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COASTAL STORM DATA ANALYSIS: PROVISION OF EXTREME WAVE DATA FOR ADAPTATION PLANNING

by

T D Shand, M A Mole, J T Carley, W L Peirson and R J Cox

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Abstract:

The Australian coast is subject to a spatially and seasonally varied mean wave climate periodically affected by large wave events. These large wave events, particularly when they coincide with high water levels, may cause widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety. Having accurate predictors of the likelihood and magnitude of large wave events is necessary for the quantification of extreme beach erosion and inundation, design of nearshore structures, and for climate change adaptation planning.

This report reviews Australian coastal storm climatology and previous extreme wave analyses undertaken using instrument and numerical data. Traditional extreme value assessment is critically dependent on temporally stable statistics. Wave data from nine wave buoys Australia-wide has been assessed and trends in mean monthly wave height and in the frequency and magnitude of storm events has been statistically analysed using linear regression and Seasonal Kendall tests. Overall, both the east and west coast buoys exhibit non-statistically significant upward trends in monthly mean wave height of up to 2 mm/year and 7 mm/year respectively and the south coast buoys exhibit non-statistically significant downward trends of -1 to -5 mm/year. No statistically significant temporal trends in storm magnitude were found and one east coast buoy showed a small increase in storm frequency.

Using this wave buoy data, extreme wave heights, wave periods and cumulative storm energy have been estimated for a range of return events. Typical storm shapes were assessed and all buoys were found to exhibit a moderate positive skew, indicating a faster increase in wave height before the storm peak than decrease following the peak. This storm shape was combined with extreme wave height, period and energy information to construct synthetic design storm time series for each buoy for average recurrence intervals of between 1 and 100 years. Spatial differences are noted in the derived events as a function of the dominant storm climatology for the different regions around Australia.

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1. INTRODUCTION

The Australian coast is subject to a spatially and seasonally varied mean wave climate periodically affected by large wave events such as those which occurred in 1899 in Queensland (*Cyclone Mahina*), 1974 in NSW (*'Sygna Storm'*) and Darwin (*Cyclone Tracy*), 1999 in Western Australia (*Cyclone Vance*) and in 2008 in NSW (the *'Pasha Bulker Storm'*). A more complete description of the wave climates and coastal storm systems affecting the Australian coastline is provided within Chapter 2. Storm systems capable of generating extreme waves include intense mid-latitude cyclones along the southern coastal margin, tropical cyclones along the northern margins and easterly trough lows off the east and south-east coastlines. These large wave events, particularly when they coincide 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). Having accurate predictors of the likelihood and magnitude of large wave events of varying duration is necessary for the quantification of extreme beach erosion and inundation, design of nearshore structures, and longer term coastal hazard assessment.

Wave buoy deployment commenced off Botany Bay NSW in 1971. Following intense and damaging storms in 1974, wave buoy networks were incrementally established along the NSW and Queensland coastlines by the respective state governments. Additional buoys have been deployed around Australia by State Governments, Federal Departments and private organisations. While some of these deployments have been short-term, many remain in use today. A summary of past and present wave buoy deployments around the Australian coast is shown within Figure 1.2. Note that this list is non-exhaustive and may be missing some commercial and short-term wave buoy deployments. It is evident from this figure that wave buoys are concentrated around regions of dense population and coastal infrastructure such as the eastern seaboard and south-west Western Australia.

Analysis of wave records, collected over a sufficient time period, allows quantification of extreme wave heights and, using appropriate extreme value analysis, characterisation of low probability, large wave events. Confidence in predicted extreme values depends primarily on the length and quality of recorded data, with confidence in estimates decreasing with longer extrapolation. As more data is collected in all locations around Australia, the accuracy and robustness of long-term extreme value estimates of storm waves will increase.

1.1 Scope of Works and Report Structure

The Australian Climate Change Adaptation Research Network for Settlements and Infrastructure (ACCARNSI) which is one of the eight networks within the National Climate Change Adaptation Research Facility (NCCARF) commissioned the Water Research Laboratory (WRL) to:

- Review previous extreme wave analyses which have been undertaken around Australia;
- Identify data availability where no analysis has yet been completed;
- Estimate extreme wave heights for Average Recurrence Intervals (ARI) of between 1 and 100 years for storm durations of between 1 hour and 6 days at sites around Australia.

A description of Australian coastal storm climatology is provided within Section Two. This includes a review of the generation mechanisms, typical storm track and coastal impacts of the various storm types known to affect the Australian coast. A review of previous assessments of extreme wave heights is also presented.

Sources of wave buoy data are presented in Section Three. The chapter details the locations, attributes and completeness of each dataset. Section Four presents the methodology for analysis of wave data sets. Wave data statistics for each of the analysed wave buoy data sets are presented and individual storm events located. Section Five presents the results of extreme value analysis and discussion on the spatial variation of the derived extreme values, the effect of storm duration and methodology for deriving synthetic design storm time series. Section Six presents conclusions and recommendations based on the study results.

1.2 Significance of Study

This study has reviewed characteristics of storms which impact the Australian coastline using data collected over the past 10 to 38 years. The study has derived extreme wave heights corresponding to low annual exceedance probability events for a range of storm durations. The study has additionally analysed the wave period and wave height time series for each of the derived extreme wave events to provide guidance on synthetic design storm events. 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 the study of beach response to extreme wave events;
- Improved understanding of extreme storm climatology leading to large wave events on the Australian coast;
- Provide a robust baseline for Australian extreme wave climate upon which climate change projections can be imposed.

2. BACKGROUND

2.1 Australian Storm Climatology

The Australian continent extends from southern mid-latitudes to tropics in the north and, as a result, the storm climatology affecting Australia's coastal margins varies both spatially and temporally with distinct climatic processes dominating different regions. The coastal margin is exposed to waves generated within two oceans and three adjacent seas.

The southern part of Australia receives persistent moderate to high wave energy from mid-latitude low pressure systems centred within the Southern Ocean at between 50 and 60° S latitude (Short and Woodroffe, 2009) with large wave events occurring intermittently as these low pressure systems intensify and/or extend further north towards the coastline. These large wave events are more frequent during winter months as the subtropical high pressure belt moves north and subsequently allows the northern migration of mid-latitude lows (Lemm *et al.* 1999). These systems have long westerly fetches and propagation paths from west to east. The resulting wavetrains have mean peak periods exceeding 12 to 14 s at Cape Sorell and Cape de Couedic (Short and Woodroffe, 2009). The uniform nature of the climatic system responsible for both the mean and extreme wave climate results in a near unidirectional wave climate along the southern continental margin. A numerical analysis by Hemer *et al.* (2007) showed waves in southern Australia generally to arrive from the SSW to WSW with seasonal variation of less than 10° S and similarly small variation in the direction of large (>99th percentile) wave events.

While a portion of this south-west directed wave energy reaches the Australian East Coast, the majority of the east coast's wave energy is generated within the Coral Sea and Tasman Sea window (Shand *et al.* 2010). Storm climatology along the NSW and southern Queensland coast has been described by PWD (1985 and 1986), Short and Trenaman (1992), Lord and Kulmar (2000), Allen and Callaghan (2001) and Speer *et al.* (2009) among others with Shand *et al.* (2010) classifying storm waves along the NSW coast according to eight synoptic types (Table 2.1). Major storm events in northern NSW and southern Queensland were found to be a mixture of tropical cyclones, tropical lows and easterly trough lows while in the mid NSW coast, major storm events also included inland trough lows and southern secondary lows. In the south of NSW, extreme waves are caused by a combination of easterly trough lows, inland and continental lows and southern secondary lows. 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. On the east coast wave direction was found to be highly variable depending on season and particular storm type (Shand *et al.* 2010).

Table 2.1
NSW East Coast Storm Type Definitions (source: Shand *et al.* 2010)

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

The synoptic types shown in Table 2.1 for NSW are generally also appropriate for south-east Queensland. In contrast, northern Queensland and the northern Australian coastal margin is subject to typically small to moderate waves caused by north-west monsoons affecting north-west exposed locations, trade winds affecting areas exposed to the south-east, particularly in summer and sea breezes also during the summer months. In northern Australia large waves are generally induced only by infrequent tropical cyclones (Short and Woodroffe, 2009) between December and March. Cyclone frequency, intensity and track have received significant attention with extensive studies by Lourensz (1977 and 1981) forming the basis of the Bureau of Meteorology *Tropical Cyclones Historical Archive* and Harper (1998) describing a number of subsequent studies. Figure 2.1 shows tropical cyclone tracks between 1996 and 2006 and the average annual occurrence of tropical cyclones. Cyclones generated within the Coral Sea are observed to generally track south-west towards northern Queensland and cyclones generated within the Arafura and Timor seas typically track south-west across the top of the Northern Territory and north-west Western Australia. Numerical models show wave direction at the coast during large wave events to be typically south-east in the northern Queensland region and Northern Territory and south-west to west off north-west Western Australia (Hemer *et al.* 2007).

The south-western Australian coastline is subject to high wave energy from mid-latitude lows centred within the Southern Ocean, particularly during the winter months when the low-pressure band moves north (Lemm *et al.* 1999) but is also subject to smaller sea breeze-induced waves during the summer months and tropical cyclones in the northern regions during summer. This sea breeze component can be important along the coast as an extensive network of offshore reefs extend some 600 km along the south-west Australian coastline which attenuate large amounts of the incident swell energy (Pattiaratchi *et al.* 1997). Extreme wave events, however, are generally caused by intense mid-latitude lows in the southern regions of Western Australia; and by a combination of large northerly propagating swell from such events and tropical cyclones along the mid-Western Australian coastline. Variation in mean and extreme wave direction is small with waves typically arriving from the SSW to WSW (Hemer *et al.* 2007).

2.2 Extreme Event Analysis

The identification and analysis of large wave events observed within a historical wave record 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), which describes 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. 2-1.

$$AEP = 1 - e\left(\frac{-1}{ARI}\right) \tag{2-1}$$

While the use of particular terminology to describe extreme events is somewhat arbitrary, the use of average recurrence interval 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, IE Aust., 1987). The probability of an event of particular magnitude (AEP) occurring within a specified timeframe (TL) is given by Eqn. 2-2 and presented within Table 2.2.

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

Table 2.2
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	0.63	0.99	1.00	1.00	1.00	1.00
	5	0.18	0.63	0.86	0.98	1.00	1.00
	10	0.10	0.39	0.63	0.86	0.99	1.00
	50	0.02	0.10	0.18	0.33	0.63	0.86
	100	0.01	0.05	0.10	0.18	0.39	0.63
	1000	0.00	0.00	0.01	0.02	0.05	0.10

Sources of wave data (height, period and direction) which may be used in extreme value analysis include:

1. Instrumentally measured wave conditions;
2. Numerically and/or analytically forecast conditions;
3. Numerically hindcast conditions;
4. Visually observed wave conditions (shore-based);
5. Visually observed wave conditions (ship-based).

These data sources each possess certain advantages and disadvantages as summarised within Table 2.3. Confidence in predicted extreme values depends primarily on the length and quality of recorded data. Goda (2000) suggests that a long, continuous record of instrumentally measured data provides the best source for robust and accurate prediction of extreme values. Hindcast data enables long datasets to be retrospectively obtained and, provided they are calibrated with instrumental records, provide the second best data source followed by forecast heights and lastly, visually observed wave heights.

Past assessments of extreme wave heights around Australia have included both site-specific and regional assessments and have used instrumental, visually observed, numerically hindcast and numerically forecast data sources. A selection of such studies presented within available literature is summarised within Table 2.4. It should be noted that there have been additional, site-specific studies undertaken for private organisations and territorial authorities.

Table 2.3
Data Sources used in Extreme Value Analysis

Data source	Advantages	Disadvantages
Instrumentally measured wave conditions	• Accurate • Continuous	• Spatially discrete • Expensive • Instrument downtime (breakdown, maintenance, vandalism)
Numerically and/or analytically forecast conditions	• Spatially-extensive • Continuous • Relatively inexpensive (once calibrated/verified)	• Reliant on accuracy of forcing parameters (wind) • Require calibration and verification • Accuracy variable, especially away from calibration locations
Numerically hindcast conditions	• Spatially-extensive • Continuous • Potentially long data record • Relatively inexpensive (once calibrated/verified)	• Reliant on accuracy of forcing parameters (wind) • Require calibration and verification • Accuracy variable, especially away from calibration locations
Visually observed wave conditions (fixed location)	• Low cost • Longer existing datasets than instrument measurements	• Low individual data accuracy • Limited to daylight hours • Spatially discrete
Visually observed wave conditions (ship report data)	• Low cost • Spatially-extensive (provided a large number of combined records used) • Longer existing datasets than instrument measurements	• Ships tend to avoid regions of large waves (negative bias) • Low individual data accuracy • Limited to daylight hours

Assessments in NSW have been undertaken since the mid 1980s with the Public Works Department (PWD, 1985; 1986) assessing extreme wave values for the north, mid-north, central and southern NSW coasts using 100 years of visual and analytically assessed wave heights. Values were found to be largest in the north, with a derived 100 yr ARI significant wave height of between 12.3 and 12.6 m. This was revised down during subsequent studies using wave buoy data by Willoughby (1995), Lord and Kulmar (2000), Carley *et al.* (2003) and You (2007). You (2007) examined the fit of nine extreme value distributions for the Sydney wave buoy and found the FT-1 (or Gumbel) and Weibull distributions provided the best fit.

Shand *et al.* (2010) undertook a comprehensive assessment of eight wave buoys on the NSW coast and the Brisbane wave buoy in south-east Queensland and derived extreme wave heights for Average Recurrence Intervals (ARI) of between 1 and 100 years for storm durations of between 1 hour and 6 days. Extreme wave heights were typically largest in central NSW and smaller to the north and south with one hour exceedance, 100 yr ARI significant wave height found to range from 9.1 m at Botany Bay to 7.6 m at Byron Bay.

Where directional wave data was available, the effect of direction was also assessed. The largest extreme waves on the south and central NSW coast were from the south-east to south and on the northern NSW and southern Queensland coast from the east to south-east. Extreme waves from the north-east to east were found to be the smallest on all coasts. Extreme wave heights were also evaluated using numerical hindcast (ERA-40 dataset: 1957 – 2002) and forecast (NOAA Wavewatch III (NWW3) dataset: 1997 – 2009) data. The accuracy of the numerical data was found to vary significantly, with the NWW3 numerical model over-predicting extreme vales in the north and under-predicting in the south; and the ERA-40 dataset generally under-predicting extreme values across all regions. Numerical agreement was particularly poor in complex locations such as Eden which is adjacent to Bass Strait and located close to a large-scale change in coastal exposure.

Allen and Callaghan (2000) undertook an assessment for south-east Queensland using 3-hour averaged Brisbane wave buoy data (1976 to 1997) with separate extreme values derived for tropical cyclone, east coast low and combined storm events. Results for the assessment gave 3 hour, 100 yr ARI significant wave heights of 7.20 m for east coast lows, 7.46 m for tropical cyclones and 7.75 m for combined events. This compares well to the combined storms, 1-hour value of 8.0 m (± 0.4 m: 90% confidence interval) derived from a longer buoy record (1976 to 2009) by Shand *et al.* (2010). Of note, an adjustment factor was derived by Allen and Callaghan (2003) and applied to early 12 and 6 hour interval data to better represent peak storm wave conditions. In northern Queensland, Hardy *et al.* (2003) simulated over 6000 Tropical Cyclones using synthesised wind fields and a WAM wave model to produce spatial maps of significant wave height for average recurrence intervals of 20 to 1000 years over the Great Barrier Reef region between Gladstone and Cape Grenville. Earlier, Dexter and Watson (1975) undertook a numerical assessment of extreme wave heights in the Australian tropics. This assessment used extreme wind velocities, cyclone occurrence frequency and fetch length to derive significant wave height for recurrence intervals of 50, 100 and 200 years at 70 locations north of 30° S and from this produced wave height isopleth charts of the Australian Tropics. An example of the wave height isopleths for a 100 yr ARI event with an average cyclone radius of 30 km is shown within Figure 2.2. Results show significant wave heights of around 8 m on the eastern Queensland coast, 7 m along the northern coasts and up to 11 or 12 m along parts of north-west Western Australia. Of note, all locations were assessed in ‘deep water’, at least 120 km from shore and results are sensitive to the choice of average cyclone radius. An average cyclone radius of 30 km was considered by the authors to be likely conservative based on a limited number of observed cyclones, but recommended due to the scarcity of data available at the time.

Additional site-specific studies have been undertaken in south-west Western Australia by Lemm *et al.* (1999) who analysed 2.5 years of Rottnest Island wave buoy data and derived 1 and 100 yr ARI significant wave heights of 6.7 m and 9.8 m and for Tasmania by Reid and Fandry (1994) and Carley *et al.* (2007). Reid and Fandry (1994) estimated 100 yr ARI significant wave heights of between 12.8 and 15.7 m for Cape Sorell with the variation in derived height due to the selected fitting type. Carley *et al.* (2007) analysed a longer fifteen year wave buoy dataset from Cape Sorell and less than 1 year of data from Wedge Island and estimated a 100 yr ARI significant wave height of 13.0 m at Cape Sorell and 9.0 m at Wedge Island.

Of note, peak significant wave heights of 13.15 and 13.59 m and maximum waves of 18.87 and 19.83 m were measured by two separate CSIRO Cape Sorell wave buoys at 20:00 on 29 July 1985. These constitute the largest waves recorded off the Australian Coastline. Reid and Fandry (1994) devoted a section to the discussion of the 29 July 1985 event and, on the basis of two buoys recording near identical statistics, believed the readings to be credible. However, reanalysis for this report of the data shows that the largest wave recorded at Buoy B (19.83 m) experienced poor radio signal at the time of maximum wave and maximum vertical water level acceleration over 10 ms^{-2}, exceeding the acceleration due to gravity (Figure 2.3). These factors yield the authenticity of this maximum wave questionable. Radio signals during the maximum wave at Buoy A were good and maximum vertical acceleration appears realistic. Additionally, each sample recorded only 400 s or approximately 33 waves. Statistics such as the significant wave height could therefore be skewed by a group of larger waves. The validity of these records and their effect on the derived extreme value statistics for Cape Sorell is further discussed within Section 4.

Extreme values for the entire Australian coastline have been derived as part of a numerical assessment by Caires and Sterl (2005) and a combined numerical/wave buoy data assessment by Hemer *et al.* (2007). Caires and Sterl (2005) undertook a global assessment of extreme wave height using the ERA-40 numerical hindcast dataset. The numerical data was found to under predict large wave heights when compared to northern hemisphere wave buoys and a global correction was applied based on a linear relationship to the return value estimates. An exponential distribution was found to produce the best fit for most data, although it tended to overestimate larger waves where a Generalised Pareto Distribution may be more appropriate. In the Australian region, estimated 100 yr ARI significant wave heights decreased with distance north, from around 15.5 m at Tasmania to 6.5 m in far northern extremities. However, the resolution of the model precluded the detailed analysis of small scale systems such as tropical cyclones, thus yielding the estimates questionable in regions where tropical cyclones dominate the extreme climate.

Hemer *et al.* (2007) analysed data from 27 wave buoys (Table 2.4) and compared mean wave height, period and direction with the C-ERA-40 numerical hindcast (1957 – 2002), NOAA WavewatchIII (NWW3, 1997 – 2009) and AusWAM (1994 – 2009) numerical forecasts, Satellite Altimeter (1985 – 2006) and BoM visual observations (SEASTATE) data (1960 – 2009). Extreme wave height values for 25, 50 and 100 yr ARI events were given for each analysed wave buoy (Table 2.5) and for the ERA-40, C-ERA-40 and NWW3 numerical datasets (Figure 2.4). The study found generally larger extreme waves (100 yr ARI H_s = 10.3 to 11.8 m) in the southern and south-west Australian buoys, although the Cape du Couedic buoy showed a smaller 9.13 m. Extreme waves on the New South Wales and southern Queensland coasts are generally in agreement with earlier studies with 100 yr ARI significant wave heights of 7.5 to 9.3 m. Of note, however, Byron Bay was found to be 6.3 m, significantly lower than the more recent finding of 7.6 m by Shand *et al.* (2010). This is attributed to the lack of recorded extreme events in the older Byron Bay record, with the two largest events on record occurring during 2009. In contrast, the 100 yr ARI significant wave heights for the Gold Coast and Tweed Heads were found to be 10.5 m and 9.5 m respectively although the nearby Brisbane buoy gave 7.7 m. While no discussion of this is presented by Hemer *et al.* (2007), the relatively shallow water depths at the Gold Coast and Tweed Heads buoys of 16 and 25 m may influence results by including shoaling transformations. Extreme wave heights behind the Great Barrier Reef were generally found to be moderate, with 100 yr ARI significant wave heights of 2.5 to 4.5 m. The derived 100 yr ARI significant wave heights for ERA-40, C-ERA-40 and NOAA WavewatchIII numerical datasets show similar decreases from south to north. The models vary in their predicted largest southern values at 9, 10 and 11 m respectively. The lower value obtained when using the ERA-40 dataset is consistent with the findings of Caires and Sterl (2005) where the model was found to under-predict large wave heights when compared to northern hemisphere wave buoys. Derived 100 yr ARI significant wave heights reduced to between 3 to 4 m in sheltered northern locations. Of interest, while neither the ERA-40 or C-ERA-40 datasets noted increased extreme wave heights in tropical cyclone prone locations, such as off north-east Queensland and north-west Western Australia, the NWW3 model did note some increase.

Table 2.4
Summary of Australian Extreme Wave Analyses

Location	Study	Data source	Finding
New South Wales	Lawson and Abernethy (1974)	Botany Bay wave buoy (1971 – 1973)	Evaluated three years of wave data 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)	Variety, generally visual reported and analytically forecast/ hindcast (1880 – 1985)	Evaluated historical storm events between 1880 and 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 sectors. 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.
	Willoughby (1995)	Botany Bay (1971 – 1995)	Presents wave and storm persistence statistics derived from 24 years of wave data from the Botany Bay wave buoy. 100yr ARI wave height estimated at 8.3 m (95% CI ±1 m).
	Lord and Kulmar (2000)	Byron Bay (1976 – 1999), Sydney (1987 – 1999) and Eden (1978 – 1999) wave buoys	Evaluation of extreme wave heights for events of between 1and 24 hours duration. The 100 yr ARI, 1 hour significant wave height was found to be 7.8 m for Byron Bay, 8.6 m for Sydney and 9.3 m for Eden. This indicated a reverse spatial trend from the PWD (1985; 1986) studies.
	Carley *et al.* (2003)	Sydney (1992 - 2001) and Port Kembla (1974 - 2001) wave buoys	Evaluation of extreme wave heights for events of between 1 hour and 7 days duration for a range of ARIs. Results gave the 100 yr ARI wave height ranging from 9.8 m for a 1 hour exceedance event to 3.2 m for a 7 day exceedance.
	You (2007)	Sydney wave buoy (1988 – 2006)	Examined the fit of nine extreme value distributions to long term wave data (1988 to 2006) for the Sydney wave buoy. 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.
New South Wales/South-east Queensland	Shand *et al.* (2010)	Brisbane, Byron Bay, Coffs Harbour, Crowdy Head, Sydney, Botany Bay, Port Kembla, Batemans Bay, Eden wave buoys (All between 1971 and 1987 - 2009); numerical forecasts; numerical hindcast datasets.	Analysed wave buoy data for nine locations along the NSW Coast and south-east Queensland to derive extreme wave heights for Average Recurrence Intervals (ARI) of between 1 and 100 years for storm durations of between 1 hour and 6 days. Extreme wave heights were typically largest in central NSW and smaller to the north and south with one hour exceedance, 100yr ARI wave height found to range from 9.1 m at Botany Bay to 7.6 m at Byron Bay. Where directional wave data was available the effect of direction was also assessed. The largest extreme waves on the south and central NSW coast were from the south-east to south and from the east to south-east on the northern NSW and southern Queensland coast. Extreme waves from the north-east to east were found to be smallest on all coasts. Extreme wave heights were also evaluated using comparative numerical datasets (ERA-40 and NWW3). Results showed the accuracy of numerically-derived extreme values to be variable with some agreement but also substantial under- and over-prediction in certain locations.

	Allen and Callaghan (2000)	Brisbane wave buoy (1976 - 1997)	Describe storm climatology in the south-east Queensland region and undertake separate extreme value analyses for tropical cyclone, east coast low and combined storm events. Results for the combined assessment range from 5.02 m for a 2 yr ARI event to 7.75 m for a 100 yr ARI event.
Northern Queensland	Hardy *et al* (2003) and James Cook University Marine Modelling Unity (MMU, 2006)	Numerically synthesised storm events	Over 6000 tropical cyclone events numerically simulated using synthesised wind fields and the WAM wave model. Extreme value analysis undertaken to produce Great Barrier Reef Wave Atlas (James Cook University Marine Modelling Unity, 2006) which gives spatial maps of significant wave height for average recurrence intervals of 20 to 1000 years for over the Great Barrier Reef region between Gladstone and Cape Grenville.
Nthn Queensland, Nthn Territory, North-west WA	Dexter and Watson (1975)	Numerically synthesised cyclone events	Assessment used extreme wind velocities, cyclone occurrence frequency and fetch length to derive significant wave height for recurrence intervals of 50, 100 and 200 years. Results given as contour charts and tables for 70 locations north of 30° latitude.
South-west Western Australia	Lemm *et al.* (1999)	Rottnest Island wave buoy (1994 - 1996)	Analysis of 2.5 years of Rottnest Island wave buoy data. Extreme value analysis gives estimates for 1 and 100 yr ARI events at 6.7 m and 9.8 m.
Tasmania	Reid and Fandry (1994)	Cape Sorell (1985-1993), Cape Grim (1991 - 1992) and Wedge Island (1993) buoys	Analysed 8 years of wave buoy data from Cape Sorell and shorter (<1 year) records from Cape Grim and Wedge Island. Using a PoT method and threshold of 6 m, 100 yr ARI significant wave heights of between 12.8 and 15.7 m were estimated for Cape Sorell using a Gumbel or FT-1 Distribution with the variation in derived height due to the selected fitting type.
	Carley *et al.* (2007)	Cape Sorell (1985 - 1993 and 1998 - 2004) and Wedge Island (1993) wave buoys	Analysed 15 years of wave buoy data from Cape Sorell and less than 1 year of data from Wedge Island. Estimated a 100 yr ARI significant wave height of 13 m at Cape Sorell and 9 m at Wedge Island using a PoT method and Gumbel or FT-1 Distribution.
Australia-wide	Alves and Young (2003)	Satellite Altimeter Data (6.5 years between 1986 and 1995)	100 yr ARI extreme wave heights were derived globally at resolution between 2°×2° and 4°×4° using different extreme value analysis methods. Results were compared with a number of buoys located in the northern hemisphere.
	Caires and Sterl (2005)	ERA-40 numerical hindcast (1957 - 2002)	Derived global 100 yr ARI estimates of H_s based on the Corrected ERA-40 hindcast dataset at 1.5° × 1.5° resolution. In the Australian region estimated 100 yr ARI wave heights increased with distance north. However, the resolution of the model limits the inclusion of tropical cyclones and yields the estimates questionable in regions where tropical cyclones dominate the extreme wave climate.
	Hemer *et al.* (2007)	Wave buoys Australia wide, several numerical forecasts and hindcast datasets, altimeter and visual observation (refer Table 2.4)	Data from 25 wave buoys (Table 2.4) analysed and mean wave height, period and direction compared with C-ERA-40 numerical hindcast (1957 – 2002), NOAA WavewatchIII (1997 – 2009) and AusWAM (1994 – 2009) numerical forecasts, Satellite Altimeter (1985 – 2006) and BoM visual observations (SEASTATE) data (1960 – 2009). Summary of Australian wave climate given including yearly and monthly mean wave height, period and direction for each individual buoy and using regional (0 to 50° S, 90 to 180° E) numerical and altimeter data. Extreme value analysis of buoy (Table 2.4) and regional numerical data undertaken for 25, 50 and 100 yr ARI events (Figure 2.4).

Table 2.5
Extreme Value Analysis of Wave Buoy Data Undertaken by Hemer *et al.* (2007)

Site	Lat (°S)	Long (°E)	Depth (m)	Date Installed	Final Date Available	Data Custo-dian	Total Record Length (yrs)	Return Value (H_{sig}; m)		
								25 yrs	50 yrs	100 yrs
Cape Sorell	42.12	145.03	100	23/03/1998	01/03/2008	BoM[1]	9.95	9.59	10.71	11.82
Cape du Couedic	36.07	136.62	80	01/11/2000	11/12/2007	BoM	7.11	7.99	8.56	9.13
Weipa	12.68	141.75	5.2	21/12/1978	24/02/2006	QDERM[2]	27.20	3.54	4.09	4.64
Cairns	16.73	145.71	14	02/05/1975	28/02/2006	QDERM	30.85	1.90	2.17	2.43
Townsville	19.16	147.06	20	16/07/1975	31/10/2006	QDERM	31.32	2.85	3.06	3.26
Mackay	21.04	149.55	25	20/09/1975	28/02/2006	QDERM	30.46	4.08	4.34	4.60
Emu Park	23.31	151.07	22	24/07/1996	28/02/2006	QDERM	9.61	3.01	3.29	3.58
Brisbane	27.49	153.62	70	30/10/1976	06/03/2006	QDERM	29.37	6.57	7.14	7.72
Gold Coast	27.97	153.44	16	20/02/1987	06/03/2006	QDERM	19.05	4.95	7.74	10.52
Tweed River	28.18	153.58	25	13/01/1995	10/03/2006	QDERM	11.16	5.35	7.44	9.53
Byron Bay	28.82	153.73	71	14/10/1976	31/12/2004	MHL[3]	28.23	5.78	6.02	6.25
Coffs Harbour	30.36	153.27	72	26/05/1976	31/12/2005	MHL	29.62	7.06	7.83	8.61
Crowdy Head	31.83	152.86	79	10/10/1985	31/12/2005	MHL	20.24	6.42	7.42	8.42
Sydney	33.78	151.43	85	17/07/1987	04/10/2000	MHL	13.23	6.98	8.13	9.29
Sydney	33.78	151.43	85	03/03/1992	31/12/2005	MHL	13.84	6.34	7.36	8.39
Port Kembla	34.47	151.03	78	07/02/1974	31/12/2005	MHL	31.92	6.11	7.08	8.05
Batemans Bay	35.71	150.35	73	27/05/1986	31/12/2005	MHL	19.61	6.58	7.40	8.22
Eden	37.30	150.19	100	08/02/1978	31/12/2005	MHL	27.91	6.62	7.08	7.53
Jurien	30.29	114.91	42	27/10/1997	31/12/2005	WA-DPI[4]	8.18	7.22	7.56	7.90
Cottesloe	31.98	115.69	17	16/08/1994	01/03/2008	WA-DPI	13.55	4.95	6.21	7.46
Rottnest	32.11	115.40	48	25/07/1991	29/02/2008	WA-DPI	16.61	7.52	9.13	10.73
Cape Naturaliste	33.36	114.78	50	07/11/1998	31/12/2005	WA-DPI	7.15	8.31	9.33	10.35
PoM A	38.18	144.34	30	01/08/2000	11/08/2003	POM[5]	3.03	4.26	5.11	5.95
PoM B	38.18	144.34	30	24/06/1994	28/02/2002	POM	7.69	4.52	4.76	5.00
PoM C	38.21	144.41	15	13/01/2003	31/12/2005	POM	2.97	5.40	6.73	8.06

[1] Bureau of Meteorology
[2] Queensland Department of Environment and Resource Management
[3] Manly Hydraulics Laboratory, NSW Department of Service Technology and Administration
[4] Western Australia Department for Planning and Infrastructure
[5] Ports of Melbourne

3. WAVE DATA

Data from nine wave buoys from around Australia were selected for detailed analysis of extreme storm events. Buoys were selected on the basis of maximising spatial coverage and record length with only records exceeding 10 years utilised. While shorter records could be used to increase spatial coverage, derived extreme wave values would only be valid for relatively short average recurrence intervals and were thus considered unsuitable.

3.1 Locations

The locations of individual wave buoys have varied through time as wave buoys are lost, removed and replaced during routine maintenance, or repositioned to improve data capture. The present locations, water depth and date range of the selected buoys are shown in Table 3.1 and Figure 3.1, with detailed current buoy locations shown within Appendix A.

The majority of buoys were located in 'deep' water. That is, water of depth greater than $\overline{L_0}/2$, where $\overline{L_0}$ is the deep water wavelength of the mean wave period at that location. This ensures wave transformations due to shoaling and other depth-influenced processes, such as refraction, are minimised. Exceptions to this are Point Nepean which is in 27 m water depth ($\sim\overline{L_0}/10$) and the Western Australian Buoys of Jurien Bay, Rottnest Island and Cape Naturaliste which are in between 42 and 50 m of water ($\sim\overline{L_0}/5$). These depths are considered 'intermediate' and while extreme waves are unlikely to be depth limited, some shoaling transformation is likely.

Additionally, the wave buoy at Eden initially located in sheltered positions north of Green Cape until 7 March 1989 with notably smaller wave heights observed during this period (Shand *et al.* 2010). This early biased data was excluded from the record for the present study.

3.2 Instrumentation

Deep water wave buoys used in NSW by MHL/DECCW, in Queensland by the Queensland EPA, in Western Australia by the Department of Transport and off South Australia and Tasmania by BoM 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 as ±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. Port of Melbourne currently use a Triaxys directional wave buoy at Point Nepean.

3.3 Data Capture and Analysis

Since their initial deployments, data has been captured by the wave buoy network at intervals of 12, 6, 3, 1 and less than 1 hour intervals, although since 2000 all of the analysed wave buoys have captured data at intervals of one hour or less. Table 3.1 shows the date ranges, the total data capture (%), the total record length (years) and the effective record length (years) for each buoy. 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 3.2. Apart from Point Nepean which has a total capture rate of just under 70%, the remaining wave buoys have total capture rates of greater than 84% (excluding the 1992 to 1998 gap between buoy installations at Cape Sorell). The Western Australian Buoys have the highest capture rates of 95 to 96%.

Data is captured for a discrete time period every sampling interval (i.e. 34 minutes for MHL wave buoys), transmitted to shore and logged. Erroneous sample points are removed before processing by zero-crossing and spectral analysis (Figure 3.3). This process extracts a range of wave height, period and direction statistics described within Table 3.2 (MHL, 2009).

Wave 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 corrupted 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).

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

Site	Present Location		Water Depth (m LAT)	Maintained by	Date Range	Total Record Length (yrs)	Total Capture (%)	Effective Record Length (yrs)
	Latitude (° S)	Longitude (° E)						
Brisbane	27º 29.77’	153º 37.76’	76	QDERM	31/10/1976 – 31/12/2009	33.26	91	30.39
Botany Bay (Sydney)	33º 46.52’	151º 25.07’	92	Sydney Ports Corp	08/04/1971 – 31/12/2009	38.84	88	34.29
Eden	37° 18.10'	150° 11.10'	100	DECCW/MHL	08/02/1978 – 31/12/2009	31.98	85	27.29
Cape Sorell	42º 07.20’	145º 01.80’	100	CSIRO; BoM	11/07/1985 – 24/09/1992; 07/01/1998 – 31/12/2009	19.20[1]	84	16.17
Point Nepean/ Point Lonsdale	38º 21.64’	144º 41.64’	27	Port of Melbourne	14/12/1993 – 31/12/2008	15.10	69	10.40
Cape du Couedic	36º 04.20’	136º 37.20’	80	BoM	29/11/2000 – 31/12/2009	9.11	91	8.31
Cape Naturaliste	33° 32.08'	114° 45.87'	50	Transport WA	28/05/1999 – 31/12/2009	10.62	95	10.04
Rottnest Island	32º 05.65’	115º 24.47’	48	Transport WA	19/01/1994 – 31/12/2009	16.04	96	15.45
Jurien Bay	30° 17.50'	114° 54.87'	42	Transport WA	02/01/1998 – 31/12/2009	12.03	95	11.42

[1]Excludes 5.3 yr gap 1992 – 1998

While most data provided for analysis had been subjected to some form of quality assurance by the respective organisation, data was again checked for irregularities by comparing outputs with adjacent wave buoys. Obviously incorrect data (i.e. Figure 3.4) was removed from subsequent analysis.

Table 3.2
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 of top 10% wave height
HMAX	metres	maximum wave height
TC	seconds	crest wave period
TZ	seconds	zero upcrossing wave period
TSIG	seconds	significant wave period
Spectral Analysis Statistics		
F0	Hertz	frequency at first spectral estimate
YRMS	metres	rms 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

4. DATA ANALYSIS

4.1 Descriptive Statistics

Wave buoy characteristics including monthly mean H_s, the relationship between H_s and T_p and wave height exceedance is shown for all buoys within Appendix B. Significant wave height (H_s) 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.

Table 4.1
Significant Wave Height Exceedance (%) Table

H_s (m)	Brisbane	Botany Bay	Eden	Cape Sorell	Point Nepean	Cape du Couedic	Cape Naturaliste	Rottnest Island	Jurien Bay
0.5	99.9	99.5	99.8	100.0	98.6	100.0	100.0	99.9	100.0
1.0	84.7	81.6	89.3	99.3	80.1	98.8	99.2	94.9	98.1
1.5	49.6	45.3	51.4	92.6	49.9	89.6	91.8	75.8	85.2
2.0	25.5	21.9	21.6	77.7	24.7	69.4	72.9	49.9	59.9
2.5	11.5	10.5	8.9	58.9	10.4	48.6	50.2	29.0	33.8
3.0	4.9	5.1	3.9	41.9	4.1	30.9	32.2	16.4	16.4
3.5	2.1	2.6	1.87	27.6	1.52	18.7	20.1	9.3	8.3
4.0	0.99	1.26	0.90	17.2	0.48	10.5	11.8	5.3	4.2
4.5	0.41	0.60	0.45	10.5	0.14	5.5	6.5	2.9	2.0
5.0	0.19	0.30	0.20	6.3	0.04	2.9	3.6	1.56	0.79
5.5	0.10	0.13	0.08	3.5	0.014	1.21	1.88	0.74	0.28
6.0	0.07	0.06	0.020	1.90	0.003	0.42	0.96	0.33	0.09
6.5	0.026	0.025	0.004	1.01	0.000	0.15	0.40	0.15	0.021
7.0	0.007	0.010	0.001	0.54	0.000	0.05	0.15	0.06	0.005
7.5	0.000	0.004	0.000	0.25	0.000	0.021	0.06	0.022	0.001
8.0	0.000	0.002	0.000	0.11	0.000	0.008	0.011	0.006	0.000
8.5	0.000	0.001	0.000	0.05	0.000	0.001	0.000	0.001	0.000
9.0	0.000	0.000	0.000	0.026	0.000	0.000	0.000	0.000	0.000
9.5	0.000	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000
10.0	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000
Descriptive Statistics (H_s, m)									
Mean H_s	1.63	1.60	1.64	2.95	1.60	2.64	2.71	2.19	2.30
Median H_s	1.47	1.43	1.52	2.75	1.50	2.47	2.51	2.00	2.18
20% Exceed	2.16	2.06	2.05	3.85	2.14	3.44	3.51	2.83	2.87
10% Exceed	2.58	2.54	2.43	4.56	2.53	4.05	4.16	3.44	3.36
5% Exceed	2.99	3.02	2.85	5.22	2.90	4.57	4.73	4.05	3.88
1% Exceed	4.04	4.17	3.93	6.51	3.70	5.60	5.98	5.31	4.89
Maximum	7.36	8.87	7.14	13.15	6.42	8.71	8.49	8.64	7.60
Variance	0.51	0.54	0.42	1.41	0.49	1.04	1.10	0.91	0.68
Effective record length (yrs)	30.4	34.3	27.3	16.2	10.4	8.3	10.0	15.5	11.4

These data show mean significant wave height along the southern Queensland and NSW coastlines to be relatively consistent at between 1.60 and 1.65 m. While the mean and median wave heights are slightly smaller at Botany Bay, the 1% exceedance and maximum waves are larger indicating more intense storms are observed along the mid NSW coast. This was similarly found by Shand *et al.* (2010) in a more comprehensive study of the NSW wave climate. Mean wave height is largest along the southern Australian Coast with Cape Sorell at 2.95 m and Cape du Couedic and Cape Naturaliste 2.64 m and 2.71 m respectively. Point Nepean has a mean H_s of only 1.60 m. This is attributed to the sheltered position of the buoy in the lee of Cape Otway, King Island and Tasmania. Wave height reduces slightly with latitude on the Australian West Coast with Rottnest Island and Jurien Bay observing mean heights of 2.19 and 2.30 m respectively. At all locations, the 1% exceedance significant wave height is 2 to 2.5 times the mean. The maximum observed height is 3 to 4 times the mean height along the west coast, 3.5 to 4.5 times the mean height along the south coast and 4.5 to 5.5 times the mean along the east coast. The values for the east coast indicate a wave climate characterised by less frequent but more intense storm events than the west coast. The largest waves are observed at Cape Sorell with a 1% exceedance H_s of 5.6 m and maximum H_s of 13.15 m, although this maximum is discussed in more detail within Section 4.3. Mean peak period is relatively consistent along similarly orientated coasts at 9.3 to 9.4 s along the exposed Australian east coast, 12.4 to 12.7 s along the south coast and 12.6 to 13.1 s along the south-west coast.

Table 4.2
Peak Wave Period Occurrence (%) Table

T_p (s)	**Brisbane**	**Botany Bay**	**Eden**	**Cape Sorell**	**Point Nepean**	**Cape du Couedic**	**Cape Naturaliste**	**Rottnest Island**	**Jurien Bay**
2 – 3.99	0.41	0.17	0.24	0.01	0.07	0.003	0.01	0.09	0.003
4 – 5.99	6.7	5.6	7.5	0.61	1.79	0.26	1.72	2.15	0.88
6 – 7.99	19.8	19.5	19.5	1.42	4.4	2.25	2.87	5.5	4.87
8 – 9.99	37.7	41.2	31.4	6.8	5.0	6.3	6.0	7.1	6.0
10 – 11.99	24.6	26.1	24.3	32.1	24.0	26.3	22.3	20.5	16.2
12 – 13.99	9.2	6.7	15.1	40.0	32.9	40.4	34.9	35.2	34.3
14 – 15.99	1.50	0.66	1.83	16.6	25.6	20.8	23.0	21.2	26.3
16 – 17.99	0.09	0.06	0.21	2.10	4.2	2.8	7.5	6.9	9.0
18 – 19.99	0.00	0.00	0.01	0.41	1.68	0.82	1.44	1.13	1.89
20 – 21.99	0.00	0.00	0.00	0.04	0.41	0.06	0.31	0.23	0.44
22 – 23.99	0.00	0.00	0.00	0.00	0.06	0.03	0.03	0.03	0.05
>24	0.000	0.000	0.000	0.000	0.010	0.000	0.000	0.024	0.003
Descriptive Statistics (T_p, s)									
Mean T_{p1}	9.3	9.3	9.4	12.4	12.7	12.7	12.8	12.6	13.1
Median T_{p1}	9.3	9.4	9.5	12.5	12.5	12.8	12.9	12.9	13.3
20% Exceed	11.0	10.8	11.1	13.9	14.3	14.4	14.8	14.6	15.1
10% Exceed	12.1	12.0	12.2	14.8	15.4	15.1	15.7	15.5	16.0
5% Exceed	13.0	12.3	13.5	15.3	16.7	15.5	16.7	16.5	17.0
1% Exceed	14.7	14.4	15.1	17.4	18.2	18.0	18.6	18.3	19.1
Maximum	18.4	23.7	19.7	22.3	33.3	22.4	23.5	25.6	30.8
Variance	4.7	5.2	5.5	3.7	6.5	4.2	6.3	7.4	6.9
Effective record length (yrs)	30.4	34.3	27.3	16.2	10.4	8.3	10.0	15.5	11.4

4.2 Seasonal Variation and Medium Term Change

Figure 4.2 presents seasonal and mean significant wave height (A) and peak spectral period (B) for each wave buoy. This seasonal variation in mean monthly wave height is also shown for each buoy in Appendix B. Neither of the New South Wales buoys analysed exhibit significant seasonal variation in mean wave height, although both observe slightly longer period waves in Autumn and Winter than Summer. The Brisbane wave buoy experiences ~ ±10% seasonal variation, with the largest waves in Autumn and smallest waves in Spring. The South and Western Australian buoys display significantly more seasonal variation with waves during the winter being 10 to 25% larger than the annual mean and waves during the summer being 10 to 20% smaller than the annual mean. An exception is Point Nepean in Victoria which exhibits virtually no seasonal change in wave height. This is again attributed to its sheltered position in the lee of Cape Otway, King Island and Tasmania, which protects the location from large winter south-west events. These South and Western Australian buoys also experience seasonal variation in wave period with an increase from just under 12 s in summer to 13 to 14 s in winter.

Mean monthly significant wave height is presented for each buoy within Appendix C along with the linear regression line and 95% confidence intervals. Mean monthly wave energy is assessed and the residual energy and cumulative residual energy also presented within Appendix C along with the Southern Oscillation Index (SOI) values as provided by the Australian Bureau of Meteorology (BoM, 2010).

Artificial trends in wave height may be introduced by changes in wave buoy position and exposure over time or through changes in the sampling interval or equipment. For example, the wave buoy at Eden was located north of Green Cape until April 1989 when it was repositioned south, close to its present location (MHL, 2009). A notable increase in wave height is observed following this reposition (Appendix C-3). Coghlan *et al*. (2010) similarly found a steep gradient in mean wave height offshore and south of Eden (Figure 4.3) when analysing high resolution numerical data. This early wave data should therefore be excluded from trend analysis to ensure results are robust. Similarly, the Point Nepean wave buoy is also known to have been moved since initial placement (Cardno, Lawson and Treloar, 2008) with the most recent placement at Point Nepean (2003 to present) more exposed than the previous location, which was approximately 15 km to the north-west at Point Lonsdale (1993 to 2003). The wave buoy at Cape Sorell was removed completely between September 1992 and January 1998, however, the buoy was replaced within 3 km of initial placement to a location with comparable wave exposure. The wave buoy at Brisbane has been moved numerous times since initial placement (Queensland EPA, 2001), although the buoy has been located in a relatively constant position since September 1994.

For the purposes of this trend assessment, the Brisbane, Eden and Point Nepean have been truncated to exclude the early, incongruent data.

Appendix C shows significant seasonal variation in monthly mean wave height and energy in the west and exposed south coast buoys. Longer-term cyclical trends in mean monthly energy are also evident in these buoys at periods of around 8 to 12 years, although the short record lengths show only one to two cycles. While no clear relation to the SOI is evident, other more localised climatic cycles such as the Indian Ocean Dipole (IOD) may influence such trends. The East Coast wave buoys show a weak relation between positive SOI and higher monthly wave energy and negative SOI and lower monthly wave energy. A notable increase in mean energy is also apparent at these buoy locations immediately following the strong negative to positive SOI transition in 1998. This is also reported as a possible phase shift in the Inter-decadal Pacific Oscillation (IPO) from a warm (positive) to cool (negative) regime (Salinger *et al*. 2001).

Linear regression analysis shows monthly mean wave height on the East Coast (Brisbane and Botany Bay) and West Coast (Rottnest Island, Jurien Bay) to be increasing at +1 to 2 mm/year and +5 to 7 mm/year respectively (Table 4.3). Mean monthly wave height along the Southern Coasts between Eden and Cape Naturaliste is found to be trending downwards at between -1 and 4 mm/year. While the Point Nepean data trends downwards more steeply, the reliable dataset spans only 5 years and therefore does not yet provide meaningful long-term trends. Overall, trends are weak, with the 95% confidence intervals straddling the zero trend in all cases.

An F-ratio test was undertaken to test the null hypothesis that the linear trend in mean monthly wave height over time is zero (Lomax, 2007). The resultant F-ratios and corresponding level of significance, P, are presented for each buoy within Table 4.3. Results show that the Null Hypothesis (that the linear trend in mean monthly wave height over time is zero) is accepted (to the 0.05 level) for all buoys. This implies that no statistically significant upward or downward trend is present.

Overall, the East and West Coast buoys exhibit non-statistically significant upward trends in mean wave height of up to +2 mm and +5 mm/year respectively and the Southern Coast buoys exhibit non-statistically significant downward trends of between -1 and -4 mm/year. Caution should, however, be emphasised for non-statistically significant trends and for shorter term (less than 10 to 15 years) records where short to medium-term climatic cycles are likely to have influenced results.

Table 4.3
Statistical Test on Mean Monthly Significant Wave Height Trend

Buoy	Monthly mean H_{sig}			
	Linear trend (mm/yr) (±95% CI)	F ratio[1]	P[2]	Statistically Significant[3]
Brisbane (Sep 1994 – Dec 2009)[4]	0.4 (-8.6, 9.4)	0.01	0.93	No
Botany Bay (Apr 1971 – Dec 2009)	1.7 (-0.4, 3.8)	2.6	0.11	No
Eden (Apr 1989 – Dec 2009)[4]	-4.3 (-8.6, 0.1)	3.7	0.06	No
Cape Sorell (Jul 1985 – Dec 2009)	-2.0 (-10.3, 6.3)	0.2	0.63	No
Point Nepean (Feb 2003 – Jan 2008)[4]	-13.6[5] (-42.4, 15.2)	0.9	0.35	No
Cape du Couedic (Nov 2000 – Dec 2009)	-0.8 (-32.4, 30.7)	0.0	0.96	No
Cape Naturaliste (May 1999 – Dec 2009)	-1.8 (-34.0, 30.4)	0.01	0.91	No
Rottnest Island (Jan 1994 – Dec 2009)	4.9 (-10.3, 20)	0.4	0.53	No
Jurien Bay (Jan 1998 – Dec 2009)	7.0 (-10.7, 24.7)	0.6	0.43	No

[1]F-ratio test of Null Hypothesis that slope is zero

[2]Level of significance of F-ratio test

[3]Is slope significant, i.e is Null Hypothesis (that slope is zero) rejected to 0.05 level,

[4] Buoy records truncated – see text

[5] Short record length reduces confidence in results

Following recent work by Young *et al*. (2011) investigating temporal trends in Satellite Altimeter data using a Seasonal-Kendall Test, similar tests have been undertaken for the long-term wave buoy deployments listed above. The Seasonal Kendall test is preferred over regression techniques due to its enhanced ability to detect a trend when present in noisy environmental data. Complete description of the test and results are provided within Appendix G. Results show both tests to give similar results with weak upward trends in wave height found for West Coast buoy data, weak downward trends for South Coast buoy data and both weak increasing and decreasing trends in East Coast data. Overall, no buoys were found to exhibit statistically significant (to the 0.05 level) trends in either the mean or extreme (90^{th} and 99^{th} percentile) wave height using the Seasonal Kendall test.

4.3 Storm History

Methods of defining data for extreme value analysis 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 specified 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 smaller confidence interval range (Goda, 2000; Mathiesen *et al.* 1994).

4.3.1 Event Detection

While the peaks over threshold method generally employs a specified threshold wave height, the range of wave climates around Australia and the requirements of the present study to evaluate extreme, long-duration events prohibit the use of a single threshold height. A variation of the standard peaks over threshold (PoT) method was therefore employed with differing thresholds selected depending on duration and wave buoy climate. An initial PoT analysis was undertaken for each buoy using the derived 10% exceedance wave height (Table 4.1) with a minimum exceedance duration of three days. A second PoT analysis was then undertaken with a higher 5% exceedance threshold with no minimum duration to capture larger events of short duration. 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 (Figure 4.4).

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 as this would violate the assumption of sample independency.

Events were manually checked against the original time series record for that buoy and against adjacent buoys to ensure:

1. Apparently erroneous spikes (where present) were removed;
2. Single storms that were detected as separate events were, if possible, combined;

3. Multiple storms which may have been detected as a single event were, if possible, separated.

This last criteria is somewhat difficult to achieve as the same storm system may re-intensify or change track, causing multiple storm peaks within the same event.

While missing data within some storm events or for entire storm periods has been noted, no new data was synthesised based on models or adjacent wave buoys as this would introduce a subjective component to the dataset. Only data missing during the largest events was likely to significantly influence the final results of the extreme value analysis.

A summary of detected storm events for each of the nine wave buoys is presented within Table 4.4 and Figure 4.5. The largest 5 storm events based on peak H_s for each wave buoy are presented within Table 4.5. The total cumulative storm energy, E (Eq 4-1: Harley *et al.* 2009), is expressed in MJh/m^2 and provides a measure of total energy occurring over the duration of the event.

$$E = \frac{1}{16}\rho g \Delta t \sum_{i=1}^{N} H_s^2 \qquad 4\text{-}1$$

Where N is the number of data points in the storm event, ρ is the density of sea water, g is the acceleration due to gravity, Δt is the temporal resolution of the dataset and H_s is the significant wave height at each time interval. This measure of total storm energy was found to provide a reasonable measure of erosive potential by a single storm event (Mendoza and Jimenez, 2006) and is similarly presented for each buoy within Table 4.5.

Table 4.4
Summary of Storm Events Detected at Each Wave Buoy

Data source	Lower (10%) Thres-hold (H_{sig})	Higher (5%) Thres-hold (H_{sig})	Effective Record length (years)	Average number of storms/ year	Largest storm peak wave height $(H_{sig})_{peak}$	Largest storm energy (MJh/m^2)	Mean storm duration (hours)
Brisbane	2.58	2.99	30.33	14.9	7.36	2.65	49.6
Botany Bay	2.54	3.02	34.16	22.4	8.87	2.17	39.9
Eden	2.43	2.85	27.22	20.5	7.14	1.84	42.6
Cape Sorell	4.56	5.22	16.17	22.6	13.15*	4.11	44.0
Point Nepean	2.53	2.90	10.42	25.8	6.17	0.74	32.6
Cape du Couedic	4.05	4.57	8.30	22.8	8.71	2.90	43.2
Cape Naturaliste	4.16	4.73	10.02	19.7	8.49	3.79	49.9
Rottnest Is.	3.44	4.05	15.41	17.5	8.64	4.39	53.5
Jurien Bay	3.36	3.88	11.39	19.7	7.60	1.93	47.2

* See discussion regarding this largest observed event in the following section.

Time series of significant wave height and peak wave period for the largest storm (based on peak H_s) detected at each wave buoy are presented within Appendix C along with the synoptic chart (sea level pressure) showing the weather system responsible for generation of the large wave event.

4.3.2 Discussion of Events

The Cape Sorell wave buoy has the highest background wave height and therefore has the highest 10% threshold to define a storm event at 4.5 m. This is followed by Cape Naturaliste and Cape du Couedic with 5% thresholds at 4.2 to 4.1 m and Rottnest Island and Jurien Bay at 3.4 m. The east coast buoys have lower thresholds of 2.4 to 2.6 m and Point Nepean has a similar lower threshold of 2.5 m, attributed to its sheltered position in the lee of Cape Otway, King Island and Tasmania. Between 15 and 26 storms per year were detected at each buoy, with south coast locations generally more frequent and east and west coast sites slightly less frequent. Brisbane detected the lowest average number of storms per year at 14.9 due to the infrequency of storm systems resulting in extreme waves at this higher latitude. Mean storm duration is relatively consistent at between 40 and 45 hours for all buoys, although the maximum energy events are typically over 100 hours and may be up to 300 hours (12 days). The Western Australia and south-east Queensland coasts exhibit slightly longer mean storm duration than the southern and NSW coasts.

Table 4.5
Largest Five Storm Events Ranked by Peak H_s for Each Wave Buoy

Brisbane								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	256	17/03/1993 10:00	7.36	12.88	12.32	3.85	9.92	2.65
2	110	04/03/2006 09:00	7.21	11.45	12.17	4.74	9.86	1.69
3	98	05/03/2004 17:00	6.98	14.31	12.12	3.70	9.93	0.93
4	157	02/05/1996 20:00	6.90	10.12	11.93	4.29	10.57	1.96
5	119	15/02/1995 06:00	6.42	10.76	11.17	3.64	9.49	1.07
*Max Energy	256	17/03/1993 10:00	7.36	12.88	12.32	3.85	9.92	2.65

Botany Bay								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	105	10/05/1997 23:45	8.87	13.69	13.09	4.60	10.50	1.63
2	83	28/07/2001 19:45	8.05	12.66	12.48	4.84	10.83	1.35
3	114	21/06/1975 08:45	7.42	13.11	NaN	3.72	10.15	1.12
4	105	25/09/1995 20:45	7.20	10.45	11.67	3.94	10.12	1.18
5	32	25/10/1985 09:45	6.98	9.46	11.27	5.34	11.30	0.59
*Max Energy	133	05/08/1986 23:45	6.78	10.35	10.78	4.63	10.76	1.90

Eden								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	62	29/06/2002 01:00	7.14	13.07	12.20	4.15	11.41	0.73
2	71	28/06/2007 16:00	7.12	10.80	12.23	4.44	11.43	0.92
3	99	01/09/1996 03:00	6.78	10.51	13.50	3.61	11.06	0.91
4	92	13/03/1994 16:00	6.71	10.98	13.50	4.84	11.42	1.41
5	95	11/07/1989 06:00	6.70	10.05	11.20	4.21	12.06	1.13
*Max Energy	266	20/06/2007 00:00	5.96	9.14	12.23	3.20	10.97	1.84

Cape Sorell								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	50	29/07/1985 20:00	13.15	19.83	17.39	8.09	14.68	2.23
2	96	05/09/2000 01:00	9.95	14.89	17.68	6.40	13.97	2.58
3	122	26/06/2008 23:00	9.93	16.86	17.85	5.79	13.66	2.73
4	26	03/04/2008 02:00	9.76	14.64	15.12	6.79	12.97	0.78
5	77	03/09/2003 05:00	9.57	15.23	15.54	6.11	13.89	1.90
*Max Energy	170	09/09/2002 07:00	9.22	12.45	15.05	6.11	14.20	4.11

Point Nepean								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	80	03/02/2005 06:00	6.17	8.96	11.15	3.12	12.60	0.55
2	37	15/04/2003 21:00	6.01	10.11	16.80	3.57	15.78	0.31
3	60	19/06/2004 15:00	5.75	12.33	13.40	3.32	13.23	0.45
4	22	14/08/2004 11:00	5.44	9.48	10.50	3.78	9.10	0.21
5	45	14/06/2003 09:00	5.16	7.86	16.05	3.47	14.79	0.36
*Max Energy	115	02/05/2004 21:00	4.43	7.41	10.25	3.15	13.88	0.74

Cape du Couedic								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	96	15/09/2008 18:00	8.71	11.19	15.40	5.41	14.42	1.85
2	163	04/09/2002 13:00	8.43	13.86	17.94	5.24	15.27	2.90
3	41	30/06/2004 19:00	8.14	14.06	17.26	6.03	15.09	0.97
4	60	28/09/2007 10:00	7.72	12.73	14.98	5.61	14.30	1.24
5	17	21/01/2007 01:00	7.25	11.53	13.08	5.44	12.54	0.33
*Max Energy	163	04/09/2002 13:00	8.43	13.86	17.94	5.24	15.27	2.90

Cape Naturaliste								
Rank	Duration (hrs)	Storm Peak				Storm Mean		Total Energy (MJh/m^2)
		Date	H_{sig}	H_{max}	T_p	H_{sig}	T_p	
1	35	08/10/1999 02:00	8.49	N/A	13.79	6.27	13.41	0.89
2	106	02/09/2002 04:00	8.46	N/A	16.00	5.76	14.90	2.30
3	156	12/07/2002 01:00	8.40	N/A	12.50	5.14	14.30	2.69
4	46	20/07/2009 20:00	8.20	N/A	16.67	6.03	14.33	1.09
5	35	06/10/2002 00:00	8.03	N/A	14.55	5.48	12.49	0.69
*Max Energy	210	14/07/2000 18:00	6.65	N/A	14.55	5.30	13.60	3.79

Rottenest Island								
Rank	**Duration (hrs)**	**Storm Peak**				**Storm Mean**		**Total Energy (MJh/m^2)**
		Date	**H_{sig}**	**H_{max}**	**T_p**	**H_{sig}**	**T_p**	
1	142	21/07/2009 05:00	8.64	N/A	16.67	4.54	12.59	2.07
2	168	12/07/2002 02:00	8.37	N/A	14.04	4.40	14.31	2.18
3	92	17/07/1996 03:00	8.31	N/A	14.66	5.97	13.83	2.14
4	35	05/10/2002 22:00	7.95	N/A	13.33	5.42	12.61	0.69
5	40	16/05/2003 10:00	7.89	N/A	13.56	5.33	11.73	0.75
***Max Energy**	311	27/07/1996 18:00	7.09	N/A	12.60	4.68	14.00	4.39

Jurien Bay								
Rank	**Duration (hrs)**	**Storm Peak**				**Storm Mean**		**Total Energy (MJh/m^2)**
		Date	**H_{sig}**	**H_{max}**	**T_p**	**H_{sig}**	**T_p**	
1	126	25/08/2004 06:00	7.60	N/A	16.33	4.75	15.28	1.88
2	55	21/07/2009 01:00	7.26	N/A	16.33	5.22	14.23	0.98
3	50	18/07/2008 17:00	6.79	N/A	12.31	4.59	12.84	0.68
4	102	29/06/2009 18:00	6.78	N/A	11.27	4.73	13.08	1.48
5	127	18/08/2005 01:00	6.72	N/A	30.77	4.19	13.66	1.45
***Max Energy**	127	07/09/2005 03:00	6.31	N/A	17.78	4.87	15.20	1.93

On the Australian East Coast, the largest recorded storm event occurred at Botany Bay in May, 1997 and had a peak significant wave height of 8.87 m. The event was the result of a strong east coast low forming in conjunction with an intense tropical anticyclone with waves greater than 5 m persisting for around 48 hours (Appendix C-2). While wave buoys were not in operation during the renowned June 1974 Storm (the *Sygna Storm),* Harley *et al.* (2009) estimated peak significant wave height at 7.45 m and total storm energy, observed over 6.75 days at 3.09 MJh/m^2. This estimate was based on analysis of the ERA-40 numerical hindcast data and is particularly significant as the highest total storm energy within the observed buoy data was only 1.90 MJh/m^2 for the 5.5 day duration, August 1986 storm event. Furthermore, the ERA-40 data has been found to under predict large events in this region (Shand *et al.* 2010) meaning the true storm energy may have been larger still.

The largest event detected at Brisbane occurred in March 1993 due to Tropical Cyclone Roger (Appendix C-1). Wave height increased from around 2.5 m to the peak of 7.36 m over 24 hours and then dropped back to around 3 m over the following 48 hours. The Eden wave buoy observed significant waves up to 7.14 m on 29 June, 2002 as strong pressure gradients were created between a high pressure system over the Great Australian Bight and a southern secondary low in the central Tasman Sea (Appendix C-3). Wave height increased rapidly at the start of this event and, while it dropped back to around 5 m within 24 hours, it then persisted at above 4 m for around 3 days.

A wave buoy off Cape Sorell on the Tasmanian West Coast observed the largest storm event on Australian record with a peak significant wave height of 13.15 m. The event, in

July 1985, was the result of an intense mid latitude cyclone centred at around 50° S. The relatively coarse and inconsistent temporal data resolution (2 to 6 hours) makes detailed analysis of the wave record difficult but wave height increased from around 8 m to 13.15 m within 6 hours and then gradually reduced back to 4 m over the following 18 hours (Appendix C-4). However, the short length of record (400 s or approximately 33 waves per data burst) means that statistics such as significant wave height could be skewed by a group of larger waves. Wave records are known to closely approximate a Rayleigh distribution (Thompson, 1977). If the observed largest wave in the record (19.83 m) is assumed to corresponded to the '*maximum wave*', a significant wave height of $H_{max}/1.86$ (USACE, 2003) or 10.66 m would be expected in a long (>1000 waves) record. Alternatively, given a significant wave height of 13.15 m, a maximum wave of 24.46 m could be expected in a sample of 1000 waves (~3.3 hours). Hence, either the derived significant wave height of 13.15 m is an over prediction for the record or a larger maximum wave than the observed 19.83 m could have been expected during the event. The second largest peak significant wave height observed at Cape Sorell was 9.95 m in September, 2000. Of interest, the Cape Sorell wave buoy peaked at H_s = 10.4 m with H_{max} = 18.4 m and T_p = 17.6 s on 16/09/2010 (Appendix C-4a). While the 2010 record has not been available for inclusion in the present analysis, this event is either second largest if the 1985 storm is included or the largest event if the 1985 storm is excluded.

Point Nepean observed its largest storm event on record on 3 February 2005 with a peak significant wave height of 6.17 m. The event occurred as a result of an inland trough low moving south and intensifying in the Bass Strait with strong pressure gradients created between the low and a high pressure system within the Great Australian Bight (Appendix C-5). Southerly to south-east waves were induced and able to propagate unaffected by Cape Otway and King Island into the wave buoy at Point Nepean. The event duration was relatively short with the wave height exceeding 3 m for only around 48 hours before the low moved east. The maximum significant height of 6.17 m is significantly below that observed at Cape Sorell or Cape du Couedic and shows that the location does not tend to experience the same large wave heights during south-west events as the remainder of southern Australia and thus, is not representative for the majority of the Victorian Coast.

The largest storm event observed at Cape du Couedic was 8.71 m in September, 2008 as a result of a deep mid latitude low centered at around 45° S and a long south-west fetch (Appendix C-6). The wave height increased from 4 to 8.7 m over around 24 hours before decreasing back to 4 m over around the same period. Cape Naturaliste and Rottnest Island experienced their largest storm events in October 1999 and July 2009 respectively and were similarly the result of intense mid-latitude lows centered at around 40° S with long south-westerly fetches (Appendix C-7/8). The events were relatively short and uniform around the storm peak. The largest event at Jurien Bay occurred in August 2004 when a mid-latitude low bifurcated as it moved across the southern Indian Ocean generating waves along a very long south-west fetch. A double peak in wave height is evident within Appendix C-9 as the swell from the first portion of the low pressure system reaching the buoy around 24 hours before the second larger peak which reached 7.6 m at 16.3 s. The effect of this is to increase the total storm energy as large wave heights were sustained for longer (> 4 m for 72 hours). These sustained events are especially important for beach erosion where sustained high energy conditions and conditions co-incident with high water levels are critical.

The storm event with maximum energy does not tend to be within the five largest wave height events (although generally within the 10 largest) with the exceptions of Brisbane (largest wave event) and Cape du Couedic (second largest wave event). This indicates that the systems responsible for events with high total energy often have different characteristics from the very intense systems responsible for the largest peak wave heights. An example of this is the event with largest observed energy at Rottnest Island which occurred between 22 July and 3 Aug 1996 (Figure 4.6). This event consisted of at least three major peaks in wave height, yet the height between the major peaks did not drop below 4 m. This event was generated by a single deep mid latitude low which was blocked by a mid-continental high pressure system and held off the south-west Australian coast for over a week. While the peak wave height did not rank in the top five for the buoy, the total energy was near double any of the larger wave height events and the largest observed in a single storm of any of the wave buoys. Of interest, the third largest storm event observed at the Rottnest Buoy occurred on 17 July 1996, immediately prior to the described high total energy event. This clustering of storms has been similarly noted on the NSW coast (Kemp and Douglas, 1981) and south-east Queensland coast (Allen and Callaghan, 2001).

4.3.3 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, 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.

4.3.4 Temporal Variation

Extreme value analysis provides an average recurrence interval for events of a particular magnitude and is based on an assumption of stable statistics. An analysis of the medium to long term trends of mean wave height (Section 4.2) showed non-statistically significant increases on the east and west coasts and increases on the south coast. Table 4.6 presents a statistical assessment of temporal changes in storm event magnitude and event frequency as defined by the number of events per year (also shown within Figure 4.7). This assessment is based on an F-ratio test of the null hypothesis that the linear trend over time is zero (Lomax, 2007) using a 0.05 (95%) level of significance (P). As both the sampling interval and sampling duration can affect the maximum observed wave height during a storm event, only data collected since the location and collection methodology of each wave buoy became consistent (i.e. hourly data) is considered. This provides a shorter data set than using all data and is therefore more susceptible to medium to long-term climatic cycles such as the ENSO and IPO.

Results show that for both the magnitude and frequency of storm events, the null hypothesis (that the linear trend over time is zero) is accepted at all buoys except Botany Bay, which shows a weak but statistically significant increase in the number of events observed per year. The average increase at Botany Bay is equivalent to +0.2 events per year with 95% confidence limits of 0 to +0.4 events per year. This result implies that the observed storm events have been statistically stable in both magnitude and frequency.

Table 4.6
Significance Test of Changes in Storm Magnitude and Frequency

Buoy	Observed events[1]	Event Magnitude				Event Frequency			
		Linear trend (mm/yr) (±95% CI)	F ratio[1]	P[2]	Statistically Significant[3]	Linear trend (Events/yr) (±95% CI)	F ratio[1]	P[2]	Statistically Significant[3]
Brisbane (Sep 1994 – Dec 2009)[4]	229	4.8 (-14.9, 24.5)	0.23	0.63	No	0.0 (-0.5, 0.4)	0.05	0.83	No
Botany Bay (Apr 1971 – Dec 2009)	765	4.0 (-1.4, 9.3)	2.11	0.15	No	0.2 (0, 0.4)	4.05	0.05	Yes
Eden (Apr 1989 – Dec 2009)[4]	460	-6.6 (-19.3, 6.0)	1.07	0.30	No	0.2 (0, 0.5)	3.07	0.09	No
Cape Sorell (Jul 1985 – Dec 2009)	240	11.7 (-25.8, 49.2)	0.38	0.54	No	-0.1 (-0.8, 0.7)	0.04	0.84	No
Point Nepean (Feb 2003 – Jan 2008)[4]	97	36.5 (-80.9, 154.0)	0.38	0.54	No	1.0 (-4.4, 6.4)	0.28	0.63	No
Cape du Couedic (Nov 2000 – Dec 2009)	189	36.0 (-5.9, 78.0)	2.87	0.09	No	0.0 (-0.8, 0.8)	0.00	0.96	No
Cape Naturaliste (May 1999 – Dec 2009)	197	-9.7 (-49.7, 30.3)	0.23	0.63	No	0.2 (-0.5, 0.9)	0.37	0.56	No
Rottnest Island (Jan 1994 – Dec 2009)	270	-5.1 (-29.2, 19.1)	0.17	0.68	No	-0.1 (-0.5, 0.3)	0.36	0.56	No
Jurien Bay (Jan 1998 – Dec 2009)	207	-8.2 (-40.6, 24.2)	0.25	0.62	No	0.3 (-0.3, 0.8)	0.99	0.34	No

[1]F-ratio test of Null Hypothesis that slope is zero

[2]Level of significance of F-ratio test

[3]Is slope significant, i.e is Null Hypothesis (that slope is zero) rejected to 0.05 level,

[4] Buoy records truncated

5. EXTREME VALUE ANALYSIS

5.1 Background

Large, low probability wave events are generally defined in terms of an 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 ARI 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 with confidence intervals increasing with extrapolation 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 some dependence within the dataset. 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.

You (2007) described 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 ARI (H_{ARI}) and estimating the confidence intervals of the resultant height.

5.2 Methodology

5.2.1 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 and found both the FT-I (Gumbel) and Weibull distributions to best fit the observed data. You (2007) suggested the FT-1 (Eqn. 5-1) as most appropriate due to its simplicity as a two-parameter distribution rather than the three-parameter Weibull (Eqn. 5-2). Goda (1988) similarly suggested the FT-I (Gumbel) and Weibull distributions as most appropriate for evaluation of extreme waves. Mathiesen *et al.* (1994) in *Recommended Practice for Extreme Wave Analysis* suggest use of the 3 parameter Weibull distribution and Shand *et al.* (2010) found the Weibull distribution to provide better agreement for a range of duration exceedance events at 9 buoy locations along the Australian East coast when the shape parameter is individually optimised for each distribution. The Weibull distribution (Eq. 5-2) has therefore been adopted for the present study.

FT-1
$$F_{(x)} = \exp\left[-\exp\left(-\frac{x-B}{A}\right)\right] \tag{5-1}$$

Weibull
$$F_{(x)} = 1-\exp\left[-\left(\frac{x-B}{A}\right)^{-k}\right] \tag{5-2}$$

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

5.2.2 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. 5-3). 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. 5-4).

$$F_{(m)} = 1-\left(\frac{m}{N+1}\right) \tag{5-3}$$

$$F_{(m)} = 1-\left(\frac{m-\alpha}{N+\beta}\right) \tag{5-4}$$

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 ($0.2 + 0.27/k^{0.5}$) and ($0.2 + 0.23/k^{0.5}$) for the Weibull distribution where *k* is the distribution shape parameter (Goda, 1988).

By plotting observed height (H) of each data point against a reduced variate (X), calculated according to Eqn. 5-5 (Weibull), the scale and location parameters (A and B) may be estimated using a fitting method.

$$X = \left[-\ln(1 - F_{(m)})\right]^{1/k} \tag{5.5}$$

Goda (1988) advocated the use of the least squares method to determine the scale and location parameters based on the relation shown within Eqn (5-6). This least-squares method was similarly adopted by You (2007). The goodness of fit may be evaluated by a variety of tests. In this case, the coefficient of regression, R^2 and the sum of the squares of the error (SSE), evaluated according to Eqn. 5-7 are used.

$$H = AX + B \tag{5-6}$$

$$SSE(H) = \sum_{i=1}^{m} (Hi - H)^2 \tag{5-7}$$

Where H_i is the i^{th} storm peak significant wave height and H is the equivalent value evaluated according to (5-6). While the parameter assessment is relatively simple for a two-parameter distribution such as the FT-1, the shape parameter, K, in the Weibull distribution influences both the plotting position formula and reduced variates and is not assessed explicitly. The shape parameter K is selected by minimising the SSE and maximising the R^2 value.

5.2.3 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 (x_R) can be assessed by Eqn. 5-8 and 5-9 respectively.

$$ARI = \frac{1}{\lambda\left[1 - F(x_u)\right]} \tag{5-8}$$

$$x_R = F^{-1}\left(1 - \frac{1}{\lambda ARI}\right) \tag{5-9}$$

Where $F(x_u)$ is the 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 and assessed for the 90% interval based on empirical values derived by Goda (1988) using a Monte Carlo simulation.

5.3 Results

5.3.1 Significant Wave Height

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 D. The 1 hour exceedance H_s for all buoys for average recurrence intervals of between 1 and 100 years is shown in Figure 5.1 and summarised for the 1, 10, 50 and 100 year ARI along with 90% confidence intervals in Table 5.1.

The Botany Bay wave buoy shows larger extreme wave conditions than either the Eden or the Brisbane Buoy. This general trend is supported by the remainder of NSW buoys (Shand *et al.* 2010), with the mid coast buoys experiencing slightly larger extreme storm events. Cape Sorell exhibits the largest extreme wave estimates with a 100 yr ARI, 1 hour exceedance height of 12.9 m. Of interest, if the July 1985, 13.15 m event is excluded, the 100 yr ARI, 1 hour exceedance height reduces by 1 m to 11.9 m. Point Nepean is substantially smaller at 7.1 m H_s for the 100 yr ARI event, increasing at Cape du Couedic (9.6 m) and Cape Naturaliste (10.1 m) before decreasing slightly up the Australian West Coast (10.0 m at Rottnest Island and 8.6 m at Jurien Bay).

Table 5.1
Summary of Spatial Variation in One Hour Exceedance H_s

Buoy	1yr ARI		10yr ARI		50yr ARI		100yr ARI	
	H_s (m)	90% CI (± m)	H_s (m)	90% CI (± m)	H_s (m)	90% CI (± m)	H_s (m)	90% CI (± m)
Brisbane	5.0	0.2	6.6	0.3	7.6	0.4	8.1	0.5
Botany Bay	5.7	0.2	7.5	0.3	8.6	0.4	9.1	0.4
Eden	5.4	0.2	7.0	0.3	8.2	0.4	8.7	0.5
Cape Sorell	8.6	0.3	10.8	0.6	12.3	0.7	12.9	0.8
Cape Sorell*	8.5	0.3	10.3	0.4	11.4	0.5	11.9	0.6
Point Nepean	4.8	0.2	6.0	0.3	6.7	0.4	7.1	0.5
Cape du Couedic	7.1	0.3	8.4	0.4	9.2	0.5	9.6	0.6
Cape Naturaliste	7.5	0.3	8.9	0.4	9.7	0.5	10.1	0.5
Rottnest Island	6.9	0.3	8.5	0.4	9.6	0.5	10.0	0.6
Jurien Bay	6.2	0.2	7.5	0.4	8.2	0.5	8.6	0.5

*denotes the exclusion of the July 1985, 13.15 m event

5.3.2 Effect of 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 D presents wave height exceedance curves for events of duration up to 144 hours (6 days). The change in exceeded wave height with duration for the estimated 100 yr ARI event is presented within Figure 5.2 for each buoy in both absolute value and relative to the 1 hour exceedance height.

This figure shows that, as expected, exceeded heights decrease with increased duration for all buoys. Exceeded wave height decreases relatively faster at Point Nepean, Sydney and Botany Bay reducing to around 40% of the peak wave height after 144 hours and slowest at the southern and south-west Australian buoys of Cape du Couedic, Cape Naturaliste and Rottnest Island, which reduce to only 50 to 55% of the peak height after 144 hours. This is likely to be a function of the generation systems responsible with deep, low pressure systems passing under the south-east Australian coast able to generate waves for longer durations (especially when blocked by continental high pressure systems) than the intense east coast lows responsible for the largest events on the Australian south-east coast (Shand *et al*. 2010). The Brisbane buoy similarly maintains extreme wave height over longer durations than the NSW buoys. This is attributed to longer duration events such as anticyclone intensifications and slow moving tropical cyclones which affect the northern coast to a greater extent.

5.3.3 Cumulative Storm Energy

The cumulative energy observed during a storm event as defined by Eqn (4-1) provides a combined measure of the storm intensity and duration. Extreme values were similarly estimated for this parameter with a Weibull distribution again found to provide a superior approximation compared to an FT-1 or Gumbel fit. Results are presented for average recurrence intervals of between 1 and 100 years in Figure 5.3 and summarised for the 1, 10, 50 and 100 yr ARI events within Table 5.2.

Results show the highest estimated energy events to occur along the south and south-western coast, with the highest energy events estimated for Cape Sorell followed by Cape Naturaliste and Rottnest Island. Estimated storm energy decreases with latitude on the west coast, reducing at Jurien Bay to near half that observed at Cape Naturaliste for the 100 yr ARI event. Conversely, energy increases with latitude on the mainland east coast, with total storm energy for Brisbane exceeding both Botany Bay and Eden for reasons described above.

Table 5.2
Summary of Average Recurrence Interval for Cumulative Storm Energy (MJh/m²)

Buoy	1yr ARI		10yr ARI		50yr ARI		100yr ARI	
	E_{cum} (MJh/m²)	90% CI (±)	E_{cum} (MJh/m²)	90% CI (±)	E_{cum} (MJh/m²)	90% CI (±)	E_{cum} (MJh/m²)	90% CI (±)
Brisbane	0.85	0.13	1.85	0.31	2.66	0.46	3.03	0.53
Botany Bay	0.82	0.08	1.53	0.16	2.06	0.21	2.29	0.24
Eden	0.73	0.07	1.32	0.14	1.74	0.18	1.92	0.20
Cape Sorell	2.36	0.27	4.13	0.52	5.39	0.69	5.93	0.77
Point Nepean	0.47	0.04	0.72	0.07	0.88	0.09	0.95	0.10
Cape du Couedic	1.67	0.25	2.85	0.46	3.67	0.61	4.03	0.67
Cape Naturaliste	2.06	0.31	3.64	0.59	4.75	0.80	5.23	0.89
Rottnest Island	1.63	0.28	3.24	0.62	4.48	0.88	5.04	1.00
Jurien Bay	1.23	0.14	2.02	0.26	2.55	0.33	2.78	0.36

5.4 Extreme Wave Period

Defining wave period during a storm event is also important when assessing beach response and structural loadings under storm conditions. Goda (2000) stated that for locations where wind waves are the major component of extreme waves, storm period may be related to storm wave height with the following relation:

$$T = \alpha(H)^{\beta} \qquad (5\text{-}10)$$

Where T and H are the significant wave period and height and α and β are coefficients with Goda (2000) recommending α ≈ 4.0 to 4.6 depending on wave height and β ≈ 0.5 for wind-wave dominated environments. However, this assumption of a wind-wave dominated extreme climate is not necessarily valid along the Southern and Western Australian coastlines. Figure 5.4 presents the relation between storm peak H_s and T_p for each buoy including the sample mean T_p at 1 m height increments and period predicted by Eqn. 5-10 using the recommended coefficient limits. While a weak linear relation between height and period, such as suggested by Eqn. 5-10 is seen in the sample mean, significant scatter is observed, particularly in the lower wave height events. While the expression (5-10) was derived to define significant rather than peak period, the coefficients, α and β may be optimised for each buoy to provide reasonable approximation of T_p at the storm peak (Table 5.3). 90% confidence intervals are obtained using the variance in T_p for the largest 10% of storms. The relation is weaker (i.e. β is lower) and confidence intervals wider for the swell-dominated southern and south-western Australian wave buoys than for the storm wave dominated south-eastern Australian Buoys. The wide confidence interval at Point Nepean is attributed to distinctly different storm systems which generate large storm events at this location. These include deep, mid latitude low pressure systems which generate long period swell and more local southern secondary lows and similar in Bass Strait which generate shorter period seas. Peak period with 90% confidence intervals **((±))** for the estimated 1, 10, 50 and 100 yr ARI storm events at each buoy are also estimated in Table 5.3.

Table 5.3
Associated Wave Period for Extreme Wave Events

Buoy	alpha	beta	Peak Tp (s) (90% CI)			
			1yr ARI	10yr ARI	50yr ARI	100yr ARI
Brisbane	7	0.3	11.4 (±0.9)	12.3 (±0.9)	12.9 (±0.9)	13.1 (±0.9)
Botany Bay	6	0.35	11.0 (±0.9)	12.1 (±0.7)	12.7 (±0.7)	13.0 (±0.7)
Eden	7	0.3	11.6 (±0.9)	12.5 (±1.5)	13.2 (±1.5)	13.4 (±1.5)
Cape Sorell	5	0.5	14.7 (±0.9)	16.4 (±1.3)	17.5 (±1.3)	18.0 (±1.3)
Point Nepean	8	0.3	12.8 (±0.9)	13.7 (±5.6)	14.2 (±5.6)	14.4 (±5.6)
Cape du Couedic	8	0.3	14.4 (±0.9)	15.1 (±2.2)	15.6 (±2.2)	15.8 (±2.2)
Cape Naturaliste	10	0.2	15.0 (±0.9)	15.5 (±3.1)	15.8 (±3.1)	15.9 (±3.1)
Rottnest Island	10	0.2	14.7 (±0.9)	15.3 (±2.8)	15.7 (±2.8)	15.8 (±2.8)
Jurien Bay	11	0.2	15.8 (±0.9)	16.5 (±4.3)	16.8 (±4.3)	16.9 (±4.3)

5.5 Deriving Synthetic Design Storm Events

A synthetic design storm provides time series information of wave height and period during an entire storm event. Such an approach was presented within Carley and Cox (2003) and is useful in the assessment of erosion and coastal inundation where temporal processes such as the joint occurrence of extreme wave height with elevated water level or catchment flooding is important. Important variables in deriving a synthetic design storm time series include storm shape, total storm energy for a particular average recurrence interval, and the envelope of H_{sig} exceedance for specific durations.

5.5.1 Storm Shape

The typical shape of observed storm events was assessed by evaluating the skewness, kurtosis and mean proportion of a storm event occurring before the storm peak. Mean values for each wave buoy are presented within Table 5.4 and show a moderate positive skewness for each buoy. This indicates a moderately asymmetric height distribution during storm events, with a longer tail following the storm peak. This is quantified by assessing the mean proportion of the storm event which occurred before the storm peak (i.e. from exceeding the defined height threshold to reaching the storm peak). Mean values ranged from 0.39 to 0.45 indicating that, on average, wave height during storm events tends to increase slightly faster preceding the storm peak. This pattern is more pronounced in eastern Australian buoys than for western Australian buoys. Kurtosis is positive for all buoys indicating the distribution of storm wave height tends to be substantially peaked compared to a Normal or Gaussian distribution. This is reflected in the rapid initial decrease in extreme wave height with increasing storm duration discussed in Section 5.3.

Table 5.4
Mean Statistics of Storm Shape

Buoy	Total number of observed storm events	Mean Skewness	Mean Kurtosis	Proportion of storm before peak
Brisbane	452	0.26	2.36	0.39
Botany Bay	765	0.23	2.26	0.39
Eden	558	0.24	2.36	0.39
Cape Sorell	365	0.24	2.31	0.45
Point Nepean	269	0.23	2.37	0.43
Cape du Couedic	189	0.23	2.34	0.39
Cape Naturaliste	197	0.16	2.43	0.42
Rottnest Island	270	0.22	2.41	0.43
Jurien Bay	224	0.16	2.30	0.41

5.5.2 Deriving event time series

To estimate synthetic design storm events, the following process is recommended with an example for a 100 yr ARI design event for Botany Bay shown within Figure 5.4.

1. Identify the envelope of H_{sig} exceedance for specific durations based on results presented within Appendix D (Figure 5.5A). This provides an upper limit of wave height as a function of duration.
2. Find the cumulative storm energy for the specific ARI event based on Table 5.2.
3. Define a synthetic height distribution so that the height-duration envelope is not exceeded and the cumulative energy (Eqn 4-1) is equal to that specified for the particular event (Figure 5.5B). The height distribution of a synthetic design storm is not necessarily unique and storms may be shorter and more intense (i.e. Event Type 1 in Figure 5.5B) or longer and less intense (i.e. Event Type 2).
4. Convert the synthetic height distribution into a time series of wave height incorporating any mean asymmetry in storm shape using Table 5.4 (Figure 5.5C).
5. Examination of the time series for the largest five events at each buoy suggest that within a singular storm event, peak period also increases with wave height, reaching a maximum at around the time of peak wave height. Estimate wave period based on relationships presented within Table 5.3 (Figure 5.5D).

6. Estimate confidence intervals for the time series' based on extreme H_s, E_{cum} and T_p confidence intervals.

5.5.3 Results

Time series for design storm events between 1 and 100 yr ARI have been derived for each buoy and are presented within Appendix E. Higher intensity events (i.e. Type 1 in Figure 5.4B) have been assumed.

The derived Botany Bay design storm series are compared to those derived for Sydney by Carley and Cox (2003) (Table 5.5). While the estimated 10 year ARI synthetic design storms are similar in terms of peak H_s, storm energy and duration, the present study estimates a longer duration and higher total energy storm for a 1 year ARI event and a smaller, shorter and lower energy storm for the 100 year ARI event. The major difference for the 100 year ARI event is that the peak H_s estimated by Carley and Cox of 9.8 m is substantially larger than the 9.1 m (±0.4) estimated within the present study. This may be due to the use of amalgamated Sydney and Port Kembla wave data by Carley and Cox rather than the Botany Bay dataset used within the present study or the shortened record length employed by Carley and Cox. Furthermore, by using the maximum exceedance wave height calculated for each duration without consideration of the total storm energy, Carley and Cox have overestimated the magnitude of the event. Storm wave period estimated within the present study is also lower than estimated by Carley and Cox, although the authors do specify that more detailed analyses of spectral peak wave periods (T_p) could be undertaken and theirs was a preliminary assumption.

Table 5.5
Comparison of the Synthetic Design Strom Parameters Estimated by Carley and Cox (2003) and those Estimated within the Present Study

ARI	**Carley and Cox (2003)**				**This Study**			
	Peak Hs (m)	**Total E (MJh/m^2)**	**Duration (hours)**	**Max Peak Period (s)**	**Peak Hs (m)**	**Total E (MJh/m^2)**	**Duration (hours)**	**Max Peak Period (s)**
1	5.8	0.6	48	N/A	5.7(±0.2)	0.8 (±0.1)	90	11.0
10	7.8	1.75	120	N/A	7.5(±0.3)	1.5 (±0.15)	120	12.1
100	9.8	3.3	168	15.0	9.1(±0.4)	2.3 (±0.25)	140	13.0

5.6 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.

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

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_s values of 7.1 to 12.9 m gives uncertainties of 0.04 to 0.13 m. While these controlled uncertainties are well within the confidence limits of derived extreme statistics, errors in wave buoy measurement or limitations in data capture may be introduced by a number of other possible sources. These include wave buoys include spinning due to vessel impact, incorrect mooring or extreme wave and wind conditions, buoy moorings failure, 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). Additionally, Bettington and Wilkinson (1997) analysed wave buoy records on the NSW coast and found minimum trough elevations (z_{min}) to consistently exceed maximum crest elevations (z_{max}) during large wave conditions (H_{sig} >3 m). The authors suggested that this was unexpected according to conventional deepwater wave theory and conclude that buoy submergence likely caused under-measurement of wave crests and therefore wave height. Using the ratios of z_{max} to z_{min} suggested by higher order Stokes theory, they calculated that significant wave height could be underestimated by up to 8%. While such an underestimation has not been verified using independent instruments or widely reported elsewhere, it is worth consideration, as the suggested error is approximately equal to the upper 90% confidence interval of the extreme statistics.

The most serious uncertainty is related to data censoring, where major storm events are excluded due to instrument downtime, sampling intervals or sample durations. 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_s reached 7.6 and 6.6 m respectively. The previous maximum measured wave height at Byron Bay was 6.0 m. While not included within the present study, Shand *et al.* (2010) showed that assessment of extreme height excluding these recent events resulted in an underestimation of extreme values by up to 0.5 m.

Manipulation of data including synthesising events where data was unavailable or applying multipliers to longer sampling interval data (i.e. to transform 6 hour interval data to 1 hour data as per Allen and Callaghan, 2000) was not undertaken as this was judged to add a subjective component to the analysis.

As previously discussed, the data used within extreme value analysis is assumed to be statistically stable. Examinations of temporal changes in mean wave height and storm magnitude have shown no statistically significant change over time and thus the requirement of statistical stability is presently satisfied. With long-term climatic change possibly affecting wave climate (i.e. DCC, 2009) this assumption of stationarity could become increasingly invalid.

Additionally, extreme value analysis provides an average recurrence interval for events of a particular magnitude and is based on an assumption of sample independence, yet clustering of storm events is frequently noted (i.e. Foster *et al*. 1975; Kemp and Douglas, 1981; Allen and Callaghan, 2000; Callaghan *et al*. 2009). Such clustering may be due to seasonal shifts in the climatic patterns (i.e. tropical cyclones are more prevalent during summer months and mid latitude cyclones are more intense during winter months), due to longer term climate shifts such as the ENSO and IPO cycles or due to direct feedback mechanisms governing synoptic genesis. While these cycles have not been assessed during this study, implications may be that during particular stages of climatic cycles, the ARI or AEP of an event of particular magnitude is decreased or that once an event has occurred, the probability of experiencing another large event is temporarily increased.

6. SUMMARY AND RECOMMENDATIONS

6.1 Overview

The Australian coast is subject to a spatially and seasonally varied wave climate periodically affected by large wave events. Storm systems capable of generating extreme waves include intense mid-latitude cyclones along the southern coastal margin, tropical cyclones along the northern margins and easterly trough lows off the east and south-east coastlines. These large wave events, particularly when they coincide with high water levels, may cause widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety. Having accurate predictors of the likelihood and magnitude of large wave events of varying duration is necessary for the quantification of extreme beach erosion and inundation, design of nearshore structures and longer term coastal hazard assessment.

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. This report has reviewed previous extreme wave analyses which have been undertaken around Australia, has identified data availability where no analysis has yet been completed and has derived extreme wave heights, periods and synthetic design storm events for nine wave buoys Australia-wide. Results of this study will have useful and highly practical application in a number of important areas including:

- Improved understanding of extreme storm climatology leading to large wave events on the Australian coast;
- 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 to assist in climate change adaptation.

6.2 Australian Wave Climate

The Australian continent extends from southern mid-latitudes to the tropics in the north, and as a result, the storm climatology affecting Australia's coastal margins varies both spatially and temporally with distinct climatic processes dominating different regions seasonally. The southern part of Australia receives persistent moderate to high wave energy from mid-latitude lows centred within the Southern Ocean at between 50 and 60° S with large wave events occurring intermittently as these low pressure systems intensify and/or extend further north towards the coastline. While a portion of this south-west directed wave energy reaches the Australian East Coast, the majority of extreme wave energy there is generated within the Coral Sea and Tasman Sea window. Major storm events in northern NSW and southern Queensland are a mixture of tropical cyclones, tropical lows and easterly trough lows while on the mid to south NSW coast, major storm events also include inland trough, continental and southern secondary lows. Northern Queensland and the northern Australian coastal margin is subject to infrequent tropical cyclones between December and March. The south-western Australian coastline is subject to significant wave energy from mid-latitude lows centred within the Southern Ocean, particularly during the winter months when the low-pressure band moves north.

Data from nine wave buoys from around Australia were selected for detailed analysis of extreme storm events. These buoys were selected on the basis of maximising spatial coverage and record length with only records exceeding 10 years assessed. These datasets show mean significant wave height along the southern Queensland and NSW coastlines to be relatively consistent at between 1.60 and 1.65 m. Mean wave height is largest along the southern Australian coast with Cape Sorell at 2.95 m and Cape du Couedic at 2.64 m. Point Nepean has a mean H_s of only 1.60 m. This is attributed to the sheltered position of the buoy in the lee of Cape Otway, King Island and Tasmania. Wave height reduces slightly with latitude on the Australian West Coast with Cape Naturaliste having a mean H_s of 2.71 m while Rottnest Island and Jurien Bay have mean significant heights of 2.19 and 2.30 m respectively.

Change in the mean significant wave height was assessed at each buoy using linear regression and Seasonal Kendall tests. Overall, while neither test found statistically significant upward or downward trends in any of the wave buoy records, weak upward trends were found in both the East Coast (one to two mm/year) and West Coast (five to seven mm/year) buoy records and weak decreasing trends (one to five mm/year) were found in South Coast buoy records. Caution should, however, be emphasised for non-statistically significant trends and for shorter term (less than 10 to 15 years) records where short to medium-term climatic cycles are likely to have influenced results.

6.3 Extreme Wave Analysis

The identification and analysis of large wave events observed within a historical wave record allows quantification of extreme wave heights and, using appropriate extreme values analysis, characterisation of large, low probability wave events. Assessments of extreme wave climate have previously been undertaken using wave buoy data along the NSW coast by Blain, Bremner and Williams and Lawson and Treloar (PWD 1985; 1986), Willoughby (1995), Lord and Kulmar (2000), Carley *et al*. (2003), You (2007) and Shand *et al*. (2010), along the Queensland coast by Allen and Callaghan (1999), along the south-west Western Australian Coast by Lemm *et al*. (1999) and along the Tasmanian Coast by Reid and Fandry (1994) and Carley *et al*. (2008). Assessments using numerical hindcasts or simulations include studies within the Great Barrier Reef (Hardy *et al*. 2003) and Australia-wide by Alves and Young (2003), Caires and Sterl (2005) and Hemer *et al*. (2007).

Storms were identified at each buoy using the peak over threshold method, with threshold varying for each location depending on the 5 and 10% exceedance height for each wave buoy. Storm characteristics were derived including start, peak and end date, duration, storm peak and mean significant wave height and period, and cumulative storm energy. Temporal variation in event frequency and magnitude was assessed to evaluate the stability of statistics. Results show no statistically significant (to the 0.05 level) temporal trends in either magnitude or frequency of storm events, except for Botany Bay, which shows a small but statistically significant increase in the number of storm events observed per year.

The Weibull distribution was adopted for use within the present study based on the recommendations of Goda (1988), You (2007) and Shand *et al*. (2010). Extreme wave heights and confidence intervals were derived for Average Recurrence Intervals (ARI) of between 1 and 100 years for storm durations of between 1 hour and 6 days. As duration increases, the wave height exceeded decreases, with wave height decreasing relatively faster at Point Nepean, Sydney and Botany Bay and more slowly at the southern and south-west Australian buoys. This is reflective of the generation systems responsible with deep, low pressure systems passing under the south-west Australian coast able to generate waves over longer durations than the intense east coast lows responsible for the largest events on the south-east coast.

Wave period corresponding to extreme wave height was similarly derived with a weak relationship found between peak wave energy and peak period at all wave buoys. Extreme storm energy was assessed to provide information on the maximum storm energy for representative average recurrence intervals. Storm shapes were assessed and all buoys were found to exhibit a moderate positive skew, indicating a faster increase in wave height before the storm peak than decrease following the peak. This storm shape was combined with maximum wave height and energy information to construct synthetic design storm time series for each buoy for average recurrence intervals of between 1 and 100 years.

6.4 Recommendations

Recommendations arising from this study of extreme wave climate around Australia include:

- That extreme values and synthetic design storms derived within this study are adopted for use in engineering design studies, hazard assessment and climate change adaptation studies;
- While this analysis shows no significant change in wave conditions for the present duration of reliable records, if robust future climate change modelling showed a substantial increase in extreme wave magnitude these values could be revised appropriately;
- That the current wave buoy network is maintained and upgraded, where possible with directional wave buoys – the value of data increases with the length of record;
- That wave buoy sampling intervals are standardised at 1 hour including 26 to 34 minute sample durations, as this will ensure more stable statistics;
- That the effect of direction on extreme wave height is investigated as adequate directional data becomes available;
- That the findings of Bettington and Wilkinson (1997) that wave crest and correspondingly wave height is underestimated by wave buoys is further investigated and, if found to occur, that extreme value estimates are revised appropriately.
- That storm clustering and seasonal variability in extreme wave height is investigated;
- That the joint occurrence of extreme water levels with the extreme wave conditions identified during this study is investigated;
- That changes in mean wave climates and estimates of extreme wave height are re-evaluated at intervals of less than 5 years as new data becomes available.

7. ACKNOWLEDGMENTS

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- Sydney Ports Corporation;
- Queensland Environmental Protection Agency, Department of Environment and Resource Management;
- Cardno Ltd with the permission of the Bureau of Meteorology;
- Port of Melbourne; and
- Western Australian Department of Transport.

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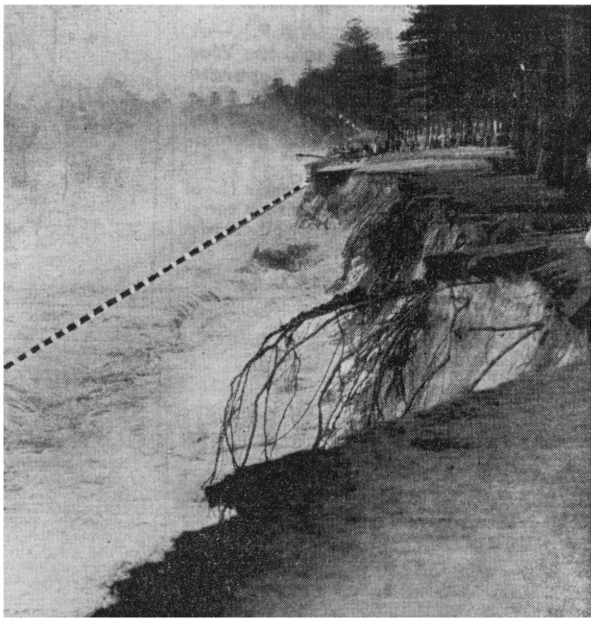
Collaroy-Narrabeen Beach, Sydney. March, 1976. Photograph: A. Short

House at the mercy of the sea

NATURE IN THE RAW IS SELDOM MILD, a fact proven by this aerial picture of damage to a house and swimming pool along the beachfront at Northcliffe. Pounding seas have cut around a breakwater of car bodies and drums.

m

Northcliff storm damage, Daily Telegraph 1967. Source: PWD, 1986.



North Steyne, Manly, Daily Telegraph 26 June 1950. Source: PWD, 1986

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WAVE MEASUREMENT SITES AROUND AUSTRALIAN COAST

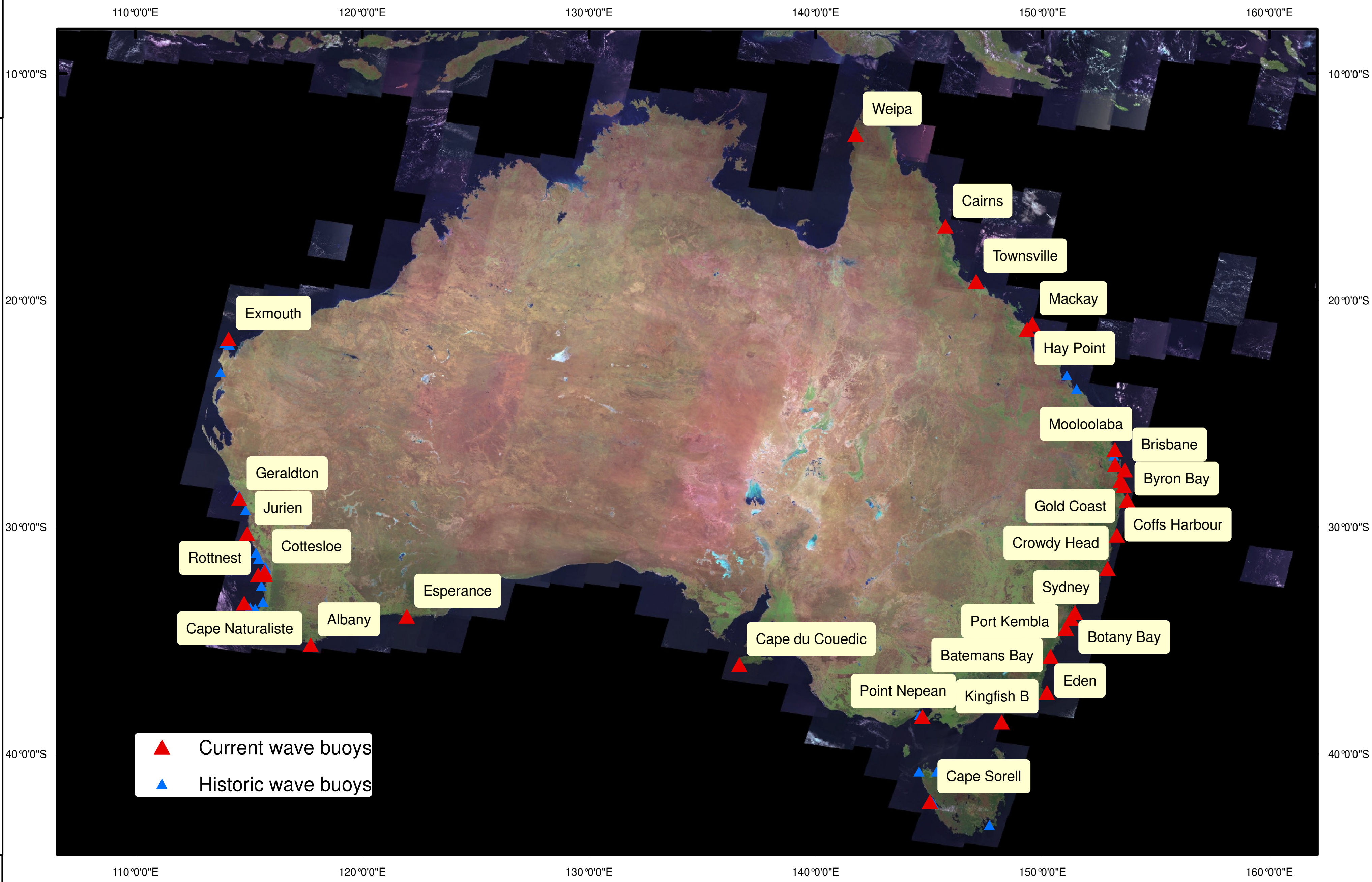
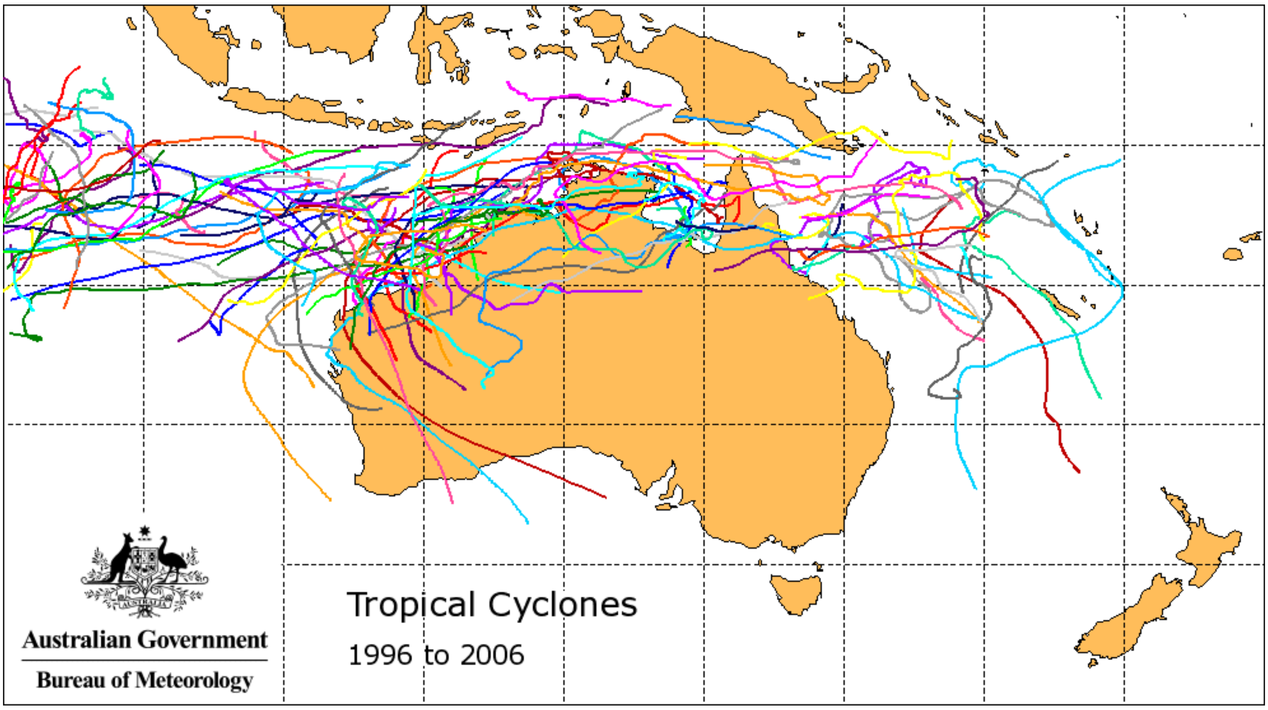
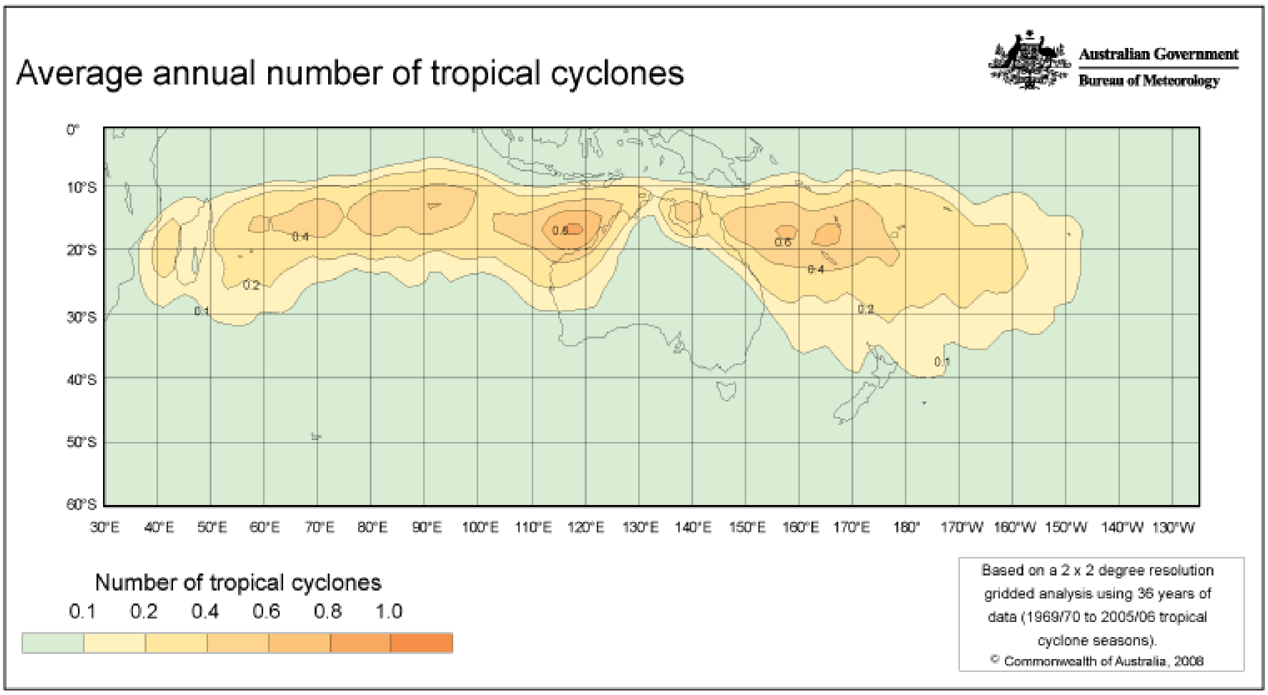


Figure 1.2

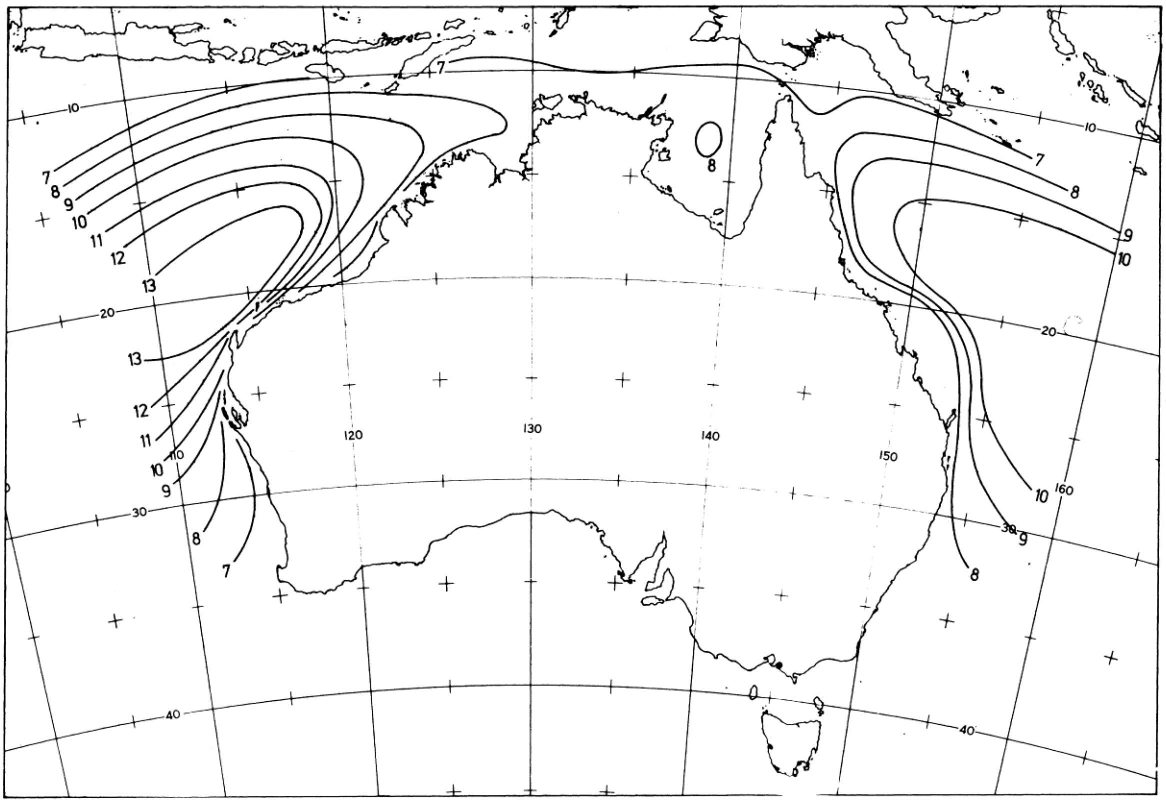


TROPICAL CYCLONE PATHS BETWEEN 1996 AND 2006 (SOURCE: BoM, 2010)



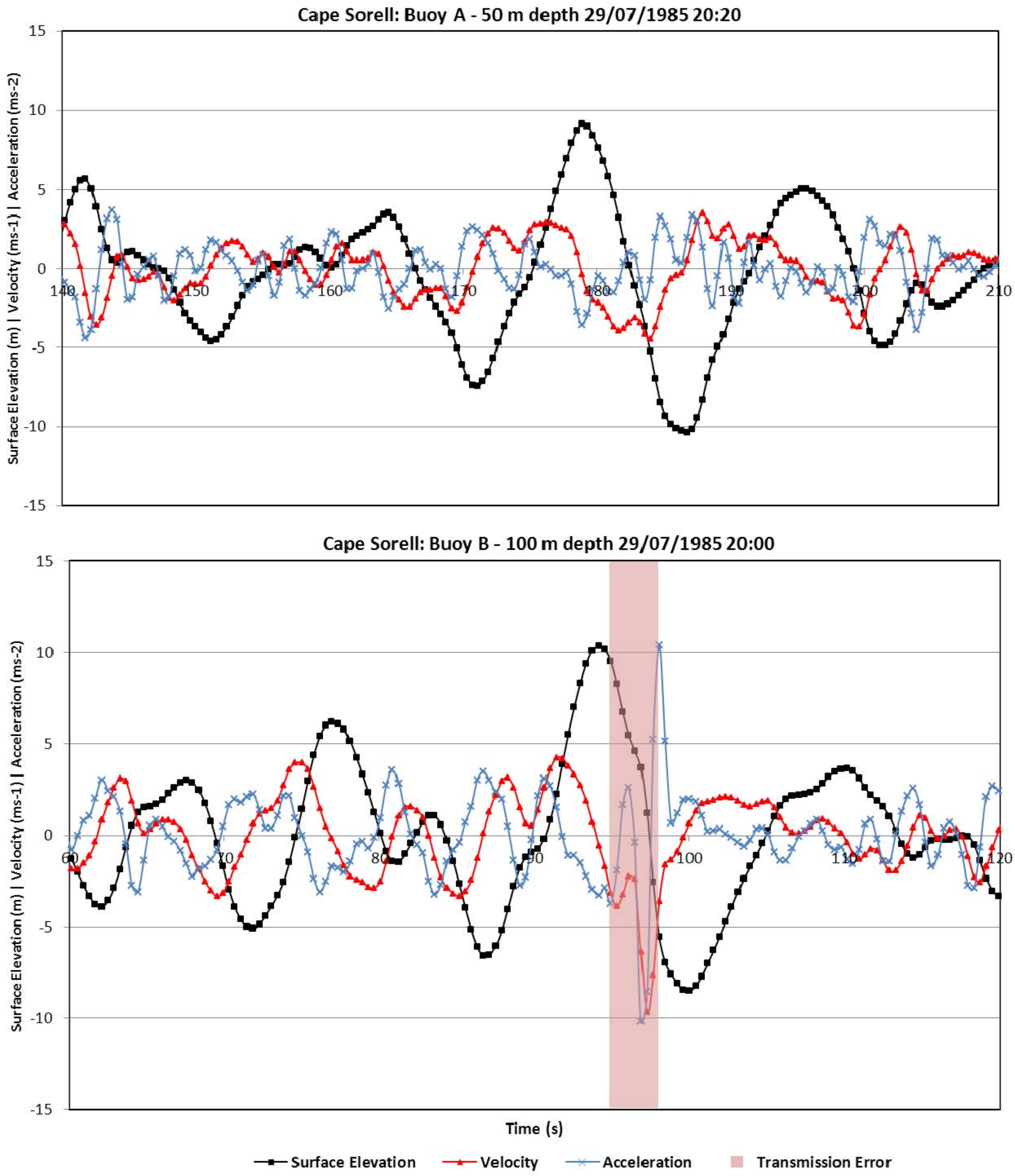
AVERAGE ANNUAL NUMBER OF TROPICAL CYCLONES (SOURCE: BoM, 2010)

TROPICAL CYCLONES WITHIN THE AUSTRALIAN REGION (SOURCE: BOM, 2010)



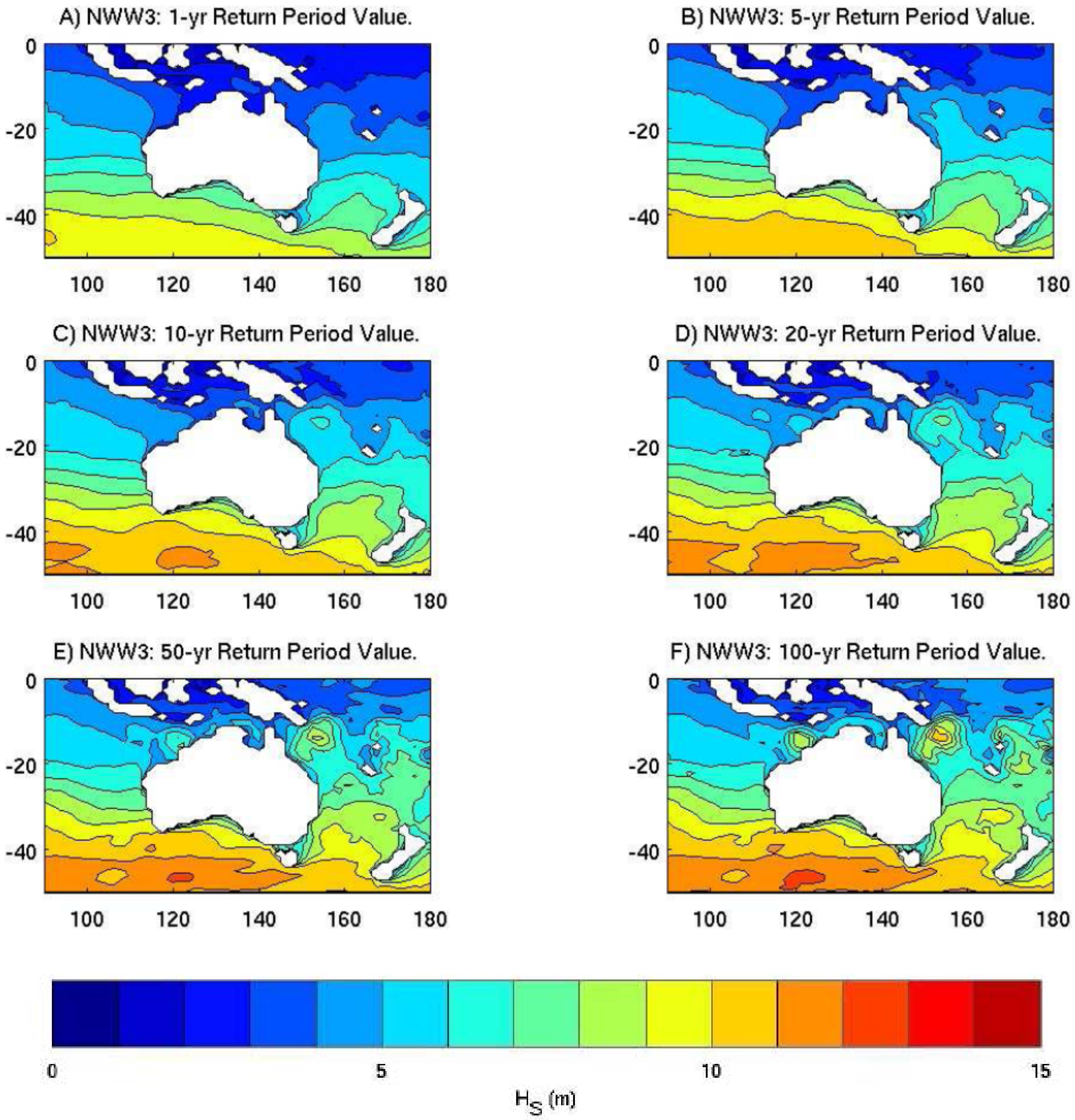
(SOURCE: DEXTER AND WATSON, 1975)

WRL Report No. RR242	ISOPLETHS OF EXTREME SIGNIFICANT WAVE HEIGHT (m) FOR 100yr ARI EVENT AND AVERAGE CYCLONE RADIUS OF 30 KM	Figure 2.2



Surface elevation traces of the two CSIRO Cape Sorell wave buoys at 20:00 and 20:20 on 29 July 1985 together with the derived vertical acceleration and velocity. Time over which poor radio signal or interferrence was observed at Buoy B is indicated by shading. Such interference could have been caused by shadowing induced by the wave or spray (Reid and Fandry, 1994).

WRL Report No. RR242	SURFACE ELEVATION TRACES OF THE TWO CSIRO CAPE SORELL WAVE BUOYS ON 29 JULY 1985	Figure 2.3



WRL Report No. RR242	N-YEAR RETURN AVERAGE RECURRENCE INTERVALS DETERMINED FROM NWW3 NUMERICAL DATASETS (SOURCE: HEMER ET AL., 2007).	Figure 2.4

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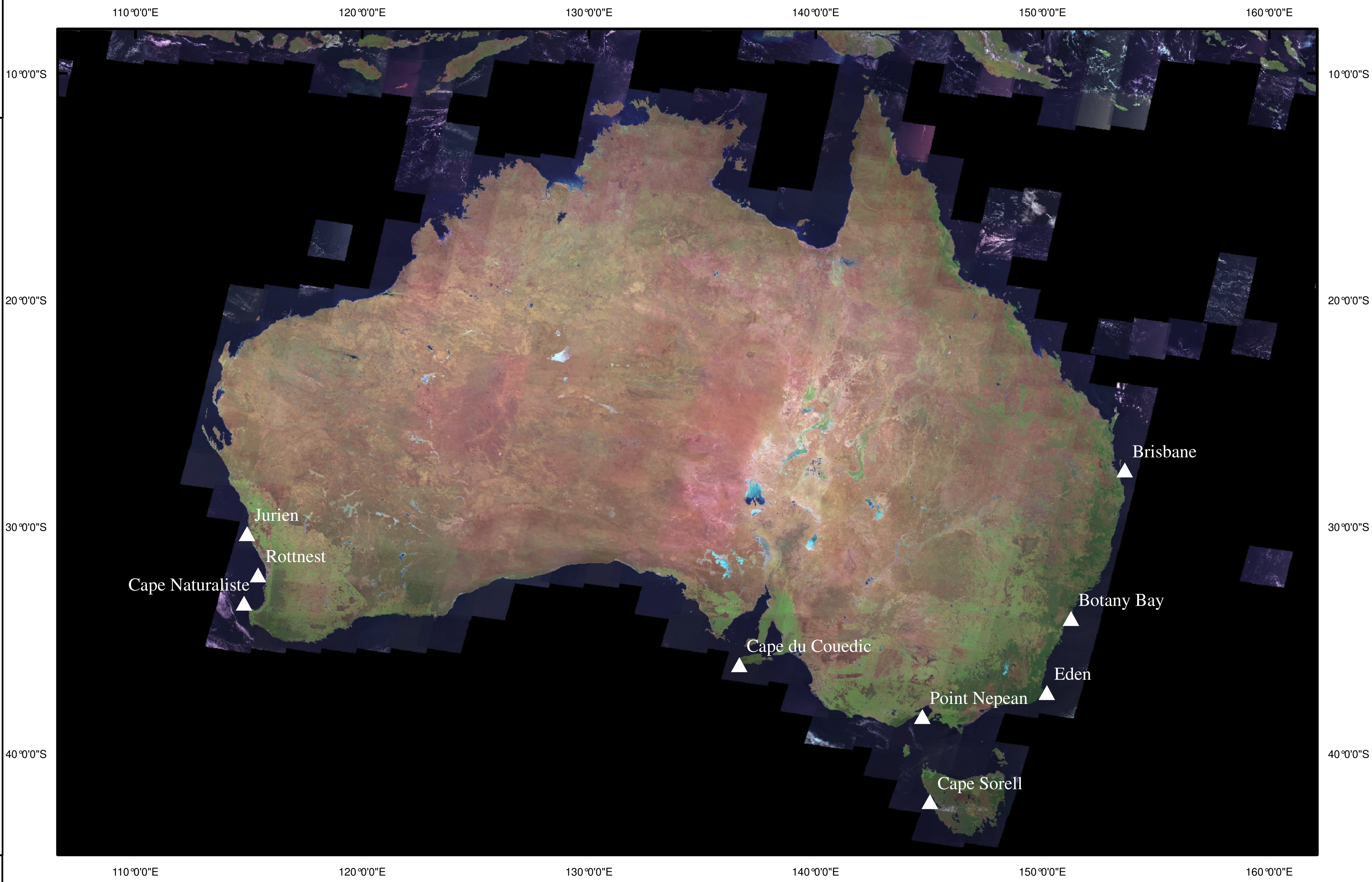
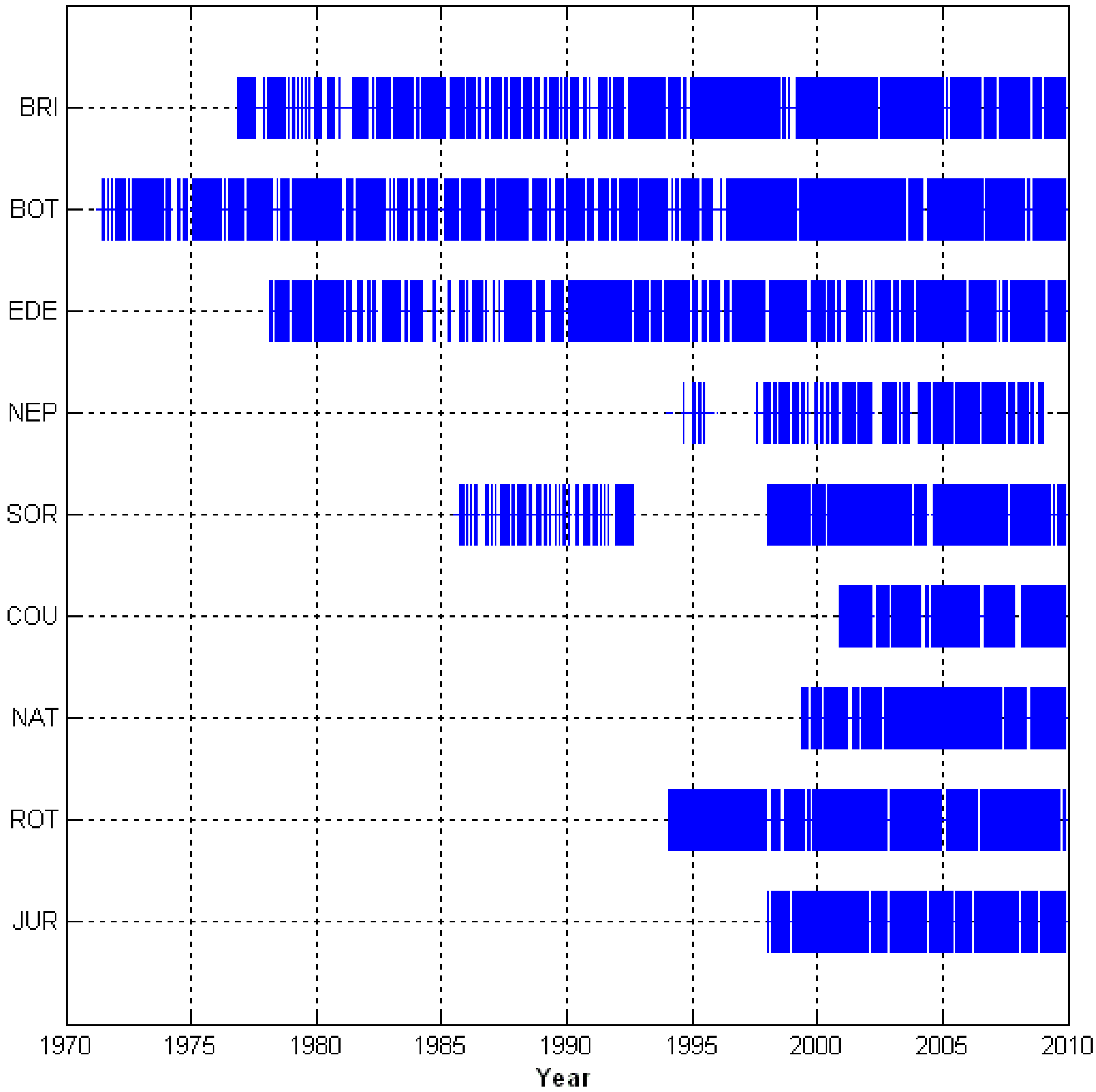
Report No. RR242

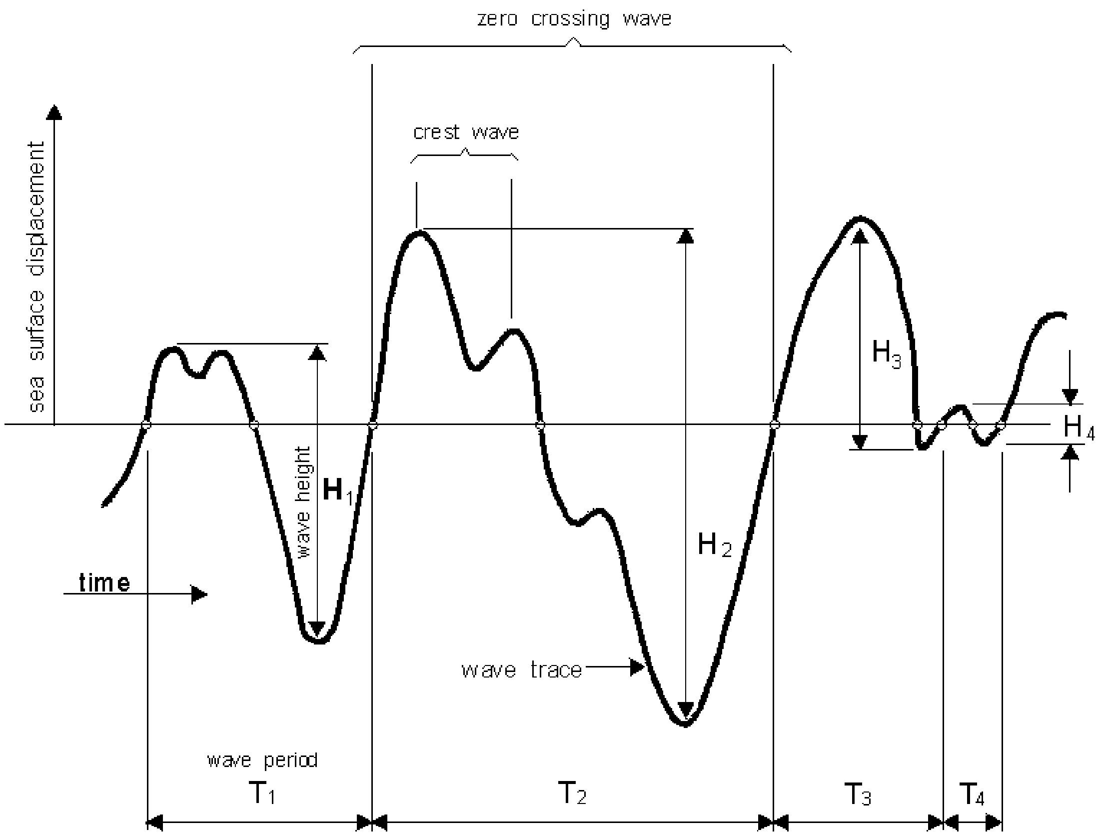


WAVE BUOYS USED WITHIN THE PRESENT STUDY

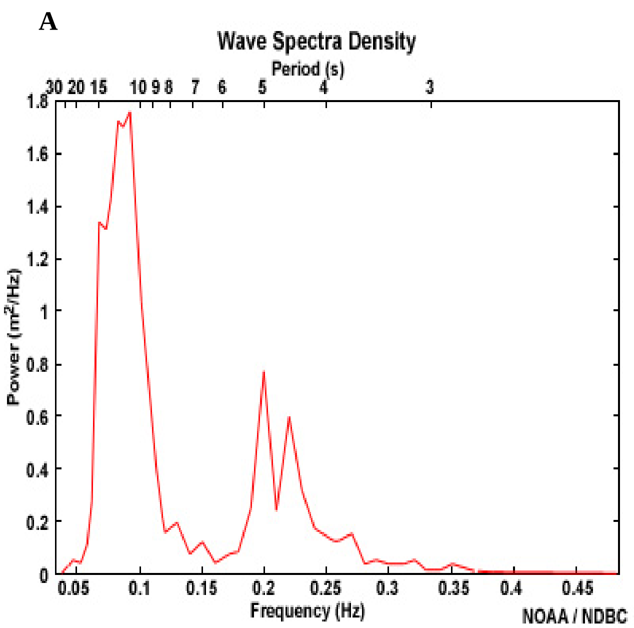
Figure 3.1

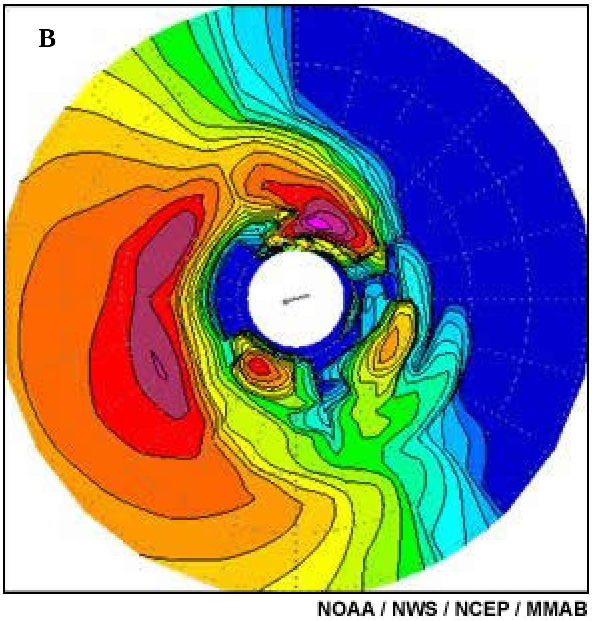


WRL Report No. RR242	WAVE BUOY DATA RECORD	Figure 3.2



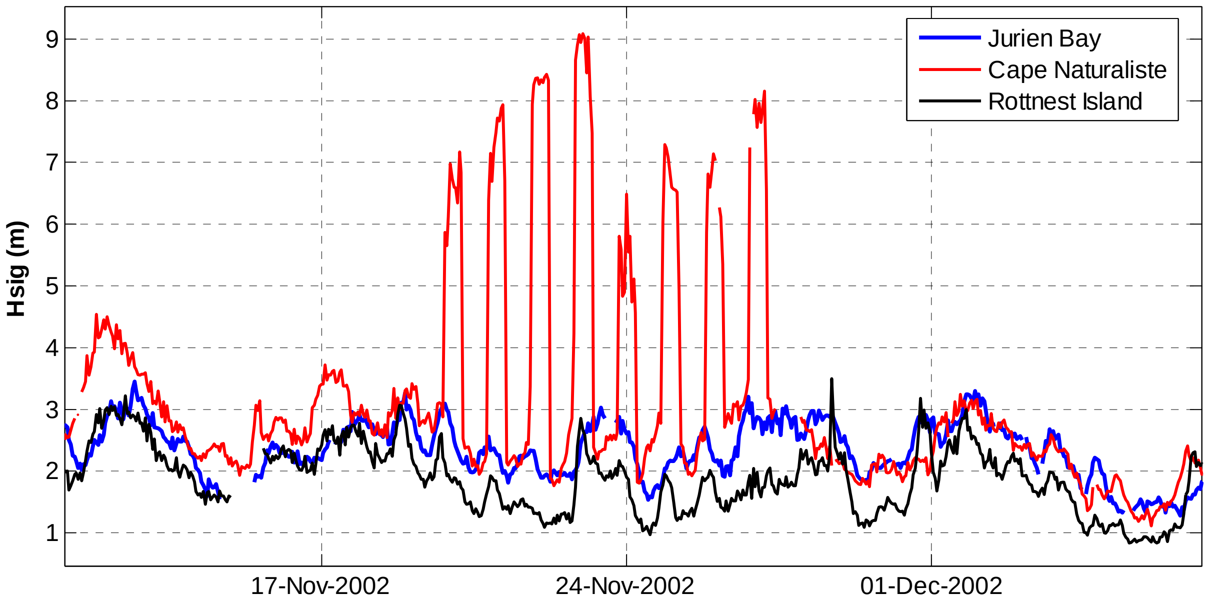
Example of wavy water surface and definitions of wave parameters
(source: Manly Hydraulics Laboratory)



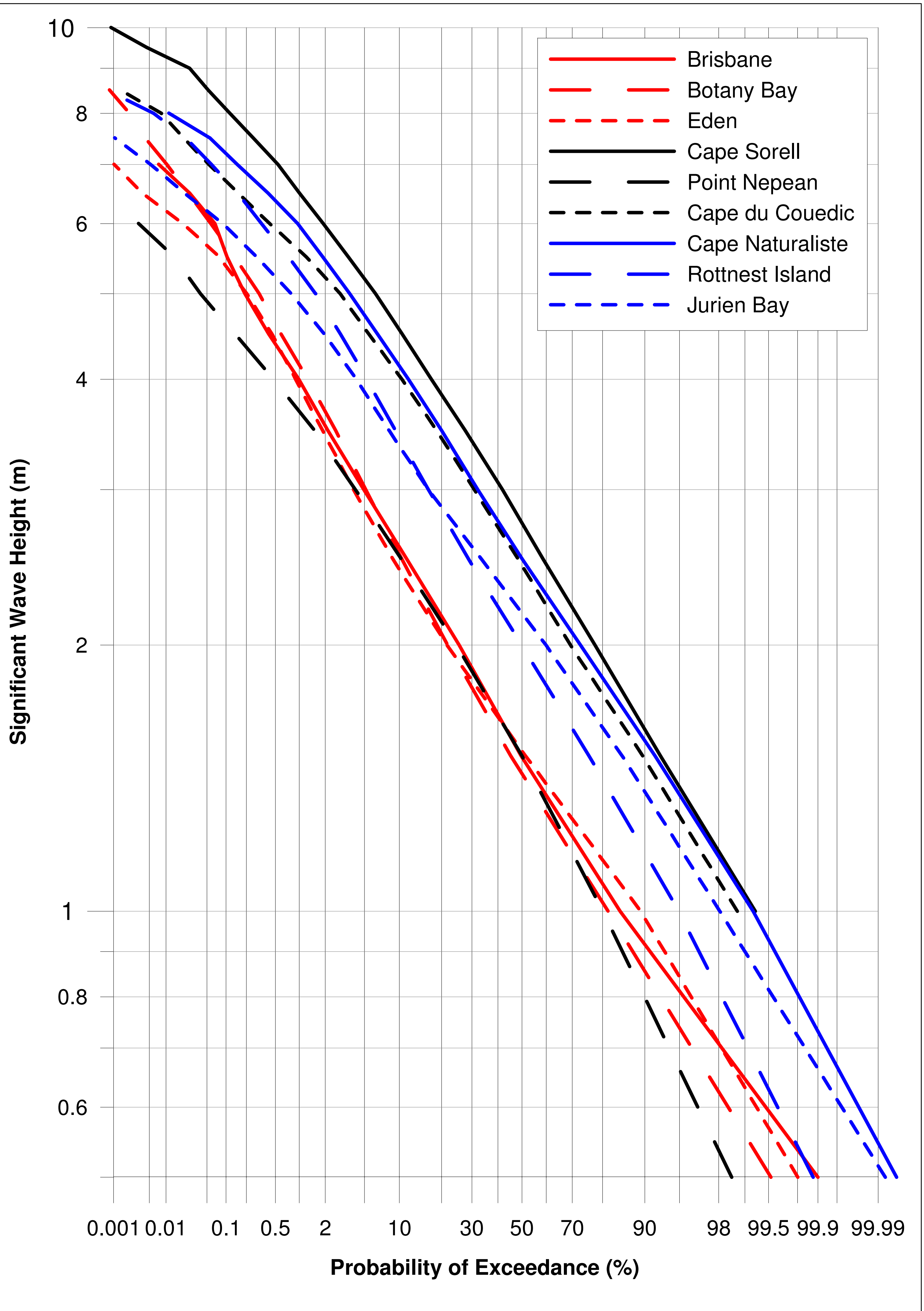


Example of two (A) and three-dimensional (B) wave spectra (source: NOAA)

WRL Report No. RR242	PARAMETERS EXTRACTED BY ZERO-CROSSING AND SPECTRAL ANALYSIS OF A WATER LEVEL TIME SERIES RECORD	Figure 3.3



WRL Report No. RR242	SIGNIFICANT WAVE HEIGHT AT THREE WESTERN AUSTRALIAN BUOYS WITH THE CAPE NATURALISTE DATA IN APPARENT ERROR	Figure 3.4



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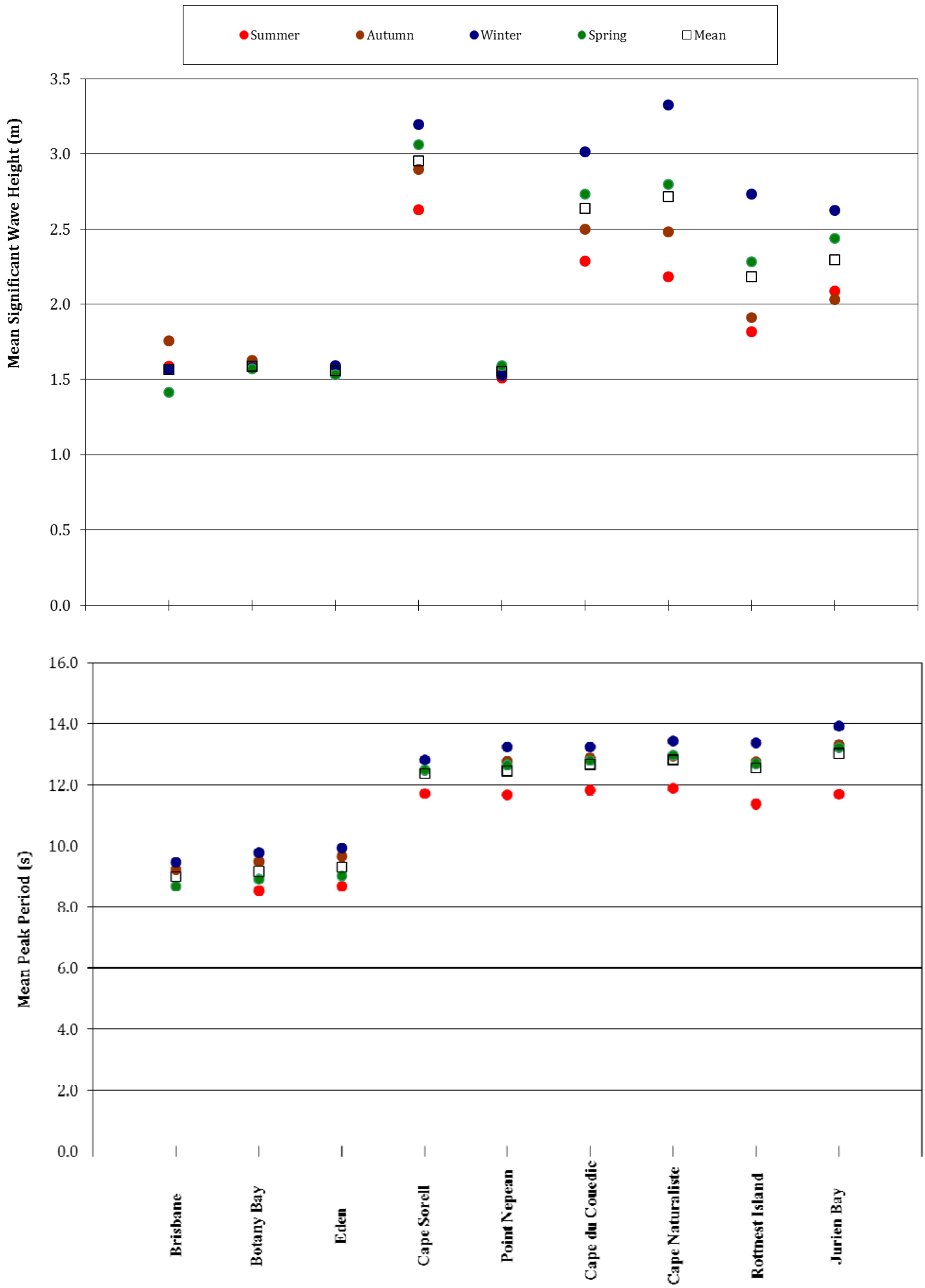
Report No. RR242

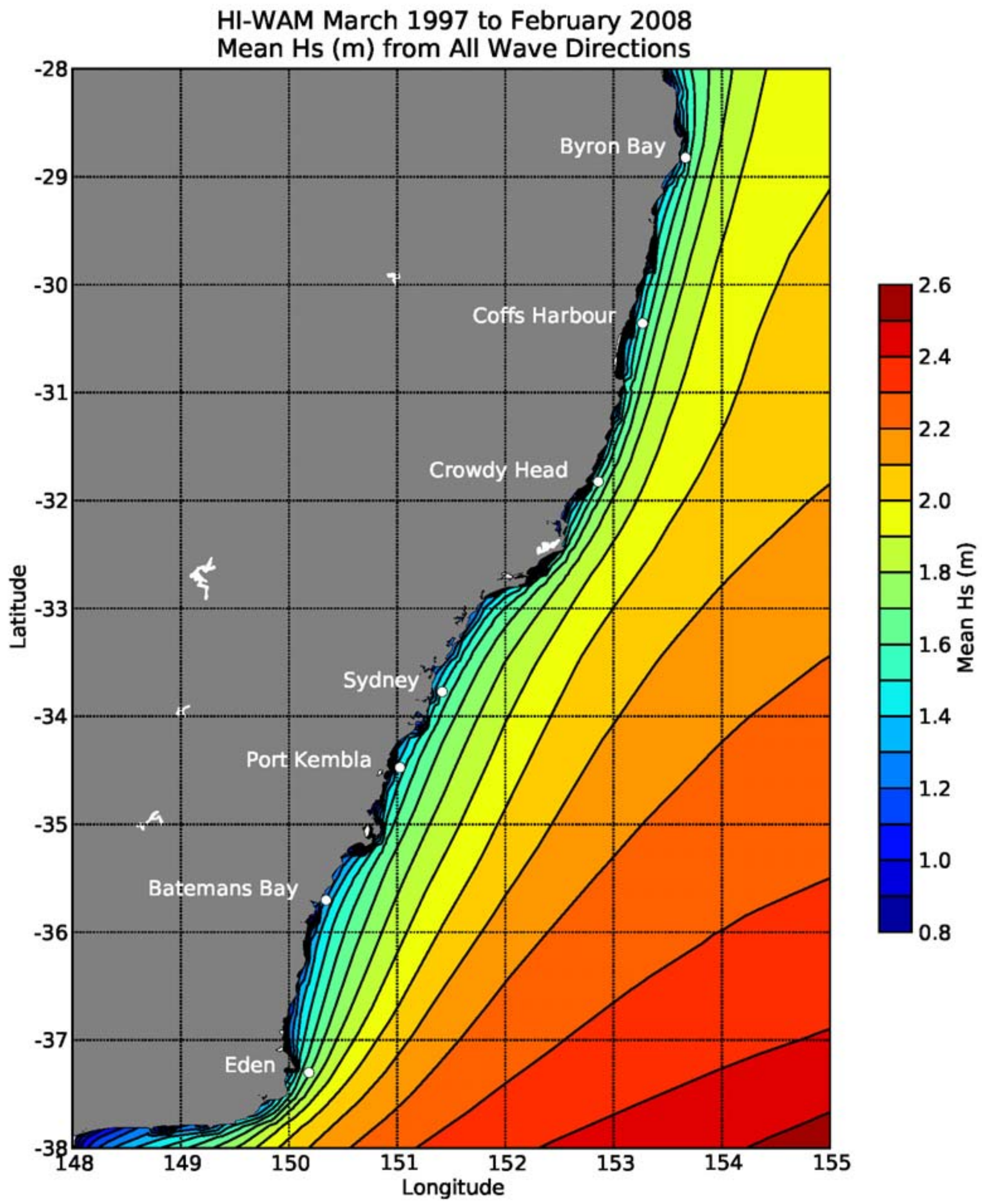
SIGNIFICANT WAVE HEIGHT EXCEEDANCE
FOR AUSTRALIAN WAVE BUOYS

Figure
4.1

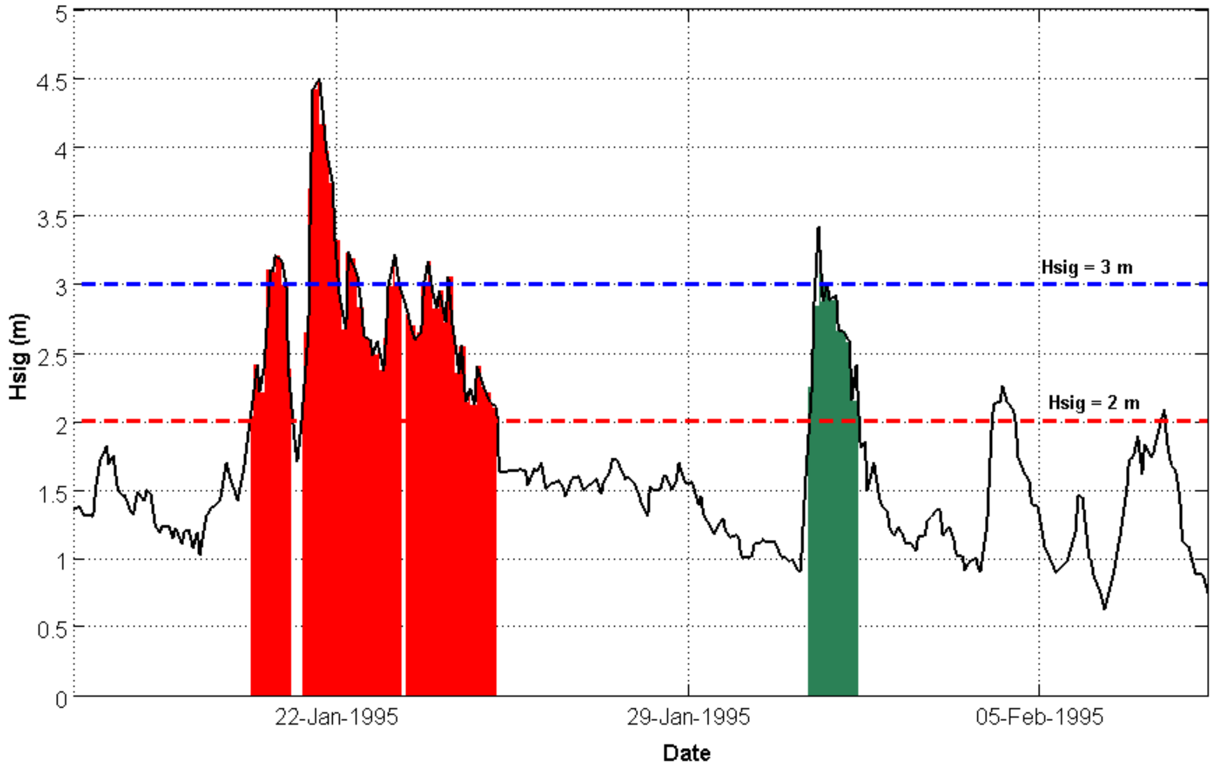
4.1 EXCEEDANCE.grf



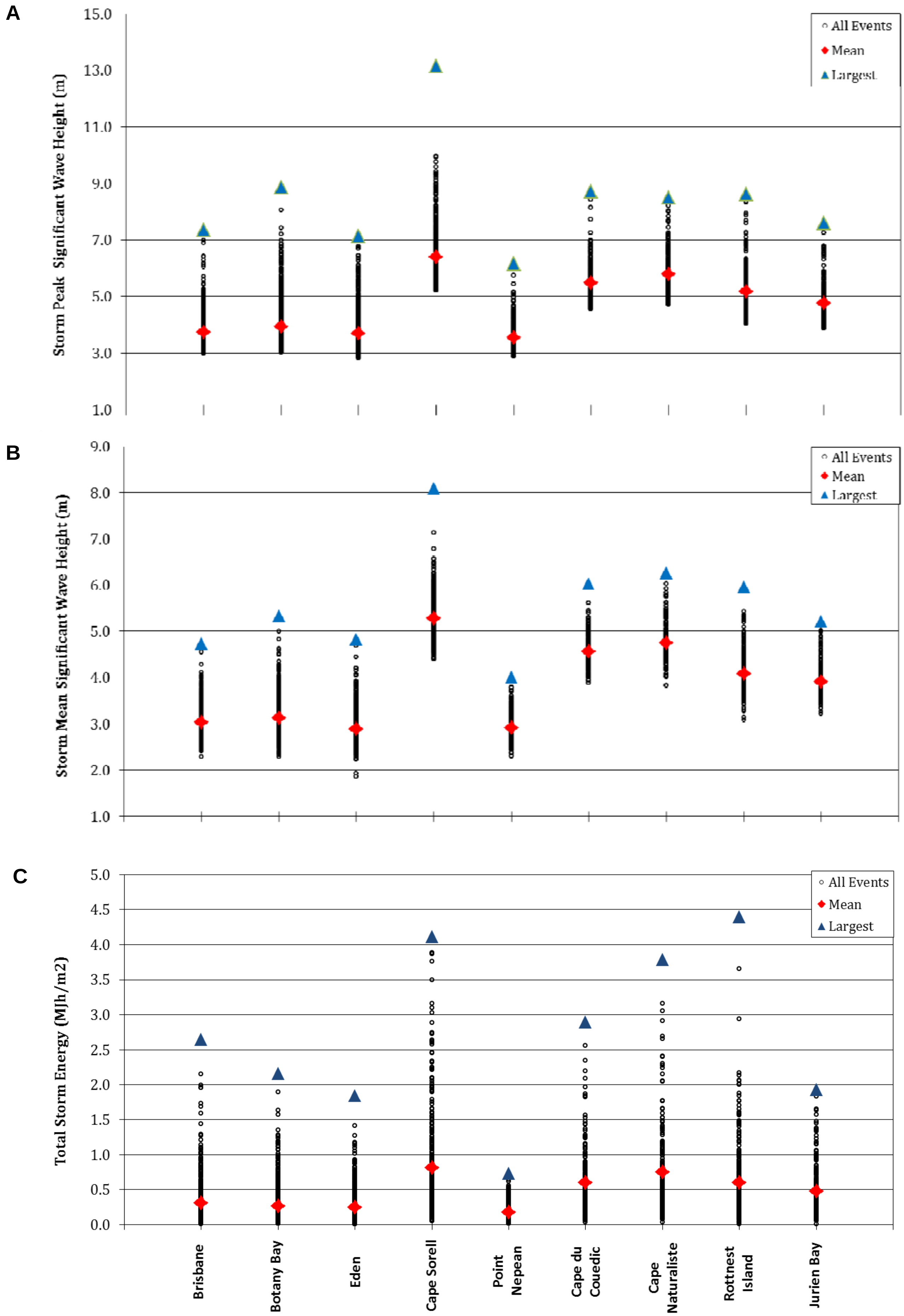
WRL Report No. RR242	SEASONAL AND OVERALL MEAN WAVE STATISTICS	Figure 4.2



WRL Report No. RR242	MEAN SIGNIFICANT WAVE HEIGHT ALONG THE NSW COAST USING HI-WAM NUMERICAL WAVE DATA (COGHLAN ET AL., 2010)	Figure 4.3

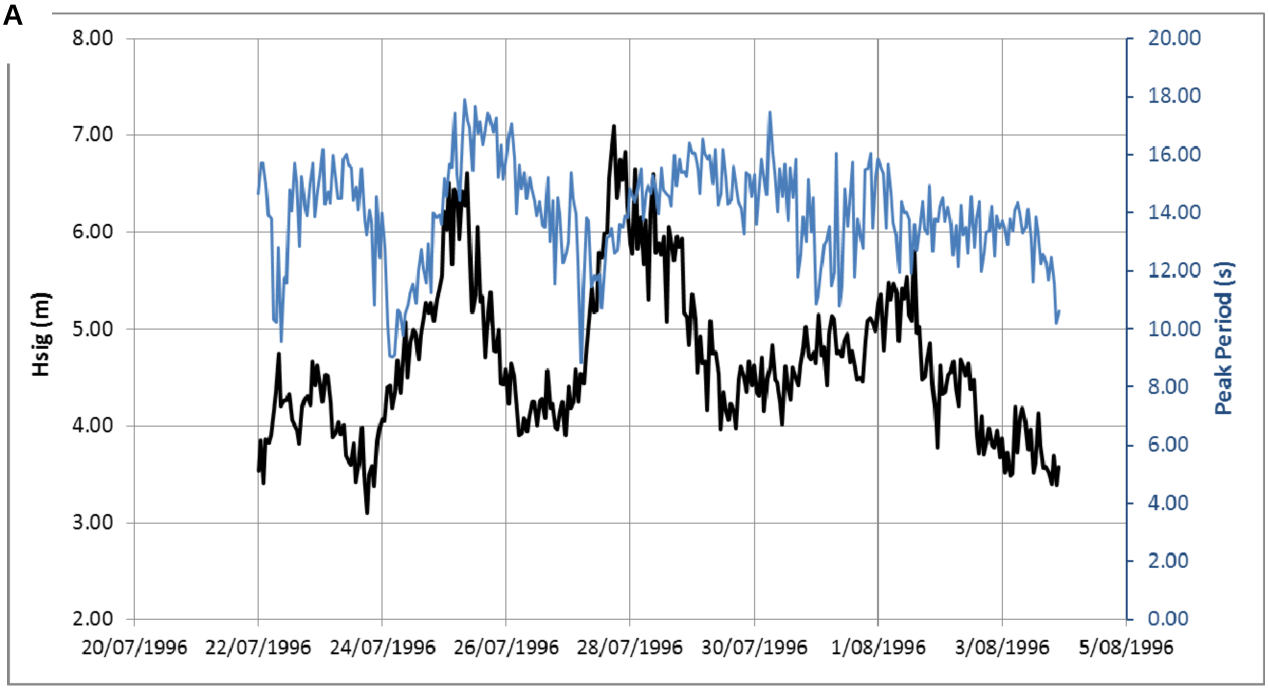


Note that the minimum storm separation of one day ensures that the January 1995 event is not split when the significant wave height drops below the 2 m threshold temporarily.

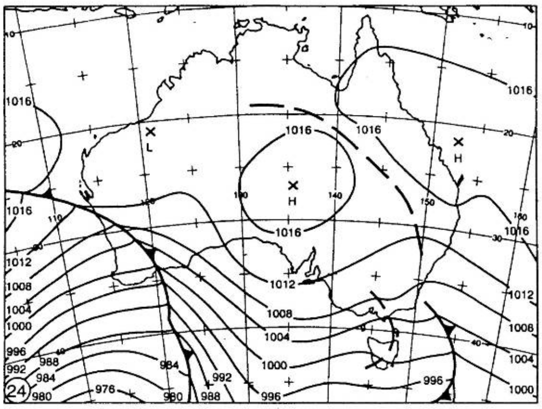


WRL Report No. RR242	STORM PEAK (A) AND MEAN (B) SIGNIFICANT WAVE HEIGHT AND TOTAL STORM ENERGY (C)	Figure 4.5

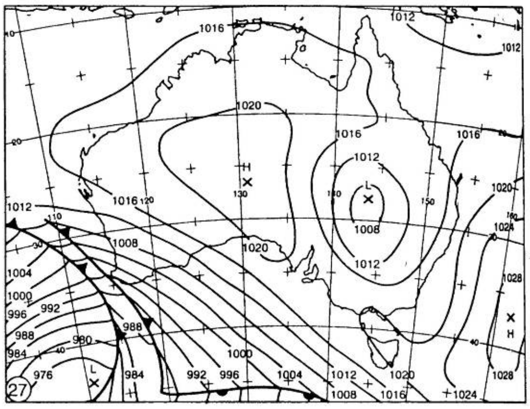
A



B



24/07/1996



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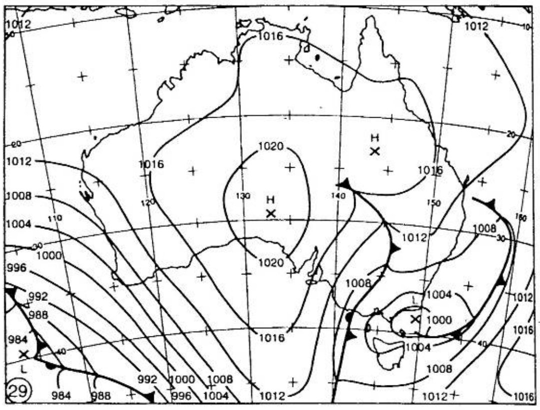
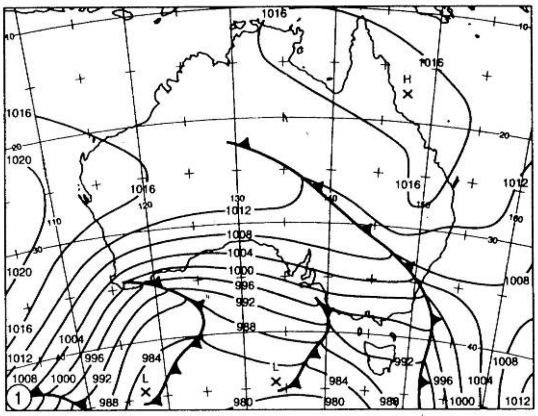


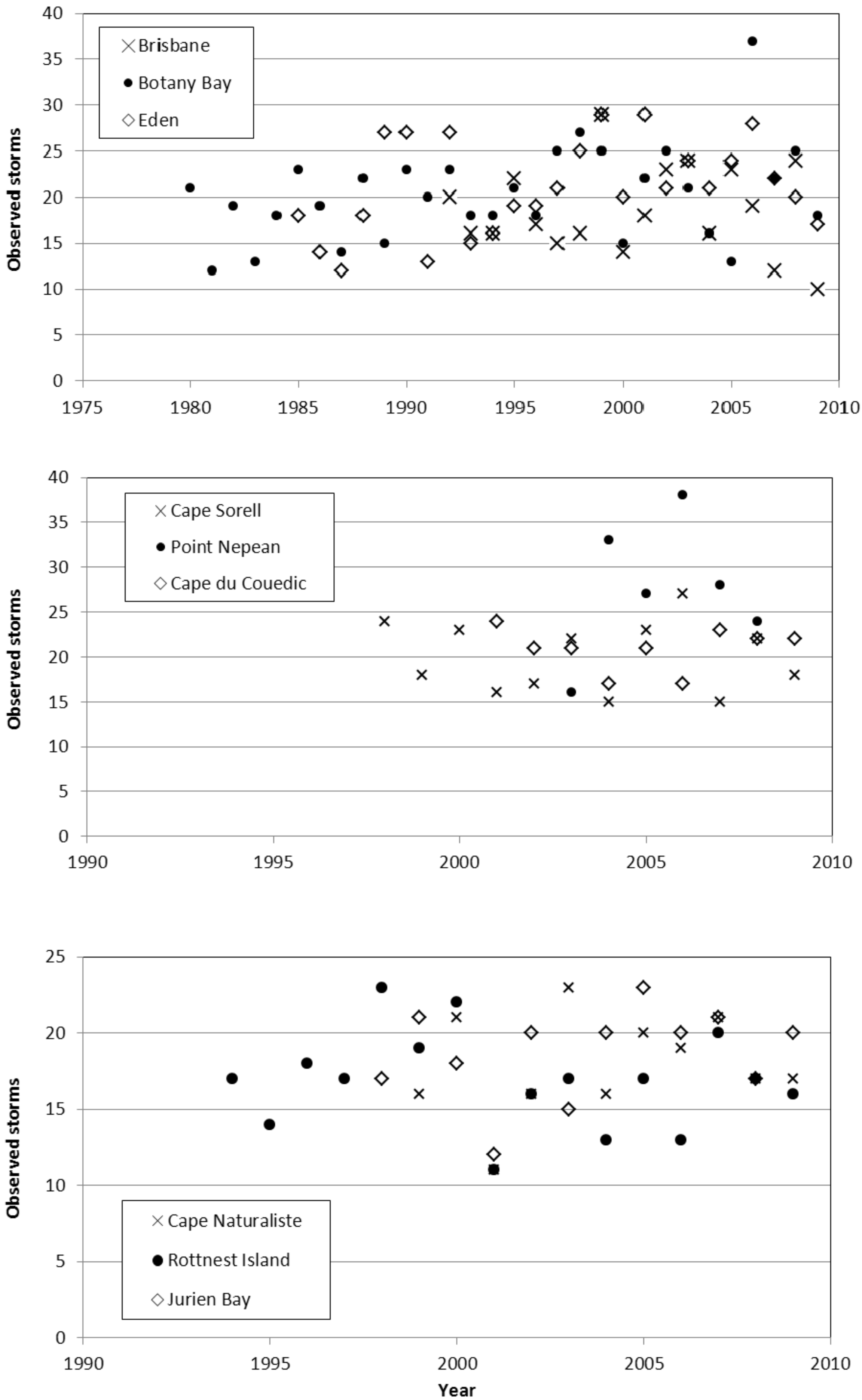
29/07/1996



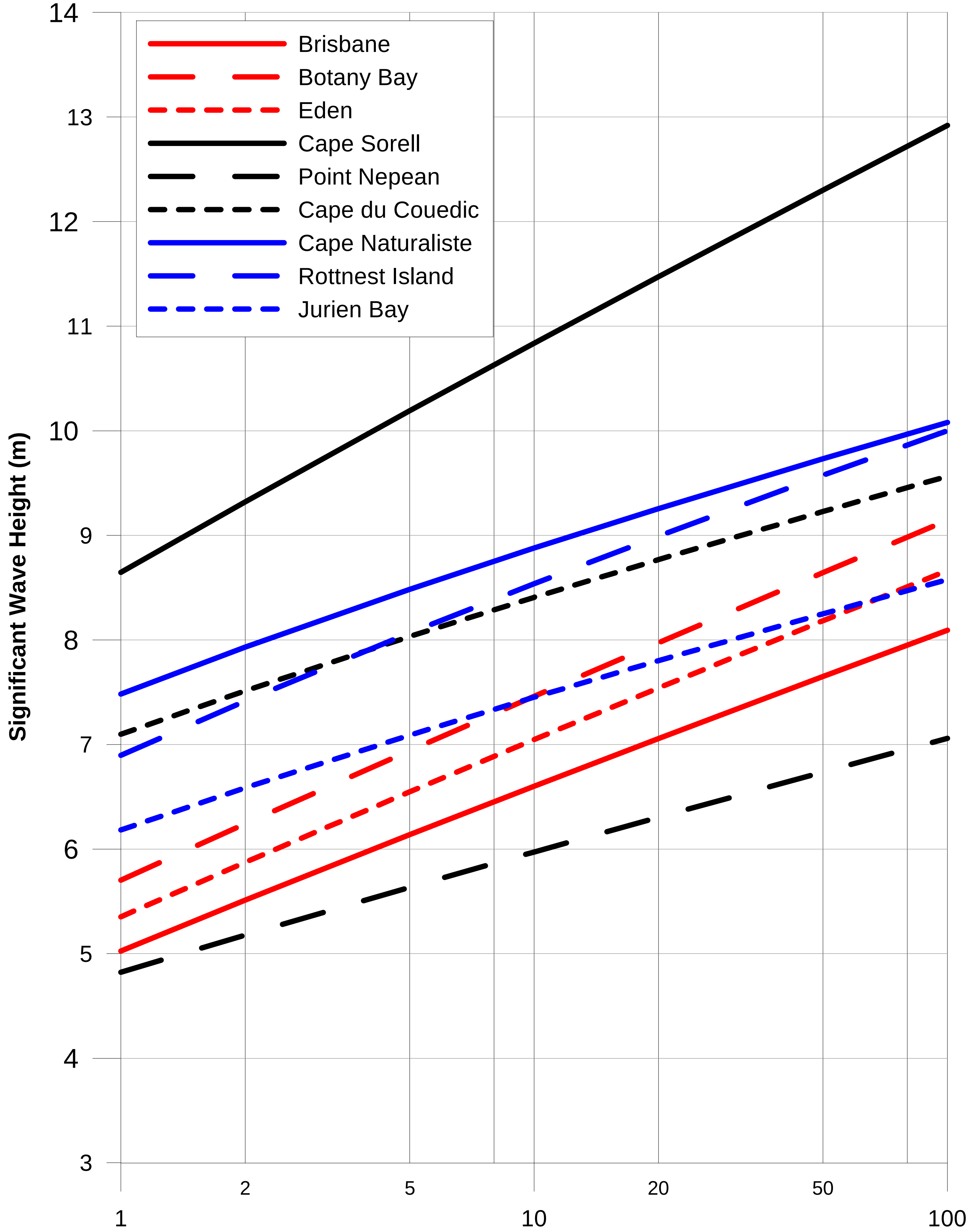
01/08/1996

Source: Bureau of Meteorology (1996)

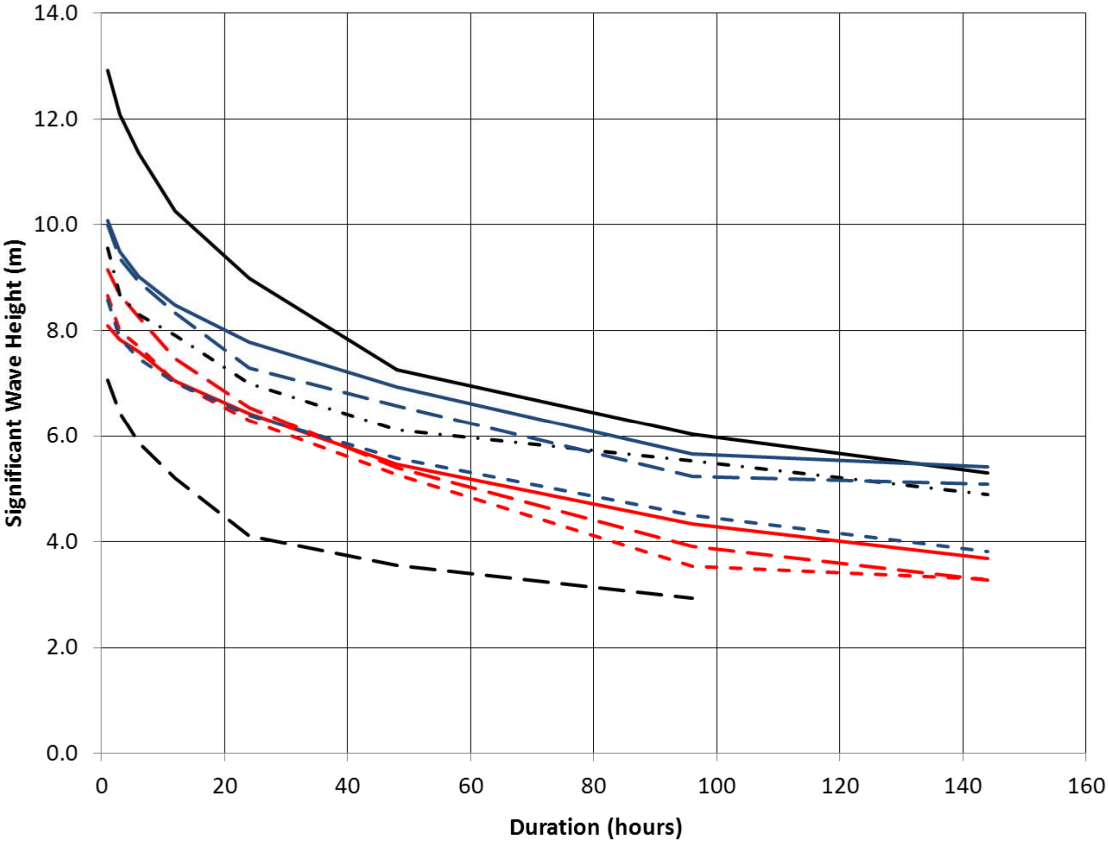
WRL Report No. RR242	TIME SERIES OF H_s and T_p (A) AND CORRESPONDING SEA LEVEL PRESSURE (B) FOR THE LARGEST TOTAL ENERGY STORM EVENT OBSERVED AT THE ROTTNEST ISLAND WAVE BUOY	Figure 4.6

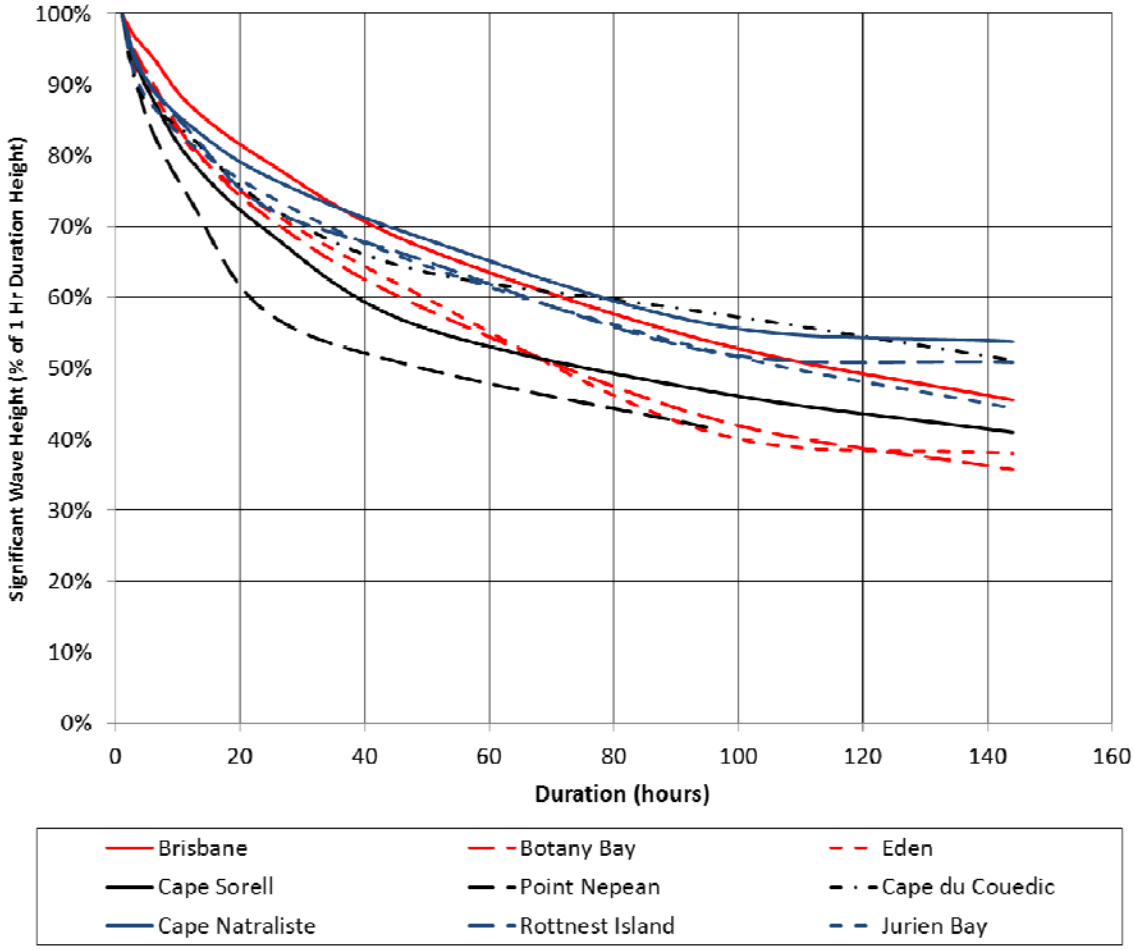


WRL Report No. RR242	NUMBER OF OBSERVED STORMS PER YEAR FOR EACH WAVE BUOY	Figure 4.7

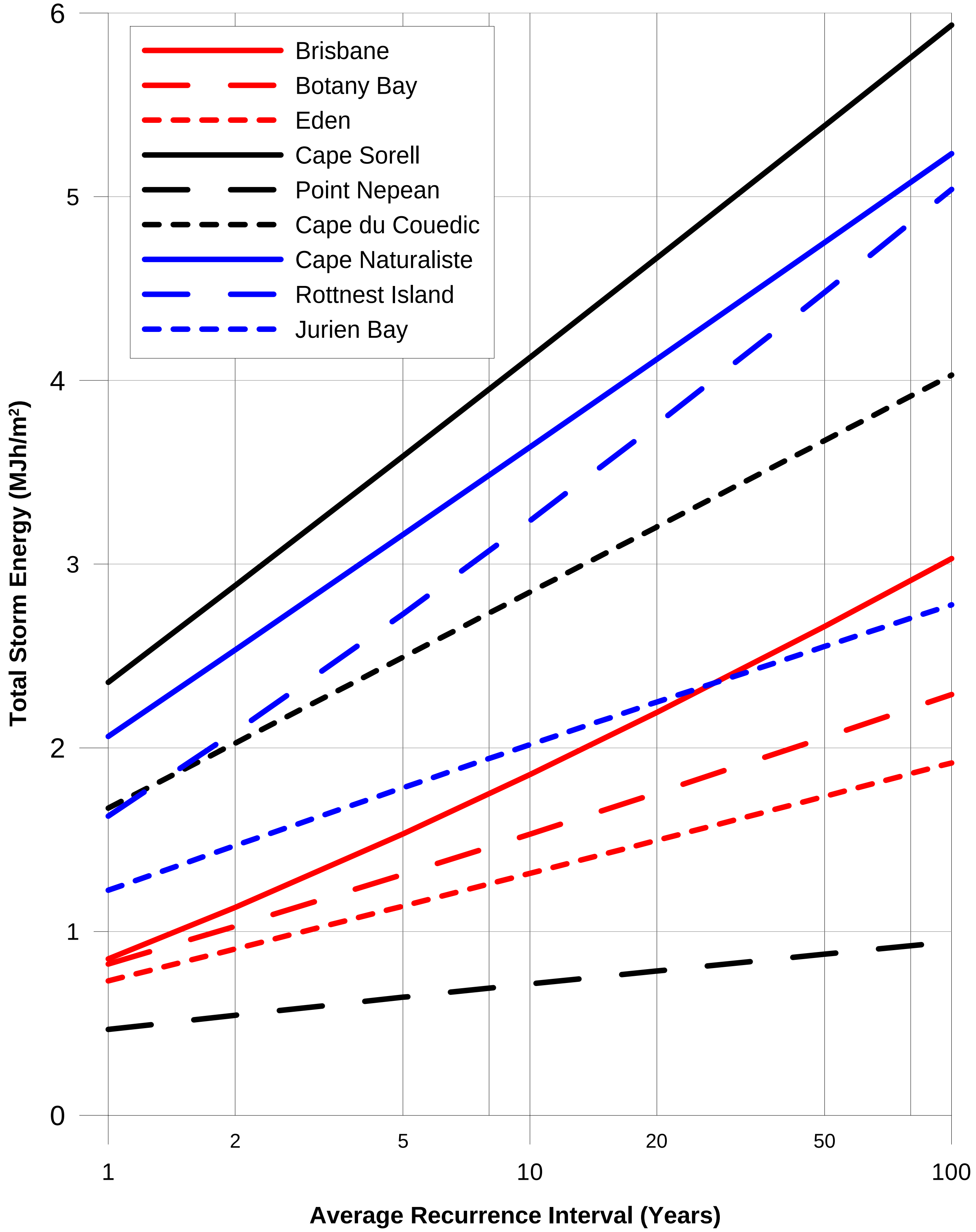


WRL Report No. RR242	ESTIMATED ONE HOUR EXCEEDANCE, 100YR ARI H_S FOR SELECT AUSTRALIAN WAVE BUOYS	Figure 5.1 4.1 EXCEEDANCE.grf





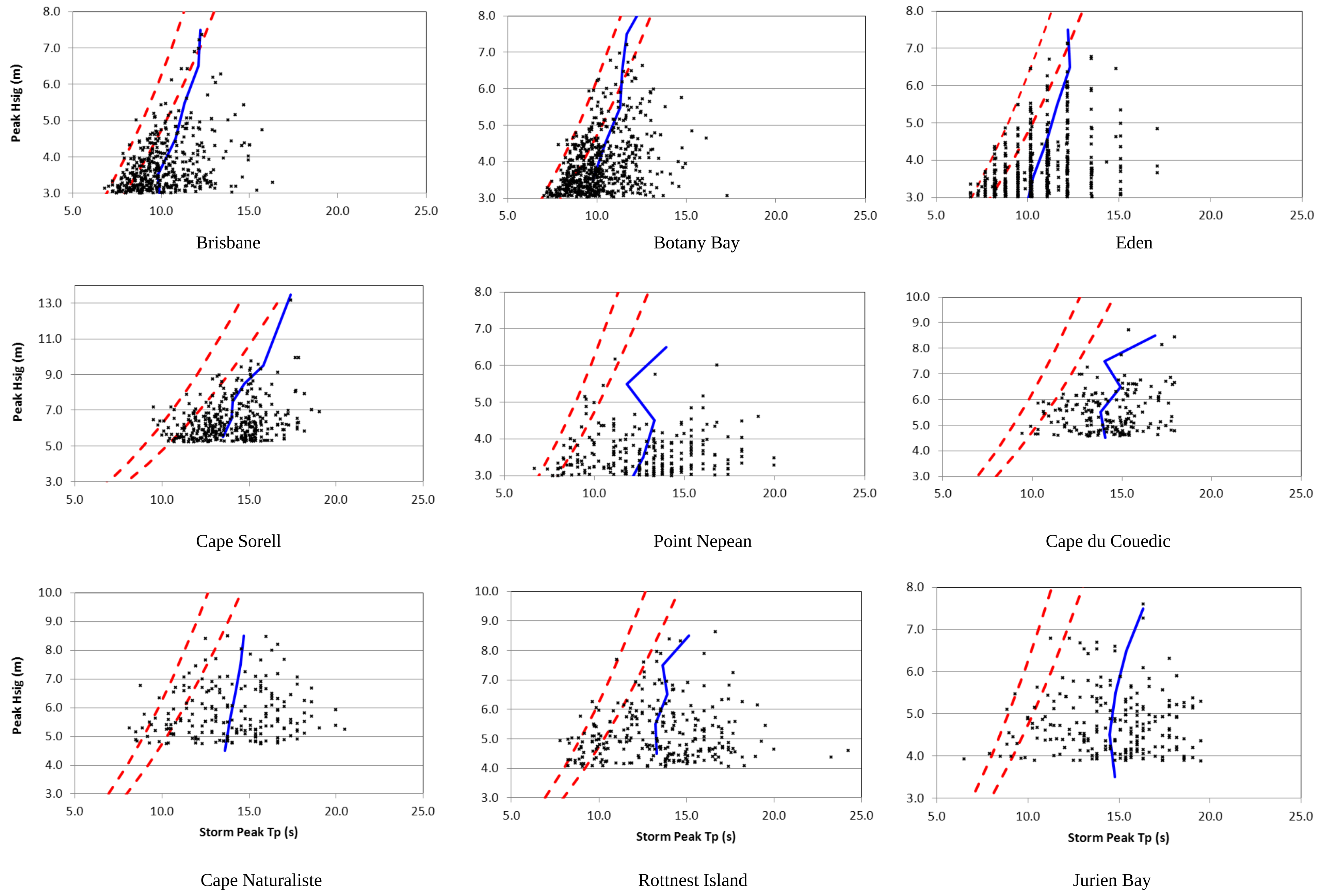
WRL Report No. RR242	DURATION EFFECTS ON ESTIMATED 100 yr ARI EXTREME VALUES	Figure 5.2



WRL Report No. RR242	ESTIMATED ONE HOUR EXCEEDANCE, 100YR ARI CUMULATIVE STORM ENERGY FOR SELECT AUSTRALIAN WAVE BUOYS	Figure 5.3

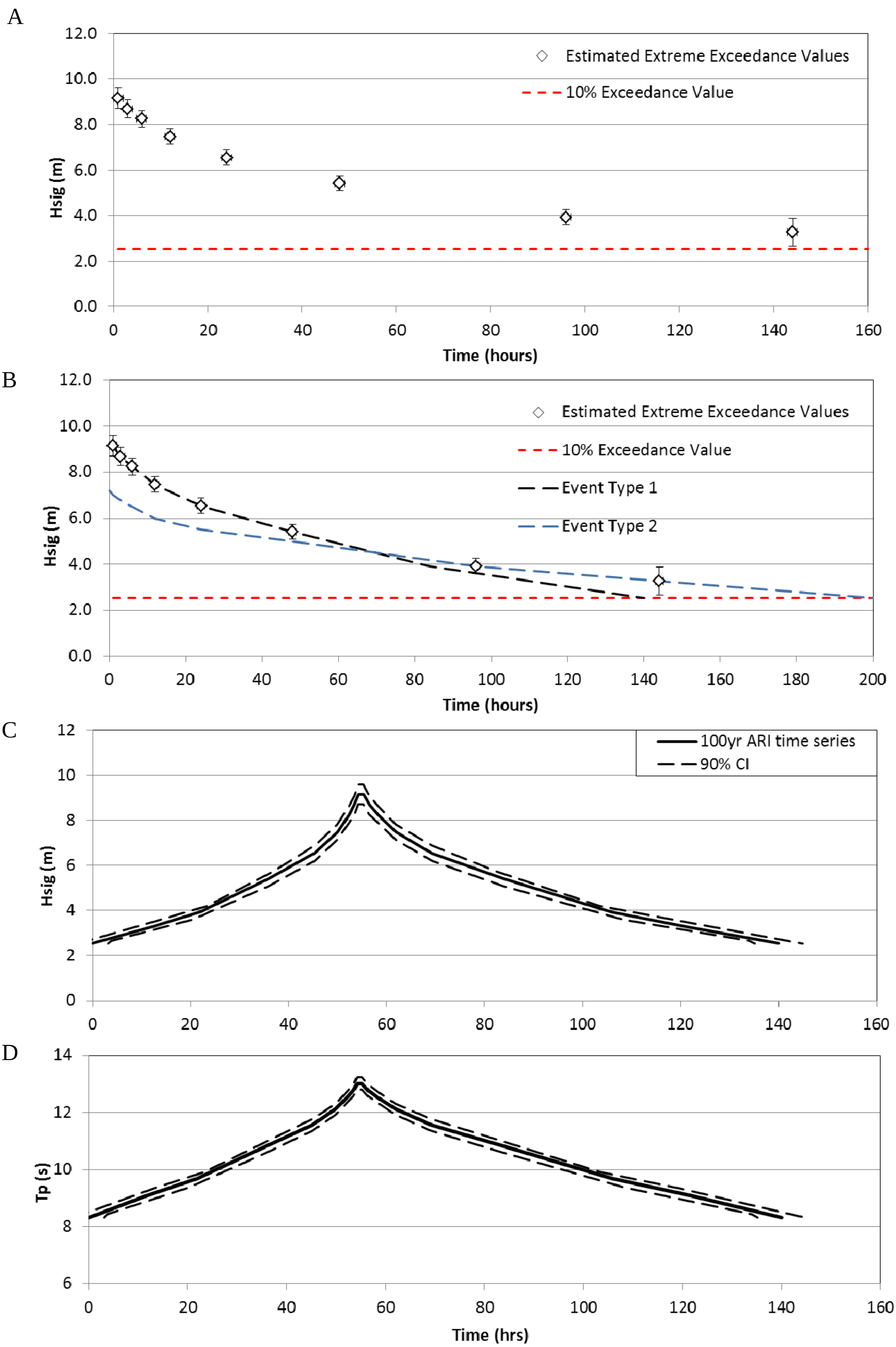
4.1 EXCEEDANCE.grf

WRL
Report No. 242



PEAK STORM T_p (s) COMPARED TO PEAK H_s (m) WITH SAMPLE AVERAGED TP (- - -) AND GODA RECOMMENDED LIMITS (- - -)

Figure **5.4**



WRL Report No. RR242	DERIVING A 100 yr ARI SYNTHETIC DESIGN STORM FOR THE BOTANY BAY WAVE BUOY (TOTAL STORM ENERGY = 2.3 ± 0.25 MJh/m^2)	Figure 5.5

APPENDIX A WAVE BUOY LOCATIONS

A-1 Brisbane

A-2 Botany Bay

A-3 Eden

A-4 Cape Sorell

A-5 Point Nepean

A-6 Cape du Couedic

A-7 Cape Naturaliste

A-8 Rottnest Island

A-9 Jurien Bay

WR

Report No. 242

BRISBANE WAVE BUOY LOCATION

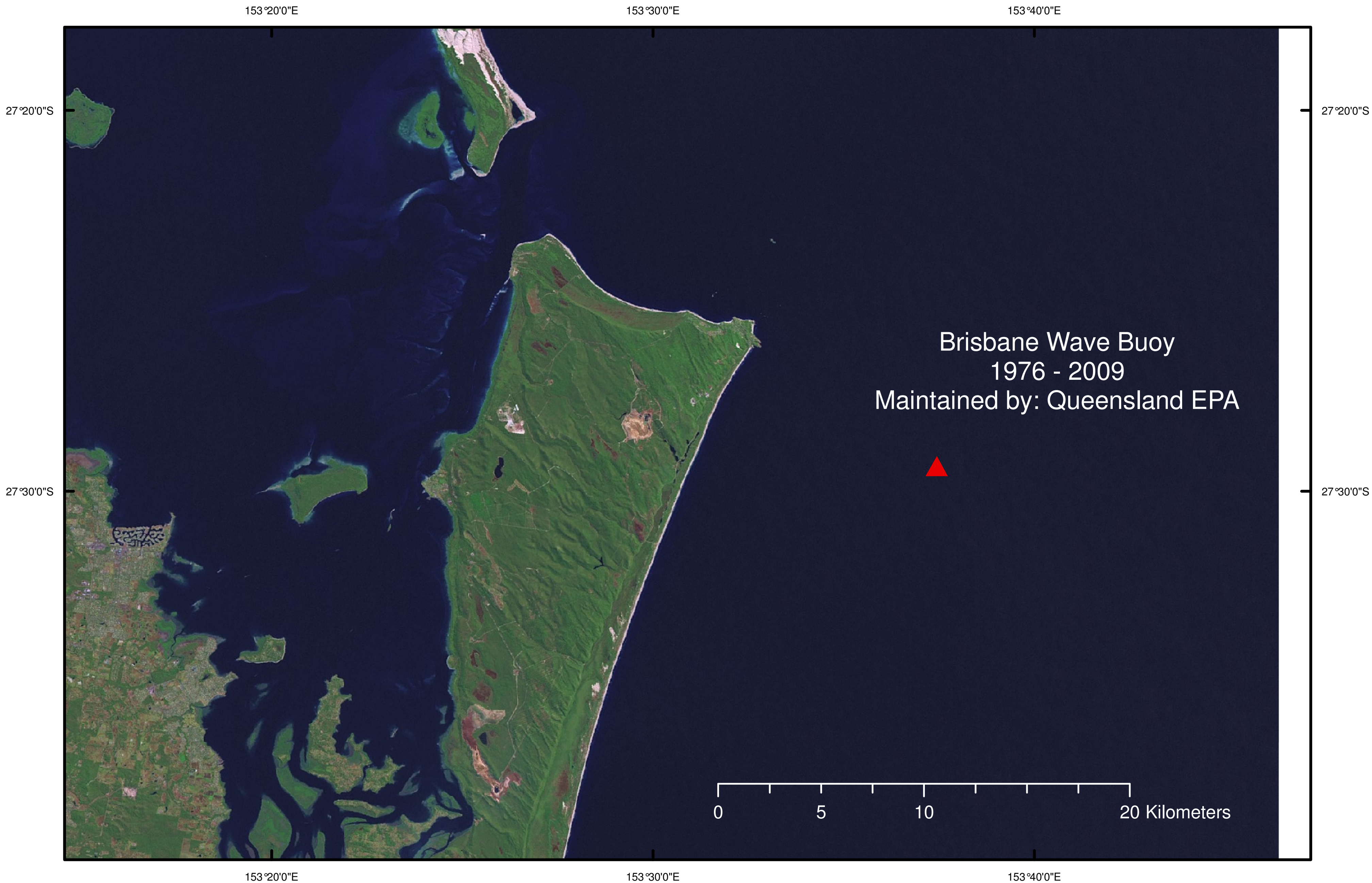


Figure A-1

WRL
Report No. 242

BOTANY BAY WAVE BUOY LOCATION

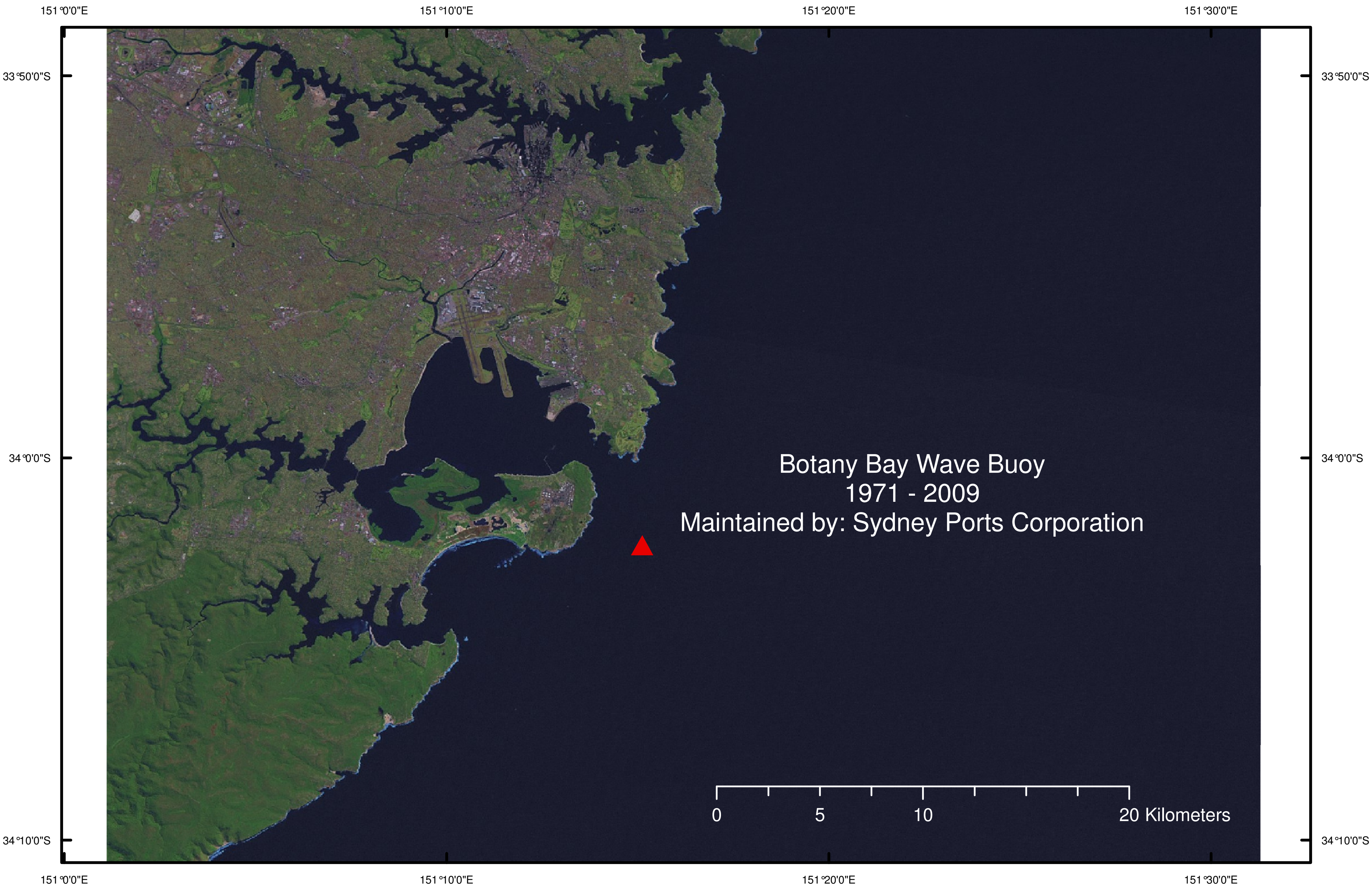


Figure A-2

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Report No. 242

EDEN WAVE BUOY LOCATION

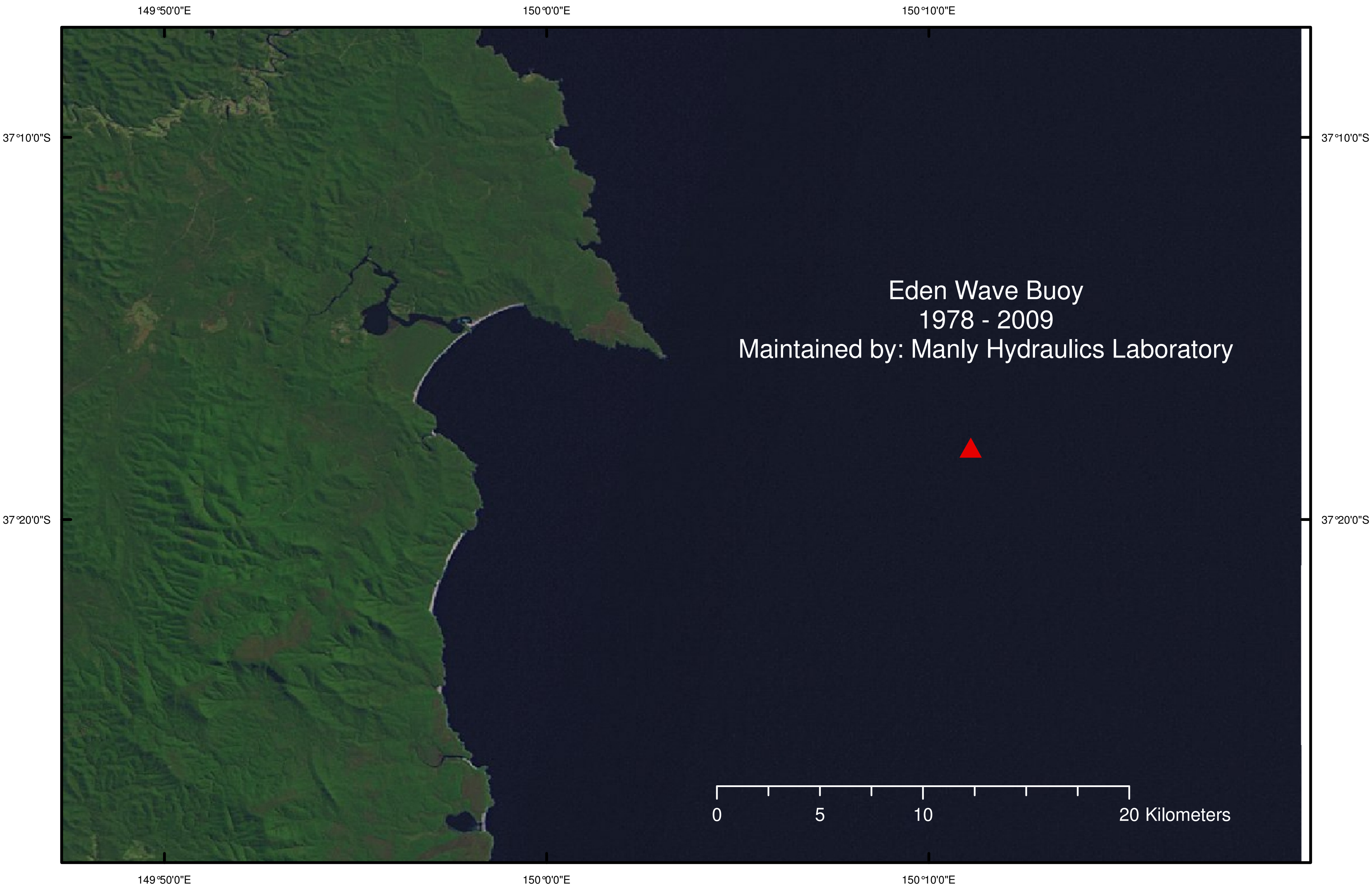

Figure A-3

WRL

Report No. 242

CAPE SORELL WAVE BUOY LOCATION

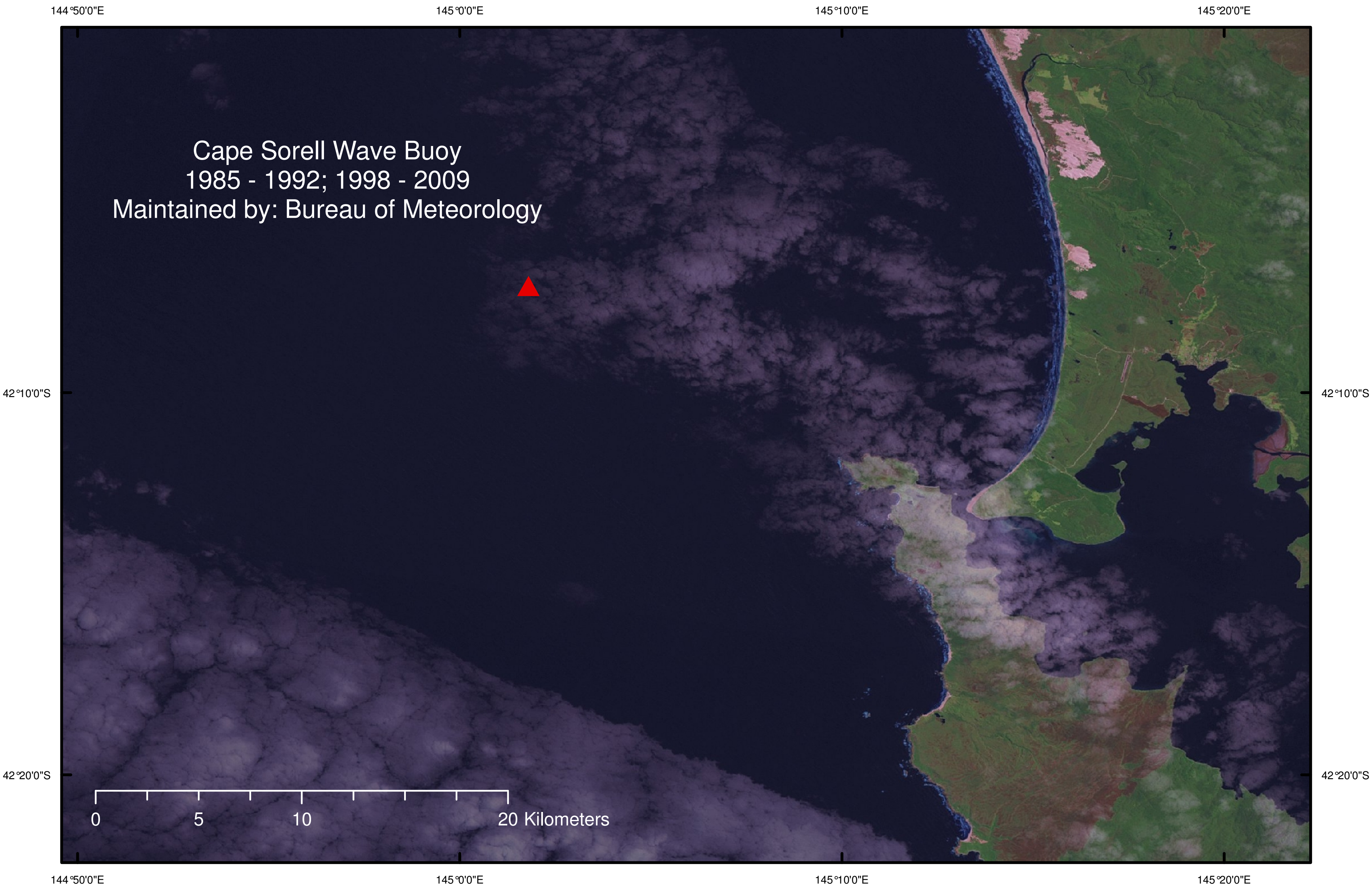

Figure A-4

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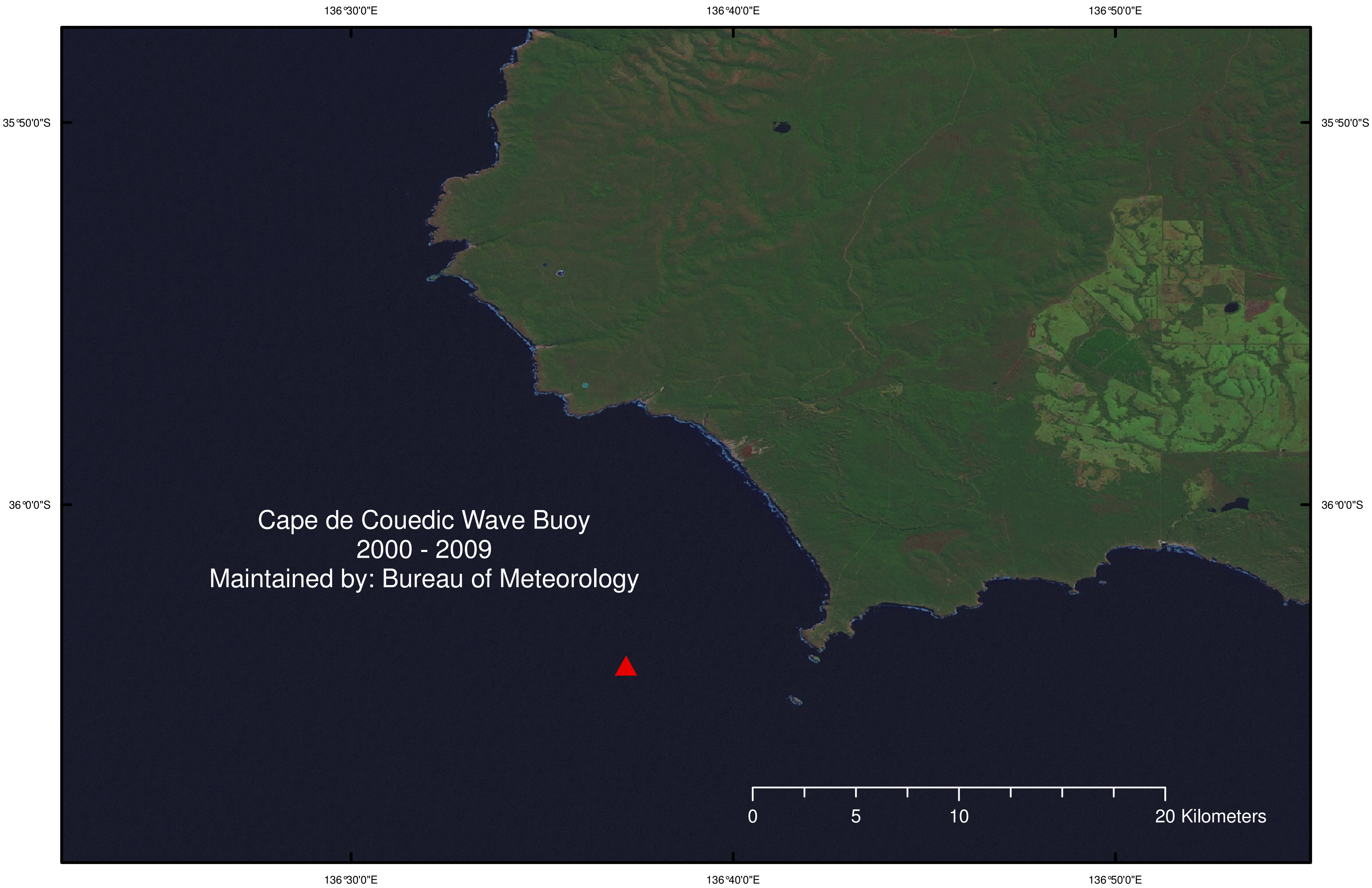
Report No. 242

POINT LONSDALE/POINT NEPEAN WAVE BUOY LOCATION

Figure A-5



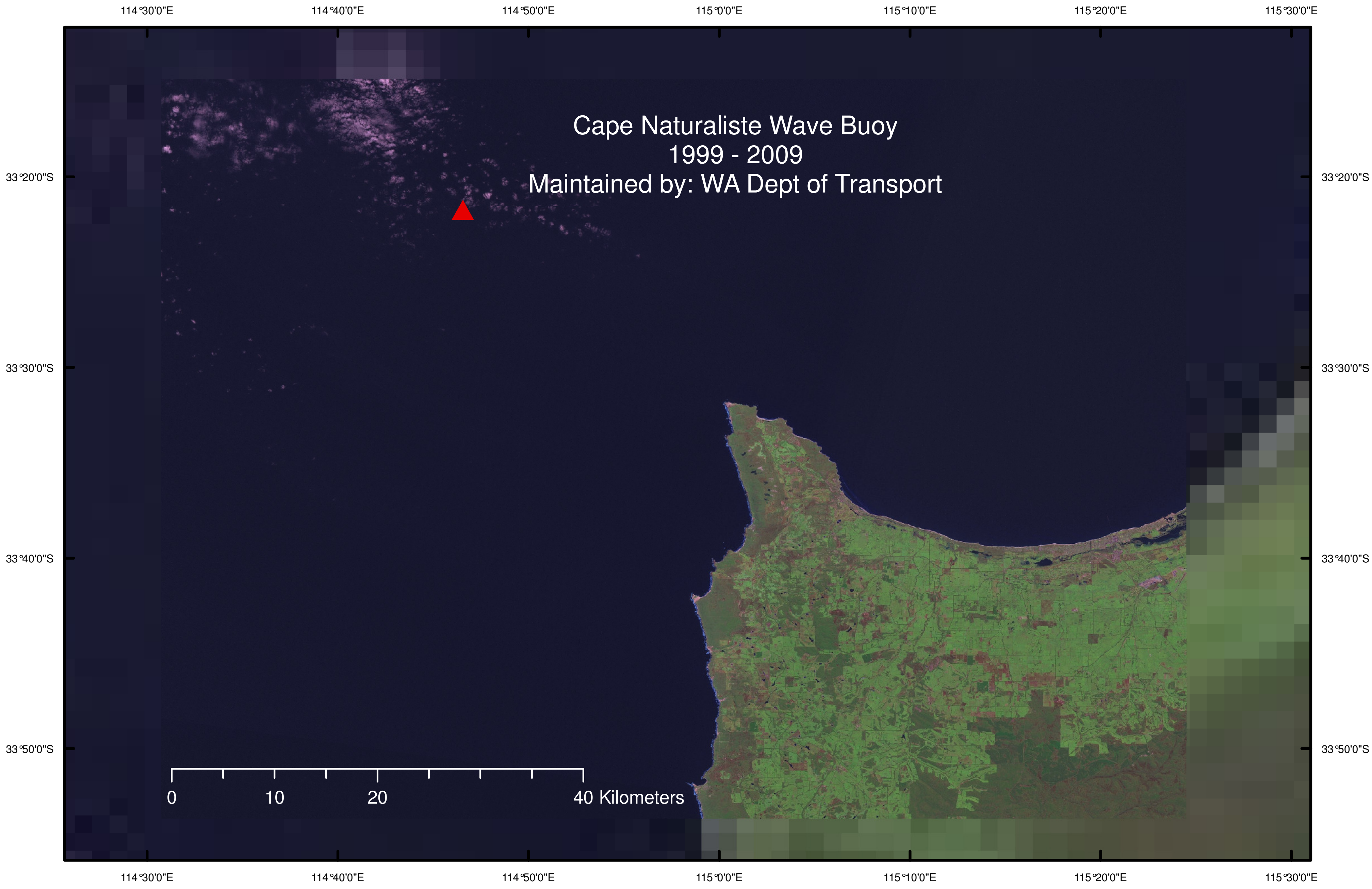
WRL Report No. 242

CAPE DE COUEDIC WAVE BUOY LOCATION

Figure A-6

WRL

Report No. 242



CAPE NATURALISTE WAVE BUOY LOCATION

Figure A-7

WRL

Report No. 242

ROTTNEST ISLAND WAVE BUOY LOCATION

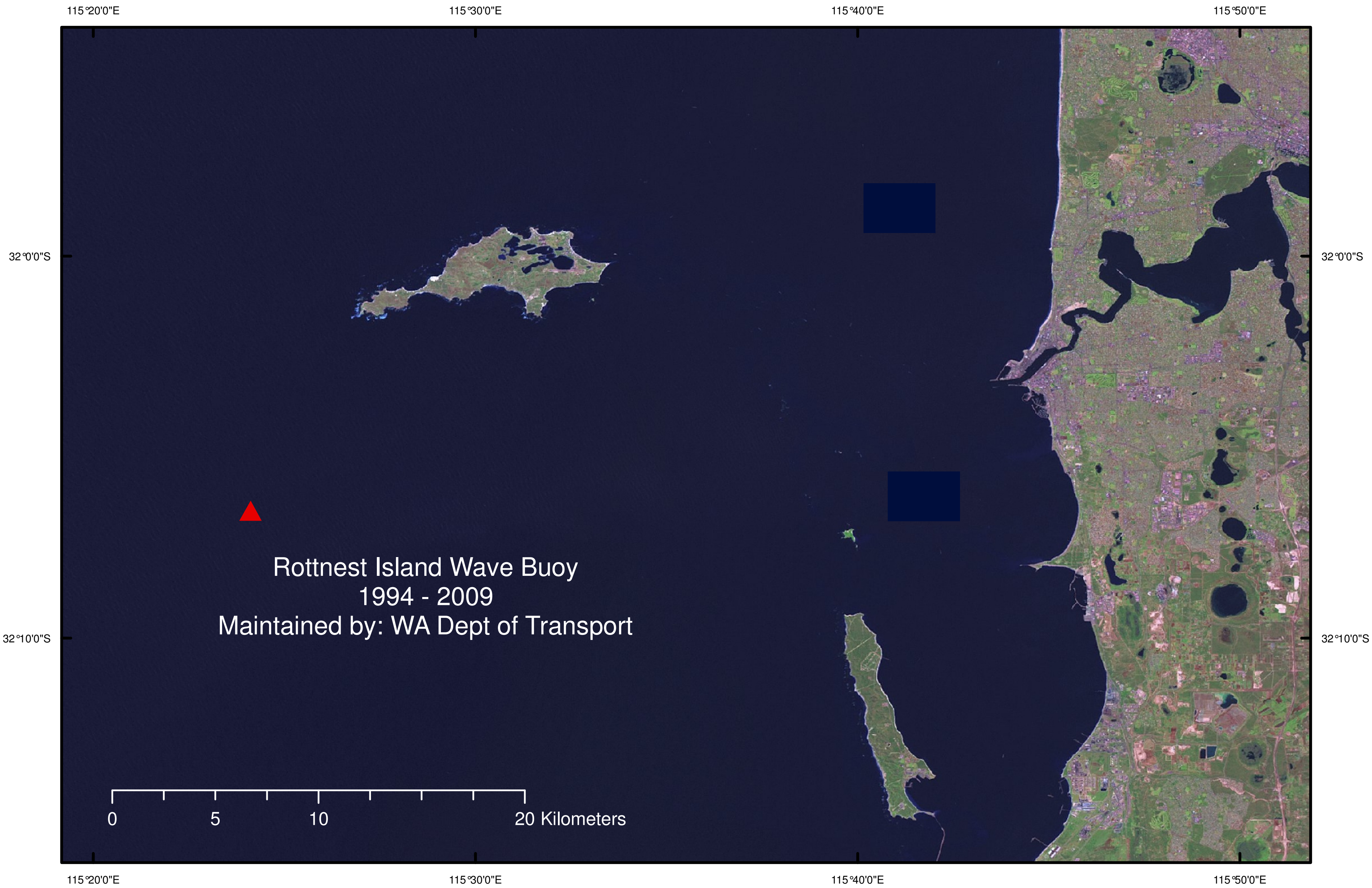


Figure A-8

WRL

Report No. 242

JURIEN BAY WAVE BUOY LOCATION

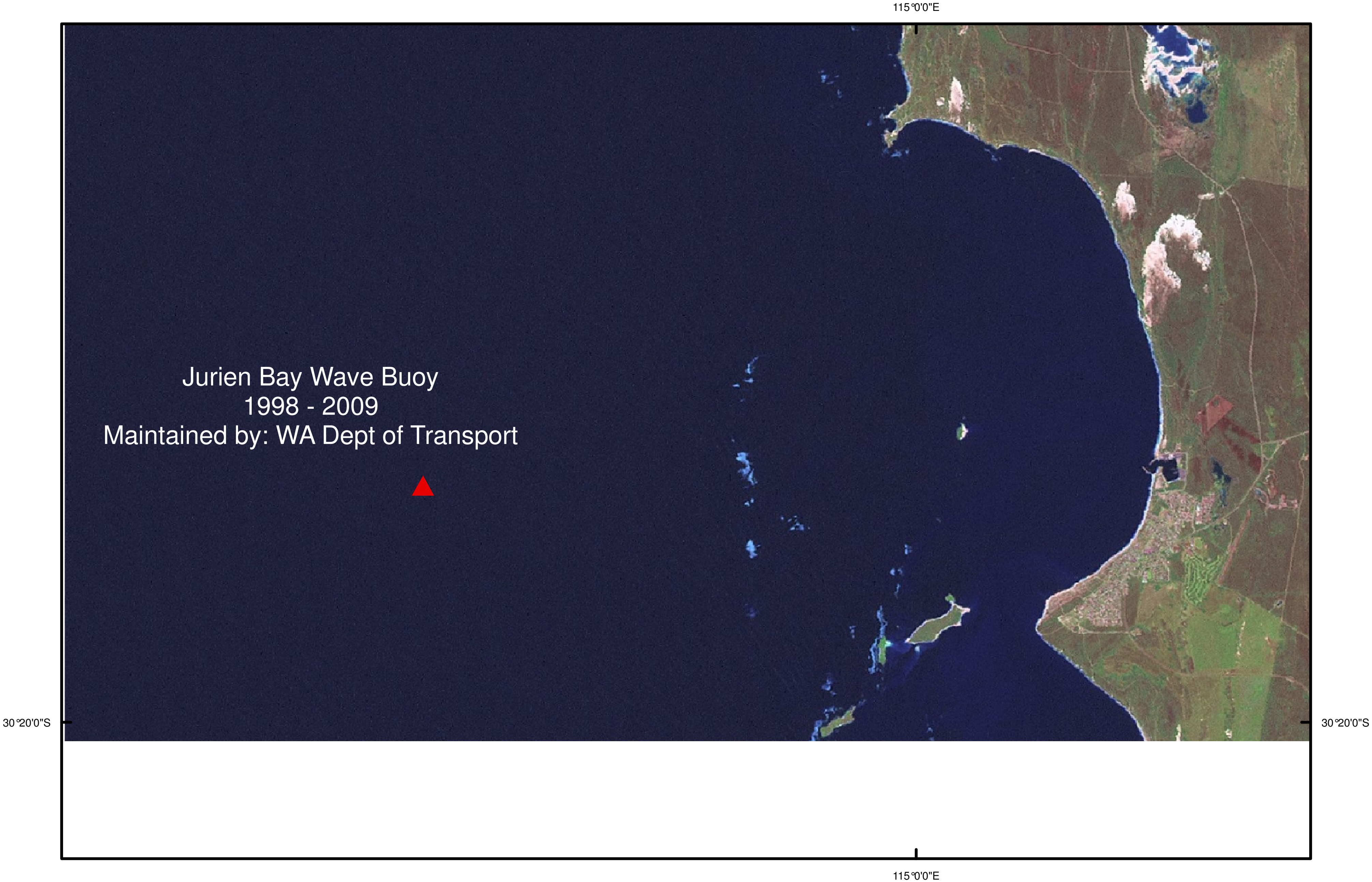
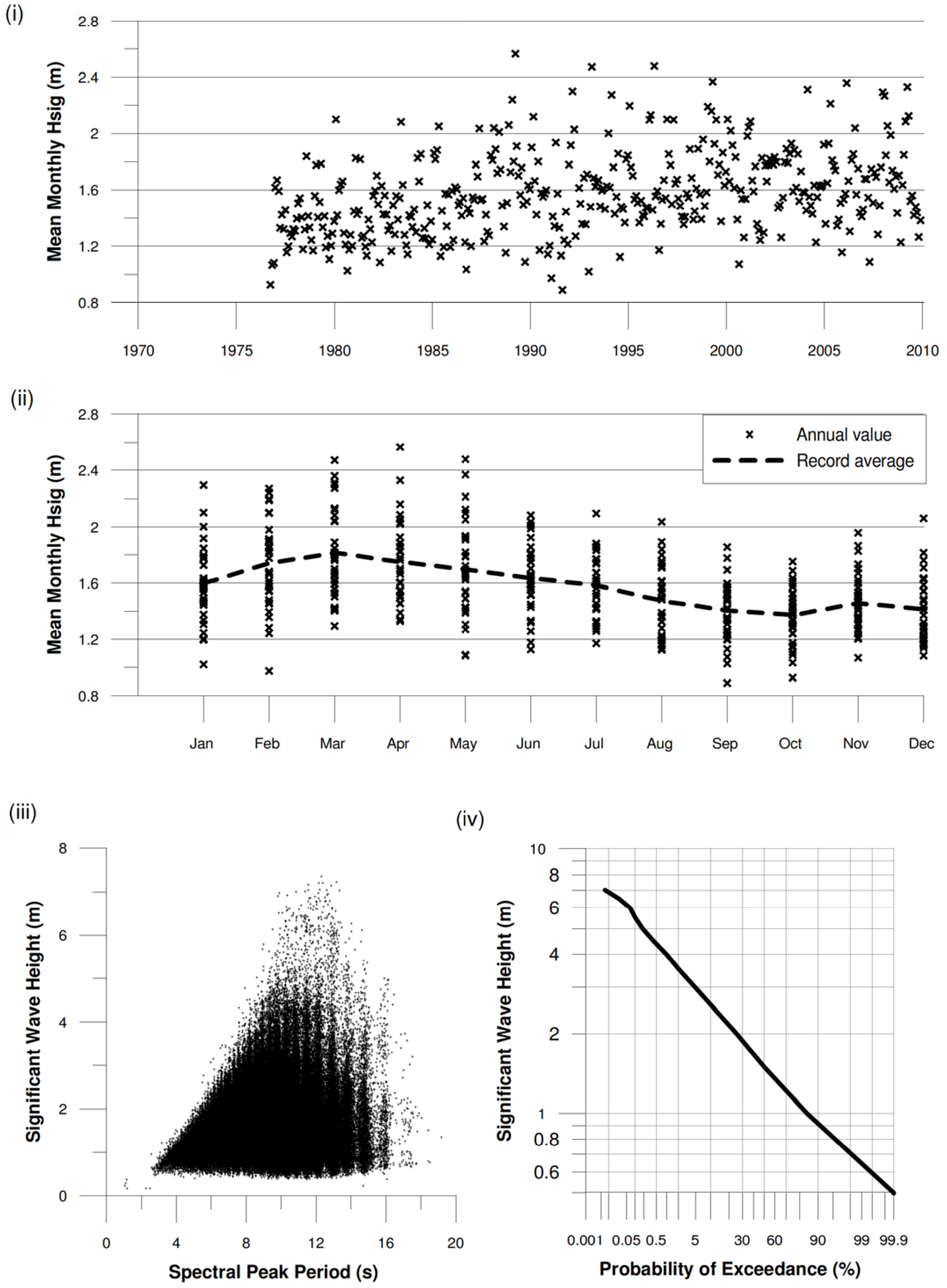
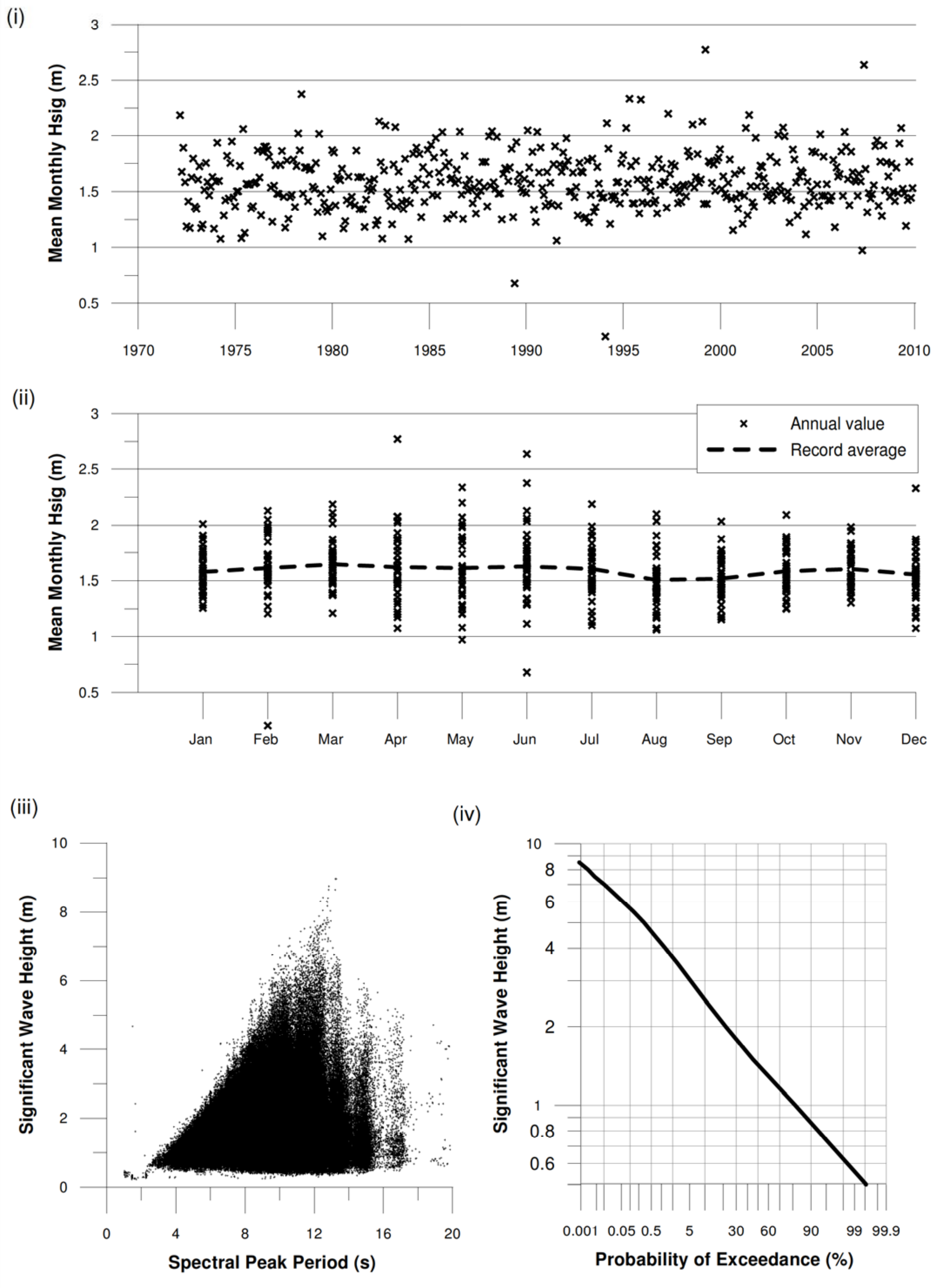


Figure A-9

APPENDIX B WAVE BUOY STATISTICS



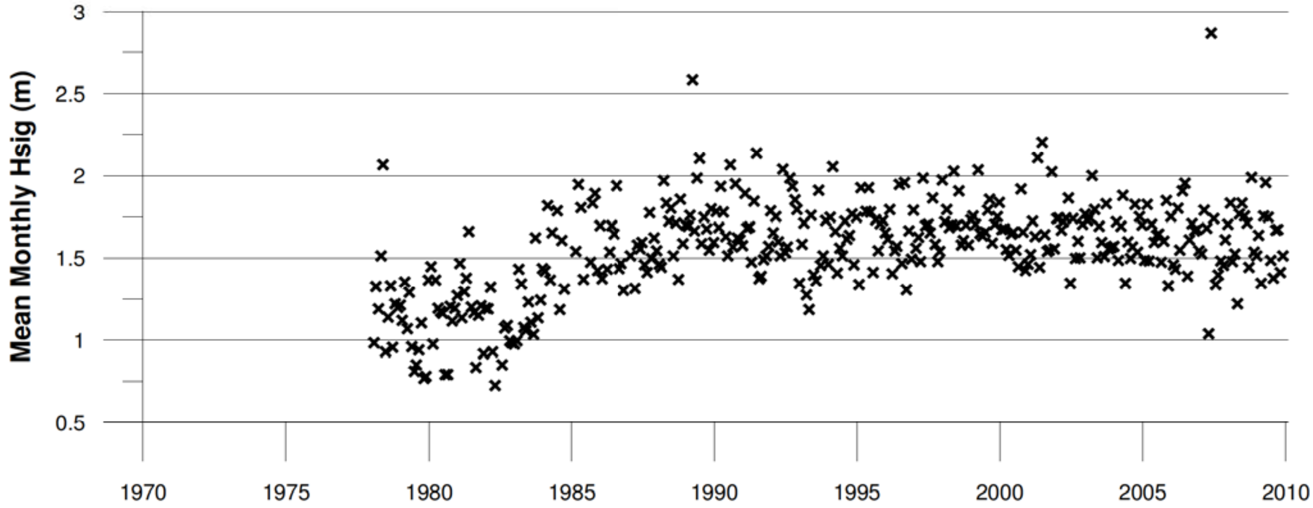
WRL Report No. 242	BRISBANE WAVERIDER BUOY STATISTICS	Figure B-1 filename.grf



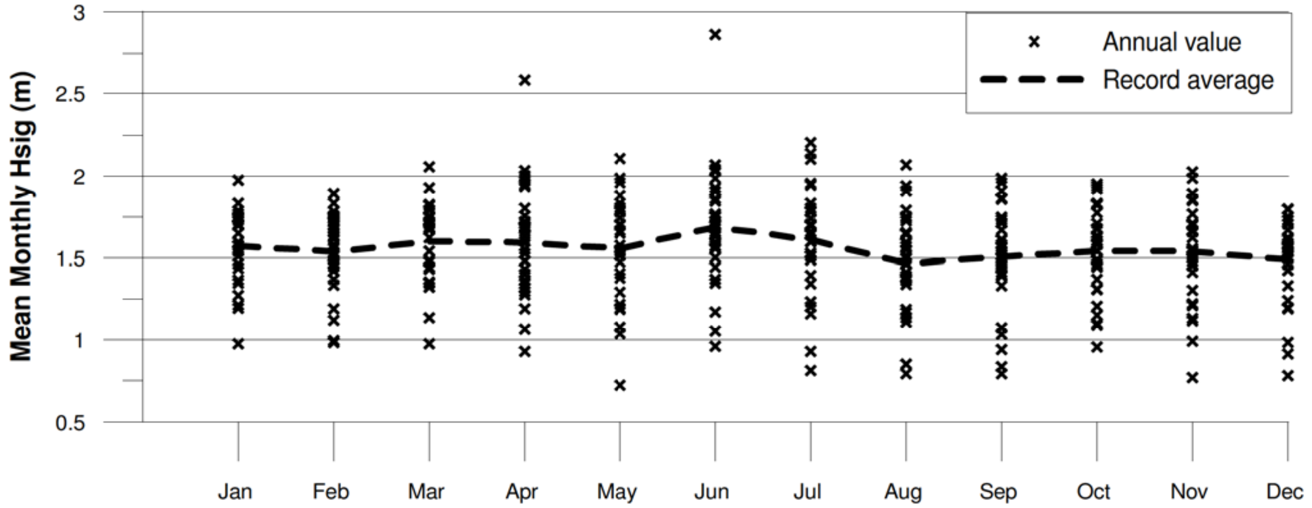
WRL Report No. 242	BOTANY BAY WAVE RIDER BUOY STATISTICS	Figure B-2

filename.grf

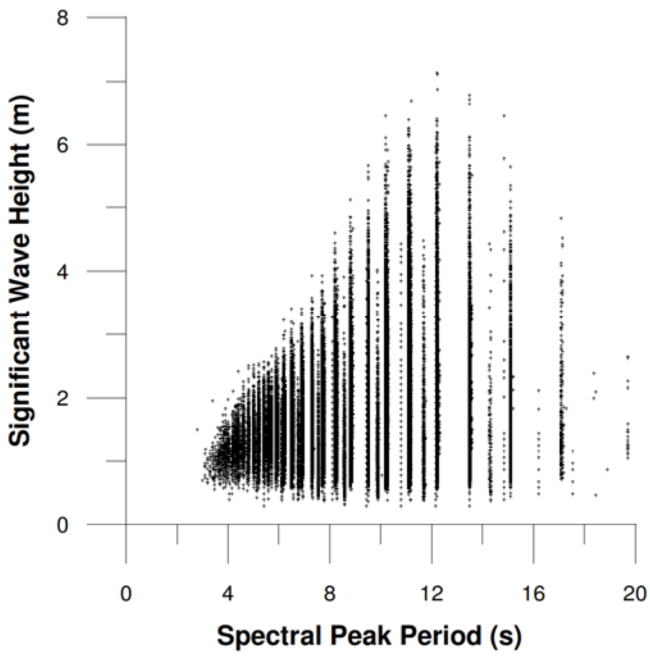
(i)



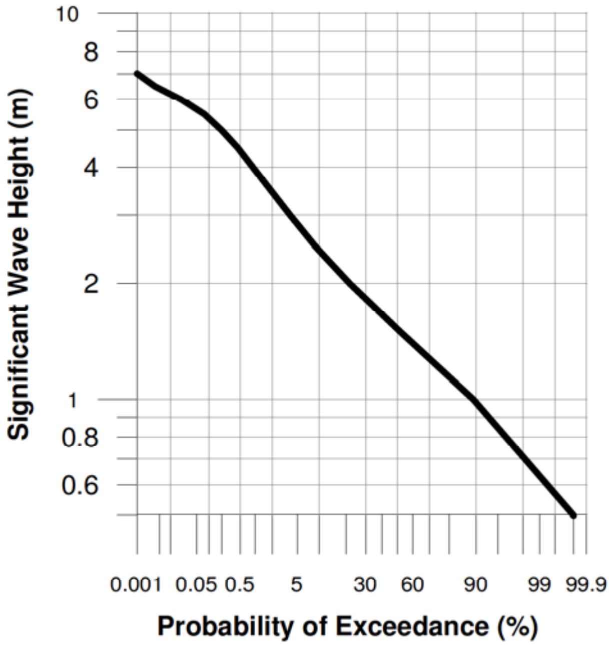
(ii)



(iii)

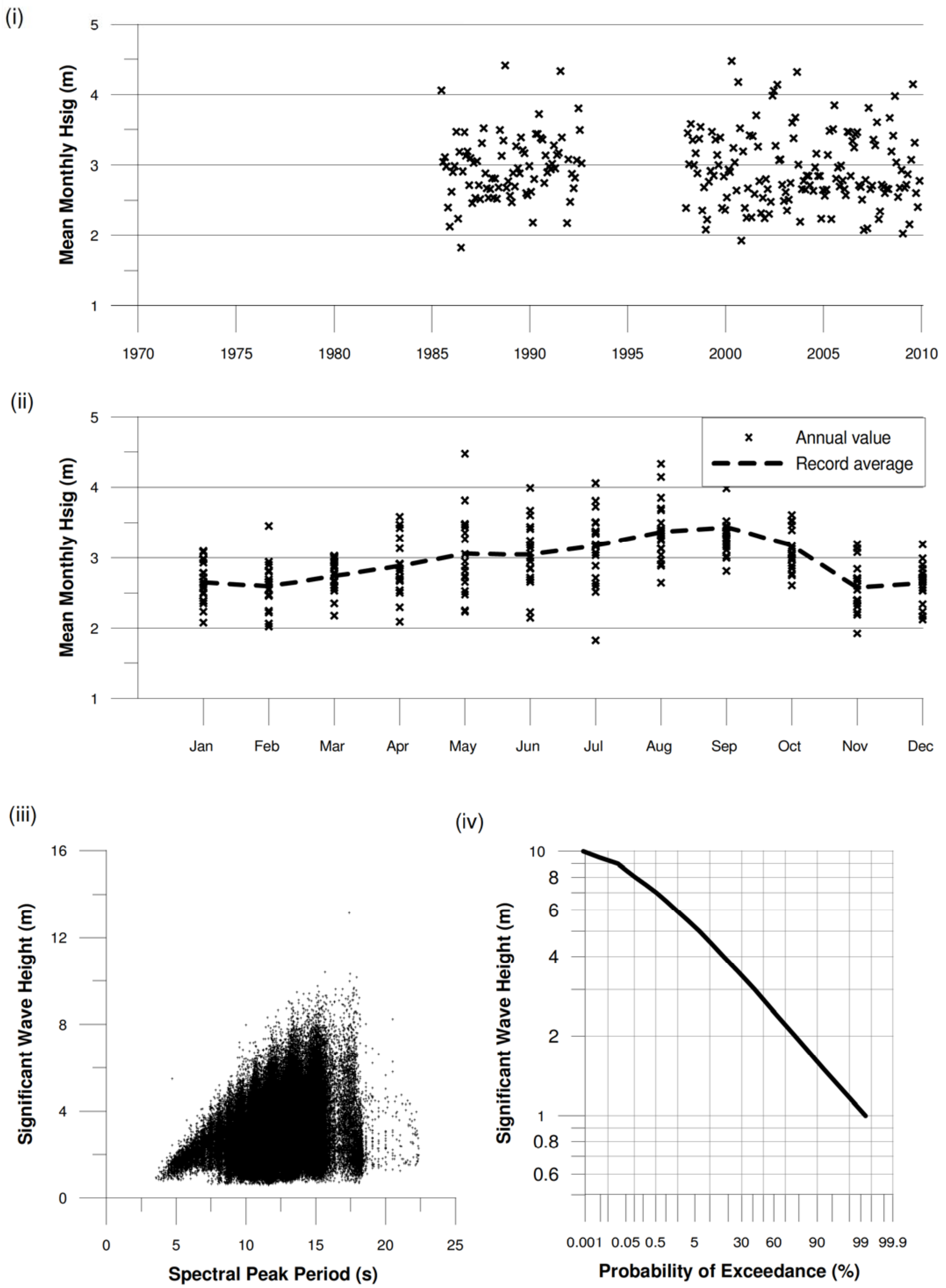


(iv)



WRL Report No. 242	EDEN WAVE BUOY STATISTICS	Figure B-3

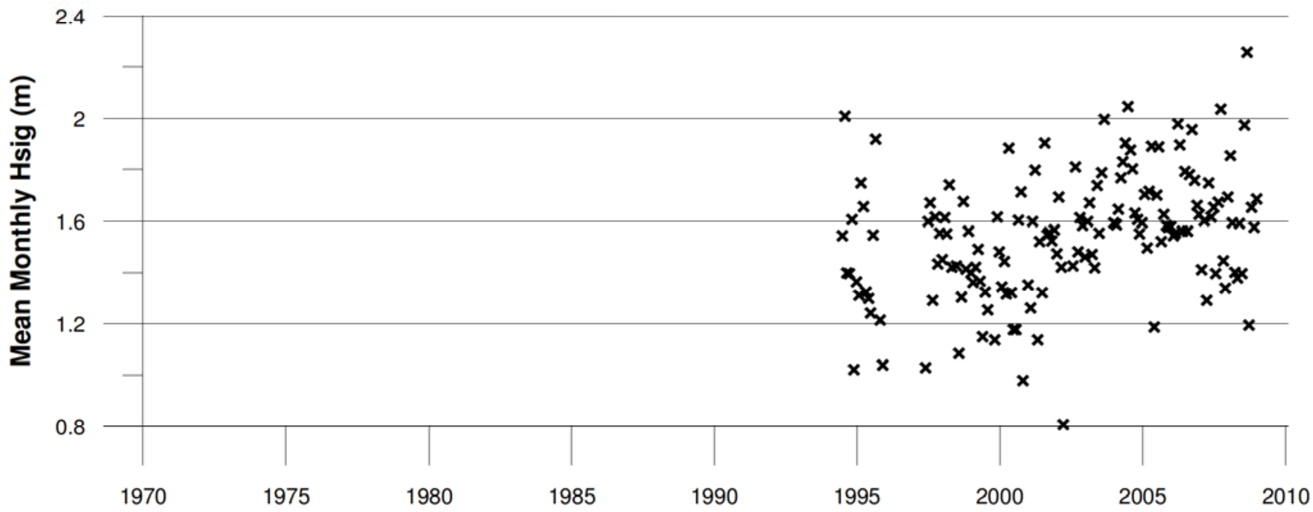
filename.grf



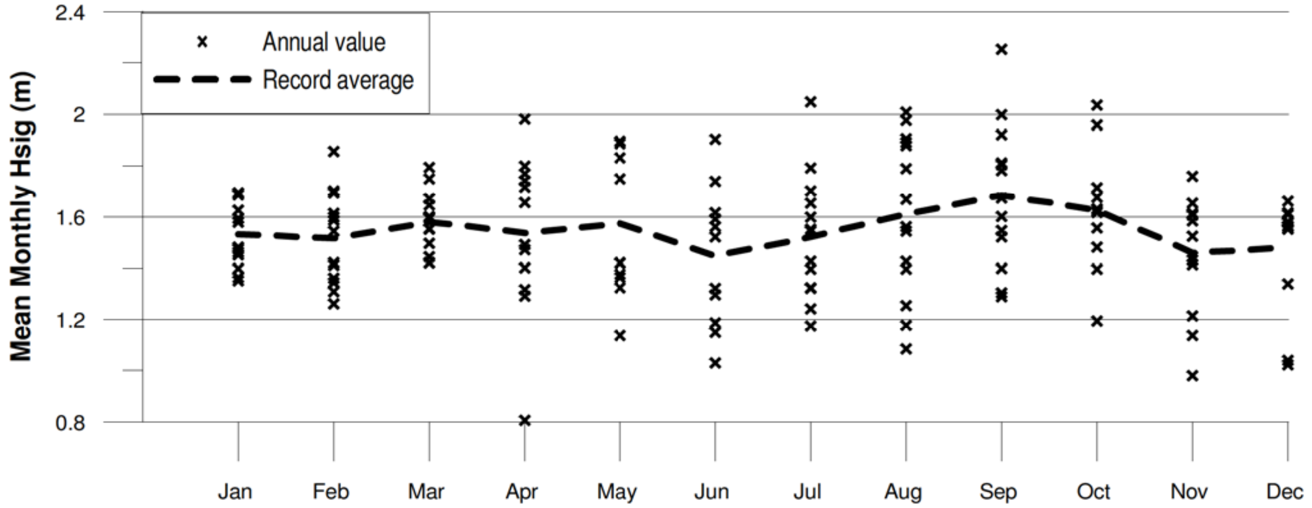
WRL Report No. 242	CAPE SORELL WAVERIDER BUOY STATISTICS	Figure B-4

filename.grf

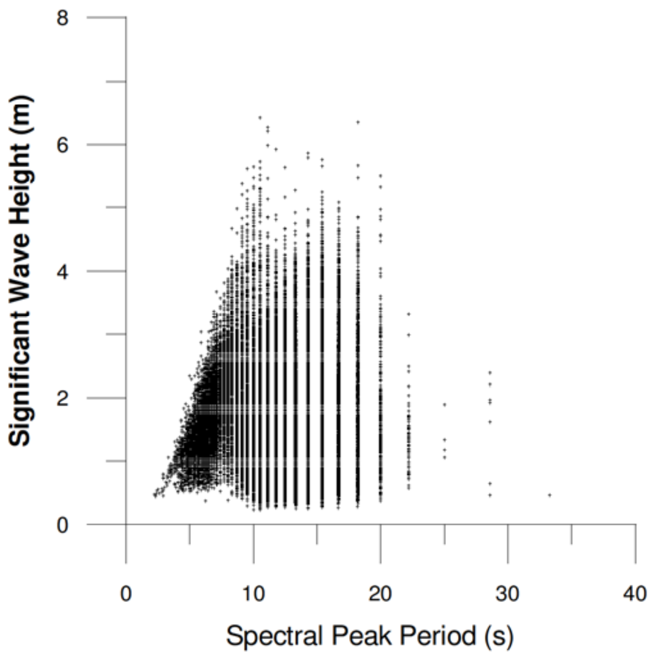
(i)



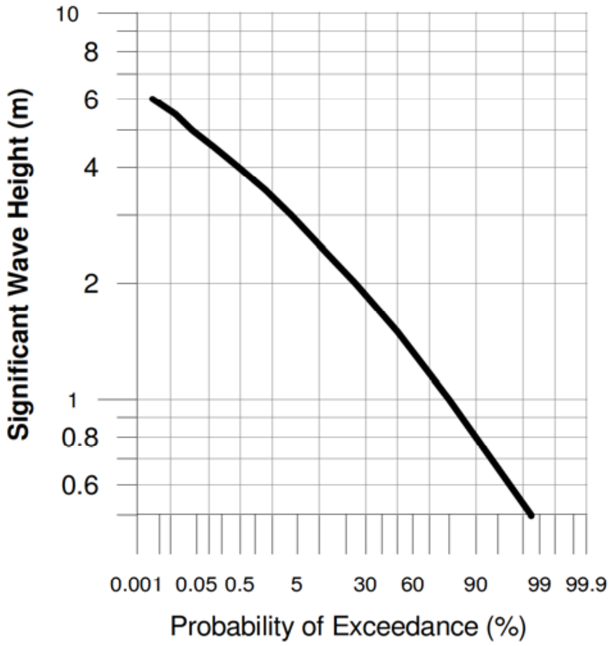
(ii)



(iii)

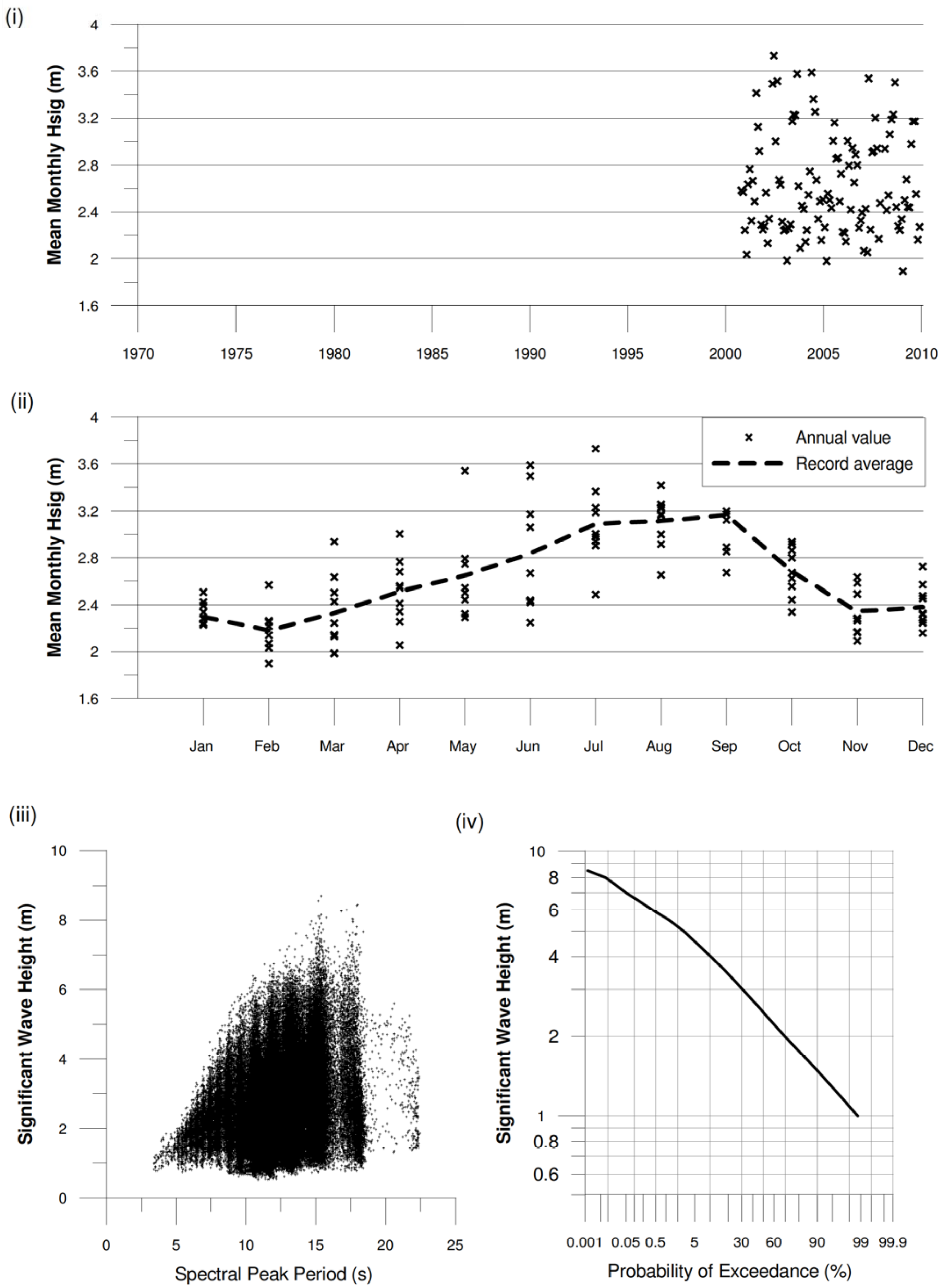


(iv)



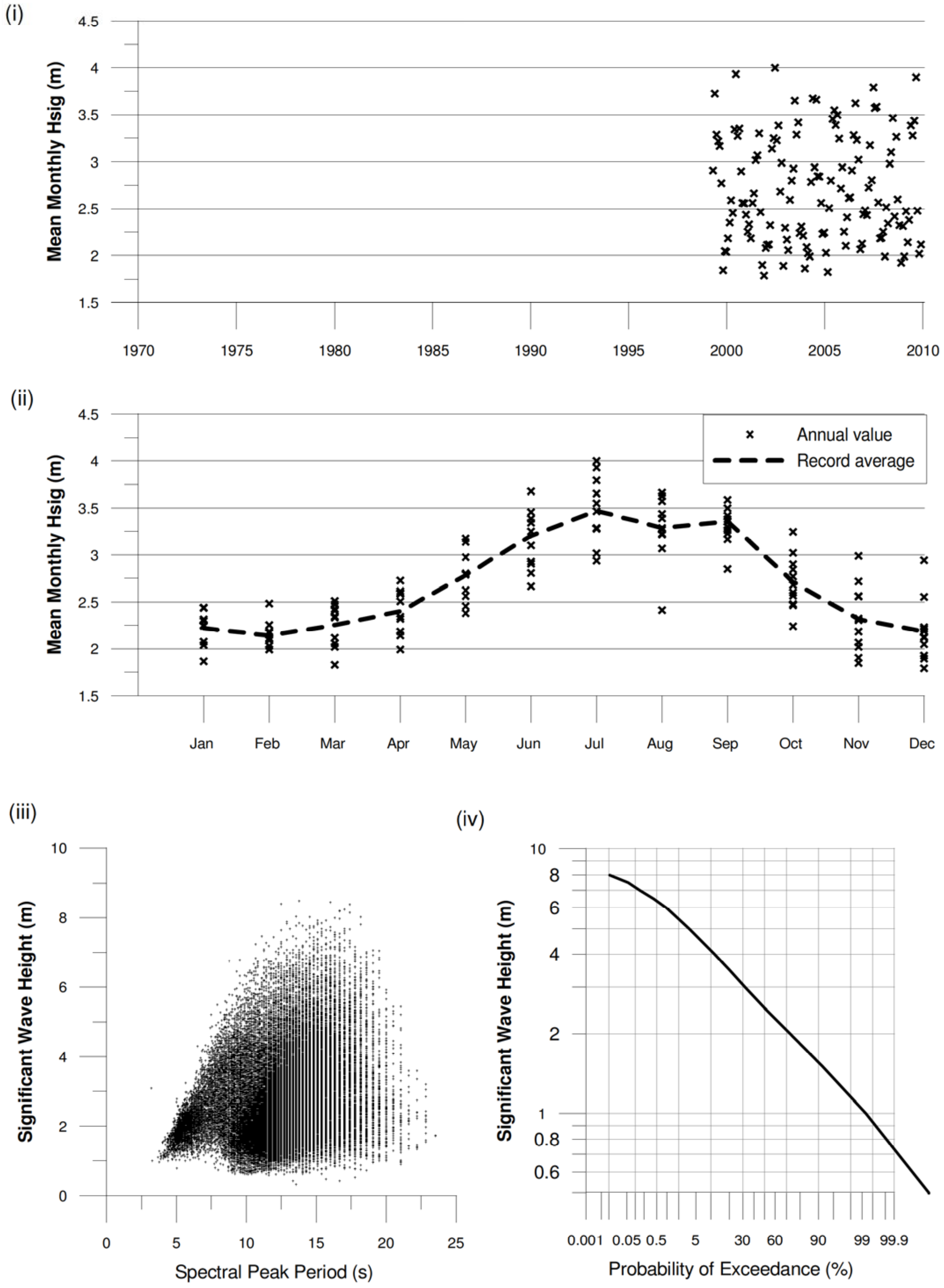
WRL Report No. 242	PORT NEPEAN WAVERIDER BUOY STATISTICS	Figure B-5

filename.grf



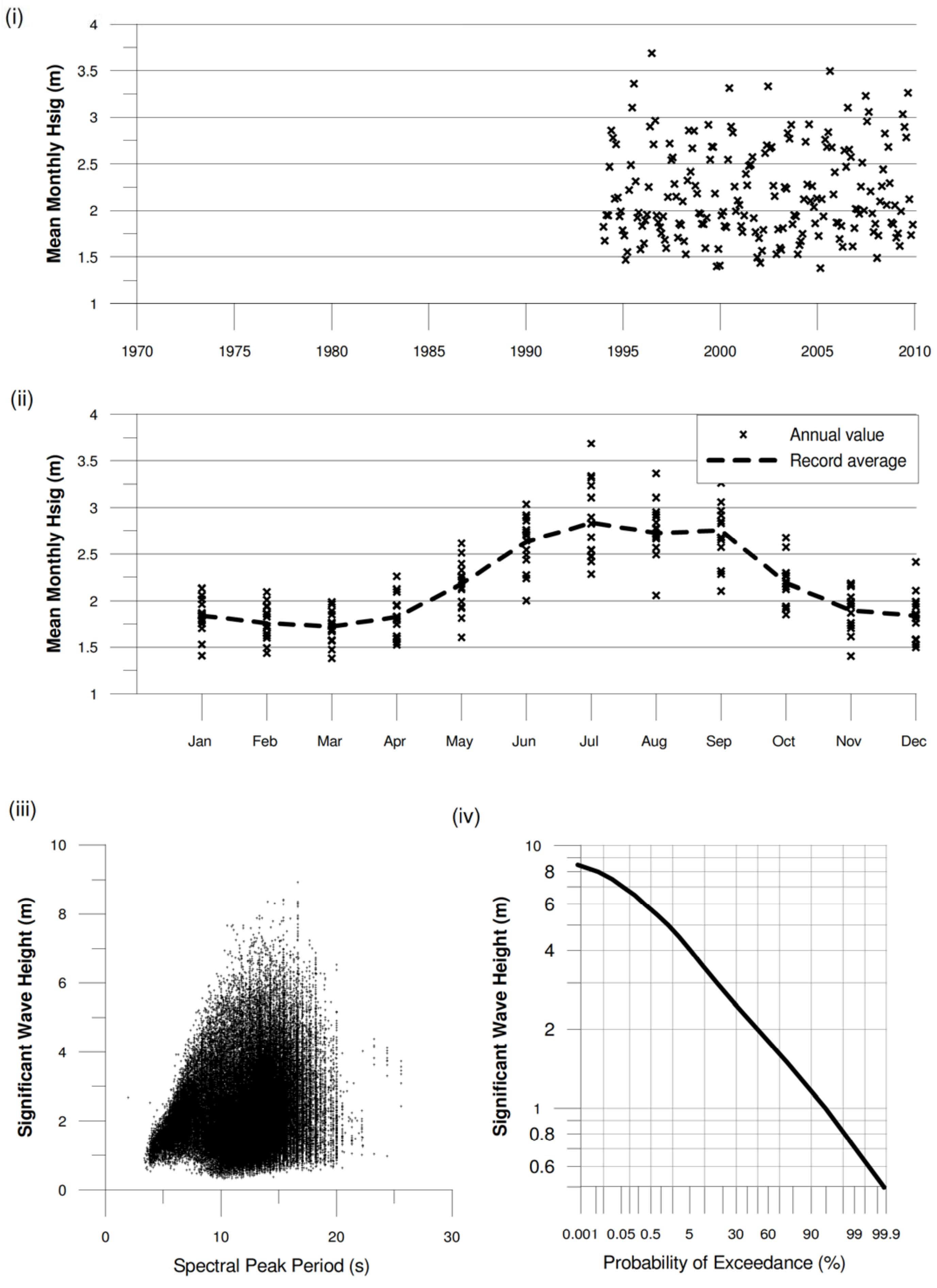
WRL Report No. 242	CAPE DE COUEDIC WAVERIDER BUOY STATISTICS	Figure B-6

filename.grf



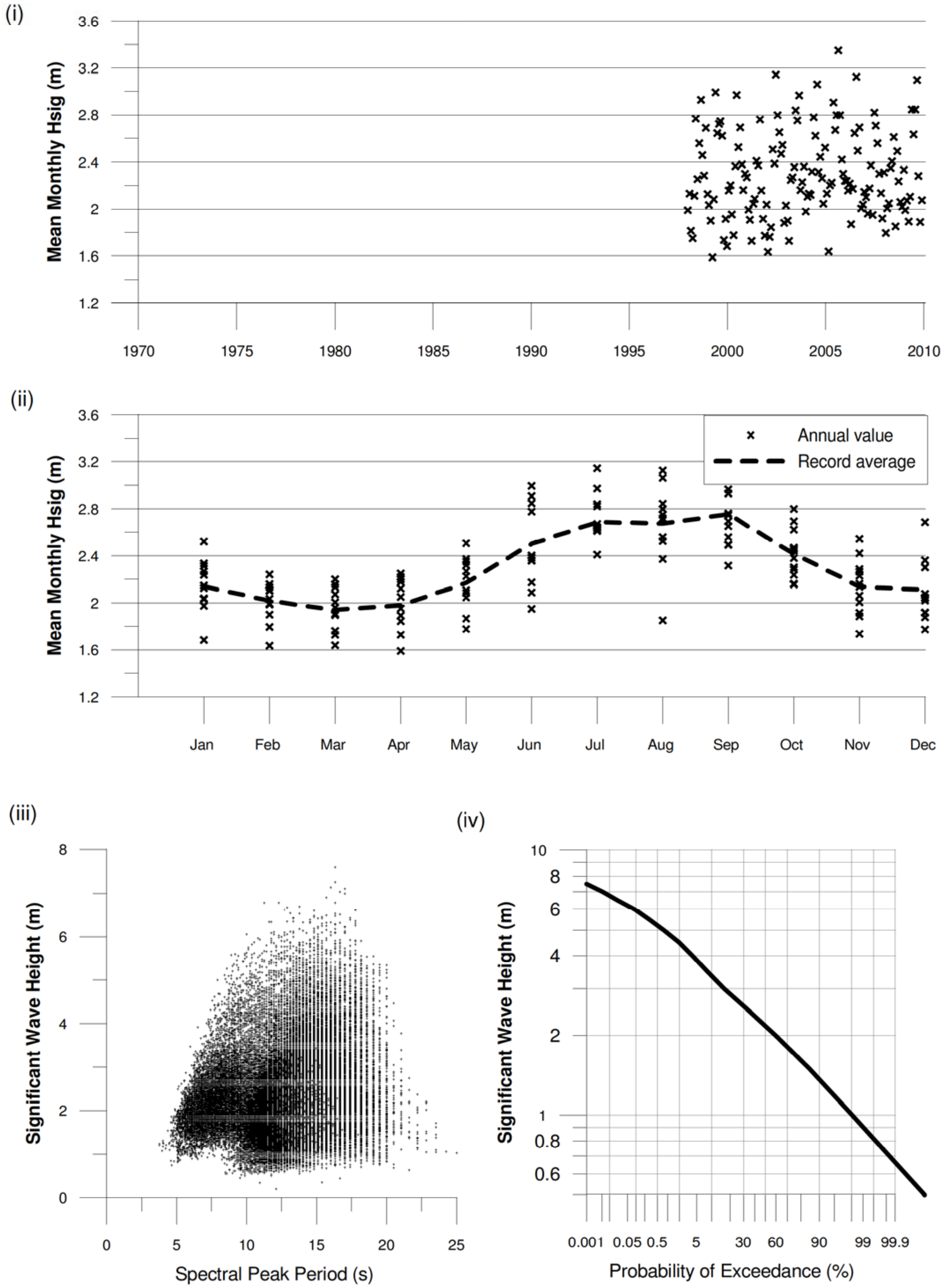
WRL Report No. 242	CAPE NATURALISTE WAVERIDER BUOY STATISTICS	Figure B-7

filename.grf



WRL Report No. 242	ROTTNEST ISLAND WAVERIDER BUOY STATISTICS	Figure B-8

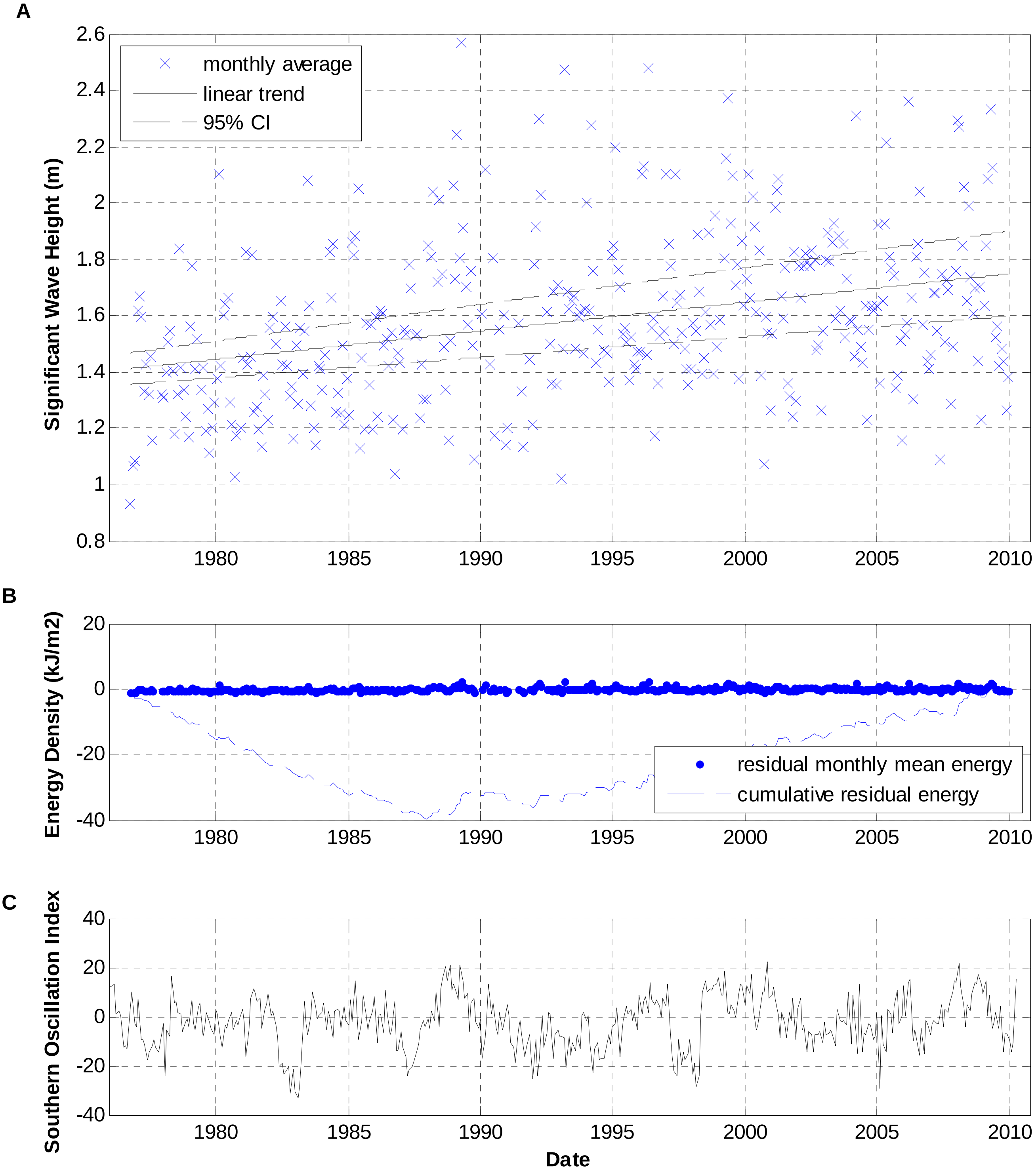
filename.grf



WRL Report No. 242	JURIEN BAY WAVERIDER BUOY STATISTICS	Figure B-9

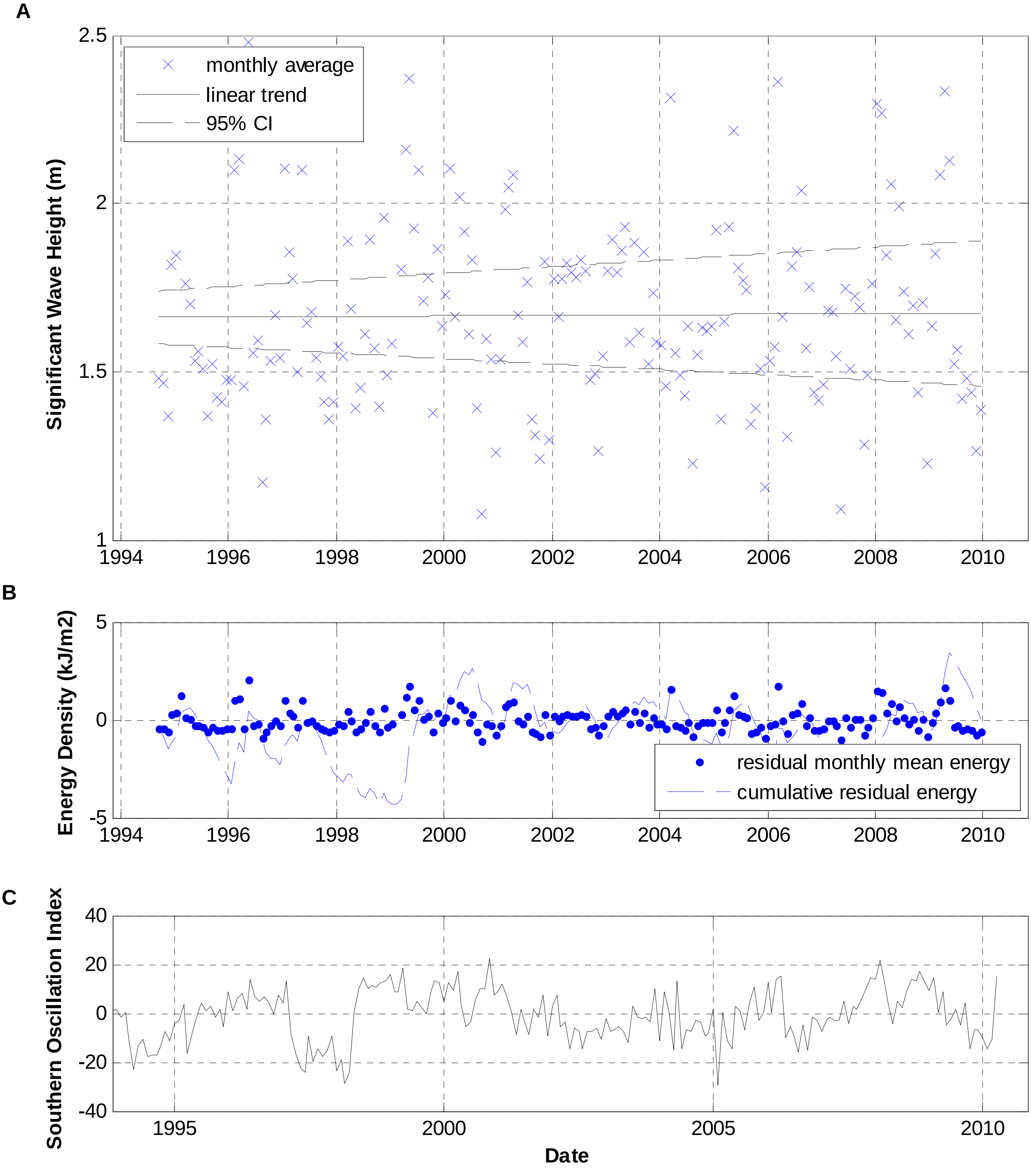
filename.grf

APPENDIX C WAVE HEIGHT AND ENERGY TRENDS

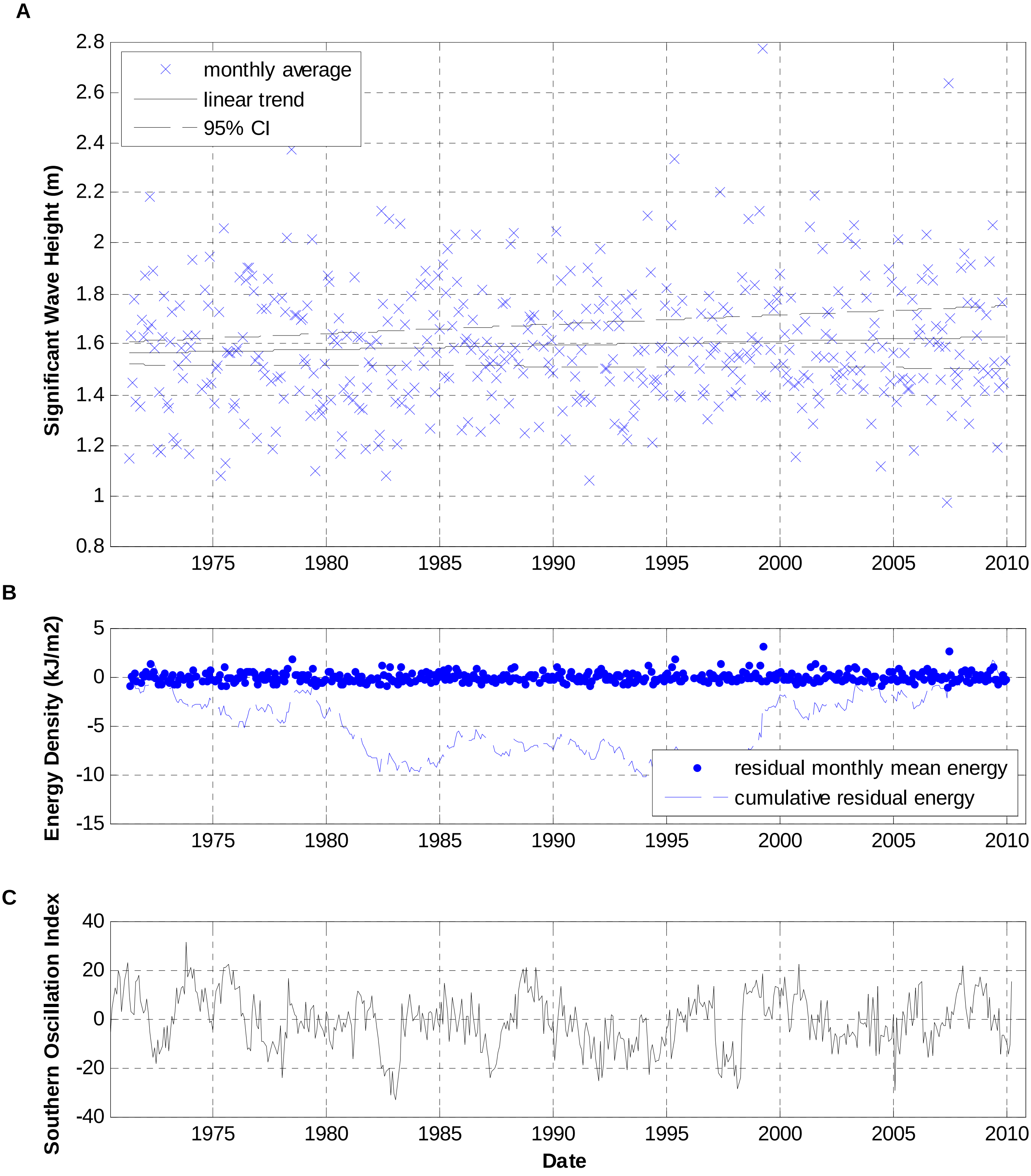


Note: Buoy believed to have been shifted to a more exposed location in 1994

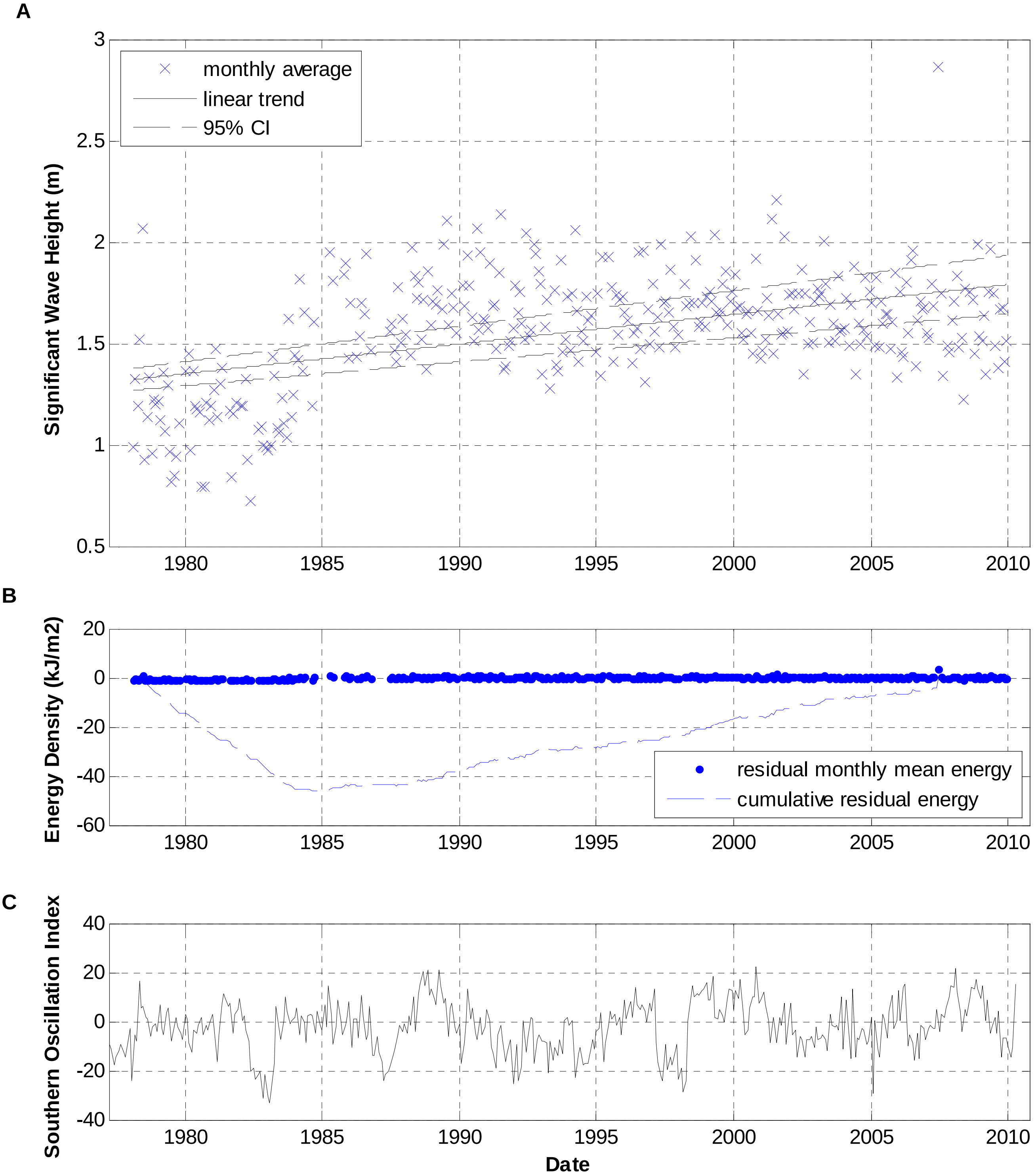
WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Brisbane (Oct 1976– Dec 2009)	Figure C-1



WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Brisbane (Sept 1994 – Dec 2009)	Figure C-1A

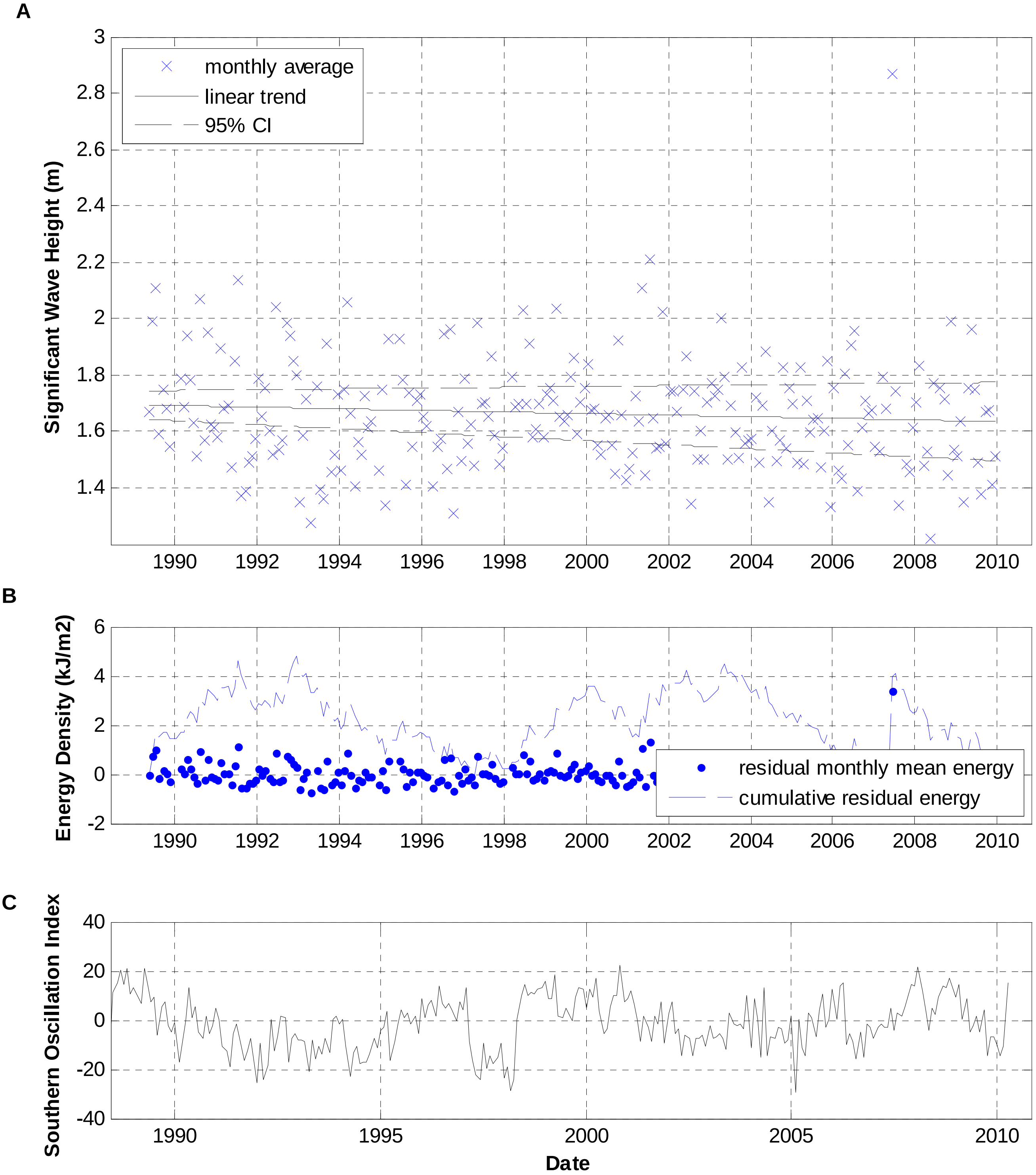


WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Botany Bay (Apr 1971– Dec 2009)	Figure C-2

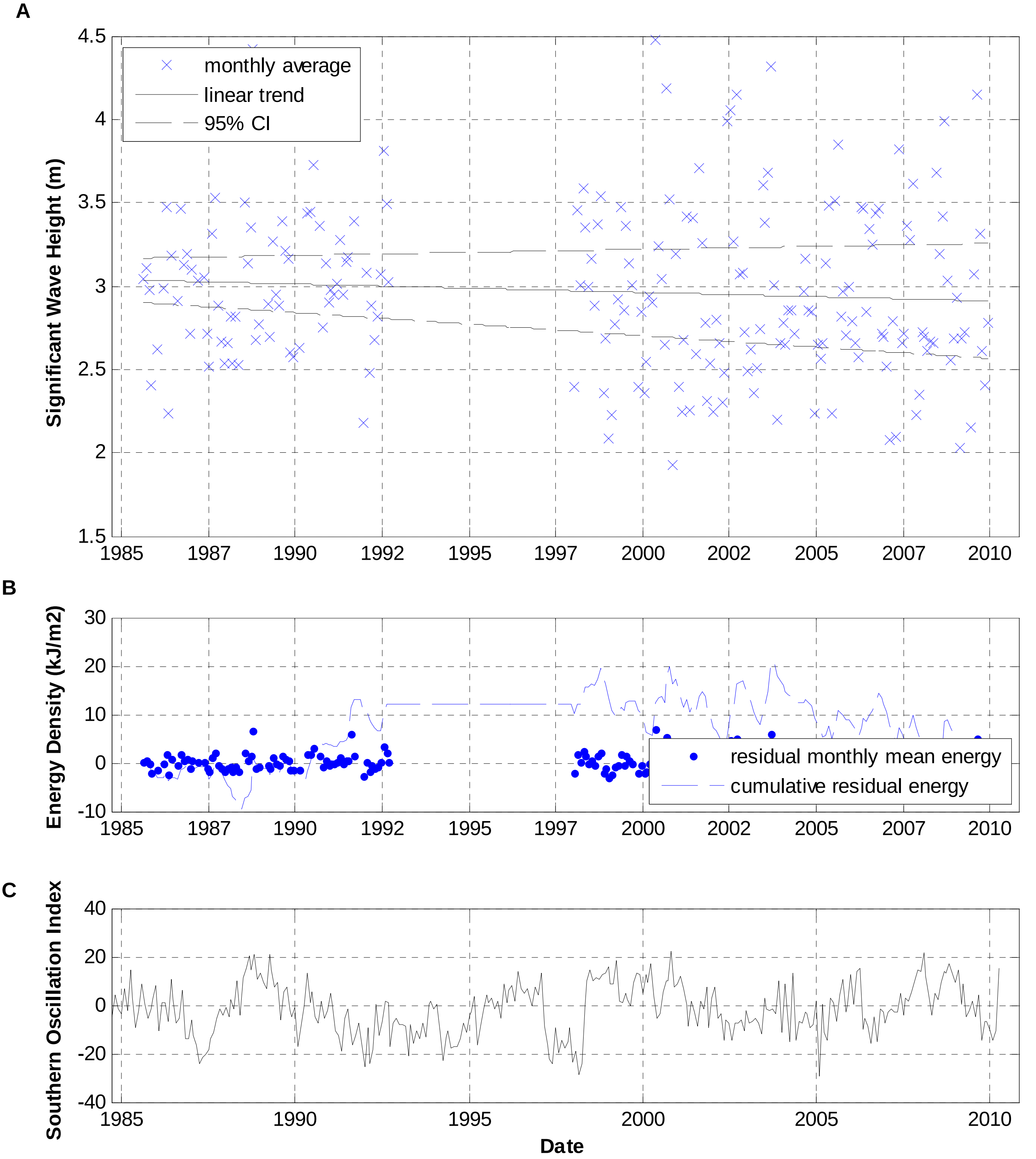


Note: Buoy believed to have been shifted to a more exposed location in 1989

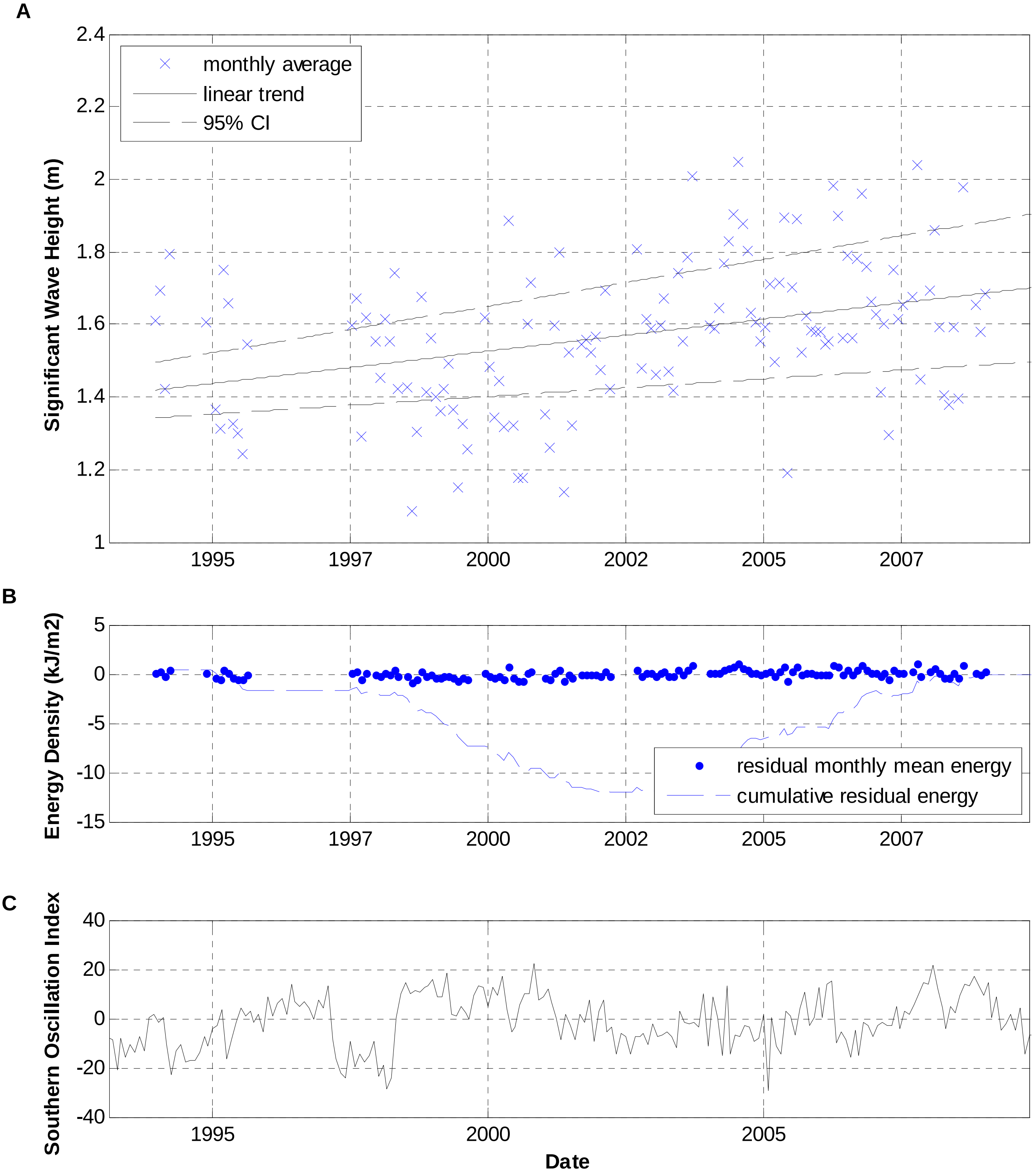
Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Eden (Feb 1978– Dec 2009)



WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Eden (Apr 1989– Dec 2009)	Figure C-3A

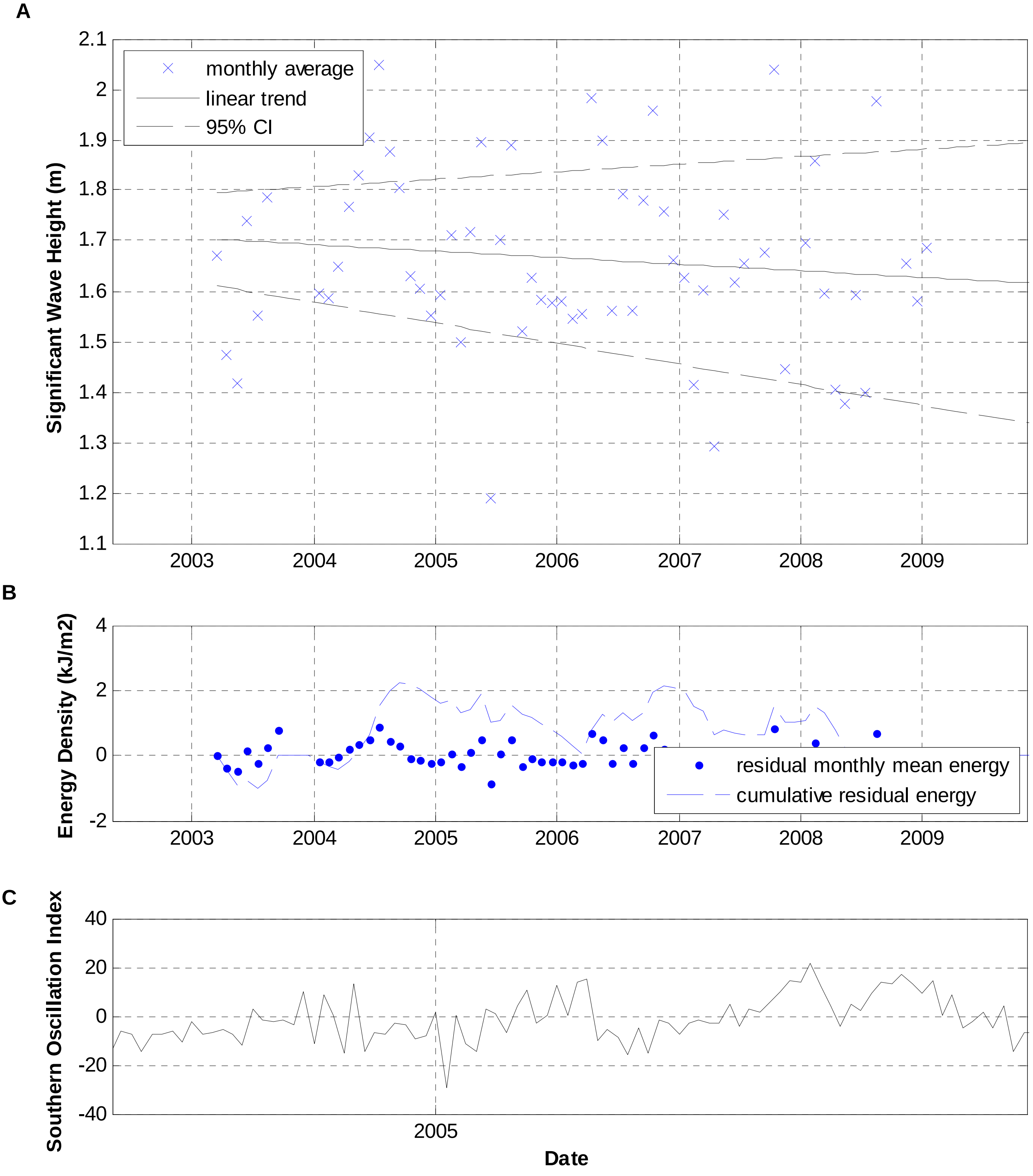


WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Cape Sorell (June 1985– Dec 2009)	Figure C-4

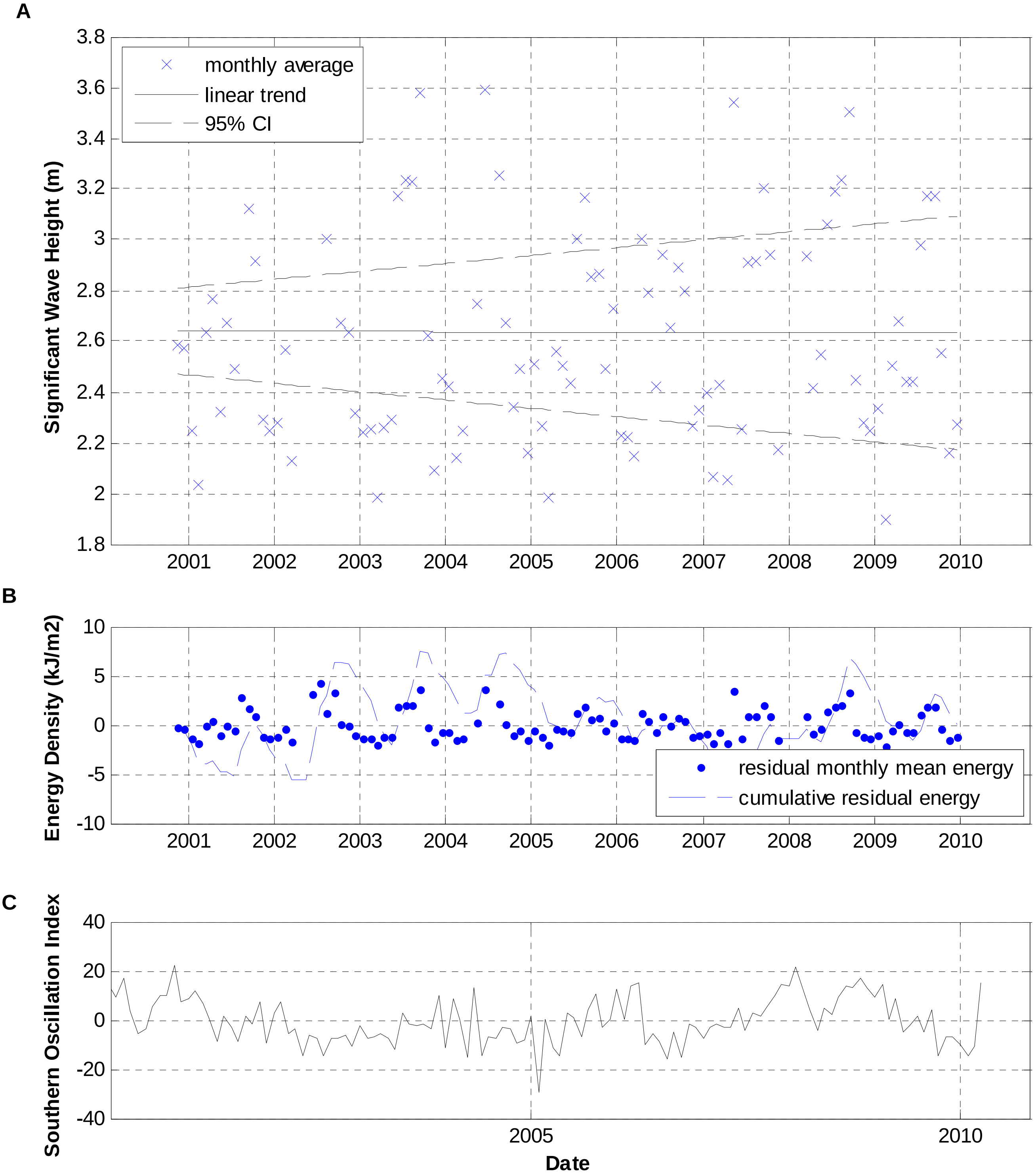


Note: Buoy believed to have been shifted to a more exposed location in 2003

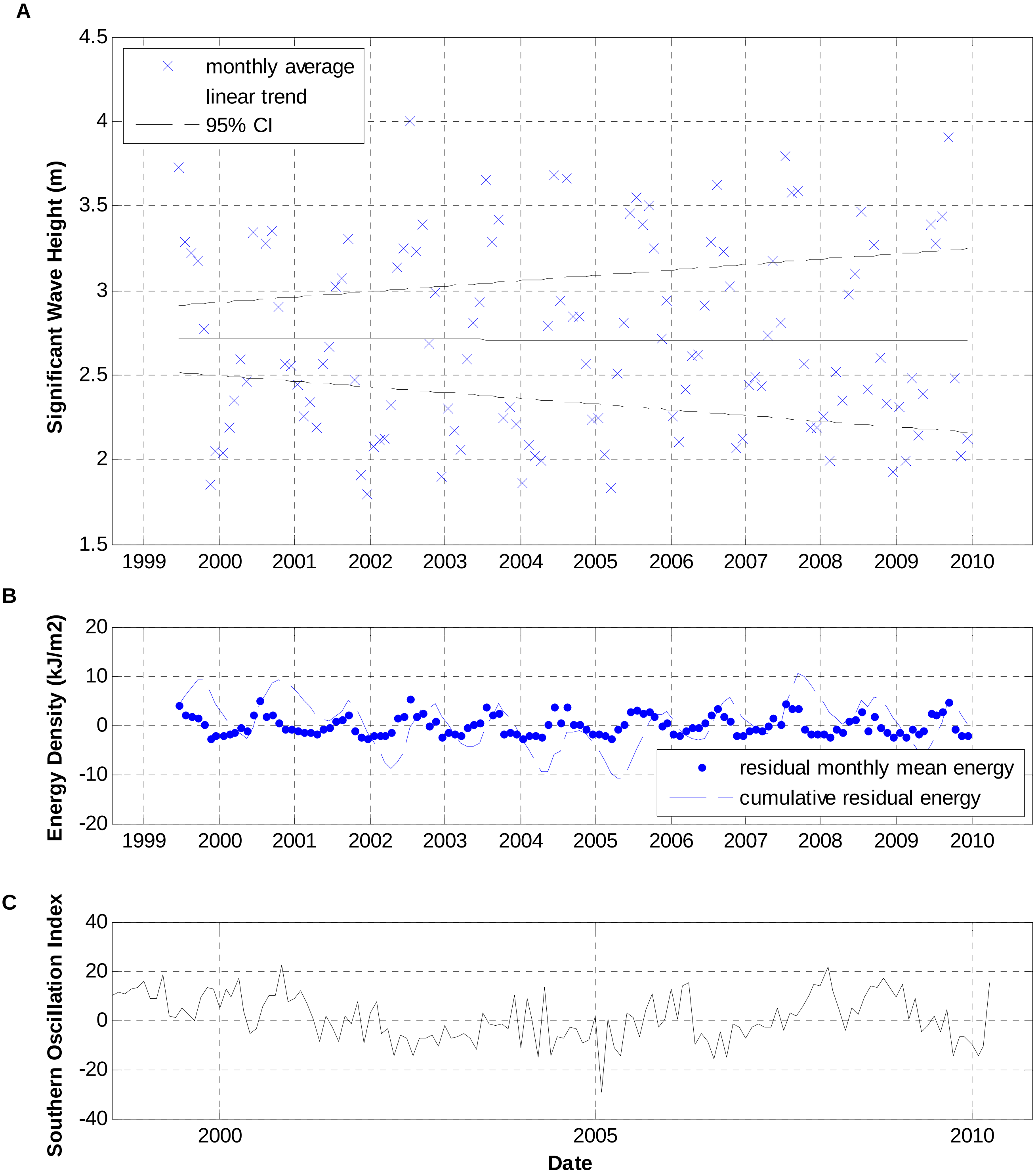
WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Point Nepean (Dec 1993– Jan 2009)	Figure C-5



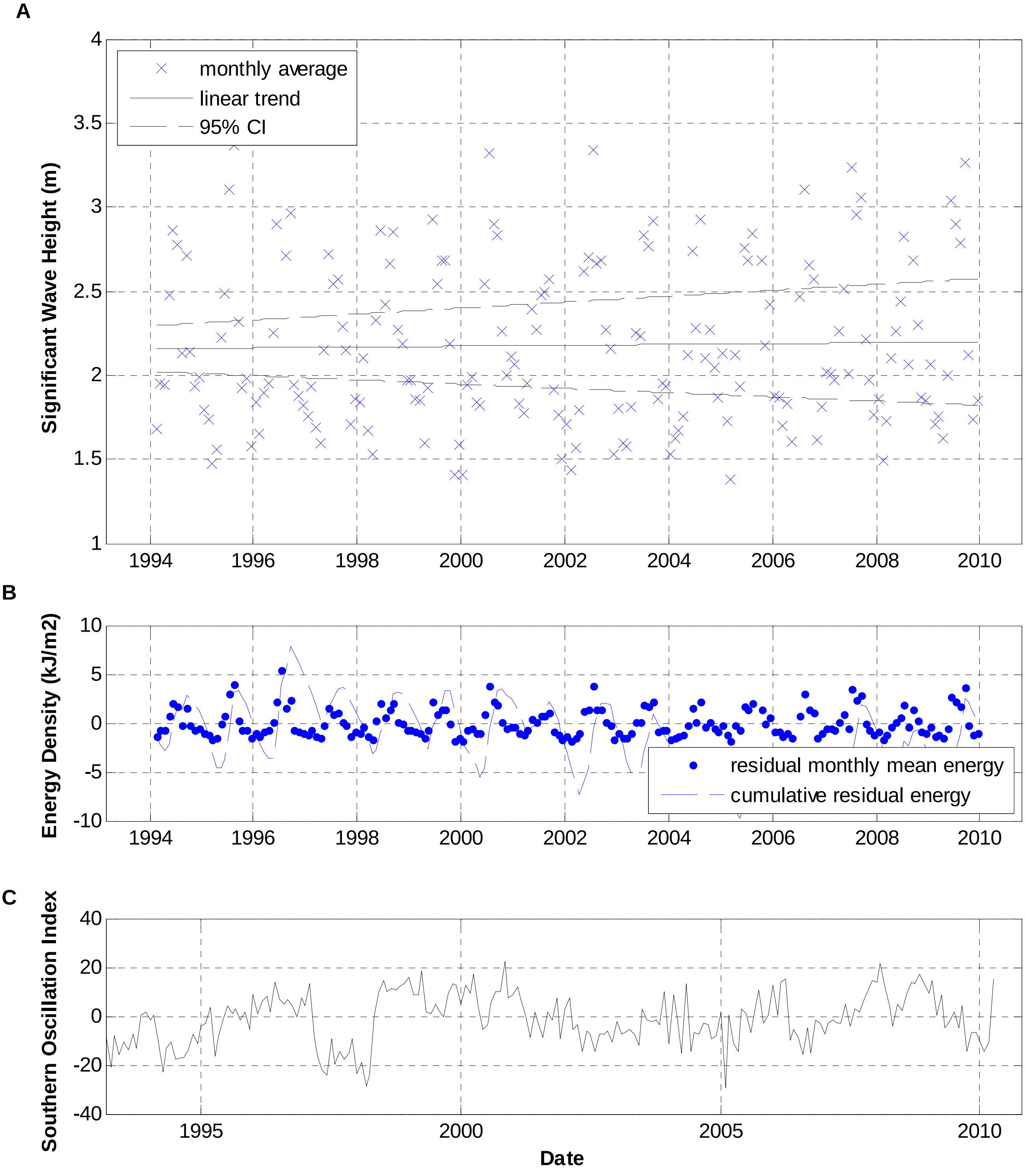
WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Point Nepean (Feb 2003 – Jan 2009)	Figure C-5A



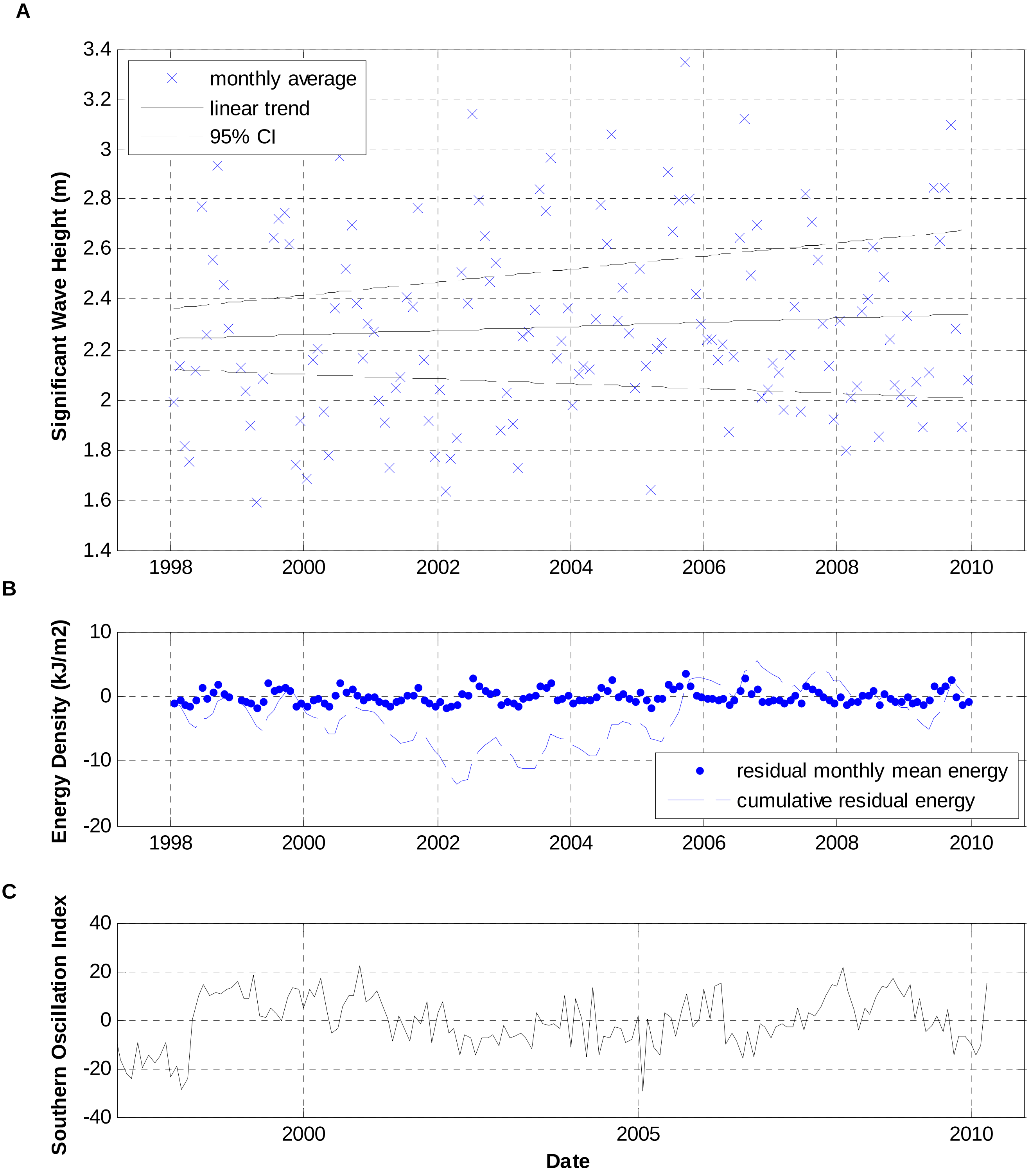
WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Cape du Couedic (Nov 2000 – Dec 2009)	Figure C-6



WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Cape Naturaliste (May 1999 – Dec 2009)	Figure C-7



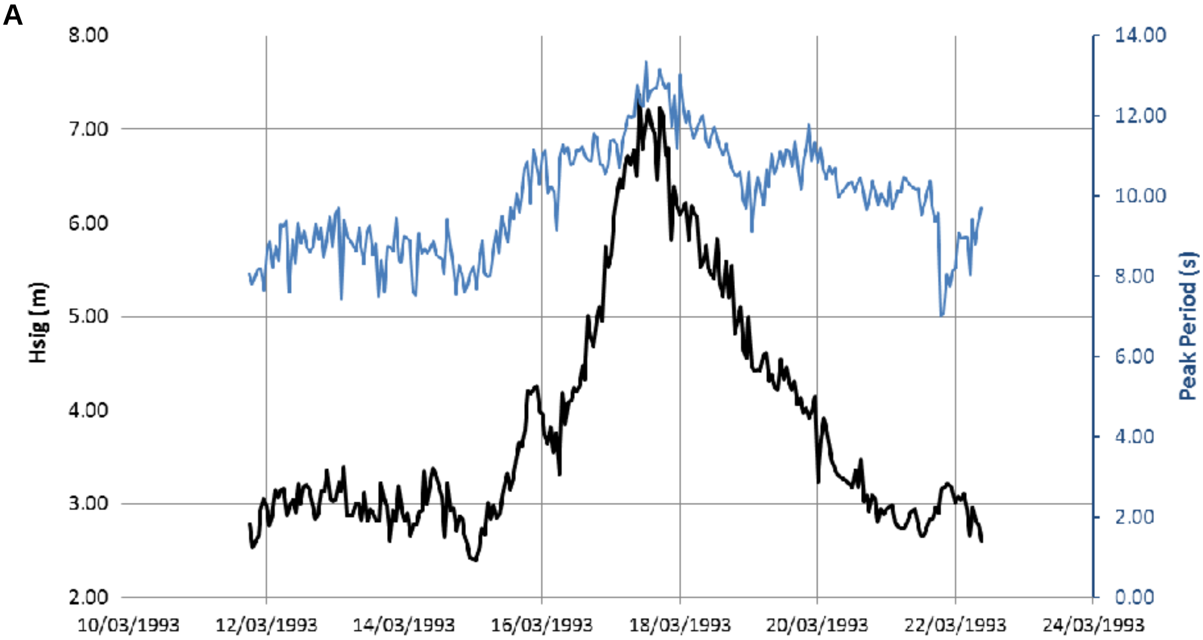
WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Rottnest Island (Jan 1994 – Dec 2009)	Figure C-8



WRL Report No. RR242	Mean Monthly H_{sig} (A), Residual and Cumulative Mean Monthly Energy (B) and SOI (C) for Jurien Bay (Jan 1998 – Dec 2009)	Figure C-9

APPENDIX D MAXIMUM WAVE HEIGHT EVENT AND MEAN SEA LEVEL PRESSURE

A



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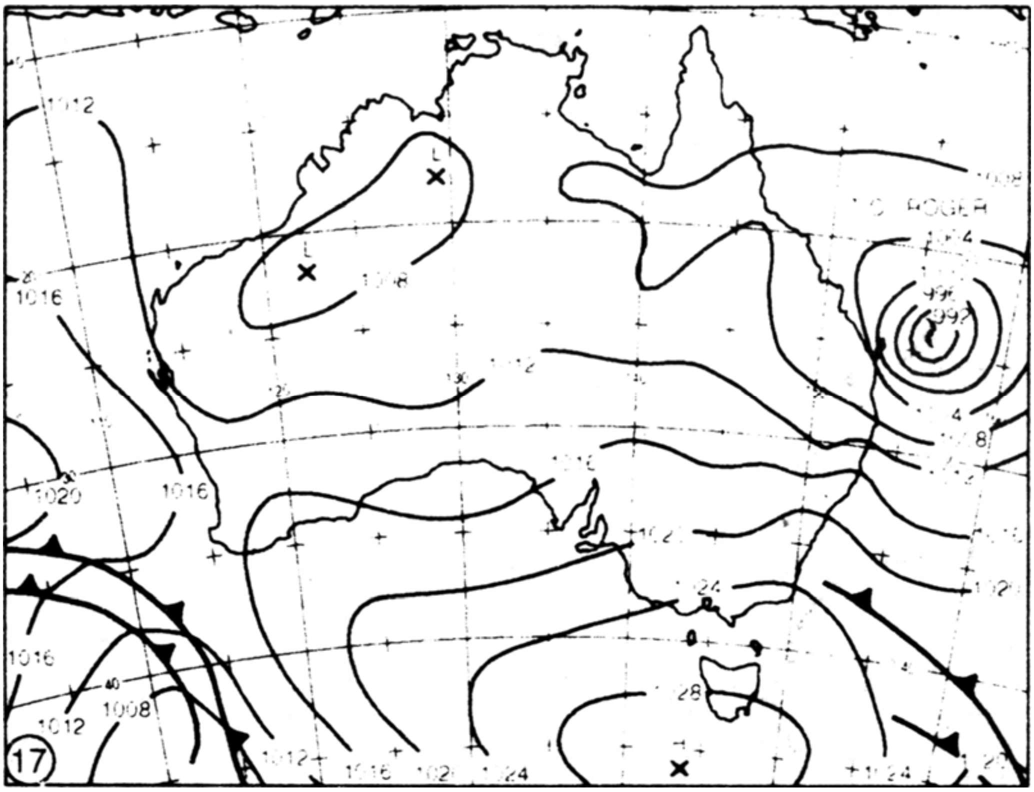
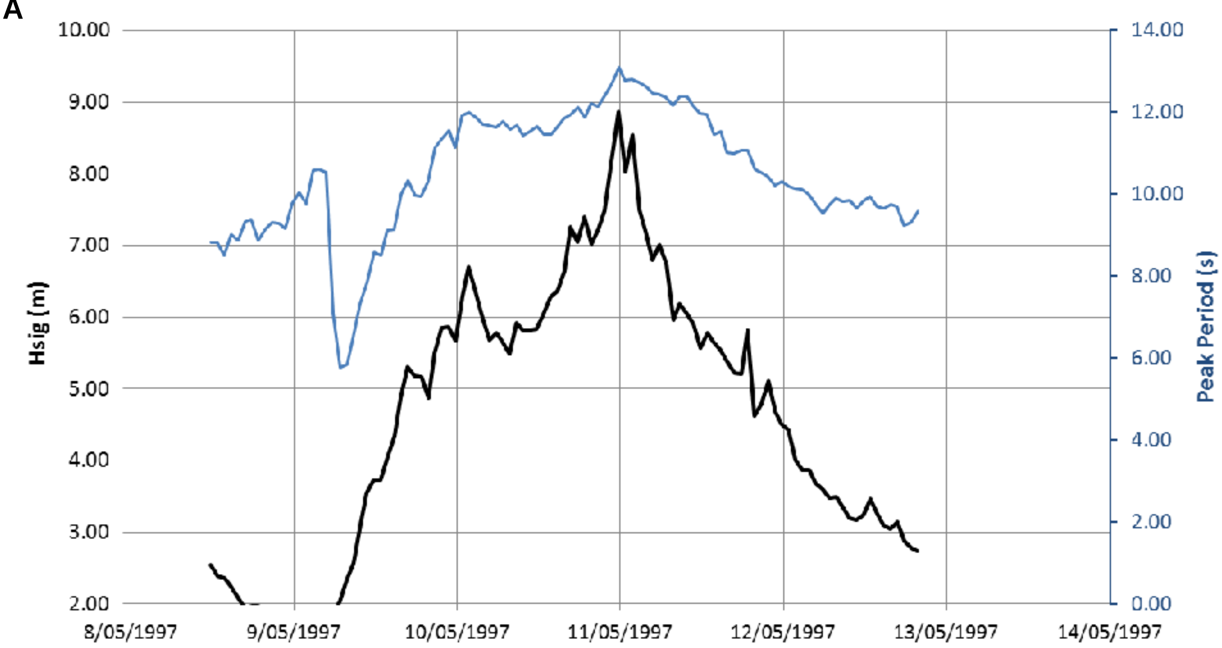


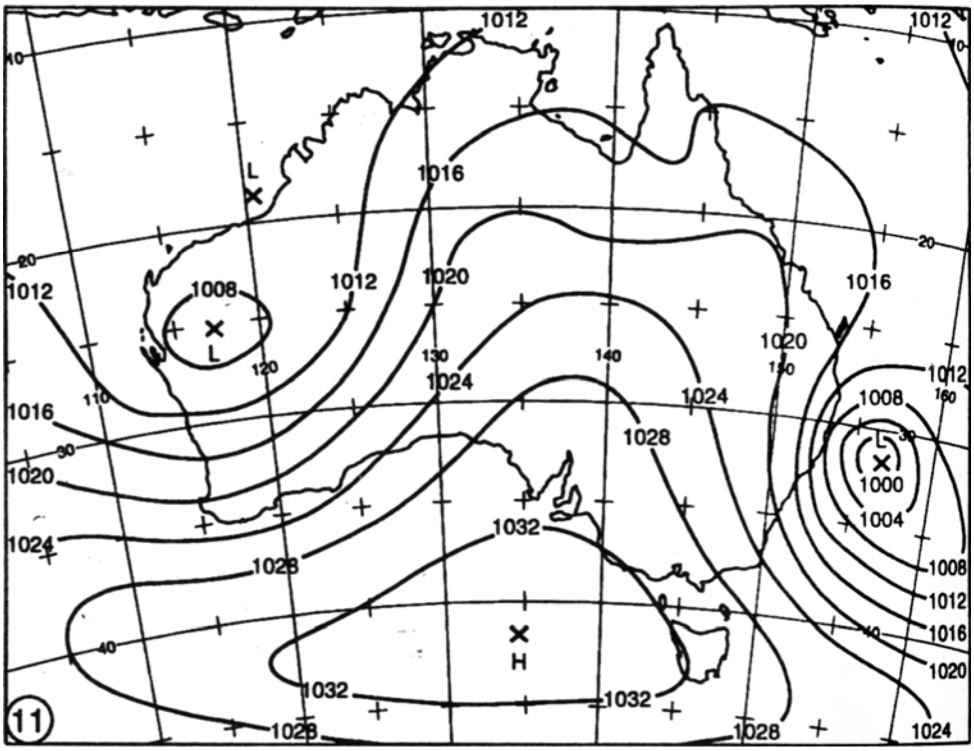
Source: Bureau of Meteorology (1993)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Brisbane Wave Buoy	Figure D-1

A

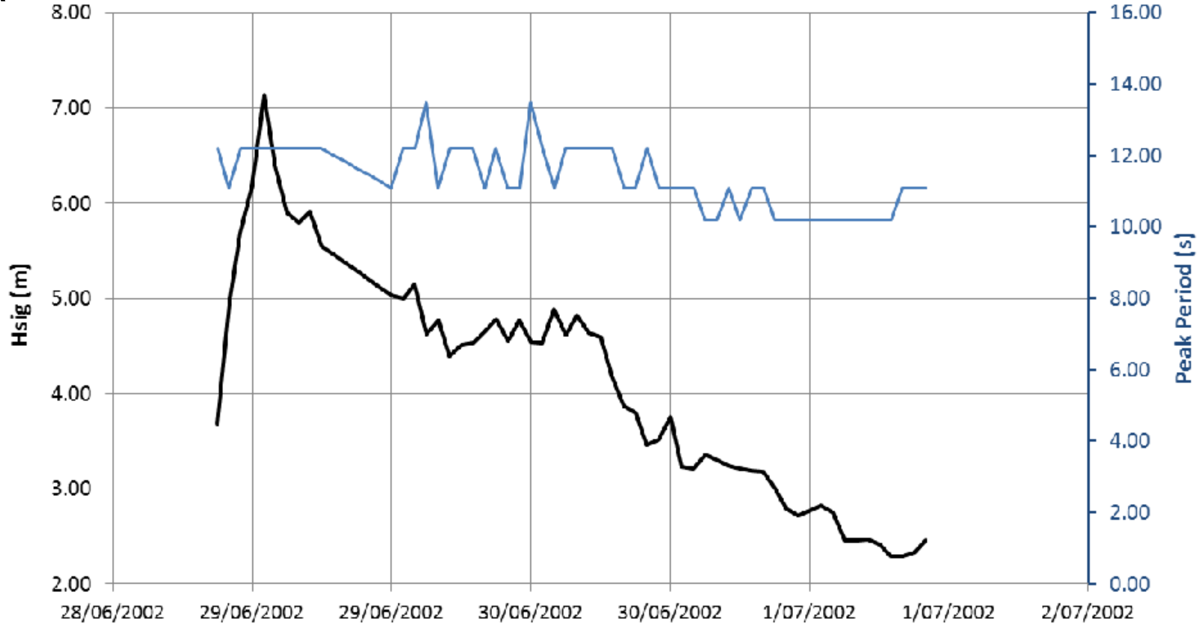


B

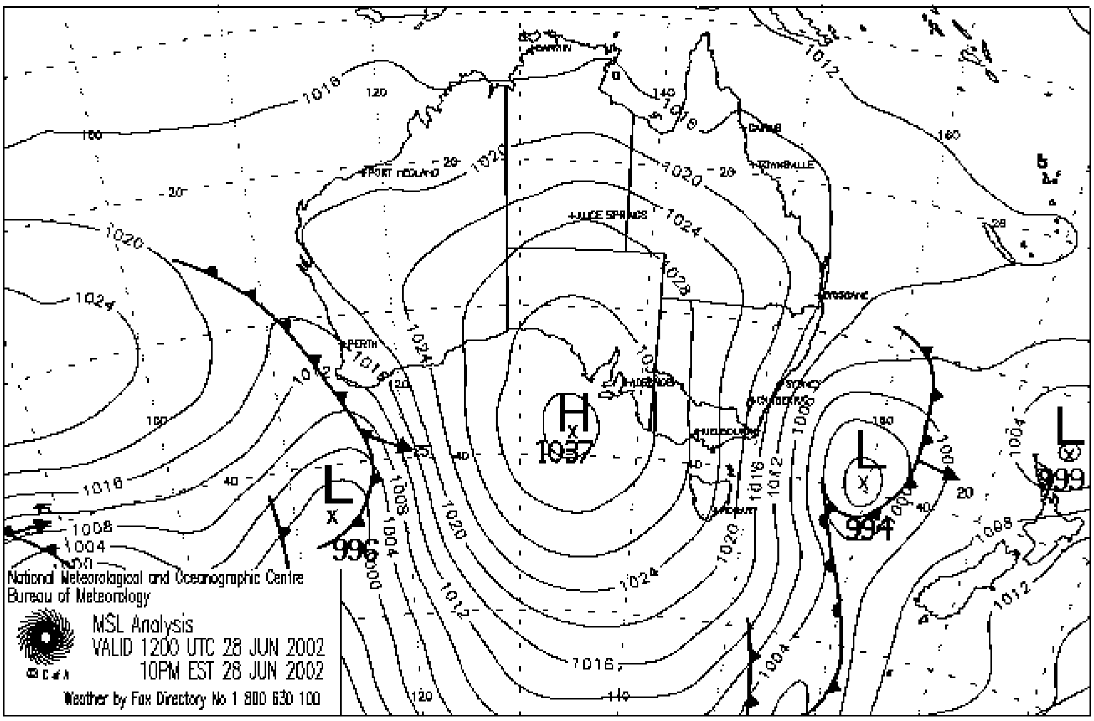


Source: Bureau of Meteorology (1997)

A



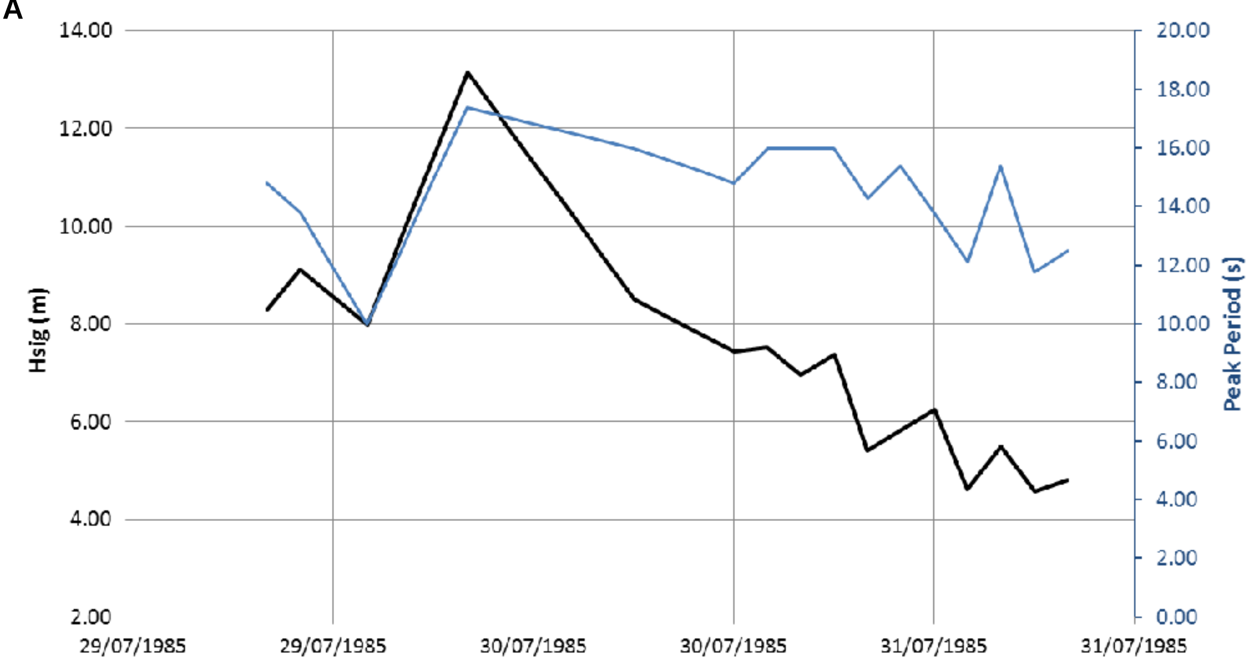
B



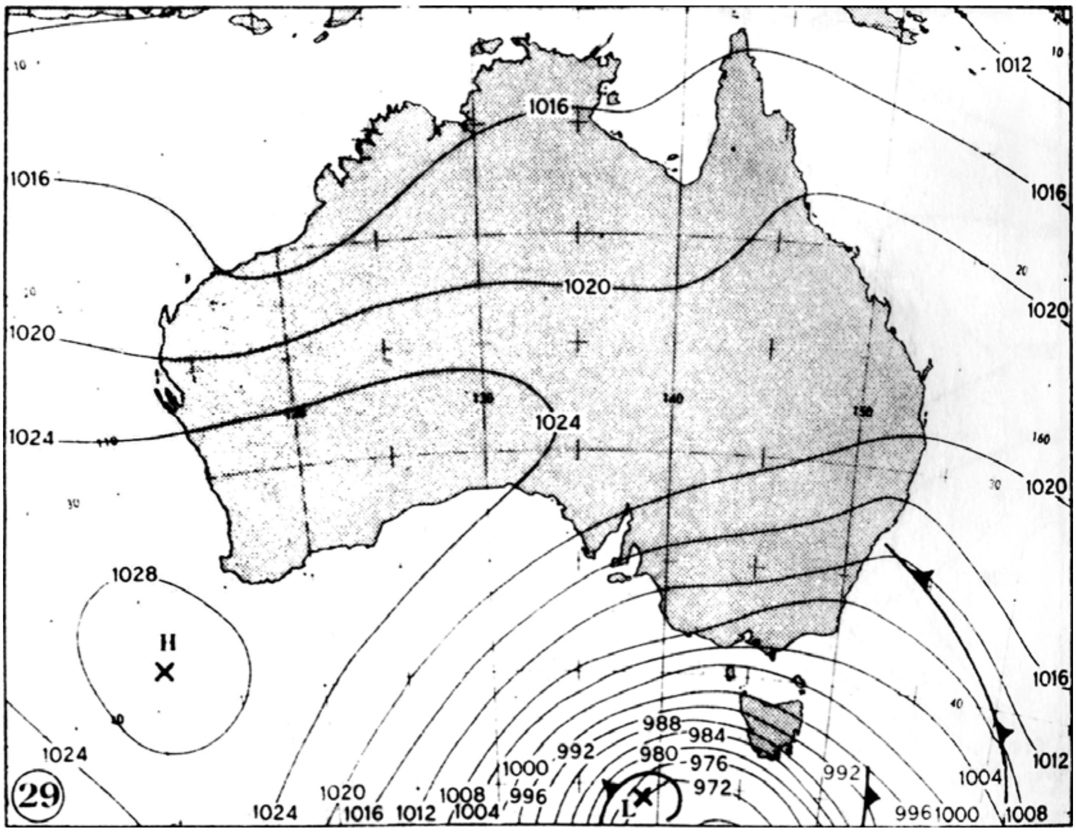
Source: Bureau of Meteorology (2002)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Eden Wave Buoy	Figure D-3

A

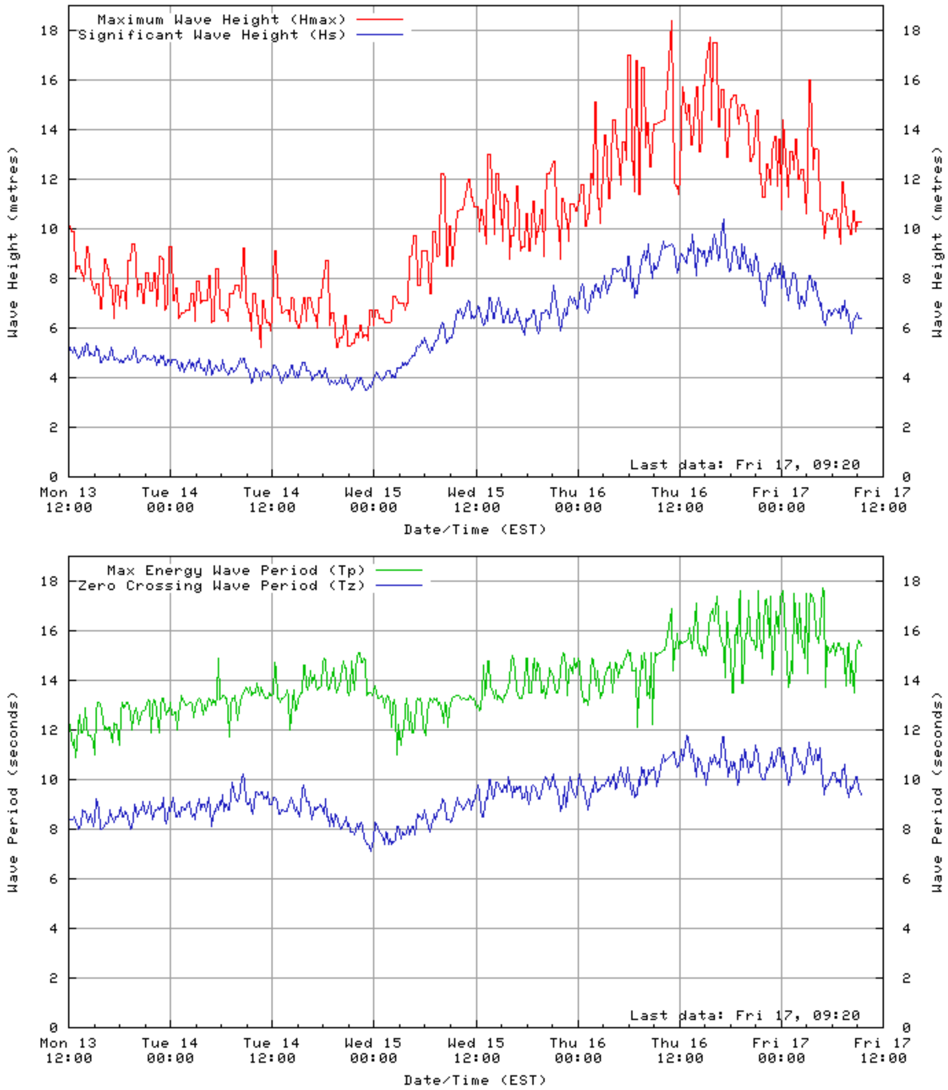


B

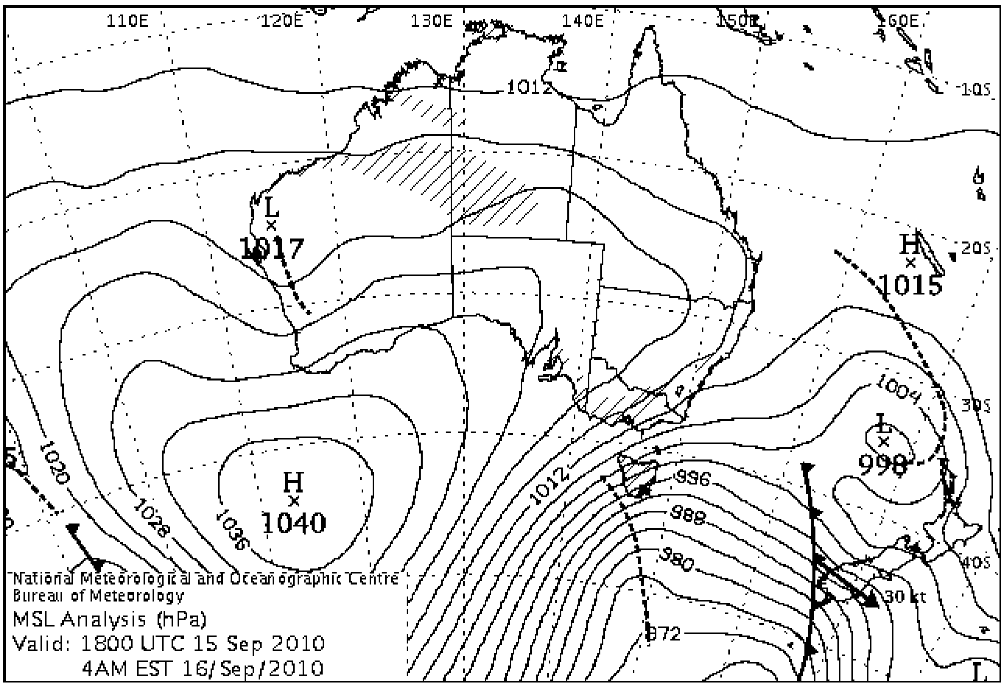


Source: Bureau of Meteorology (1985)

A



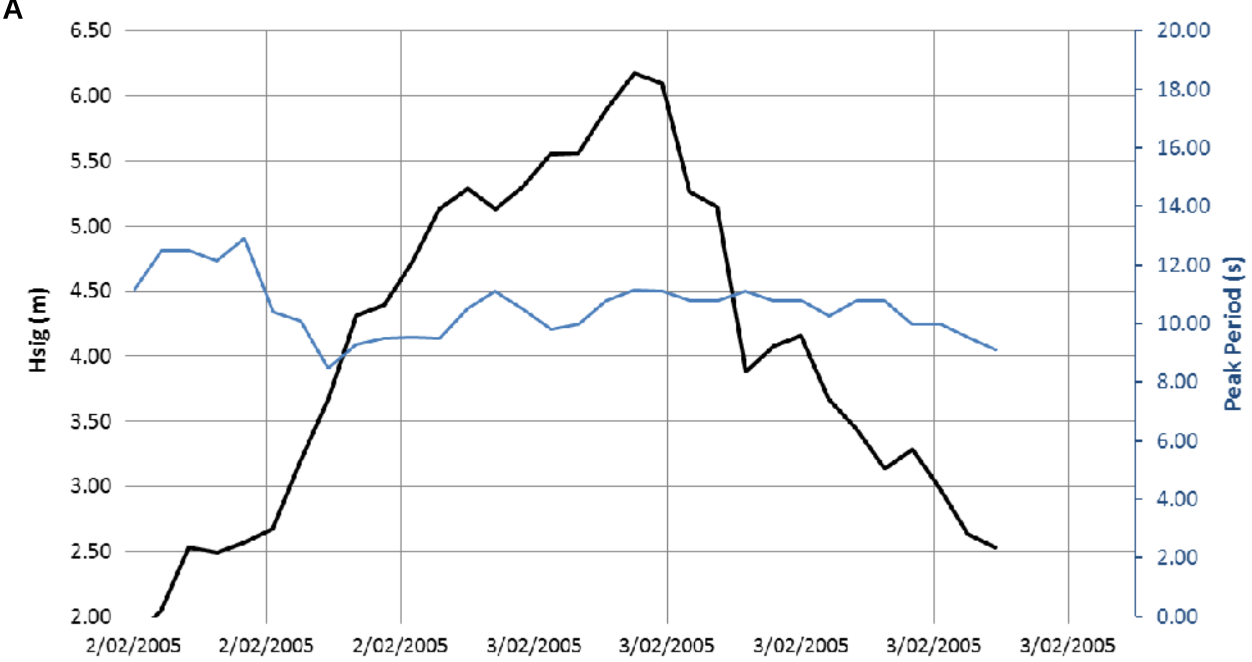
B



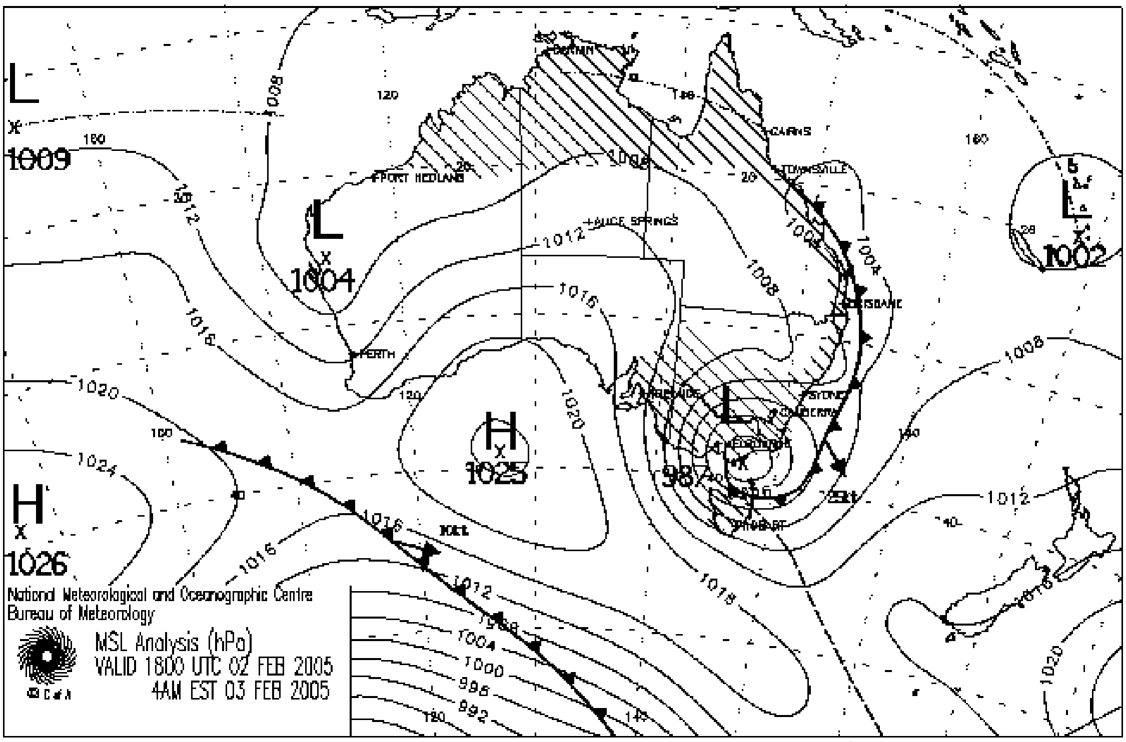
Source: Bureau of Meteorology (2010)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the September 2010 Event Observed at the Cape Sorell Wave Buoy	Figure D-4a

A



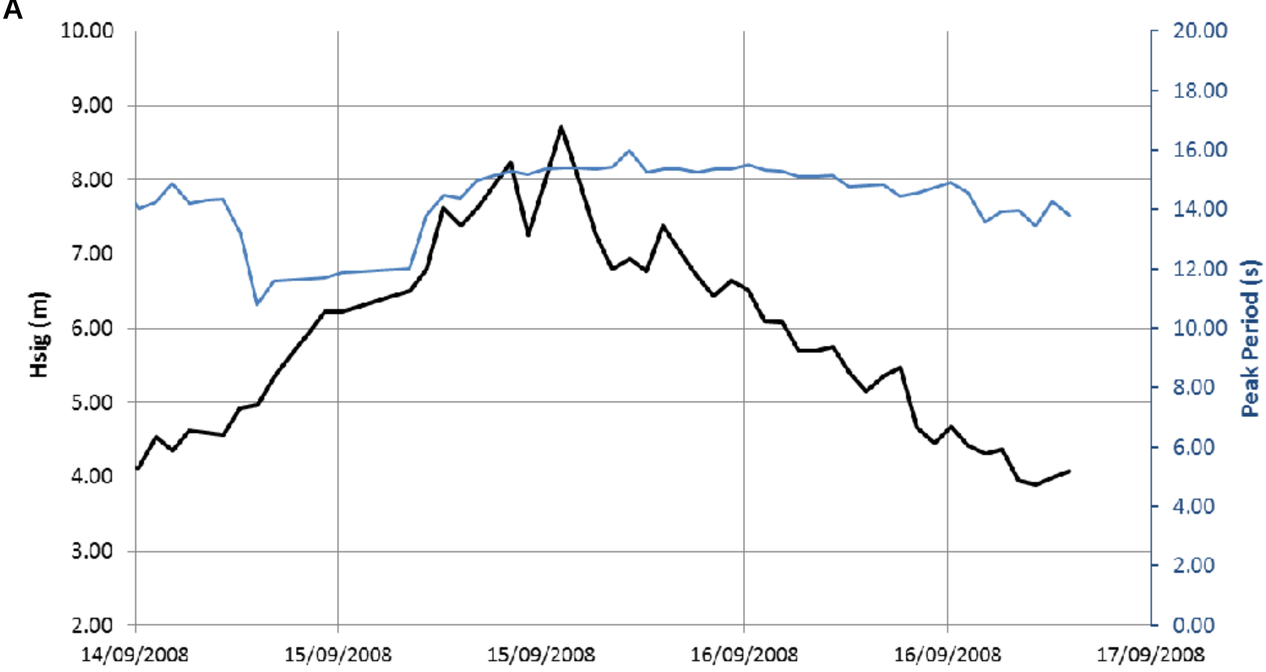
B



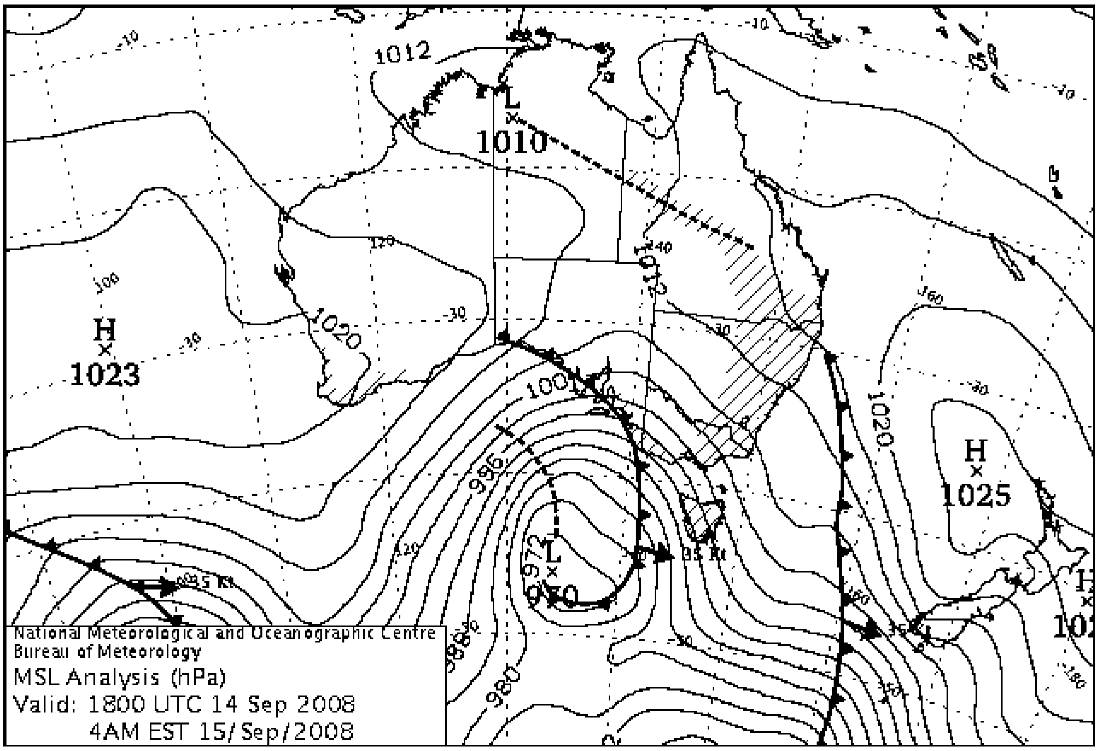
Source: Bureau of Meteorology (2005)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Point Nepean Wave Buoy	Figure D-5

A



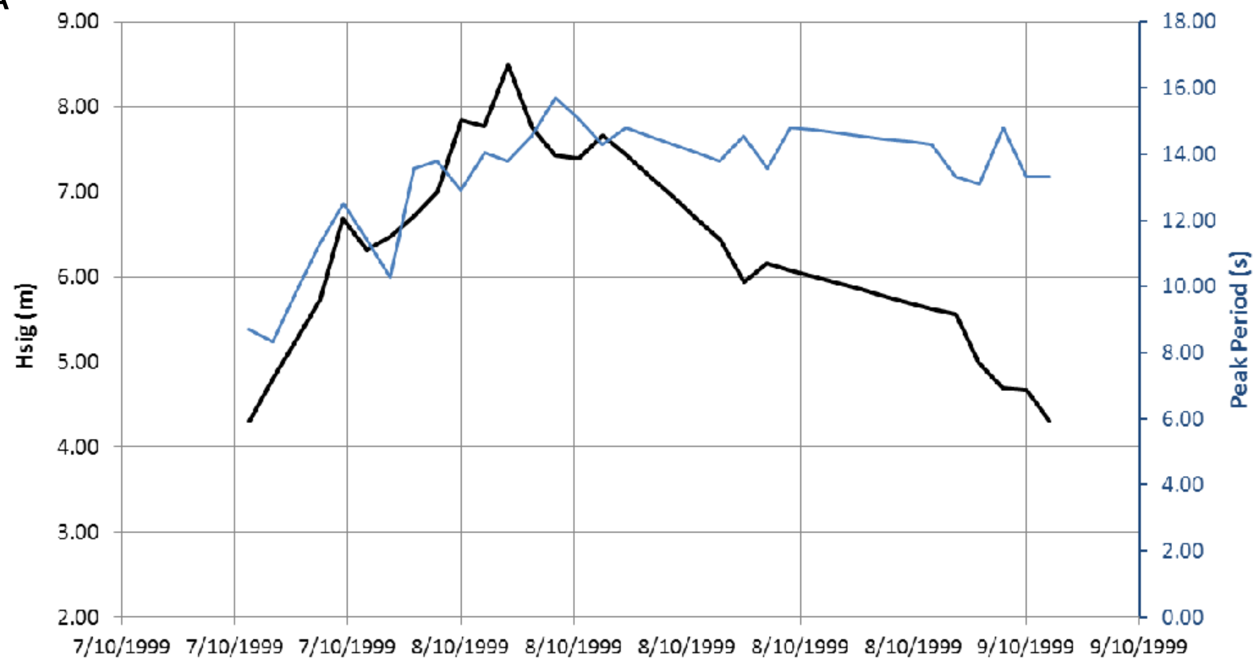
B



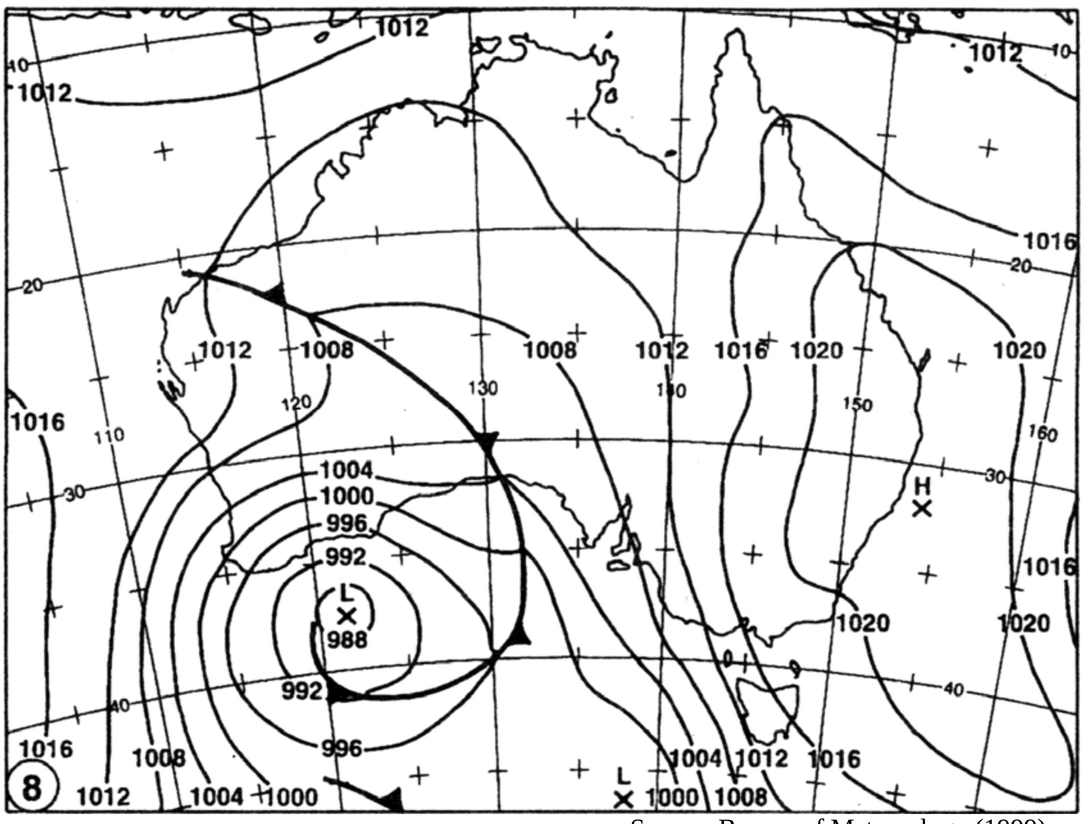
Source: Bureau of Meteorology (2008)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Cape du Couedic Wave Buoy	Figure D-6

A

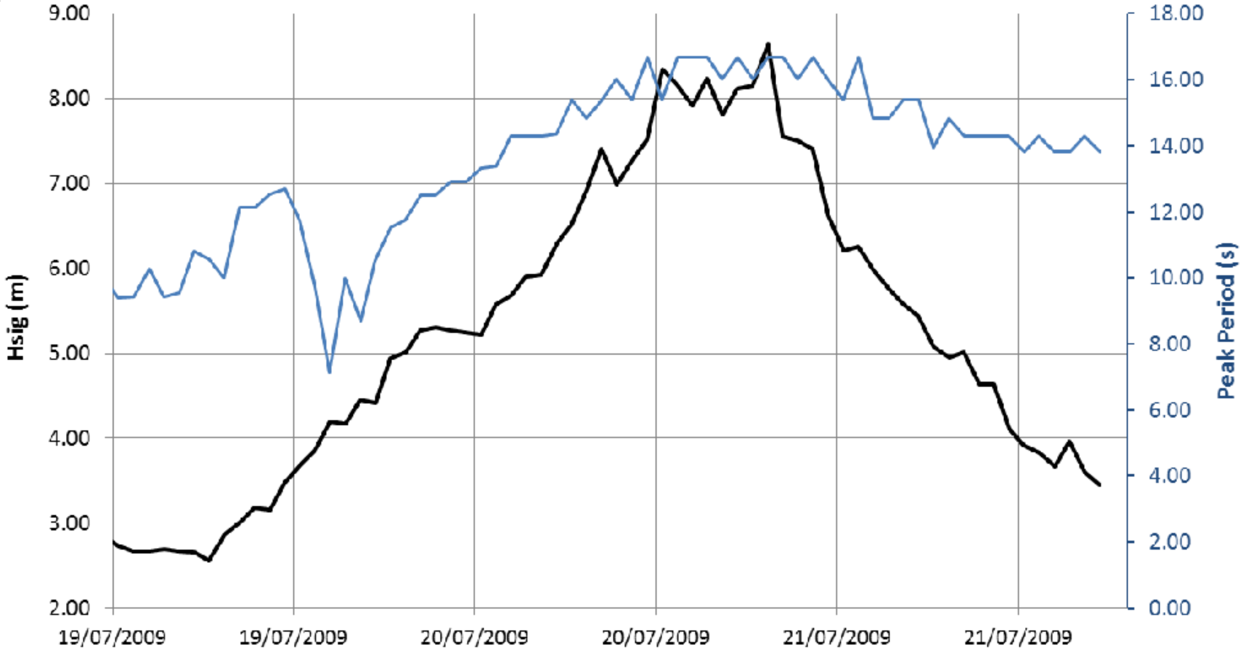


B

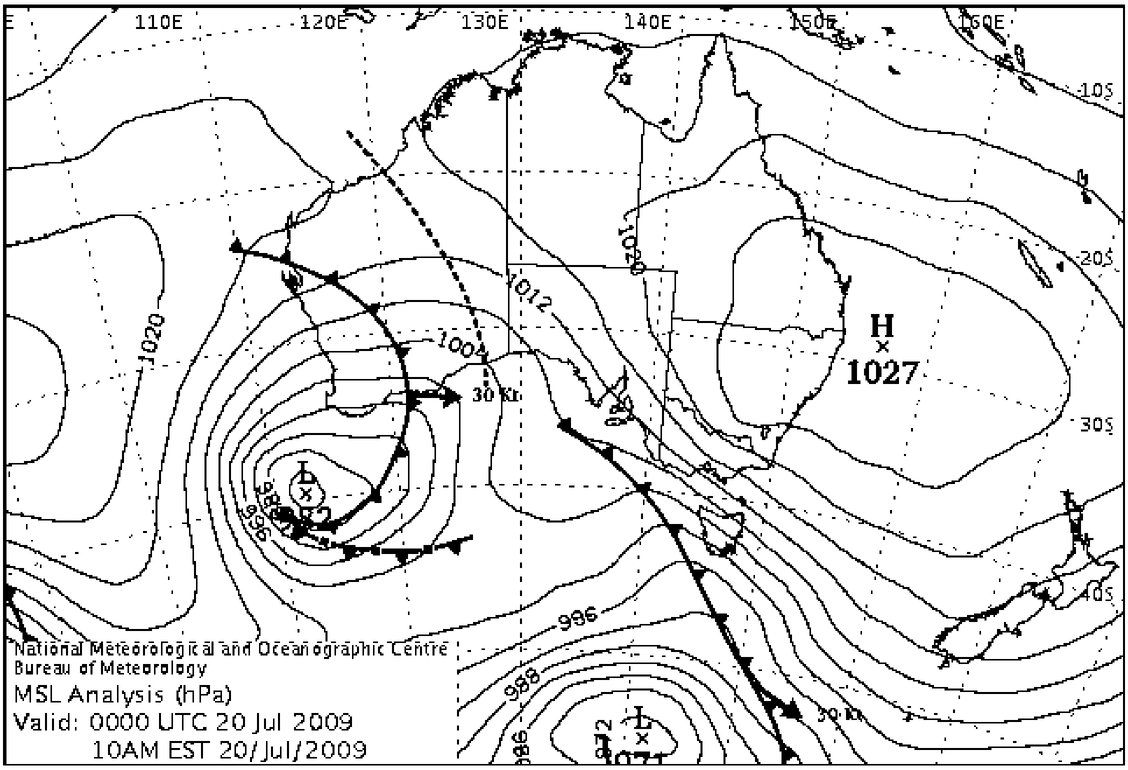


Source: Bureau of Meteorology (1999)

A



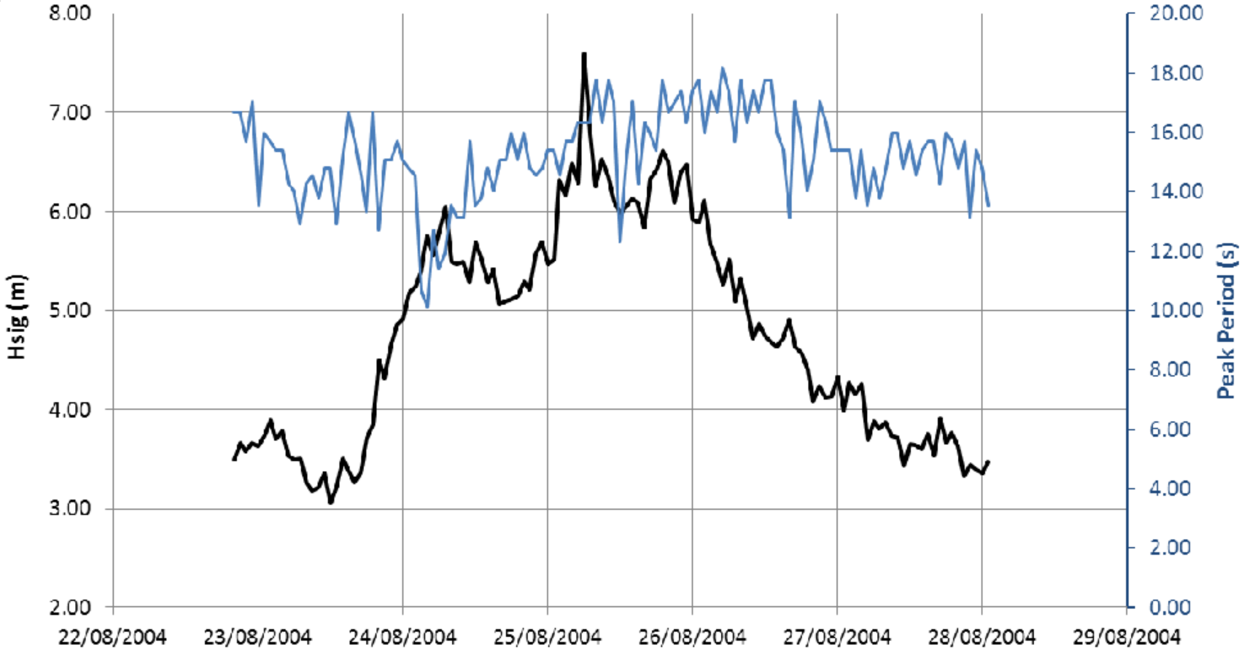
B



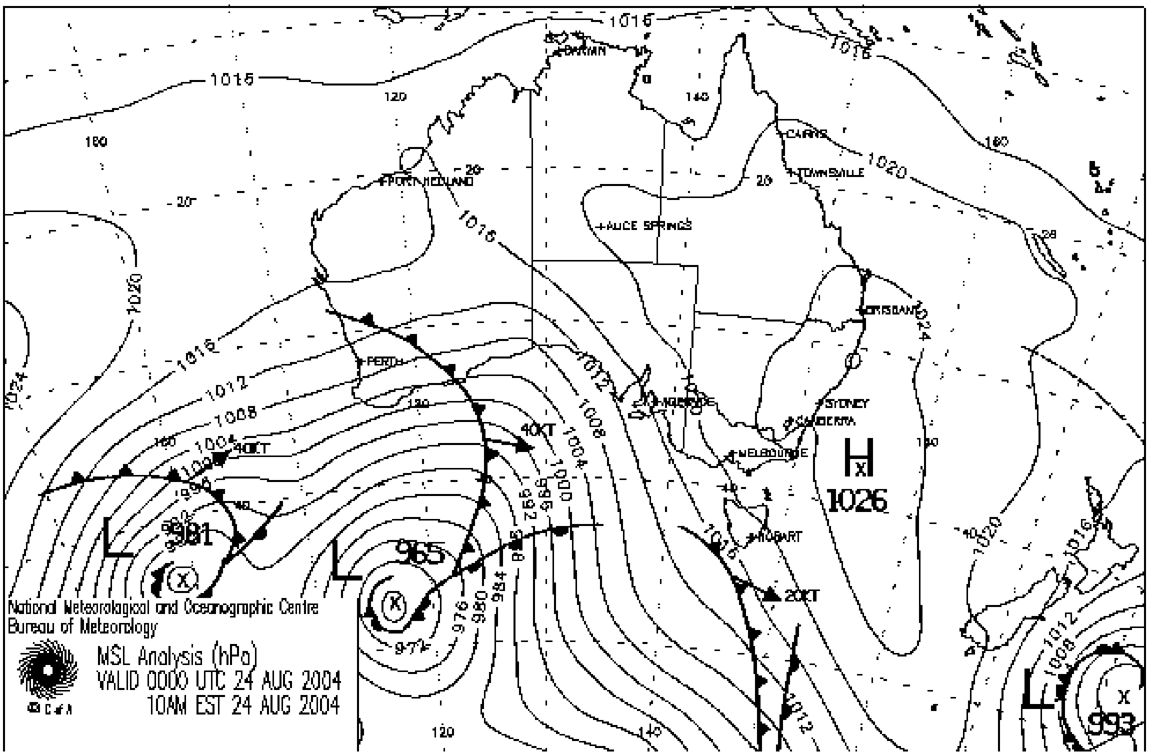
Source: Bureau of Meteorology (2009)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Rottnest Island Wave Buoy	Figure D-8

A



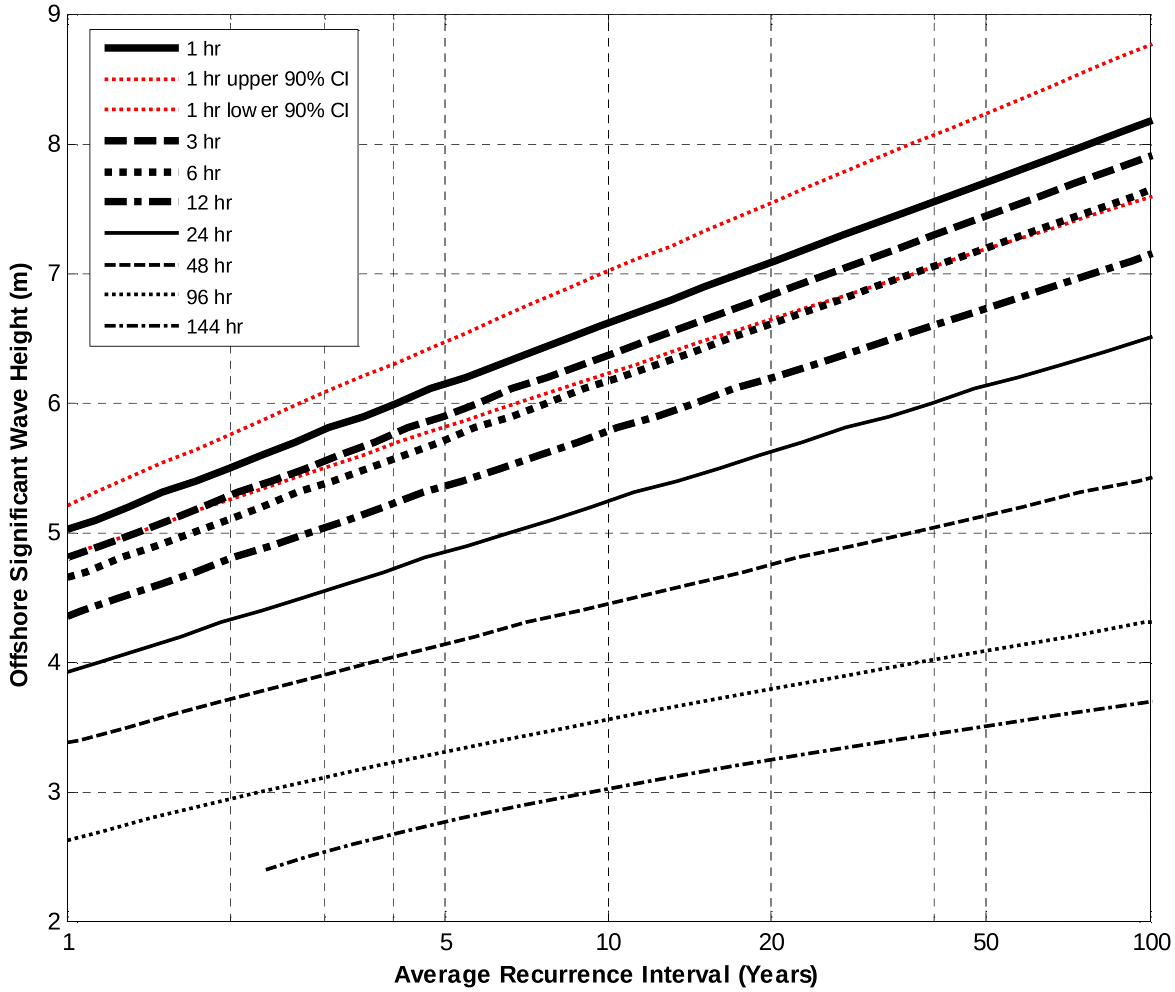
B



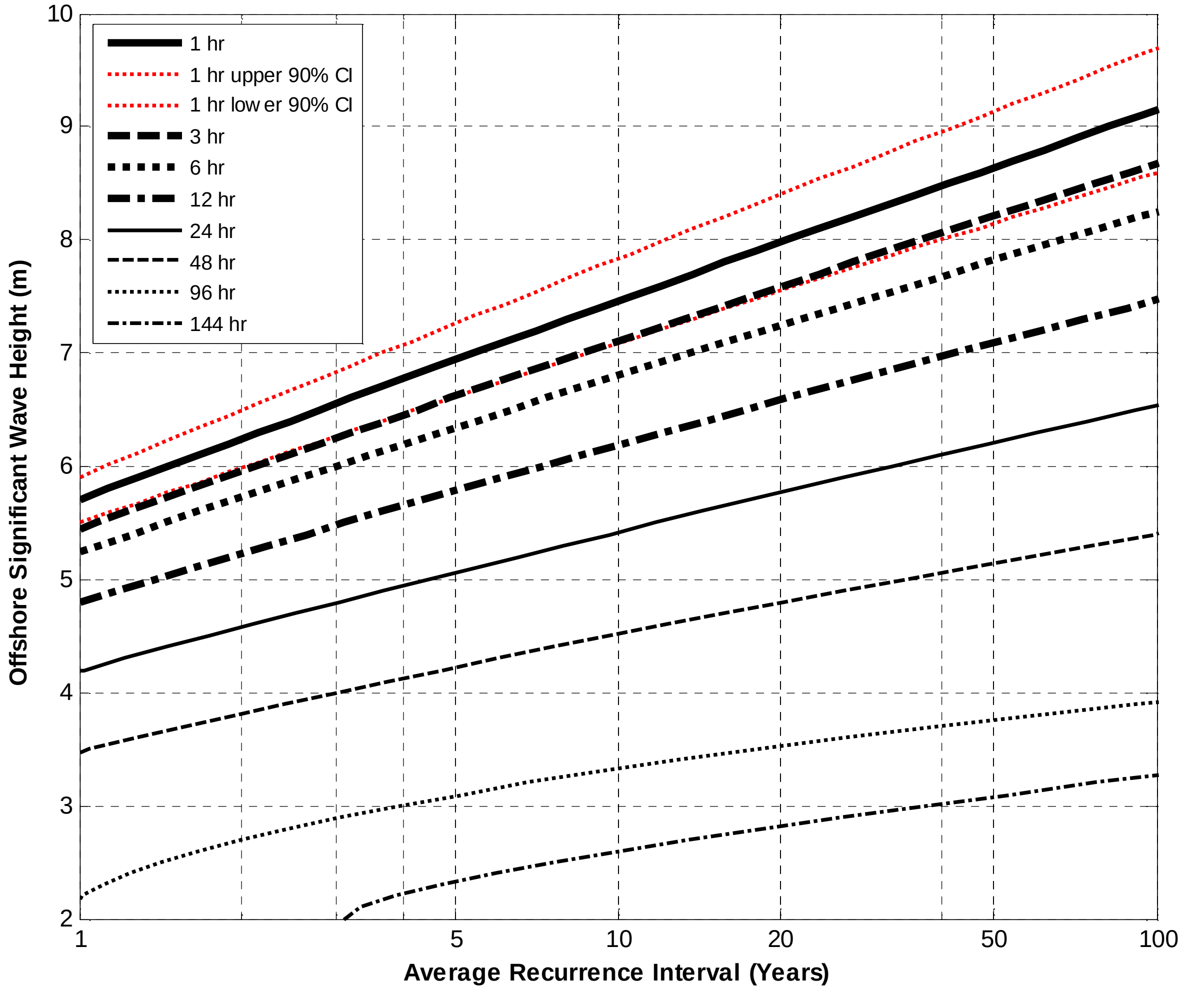
Source: Bureau of Meteorology (2004)

WRL Report No. RR242	Significant Wave Height Timeseries (A) and Sea Level Pressure (B) for the Largest Storm Event Observed at the Jurien Bay Wave Buoy	Figure D-9

APPENDIX E EXTREME WAVE HEIGHTS FOR VARYING AVERAGE RECURRENCE INTERVAL AND DURATION

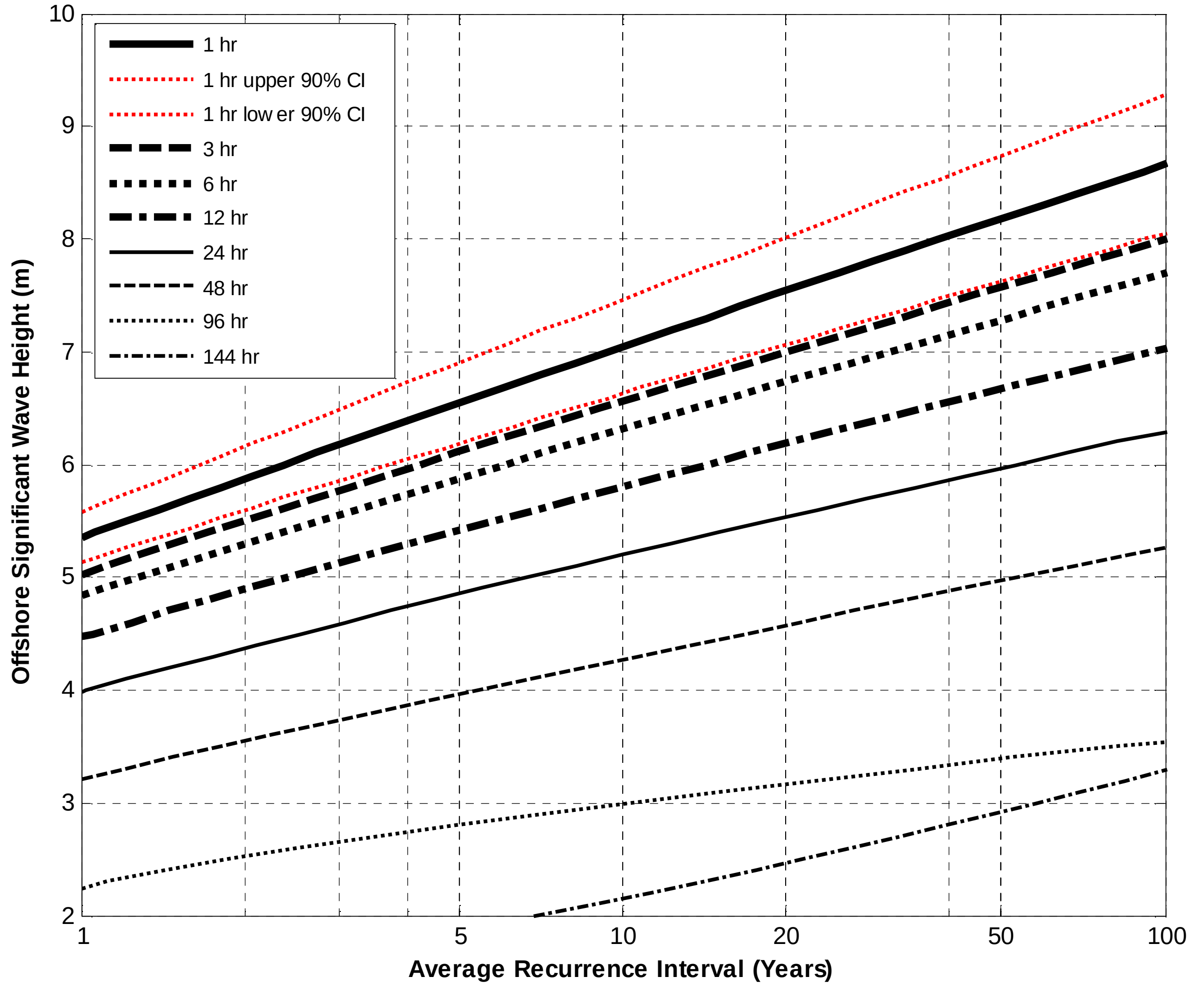


Brisbane Wave Buoy		ARI (years)						
		1	**2**	**5**	**10**	**20**	**50**	**100**
1 hour	**Hs (m)**	5.0	5.5	6.1	6.6	7.1	7.6	8.1
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.5
3 hours	**Hs (m)**	4.8	5.3	5.9	6.4	6.8	7.4	7.8
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.5
6 hours	**Hs (m)**	4.7	5.1	5.7	6.2	6.6	7.2	7.6
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.5
12 hours	**Hs (m)**	4.4	4.8	5.3	5.7	6.1	6.7	7.0
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.4	0.4
24 hours	**Hs (m)**	3.9	4.3	4.8	5.2	5.6	6.1	6.4
	90% CI (± m)	0.1	0.2	0.2	0.3	0.3	0.4	0.4
48 hours	**Hs (m)**	3.4	3.7	4.1	4.5	4.8	5.2	5.5
	90% CI (± m)	0.1	0.2	0.2	0.2	0.3	0.3	0.4
96 hours	**Hs (m)**	2.7	3.0	3.3	3.6	3.8	4.1	4.3
	90% CI (± m)	0.1	0.1	0.2	0.2	0.3	0.3	0.4
144 hours	**Hs (m)**	2.3	2.5	2.8	3.0	3.2	3.5	3.7
	90% CI (± m)	0.1	0.1	0.2	0.2	0.3	0.4	0.4
Energy	**E (MJh/m2)**	0.85	1.13	1.53	1.85	2.19	2.66	3.03
	90% CI (+/- m)	0.13	0.18	0.25	0.31	0.38	0.46	0.53

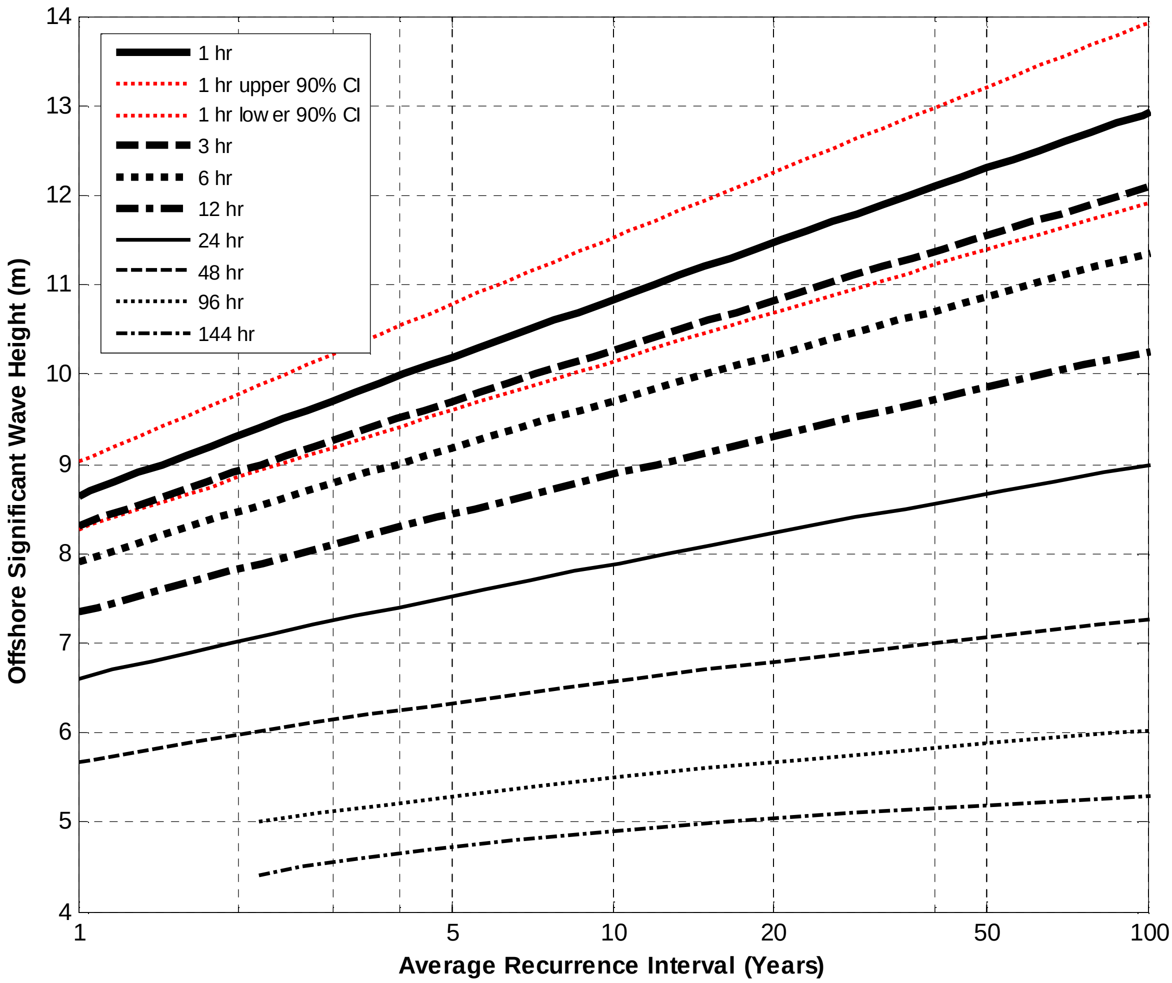


Botany Bay Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	5.7	6.2	6.9	7.5	8.0	8.6	9.1
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.4
3 hours	Hs (m)	5.4	6.0	6.6	7.1	7.6	8.2	8.7
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
6 hours	Hs (m)	5.2	5.7	6.3	6.8	7.2	7.8	8.2
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.4
12 hours	Hs (m)	4.8	5.2	5.8	6.2	6.6	7.1	7.5
	90% CI (± m)	0.1	0.2	0.2	0.2	0.3	0.3	0.3
24 hours	Hs (m)	4.2	4.6	5.1	5.4	5.8	6.2	6.5
	90% CI (± m)	0.1	0.2	0.2	0.2	0.3	0.3	0.3
48 hours	Hs (m)	3.5	3.8	4.2	4.5	4.8	5.1	5.4
	90% CI (± m)	0.1	0.2	0.2	0.2	0.3	0.3	0.3
96 hours	Hs (m)	2.2	2.7	3.1	3.3	3.5	3.8	3.9
	90% CI (± m)	0.1	0.1	0.2	0.2	0.3	0.3	0.3
144 hours	Hs (m)	1.7	1.8	2.3	2.6	2.8	3.1	3.3
	90% CI (± m)	0.4	0.3	0.2	0.2	0.4	0.5	0.6
Energy	E (MJh/m2)	0.82	1.03	1.31	1.53	1.75	2.06	2.29
	90% CI (+/- m)	0.08	0.10	0.13	0.16	0.18	0.21	0.24

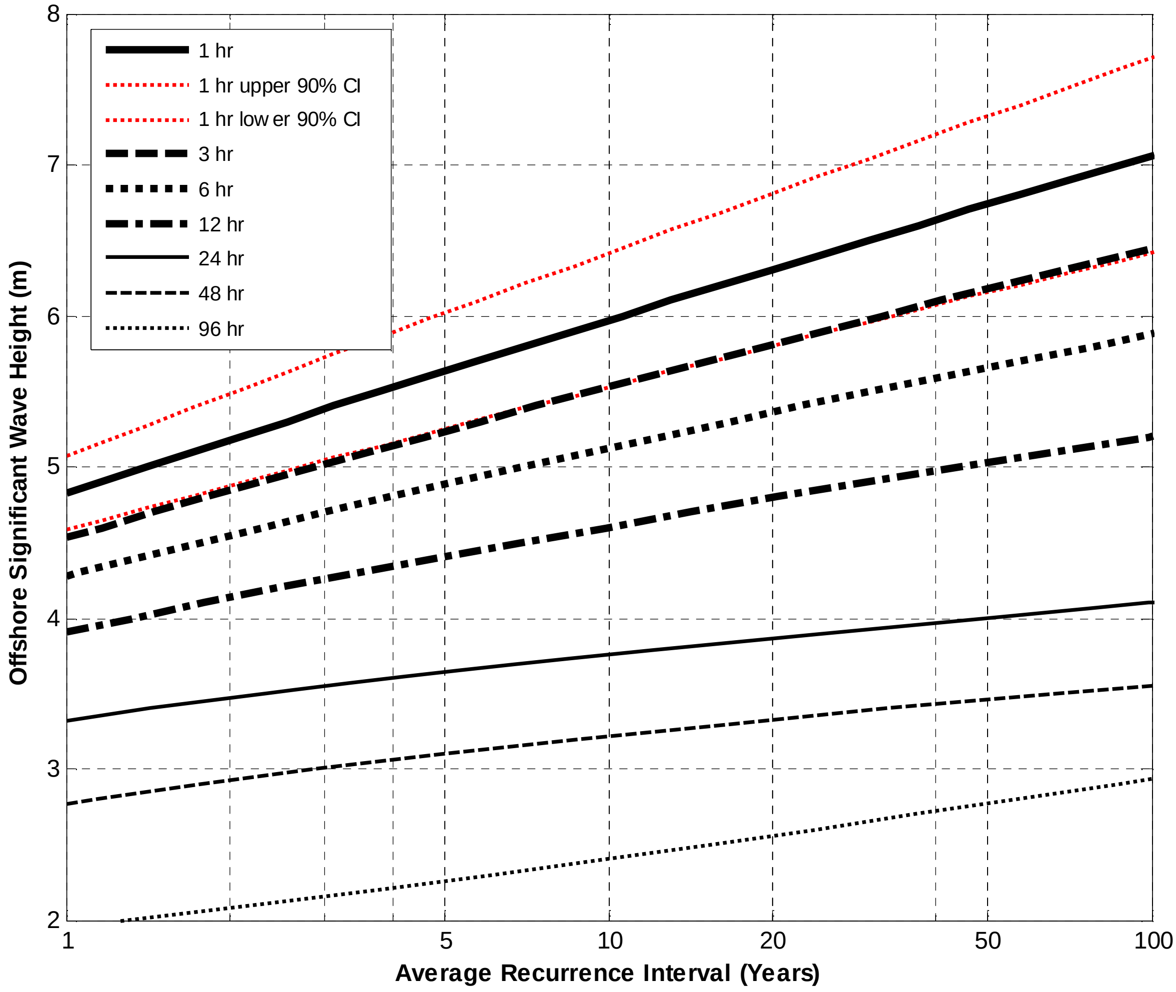
WRL Report No. RR242	ESTIMATED EXTREME VALUES FOR BOTANY BAY	Figure E-2



Eden Wave Buoy		**ARI (years)**						
		1	**2**	**5**	**10**	**20**	**50**	**100**
1 hour	**Hs (m)**	5.4	5.9	6.5	7.0	7.5	8.2	8.7
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.5
3 hours	**Hs (m)**	5.0	5.5	6.1	6.6	7.0	7.6	8.0
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
6 hours	**Hs (m)**	4.8	5.3	5.9	6.3	6.7	7.3	7.7
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
12 hours	**Hs (m)**	4.5	4.9	5.4	5.8	6.2	6.7	7.0
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.4
24 hours	**Hs (m)**	4.0	4.4	4.9	5.2	5.5	6.0	6.3
	90% CI (± m)	0.1	0.2	0.2	0.3	0.3	0.3	0.4
48 hours	**Hs (m)**	3.2	3.5	4.0	4.3	4.6	5.0	5.3
	90% CI (± m)	0.1	0.2	0.2	0.3	0.3	0.4	0.4
96 hours	**Hs (m)**	2.2	2.5	2.8	3.0	3.2	3.4	3.5
	90% CI (± m)	0.1	0.1	0.2	0.2	0.3	0.3	0.4
144 hours	**Hs (m)**	1.2	1.5	1.9	2.1	2.5	2.9	3.3
	90% CI (± m)	3.1	2.1	1.0	0.4	0.8	2.1	3.2
Energy	**E (MJh/m2)**	0.73	0.91	1.14	1.32	1.50	1.74	1.92
	90% CI (+/- m)	0.07	0.09	0.12	0.14	0.16	0.18	0.20



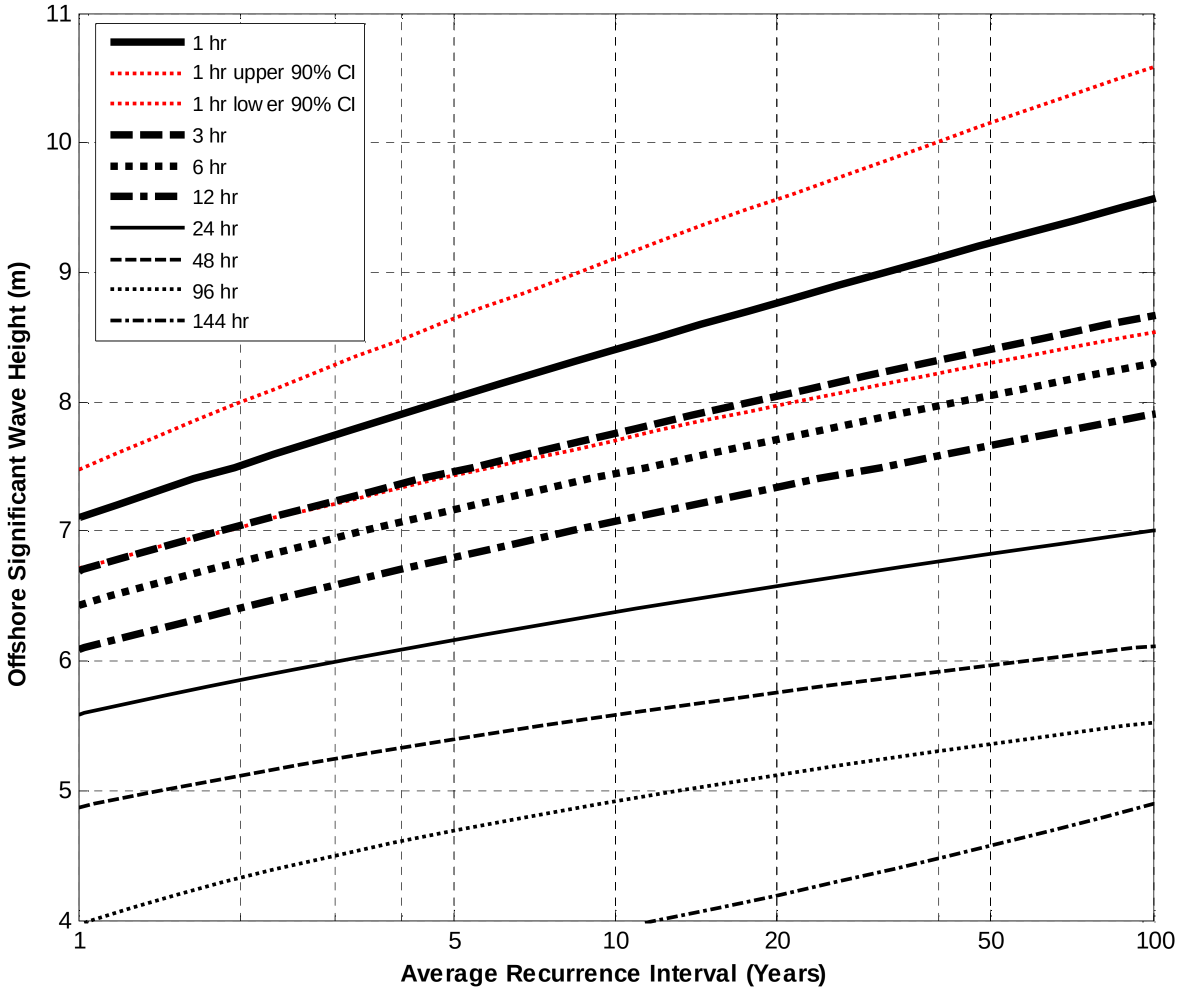
Cape Sorell Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	8.6	9.3	10.2	10.8	11.5	12.3	12.9
	90% CI (± m)	0.3	0.4	0.5	0.6	0.6	0.7	0.8
3 hours	Hs (m)	8.3	8.9	9.7	10.3	10.8	11.6	12.1
	90% CI (± m)	0.3	0.3	0.4	0.5	0.5	0.6	0.7
6 hours	Hs (m)	7.9	8.5	9.2	9.7	10.2	10.9	11.4
	90% CI (± m)	0.3	0.3	0.4	0.4	0.5	0.6	0.6
12 hours	Hs (m)	7.3	7.8	8.4	8.9	9.3	9.9	10.3
	90% CI (± m)	0.2	0.3	0.3	0.4	0.4	0.5	0.5
24 hours	Hs (m)	6.6	7.0	7.5	7.9	8.2	8.7	9.0
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.4
48 hours	Hs (m)	5.7	6.0	6.3	6.6	6.8	7.1	7.3
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.3
96 hours	Hs (m)	4.6	5.0	5.3	5.5	5.7	5.9	6.0
	90% CI (± m)	0.1	0.2	0.2	0.3	0.3	0.4	0.4
144 hours	Hs (m)	4.1	4.3	4.7	4.9	5.0	5.2	5.3
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.4	0.5
Energy	E (MJh/m2)	2.36	2.88	3.59	4.13	4.67	5.39	5.93
	90% CI (+/- m)	0.27	0.34	0.44	0.52	0.59	0.69	0.77



Point Nepean Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	4.8	5.2	5.6	6.0	6.3	6.7	7.1
	90% CI (± m)	0.2	0.3	0.3	0.3	0.4	0.4	0.5
3 hours	Hs (m)	4.5	4.8	5.2	5.5	5.8	6.2	6.4
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
6 hours	Hs (m)	4.3	4.5	4.9	5.1	5.4	5.7	5.9
	90% CI (± m)	0.2	0.2	0.2	0.2	0.3	0.3	0.3
12 hours	Hs (m)	3.9	4.1	4.4	4.6	4.8	5.0	5.2
	90% CI (± m)	0.1	0.1	0.2	0.2	0.2	0.2	0.3
24 hours	Hs (m)	3.3	3.5	3.6	3.8	3.9	4.0	4.1
	90% CI (± m)	0.1	0.1	0.1	0.1	0.1	0.1	0.2
48 hours	Hs (m)	2.8	2.9	3.1	3.2	3.3	3.5	3.6
	90% CI (± m)	0.1	0.1	0.2	0.2	0.2	0.2	0.2
96 hours	Hs (m)	2.0	2.1	2.3	2.4	2.6	2.8	2.9
	90% CI (± m)	0.3	0.1	0.2	0.5	0.7	1.0	1.2
144 hours	Hs (m)	-	-	-	-	-	-	-
	90% CI (± m)	-	-	-	-	-	-	-
Energy	E (MJh/m2)	0.47	0.54	0.64	0.72	0.79	0.88	0.95
	90% CI (+/- m)	0.04	0.05	0.06	0.07	0.08	0.09	0.10

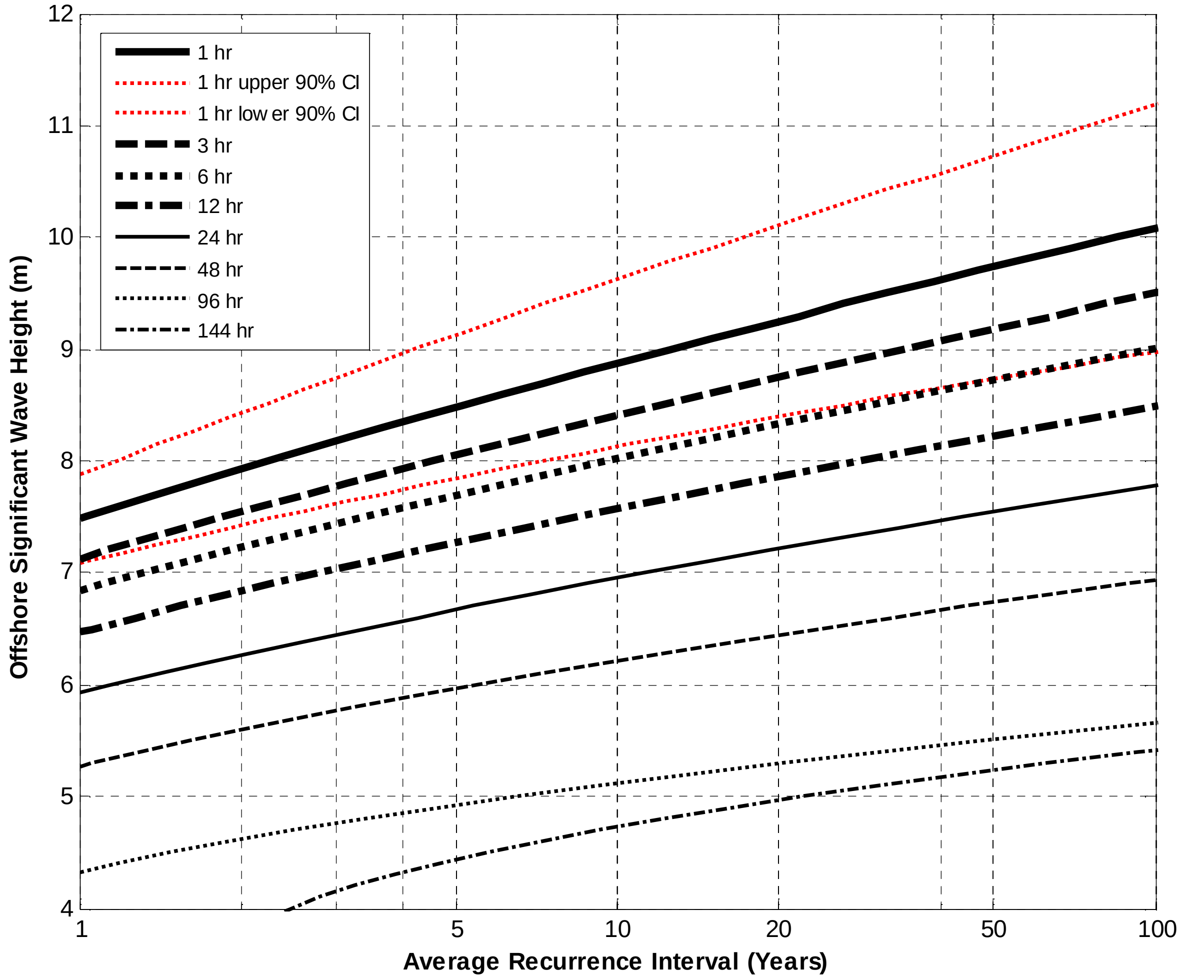
ESTIMATED EXTREME VALUES FOR POINT NEPEAN

Figure
E-5

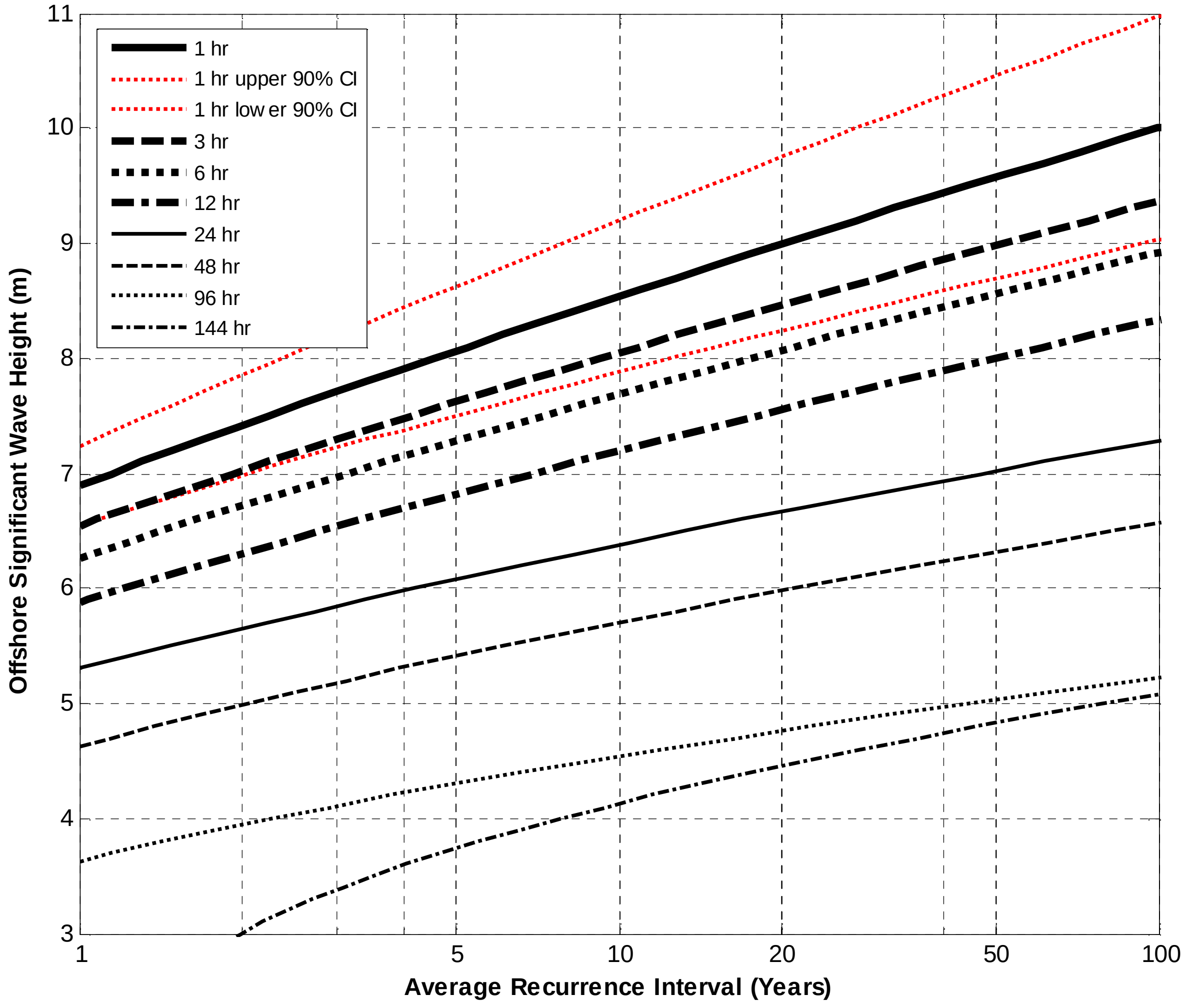


Cape du Couedic Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	7.1	7.5	8.0	8.4	8.8	9.2	9.6
	90% CI (± m)	0.3	0.3	0.4	0.4	0.5	0.5	0.6
3 hours	Hs (m)	6.7	7.0	7.5	7.8	8.1	8.4	8.7
	90% CI (± m)	0.2	0.3	0.3	0.3	0.4	0.4	0.4
6 hours	Hs (m)	6.4	6.8	7.2	7.4	7.7	8.1	8.3
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
12 hours	Hs (m)	6.1	6.4	6.8	7.1	7.3	7.7	7.9
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
24 hours	Hs (m)	5.6	5.9	6.2	6.4	6.6	6.8	7.0
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.3
48 hours	Hs (m)	4.9	5.1	5.4	5.6	5.8	6.0	6.1
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.3	0.4
96 hours	Hs (m)	4.0	4.3	4.7	4.9	5.1	5.4	5.5
	90% CI (± m)	0.2	0.3	0.4	0.5	0.5	0.6	0.7
144 hours	Hs (m)	3.5	3.5	3.7	3.9	4.2	4.6	4.9
	90% CI (± m)	0.7	0.4	0.3	1.0	1.9	3.2	4.3
Energy	E (MJh/m2)	1.67	2.03	2.49	2.85	3.20	3.67	4.03
	90% CI (+/- m)	0.25	0.31	0.39	0.46	0.52	0.61	0.67

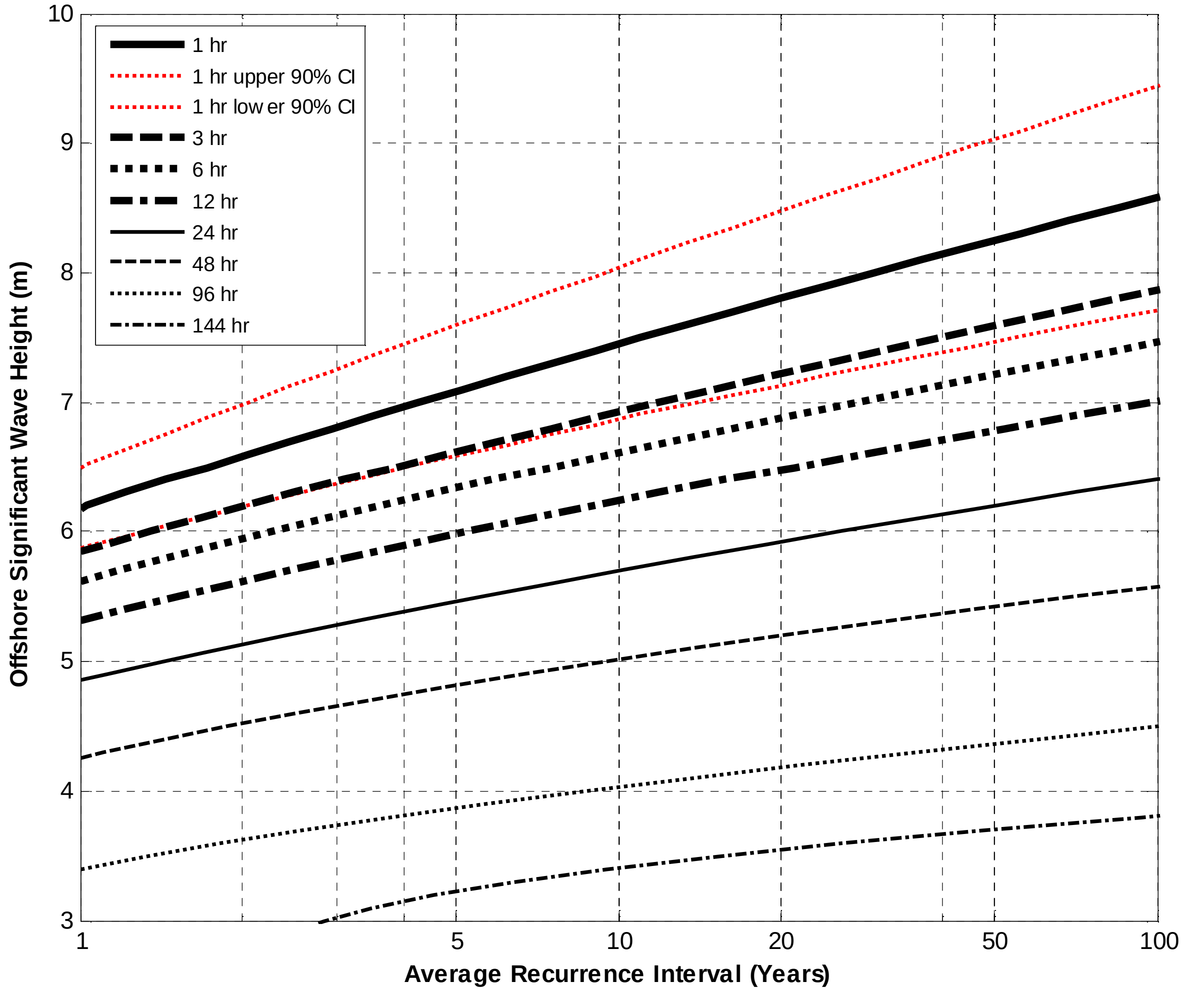
WRL Report No. RR242	ESTIMATED EXTREME VALUES FOR CAPE DU COUEDIC	Figure E-6



Cape Naturaliste Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	7.5	7.9	8.5	8.9	9.3	9.7	10.1
	90% CI (± m)	0.3	0.3	0.4	0.4	0.5	0.5	0.5
3 hours	Hs (m)	7.1	7.5	8.1	8.4	8.8	9.2	9.5
	90% CI (± m)	0.2	0.3	0.3	0.4	0.4	0.4	0.5
6 hours	Hs (m)	6.8	7.2	7.7	8.0	8.3	8.7	9.0
	90% CI (± m)	0.2	0.3	0.3	0.3	0.4	0.4	0.4
12 hours	Hs (m)	6.5	6.8	7.3	7.6	7.9	8.2	8.5
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
24 hours	Hs (m)	5.9	6.3	6.7	6.9	7.2	7.5	7.8
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
48 hours	Hs (m)	5.3	5.6	6.0	6.2	6.5	6.7	6.9
	90% CI (± m)	0.2	0.3	0.3	0.3	0.4	0.4	0.4
96 hours	Hs (m)	4.3	4.6	4.9	5.1	5.3	5.5	5.7
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.5
144 hours	Hs (m)	3.4	3.8	4.4	4.7	5.0	5.2	5.4
	90% CI (± m)	0.5	0.3	0.5	0.8	0.9	1.1	1.3
Energy	E (MJh/m2)	2.06	2.53	3.16	3.64	4.12	4.75	5.23
	90% CI (+/- m)	0.31	0.39	0.51	0.59	0.68	0.80	0.89

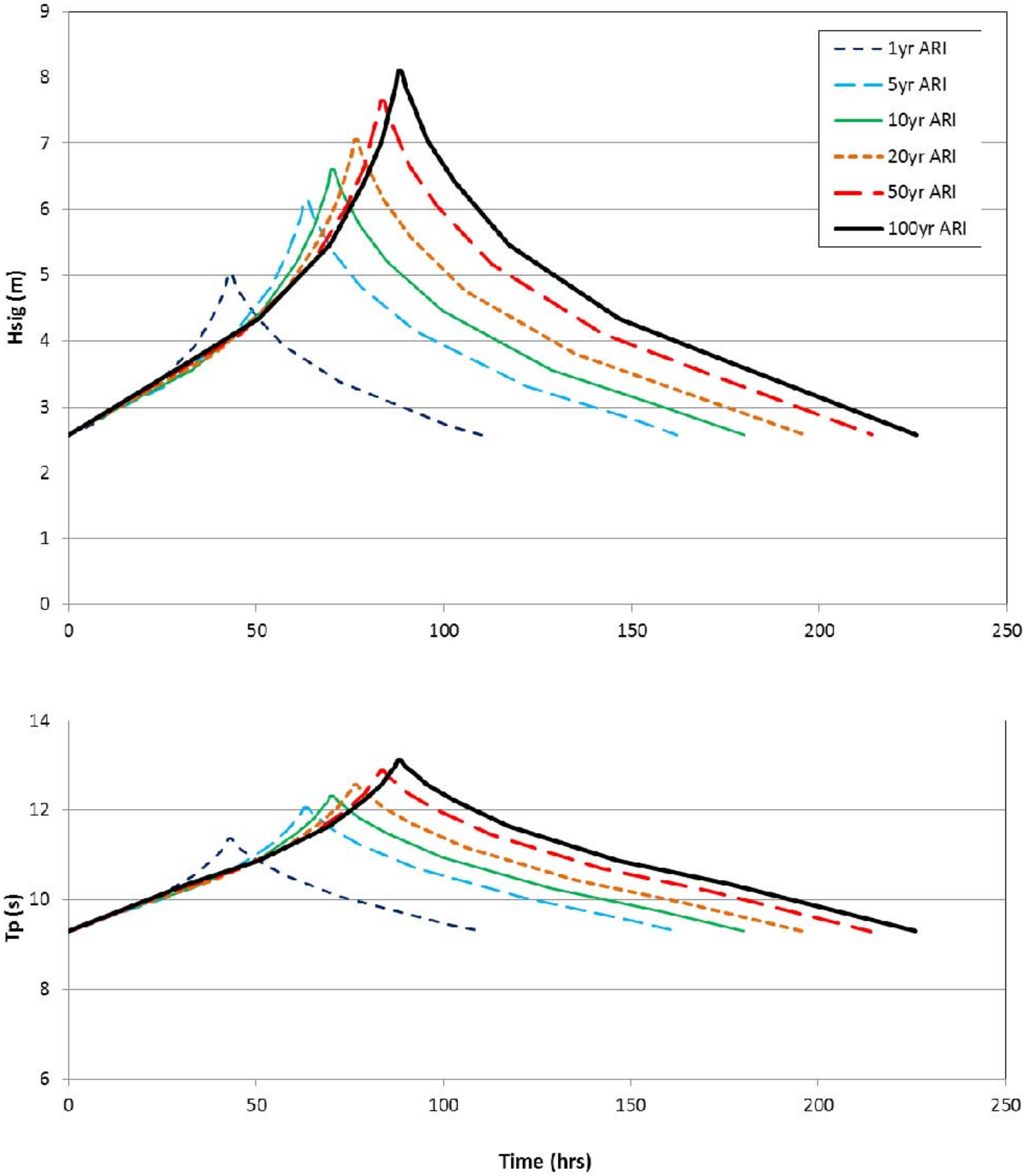


Rottnest Is. Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	6.9	7.4	8.1	8.5	9.0	9.6	10.0
	90% CI (± m)	0.3	0.3	0.4	0.4	0.5	0.5	0.6
3 hours	Hs (m)	6.5	7.0	7.6	8.0	8.5	9.0	9.4
	90% CI (± m)	0.2	0.3	0.3	0.4	0.4	0.5	0.5
6 hours	Hs (m)	6.3	6.7	7.3	7.7	8.1	8.6	8.9
	90% CI (± m)	0.2	0.3	0.3	0.4	0.4	0.4	0.5
12 hours	Hs (m)	5.9	6.3	6.8	7.2	7.6	8.0	8.3
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.4
24 hours	Hs (m)	5.3	5.7	6.1	6.4	6.7	7.0	7.3
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.4
48 hours	Hs (m)	4.6	5.0	5.4	5.7	6.0	6.3	6.6
	90% CI (± m)	0.2	0.2	0.3	0.3	0.4	0.4	0.4
96 hours	Hs (m)	3.6	3.9	4.3	4.5	4.8	5.0	5.2
	90% CI (± m)	0.1	0.2	0.3	0.3	0.4	0.5	0.5
144 hours	Hs (m)	2.0	3.0	3.7	4.1	4.5	4.8	5.1
	90% CI (± m)	0.4	0.3	0.5	0.6	0.7	0.9	1.0
Energy	E (MJh/m2)	1.63	2.09	2.73	3.24	3.76	4.48	5.04
	90% CI (+/- m)	0.28	0.37	0.51	0.62	0.73	0.88	1.00

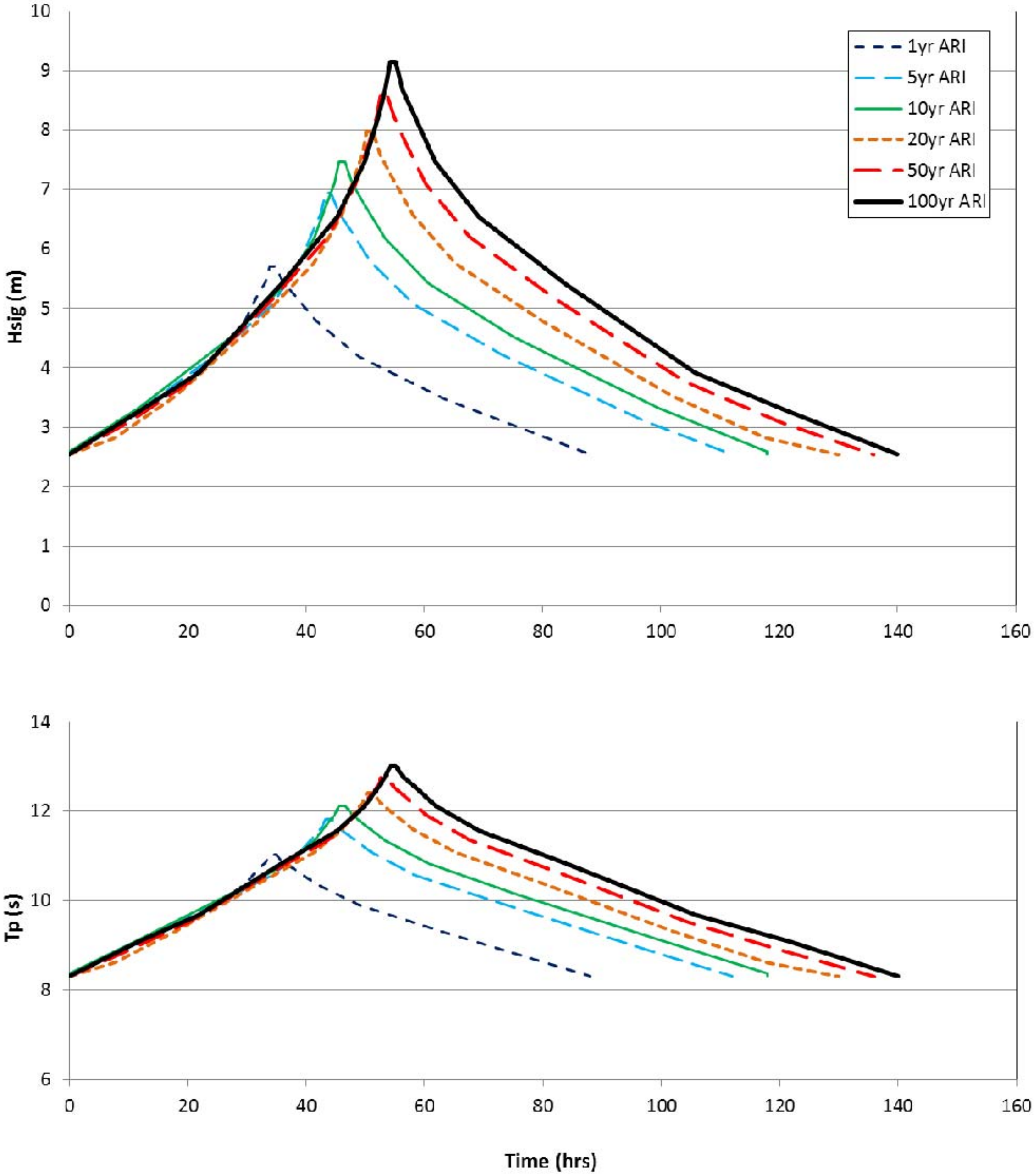


Jurien Bay Wave Buoy		ARI (years)						
		1	2	5	10	20	50	100
1 hour	Hs (m)	6.2	6.6	7.1	7.5	7.8	8.2	8.6
	90% CI (± m)	0.2	0.3	0.3	0.4	0.4	0.5	0.5
3 hours	Hs (m)	5.8	6.2	6.6	6.9	7.2	7.6	7.9
	90% CI (± m)	0.2	0.2	0.3	0.3	0.3	0.4	0.4
6 hours	Hs (m)	5.6	5.9	6.3	6.6	6.9	7.2	7.5
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.4
12 hours	Hs (m)	5.3	5.6	6.0	6.2	6.5	6.8	7.0
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.3
24 hours	Hs (m)	4.9	5.1	5.5	5.7	5.9	6.2	6.4
	90% CI (± m)	0.2	0.2	0.2	0.2	0.3	0.3	0.3
48 hours	Hs (m)	4.3	4.5	4.8	5.0	5.2	5.4	5.6
	90% CI (± m)	0.2	0.2	0.2	0.3	0.3	0.3	0.3
96 hours	Hs (m)	3.4	3.6	3.9	4.0	4.2	4.4	4.5
	90% CI (± m)	0.1	0.2	0.2	0.3	0.3	0.4	0.4
144 hours	Hs (m)	2.7	2.7	3.2	3.4	3.6	3.7	3.8
	90% CI (± m)	0.3	0.3	0.3	0.4	0.6	0.7	0.8
Energy	E (MJh/m2)	1.23	1.47	1.78	2.02	2.25	2.55	2.78
	90% CI (+/- m)	0.14	0.18	0.22	0.26	0.29	0.33	0.36

APPENDIX F SYNTHETIC DESIGN STORM EVENTS



WRL Report No. RR242	SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR BRISBANE	Figure F-1



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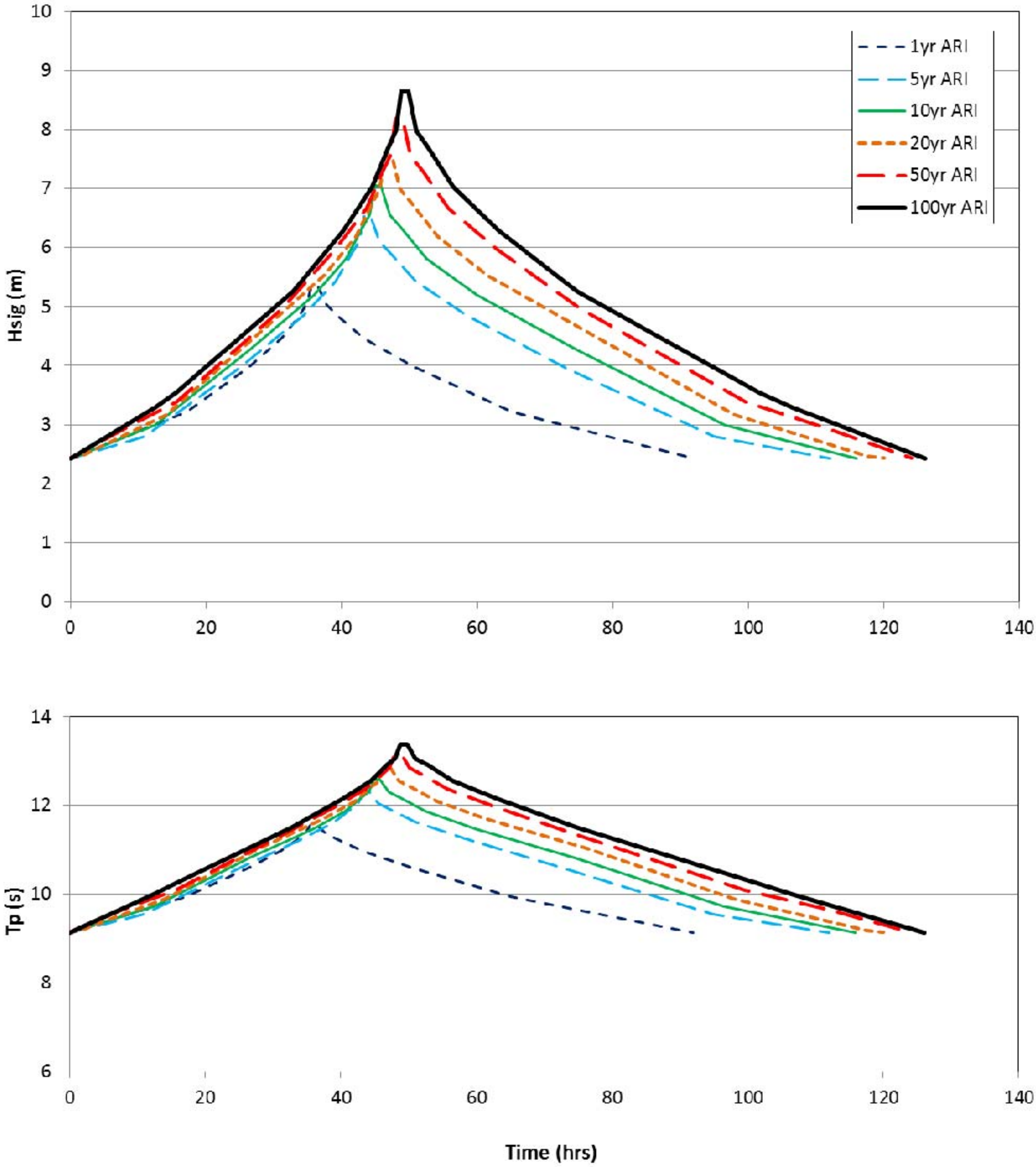
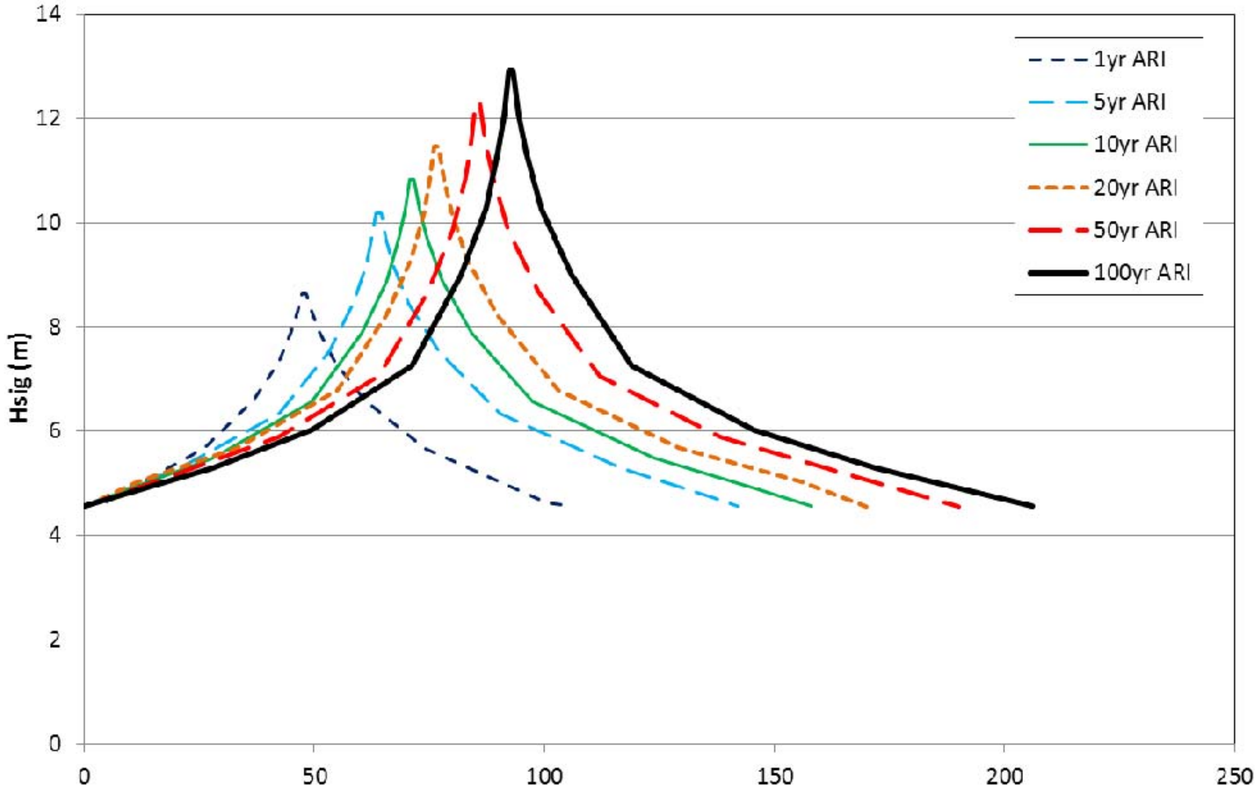
Report No. RR242

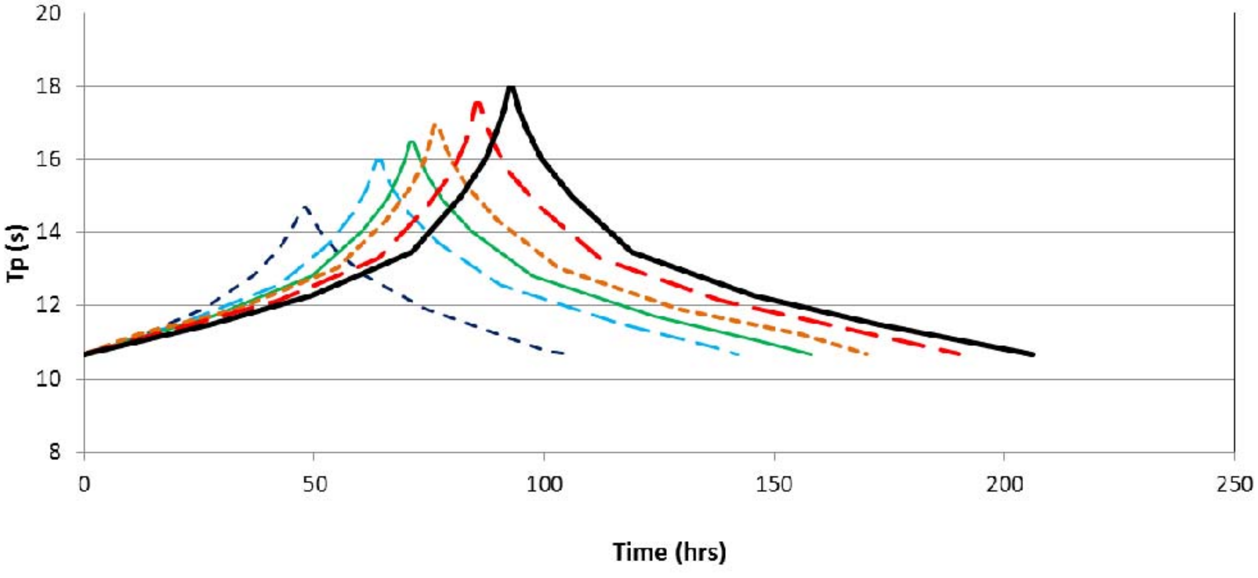
SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR BOTANY BAY

Figure F-2

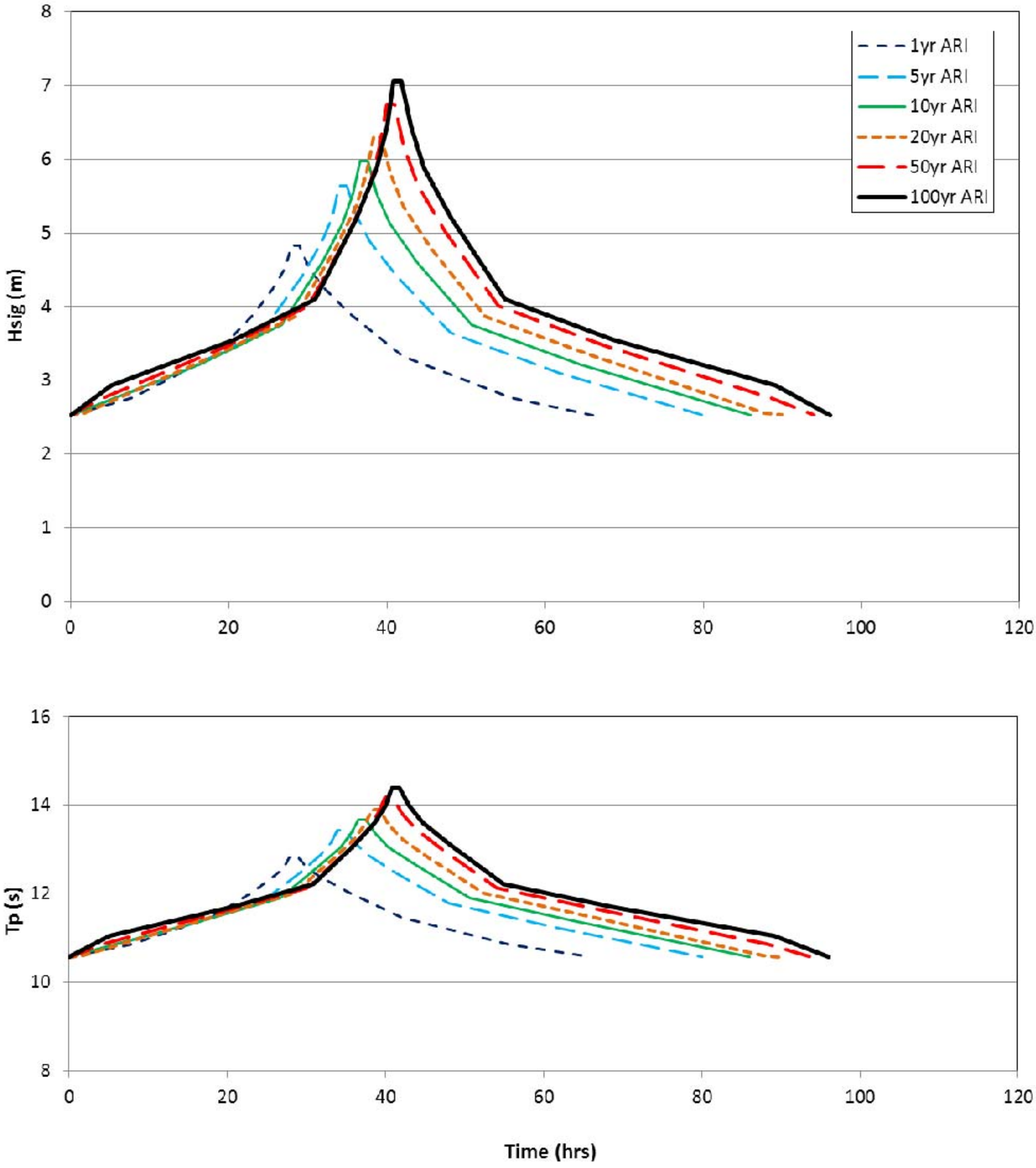


WRL Report No. RR242	SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR EDEN	Figure F-3





WRL Report No. RR242	SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR CAPE SORELL	Figure F-4

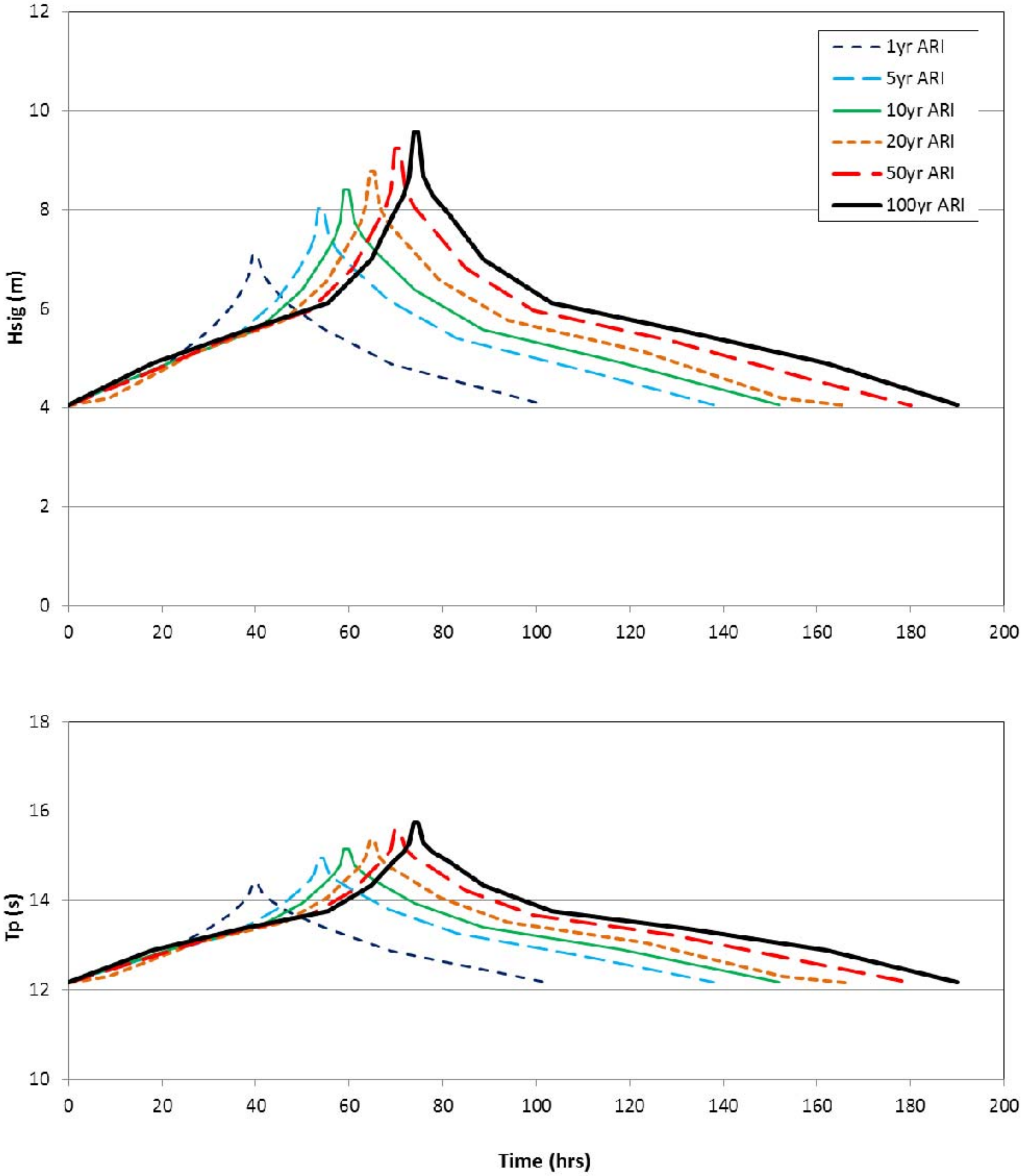


WRL

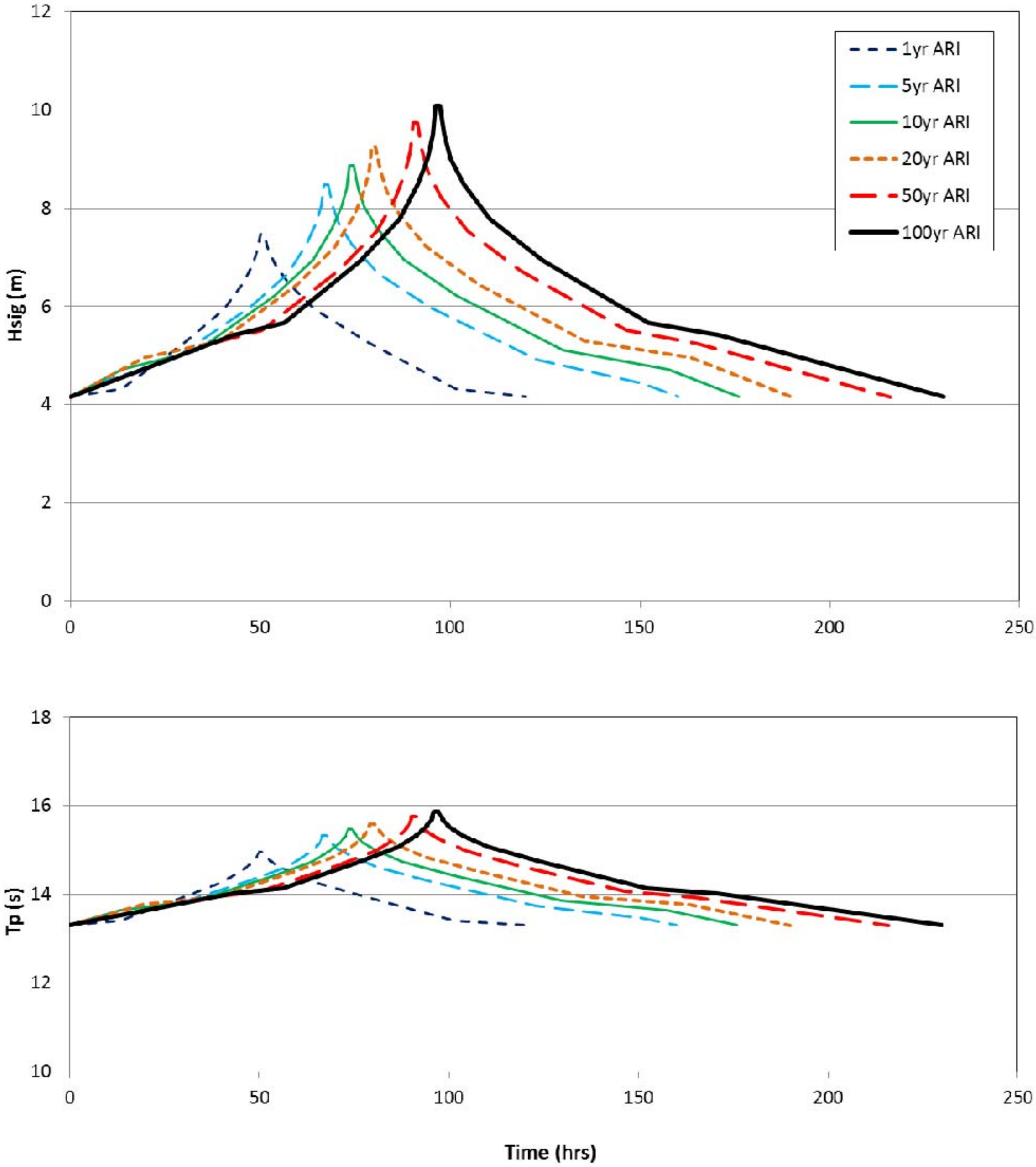
Report No. RR242

SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR POINT NEPEAN

Figure F-5



WRL Report No. RR242	SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR CAPE DU COUEDIC	Figure F-6

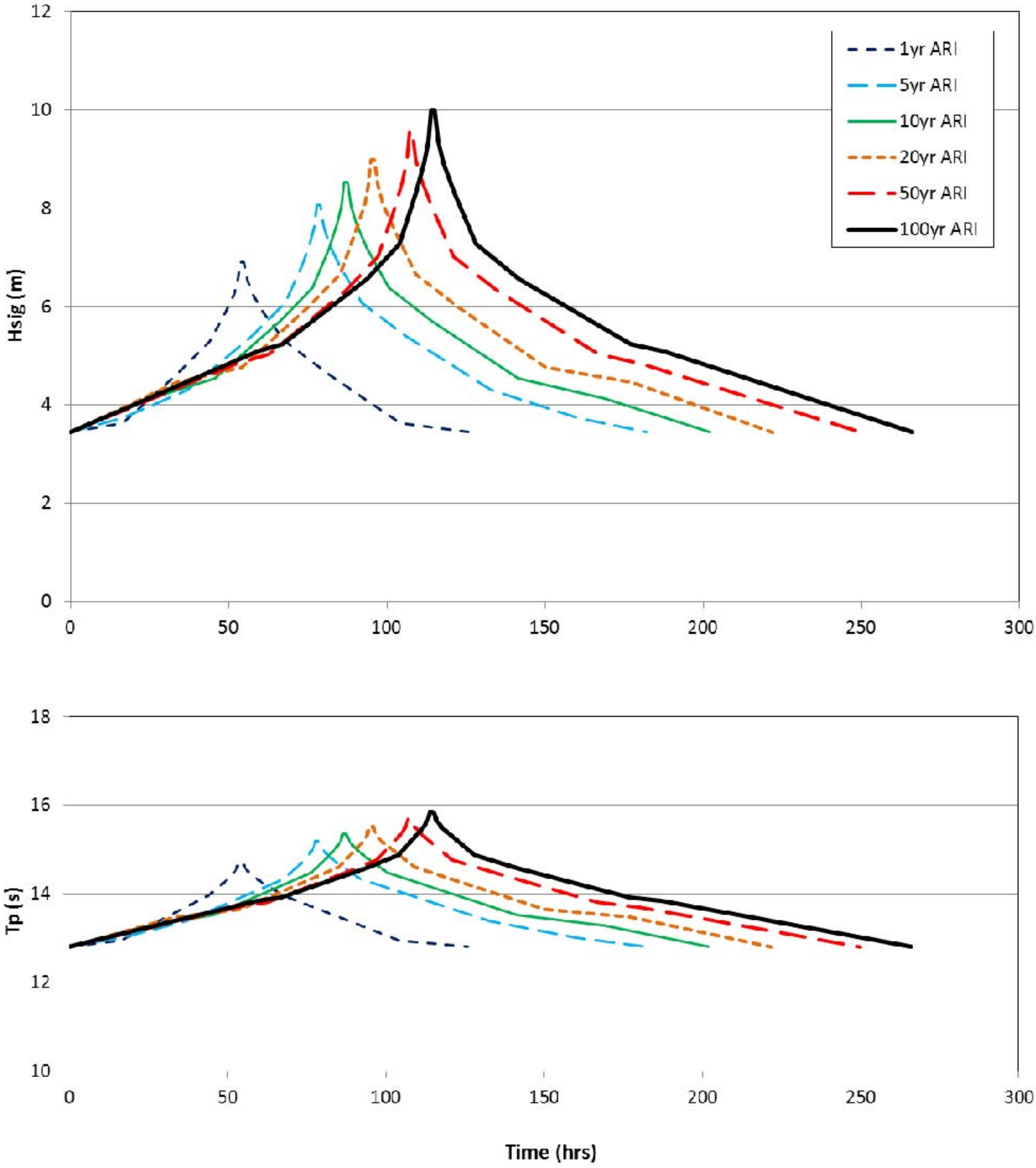


WRL

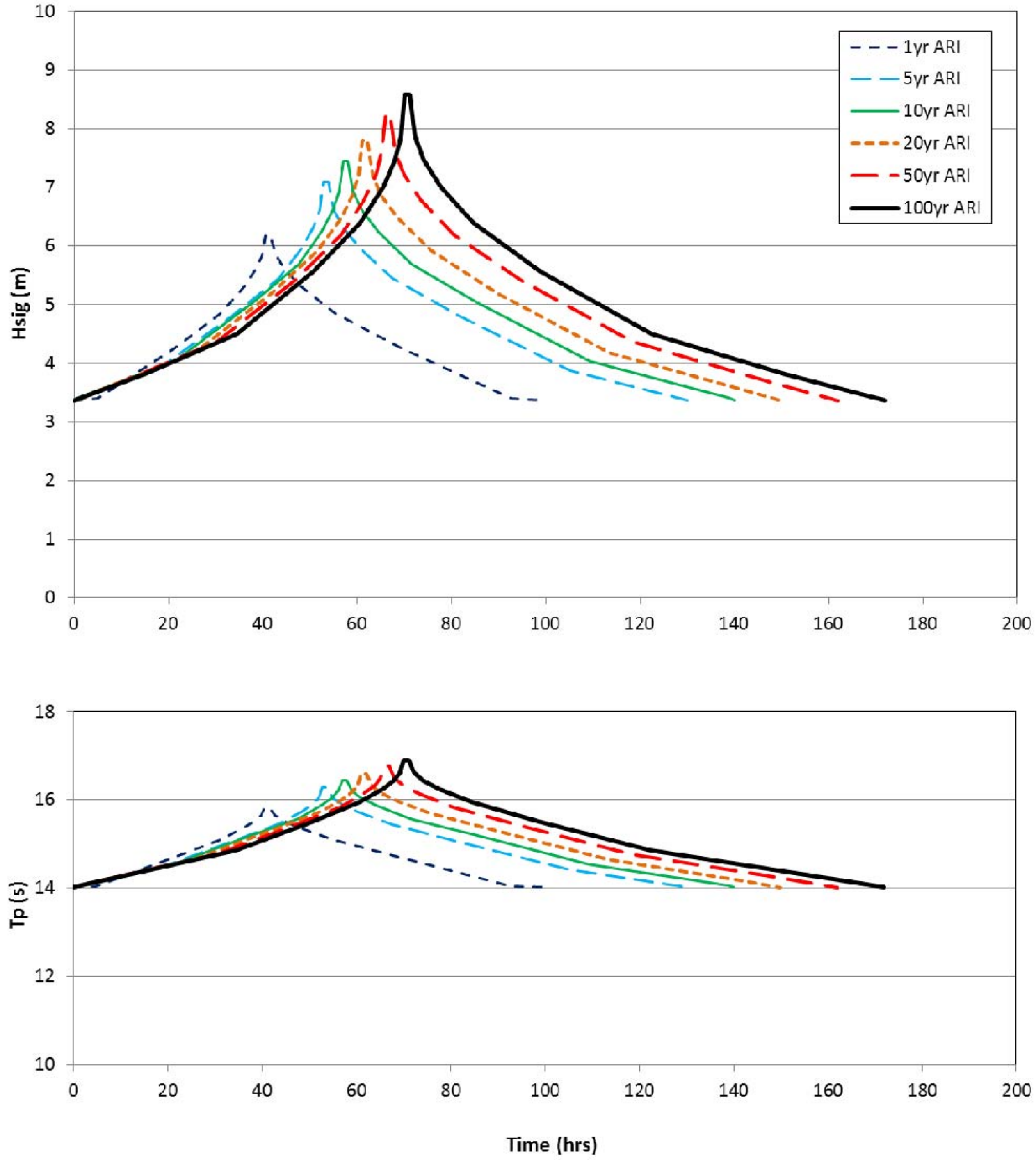
Report No. RR242

SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR CAPE NATURALISTE

Figure F-7



WRL Report No. RR242	SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR ROTTNEST ISLAND	Figure F-8



WRL

Report No. RR242

SYNTHETIC DESIGN STORM SERIES ESTIMATED FOR JURIEN BAY

Figure

F-9

APPENDIX G DETAILED ASSESSMENT OF TEMPORAL TRENDS IN BUOY MEASUREMENTS OF AUSTRALIAN WAVE CLIMATE

1. Introduction

The Water Research Laboratory (WRL) was engaged to assess temporal trends in wave buoy data from long-term deployments at seven locations around Australia. The Seasonal Kendall test was used to test for trends in the monthly mean, 90th percentile (highest 10 %), and 99th percentile (highest 1 %) significant wave heights. The results of this analysis were then compared to similar studies recently undertaken including the work of Young *et al*. (2011) in which satellite altimeter measurements were tested for temporal trend.

2. Methodology

2.1 Seasonal Kendall Test

The seasonal Kendall test (Hirsch *et al*. 1982), is a nonparametric test for trend in data that exhibits seasonality. It performs the Mann-Kendall trend test for individual seasons of the year and then combines the individual results into one overall test for trend. The Seasonal Kendall test is preferred over regression techniques due to its superior ability to detect a trend when present in highly variable environmental data (Taylor and Loftis, 1989; Young *et al*. 2011). Although this test assumes the data is independent, this assumption can be relaxed in a test modified to account for serial dependence (Hirsch and Slack, 1984). Both variations of the Seasonal Kendall Tests were implemented in MATLAB (after Jeff Burkey, 2009).

The seasonal Kendall test is described below. Let

$$X = (X_1, X_2, \dots, X_{12}) \tag{1}$$

and

$$X_i = (x_{i1}, x_{i2}, \dots, x_{in}) \tag{2}$$

Where X is the entire sample made up of subsamples X_i, (one for each month) and each of the subsamples contains n annual values from month, i. The test statistic for each month then is:

$$S_i = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_{ij} - x_{ik}) \tag{3}$$

where $sgn\ x = \begin{cases} 1 & if\ x > 0 \\ 0 & if\ x = 0 \\ -1 & if\ x < 0 \end{cases}$

The seasonal Mann-Kendall test statistic is:

$$S' = \sum_{i=1}^{12} S_i \tag{4}$$

This test statistic is asymptotically normally distributed with zero mean and variance:

$$Variance(S') = \sum_{i=1}^{12} \sigma_i^2 + \sum_{\substack{i=1,j=1 \\ i \neq j}}^{12} \sigma_{ij} \tag{5}$$

where $\sigma_i^2 = variance(S_i)$ and $\sigma_{ij} = covariance(S_i, S_j)$

The evaluation of these terms is summarised in Hipel and McLeod (1994). When independence is assumed in the Seasonal Kendall test, the covariance term in the above equation is equal to zero. The test statistic can be tested against the standard normal distribution using:

$$Z' = \frac{S' - sgn(S')}{\sqrt{Variance(S')}} \tag{6}$$

An estimate of the magnitude of the linear trend is given by calculating the slope estimator, *B* (Hirsch *et al.* 1982), where *B* is the median of:

$$d_{ijk} = \frac{(x_{ij} - x_{ik})}{(j-k)} \text{ for all } (x_{ij}, x_{ik}) \text{ pairs } i=1,2,\ldots,12 \text{ where } 1 \leq k \leq j \leq n \tag{7}$$

Note that *B* is largely unaffected by effects of serial correlation, because the slopes are computed between values and are multiples of 12 months apart (Hirsch *et al.* 1982).

2.2 Verification of Seasonal Kendall Test

The implementation of the Seasonal Kendall test in MATLAB was verified by:

(a) Generating 10 000 samples of a 25 year long, monthly time series of normally distributed random data.

(b) Generating 10 000 samples of a 25 year long, monthly time series with a superimposed linear trend of 0.005 units/year in the form (after Young *et al*., 2011):

$$y(t) = 3.2 + \frac{0.005}{12}t + \cos\left(\frac{2\pi}{12}t + 1.5\right) + \epsilon_t \tag{8}$$

where ϵ_t is uniform random noise ranging from 0 to 0.5.

In case (a), at the 5% significance level, approximately 5% of the test results were found to have a statistically significant trend which is expected in data sampled from a random normal distribution. In case (b), based on the average of the 10 000 samples, a statistically significant trend of 0.0050 units/year was found, with 95 % confidence limits of 0.0026 to 0.0074 units/year.

2.3 Application of Seasonal Kendall Test to Wave Buoy Data

The verified Seasonal Kendall Test was applied to the seven long-term deployments summarised in Table 1. The deployments include buoys off the coast of Queensland, New South Wales, Victoria, South Australia, Tasmania and Western Australia with record lengths varying from 9 years to over 30 years.

Note that artificial trends in wave heights may be introduced by changes in wave buoy position and improvements in capture methodology. In order to account for this, early portions of the time series at Brisbane, Eden and Point Nepean were removed after it was found that the buoys were moved to more exposed positions. Further details on the truncation of these data sets can be found in Shand *et al*. (2011). The length of the time series used in the analysis as well as the results of the analysis are shown in Table 2.

3. Results

The results of the application of the Seasonal Kendall test to the buoy data listed in Table 1 are presented in Table 2. The results presented are:

- The slope estimating the magnitude of the linear trend as well as the 95 % confidence limits;
- The p-value used for testing for significance of a trend (not necessarily linear); and
- Whether a statistically significant trend has been detected in the data at the 5 % level.

The results show a decreasing trend in the monthly mean wave height at Brisbane, Eden, Cape Sorell, Point Nepean and Cape de Couedic and an increasing trend in the monthly mean wave height at Cape Naturaliste, Rottnest Island, Jurien Bay and Botany Bay. With the exception of Botany Bay, the east and south coast buoys show a decreasing trend in the monthly mean wave height, while all the west coast buoys show an increasing trend. All the trends, however, include zero in their confidence limits (with the exception of Eden, see table footnote for discussion) and none of the trends observed are statistically significant.

For the 90th percentile (highest 10 %) monthly wave heights, decreasing trends are again observed at all the east and south coast buoys except Cape Sorell which shows an increasing trend. All the West Australian buoys show an increasing trend in the 90th percentile monthly wave height. However, none of the 90th percentile monthly wave height trends are statistically significant.

The 99th percentile (highest 1 %) monthly wave heights show a decreasing trend at Brisbane, Eden, Point Nepean and Rottnest Island. An increasing trend is found at Botany Bay, Cape Sorell, Cape du Coudiec, Cape Naturaliste and Jurien Bay. None of the trends are statistically significant and none of the trends can be grouped by buoy location.

3.1 Comparison to Similar Studies

3.1.1 Lord and Kulmar, 2000

The long-term trend was tested using wave buoy data from Byron Bay, Sydney and Eden. The average value of the significant wave height on an annual basis was analysed. Using records from 1985 to 2000 a line of best fit (linear regression) was fitted to the data. An average increase in wave height of 5 mm/year to 7 mm/year was found at each of the sites, however, the significance of such a trend was not investigated. In addition it also suggested that this could be an overestimate of trend due to annual variability in wave height. The results of the Seasonal Kendall test presented in Table 2 show a non-statistically significant increasing trend of 1.1 mm/year at Botany Bay and decreasing trend of -4.3 mm/year at Eden which differ somewhat form those found by Lord and Kulmar (2000).

3.1.2 Shand et al. 2011

The results presented in Table 2 can be compared to the statistics calculated for the monthly mean significant wave height in Shand *et al*. (2011) which are presented in Table 3. Shand *et al*. (2011) used an F-statistic to test the null hypothesis that the linear trend over time was zero. This statistic is analogous to regression techniques, however, in environmental data the Seasonal Kendall test is often preferred over regression techniques due to its superior ability to detect a trend when present in environmental data which exhibits seasonality, non-normality, and dependence. Both the Seasonal Kendall and F-statistic test results show general agreement. No buoy was found to have a statistically significant trend using either of the statistical tests. However, the direction of the trend for the Brisbane and Cape Naturaliste buoys are reversed in the two tests. Trends in the longer term buoy data of Botany Bay, Eden and Rottnest Island show close agreement.

The Seasonal Kendall test results also show no statistically significant long-term trend in either the monthly 90th percentile (highest 10 %), or 99th percentile (highest 1 %) significant wave heights. This result suggests that there is no statistically significant long-term trend in extreme waves at the buoy locations. This result is supported by the finding of Shand *et al*. (2011) who found no statistically significant trend in the magnitude or frequency of storm events.

3.1.3 Young et al. 2011

Young *et al*. (2011) used satellite altimeter measurements from 1985 to 2008 to investigate global changes in oceanic wind speed and wave height using the Seasonal Kendall test. In addition, twelve buoys in the Northern Hemisphere were analysed for trend and compared to corresponding altimeter data with the results presented in Table 4. For the twelve buoys:

- Eight of the buoys had an increasing trend in the monthly mean significant wave height, with one being statistically significant at the 5 % confidence level.
- Four of the buoys had an increasing trend in the 90th percentile (highest 10 %) monthly significant wave height, with one being statistically significant at the 5 % confidence level.
- Eight of the buoys had an increasing trend in the 99th percentile (highest 1 %) monthly significant wave height, with the only buoy being statistically significant at the 5 % confidence level showing a decreasing trend.

The altimeter data at each of the 12 buoy positions was also analysed. In summary:

- Four of the buoy positions had an increasing trend in the monthly mean significant wave height in the altimeter data, with the only buoy being statistically significant at the 5 % confidence level showing a decreasing trend.
- Ten of the buoy positions had an increasing trend in the 90th percentile (highest 10 %) monthly significant wave height in the altimeter data. Of the four locations that were statistically significant at the 5 % confidence level, three showed an increasing trend, and one a decreasing trend.
- Eleven of the buoys had an increasing trend in the 99th percentile (highest 1 %) monthly significant wave height in the altimeter data, of which eight were statistically significant at the 5 % confidence level.

Of the three sets of buoys that were statistically significant at the 5 % level, only one showed a corresponding trend in the altimeter data with the direction of the trend reversed for the other two buoys. The global trends in significant wave height for the altimeter data (Young *et al*. 2011) are presented in Figure 1. Averaged over the globe, at the 5 % confidence level:

- 8 % of the altimeter mean monthly wave height trends were statistically significant;
- 12 % of the altimeter 90th percentile (highest 10 %) monthly wave height trends were statistically significant;
- 47 % of the altimeter 99th percentile (highest 1 %) monthly wave height trends were statistically significant.

The average global results for the altimeter data appear to support the claimed global increase in mean wave height particularly for the extreme significant wave heights (90th and 99th percentile exceedance). However the analysis of the twelve northern hemisphere buoys suggests there that there is less evidence of an overall trend in either the mean monthly wave height, or extreme conditions.

In comparing the trends found in the altimeter data (Figure 1) with the results for the Australian buoy data (Table 2), the altimeter data results at the buoy locations can be summarised generally as follows:

- For the mean condition, a non-statistically significant decreasing trend (0 to -5 mm/year) is found on the east coast of Australia. The south and west coasts show, on average a non-statistically significant increasing trend (0 to +10 mm/year).
- For the 90th percentile monthly significant wave height, the central to northern east coast shows a non-statistically significant increasing trend (0 to +10 mm/year). The south and south-west coasts, including southern New South Wales show a generally statistically significant increasing trend (+10 to 25 mm/year).
- For the 99th percentile monthly significant wave height the east, south and south-west coasts all show a statistically significant upward trends of between +10 and +30 mm/year on the east coast and +20 to +40 mm/year on the south and southwest coasts.

For the mean condition, both the altimeter data and wave buoy data agree that trends in wave height are generally non-statistically significant. However, for more extreme conditions, the statistically significant trends of increasing wave height found in the altimeter data are not supported by the wave buoy analysis.

4. Summary

The temporal trends in wave buoy data from long-term deployments, ranging from 9 to 38 years in length, at seven locations around Australia were assessed using the Seasonal Kendall test. This test was used to assess the statistical significance of trend in the monthly mean, 90th percentile (highest 10 %), and 99th percentile (highest 1 %) significant wave height. The results show no statistically significant trend in any of the buoy data regardless of the percentile of wave height chosen. The results are similar to those presented in Shand *et al*. (2011) which found no statistically significant trend in the monthly mean significant wave height, and little evidence supporting an increase in the magnitude or frequency of storm events. The results are analogous to the statistical analysis performed by Young *et al*. (2011) on global altimeter data. The global trend of increasing wave height, with the rate of increase greater for extreme events found in the altimeter data was not supported by the data of any of the Australian wave buoys analysed.

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Table 1: Wave Buoys Used in Analysis

Site	State	Location - Latitude (°S)	Location - Longitude (°E)	Water Depth (m LAT)	Date Range	Total Record Length (Years)	Total Capture (%)
Brisbane	QLD	27º 29.77′	153º 37.76′	76	31/10/1976 – 31/12/2009	33.26	91
Botany Bay (Sydney)	NSW	33º 46.52′	151º 25.07′	92	08/04/1971 – 31/12/2009	38.84	88
Eden	NSW	37° 18.10'	150° 11.10'	100	08/02/1978 – 31/12/2009	31.98	85
Cape Sorell	TAS	42º 07.20′	145º 01.80′	100	11/07/1985 – 24/09/1992; 07/01/1998 – 31/12/2009	19.201	84
Point Nepean/Point Lonsdale	VIC	38º 21.64′	144º 41.64′	27	14/12/1993 – 31/12/2008	15.10	69
Cape du Couedic	SA	36º 04.20′	136º 37.20′	80	29/11/2000 – 31/12/2009	9.11	91
Cape Naturaliste	WA	33° 32.08'	114° 45.87'	50	28/05/1999 – 31/12/2009	10.62	95
Rottnest Island	WA	32º 05.65′	115º 24.47′	48	19/01/1994 – 31/12/2009	16.04	96
Jurien Bay	WA	30° 17.50'	114° 54.87'	42	02/01/1998 – 31/12/2009	12.03	95

Table 2: Seasonal Kendall Test Results

	Monthly Mean			Monthly 90th Percentile			Monthly 99th Percentile		
Buoy	Slope (mm/year) (95% CI)	p-value	Statistically Significant[2]	Slope (mm/year) (95% CI)	p-value	Statistically Significant[2]	Slope (mm/year) (95% CI)	p-value	Statistically Significant[2]
Brisbane (Sep 1994 – Dec 2009)[1]	-3.7 (-12.3,4.2)	0.45	No	-1.9 (-18.0,16.4)	0.84	No	-3.1 (-26.8,25.7)	0.89	No
Botany Bay (Apr 1971 – Dec 2009)	1.1 (-1.1,2.8)	0.28	No	-0.3 (-4.3,3.7)	0.88	No	4.4 (-2.6,11.4)	0.19	No
Eden (Apr 1989 – Dec 2009)[1]	-4.3 (-8.7,-0.2)	0.06	No[3]	-3.1 (-12.4,3.5)	0.41	No	-6.6 (-24.9,11.0)	0.37	No
Cape Sorell (Jul 1985 – Dec 2009)	-2.8 (-9.2,5.0)	0.51	No	1.4 (-10.5,11.7)	0.80	No	6.7 (-9.7,23.8)	0.42	No
Point Nepean (Feb 2003 – Jan 2008)[1]	-7.1 (-28.5,25.9)	0.71	No	-6.0 (-72.9,41.8)	0.93	No	-25.8 (-121,46.7)	0.48	No
Cape du Couedic (Nov 2000 – Dec 2009)	-12.2 (-38.2,7.5)	0.06	No	-8.2 (-40.2,24.3)	0.71	No	30.5 (-22.8,91.5)	0.10	No
Cape Naturaliste (May 1999 – Dec 2009)	4.9 (-15.9,21.3)	0.66	No	10.2 (-26.2,42.4)	0.63	No	10.5 (-42.5,60.4)	0.79	No
Rottnest Island (Jan 1994 – Dec 2009)	3.4 (-4.7,11.6)	0.46	No	1.4 (-10.3,14.4)	0.79	No	-2.7 (-23.3,18.6)	0.86	No
Jurien Bay (Jan 1998 – Dec 2009)	7.0 (-8.3,18.0)	0.54	No	10.0 (-9.4,22.6)	0.38	No	22.0 (-2.5,47.4)	0.14	No

[1]Recording truncated to remove effect of buoy repositioning (after Shand *et al.*, 2011)

[2]Signficance is tested at the 0.05 level using p-values adjusted for serial correlation

[3]This is significant when the value not adjusted for serial correlation is used and hence the slope confidence limits do not include zero

Table 3: F-Test Results (Shand *et al*. 2011)

Buoy	Linear trend (mm/year) (95 % CI)	F-ratio[1]	p-value[2]	Statistically Significant[3]
Brisbane (Sep 1994 - 2009)	0.4 (-8.6, 9.4)	0.0	0.93	No
Botany Bay (Apr 1971 – Dec 2009)	1.7 (-0.4, 3.8)	2.6	0.11	No
Eden (Apr 1989 – Dec 2009)	-4.3 (-8.6, 0.1)	3.7	0.06	No
Cape Sorell (Jul 1985 – Dec 2009)	-2.0 (-10.3, 6.3)	0.2	0.63	No
Point Nepean (Feb 2003 – Jan 2008)	-13.6 (-42.4, 15.2)	0.9	0.35	No
Cape du Couedic (Nov 2000 – Dec 2009)	-0.8 (-32.4, 30.7)	0.0	0.96	No
Cape Naturaliste (May 1999 – Dec 2009)	-1.8 (-34.0, 30.4)	0.0	0.91	No
Rottnest Island (Jan 1994 – Dec 2009)	4.9 (-10.3, 20.0)	0.4	0.53	No
Jurien Bay (Jan 1998 – Dec 2009)	7.0 (-10.7, 24.7)	0.6	0.43	No

[1]F-ratio test of null hypothesis that the slope is zero

[2]Level of significance of F-ratio test

[3]Is the slope significant? i.e. is the null hypothesis (that the slope is zero) rejected at the 0.05 level

[4]Buoy records truncated – see text

Table 4: Comparison of Trend Estimates for Buoy and Altimeter Data (Young *et al*. 2011)

Region	Buoy Number	Latitude (°N)	Longitude (°N)	Buoy Trend (cm/year)[1]			Altimeter Trend (cm/year)[1]		
				Mean	90^{th}	99^{th}	Mean	90^{th}	99^{th}
Gulf of Mexico	42001	25.9	89.7	0.24	0.00	1.42	-0.41	0.43	**2.41**
	42002	25.8	93.7	**0.55**	0.50	1.00	-0.44	0.24	1.46
North Atlantic	44004	38.5	70.4	0.14	0.40	1.27	-0.54	0.51	**2.74**
	44011	41.1	66.6	0.42	**1.11**	1.47	0.34	**1.64**	**5.20**
	41002	32.4	75.4	-0.05	0.00	0.54	-0.41	-0.02	**2.82**
North Pacific	46001	53.3	148.0	-0.45	0.00	0.50	0.08	**1.24**	**3.03**
	46002	42.6	130.5	0.06	0.00	-0.06	0.01	0.58	**2.59**
	46005	46.1	131.0	0.36	0.00	1.84	0.42	**1.67**	**4.50**
	46006	40.9	137.5	0.98	1.25	1.61	-0.21	0.24	**2.64**
	46035	57.1	177.8	-0.31	-0.95	**-2.54**	-0.36	0.84	2.59
Hawaii	51001	23.5	162.3	-0.71	-0.71	-0.65	-0.88	**-0.95**	-0.06
	51002	17.1	157.8	0.02	0.00	-0.51	-0.16	0.27	0.66

[1]Values shown in bold are statistically significant at the 5 % confidence level

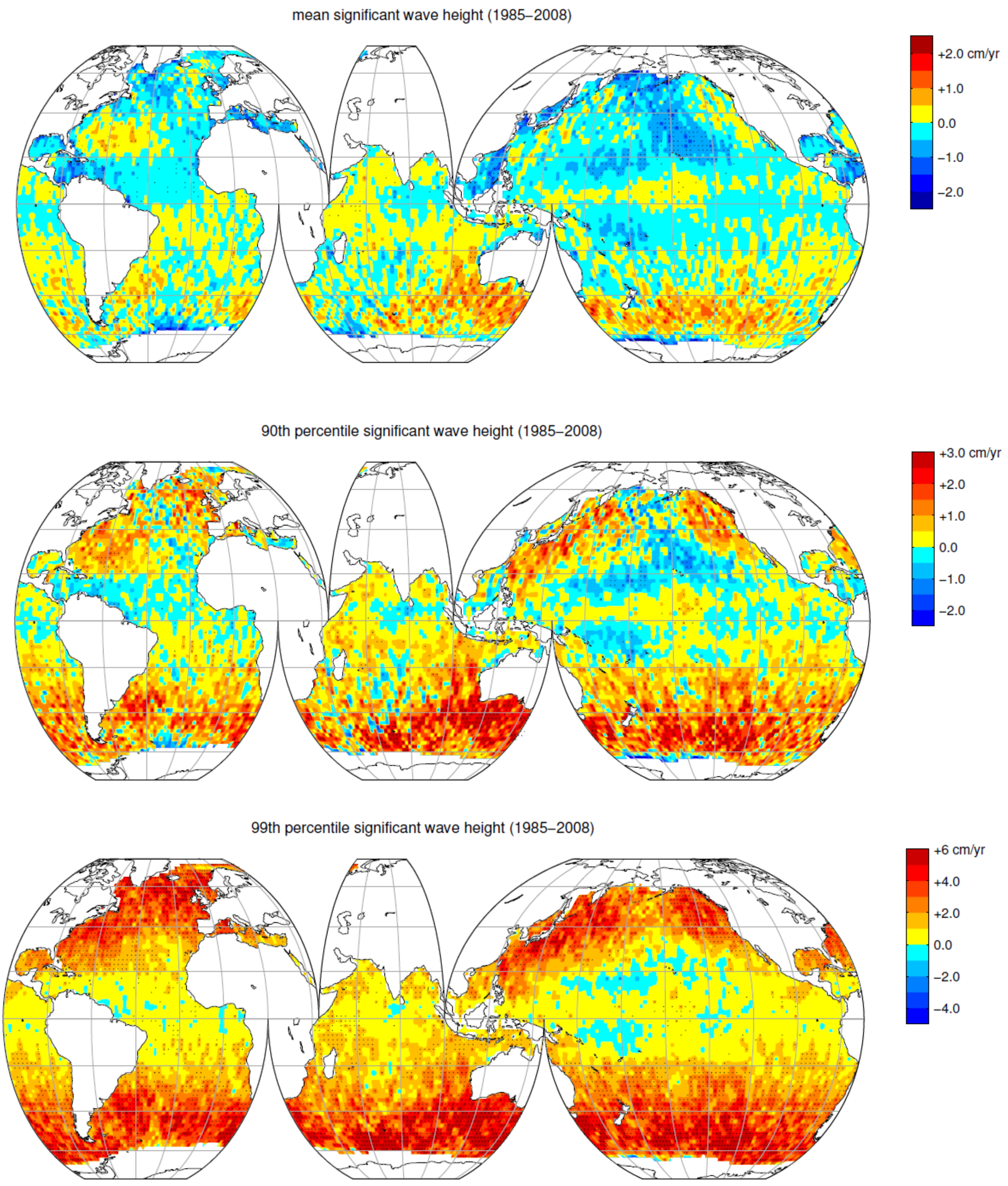

Figure 1: Altimeter Data Trend Estimated (Young *et al*. 2011)