NSW COASTAL OCEAN WAVE MODEL: INVESTIGATING SPATIAL AND TEMPORAL VARIABILITY IN COASTAL WAVE CLIMATES

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The Office of Environment and Heritage (OEH), with the assistance of Cardno (NSW/ACT) and Baird Australia, have developed the NSW Coastal Ocean Wave Model – a coupled WAVEWATCH III/SWAN modelling system that has been designed to simulate historical and potential future coastal wave climates. The purpose of the model is to investigate latitudinal and temporal variability in NSW deep-water wave climates, and alongshore variability in nearshore wave conditions. This paper describes the wave modelling facility, discusses the evaluation of model performance to date, and describes the proposed wave data products, which will be useful for assessing coastal hazard risks in NSW.

Measured wave records in NSW are enviable by global standards, with Waverider buoys (WRBs) deployed along the coastline since the mid-1970s. However, wave modelling provides an opportunity to address some limitations of the existing measurement records, including: the sampling frequency of earlier instruments; instrument failure (particularly during storms); the relatively recent capability to measure wave directions; and deployment durations at different locations – e.g. prior to 2011, directional buoys were only deployed at Sydney (1992), Byron Bay (1999) and Batemans Bay (2001). As measurements are not available for particularly stormy periods experienced during the 1950s, 1960s and early 1970s, extreme values derived from more recent data may under estimate storm-wave climates. Thus the directionality and extreme nature of NSW wave climates may not be fully resolved.

Simulated wave climates generated by the NSW Coastal Ocean Wave Model have been evaluated against measurement records and other wave models. For example, comparison of CFSR-driven model predictions with WRB data for 1998-2009 suggest that predicted peak storm wave height and direction are overall very good, whilst mean wave period is typically under predicted. Although model-data agreement varies along the NSW coastline, the simulated wave climates are consistent with available measurement data, and improve on existing model data. Therefore the wave model products will address some limitations of WRB records, particularly wave directions and the definition of storm peaks.

Introduction

The deployment of Waverider buoy (WRB) instruments off the NSW coast since the mid-1970s has provided an invaluable measurement record of NSW wave climates. However, wave modelling provides an opportunity to address data limitations that arise from: deployment durations, the sampling frequency of earlier instruments, periodic instrument failure (particularly during storms), and, the relatively recent use of directional WRB instruments. Until recently, directional instruments were only deployed at Sydney (from 1992), Byron Bay (1999) and Batemans Bay (2001). Furthermore, as the measurement records do not include particularly stormy periods experienced during the 1950s, 1960s and early 1970s, derived extreme value statistics may under estimate reality. Thus wave models may be used to further improve our understanding of wave climate directionality and extreme events.

Spectral wind wave models use numerical techniques to simulate wave conditions in response to the applied climate forcing conditions (e.g. surface wind, air-sea temperature difference). Broadly, these models can be classified into two types: (1) ocean-scale spectral wave models (e.g. WAVEWATCH III) that simulate deep-water wave climates; and (2) nearshore spectral wave models (e.g. SWAN) that simulate wave transformation in shallow-water environments. The models simulate wave growth and propagation across a regular grid or irregular mesh, and output continuous time series (e.g. hourly) of parametric and spectral wave data at user-specified locations. Therefore, where reliable climate forcing data is available, spectral wind wave models may be used to simulate coastal wave climates.

The Office of Environment and Heritage (OEH), with the assistance of Cardno (NSW/ACT) and Baird Australia, have developed the NSW Coastal Ocean Wave Model, which is a coupled WAVEWATCH III/SWAN modelling system that has been designed to simulate historical and potential future coastal wave climates. The model provides a tool with which to investigate regional and temporal variability in NSW deep-water wave climates, and alongshore variability in nearshore wave conditions, beyond the limitations of existing measurement records.

This paper presents the development and application of the NSW Coastal Ocean Wave Model to date, including the evaluation of model performance against other datasets, and describes prospective datasets that will be generated through the ongoing development of the wave model. Modelled wave data is anticipated to assist NSW governments and industry in managing and planning for coastal hazards such as wave impact, beach erosion, and oceanic inundation.

Available wave climate data

Existing wave datasets

Historical records of ocean wave conditions along the NSW coast are enviable by global standards. The deployment of Waverider buoy instruments since the mid-1970s means that up to 40 years of measurement data is potentially available at some locations. Nonetheless, it is unlikely that existing records capture the full range of potential conditions, and therefore they cannot provide a complete understanding of NSW wave climates. This section describes some key wave climate datasets.

Waverider buoy network

Measurement of wave conditions in NSW using Waverider buoys began with the installation of the Botany Bay WRB by the Sydney Ports Corporation in 1971. Following a series of catastrophic storms experienced during the early 1970s, between 1976 and 1987 the NSW Government expanded WRB deployments into a statewide network (Fig. 1). Whilst all WRBs were originally non-directional – i.e. they did not collect wave direction data – the Sydney (Long Reef), Byron Bay and Batemans Bay stations were upgraded to directional WRBs in 1992, 1999 and 2001 respectively. Recently, all remaining stations have been updated with directional instruments that collect the full suite of parametric and spectral wave data. An additional WRB has been deployed off Brisbane by the Queensland Government since 1976, which has collected directional data since 1996 (Fig. 1).

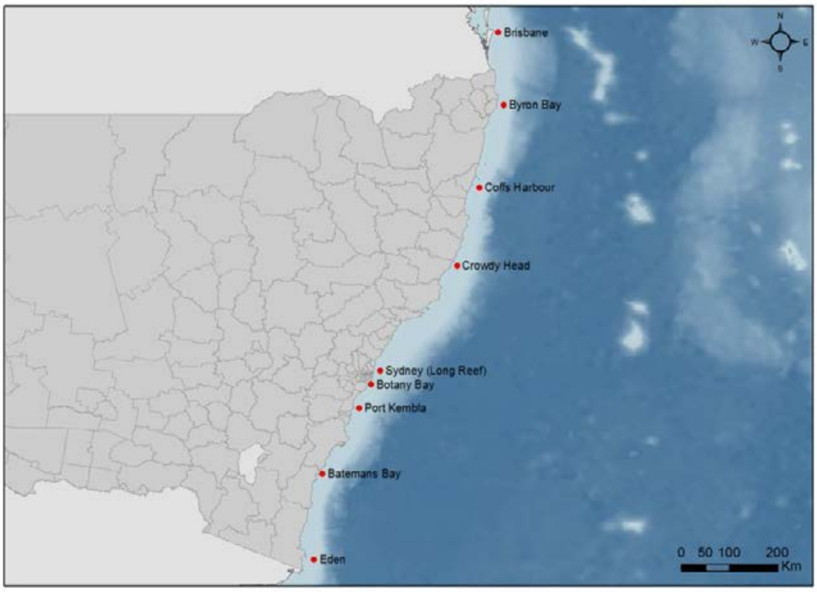

Figure 1 – Locations of Waverider buoy deployments along the southeast Australian coastline. NOTE: All Waverider buoy deployments were recently upgraded with directional instruments, although long-term historical records of wave directions remain limited to Brisbane, Byron Bay, Sydney and Batemans Bay.

Whilst data capture spans between 70-90% of total deployment times for all WRB stations (Tab. 1), some instruments have suffered from data omission errors during extreme storms and sensitivities to mooring locations (Shand et al., 2011). Such issues, and the limited historical extent of WRB time series, suggest that derived extreme wave climate statistics for low-probability high-magnitude events (e.g. 100-year ARI) may under-predict NSW wave climates in reality. For example, significant storms experienced during the 1950s, 1960s, and, in particular the early 1970s, are absent from the WRB measurement records. Shand et al. (2011) found that the low-frequency high-magnitude events of particular importance to extreme beach erosion exceed fitted extreme-value distributions, and thus may potentially belong to a distinctly separate and sparsely sampled statistical population.

Table 1 – Sampling interval, data capture and record length of Waverider buoy deployments in southeastern Australia, as at the end of 2009 (Shand et al., 2011). ND = non-directional instrument, D = directional instrument.

Deployment	**Sampling Interval (hrs)**			**Total Capture (%)**	**Total Record Length (yrs)**	**Effective Record Length (yrs)**
	12	**6**	**1**			
Brisbane (ND)	1976-1982	1982-1991	1991-1996	85.9	33.2	28.5
Brisbane (D)			1996-2009			
Byron Bay (ND)		1976-1984	1984-1999	73.1	33.2	24.3
Byron Bay (D)			1999-2009			
Coffs Harbour		1976-1984	1984-2009	84.7	33.6	28.5
Crowdy Head			1985-2009	85.6	24.2	20.7
Sydney (ND)			1987-2000	84.5	22.5	19.0
Sydney (D)			1992-2009			
Botany Bay (ND)		1971-1980	1980-2009	87.7	38.8	34.0
Port Kembla (ND)		1974-1984	1984-2009	85.1	35.9	30.6
Batemans Bay (ND)			1986-2001	89.7	23.6	21.2
Batemans Bay (D)			2001-2009			
Eden		1978-1984	1985-2009	83.5	31.9	26.6

Whilst all non-directional WRB deployments have been recently upgraded to directional instruments, historical records of wave direction remain limited. Figure 2 shows the seasonal and latitudinal wave climate variability between the Byron Bay, Sydney and Batemans Bay deployments. Whilst similar patterns of seasonal wave climate variability occur along the NSW coast, the nature and magnitude varies between the three sites. The Sydney deployment remains the only location where decadal-scale directional wave climate variability can potentially be considered, with 22 years of directional data now collected. An improved understanding of directional wave climate variability will require ongoing data collection across the WRB network to develop longer measurement records.

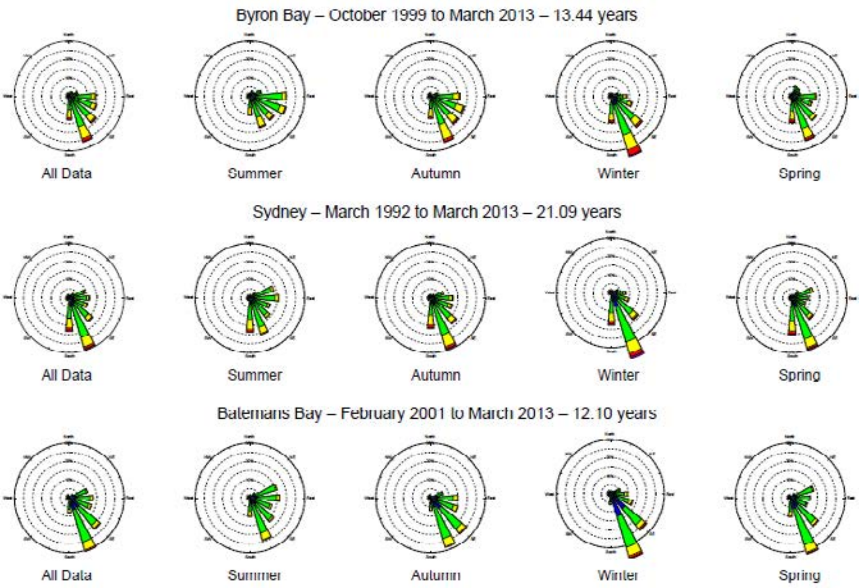

Figure 2 – Measured directional wave climates along the NSW coastline show both seasonal and latitudinal variability in both wave height and wave directions (Kulmar et al., 2013).

High-frequency radar

Coastal wave conditions have also been measured using high-frequency (HF) radar instruments. The Australian Coastal Ocean Radar Network (ACORN) has one radar site in NSW at Coffs Harbour. The array consists of two stations at Red Rock and North Nambucca, which have overlapping ranges of 100 km. Whilst the primary purpose of the facility is to measure ocean currents within the overlapping range of the two stations, wave statistics are also collected. Wave measurements using the Coffs Harbour array are presently limited to a semi-empirical estimation as described by Gurgel et al. (2006). The method provides single radar estimates of the wave frequency spectrum from which significant wave height and primary wave period can be extracted. The limited range and deployment duration of the HF radar system limits its use for coastal hazard assessments in NSW. Furthermore, the reliability of HF radar estimates of wave conditions remains in evaluation, although may be improved in future by combining the data from each of the radar instruments.

Hindcast & forecast wave models

Climate model reanalysis data provides an opportunity to extend measured wave data records back through history by simulating wave conditions using spectral wind wave models. Climate reanalyses use data assimilation techniques to constrain the physics of global and regional climate models, to generate hindcast climate data that best agrees with observations. The measurement data used in the assimilation may include *in situ* observations or data collected using remote sensing techniques (e.g. satellite observations). A wave simulation may be carried out for the duration of the reanalysis product to provide a continuous hindcast record of wave conditions across global and regional-scale grids. Some climate models are also run using real-time meteorological data to generate reliable near-term forecasts. Similar to climate reanalysis datasets, forecast climate model data may be used to drive spectral wind wave models to generate simulated forecast wave conditions.

Table 2 summarises available wave model datasets covering the NSW region. Most notably, the Centre for Australian Weather and Climate Research (CAWCR), a partnership between CSIRO and the Bureau of Meteorology, has recently published a 35-year (1979-2013) global wave hindcast featuring 7-km resolution output for the Australian region. The CAWCR Wave Hindcast and CAWCR Wave Hindcast Extension used Climate Forecast System (CFSR and CFSv2) wind data to generate a continuous global to regional wave hindcast for the period 1979-2013 (Durrant et al., 2014).

Whilst the Climate Forecast System datasets provide a reliable representation of the storm systems and meteorological patterns that generate observed wave conditions, extreme coastal storms may be under predicted due to the relatively coarse model grid resolutions and the imperfect representation of coastal meteorological processes. For example, Cardno (2012) found that the application of unscaled CFSR data in the NSW Coastal Ocean Wave Model resulted in the systematic under prediction of peak storm wave heights at Waverider buoy locations.

Table 2 – Available wave model datasets showing the climate reanalysis/forecast model and wave model used, and the duration, grid resolution and time step of the wave data products.

Wave dataset	Climate Model	Wave Model	Duration	Grid Resolution	Time step
ERA-40 Wave (ECMWF)	ECMWF ERA-40 reanalysis	WAM	Sep 1957 – Sep 2002	Global (1.5° x 1.5°)	6 hour
WAVEWATCH III (NOAA-MMAB)	NCEP-CFSR reanalysis	WW-III v2.22	Jan 1997 – Dec 2010	Global (1.25° x 1°) Australia-Indonesia (0.25° x 0.25°)	3 hour 3 hour
CAWCR Wave Hindcast and Extension (CSIRO/BoM)	NCEP-CFSR reanalysis NCEP-CFSv2 reforecast	WW-III v4.08	Jan 1979 – Dec 2010 Jan 2011 – May 2013	Global (0.4° x 0.4°) Australia (10' x 10') Australia (4' x 4')	1 hour 1 hour 1 hour
AUSWAVE Forecast (BoM)	ACCESS-G and ACCESS-R APS1 forecast models	WW-III v3.14	July 2012 onwards April 2013 onwards	Global (0.4° x 0.4°) Region (0.1° x 0.1°)	3 hour 1 hour

Knowledge gaps and data needs

Despite having historical wave measurement records that are impressive by global standards, the directionality and extreme characteristics of NSW wave climates remain only partially known. An improved understanding may be developed through continued wave climate monitoring using WRB instruments, supplemented with improved wave model data products. The limitations of existing wave data suggest the following data needs, which may be partly fulfilled through wave modelling:

1. **Continuous directional deep-water wave records**

   The limited length and distribution of directional wave measurement records suggest that available datasets may not provide a complete description of wave climate directionality in NSW. Site-specific investigations of nearshore wave climates and coastal hazards require detailed historical wave data to calibrate numerical models against observed events, and robust frequency distributions describing the wave energy originating from different directions.

2. **Long-term deep-water wave climate statistics (beyond measurement records)**

   Wave climate statistics derived from historical wave measurement data are limited by the durations of deployments and instrument outages experienced during storms. Whilst ambient wave climate statistics may be well resolved, extreme wave climate statistics are particularly sensitive to the limitations of measurement records. Furthermore, the durations of existing records may be insufficient to investigate multi-decadal-scale wave climate variability.

3. **Design inshore wave statistics**

   It is unlikely that the full range of feasible coastal wave conditions has been experienced along the NSW coastline during historical measurement and model hindcast periods (i.e. mid 1970s to present). This suggests that even a complete record of coastal wave conditions during that period may not provide a complete understanding of the potential for extreme wave conditions and associated coastal hazards.

4. **Detailed inshore wave scenarios**

   Site-specific studies coastal erosion and inundation require high-resolution wave predictions that consider inshore wave transformation. This is typically achieved using an irregular mesh, where model resolution can be maximised where necessary, and where data permits. The performance of hydrodynamic and coastal response models is sensitive to the reliability of the input shallow-water wave conditions.

5. **Near-term forecast inshore wave conditions**

   Forecast inshore wave conditions extending several days into the future would be useful for predicting coastal hazards such as erosion and inundation, and for issuing public warnings for recreational activities in coastal environments. Continuous near-term coastal wave forecasts can be used to force hydrodynamic and coastal response models to predict coastal hazards. While the Bureau of Meteorology provides near-term deep-water wave forecasts for Australia, the resolution of model predictions is not always suitable for coastal uses.

6. **Long-term forecast wave climate statistics**

   The potential for future change in NSW wave climates due to the climate change remains poorly understood. Although some forecast climate models have been used to infer changes in wave climates (McInnes et al., 2007), long-term wave climate forecasts are lacking. This limits the ability to incorporate the potential impacts of altered wave climates into coastal hazard studies and associated planning measures.

The NSW Coastal Ocean Wave Model provides a tool that will contribute to addressing the above data needs. However, ongoing data collection using WRBs, and the expansion of measurements to inshore waters, remains vital to improving our understanding of: wave climate directionality; the probabilities associated with extreme wave events; multi-decadal-scale wave climate variability; and, the reliability of wave modelling capabilities.

NSW Coastal Ocean Wave Model

The NSW Coastal Ocean Wave Model was developed by Cardno (NSW/ACT), under the direction of OEH, to investigate deep-water and nearshore wave conditions along the NSW coast (Cardno, 2012). The model system comprises coupled WAVEWATCH III (WW-III) and SWAN spectral wind wave models to simulate both deep-water and inshore wave conditions. The WW-III model is driven by climate model wind and air-sea temperature data (e.g. CFSR/CFSv2), whilst the SWAN model can be driven by the WW-III output or measured wave data (e.g. WRB records). The model system is capable of generating deep-water wave hindcast and forecast data globally (using hindcast/forecast climate model data), and detailed inshore wave predictions for NSW coastal waters.

The WW-III model (v3.14) features nested Global, Australia and NSW grids (Fig. 3), to provide deep-water parametric and spectral wave data for NSW waters at a resolution of approximately 5 km. The default atmospheric forcing conditions are provided by the NCEP-CFSR reanalysis (1979-2010) and NCEP-CFSv2 reforecast model (2011-ongoing). Model bathymetry for each grid was derived from Geoscience Australia's 9-arc-second digital elevation model for Australian territorial waters, and WW-III global distribution bathymetry elsewhere. Sensitivity testing carried out by Cardno (2012) indicated that model performance did not improve significantly for grid resolutions higher than 5 km (based on CFSR forcing), and were not sensitive to bottom friction for the depths at which the model is used.

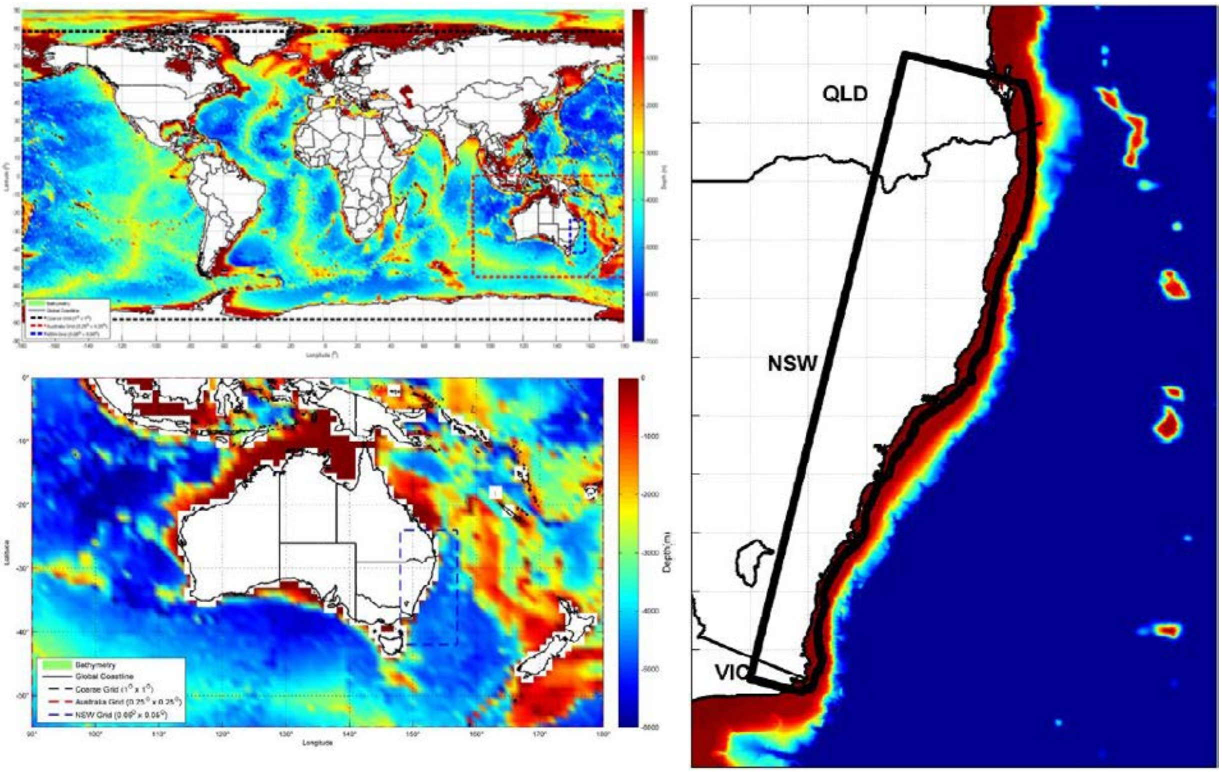

Figure 3 – Global (1° resolution), Australia (0.25°) and NSW (0.05°) computation grids for the WAVEWATCH III component of the NSW Coastal Ocean Wave Model (Cardno, 2012). The black outline around the NSW coastline shows the extent of the SWAN transition model grid (0.025°).

Inshore SWAN wave models are coupled to the WW-III model via a SWAN transition model (2.5 km grid resolution). The transition model covers all NSW coastal waters (Fig. 3), and is driven by spectral output wave data from the WW-III model applied along the ocean boundaries, and wind fields from the CFSR/CFSv2 climate models. To allow for high resolution wave predictions at inshore sites of interest, the model allows a user-defined regular grid or irregular mesh to be nested within the SWAN transition model. The inshore grid/mesh supports detailed wave predictions based on high-resolution bathymetry that can influence wave transformation (e.g. shoaling, refraction, breaking) in shallow coastal waters. Using the coupled WW-III/SWAN design, the NSW Coastal Ocean Wave Model is capable of inshore wave predictions for any location along the NSW coast from 1979 onwards.

Calibration for storm conditions

In designing the NSW Coastal Ocean Wave Model, Cardno (2012) evaluated the performance of GFS, CCMP and CFSR modelled wind datasets to drive the WW-III model, against measured wind data and QuickSCAT Satellite Scatterometer data. Whilst the CFSR dataset was found to provide the best representation of historical wind fields, all wind datasets were found to suffer from diminishing wind speeds in the vicinity of the coastline. That is, whereas observed coastal wind speeds were often greater than offshore wind speeds, the modelled wind datasets systematically depicted reduced wind speeds in the coastal zone.

Based on the wind data analysis, Cardno (2012) developed a wind speed factoring matrix for CFSR wind data in the NSW region, with the objective of achieving a more reliable representation of coastal wind speeds. The factoring matrix enhances wind speeds by: 5% from 60-100km offshore; 10% from 30-60km; and 20% from 30km offshore to the coastline. The factored wind fields were anticipated to allow for more reliable predictions of peak wave heights generated by coastal storms in particular.

Model development and applications

Development of the NSW Coastal Ocean Wave Model and datasets has proceeded through three phases thus far, which are summarised as follows (key references included):

1. Design, development and evaluation of the NSW Coastal Ocean Wave Model (Cardno, 2012)
    - Development of the coupled WAVEWATCH-III/SWAN wave modelling system
    - Model calibration for storm-wave conditions and scaling of CFSR/CFSv2 wind data
    - Continuous 12-year (1998-2009) WW-III deep-water wave hindcast using CFSR data
    - Deep-water wave (WW-III) simulation of top 30 storms occurring between 1979-1997
    - Evaluation of WW-III model performance against deep-water WRB records
    - Inshore (SWAN) wave hindcast at Newcastle for 2006 and SWAN model evaluation
    - Development of wave modelling toolbox for data post-processing and analysis
2. Hindcast extension, model refinement, and evaluation of nearshore model performance
    - Deep-water wave hindcast extension (2010-2012) using CFSv2 data (Cardno, 2013)
    - Evaluation of inshore (SWAN) wave model at Wamberal (Mortlock & Goodwin, 2013)
3. Exploratory 60-year (1950-2010) deep-water wave hindcast using NCEP-NCAR reanalysis and NARCLiM regional climate models (Baird Australia, 2014a; 2014b; Dent et al., 2014)
    - Developed MPI WW-III model for NCI 'Raijin' high-performance computing facility
    - Evaluate WW-III model performance using three NARCLiM hindcast RCMs
    - Continuous 60-year (1950-2010) wave hindcast using NCEP-NCAR/NARCLiM RCM

Figure 4 shows the existing output locations for the NSW WW-III model grid, at which parametric and spectral wave data has been stored. The locations shown in red cover a regular array of output points along the coastline (including all wave measurement locations), at which both parametric (point) and spectral wave data is saved. The locations shown in orange indicate the 5-km spaced WW-III spectral output that is used to drive the SWAN transition model.

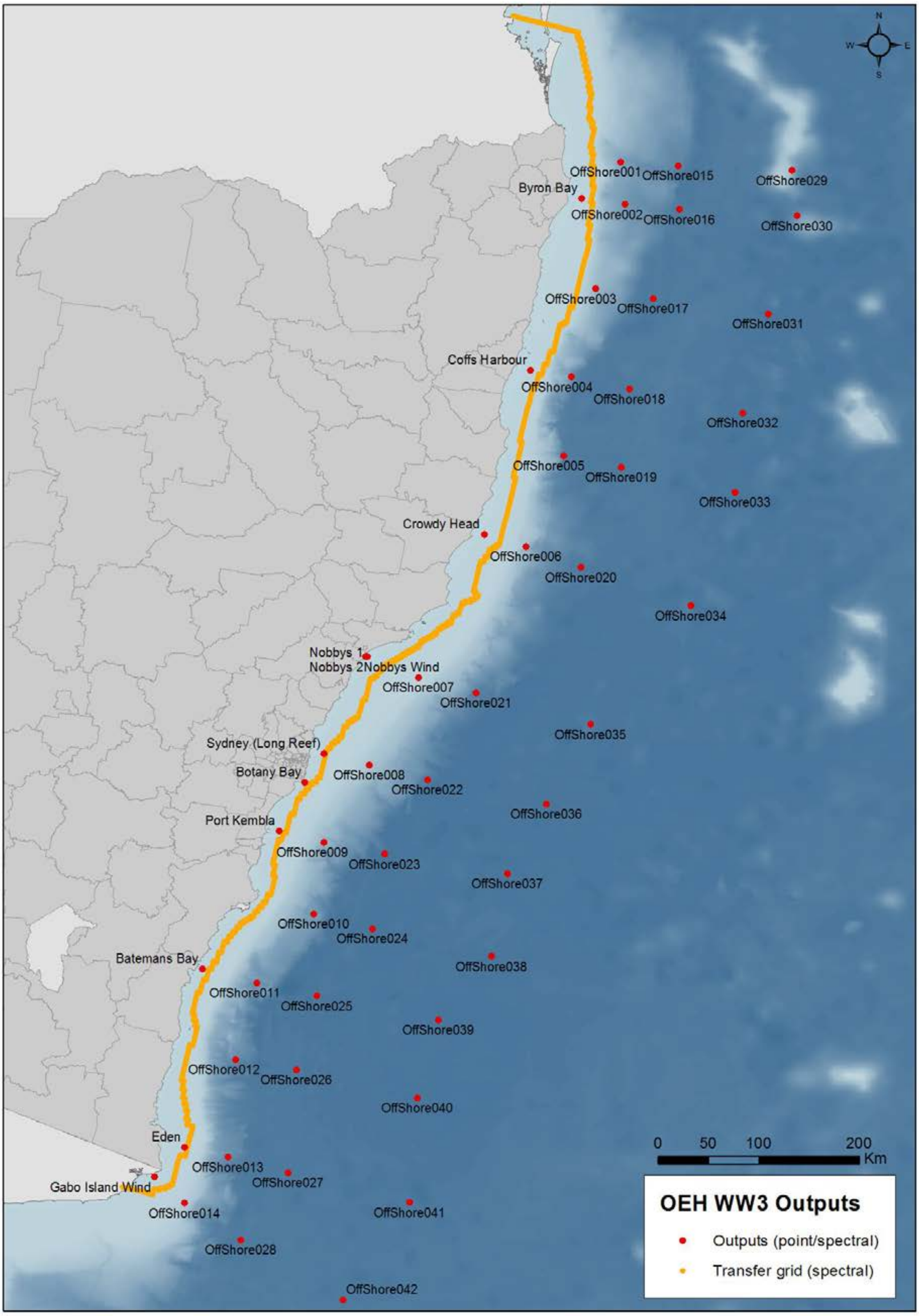

Figure 4 – Output locations for the NSW WAVEWATCH III grid where processed wave data has been saved during development of the NSW Coastal Ocean Wave Model. The output locations include an even array of oceanic sites and the positions of wave measurement instruments, including all Waverider buoy deployments.

Evaluation of wave model performance

The storm-calibrated wave hindcast (hereafter NSW Storm-Wave Hindcast) simulated using the NSW Coastal Ocean Wave Model have been compared with measured wave records and publically available simulated wave hindcast datasets to evaluate model performance. Figure 1 and Table 1 describe the deep-water data that has been collected using Waverider buoys. Permanent inshore WRBs at Newcastle (Fig. 4) and a temporary inshore WRB at Wamberal have also been used to evaluate wave model predictions.

It should be kept in mind that the WRB measurement records are subject to data omission where the instruments have been damaged or otherwise out of service. This has resulted in shorter effective record lengths relative to total deployment times (Tab. 1). In comparison, the wave climates that have been simulated using WW-III are continuous records over the periods considered. This suggests that even if the wave model was completely accurate, the wave climate statistics generated from the measured and simulated records may vary due to the different number of samples. This difference would be more apparent where storms have been omitted from the measurement records, due to the comparatively low occurrence of storm waves relative to ambient conditions.

Deep-water waves (WAVEWATCH III)

Measured wave records

Deep-water (WW-III) wave model predictions carried out using the factored CFSR wind data were compared with measured wave records at the seven MHL Waverider buoy deployments for the initial 12-year hindcast period (1998-2009). Significant wave height (H_{m0}), mean wave period (T_{m01}), peak storm H_{m0} and peak spectral wave directions during significant storms (H_{m0} > 4 m) were considered.

Figure 5 shows quantile-quantile (QQ) plots of significant wave height, which compare the simulated and measured H_{m0} distributions over the period 1998-2009, across the range of wave heights sampled at each WRB deployment. For perfect agreement between simulated and measured wave heights, the sampled data should follow the 1:1 trend line. The comparisons indicate that the simulated wave conditions are very consistent with the measured waves for H_{m0} up to 5-6 m at most sites. For extreme wave conditions during which H_{m0} exceeds 5-6 m, the model shows a tendency to over predict wave heights in northern NSW, and under predict wave heights in central and southern NSW.

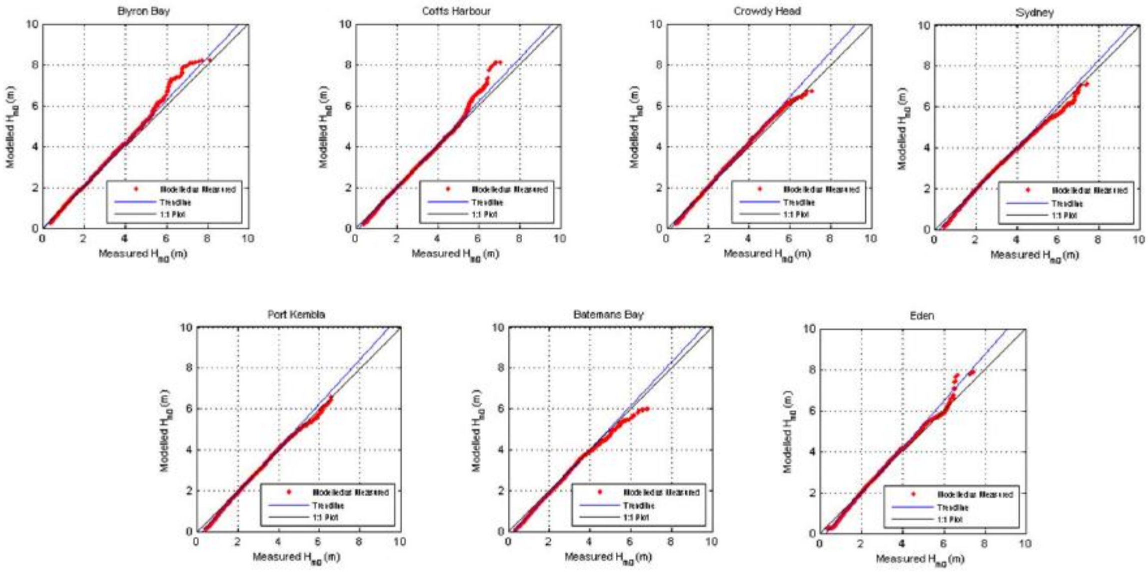

Figure 5 – Quantile-Quantile (QQ) plot comparing modelled and measured significant wave height (H_{m0}) at the seven deep-water Waverider buoy locations over the 12-year hindcast period 1998-2009 (Cardno, 2012).

Similarly, Figure 6 shows a QQ plot for mean wave period, comparing the simulated and measured T_{m01} distributions over the period 1998-2009. Mean wave period was generally well predicted by the model, although model skill decreased for the case of T_{m01} above 10-12 s.

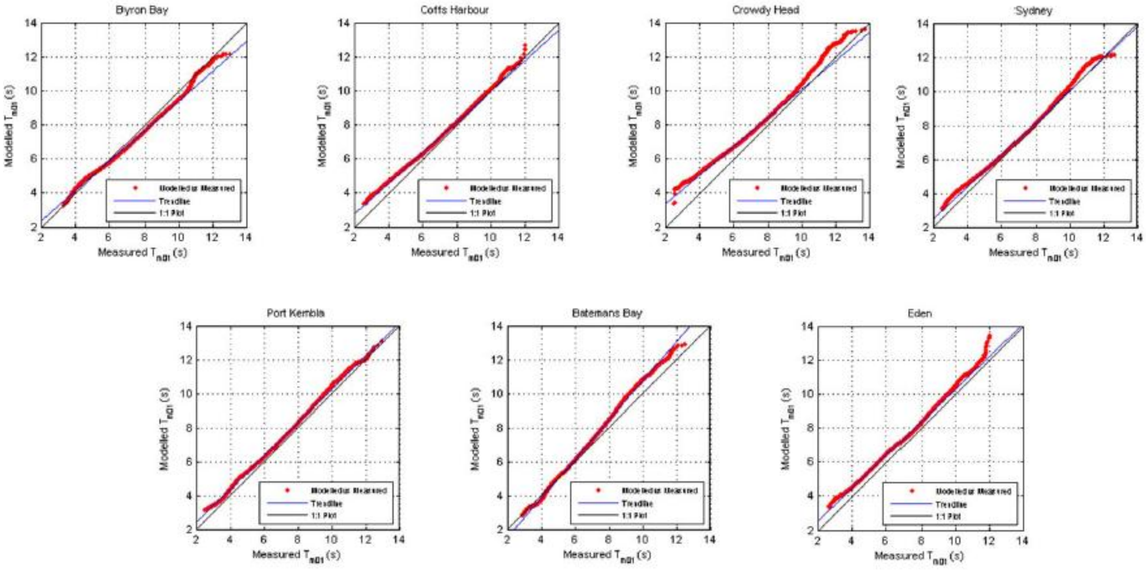

Figure 6 – Quantile-Quantile (QQ) plot comparing modelled and measured mean wave period (*T_{m01}*) at the seven deep-water Waverider buoy locations over the 12-year hindcast period 1998-2009 (Cardno, 2012).

The best agreement between the simulated and measured wave records occurred at the Sydney and Port Kembla WRB deployments, particularly for the cases of H_{m0} > 4 m and T_{m01} > 10 s (Figs. 5 & 6). To further evaluate model performance in predicting storm wave conditions, the 12-year hindcast was extended to include the top 30 storms measured at the Port Kembla WRB between 1979 and 1998 (based on peak H_{m0}). Figure 7 shows scatter plots comparing modelled and measured peak H_{m0} for the top 30 storms (1979-1998) and all storms exceeding H_{m0} = 3 m for the 1998-2009 period. The fit of the trend line suggests that on average the model may under estimate peak H_{m0} at Sydney by about 10%. The fit was slightly better at Port Kembla where the model under predicted storm peaks by 8% on average. For measured wave heights above H_{m0} = 6 m, simulated peak wave heights at Port Kembla showed a reasonable fit with the measured wave data.

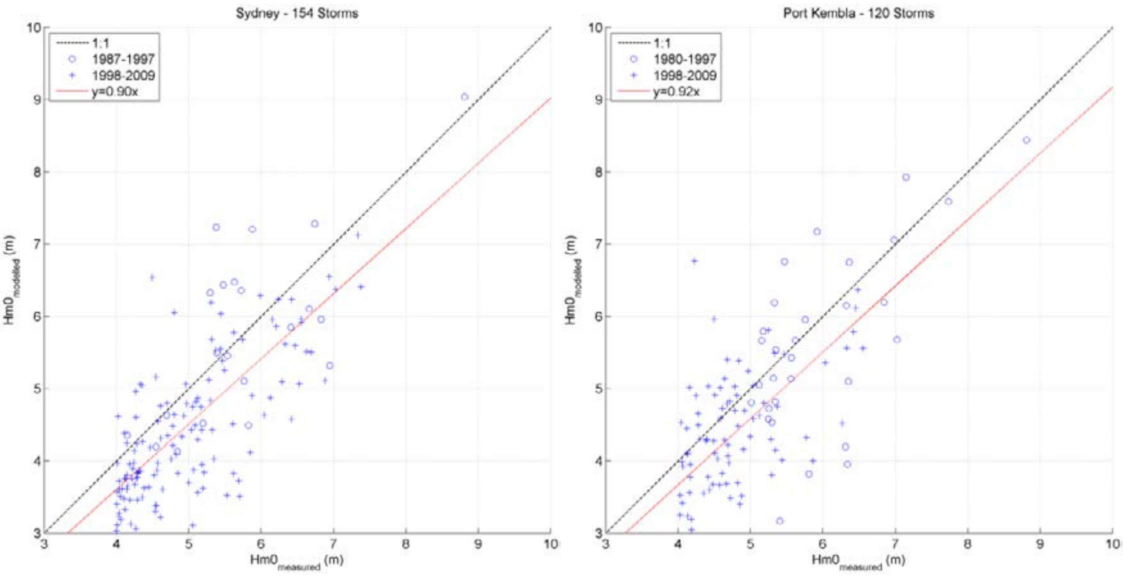

Figure 7 – Scatter plots comparing modelled and measured peak significant wave height (H_{m0}) at Sydney (left) and Port Kembla (right), based on the NSW Storm-Wave Hindcast (Cardno, 2012). Storms derived from the continuous 1998-2009 wave hindcast (+) are distinguished from the top 30 storms 1979-1998 wave hindcast (o).

Table 3 compares the extreme value statistics for Sydney and Port Kembla calculated from the NSW Storm-Wave Hindcast (top 30 storms 1979-1998 and continuous 1998-2009 hindcast) and measured wave records (all available data). A Weibull distribution with a threshold of H_{m0} > 4 m and an independent peak threshold of 72 hours were used to calculate the statistics. The effective WRB record lengths (Tab. 1) were used in the calculations to account for data omission.

Table 3 – Extreme value analysis of H_{m0} at Sydney and Port Kembla based on the simulated (1979-2009) and measured (all available data) wave records, including percent relative error between each value (Cardno, 2012).

ARI (yrs)	**Sydney**			**Port Kembla**		
	Simulated	**Measured**	**% Rel. Error**	**Simulated**	**Measured**	**% Rel. Error**
1	5.70 (±0.23)	6.19 (±0.27)	-7.9%	5.42 (±0.23)	5.65 (±0.22)	-4.1%
2	6.31 (±0.29)	6.71 (±0.36)	-6.0%	6.04 (±0.30)	6.20 (±0.30)	-2.6%
5	7.04 (±0.41)	7.37 (±0.51)	-4.5%	6.80 (±0.43)	6.90 (±0.44)	-1.4%
10	7.55 (±0.54)	7.85 (±0.64)	-3.8%	7.34 (±0.54)	7.43 (±0.56)	-1.2%
20	8.04 (±0.68)	8.32 (±0.78)	-3.4%	7.87 (±0.67)	7.96 (±0.68)	-1.1%
50	8.65 (±0.88)	8.93 (±0.98)	-3.1%	8.54 (±0.84)	8.65 (±0.86)	-1.3%
100	9.09 (±1.04)	9.37 (±1.13)	-3.0%	9.03 (±0.99)	9.17 (±1.00)	-1.5%

Simulated wave records

An initial comparison was also made between modelled peak significant wave heights (H_{m0}) predicted by the NSW Storm-Wave Hindcast (OEH) and the CAWCR Wave Hindcast (Durrant et al., 2014), to evaluate the influence of the factored CFSR wind data on simulated storm-wave climates. Figure 8 suggests that the NSW Storm-Wave Hindcast has greater skill in predicting storm peaks at the Sydney Waverider buoy deployment compared with the CAWCR Wave Hindcast – both hindcast datasets under predict peak storm H_{m0}, but by 10% (OEH) and 23% (CAWCR) on average respectively.

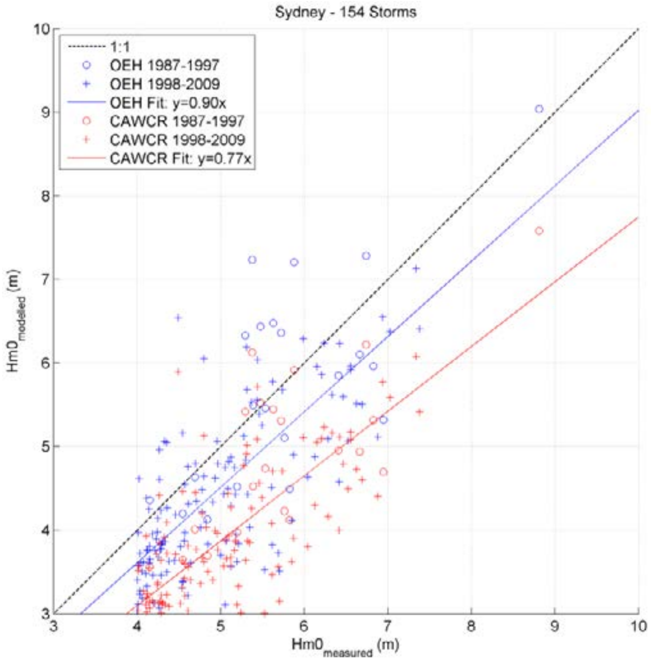

Figure 8 – Scatter plot comparing modelled and measured peak significant wave height at Sydney for the period 1987-2009, based on the NSW Storm-Wave Hindcast and the CAWCR Wave Hindcast. Storms derived from the continuous 1998-2009 wave hindcast (+) are distinguished from the top 30 storms 1979-1998 wave hindcast (o).

The NSW Storm-Wave Hindcast was also compared with the NOAA WAVEWATCH III dataset to compare the higher resolution storm-wave calibrated model with publically available wave data. Extreme value statistics for H_{m0} were derived from the OEH and NOAA WW-III models and compared with statistics derived from the WRB measurement records for the period 30/01/1997 to 01/08/2009. The findings are presented below in the discussion of extreme wave climate variability in NSW.

Inshore waves (SWAN)

The skill of the SWAN component of the NSW Coastal Ocean Wave Model in predicting shallow-water wave transformation was evaluated against inshore wave measurement datasets from Newcastle and Wamberal (NSW Central Coast/Hunter region). Figure 9 shows QQ plots comparing SWAN model predictions during 2006 with data from two inshore WRBs that have been deployed in 12-15 m water depth near the entrance to the Hunter River by Newcastle Ports Corporation.

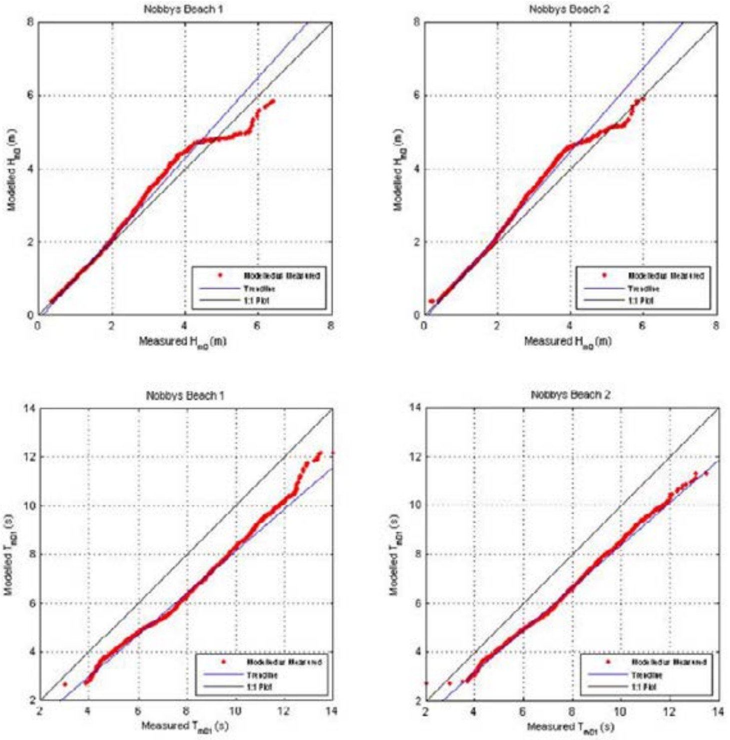

Figure 9 – Scatter plots comparing modelled and measured significant wave height, H_{m0}, (top) and mean wave period, T_{m01}, (bottom) for the calendar year 2006, at two inshore Waverider buoys operated by Newcastle Ports Corporation (Cardno, 2012).

The comparison suggests that predicted wave heights at Newcastle were reasonable across the sampled range, although wave period was typically under-predicted by 1.5-2 s on average. The model used an irregular mesh extending 20-25 km offshore with a variable resolution increasing from 1500 m offshore to 40 m within the 15 m water depth contour. Sensitivity testing found that the optimal model physics used the JONSWAP bottom friction scheme with a coefficient of 0.038m^{2}s^{-3}, although the Newcastle model was relatively insensitive to bottom friction in 12-15 m water depth.

Mortlock & Goodwin (2013) carried out further evaluation of inshore SWAN model performance using wave data collected off Wamberal Beach in 12 m water depth, between August 2011 and March 2012. The objective of the study was to investigate the general ability of the NSW Coastal Ocean Wave Model to simulate inshore wave conditions in NSW open-coast settings. The study considered the sensitivity of inshore SWAN model predictions to:

- Inshore bathymetry grid resolution
- the application of factored CFSR wind fields in inshore SWAN models
- model forcing from measured wave data (Sydney WRB) or WW-III spectral output data
- direct forcing with WW-III spectral output data or coupling via the SWAN transition model

A regular grid of 200-m resolution was found to be adequate for reliable inshore wave predictions to 12 m water depth at Wamberal. Similar to the Newcastle model, the Wamberal model was found to be relatively insensitive to bottom friction and a JONSWAP coefficient of 0.038m^{2}s^{-3} was suitable. Some of their findings are presented in Mortlock et al. (2014).

Table 4 shows the model skill statistics for SWAN simulations at Wamberal as reported by Mortlock et al. (2014). The statistics summarise the sensitivity of model predictions to the inclusion of wind forcing (factored CFSv2 winds), and to deep-water wave forcing from measured (Sydney WRB) and modelled (WW-III spectral output) datasets. The findings suggest that the inclusion of wind forcing results in a slightly improved model representation of wave heights, and a marked improvement in simulated wave periods in particular. Figure 10c shows the improved distribution of modelled wave periods where wind forcing from the factored CFSv2 winds is included. Whilst the overall representation of wave periods is improved (as seen in the closer fit between the modelled and measured distributions), the inclusion of wind forcing appears to contribute to the over prediction of high-frequency (short period) wave energy in the SWAN model. This is consistent with the Newcastle example, which also suggests a bias in the SWAN model for high-frequency waves that was not apparent in the WW-III model (Cardno, 2012).

Table 4 – Model skill statistics (for wave height, period and direction) showing the sensitivity of SWAN wave model predictions at Wamberal (NSW Central Coast) to the inclusion of wind forcing (factored CFSv2), and for deep-water wave forcing from the Sydney WRB and WW-III spectral output data (Mortlock et al., 2014). W = wind forcing, NW = no wind forcing; WRB = Waverider buoy forcing, WW3 = WW-III spectral output forcing.

	No Wind vs. Factored CFSv2 Wind Forcing						**WRB vs. WW-III Spectral Wave Forcing**					
	H_s		T_{m02}		**MWD**		H_s		T_{m02}		**MWD**	
n = 5015	**W**	**NW**	**W**	**NW**	**W**	**NW**	**WRB**	**WW3**	**WRB**	**WW3**	**WRB**	**WW3**
R^2	0.86	0.84	0.53	0.33	0.68	0.68	0.86	0.75	0.53	0.42	0.68	0.45
RMSE	0.23	0.21	1.26	1.88	13.50	14.67	0.23	0.25	1.26	2.18	13.50	15.58
Bias	0.22	0.14	-0.45	1.81	14.43	15.02	0.22	0.01	-0.45	-1.52	14.43	9.40
Scatter (%)	19.40	17.40	20.40	30.40	11.40	12.40	19.40	21.10	20.40	35.40	11.40	13.20
Slope (m)	0.99	0.97	0.82	0.85	0.77	0.90	0.99	0.91	0.82	0.59	0.77	0.39

Although modelled wave directions based on WW-III spectral data forcing were comparatively poor relative to model simulations forced by Sydney WRB data, the relationship was improved by applying the WW-III spectral data closer to the coastline. Figure 10 shows that the distribution of modelled wave direction improves where WW-III spectral data is applied closer to the coastline (i.e. in reduced water depth), which has the effect of reducing the extents of the lateral grid boundaries. A similar improvement was also achieved when the WW-III spectral forcing was applied via the SWAN transition model. That is, for the Wamberal model, direct application of WW-III spectral forcing to the inshore SWAN model at 60 m depth produced comparable results to nesting the inshore model within the SWAN transition model (Mortlock & Goodwin, 2013). Whilst the overall representation of wave directions is improved, the findings suggest that driving the SWAN model with WW-III spectra may under estimate the direction spread of the inshore wave climate at Wamberal.

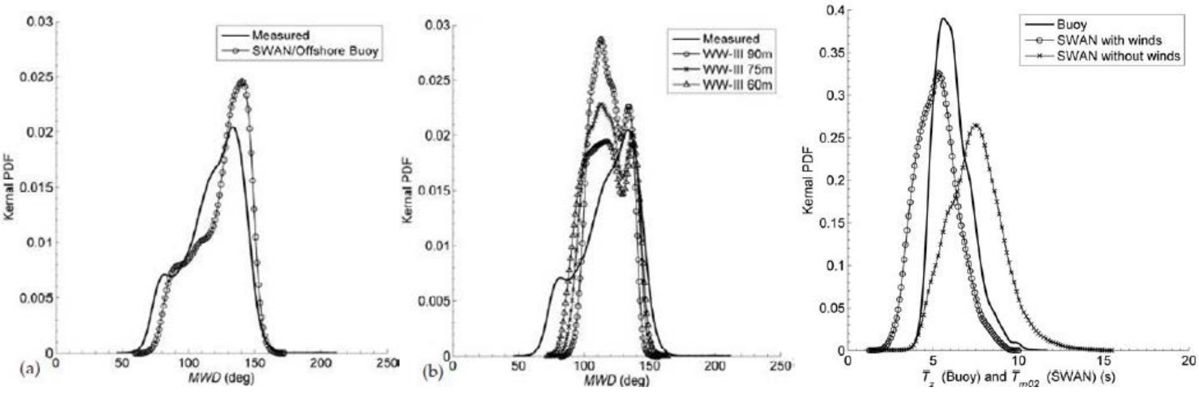

Figure 10 – Probability density functions comparing the distributions for modelled and measured (Wamberal inshore buoy) mean wave directions (MWD) and wave periods (T_z, T_{mo2}): (a) SWAN wave direction based on Sydney WRB wave forcing; (b) SWAN wave direction based on WW-III spectral wave forcing applied at 90 m, 75 m, and 60 m water depth; (c) SWAN wave period with and without wind forcing from factored CFSv2 wind data (Mortlock et al., 2014).

Extreme wave climate variability

The NSW Storm-Wave Hindcast dataset provides an opportunity to investigate regional variability in extreme wave climates along the NSW coastline, beyond previous studies of measured wave records (e.g. Webb & Kulmar, 1989; Lord & Kulmar, 2000; Kulmar et al., 2013, Shand et al., 2011). The frequency of occurrence of extreme waves may be expected to vary due to the typical origins and tracks of east coast storm systems, as well as regional variability in the coastal and continental-shelf geomorphology and oceanographic processes.

Table 5, Table 6 and Table 7 show extreme value statistics (derived using the same methods as for the statistics presented in Table 3) for northern, central and southern NSW Waverider buoy deployment locations, as calculated for the period 30/1/1997 to 1/8/2009 from:

1. Global NOAA WAVEWATCH III model (NOAA)
2. NSW Storm-Wave Hindcast: WW-III (OEH)
3. Waverider buoy measurement records (WRB)

The findings suggest that the NSW Storm-Wave Hindcast provides more reliable predictions of the measured extreme wave climate relative to the NOAA model, with the exception of the Byron Bay site. Both the NOAA and OEH models appear to overestimate measured wave climates at Byron Bay, Coffs Harbour and Batemans Bay. However, it should be noted that the Waverider buoys at those sites are known to have missed a number of significant storm events during their deployment histories, which would result in the under prediction of extreme value statistics based on the buoy data. Shand et al. (2011) interpolated the likely peak significant wave heights of key omitted events from adjacent buoys and estimated that their inclusion could increase 100-year ARI peak H_{m0} values by up to 0.5 m.

Table 5 – Extreme value analysis of H_{m0} (±95% CI) for northern NSW sites (Byron Bay, Coffs Harbour, Crowdy Head) derived from NOAA WAVEWATCH III, the NSW Coastal Ocean Wave Model (OEH) and Waverider buoy (WRB) records, for the period 30/1/1997 to 1/8/2009 only (Cardno, 2012).

ARI (yrs)	Byron Bay			Coffs Harbour			Crowdy Head		
	NOAA	OEH	WRB	NOAA	OEH	WRB	NOAA	OEH	WRB
1	5.37±0.29	5.46±0.31	5.58±0.33	5.67±0.30	5.34±0.33	5.63±0.27	6.45±0.34	5.58±0.26	5.65±0.28
10	6.89±0.55	7.10±0.94	6.84±0.92	7.32±0.61	7.12±0.90	6.91±0.49	8.32±0.70	6.83±0.34	7.01±0.49
50	7.88±0.80	8.21±1.49	7.62±1.38	8.39±0.92	8.33±1.42	7.67±0.72	9.56±1.02	7.55±0.43	7.85±0.67
100	8.30±0.92	8.69±1.75	7.95±1.59	8.84±1.06	8.85±1.66	7.97±0.83	10.09±1.17	7.85±0.48	8.19±0.75

Table 6 – Extreme value analysis of H_{m0} (±95% CI) for central NSW sites (Sydney, Port Kembla) derived from NOAA WAVEWATCH III, the NSW Coastal Ocean Wave Model (OEH) and Waverider buoy (WRB) records, for the period 30/1/1997 to 1/8/2009 only (Cardno, 2012).

ARI (yrs)	Sydney			Port Kembla		
	NOAA	OEH	WRB	NOAA	OEH	WRB
1	5.30±0.29	5.89±0.34	6.33±0.34	5.30±0.28	5.63±0.31	5.67±0.36
10	6.88±0.99	7.65±1.00	8.05±0.79	6.88±0.96	7.34±0.88	7.36±0.99
50	7.92±1.63	8.80±1.58	9.16±1.21	7.92±1.59	8.46±1.37	8.53±1.54
100	8.35±1.93	9.28±1.84	9.63±1.41	8.35±1.88	8.94±1.59	9.03±1.79

Table 7 – Extreme value analysis of H_{m0} (±95% CI) for southern NSW sites (Batemans Bay, Eden) derived from NOAA WAVEWATCH III, the NSW Coastal Ocean Wave Model (OEH) and Waverider buoy (WRB) records, for the period 30/1/1997 to 1/8/2009 only (Cardno, 2012).

ARI (yrs)	Batemans Bay			Eden		
	NOAA	OEH	WRB	NOAA	OEH	WRB
1	5.97±0.26	4.97±0.28	5.18±0.29	4.67±0.26	5.67±0.30	5.71±0.31
10	7.38±0.36	6.73±0.85	6.61±0.62	5.82±0.39	7.21±0.67	7.25±0.57
50	8.27±0.49	7.98±1.44	7.53±0.91	6.50±0.50	8.19±1.03	8.24±0.84
100	8.63±0.56	8.53±1.72	7.91±1.05	6.78±0.57	8.60±1.20	8.65±0.96

The regional variability in NSW extreme wave climates described in Table 5, Table 6 and Table 7 is summarised in Figure 11, which plots the 100-year ARI significant wave height (calculated approximately 50 km offshore) along the NSW coastline, based on the continuous 1998-2009 OEH wave hindcast. The plot suggests that the wave climate is most extreme in central NSW, particularly near Newcastle, with the derived offshore 100-year ARI significant wave height exceeding 10.5 m between Crowdy Head and Port Kembla. In comparison, northern NSW experiences a slightly less extreme wave climate, which has been previously shown to be predominantly influenced by Tropical Cyclone, Tropical Low and Easterly Trough Low storm systems (Shand et al., 2011). The southern NSW wave climate shows lower extreme wave heights in the vicinity of Batemans Bay, whilst the 100-year ARI significant wave height at Eden is comparable to that of northern NSW.

Regardless of data omission and potential sensitivity to mooring location at the Batemans Bay WRB deployment, the storm-calibrated 12-year wave hindcast suggests that southern NSW experiences a less extreme storm wave climate relative to central and northern NSW, with the exception of the Eden region, which appears to be exposed to a markedly different wave climate due to its proximity to Bass Strait and the southern Tasman Sea. In their investigation of the Batemans Bay wave climate using measured and modelled (HI-WAM) datasets, MHL (2010) found that the coastal wave climate between Jervis Bay and Eden is attenuated due to land-mass sheltering from Victoria, Tasmania and New Zealand. Furthermore, the storm climatology analysis carried out by Shand et al. (2011) suggested that the wave climate between Port Kembla and Eden is also subject to moderated influence from the Southern Secondary Low storm systems that contribute to the extreme wave climate in central NSW, and is comparatively protected from the influence of Southern Tasman Low systems relative to Eden.

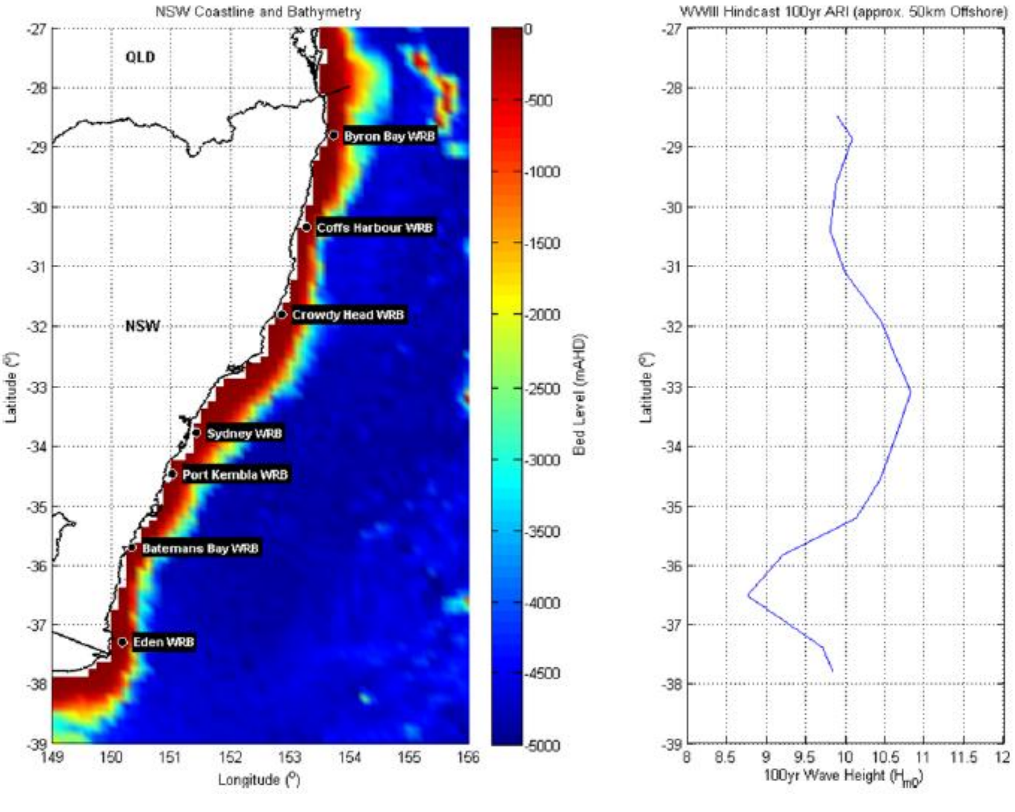

Figure 11 – 100-year ARI deep-water significant wave height (H_{m0}) values by latitude along the NSW coastline, as derived 50 km offshore from the continuous 1998-2009 wave hindcast (Cardno, 2012). Note that these values vary from Tables 4-6 due to the more seaward location of measurement relative to Waverider buoy locations.

At a finer scale, the peak significant wave height experienced during storm conditions along the NSW coastline may vary considerably over relatively small distances. For example, Figure 12 shows time series plots of two significant storm events that were recorded by the Sydney and Port Kembla WRBs in June 2006. Whilst the occurrence and duration of the two storms was comparable at both sites, peak H_{m0} recorded at Sydney exceeded 6 m for both storms, whilst the Port Kembla WRB recorded peak H_{m0} of around 5 m in both cases. The red lines in Figure 12 show the simulated storm time series at each site as predicted by the NSW Coastal Ocean Wave Model. It can be seen that the model provides a good representation of the events at Port Kembla, although under predicts peak significant wave heights for both storm events at Sydney.

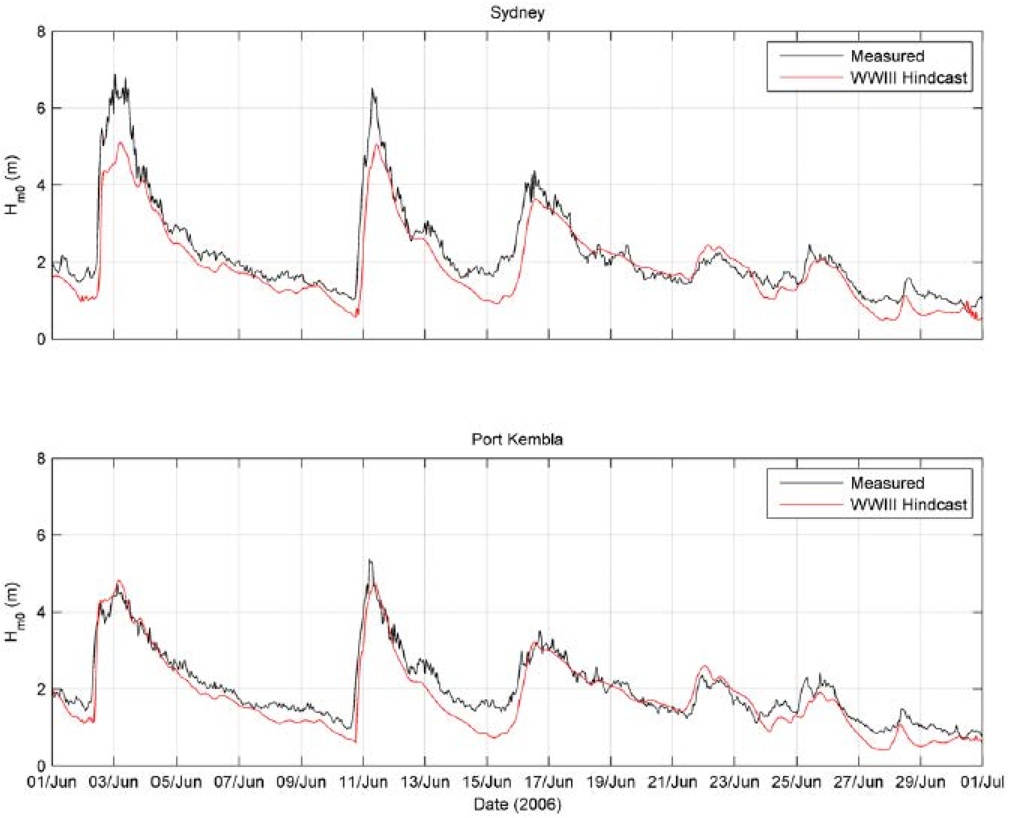

Figure 12 – Simulated and measured time series of two significant storm events recorded by the Sydney (top) and Port Kembla (bottom) Waverider buoys in June 2006 (Cardno, 2012).

The comparison in Figure 12 and the extreme value analyses in Table 3 together suggest that the Sydney region experiences a more intense storm-wave climate relative to Port Kembla. Whilst this may reflect the typical tracks of storm systems in the central NSW region, it may also suggest that the Sydney region is characterised by topographic and/or oceanographic conditions that contribute to intensified winds and elevated peak storm wave heights. For example, Figure 13 shows synoptic charts from the Bureau of Meteorology for the peak of the storms on 3 June and 11 June 2006 (as shown in Figure 12). In both cases, the synoptic charts suggest that the Sydney and Port Kembla regions were similarly exposed to meteorologic conditions from the east coast low storms. However, the scale of the charts is insufficient to capture any fine-scale variability in the system dynamics.

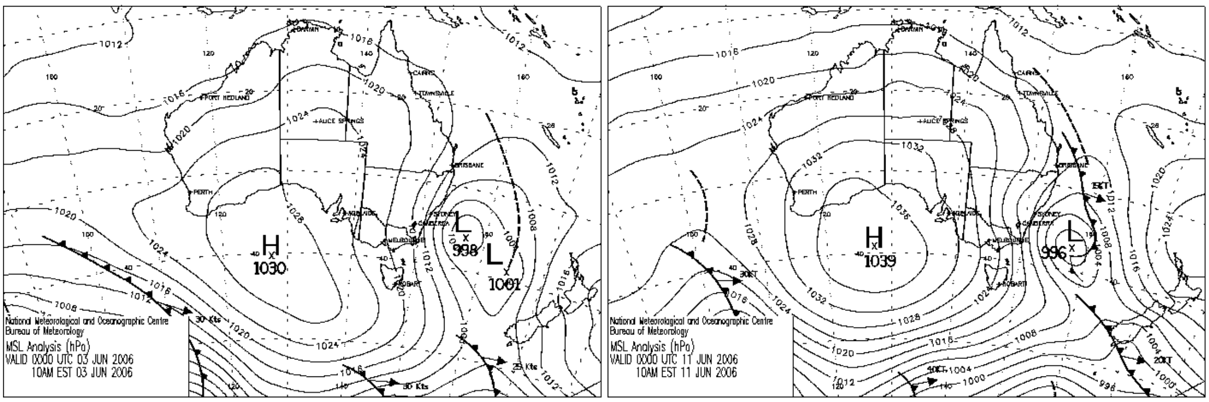

Figure 13 – Synoptic charts published by the Bureau of Meteorology for two east coast low storms experienced on 3 June (left) and 11 June (right) 2006. Measured and modelled significant wave height experienced at the Sydney and Port Kembla Waverider buoy locations is shown in Figure 12.

Development of wave model data products

The initial development phases of the NSW Coastal Ocean Wave model have seen the generation of a considerable amount of model output data and the evaluation of wave model performance against wave measurement records and existing simulated wave hindcast datasets. The next stages of model development will involve the completion of deep-water and inshore wave datasets, including:

- Completion of the continuous 35-year (1979-2013) deep-water NSW Storm-Wave Hindcast
- Development of a statewide shallow-water wave transformation matrix to transfer measured and modelled deep-water wave conditions to inshore coastal waters
- Derivation of design inshore wave statistics based on measured and modelled historical deep-water wave records
- Development of continuous inshore storm-wave hindcast datasets for selected locations.

It is envisioned that the completed wave model datasets will support and advance existing approaches to assessing coastal hazard risks in NSW.

Conclusions

The NSW Coastal Ocean Wave Model has been developed to investigate wave climate extremes and variability in NSW waters, beyond the spatial and temporal limits of the existing measurement data collected by the Waverider buoy network. System development to date has resulted in a coupled deep-water/inshore spectral wave model that is capable of simulating wave conditions along the NSW coastline from 1979 onwards, using CFSR climate reanalysis data. The model has been calibrated for storm-wave conditions, to better resolve the extreme wave climates that are associated with coastal hazards such as beach erosion and oceanic inundation. Exploratory wave modelling using downscaled regional climate hindcast data generated by the NARCLiM project has been carried out to investigate long-term historical trends in NSW wave climate extremes and variability.

The evaluation of deep-water (WW-III) wave model performance against existing wave measurement records found that model predictions were generally reliable along the NSW coastline. Although the model tended to over predict storm-wave heights in northern NSW, data omission from Waverider buoy records during storms suggests that the measured wave records may in fact under estimate extreme values. Comparisons with publically available simulated wave hindcast datasets suggest that the NSW Coastal Ocean Wave Model provides a more reliable representation of peak storm-wave conditions, which are sensitive to the input (climate) forcing conditions and wave model grid resolution. Inshore predictions of wave height at Newcastle and Wamberal compared well with measured wave conditions, although the SWAN wave model was found to over predict high frequency (short period) waves. The sensitivity of simulated wave directions to model grid design, and the application of spectral wave forcing conditions, requires further investigation.

The investigation of regional variability in NSW wave climates for the period 1979-2009 suggests that central NSW, including the Sydney and Central Coast/Hunter regions, experiences the most extreme wave climate. For that period, the 100-year ARI significant wave height at the Sydney Waverider buoy, derived from the 1979-2009 NSW Storm-Wave Hindcast (top 30 storms 1979-1997 only), was 9.09 m (±1.04 m). In comparison, the equivalent statistic derived from all available measured data was 9.37 m (±1.13 m). The wave climate of northern NSW is comparatively less extreme, whilst southern NSW experiences the least extreme wave climate, with the exception of Eden, which is particularly exposed to storms originating in the southern Tasman Sea.

The next stages of model development and application will focus on completion of the continuous NSW Storm-Wave Hindcast – a storm-calibrated continuous 35-year (1979-2013) deep-water wave hindcast dataset – and the development of an automated approach to efficiently transfer simulated deep-water wave conditions to inshore coastal waters. The potential for developing long-term wave forecast data based on NARCLiM regional climate forecast data is also being investigated.

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