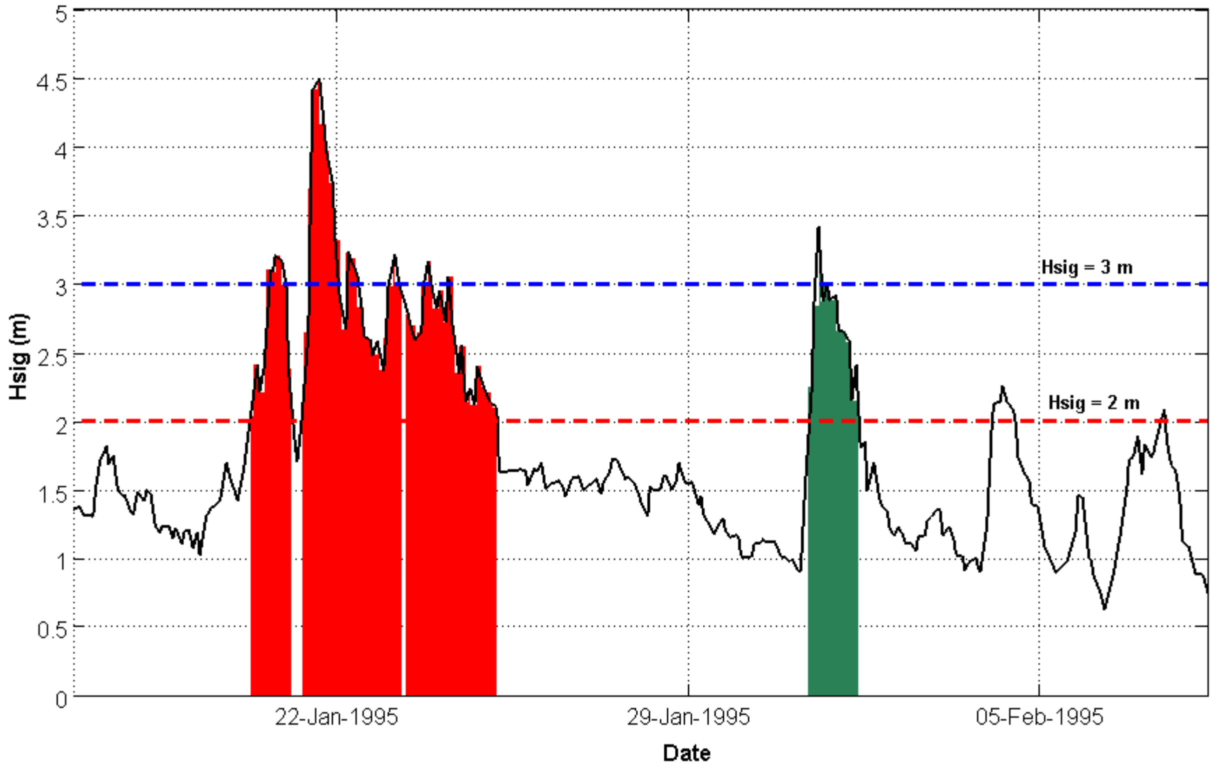


WRL Report No. 2010/16	SEASONAL AND OVERALL MEAN WAVE STATISTICS	Figure 4.2



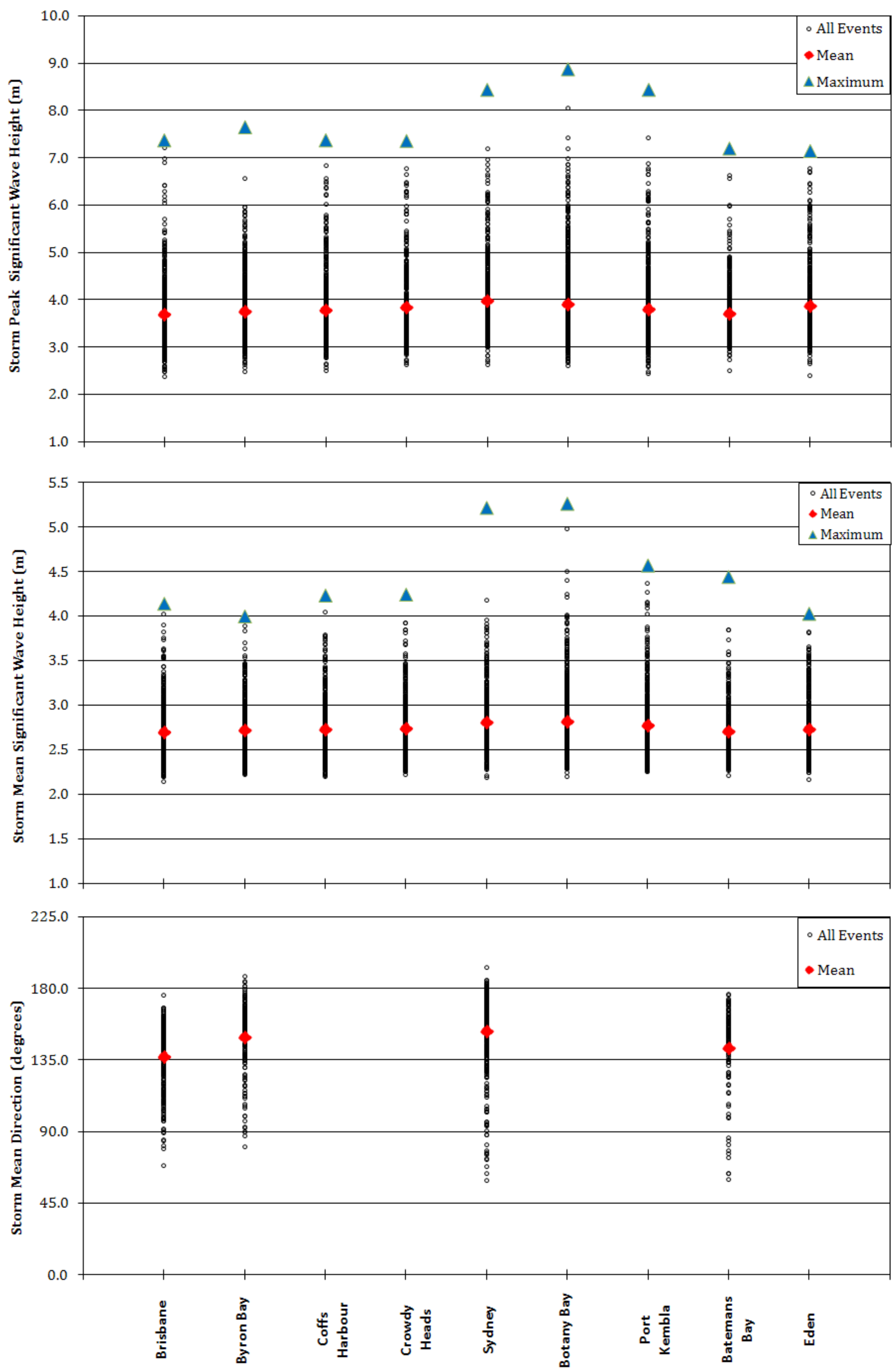
WRL Report No. 2010/16	WAVE ROSES FOR DIRECTIONAL WAVE BUOYS	Figure 4.3

4.3 DirectionalWaveRoses.grf

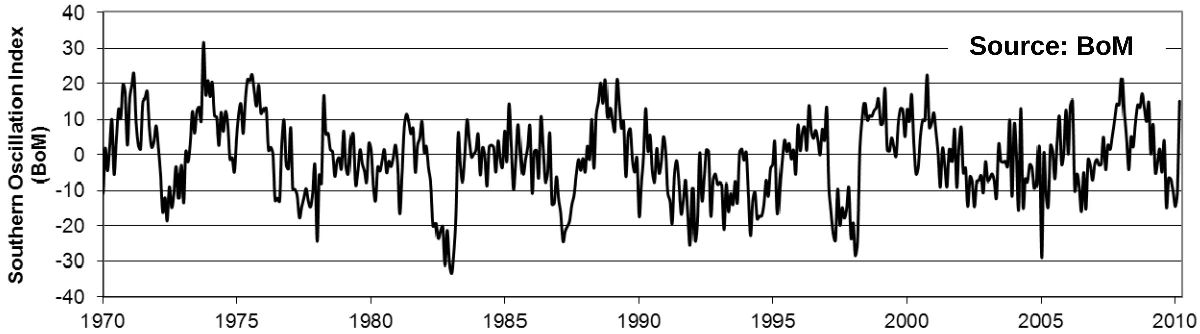


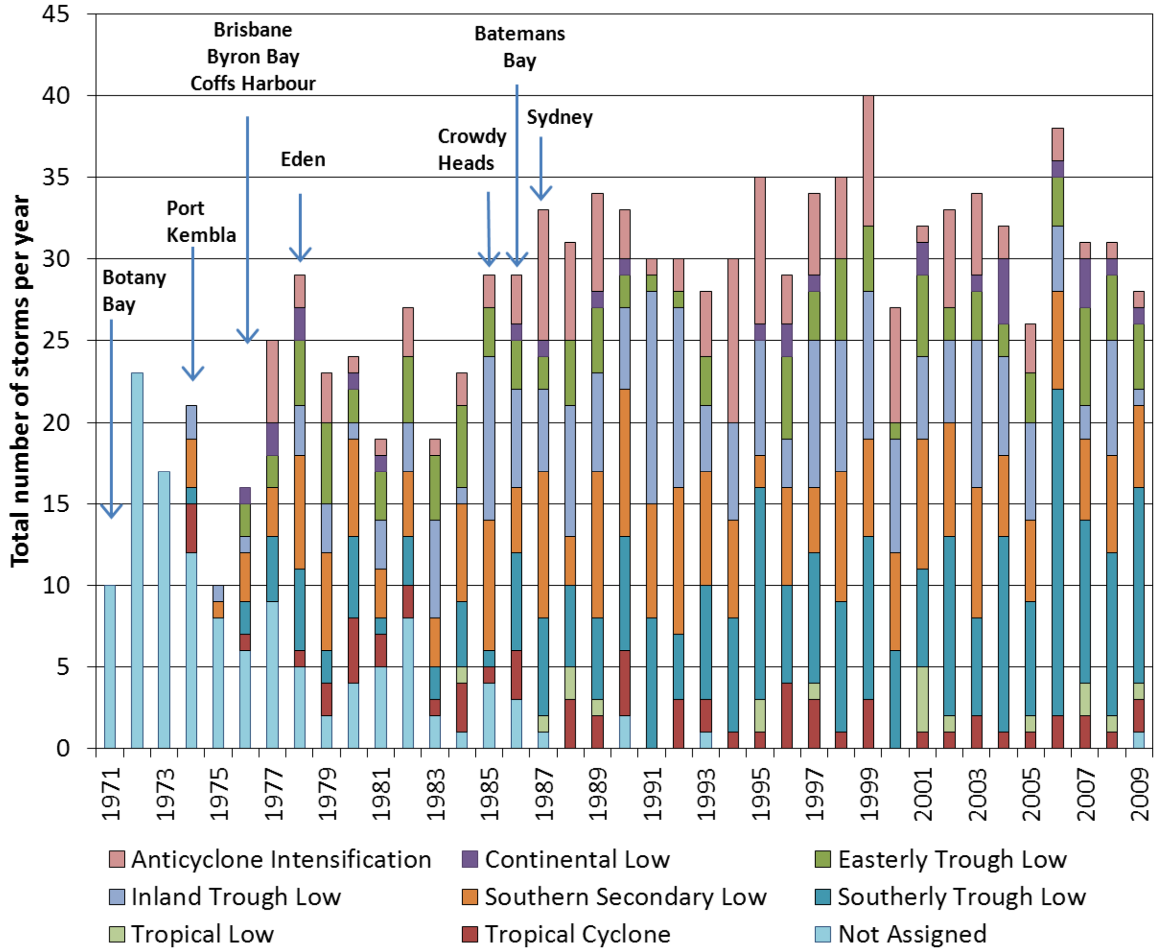
EXAMPLES OF DEFINING STORM EVENTS

Figure 4.4



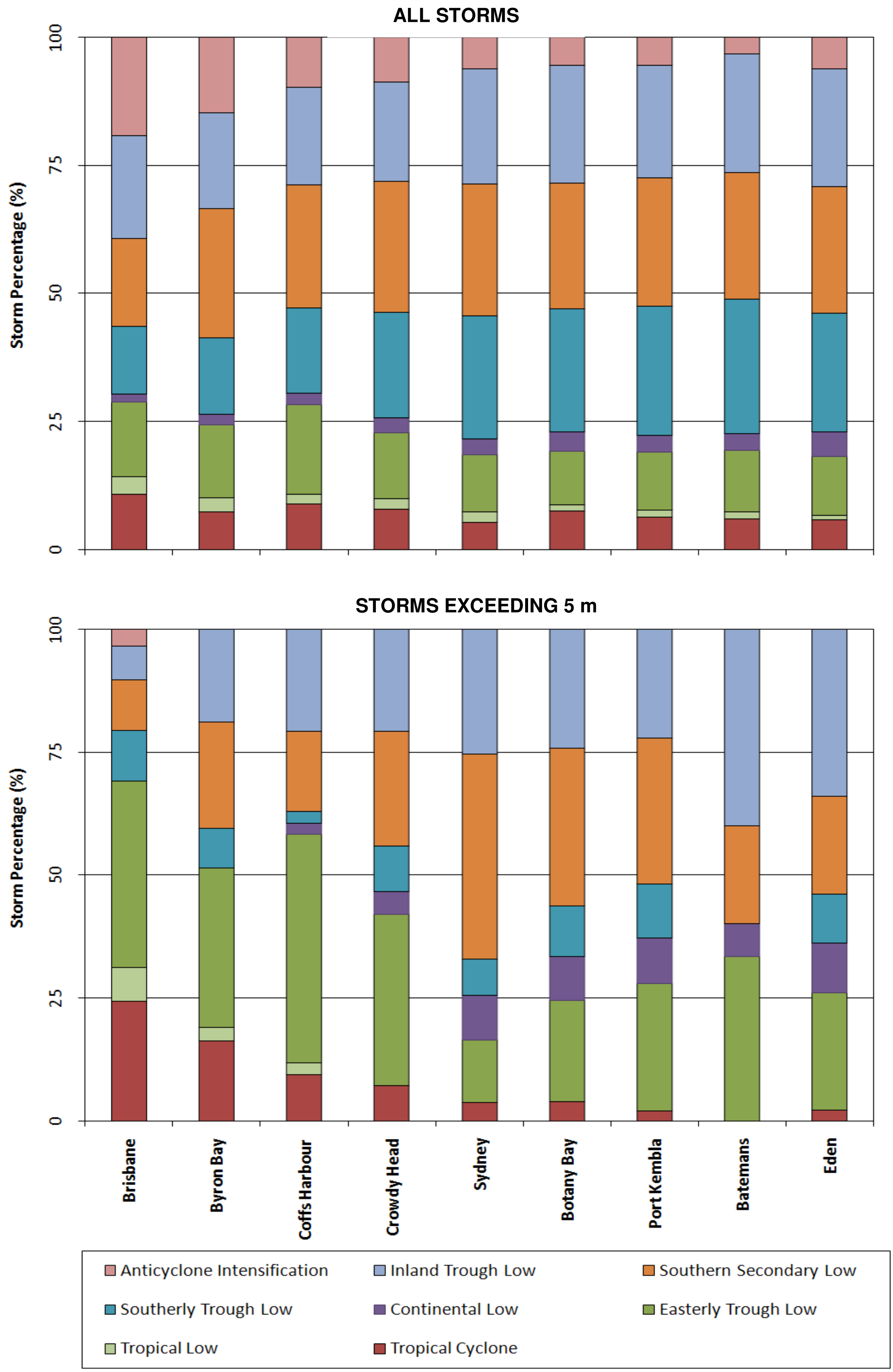
WRL Report No. 2010/16	STORM PEAK (A) AND MEAN (B) SIGNIFICANT WAVE HEIGHT AND MEAN SPECTRAL DIRECTION (C)	Figure 4.5



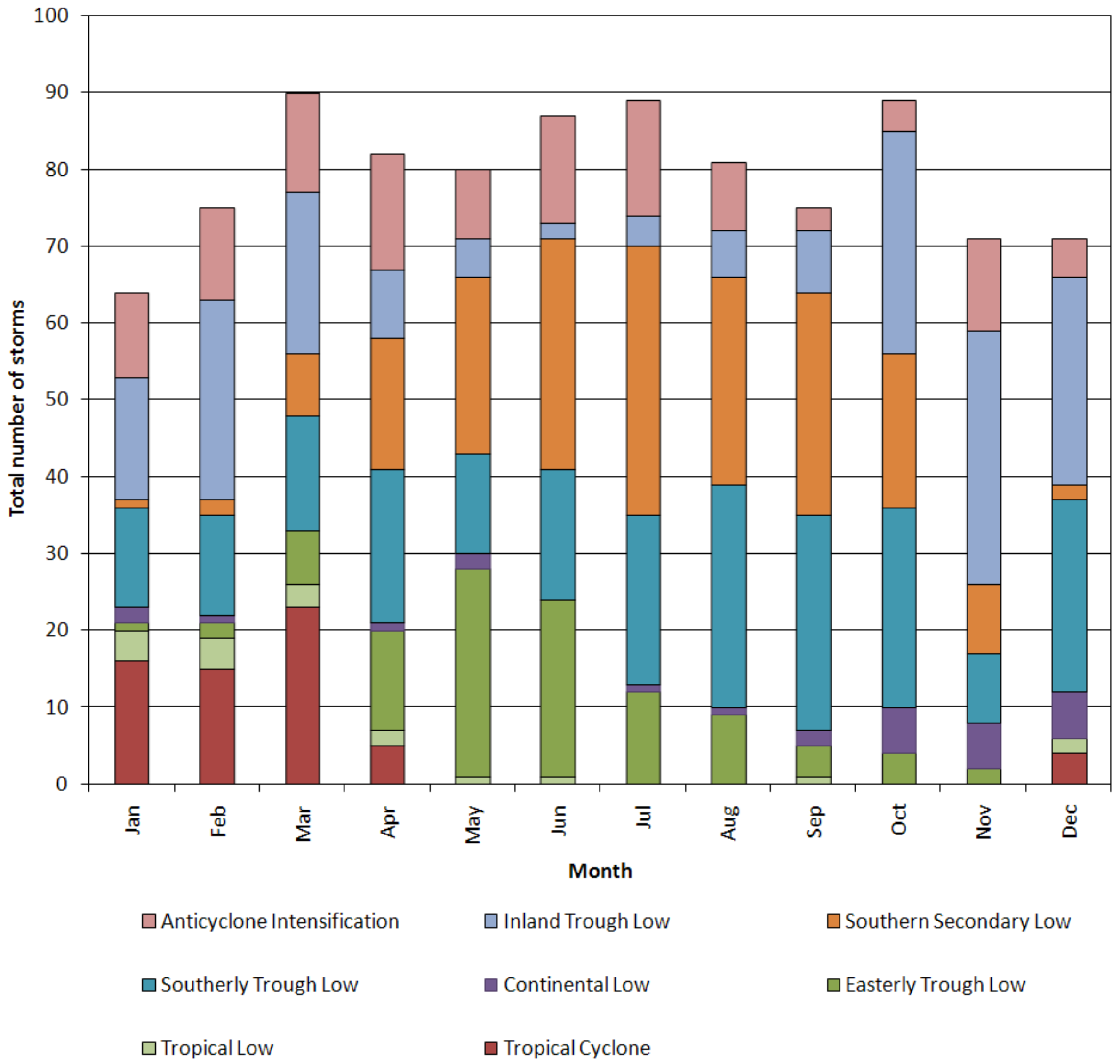


Arrows indicate year of wave rider buoy commission

WRL Report No. 2010/16	TOTAL NUMBER OF STORMS TYPES OBSERVED YEARLY	Figure 4.6

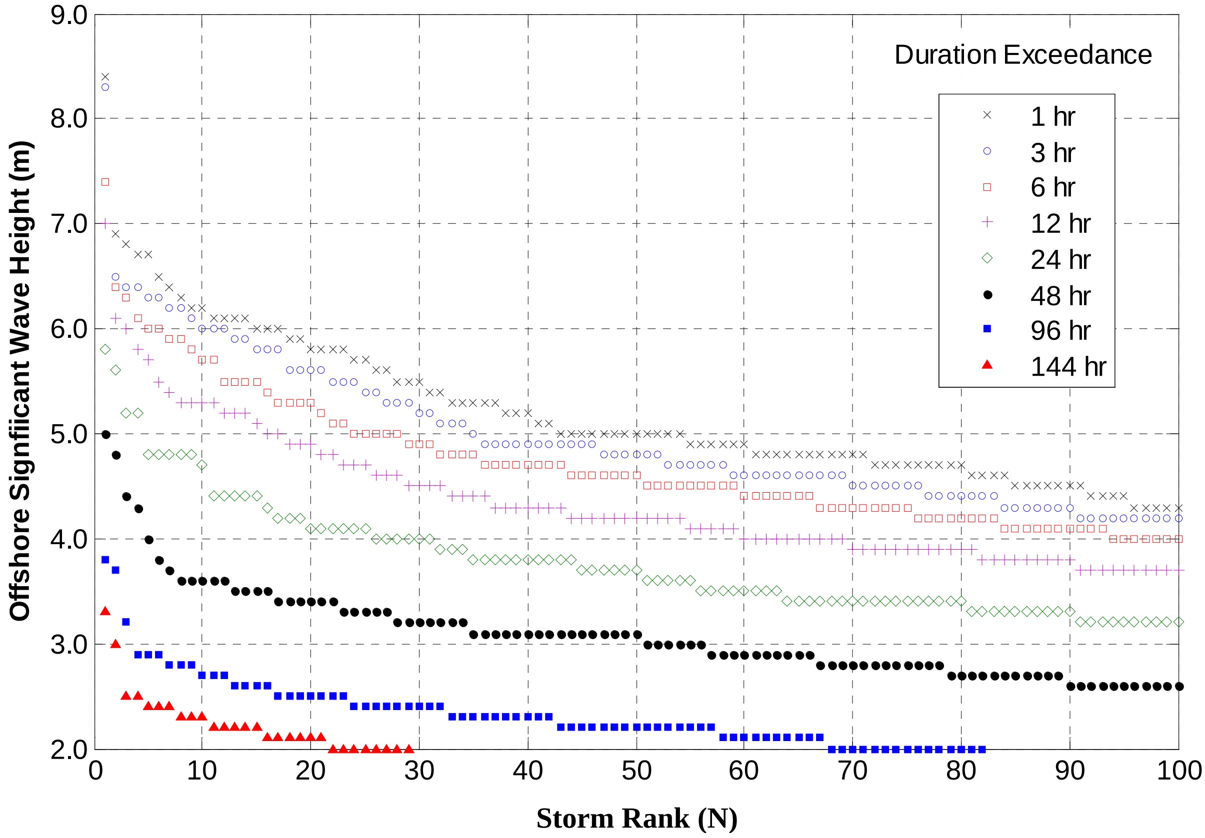


WRL Report No. 2010/16	STORM TYPES BY PERCENTAGE FOR EACH WAVE BUOY FOR ALL STORMS AND STORMS >5 m	Figure 4.7



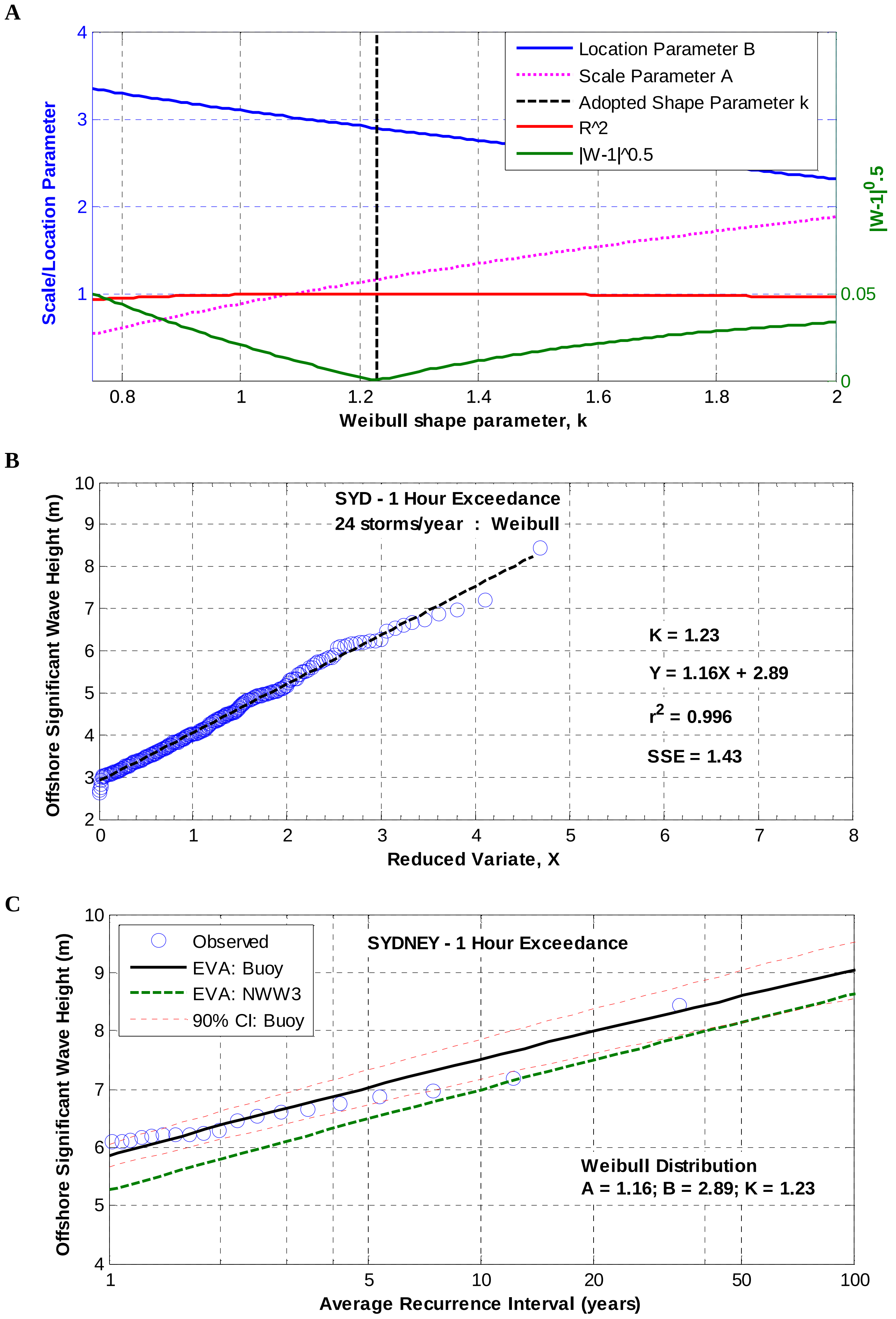
TOTAL NUMBER OF STORMS OBSERVED FOR EACH MONTH

Figure
4.8

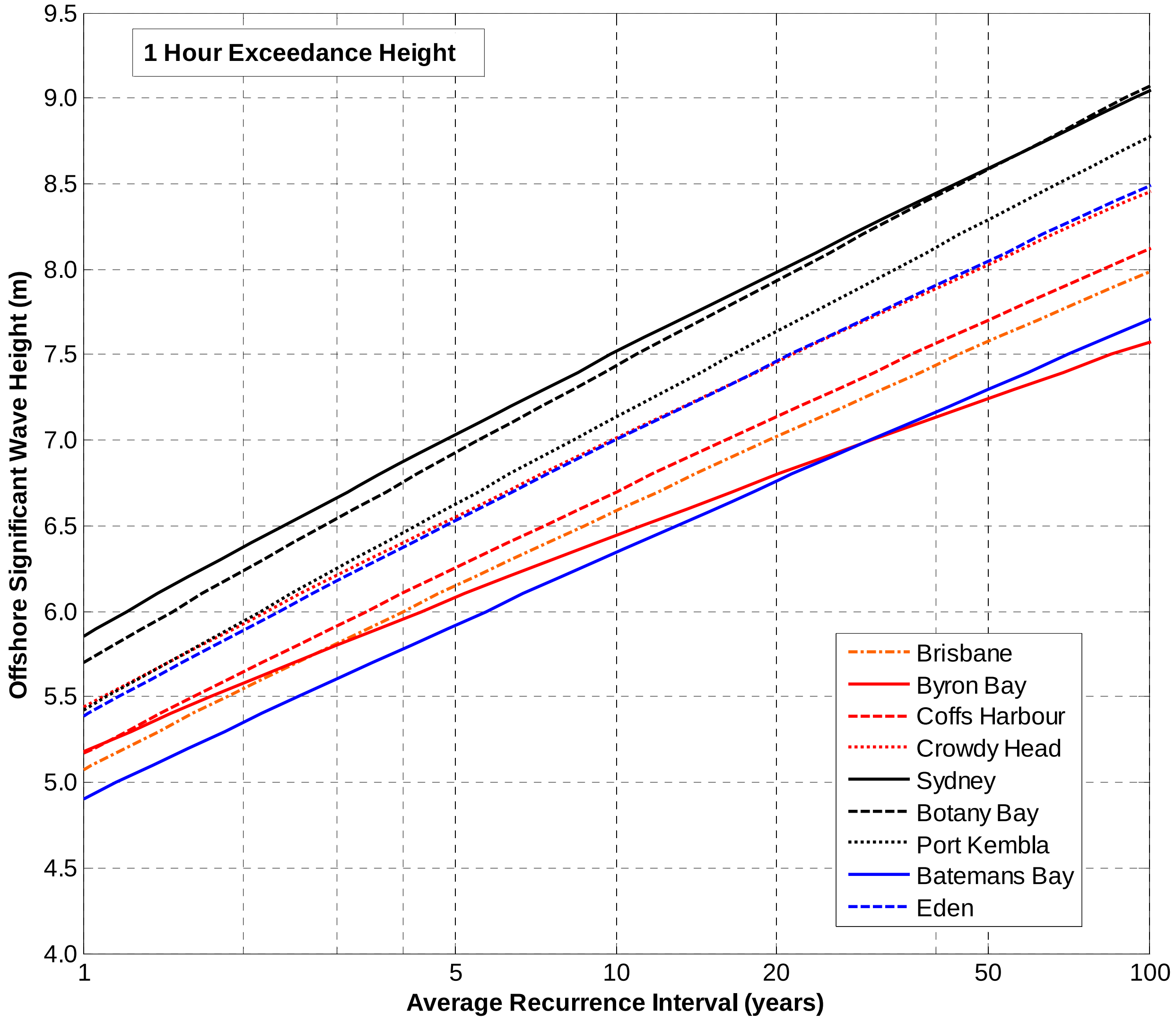


Note: First 100 storms only shown

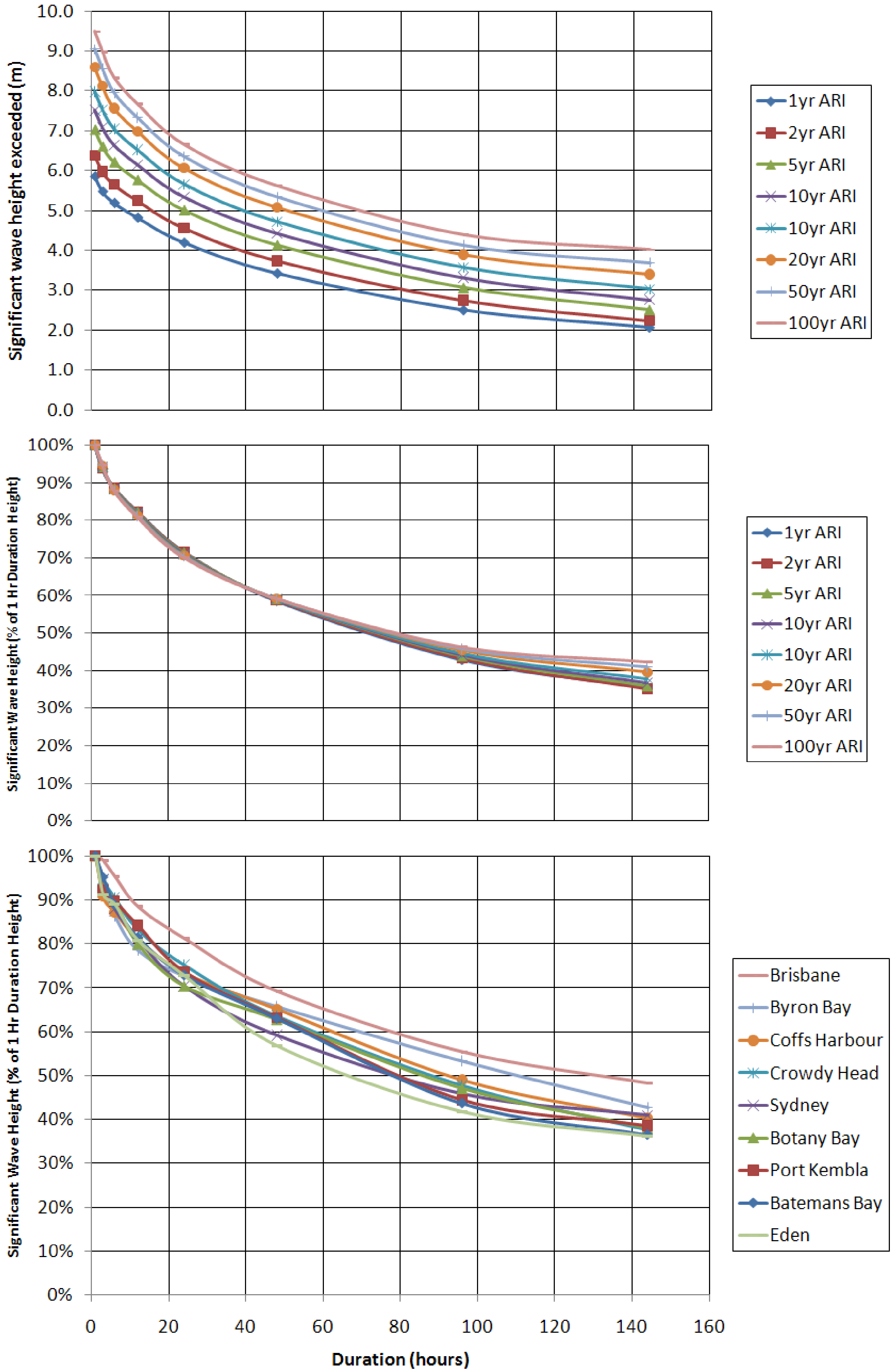
WRL Report No. 2010/16	CHANGE IN H_{sig} EXCEEDANCE AND NUMBER OF EVENTS WITH STORM DURATION FOR SYDNEY	Figure 4.9



WRL Report No. 2010/16	EXAMPLE OF SHAPE PARAMETER OPTIMISATION (A), DETERMINATION OF SHAPE AND LOCATION PARAMETERS (B) AND FITTING THE PDF TO OBSERVED DATA (C) FOR THE SYDNEY BUOY	Figure 4.10



WRL Report No. 2010/16	ONE HOUR EXCEEDANCE SIGNIFICANT WAVE HEIGHT FOR ALL WAVE BUOYS	Figure 4.11



WRL Report No. 2010/16	DURATION EFFECTS ON EXTREME VALUES	Figure 4.12

WRL

Report No. 2010/16

EXTREME SIGNIFICANT WAVE HEIGHT (1 HR) COMPARED TO OBSERVED VALUES AND NUMERICAL

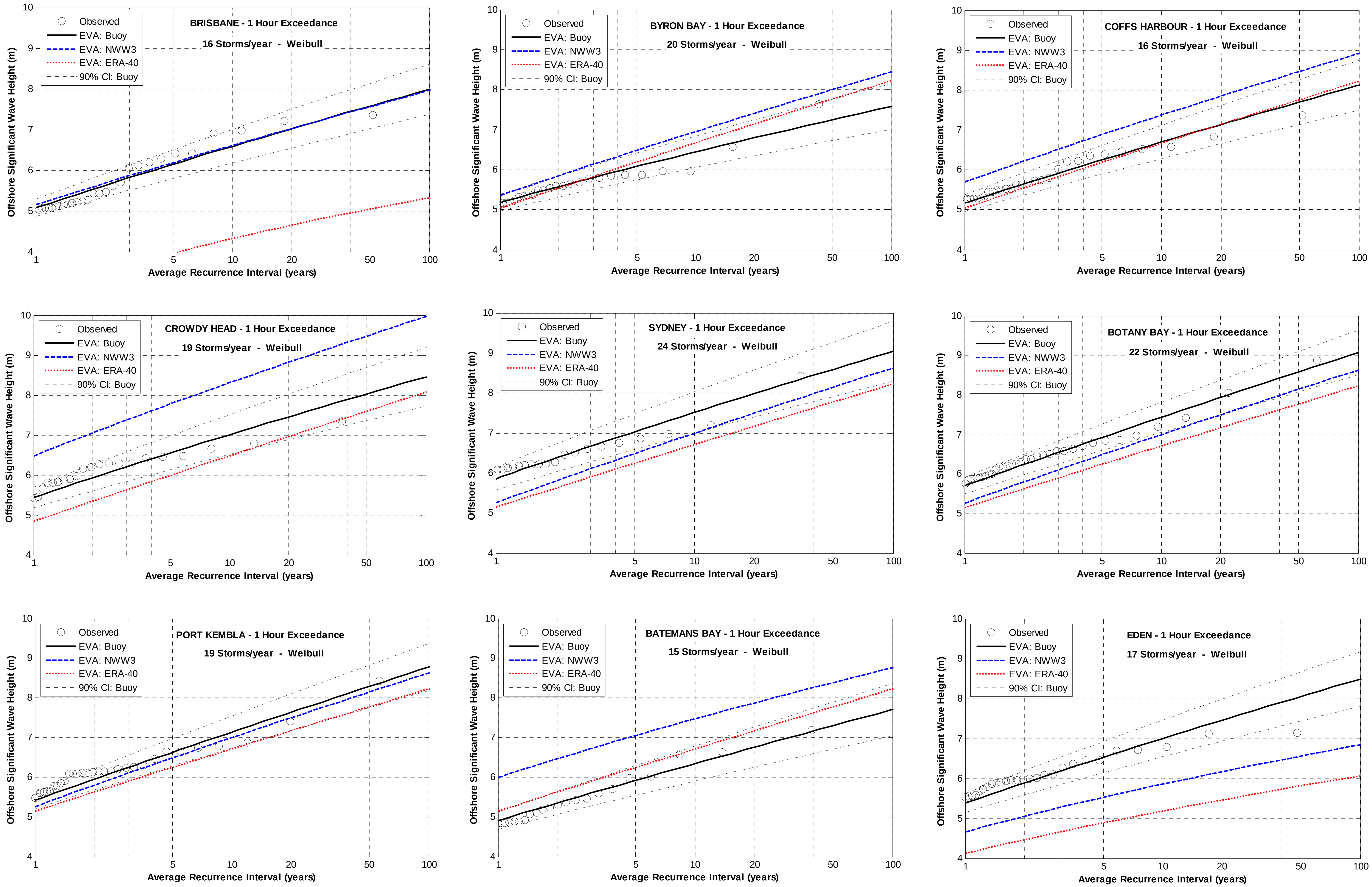
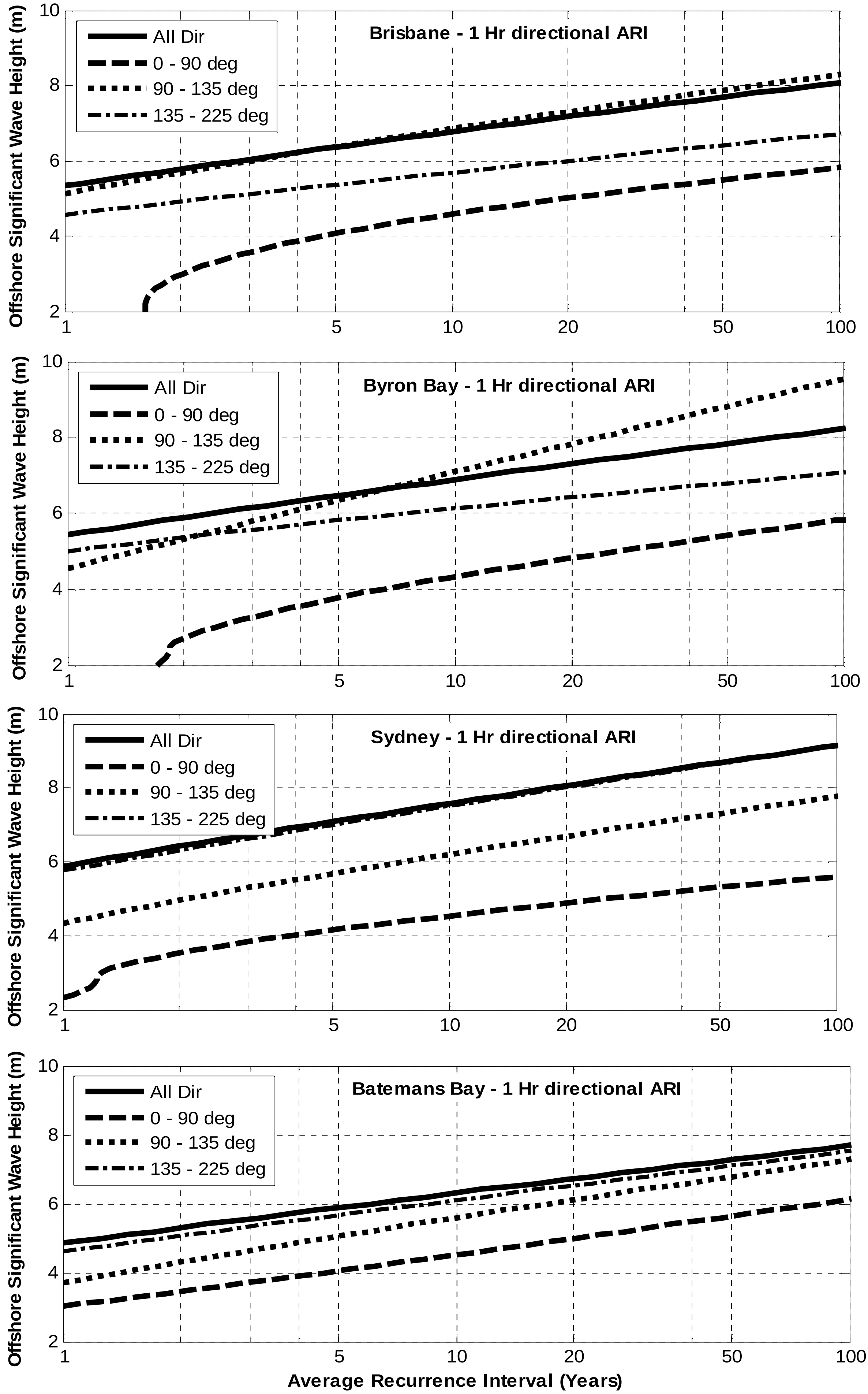


Figure 4.13



WRL Report No. 2010/16	EFFECT OF WAVE DIRECTION ON EXTREME VALUES	Figure 4.14

5. SUMMARY AND RECOMMENDATIONS

5.1 Overview

The Water Research Laboratory, UNSW (WRL) and Climate Futures at Macquarie University were commissioned by the Department of Environment, Climate Change and Water to investigate coastal storms affecting the NSW coastline. This involved:

- Critically reviewing the NSW coastal storm types that affect the NSW coast;
- Determining the spatial distribution and seasonal variation of these classified storm types;
- Determining the statistical distribution of extreme wave height and storm duration using wave buoy data from nine locations along the NSW and southern Queensland coast spanning the years 1971 to 2009, and
- Deriving extreme wave height with different return periods along the NSW coast.

5.2 New South Wales Wave Climate

Mean significant wave height (H_{sig}) along the NSW coast was found to be relatively consistent, ranging from 1.43 m at Batemans Bay to 1.63 m at Sydney. The 1% exceedance and maximum observed H_{sig} were highest at Sydney and Botany Bay, with a maximum H_{sig} of 8.86 m observed at Botany Bay, followed by Sydney and Port Kembla at 8.43 m. More notable along-coast variation in mean H_{sig} was observed seasonally, with larger waves occurring in the north during autumn and smaller waves occurring during spring and summer. Wave height in the south was more uniform year-round. Similarly, mean peak wave period (T_p) was longer and direction more southerly during winter and shorter and more easterly during summer months. The significant wave height exceedance and peak wave period occurrence tables are presented for each wave buoy within the report.

5.3 NSW Storm Climatology

The NSW coast spans from the southern Coral Sea to Southern Tasman Sea across the sub-tropical to mid-latitude zone. Extreme wave energy is mainly generated within the Coral Sea and Tasman Sea window, but can also be generated from outside this zone: in the South – West Pacific tropics; and in the Southern Ocean in the extra-tropics.

To ensure both long and short duration storm events are included in statistical analysis, storms were defined based on the significant wave height exceeding a specific threshold for a specific duration. This threshold was 2.0 m for storms of duration greater than three days or 3.0 m for any duration. The storm climatology in this study is based on a synoptic classification approach which expanded upon that used in the PWD (1985) study. Storm wave data has been classified into one of the following six synoptic types: Tropical Cyclone; Easterly Trough Low; Continental Low; Southern Tasman Low; Southern Secondary Low; Inland Trough Low; Anticyclone Intensification; Tropical Low.

Major storm events (H_{sig} > 6 m) in the north are a mixture of tropical cyclones, tropical lows and easterly trough lows while in the mid coast, major storm events also include inland trough lows and southern secondary lows. In the south, tropical cyclones and lows do not contribute to major storm events which are instead a combination of easterly trough lows, inland and continental lows and southern secondary lows, with a number of southerly trough (Southern Tasman) lows causing waves in excess of 5 m but not reaching 6 m. A seasonal analysis of storminess (i.e. storm frequency) shows March, July and October to be the stormiest months, with November, December and January being the least stormy. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August.

5.4 Extreme Value Analysis

Extreme value statistics were derived based on the peaks over threshold method with an average number of between 15 and 24 storms detected per year depending on spatial location. Storm data was interrogated to provide wave height exceedance for a range of durations from 1 hour to 144 hours (6 days). The height exceedance and number of detected storms reduced for the long duration events. The Weibull probability distribution function was found to provide the best fit to data across a wide number of locations and for a range of exceedance durations.

The 1 hour exceedance H_{sig} for all buoys for the 10, 50 and 100 year ARI along with 90% confidence intervals are presented below. ***These results show the mid NSW coast to exhibit the highest extreme wave climate with a 100 year ARI, one hour exceedance height of 9.0 m at Sydney and 9.1 m at Botany Bay***. Extreme height decreases to the north and south reaching 8.0 m at Brisbane and 8.5 m at Eden. Both Batemans Bay and Byron Bay exhibit the lowest extreme heights of 7.7 and 7.6 m respectively. Inclusion of notable missing storm events at Byron Bay and Batemans Bay by interpolation from adjacent buoys were found to increase the extreme statistics slightly, however, the values remained within the 90% confidence limits.

The effect of direction on extreme wave height was similarly investigated. Results showed that for wave events arriving from north of 90°, the extreme values were approximately 75% of the *'all direction'* values, wave events from the east to southeast were approximately 5% lower than the *'all direction'* values and ***waves arriving from south of south-east were typically 100% of the 'all direction' values and would be adopted as the design direction***.

Extreme values derived using buoy measurements were compared with those derived using NOAA's Wavewatch III (NWW3) numerical wave model and the ERA-40 numerical hindcast dataset. Overall, the NWW3 numerical model resulted in over prediction of extreme values in the north and under prediction in the south, while the ERA-40 dataset resulted in general under prediction of extreme values across all regions. Apart from a limited number of locations, differences were generally outside the evaluated 90% confidence limits. This result indicates that numerical models should not be used to derive extreme wave climates on the NSW coast.

Analysis undertaken within this present study shows that the 90% confidence limits for design waves along the NSW coast for the 100 year storm are now less than 10%. Examination of changes in mean or peak storm wave height over time have not been undertaken within this study with statistics assumed to be static for the purposes of extreme value analysis.

5.5 Recommendations

A number of recommendations are presented based on the results of this investigation:

- That wave buoy monitoring is continued to improve the accuracy of long duration and directional events and to quantify long term changes in wave climate on the NSW coast – the longer the dataset, the greater is its value.
- That the detailed, event-specific studies by the Public Works Department (PWD, 1985; 1986) are extended to cover the period from 1985 to present.
- Due to issues with data completeness and validity at Byron Bay and Batemans Bay, it is recommended that the upper 90% confidence interval values are used for these buoys until additional wave buoy data becomes available or site-specific assessments of these buoy locations is undertaken.

- A specific study of the Batemans Bay Region should be undertaken to ascertain reasons for the lower observed mean and extreme wave heights and whether a shift in buoy position would result in observed values more similar to those of Eden and Port Kembla.
- Investigate physical reasons (i.e. storm genesis, track, speed, etc.) for the very rare, large events which appear to exceed the fitted extreme distributions (i.e. at Sydney and Byron Bay) as these appear to belong to a different statistical population.
- Examination of changes in mean or storm wave height over time have not been undertaken within this study. Any future increase in storm intensity and corresponding wave heights would likely result in the derivation of larger extreme wave values. It is suggested that a sensitivity assessment is undertaken investigating the effects of an increasing storm wave climate on derived extreme wave height.
- Investigate physical reasons for the differences in buoy and numerical model wave climates evident at particular locations along the NSW coast. Resolving these differences is of high importance for coastal engineers and scientists who use such model results for engineering design, nearshore research and public weather forecasting and hazard prediction.
- Using the combined results of this and the extreme water levels component of the State-wide Coastal Inundation Study, a joint probability assessment of extreme waves and water level along the NSW coast should be undertaken for use in coastal and floodplain hazard assessment and climate change adaptation planning.

6. ACKNOWLEDGMENTS

Funding for this project was provided by the New South Wales Department of Environment, Climate Change and Water as part of the Natural Disaster Mitigation Program, NSW Coastal Inundation Hazard Study. NSW wave buoy data was kindly supplied by Manly Hydraulics Laboratory, Department of Services, Technology and Administration with the permission of NSW Department of Environment, Climate Change and Water. Wave data for Brisbane was kindly supplied by Queensland Environmental Protection Agency, Department of Environment and Resource Management. Sydney Ports Corporation and Mr Garry Noyes are thanked for the supply of the Botany Bay wave data.

Dr Bob You of the Coastal Science Unit, NSW Department of Environment, Climate Change and Water is acknowledged and thanked for his discussion and advice on extreme value analysis. Mr Mark Kulmar of Manly Hydraulics Laboratory is thanked for his assistance in the supply of NSW wave buoy data and advice on data processing. Professor Peter Nielsen of the University of Queensland is thanked for his insightful and useful comments during the project.

REFERENCES AND BIBLIOGRAPHY

Allen, M and Callaghan, J. (2001), Extreme Wave Conditions for the South Queensland Coastal Region. Report for the Queensland Environmental Protection Agency, 2001. Environment technical report no. 32. 28 p.

Bettington, S H and Wilkinson, D L (1997), Extreme Water Surface Excursions During Storm Events. Combined Australasian Coastal Engineering and Ports Conference, Christchurch, 1997.

Caires, S, Sterl, A (2005), "100-year return value estimates for ocean wind speed and significant wave height from the ERA-40 data". Journal of Climate 18, 1032–1048.

Carley, J T and Cox, R J (2003), "A Methodology for Utilising Time-Dependent Beach Erosion Models for Design Events", Proceedings of Australasian Coasts and Ports Conference, Auckland, The Institution of Engineers Australia.

Carley, J T, Blacka, M J, Timms, W A, Andersen, M S, Mariani, A, Rayner, D S, McArthur, J and Cox, R J (2008), Coastal Processes, Coastal Hazards, Climate Change and Adaptive Responses for Preparation of a Coastal Management Strategy for Clarence City, Tasmania. WRL Technical Report 2008/4. 139p + Appendices.

Chapman, D M, Geary M, Roy, P S and Thom, B G (1982), Coastal evolution and coastal erosion in NSW.

CMM (1990), Coastal Management Manual, ISBN 0730575063, New South Wales Government.

Coghlan, I R (2009), Validation of Australian Bureau of Meteorology High Resolution Wave Model (HI-WAM). WRL Research Report 237. 184p.

Department of Climate Change (2009).,Climate Change Risks to Australia's Coast. A First Pass National Assessment. Department of Climate Change, Commonwealth of Australia. 170 p.

Goda, Y (1988), On the Methodology of selecting design wave height. Proc. 21st Int. Conf. Coastal Engrg. (Malaga, 1988), pp. 899-913.

Goda, Y (2000), Random Seas and Design of Maritime Structures. World Scientific. 443p.

Goodwin, I D (2005), A mid-shelf wave direction climatology for south-eastern Australia, and its relationship to the El Niño – Southern Oscillation since 1877 AD, Int. J. Climatol. 25, 1715–1729

Gringorten, I I (1963), A Plotting Rule for Extreme Probability Paper. J. Geophys. Res. 86 (3), pp. 813-814.

Harley, M D, Turner, I L, Short, A D and Ranasinghe, R (2009), Interannual variability and controls of the Sydney wave climate. International Journal of Climatology.

Helman, P B (2007), Two Hundred Years of Coastline Change and Projected Future Change, Fraser Island to Coffs Harbour, East Coast, Australia. PhD Thesis, Southern Cross University. 210p + Appendices.

Hemer, M A, Church, J and Hunter, J (2007), A Wave Climatology for the Australian Region. Report prepared for the Australian Greenhouse Office, Department of Environment and Water Resources. CSIRO Marine and Atmospheric Research, Hobart. June 2007. 63p.

Holland, G J, Lynch, A H and Leslie, L M (1987), Australian east-coast cyclones. Part I: Synoptic overview and case study. *Monthly Weather Review*. 115, 3024-3026.

Hopkins, L C and Holland, G J (1997), Australian Heavy-Rain Days and Associated East Coast Cyclones: 1958-92. *Monthly Weather Review*, 10: 621-635.

Institution of Engineers, Australia (1987), Australian Rainfall and Runoff: A Guide to Flood Estimation , Vol. 1, Editor-in-chief D.H. Pilgrim, Revised Edition 1987 (Reprinted edition 1998), Barton, ACT.

Kalnay, E and Coauthors (1996), The NCEP/NCAR Reanalysis 40-year Project. Bull. American Meteorological. Society, 77, 437-471.

Kulmar, M, Lord, D and Sanderson, B (2005), "Future Directions for wave Data Collection in New South Wales", Proceedings of Australasian Coasts and Ports Conference, Adelaide, The Institution of Engineers Australia.

Lawson, N V and Abernethy, C L (1974), Long Term Wave Statistics of Botany Bay.

Lord, D B and Kulmar M (2000), "The 1974 Storms Revisited: 25 years Experience in Ocean Wave Measurement Along the South-East Australian Coast", Proceedings International Conference of Coastal Engineering, pp 559-572, American Society of Civil Engineers, USA.

McAneney, J, Crompton, R, Chen, K and Hunter, L (2007), Century of damage – property losses due to natural perils. Journal of the Australian and New Zealand Institute of Insurance and Finance. 30: 16-22.

Manly Hydraulics Laboratory (2009), NSW Wave Climate and Coastal Air Pressure Annual Summary 2008-2009.

New South Wales State Government (1990), NSW Coastline Management Manual. New South Wales Government September 1990. ISBN 0730575063

Phinn, S R and Hastings, P A (1992), Southern Oscillation influences on the wave climate of south-eastern Australia. *Journal of Coastal Research* **8**: 579–592.

Pugh, D T (1987), Tides, Surges and Mean Sea-Level, John Wiley and Sons, Chichester, UK.

Pugh, D T (2004), Changing Sea Levels Effects of Tides, Weather and Climate, Cambridge University Press UK.

PWD (1985), Elevated ocean levels – Storms affecting the NSW coast 1880-1980. Report No. 85041. Report prepared by Blain, Bremner and Williams Pty Ltd.

PWD (1986), Elevated ocean levels – Storms affecting the NSW coast 1980-1985. Report No. 86026. Report prepared by Lawson and Treloar Pty Ltd.

Ranasinghe, R, McLoughlin, R, Short, A and Symonds, G (2004), The Southern Oscillation Index, Wave Climate, and Beach Rotation. Marine Geology, Vol. 204, 273-287.

Short, A D and Trenaman, N L (1992), Wave Climate of the Sydney Region, an Energetic and Highly Variable Ocean Wave Regime. Aust. J. Mar. Fresh Res., 1992, 43, 765-791.

Speer, M S, Wiles, P and Pepler, A (2009), Low pressure systems off the New South Wales coast and associated hazardous weather: establishment of a database. Australian Meteorological and Oceanographic Journal, 58: 29-39.

Thom, B G (1974), Coastal erosion in Eastern Australia, Search 5, pp 198-209.

Tucker, M J (1994), Nearshore wave height during storms. Coastal Eng., 24: 111-136.

Watson, P, Lord, D, Kulmar, M, McLuckie, D and James, J (2008), Analysis of a storm – June, 2007.

Webb, T T and Kulmar, M A (1989), Coastal wave climate of New South Wales: an update. In: 9th Australasian Coastal and Ocean Engineering Conference (Adelaide), pp. 374–379.

Wyllie, S J and Kulmar, M A (1995), Coastal Wave Monitoring. Australian Marine Data Collection and Management Guidelines Workshop, Environmental Resources Information Network, Hobart, December 1995.

You, Z J and Jayewardene, I (2003), The occurrence of extreme coastal storms along the NSW coast. In: National Environment Conference 2003 (Brisbane, EES), CD-ROM.

You, Z J (2007), Extrapolation of extreme wave height with a proper probability distribution function. Australasian Coasts and Ports Conference, 17-20 July, Melbourne.

You, Z J and Lord, D (2008), Influence of the El Niño Southern Oscillation on the NSW coastal storm severity. Journal of Coastal Research, 24: 203-207.