High Resolution Wave Modelling (HI-WAM) for Batemans Bay Detailed Wave Study

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Abstract
Seven offshore wave buoys in the NSW coastal wave monitoring network have been deployed in water depths of 60 to 100 m to collect long-term wave data along the NSW coast. Previous studies have indicated that the mean and extreme wave heights measured at Byron Bay, Coffs Harbour, Crowdy Head, Sydney, Port Kembla and Eden are generally similar, but all are higher than the wave heights measured at Batemans Bay. This study investigated the causes of this disparity. Initially, the physical mechanisms which may influence the wave climate in the region were identified. The wave climate in the Batemans Bay region was then analysed in a two-part study based on the output of the Australian Bureau of Meteorology's HI-WAM model; a high resolution version of the ocean wave prediction model WAM.

Part 1 of the study assessed the performance of HI-WAM. It was found that that the HI-WAM model was capable of reproducing the measured mean wave heights at all seven offshore locations on the NSW coast, including the reduced measured mean wave heights at Batemans Bay.

Part 2 of the study determined how far offshore and alongshore this reduced wave climate extends. It was found that the alongshore variation in significant wave height is minor in the vicinity of Batemans Bay indicating that Batemans Bay wave buoy is, in general, representative of the nearshore region between Eden and Jervis Bay. However, there is a strong trend for significant wave height to increase with the shore-normal distance offshore under most conditions. This trend was found not to be attributable to ocean circulation currents or bottom friction, but due to land mass sheltering effects and wind field variations.

The findings of this study indicate that maritime structures and activities planned for locations seaward of all the buoys in the NSW coastal wave monitoring network, not just the Batemans Bay buoy, should consider exposure to higher wave heights than that measured at each respective wave buoy.

Keywords: ocean wave, wave model, wave buoy, wave measurement, statistical analysis.

1. Introduction

Following a series of intense and damaging storms in 1974, the NSW coastal wave monitoring network was incrementally established by deploying offshore wave buoys along the NSW coast. Wave data from the buoys has been collected by Manly Hydraulics Laboratory (MHL) for the NSW Office of Environment and Heritage (OEH). At present, seven offshore wave buoys are located seaward of coast at Byron Bay, Coffs Harbour, Crowdy Head, Sydney, Port Kembla, Batemans Bay and Eden in water depths of 60 to 100 m.

The seven offshore wave buoys are expected to record the deep-water wave climate with minimal attenuation across the distance between the wind fields forcing wave evolution and each buoy. However, shortly after the Batemans Bay wave buoy was deployed in 1986, it was observed that the wave climate was often less energetic than that recorded at the other six offshore wave buoy locations. This observation has been noted previously [6, 11], but no plausible explanation of this disparity has been made. This study was designed to determine the cause of this disparity.

The wave records from all seven locations were first analysed to clearly define the disparity in wave climate at Batemans Bay. The physical mechanisms which may influence the wave climate in the region were then identified. Having confirmed it appropriate to consider regional wave climatology, the wave climate in the Batemans Bay region was analysed based on the output of the Australian Bureau of Meteorology's (BoM) HI-WAM model; a high resolution version of the ocean wave prediction model WAM (WAve Model) [1, 5, 13].

This paper summarises the major outcomes from the detailed wave study for the Batemans Bay area by the Water Research Laboratory (WRL) of the University of New South Wales [3] and discusses their implications for coastal and maritime structure designs and NSW coastal inundation studies.

2. Wave Measurement Records

In another recent study by WRL [11], the mean and extreme wave heights measured at Byron Bay, Coffs Harbour, Crowdy Head, Sydney, Port Kembla and Eden were found to be generally similar, but all were higher than the wave heights measured at Batemans Bay. The exception to this is that the measured maximum significant wave height (H_S) at Eden is lower than that at Batemans Bay. Figure 1 illustrates the locations of all seven wave buoys. The statistics for H_S (considering all available data up to December 2009) are shown in Table 1. Coincident difference distributions were also determined by MHL [8] but will not be presented here for brevity.

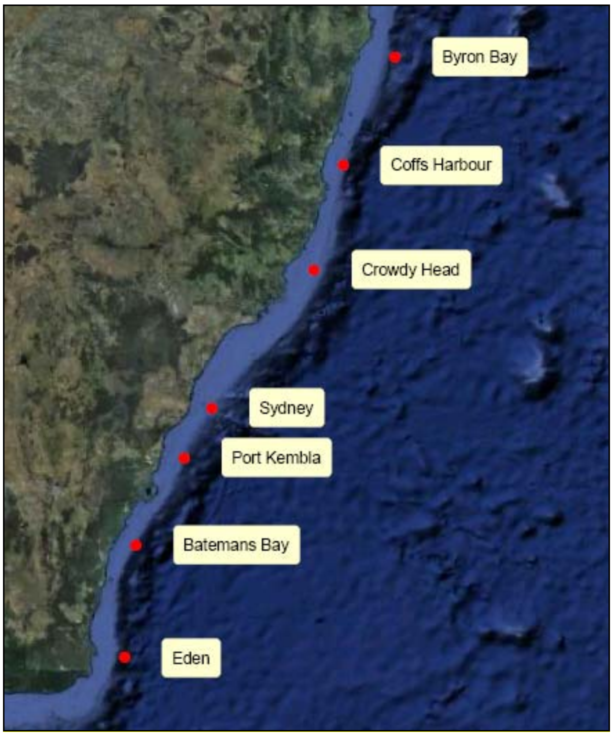

Figure 1 MHL/OEH Wave Buoy Sites on NSW Coast.

Table 1 Wave statistics for H_S (m) measured at the seven offshore locations along the NSW coast [11].

Location	Mean	Median	10% Exc.	1% Exc.	Max.
Byron Bay	1.66	1.50	2.59	3.93	7.64
Coffs Harbour	1.58	1.43	2.44	3.85	7.37
Crowdy Head	1.61	1.46	2.48	3.94	7.35
Sydney	1.63	1.46	2.55	4.19	8.43
Port Kembla	1.58	1.43	2.47	3.94	8.43
Batemans Bay	1.43	1.30	2.22	3.57	7.19
Eden	1.64	1.52	2.43	3.93	7.14

The wave statistics in Table 1 are reproduced in Table 2 as the ratios of the wave statistics for H_S at Byron Bay, Coffs Harbour, Crowdy Head, Sydney, Port Kembla and Eden to those at Batemans Bay. Examination of the H_S statistics ratios for the three adjacent wave buoys, Sydney, Port Kembla and Eden, indicates that H_S is higher for all parameters except Maximum H_S, relative to Batemans Bay. It is noteworthy that Mean, Median and 10% exceedance H_S across each of these three sites, were approximately 1.13 times the same wave statistics for H_S at Batemans Bay.

Table 2 Ratios of the wave statistics for H_S at the other six locations along the NSW coast to those at Batemans Bay (-)

Location	Mean	Median	10% Exc.	1% Exc.	Max.
Byron Bay	1.16	1.15	1.17	1.10	1.06
Coffs Harbour	1.10	1.10	1.10	1.08	1.03
Crowdy Head	1.13	1.12	1.12	1.10	1.02
Sydney	1.14	1.12	1.15	1.17	1.17
Port Kembla	1.10	1.10	1.11	1.10	1.17
Eden	1.15	1.17	1.09	1.10	0.99

It is plausible that a lower data capture rate or missing storm events are responsible for the lower wave climate measured at Batemans Bay. There are several reasons why the wave data capture rate may be less than 100 % including wave buoy spinning, mooring failure due to vessel collision or extreme storms and receiving station failure [8]. Table 3 lists the mooring depth, approximate distance offshore, data capture rate and record length for each wave buoy. Note that the Batemans Bay buoy has the highest capture rate at 89.7 % and a comparable total record length. This demonstrates that the wave climate disparity is not caused by a lower data capture rate at Batemans Bay or missing storm wave data.

Table 3 Site details and data capture rate [11].

Location	Depth (m)	Distance Offshore (km)	Capture Rate (%)	Length (years)
Byron Bay	62	6.0	73.1	33.2
Coffs Harbour	72	12.4	84.7	33.6
Crowdy Head	79	10.3	85.6	24.3
Sydney	92	9.5	84.5	22.5
Port Kembla	80	10.4	85.1	35.9
Batemans Bay	73	5.0	89.7	23.6
Eden	100	12.8	83.5	31.9

It should be noted here that possible sources of error in the wave buoy data also include submergence of the wave buoys at wave crests and due to strong currents, resulting in underestimation of wave height and increased linearity in observed waveforms due to loose buoy tether lines [11]. However, the errors and uncertainties associated with the observations at each of the wave buoy sites are significantly smaller than those associated with the modelled wave climate.

3. Physical Mechanisms Influencing Waves

3.1 Wave and Current Interaction

The potential influence of ocean currents on the Batemans Bay regional wave climate was investigated by MHL [8]. Long-term ocean current measurements in the region were unavailable for assessment. A literature review indicated that the formation of large eddies off the NSW south coast leads to ocean currents which are highly variable in both velocity and direction. While ocean currents are known to change the incident wave spectra in wave height, period and directional spreading under specific circumstances, it was concluded that the influence of ocean currents was insignificant compared with the other mechanisms investigated.

3.2 Wave and Bed Interaction

3.2.1 Bathymetry Review

A recent detailed hydrographic survey of the seabed in the Batemans Bay region has been undertaken by MHL [7]. A chart derived from this survey is reproduced as Figure 2. The location of the Batemans Bay wave buoy is also included on the figure for reference.

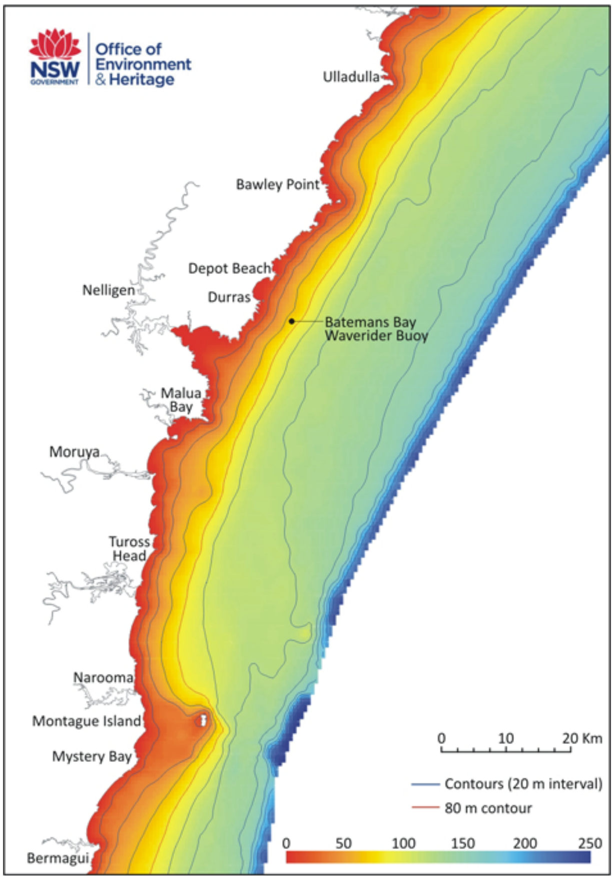

Figure 2 Local Batemans Bay Bathymetry [7].

Examination of Figure 2 shows the seabed in the vicinity of the Batemans Bay wave buoy has a consistent profile perpendicular to the coastline, with a slope of approximately 1:100 to a water depth of 100 m, a broad and gently sloping continental shelf to approximately 25 to 30 km offshore to a water depth of 200 m, and a rapid drop off to the deeper ocean waters beyond the continental shelf. This profile is consistent to the north and south of Batemans Bay for 100 and 50 km, respectively. Montague Island and the surrounding reef maintain shallower waters further out on to the shelf for a distance of 50 to 100 km south of Batemans Bay. The shallower water south of the buoy location is best described by the 80 m depth contour which shows the tongue of shallower water extending south of Narooma to Montague Island. It is considered that this seabed feature would have an insignificant impact on the wave climate at the wave buoy as the water is sufficiently deep to cause minimal wave shoaling or refraction. There are no other unusual features or areas of shallow water that would have any influence on ocean waves as they approach the buoy location from deep water from any offshore direction.

3.2.2 Bottom Friction

The total loss of wave energy due to bottom friction during the propagation of a wave train up into transitional and shallow waters is not only dependent on wavelength, but also on wave height. Ocean wave energy begins to be reduced by bottom friction when the water depth to local wavelength ratio is less than 0.5 [12]. However, this force is only considered substantial when this ratio is reduced to less than 0.25 [10]. The Batemans Bay wave buoy is currently positioned in a water depth of 73 m. At this water depth, bottom friction exists only when wave periods are greater than 9.5 s and it is considered substantial only when wave periods are greater than 14 s.

To quantify this, calculations were undertaken by WRL using Airy (linear) wave theory for the area offshore of Batemans Bay by selecting a friction factor of 0.02 [9, 14]. For a wave period of 18 s from the south-east, the deep water wave height must be at least 9 m if bottom friction is to reduce this height by at least 1 % between deep water and the water depth of 73 m. While wave periods in excess of 18 s are present in most spectra at Batemans Bay, their proportion in the overall spectrum (particularly those with wave heights of at least 9 m) are negligible. As such, bottom friction is considered to be a negligible influence on the Batemans Bay disparity.

3.3 Wave Climatology

Following the elimination of interactions with currents and the seabed as possible influences on the reduced wave climate at Batemans Bay, an assessment of regional wave climatology was undertaken with a two-part study based on the output of the HI-WAM model.

4. Specifications of the HI-WAM Model

Previously, BoM predicted coastal and offshore wave conditions using HI-WAM; a model developed for examining sediment mobility on the Australian continental shelf [10] from 1997 to 2008. During this period, HI-WAM was the most detailed (and computationally intensive) wave model of the Australian coastline developed by BoM. The model output from HI-WAM has been made available for research purposes only and should be considered experimental.

The source/sink forcing terms in the HI-WAM model were unmodified from the default Cycle 2 WAM physics with the exception of the white-cap dissipation which was tuned for Australian conditions. Note that bottom friction was included as a sink term in HI-WAM. However, other finite depth processes, such as depth-limited wave breaking and triad non-linear interactions as well as ocean currents were not considered in this wave model.

The HI-WAM model had a grid spacing of 0.1 ° (approximately 11 km) and a domain spanning longitudes from 110°E to 156°E and latitudes ranging from 7°S to 46°S and was nested inside a coarser resolution WAM model. Surface wind velocity estimates generated by BoM's Meso Limited Area Prediction System provided the wind input to the model with a grid spacing of 0.125 °. The bathymetric model coupled with HI-WAM for defining water depths had a grid spacing of 0.01° (approximately 1 km).

The HI-WAM model outputs of significant wave height, mean wave period (T_1) and mean wave direction (*Drn*) were archived at six-hourly intervals for a record length of 11 years.

5. Part 1 (Validation of the HI-WAM Model)

Part 1 of the study was undertaken to benchmark the performance of the HI-WAM model against the data collected by all seven wave buoys along the NSW coast and to determine whether the HI-WAM model was capable of reproducing a similar reduced wave climate at Batemans Bay. The long-term wave records from the buoys were required to make comparisons with the modelled values to quantify how well HI-WAM predicts wave height, period and direction.

During this study, the capability of reproducing the mean wave climate on the NSW coast was demonstrated by the HI-WAM model. An example time series plot comparing measured and predicted H_S values for one location (Batemans Bay) for one representative month (June 2005) is shown in Figure 3. For any given NSW wave buoy location, the general difference between the measured and wave predicted parameters was ± 0.45 m for H_S, ± 1.30 s for T_1 and ± 30 ° for Drn ($H_S \geq 1$ m).

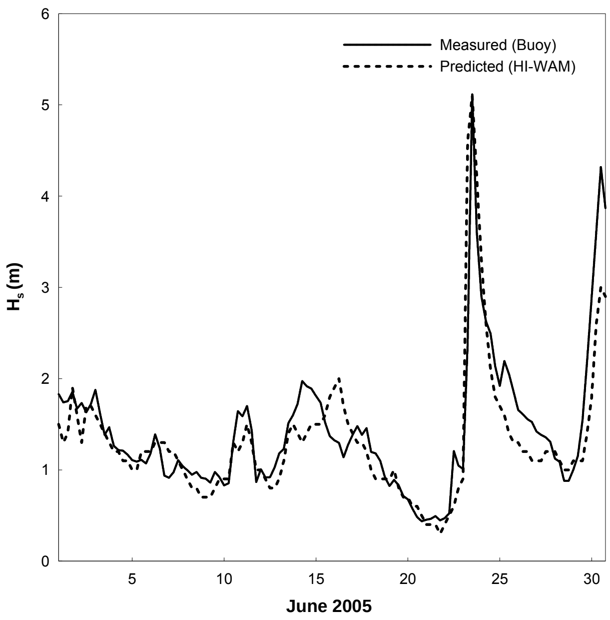

Figure 3 Comparison of the measured and predicted wave heights (*H_S*) at Batemans Bay.

Model predictions for H_S were considered to be robust down to a 10 % probability of exceedance (typically $H_S \approx 3.0$ m) [2]. The HI-WAM model was not suitable for prediction of extreme wave conditions (typically $H_S > 3.0$ m) and therefore should not be used to represent storm wave conditions along the NSW coast. It followed that reporting of model results in Part 2 of the study excluded lower probability statistics, such as 5 % exceedance, 1 % exceedance and maximum H_S.

It was necessary to determine if the HI-WAM model predicts a similar reduced wave climate at Batemans Bay as noted with the buoy data. In order to do this, ratios of the wave statistics for H_S at the three adjacent wave buoys (Sydney, Port Kembla and Eden) to those at Batemans Bay were again calculated. Ratios of the wave statistics for H_S were determined for both the measured (buoy) and predicted (HI-WAM) data during the 11 year validation period and presented in Table 4. While it is acknowledged that differences exist between the exact magnitudes of the measured and predicted H_S statistics ratios, the HI-WAM model generally reproduced a reduced wave climate at Batemans Bay.

Table 4 Ratios (-) of the wave statistics for H_S at Sydney, Port Kembla and Eden to those at Batemans Bay (Mar. 1997 – Feb. 2008)

Location	Source	Mean	Median	10% Exc.
Sydney	Buoy	1.18	1.16	1.18
	HI-WAM	1.13	1.15	1.16
Port Kembla	Buoy	1.13	1.13	1.15
	HI-WAM	1.06	1.08	1.08
Eden	Buoy	1.18	1.21	1.13
	HI-WAM	1.24	1.25	1.29

6. Part 2 (Detailed Assessment of HI-WAM Model Dataset around Batemans Bay)

On the basis that the HI-WAM model could reproduce a reduced wave climate at Batemans Bay with a similar magnitude to the measured wave data, Part 2 of the study was undertaken to determine how far offshore and alongshore this reduced wave climate extends. The influence of wave direction and wave period was also considered in this detailed assessment but will not be presented here for brevity [3].

A sub-set of the HI-WAM model domain was interrogated for longitudes ranging from 146°E to 156°E (West to East) and latitudes ranging from 25°S to 40°S (North to South). This domain includes the entire New South Wales coastline, extending from Fraser Island (Queensland) in the north to Wilsons Promontory (Victoria) in the south. Time series of H_S were extracted from the HI-WAM model at six-hourly time steps over the period of 01/03/1997 to 01/03/2008.

After sorting the extracted series, H_S ratios for all model grid points were again calculated relative to the same statistic at the grid point closest to the Batemans Bay wave buoy location (Latitude: 35.7°S, Longitude: 150.4°E). A surface representing H_S ratios across the domain was interpolated from the values calculated at discrete grid points. A contour plot highlighting the spatial variation in mean H_S for the region of interest between Sydney and Eden is shown in Figure 4.

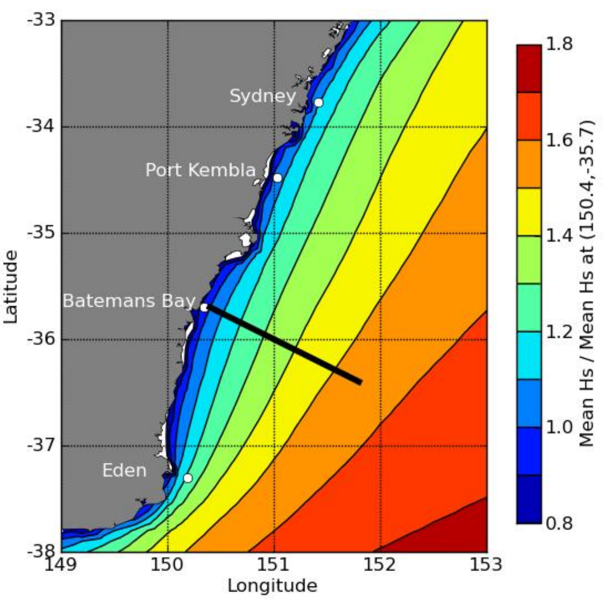

Figure 4 Mean H_S relative to Batemans Bay.

This illustrates how the ratios for mean H_S determined at discrete points (for each wave buoy location), fit into the broader picture of wave climate variation along the south coast of NSW. Figure 4 also illustrates clearly that alongshore variation for mean H_S ratios within the nearshore region between 60 m and 120 m water depth from Green Cape, near Eden (Latitude: 37.3°S, Longitude: 150.1°E) to St Georges Head, near Jervis Bay (Latitude: 35.2°S, Longitude: 150.7°E) is minimal and was not investigated further. As such, the Batemans Bay wave buoy is correctly measuring a lower wave climate representative of the nearshore region between Eden and Jervis Bay at its current deployment location.

To assess the variability in H_S offshore from Batemans Bay, a shore-normal transect was adopted, with an approximate bearing of east-south-east (ESE). Mean H_S ratios (relative to Batemans Bay) were then extracted from grid points on this bearing as shown in Figure 5. H_S clearly increases rapidly along this transect in a shore-normal direction. This indicates that the Batemans Bay wave buoy would need to be relocated between approximately 20 and 30 km further to the ESE to measure a wave climate of similar magnitude to the three adjacent buoys (Eden, Port Kembla and Sydney).

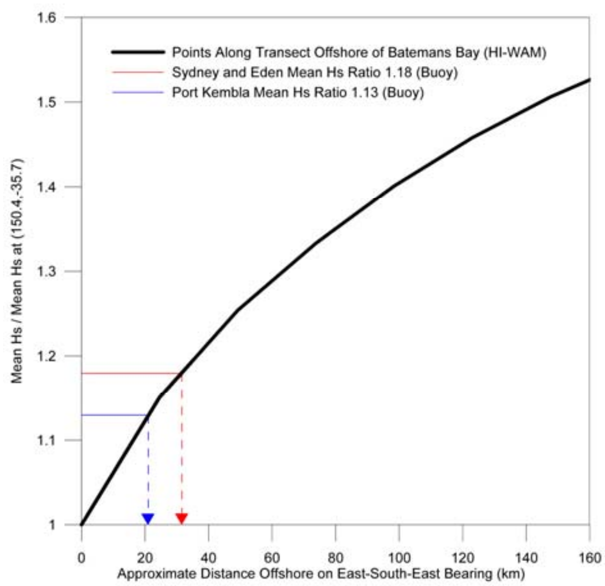

Figure 5 Transect of Mean H_S ratios to the ESE.

For water depths exceeding 120 m, the shore-normal gradient in H_S offshore of the NSW coast increases with decreasing latitude (Figure 4).

7. Discussion

The trend for H_S to increase with shore-normal distance offshore of the southern coast of NSW is consistent with a national climatology study [4]. This study was conducted using both observed satellite altimetry data and output from numerical wave models different to HI-WAM. While analysis was conducted at a more coarse resolution than HI-WAM, [4] noted that a “tongue” of increased H_S was observed extending into the Tasman Sea between the NSW coast and NZ (reproduced in Figure 6). The maximum of this “tongue” is located approximately two-thirds of the way from the NSW coast to New Zealand.

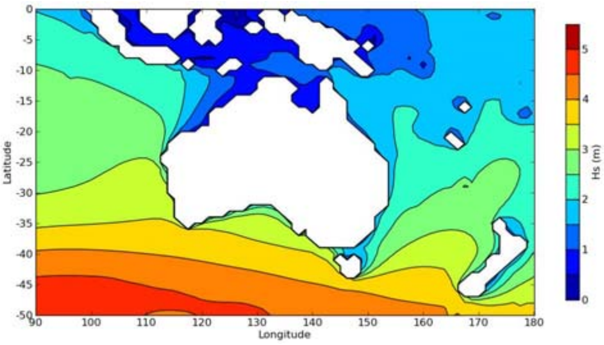

Figure 6 Mean H_S over all NWW3 Data [4].

Within the sectors of source wave energy in the Tasman Sea and the South Pacific Ocean, there is extensive variability of the strength, position, direction and track of wind fields forcing wave evolution, however, [11] found storm events on the NSW coast to be more frequent and intense on the mid to north coasts than the south coast. Additionally, southerly orientated events reach NSW through directional dispersion processes with relatively less directional dispersion required to reach the mid NSW coast than the south coast [3]. It follows that the lower wave climate in the vicinity of Batemans Bay can be attributed to:

- a combination of land mass sheltering from Victoria and Tasmania during southerly events; and
- a northern bias in the distribution of strong wind fields responsible for generating wave events.

8. Conclusions

A comprehensive study has confirmed that the mean wave climate in the vicinity of Batemans Bay is less energetic than along the rest of the NSW coast. Data capture rate, currents, bathymetry and bottom friction were found to have an insignificant influence on this disparity. Instead, the reduced wave climate is attributed to land mass sheltering effects and wind field variations.

The Batemans Bay wave buoy is correctly measuring a lower wave climate representative of the nearshore region between Eden and Jervis Bay at its current deployment location. Based on the findings of this investigation, it is recommended that maritime structures and activities planned for locations seaward of the NSW coastal wave monitoring network should consider exposure to higher wave climates.

Further research opportunities are required to enhance the existing understanding of the NSW wave climate including, short term deployments of additional wave buoys, coupled analysis of meteorological data and wind fields from an atmospheric model and analysis of lower probability H_S wave statistics from a more robust wave model validated under extreme conditions.

9. Acknowledgments

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10. References

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