Long Term Trends in NSW Coastal Wave Climate and Derivation of Extreme Design Storms

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Abstract

The NSW coast is subject to a generally moderate wave climate that is periodically affected by large coastal storm events arising from a range of synoptic weather systems. Extreme wave events may cause coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety, while the persistent background climate may influence beach recovery and long-term trends in sediment transport and beach orientation.

This paper describes analysis of the long-term trends in the mean and extreme wave climate along the NSW coast based on historical wave buoy data. Changes in buoy location and exposure over time have been found to notably influence results, with small changes in buoy position able to introduce apparently significant but fictitious trends. After removing this invalid data, some northern wave buoys show small (<5mm/year) but statistically significant increases in monthly mean wave climate and some southern buoys show statistically significant decreases of similar magnitude. More extreme wave climates (10% and 1% exceedance) show slightly larger long-term trends with northern buoys again trending up and southern buoys typically trending down.

Using the wave buoy data, extreme wave heights, wave periods and cumulative storm energy have been estimated for a range of average recurrence interval events allowing construction of synthetic design storm time series for each buoy. Spatial differences are noted in the derived events as a function of the dominant storm climatology at different locations along the Eastern Australian Coastline.

Introduction

The NSW coast is subject to a generally moderate wave climate predominantly from the south to south-east. Previous studies have found an average offshore significant wave height of between 1.5 to 1.6 m and average peak period of 9.4 to 9.7 s (Lord and Kulmar, 2000). This generally moderate wave climate is periodically affected by large wave events originating from coastal storm systems. These storms vary both spatially and temporally in their genesis, intensity and track. Very large storm events such as occurred in 1974 (*'Sygna Storm'*), 1997 (*'Mothers Day Storm'*) and 2007 (*'Pasha Bulker Storm'*) occasionally impact the coastline (Figure 1). In particular, when they are co-incident with high water levels, they can cause widespread coastal inundation, beach erosion, damage to property and marine structures, and risks to public safety. Accurate estimation of the likelihood and magnitude of large wave events is essential for the quantification of extreme beach erosion and inundation, design of nearshore structures, and longer term coastal hazard assessment.

Figure 1: Collaroy-Narrabeen Beach, Sydney. March, 1976. Photograph: A. Short

New South Wales Climatology

The NSW coast spans the southern Coral Sea to the Southern Tasman Sea across the sub-tropical to mid-latitude zone. Extreme wave energy is mainly generated within the Coral Sea and Tasman Sea window, but can also be generated from outside this zone: in the South – West Pacific tropics; and, in the Southern Ocean in the extra-tropics. Aspects of the modal wave climate for the NSW coast have been previously described by Short and Trenaman (1992), Lord and Kulmar (2000), Hemer et al. (2007) and Callaghan and Helman (2008) amongst others.

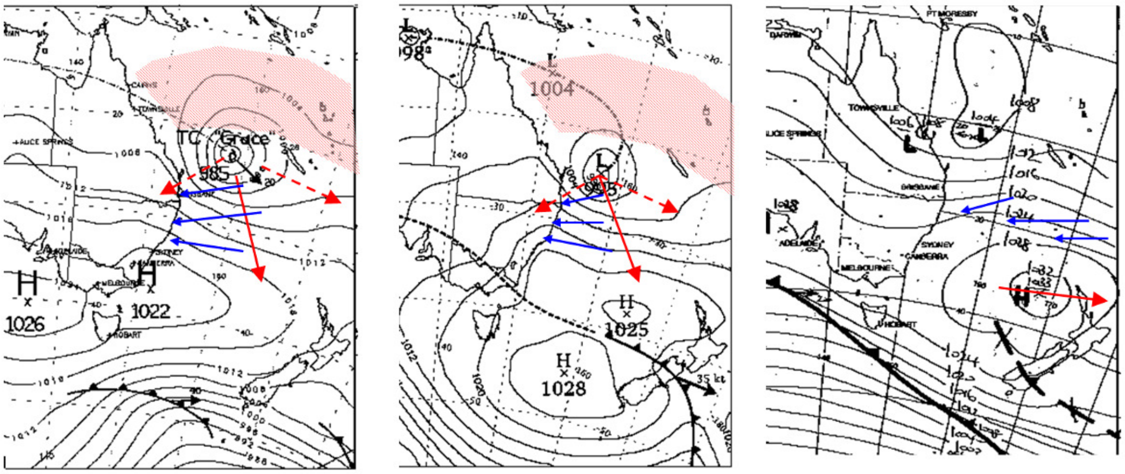
Due in part to their rapid intensification and complexity, East Coast Cyclones (ECC) have proven difficult to both forecast and categorise. The Australian Bureau of Meteorology (BOM) used seven different storm categories to compile their NSW maritime low database, while the PWD report used a different six categories. Holland et al. (1987) discussed three types of ECC events and Hopkins and Holland (1997) used a different eight classifications. As there is no broad consensus on what constitutes an ECC, discrepancies exist between these reports. Definitions used to classify storms in this study was based on the synoptic classification in Browning and Goodwin (2011) that resulted in 8 storm types that are presented in Table 1 and examples shown in Figure 2.

Shand et al. (2010) present a detailed reanalysis of historic storm events along the NSW coast during the wave buoy epoch with a synoptic type assigned to each defined event based on the synoptic genesis of the storm and the synoptic pattern at the time of the observed peak wave climate. The spatial and temporal distribution of the various storm types was examined with major storm events ($H_s > 5$ m) on the northern NSW coast found to be a mixture of tropical cyclones, tropical lows and easterly trough lows while on the central NSW coast, major storm events also include inland trough lows and southern secondary lows. Along the southern NSW coast, major storm events are mainly associated with a combination of easterly trough lows, inland and continental lows and southern secondary lows, with a number of Southern Tasman lows causing waves in excess of 5 m.

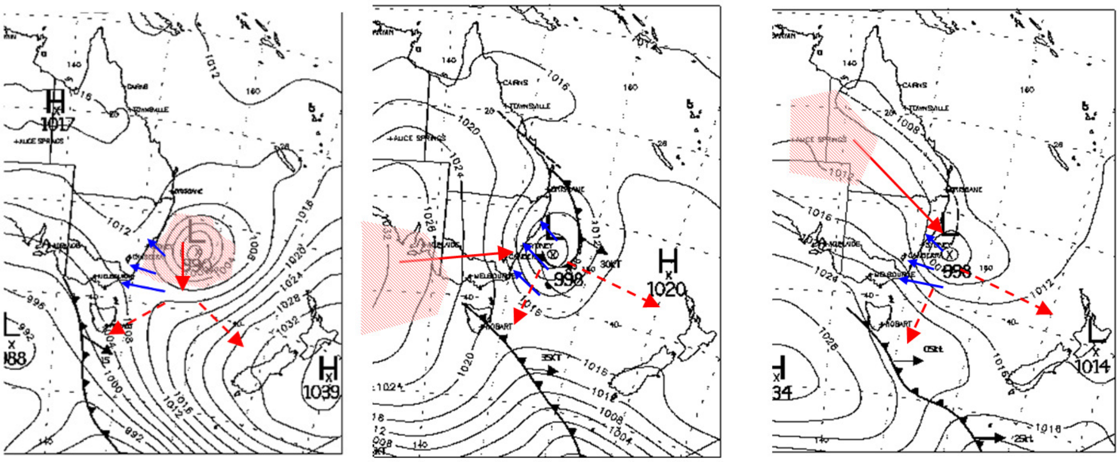
Seasonal changes in the occurrence of various storm types along the NSW coast were found with March, July and October the stormiest months, and November, December and January being the least stormy. Tropical cyclones and lows are restricted to December to April with most occurring between January and March. Easterly trough lows are concentrated between April and August. Both anticyclone intensifications and Southern Tasman lows occur throughout the year, although anticyclone intensification events tend to be more concentrated and produce larger wave events between January and June and Southern Tasman lows are concentrated and produce larger wave events between July and December.

Table 1 Storm Type Definitions

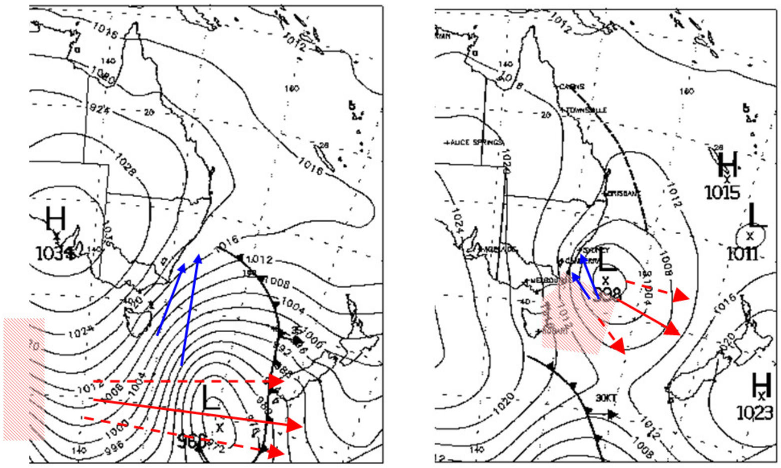
Number	Abbrev	Full Name	Description
1	TC	Tropical Cyclone	Swell related to named Tropical Cyclones forming in the Coral Sea between 5-10° latitude.
2	TL	Tropical Low	Low pressure systems forming in the Coral Sea but not reaching the low pressure intensity of a named tropical cyclone
3	AI	Anti-Cyclone Intensification	Form when a high across the Tasman Sea directs onshore E to SE winds to the coast
4	ETL	Easterly Trough Low	Primary type of ECC. Cyclonic depressions that initially form as a trough in the easterly flow along the Queensland / Northern NSW coast. These storms move parallel to the coast and often intensify rapidly causing significant damage
5	CL	Continental Low	Storms originating in Western Australia of 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 as a cut off low in the wake of a cold front in the mid-latitude westerly circulation
8	STL	Southern Tasman Low	Major lows in the southern ocean south of 38°S



Tropical Cyclone (TC) *Tropical Low (TL)* *Anti-cyclone Intensification (AI)*



Easterly Trough Low (ETL) *Continental Low (CL)* *Inland Trough Low (ITL)*



Southern Tasman Low (STL) *Southern Secondary Low (SSL)*

All Charts: Bureau of Meteorology

▨ Storm genesis region → General storm path → Typical Wave Direction

Figure 2: Example Sea Level Pressure Synoptic Charts For Systems Causing Storm Waves On The NSW Coast.

Coastal Wave Data

After a series of intense and damaging storms in 1974, a network of wave buoys has been incrementally established along the NSW coast. The present network, maintained by Manly Hydraulics Laboratory and administered by the NSW Office of Environment and Heritage, consists of seven buoys. Data from these wave buoys have been used in this study together with an offshore wave buoy at Botany Bay maintained by Sydney Ports and a Brisbane wave buoy maintained by Queensland Department of Environment and Resource Management (DERM). Locations of these wave buoys are shown in Figure 3.

Wave buoy locations, date range, data capture rate (%) and effective record length (product of the total record length and the total data capture) are presented within Table 2. Data have been captured by the wave buoy network at various minimum intervals of 12, 6 or 1 hour since they were commissioned, although since 1984 all MHL wave buoys captured data at 1 hour intervals. The total data capture rate for the wave buoys ranges from 73.1% at Byron Bay to 89.7% at Batemans Bay.

A summary of wave statistics is presented within Table 2. Results show that with the exception of Batemans Bay, all buoys exhibit relatively uniform mean wave height of 1.55 to 1.66 m. Batemans Bay exhibits a slightly reduced mean wave climate of 1.43 m. Reasons for this difference have been assessed and are described in detail within Coghlan et al. (2011). This study found the reduced climate at Batemans Bay to be due to coastal orientation and land-mass sheltering and therefore generally representative of the coastal region between Jarvis Bay and Eden.

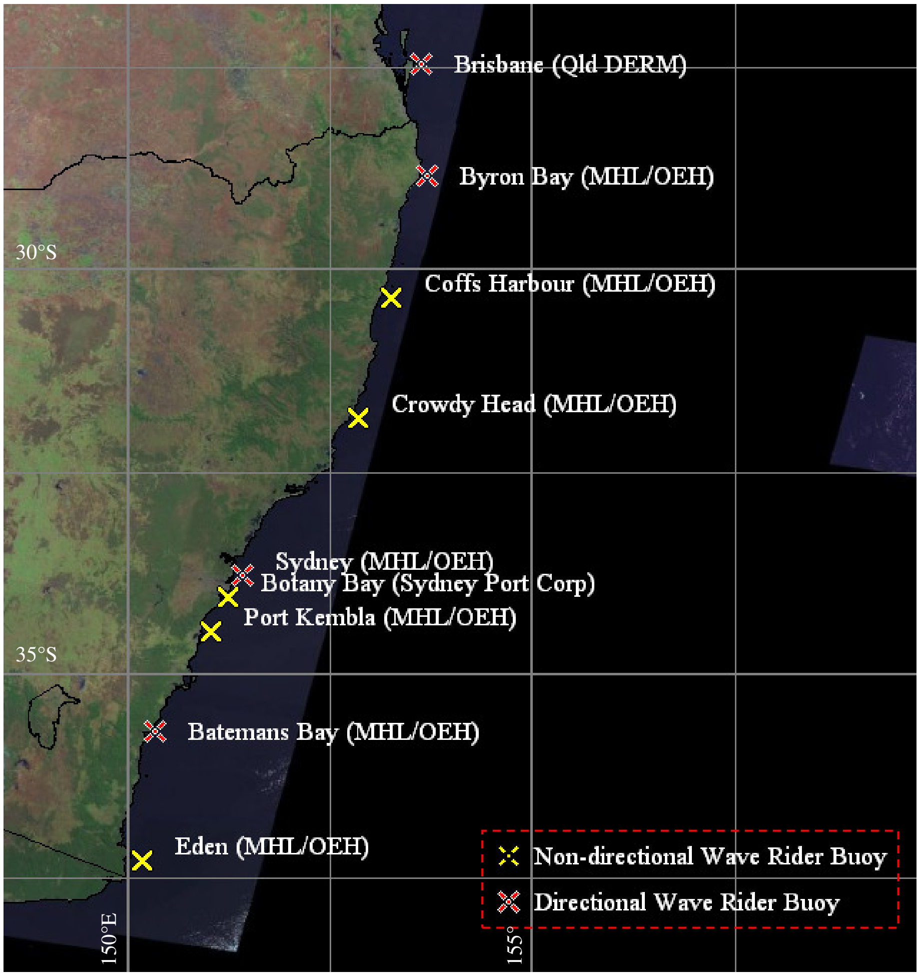


Figure 3: Location of nine wave buoys on the New South Wales Coast.

Table 2 Descriptive H_s and T_{p1} Statistics for SE Australian Wave Buoys

H_{sig} (m)	Brisbane	Byron Bay	Coffs Harbour	Crowdy Head	Sydney	Botany Bay	Port Kembla	Batemans Bay	Eden
Date Range	1976 - 2009	1976 - 2009	1976 - 2009	1985 – 2009	1987 – 2009	1971 – 2009	1974 – 2009	1986 – 2009	1978 – 2009
Effective record (yrs)	28.5	24.3	28.5	20.7	19	34	30.6	21.2	26.6
Descriptive Statistics (H_{sig}, m)									
Mean H_{sig}	1.63	1.66	1.58	1.61	1.63	1.60	1.58	1.43	1.64
Median H_{sig}	1.47	1.50	1.43	1.46	1.46	1.43	1.43	1.30	1.52
10% Exceed	2.57	2.59	2.44	2.48	2.55	2.54	2.47	2.22	2.43
1% Exceed	4.04	3.93	3.85	3.94	4.19	4.17	3.94	3.57	3.93
Maximum	7.36	7.64	7.37	7.35	8.43	8.86	8.43	7.19	7.14
Variance	0.51	0.48	0.44	0.46	0.54	0.55	0.48	0.39	0.42
Descriptive Statistics (T_{p1}, s)									
Mean T_{p1}	9.32	9.59	9.58	9.71	9.72	9.27	9.57	9.36	9.41
Median T_{p1}	9.31	9.50	9.50	9.50	9.77	9.38	9.50	9.50	9.50
10% Exceed	12.14	12.20	12.20	12.20	12.50	11.98	12.23	12.20	12.20
1% Exceed	14.67	15.10	15.10	15.10	15.10	14.38	15.10	15.10	15.10
Maximum	19.17	19.70	19.79	19.79	20.00	23.65	19.70	19.70	19.69
Variance	4.75	4.92	4.99	5.12	5.57	5.24	5.60	5.17	5.46

Temporal Trends in Wave Height

Extreme value analysis is based on an assumption of stable statistics, i.e. long-term wave height trends are zero. Changes in the monthly mean, 10% exceedance and 1% exceedance significant wave height was assessed at each buoy using a 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).

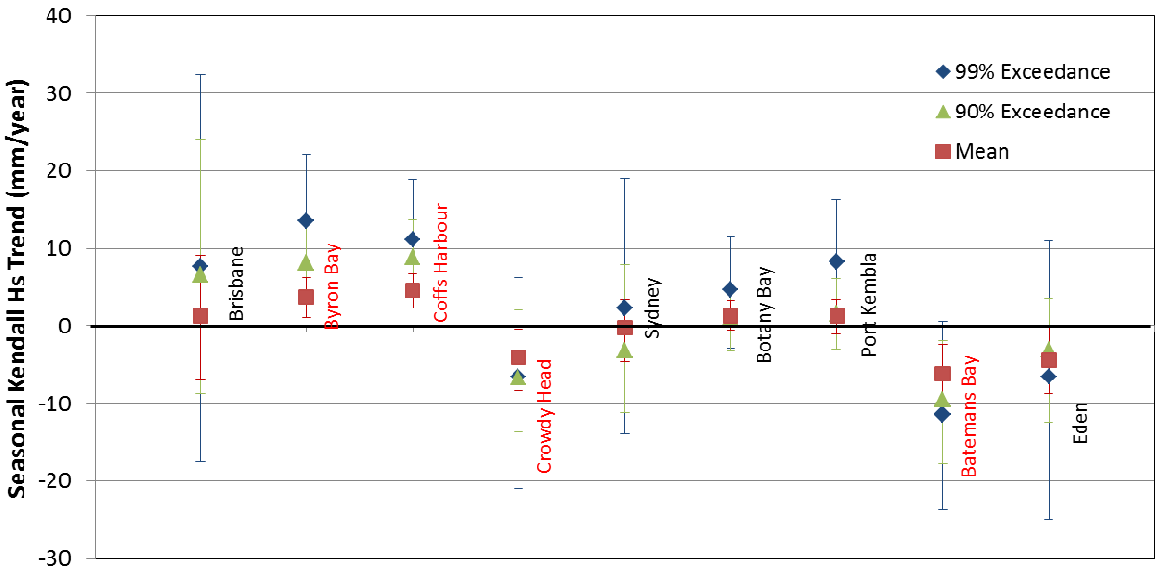
Artificial trends in wave height may be introduced by changes in wave buoy position and exposure over time. Changes in buoy location at Eden (significant change in location and exposure from April 1989 onwards) and Brisbane (changes in location and equipment until 1994) resulted in fictitious upward trends in wave climate. After removing this early data, results showed an increase in monthly mean wave climate of up to 5mm/year in the north, reducing to a decrease of similar magnitude in the south, with central NSW wave buoys showing negligible apparent trend (Table 3). Results were, however, only statistically significant (to a 0.05 level) at Coffs Harbour (+4.6 mm/year), Crowdy Head (-4.0 mm/year) and Batemans Bay (-6.1 mm/year), although Byron Bay (+3.8 mm/year) and Eden (-4.3 mm/year) are significant to the 0.1 level. The lack of decisive trend at many buoys is exemplified in Figure 4, where the confidence limits of many trends straddle zero. Lower probability events (90% and 99% exceedance) wave height show generally higher trends in agreement with findings of Young et al. (2011) using satellite altimeter data.

Overall, Young et al. (2011) found small decreasing trends (<5 mm/year) in mean wave climate along the NSW coast, except for the far south where small increasing trends (<5 mm/year) were found. This analysis of buoy data shows a reverse situation with small increasing trends along northern NSW and decreasing trend along southern NSW. Young et al. found progressively increasing trends for 90% and 99% exceedance Hs in northern NSW. Trends found within this study are in general agreement, although with generally smaller magnitudes (<10 and <15 mm/year respectively). The increase in wave climate in far southern buoys for the 99% Hs found by Young et al. was not supported by findings of this study which showed reductions in wave climate.

Table 3: Temporal Trends in SE Australian Wave Buoys

Location	**Monthly Mean Hs**			**90% Exceedance**			**99% Exceedance**		
	Slope[1] (95% CI)	**P[2]**	**Sig[3]**	**Slope[1] (95% CI)**	**P[2]**	**Sig[3]**	**Slope[1] (95% CI)**	**P[2]**	**Sig[3]**
Brisbane	1.4 (-6.9,9.1)	0.73	No	6.6 (-8.7,24.1)	0.41	No	7.7 (-17.5,32.3)	0.64	No
Byron Bay	3.8 (1.1,6.3)	0.07	No	**8.1 (3.1,13.7)**	**0.02**	**Yes**	**13.6 (4.0,22.1)**	**0.01**	**Yes**
Coffs Harbour	**4.6 (2.4,6.8)**	**0.01**	**Yes**	**8.9 (4.6,13.6)**	**0.00**	**Yes**	**11.2 (3.6,18.9)**	**0.01**	**Yes**
Crowdy Head	**-4.0 (-8.3,-0.5)**	**0.04**	**Yes**	-6.7 (-13.7,2.1)	0.12	No	-6.5 (-20.9,6.2)	0.20	No
Sydney	-0.2 (-4.6,3.4)	0.91	No	-3.2 (-11.2,7.9)	0.53	No	2.3 (-13.9,19.1)	0.87	No
Botany Bay	1.3 (-0.5,3.3)	0.16	No	0.9 (-3.1,4.8)	0.57	No	4.8 (-2.9,11.4)	0.21	No
Port Kembla	1.3 (-1.0,3.4)	0.35	No	1.6 (-2.9,6.1)	0.60	No	**8.3 (1.2,16.3)**	**0.04**	**Yes**
Batemans Bay	**-6.1(-9.7,-2.4)**	**0.01**	**Yes**	**-9.5 (-17.8,-1.9)**	**0.03**	**Yes**	-11.4 (-23.7,0.7)	0.13	No
Eden	-4.3 (-8.7,-0.2)	0.06	No	-3.1 (-12.4,3.5)	0.41	No	-6.6 (-24.9,11.0)	0.37	No

[1] The slope estimating the magnitude of the linear trend as well as the 95 % confidence limits
[2] The p-value used for testing for significance of a trend (not necessarily linear)
[3] Whether a statistically significant trend has been detected in the data at the 5 % level – Indicated by grey shading



Locations exhibiting statistically significant trends shown in red. 95% confidence limits for each statistic indicated by coloured error bars

Figure 4: Temporal Trends in SE Australian Wave Climate

Extreme Value Analysis

Large, low probability wave events are often defined in terms of an average recurrence interval (ARI). The commonly used approach to derive extreme wave height for a particular ARI (or assign an ARI to a particular wave height) 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.

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

In agreement with Mathiesen et al. (1994) in *Recommended Practice for Extreme Wave Analysis,* the 3 parameter Weibull distribution (Eq. 1) was adopted for the present study. Studies by You (2007) similarly recommend either the FT-I (Gumbel) or Weibull distributions for evaluation of extreme wave climate.

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

Where $F_{(x)}$ is the distribution function and *A*, *B* and *k* are scale, location and shape parameters estimated using a least-squares fitting method.

Extreme wave heights were derived for events with ARI's of between 1 and 100 years and for storm durations of between 1 hour and 6 days. The 1 hour exceedance H_s for 1, 10, and 100 year ARI events along with 90% confidence intervals are presented for each wave buoy within Table 4. The central NSW buoys show larger extreme wave conditions than either the northern or southern NSW buoys.

Table 4 Summary of One Hour Exceedance H_s along the SE Australian Coast

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

For durations longer than one hour, the wave height exceeded for that length of time decreases, with wave height decreasing relatively faster in southern NSW and slower in northern NSW. This is reflective of the generation systems responsible, with longer duration events such as anticyclone intensification and slow moving tropical cyclones and lows affecting the northern coast to a greater extent.

The effect of storm direction on extreme wave height is shown within Table 5. In all cases, extreme waves arriving from north of 90° are predicted to be lowest. Brisbane and Byron Bay predict extreme waves from between east and south-east (90 to 135°) to be largest, while Sydney and Batemans Bay predict extreme waves from south of 135° to be largest. Due to the shorter relative length of data for specific directions, confidence intervals are generally wider, particularly for the directions north of 90° where few events have been observed.

Uncertainties in extreme value analysis may arise from several sources. Most influential is the accuracy and completeness of the original data and the appropriateness of the fitted extreme value distribution. The accuracy of the data is generally well within the derived confidence limits and increasing record lengths are providing increased confidence in detection of sufficient extreme events. This will continue to improve over time and extreme value estimates should be periodically updated to include new data.

Table 5 Directional Variation in 10 year ARI One Hour Exceedance H_s for Directional Wave Buoys

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

Deriving Synthetic Design Storm Events

A synthetic design storm for defined ARI provides time series information of wave height and period for the calculation of beach erosion and coastal inundation (Carley and Cox, 2003). To estimate synthetic design storm events, the following process is recommended and illustrated in Figure 5:

1. Identify the envelope of H_s exceedance for specific durations (Figure 5, Upper Panel). This provides an upper limit of wave height as a function of duration;
2. Find the total cumulative storm energy for the specific ARI event. The total cumulative storm energy is a function of wave height and storm duration. The resultant value has been found to provide a good measure of storm erosive potential (Harley et al. 2009);
3. Define a synthetic height distribution so that the height-duration envelope is not exceeded and the cumulative energy is equal to that specified for the particular event (Figure 5, Second Panel). 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) 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 (Figure 5, Third Panel).

NSW Buoys generally showed moderate positive skewness indicating a faster initial increase in wave height followed by a slower decrease;

5. Define a synthetic wave period for the storm event. 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 (Figure 5, Lower Panel);
6. Estimate confidence intervals for the time series' based on extreme H_s, E_{cum} and T_p confidence intervals.

More complete data upon which to base design of synthetic storm events is provided within Shand et al. (2010 and 2011).

Conclusions

This study has examined wave buoy data collected along the NSW and SE Queensland coast for long-term trends and to estimate the magnitude of extreme events and derive synthetic design storms. Changes in buoy location and exposure over time have been found to notably influence results, with small changes in buoy position able to introduce apparently significant but fictitious trends. After removing this invalid data, some northern wave buoys show small (<5mm/year) but statistically significant increases in monthly mean wave climate and some southern buoys show statistically significant decreases of similar magnitude. More extreme wave climates (10% and 1% exceedance) show slightly larger long-term trends with northern buoys again trending up and southern buoys typically trending down. It should be remembered that data covers wave conditions over the past 20 to 38 years only and that medium-term cycles such as the Inter-decadal Pacific Oscillation could be inducing (or masking) observed trends. For example, the 1950's to 1970's were anecdotally highly energetic with photographic evidence of significant erosion at many locations on the NSW coast. Additionally, future changes in extreme climate which are not correlated with previous trends (i.e. due to future climate change) could result in substantially different trends from those presently observed.

Results of extreme value analysis show the mid NSW coast to exhibit the highest extreme wave climate with a 100 year ARI, one hour exceedance height estimated at 9.0 m at Sydney and 9.1 m at Botany Bay. Extreme height decreases to the north and south reaching 8.0 m at Brisbane and 8.5 m at Eden. Both Batemans Bay and Byron Bay exhibit the lowest extreme heights of 7.7 and 7.6 m respectively. While the lower height observed at Batemans Bay have been found to be caused by land-mass sheltering and storm climatology (Coghlan et al., 2011), the lower heights at Byron Bay likely due to missing storm data. Until additional buoy data is collected, using either the upper confidence limit value or the value derived for the Brisbane Buoy is recommended at Byron Bay. When calculating extreme conditions for future periods, the effect of wave height increase should be considered.

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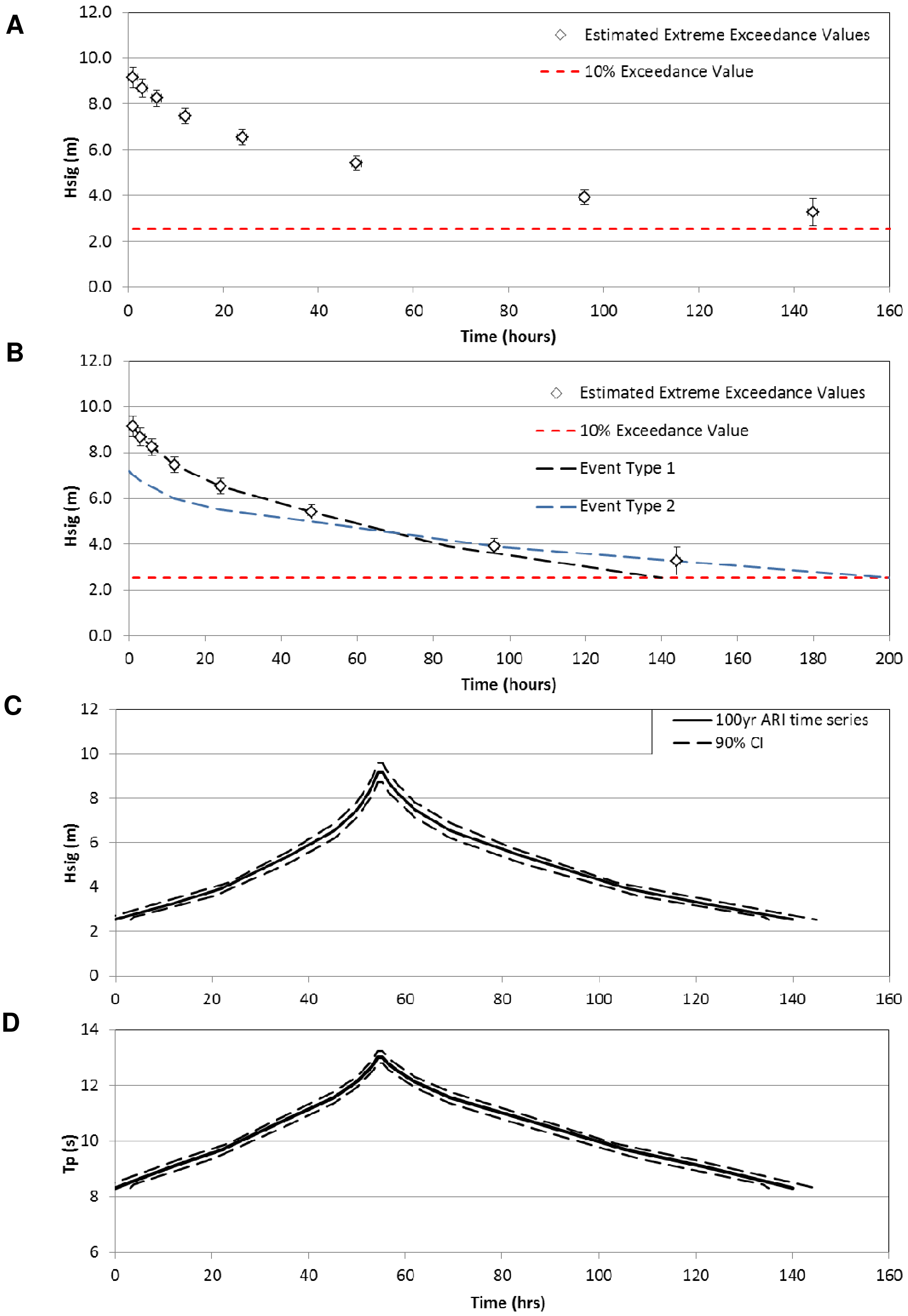

Figure 5: Example of the construction of a Synthetic Design Storm for a 100yr ARI event at Botany Bay.

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