Wave energy resource along the southeast coast of Australia

by
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Bachelor of Engineering Science
(Energy and Environmental Engineering)

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submitted in fulfillment of the requirements of the degree of
Master of Philosophy

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Griffith School of Engineering
Griffith University
August 2015
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Statement of originality

This work has not previously been submitted for a degree or diploma in any university. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made in the thesis itself.

Candidate signature:

Date: 4 August 2015
Acknowledgments

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Lastly, I cannot find words to express my honest and genuine gratefulness to my parents for unconditional support and guidance knowing that without them I could not have done my degree.
Abstract

The Australian Government has set a 20% target for renewable energy by 2020 as part of a long-term commitment to decrease Australia’s greenhouse gas emissions by 60% on 2000 levels by 2050. In order to accomplish such goal, Australia will need to generate an additional 45 MWh of renewable energy yearly by 2020 where wave energy may play a significant role. Coastal waters of Australia’s southeast margin have been recognised to be suitable for exploiting wave energy resources and potentially capable of significantly contributing to Australia’s annual electricity generation. Nevertheless, until now, no thorough research has yet been conducted to adequately characterize such an unexploited resource along shallow coastal waters.

This dissertation presents a detailed assessment of the wave energy resource potential for Australia’s southeast coastal waters, focusing on promising nearshore regions where full-scale wave energy converter farms could potentially be deployed. The study methodology employed the wave energy transformation model SWAN to predict wave conditions along Australia’s southeastern coast from deep to shallow water depths at hourly resolution for a period of 30 years between 1979 and 2010. The model was driven with high-resolution non-stationary winds and full directional spectra boundary conditions to account for the multimodal sea states, which often subsist along Australia’s southeast coast. SWAN was calibrated and validated against measurements from several wave rider buoy locations for a wide range of sea states.

The geographical and temporal distributions of the wave energy resource were analysed and are presented based on maps of wave energy resource magnitude, variability and consistency derived from SWAN wave outputs. Australia’s southeastern coast was found to be endowed with annual average wave power levels of approximately 6 to 12 kW/m, showing small synoptic spatial variability when compared, for example, to Australia’s southern margin. The seasonal variability of wave power was also found to be relatively low compared to Australia’s southern coast, with winter and autumn only exhibiting a mean wave power twice as large as summer and spring. The highest and most consistent average wave powers are located along the central New South Wales coast, from Sydney to Crowdy Head, with approximately 7 to 11 kW/m in water depths of less than 100 m. In terms of reliability and survivability, there is a low probability of waves exceeding an assumed survivability threshold of a 6m significant wave height and thus
only a small chance of wave energy converters having to cope with such extreme loading scenarios.

A more thorough analysis was conducted for nine sites of high-energy concentration between Sydney and Crowdy Head using whisker-box plots, cumulative probability distributions, bivariate probability distributions and directional wave power roses. The optimal site for commercial wave farms was found to be located offshore from Seal Rocks on the mid-north NSW coastline. The mean wave energy level there is nearly 11 kW/m with a top 75th quartile of 15 kW/m, delivering a total energy of 330 GJ/m annually. The greatest proportion of the annual mean wave power was observed to be generated by south-easterly and south-southeasterly waves, arriving from between approximately 135 and 170°. The greatest contribution to the annual energy comes from sea states with significant wave heights between 1 and 2.5 m and energy periods between 7 and 10 s, while sea states characterized by large wave heights (>4 m) contribute little to the annual total. Based on these results, the New South Wales central coast may be a good candidate for wave energy development, since the region provides a resource potential similar to that available at established test bed sites; such as that of Gran Canaria (Spain) and Galway Bay (Ireland).

The other eight sites also showed adequate levels of exploitable energy and the data provided here can be used to assess in detail how well wave power capture at each site might be offset by costs of deployment, maintenance and operation as well as compatibility with existing human uses.
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<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>[m]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Wave direction</td>
<td>$[^{\circ}]$</td>
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<tr>
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<td>[kg/s$^3$]</td>
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### Non-greek symbols

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<td>Propagation velocity of wave energy along $x$</td>
<td>[m/s]</td>
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<tr>
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<td>$\tilde{k}$</td>
<td>Mean wave number</td>
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<tr>
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<td>Spectral wave moments</td>
<td>[m$^2$Hz$^n$]</td>
</tr>
<tr>
<td>$p_i$</td>
<td>Probability of occurrence of a sea state $i$</td>
<td>[-]</td>
</tr>
</tbody>
</table>
\( \tilde{s} \) Mean wave steepness [-]
\( \tilde{s}_{PM} \) Mean wave steepness for Pierson-Moskowitz’s spectrum [-]
\( \Delta t \) Model time step \( t \) [min]
\( \Delta x \) Node spacing in \( x \)-direction [m]
\( \Delta y \) Node spacing in \( y \)-direction [m]
\( \Delta f \) Interval size of \( f \) [Hz]
\( \Delta \theta \) Interval size of \( \theta \) [°]
\( C \) Courant number [-]
\( E_f \) Wave energy flux [kW/m]
\( E_x \) Wave energy flux \( x \) component [kW/m]
\( E_y \) Wave energy flux \( y \) component [kW/m]
\( E_{sea} \) Wave energy flux harvested by a WEC [kWh]
\( H_s \) Significant wave height [m]
\( P_{WEC} \) Wave power output for a WEC [kW]
\( T_m \) Spectral mean wave period [s]
\( T_e \) Spectral energy wave period [s]
\( T_z \) Spectral zero-crossing wave period [s]
\( U_f \) Wind friction velocity [m/s]
\( U_{10} \) Wind speed at 10 m elevation [m/s]
\( U_z \) Wind speed at \( z \) elevation [m/s]
\( U_{rms} \) Root mean square error of orbital velocity near the bottom [m/s]

**Function symbols**

\( B(k) \) Spectral saturation function density function [-]
\( D(f, \theta) \) Directional wave spreading function [°]
\( E(\sigma, \theta) \) Energy wave density spectrum \([m^2/Hz/\text{rad}]\)
\( N(\sigma, \theta) \) Wave action density spectrum \([m^2/Hz/\text{rad}]\)
\( S(f) \) Frequency wave spectrum \([m^2/Hz]\)
\( S(f, \theta) \) Directional wave spectrum \([m^2/Hz/\text{rad}]\)
## List of acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>ABARE</td>
<td>Australian Bureau of Agricultural and Resource Economics</td>
</tr>
<tr>
<td>ABS</td>
<td>Australian Bureau of Statistics</td>
</tr>
<tr>
<td>AEMO</td>
<td>Australian Energy Market Operator</td>
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<tr>
<td>CAWCR</td>
<td>Centre for Australian Weather and Climate Research</td>
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<tr>
<td>CCA</td>
<td>Climate Change Authority</td>
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<tr>
<td>CETO</td>
<td>Cylindrical Energy Transfer Oscillating</td>
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<tr>
<td>CFL</td>
<td>Courant-Friedrichs-Lewy</td>
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<tr>
<td>CFSR</td>
<td>Climate Forecast System Reanalysis</td>
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<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific and Industrial Research Organization</td>
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<tr>
<td>DCCEE</td>
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<td>DEH</td>
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<td>DEWHA</td>
<td>Department of Environment, Heritage, Water and the Arts</td>
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<tr>
<td>DIA</td>
<td>Discrete-Interaction Approximation</td>
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<td>DHI</td>
<td>Danish Hydraulics Institute</td>
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<td>DSITIA</td>
<td>Department of Science, Information Technology, Innovation and Arts</td>
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<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
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<td>ENSO</td>
<td>El-Niño Southern Oscillation</td>
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<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
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<td>IPO</td>
<td>Interdecadal Pacific Oscillation</td>
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<td>JMA</td>
<td>Japan Meteorological Agency</td>
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<td>JONSWAP</td>
<td>Joint North Sea Wave Observation Project</td>
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<td>MHL</td>
<td>Manly Hydraulics Laboratory</td>
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<td>MFD</td>
<td>Mean Failure Duration</td>
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<td>MTBF</td>
<td>Mean Time Between Failures</td>
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<td>National Centers for Environmental Prediction</td>
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<td>NEM</td>
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<td>National Oceanic and Atmospheric Administration</td>
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<td>LTA</td>
<td>Lumped Triad Approximation</td>
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<td>OEH</td>
<td>Office of Environment and Heritage</td>
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<td>RET</td>
<td>Renewable Energy Target</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<td>SAM</td>
<td>Southern Annular Mode</td>
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<td>Weather Research &amp; Forecasting Model</td>
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<td>WW3</td>
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Chapter 1

1 Introduction

1.1 Statement and contextualisation of the problem

It is widely recognised that our atmosphere’s ability to accept greenhouse gas emissions is limited. Therefore, future mitigation efforts will have a great effect on whether greenhouse gas concentrations can be stabilised at a level low enough to reduce potential risks of more serious climate change. In terms of efficiency and concentration, carbon dioxide has accounted for approximately 60% of anthropogenic greenhouse effects since 250 years ago (CSIRO, 2014).

The majority of our anthropogenic carbon dioxide emissions (at least 85%) has been derived from combustions of fossil fuels for electricity and heat production (CSIRO, 2014). Nevertheless, energy can be alternatively produced from sustainable sources that
are naturally renewed without producing any greenhouse gases and or air pollutants. These renewable sources have potential to be combined to offer sufficient clean energy to sustain wealthy civilizations, whilst keeping anthropogenic carbon dioxide emissions below safe levels (IPCC, 2014).

Australia is considered to be a major greenhouse gas producer releasing more carbon dioxide per capita yearly than almost every other western country. Only Bahrain, Bolivia, Brunei, Qatar, and Kuwait produce more on a per capita basis (DCCEE 2012). In 2014, Australia’s carbon footprint per capita stood at nearly 24 tonnes of carbon dioxide equivalent, more than four times greater than the global average carbon dioxide emissions per capita (Australian Department of Environment 2014). The high carbon footprint per capita is a natural result of Australia’s heavy dependence on coal and gas-fired power plants for energy generation (Figure 1.1). In 2013, coal and natural gas accounted for 63.9% and 20.5% of Australia’s annual electricity production, respectively. In contrast, renewable sources only accounted for a mere 13% (see BREE 2014), even though carbon-free energy can potentially supply up to 100% of Australia’s annual electricity needs (AEMO, 2013).

![Figure 1.1 - Australian annual electricity generation from fossil fuels from 1991–92 to 2012–13 (BREE, 2014)](image)

In response to climate change a national renewable energy target policy was legislated to ensure that at least 20% of Australia’s national electricity supply (approximately 45 MWh) will come from renewable energy by 2020. The national renewable energy target is part of a long-term national goal to cut greenhouse gas pollution by 80% to 2000 levels by 2050 (CCA, 2012). Australia has access to a diversity of high quality and abundant renewable energy sources that are yet relatively untapped, particularly wave energy...
The Australian coastline is exposed to high levels of wave energy resources that represent a promising and currently untapped market for deploying wave energy harnessing technology (see Geoscience Australia and ABARE, 2010). Considering that more than 85% of Australia’s population live along or close to coastal areas, wave energy has great potential to become part of Australia’s total energy mix, possibly reaching a share of up to 11% by 2050 (CSIRO, 2012).

The current MPhil dissertation aims to provide a detailed evaluation of wave energy resources along Australia’s southeast coast using a 30-year wave hindcast.

Figure 1.2 - Australian annual electricity generation from renewable energy sources from 1991–92 to 2012–13 (BREE, 2014).

1.2 The need for wave energy resource assessment

Similar to other sources of renewable energy, the distribution of wave energy varies spatially and temporally. The characteristics of the sea states and associated energy vary over distances as short as a few hundred meters owing to localised sheltering bathymetric effects and also on sub-monthly to multi-decadal timescales. Therefore, assessment of the distribution of the wave energy resource is required in order to determine which areas are best endowed with wave energy resources. Furthermore, wave energy converter (WEC) devices cannot be designed for one specific type of sea state and require optimisation for a range of typical sea states present at a given location. In order to do so, detailed knowledge and long-term statistics describing the wave energy resource is a necessary requirement to support site selection and WEC design and operation (Smith et al., 2013).
The first stage in the assessment of a wave energy resource (WER) provides a spatial and temporal analysis of the WER potential, focusing on recognising and comparing energy-rich and sustained resource locations. These locations typically offer a greater economic viability for siting WEC plants. There are others aspects that can be often limiting, such as availability of a grid connection, proximity to ports and marine protected zones. Nevertheless, without suitable resources a project is not viable (Iglesias and Carballo, 2011).

The second stage of a WER assessment provides a site-specific analysis of wave energy resource magnitude, variability and harvestability, based on long-term wave statistics. These statistics are typically disseminated as energy scatter diagrams and bivariate probability distributions of cumulative energy and frequency of occurrence for significant wave heights and periods. This is because WEC manufacturers supply performance data within a ‘power matrix’, also as a function of significant wave heights and energy periods. Therefore, engineers can design and tune WEC devices to operate at maximum efficiency for a given location (Cahill and Lewis, 2013).

The available WER can then be used to economically assess potential projects, based on capital investment frameworks (Kim et al., 2012). The knowledge provided by such reports is typically used as practical decision-making tools by wave energy development sectors, namely:

- Prospectors: seeking commercially viable projects;
- Technology developers: pursuing resource knowledge to enable the optimisation of the wave energy technology;
- Energy load managers: requiring analyses of the potential power delivery to negotiate reliable power purchasers;
- Maintenance engineers: requiring information to decide engineering installation, operation and maintenance requirements;
- Financers: seeking information to assess whether wave projects are economically viable, enabling developers to access capital;
- Marine resource managers and policy makers: trying to incorporate wave resource knowledge into multiple-use management and policies;
- Environmental managers: understanding conditions prior to wave plant installation as environmental benchmarks;
1.2.1 The case of Australia’s southeast coast

Hughes and Heap (2010) presented a national scale wave energy resource study for Australia suggesting that coastal shelf waters off Southern Queensland and New South Wales are likely to be suitable for extracting wave energy resources. These regions are exposed to relatively moderate, sustained mean wave powers, which are potentially capable of significantly contributing to Australia’s total electricity generation. Nonetheless, Hughes and Heap’s (2010) deepwater wave energy projections are only sufficient to inform policy on wave energy resources at a national scale as well as guiding industry to promising coastal areas. Hence, Hughes and Heap (2010) suggested that a more thorough research focusing on transitional and shallow water depths where wave farms are typically positioned was necessary.

In order to properly identify potential areas for deploying WEC farms and also to predict wave farm productivity, a new long-term, high-resolution nearshore WER assessment is needed (Hemer and Griffin, 2010). The effects of shallow water physics (e.g. shoaling, refraction, bottom friction and nonlinear triad wave interactions) waves can be accurately accounted for by numerical wave transformation models that are specifically designed for transferring deep-water wave conditions to nearshore waters. They are also able to simulate wave energy propagation and redistribution on high resolution over complex shallow water bathymetry.

Identifying and characterising promising locations for developing WEC projects is important along Queensland and New South Wales’ coastlines, given that Queensland and New South Wales are home to more than half of Australia’s population, from which 81% live along or close to coastal regions. Such areas offer a great opportunity for wave projects to become cost-effective and economically attractive (ABS 2012).

1.3 Research objectives

The current dissertation provides a detailed characterisation of the distribution and variability of the wave energy resource for the continental shelf waters along Australia’s southeast coast from Fraser Island (Queensland) to East Gippsland (Victoria). The assessment is based on a 30-year numerical wave hindcast using a third-generation wave transformation model. The specific research objectives are to:

1. Develop a regional-scale SWAN wave transformation model to transfer deep-
water wave conditions to coastal waters of Australia’s southeast coast;

2. Calibrate and validate SWAN against wave measurements from several Waverider buoy locations covering a range of sea state conditions;

3. Undertake a numerical wave hindcast with SWAN based on wave and wind model data of a 30-year period between 1979 and 2010;

4. Analyse the modelling results to establish the spatial and temporal variability of the wave power magnitude;

5. Identify and characterise potential wave energy resource ‘hotspots’ with the potential for deploying wave energy converter projects;
Chapter 2

2 Literature review

2.1 Introduction to wave energy resources

The frictional drag of wind (air molecules) over the sea surface (water molecules) leads to a transfer of wind energy into the water column resulting in the generation of ‘wind waves’. Typically, wind seas are short crested, highly complex and irregular, showing a wide range of wave heights and periods, whereas swells are more regular and smooth, with long defined crests and a narrower diversity of wave heights, periods and directions (Holthuijsen, 2010). As shown in Figure 2.1, wind waves account for the majority of energy observed in the ocean.
The ‘sea state’ is described by a range of characteristics including wave height, period and direction. The sea state (at any point) reflects locally generated waves and any swells that may have been generated far away and travelled to that location. The ocean climate variability at any point is consequently not only a product of the variability in local wind fields, but also potentially from many wind fields across wide areas of ocean.

In deep water, swell waves can travel effortlessly for long distances (tens of thousands of kilometers) without losing much energy, which they previously acquired from atmospheric winds. Nevertheless, as waves approach shallow water they start to be influenced by topographic water depth sheltering effects. The wave-driven, free orbital motion of water particles is disrupted and original circular orbits of water parcels start to become flattened. The waves slow down, become steeper, change direction and also loose energy, assuming a sharp-crested form (Figure 2.2).

Typically, a ratio between water depth (h) and wavelength (λ) is used to define transitions between deep (h > λ/2), transitional (λ/20 < h < λ/2) and shallow water (h < λ/20) (see Holthuijsen, 2010). In very shallow water, waves become unstable and break, thus losing most of its energy as illustrated in Figure 2.2.
Figure 2.2 - Illustration of wave motion being influenced by water depth and shape of the shoreline. 1) dispersive waves, 2) original oscillation of water particles, 3) flattened oscillation of water particles, 4) waves slowing down, 5) sea-land layer (adapted from Bakersfield College, 2013).

In oceanic waters, solar radiation energy levels of about 100–300 W/m² on average are converted through winds to swells with locally concentrated energy exceeding 100 kW/m, depending on location and time. Potentially, harvesting only a relatively small quantity of such energy and combining it with other sources of renewable energy could supply a significant share of our future electricity needs and vastly lower our greenhouse gas emissions (Gunn and Stock-Williams, 2012).

The energy transported by ocean waves is regarded as a major and promising renewable energy resource, showing numerous advantages compared not only to fossil fuels, but also to other renewable energy sources. In addition to being renewable, carbon-free and widely available, wave energy has greater density (2 to 3 kW/m²) compared to wind (0.4 to 0.6 kW/m²) and solar (0.1 to 0.2 kW/m²). Therefore, more energy can effectively be exploited per unit area, leading to a footprint that does not sacrifice large tracts of coastal real estate. Furthermore, wave energy is accessible 24 hours a day, 365 days a year, whilst solar radiation and winds are not. The predictability and consistency of wave energy is also greater compared to that of wind and solar energy, which display a more dramatic natural short-term resource variability. These characteristics suggest that wave energy has greater potential to be a source of energy with lower cost (see Iglesias et al., 2009; Lopez et al., 2013).
Wave energy resources also exhibit a good relationship between source and demand, with approximately 40% of world population living close to ocean waters. Lastly, waves can be tapped with low environmental effect, even though more research needs yet to be conducted (Lopez et al., 2013).

There are, nevertheless, several challenges that need to be overcome for wave energy to become more commercially competitive with wind and solar energy. For example, WEC efficiency drops significantly under rough sea states due to technical limitations. There are also limited coastal areas where waves are strong enough to generate electricity without damaging equipment or leading to complicated structural engineering challenges. Similar to wind energy, waves are also unpredictable and far from reliable compared to non-renewable sources of energy. Lastly, funding and start-up costs for wave projects are yet high (Falnes, 2007; Lopez et al., 2013).

2.2 Mathematical description of wave energy

The ocean surface is complex in nature and is typically described by assuming it is a stationary, stochastic and homogeneous process. The random-phase/amplitude model describes the sea surface as a linear superposition of a multitude of long-crested, independent sinusoidal waves characterised by different amplitudes, phases and directions. The model leads to a concept of directional variance density spectrum using fast Fourier transformations. The directional variance wave density spectrum $S(f, \theta)$ displays how wave variances (or sea surface elevations) are distributed over different frequency bands ($f$) and propagation directions ($\theta$). It is described as the combination of two functions (Holthuijsen, 2010):

$$S(f, \theta) = S(f)D(\theta; f)$$

(1)

where $D(\theta; f)$ is the directional spreading function and $f$ is the wave frequency. The omnidirectional or so-called wave frequency spectrum $S(f)$ shows how much spectral energy is contained within each frequency band (Figure 2.3). The frequency spectrum is related to the directional spectrum $S(f, \theta)$ as follows (Holthuijsen, 2010):

$$S(f) = \int_{0}^{2\pi} S(f, \theta) \, d\theta$$

(2)
Figure 2.3 - Example of the annual variation of the frequency wave spectrum \( S(f) \) from which sea state parameters can be derived (Holthuijsen, 2007).

The directional wave spectrum \( S(f, \theta) \) can be characterised by a number of wave sea state parameters, which can be derived based on spectral moments. The ‘\( nth \)-order moment’ of \( S(f, \theta) \) is expressed by (Iglesias and Carballo, 2011):

\[
m_n = \int_0^{2\pi} \int_0^{\infty} f^n S(f, \theta) df d\theta, \quad n = -1, 0, 1, 2, 3 ... \tag{3}
\]

The most widely used non-directional wave parameters to describe a sea state are:

- Significant wave height \((H_s)\): \( H_s = 4\sqrt{m_0} \) \tag{4}
- Mean wave period \((T_m)\): \( T_m = \frac{m_0}{m_1} \) \tag{5}
- Energy wave period \((T_e)\): \( T_e = \frac{m_{-1}}{m_0} \) \tag{6}
- Peak wave period \((T_p)\): \( T_p = \frac{1}{f_p} \) \tag{7}
• Zero-crossing wave period ($T_z$): \[ T_z = \sqrt{m_0/m_2} \] (8)

The most widely used directional wave parameter to describe a wave sea state is defined by (Gunn and Stock-Williams, 2010):

• Mean wave direction ($\theta_m$): \[ \theta_m = \frac{m_0^{-1}}{2\pi} \int_0^\infty \int_0^\infty \theta S(f, \theta) df d\theta \] (9)

The wave energy transport (or wave power) per unit crest length (kW/m) is expressed by (Holthuijsen, 2010):

\[ E(f, \theta) = \rho g \int_0^{2\pi} \int_0^\infty c_g(f, h)S(f, \theta) df d\theta \] (10)

where $g$ stands for gravitational acceleration and $\rho$ for water density. The wave group celerity $c_g$ can be obtained from (Holthuijsen, 2010),

\[ c_g(f, h) = \frac{g}{2\omega} \left( 1 + \frac{2kh}{\sinh(kh)} \right) \tanh h(kd) \] (11)

where $h$ stands for water depth, $k = 2\pi/\lambda$ for wave number and $c$ for phase velocity. The frequency is obtained from a Doppler-shifted dispersion relation,

\[ \omega^2 = gk \tanh(kh) \] (12)

In deep water, $h \rightarrow \infty$ and $kh \gg 1$ whereby equation (11) can be simplified as,

\[ \lim_{kd \rightarrow \infty} c_g \approx \frac{g}{2\omega} \] (13)

Therefore, the approximate expression for wave energy transmitted per unit surface area (or crest) for deep water is (Gunn and Stock-Williams, 2012),

\[ E_f = \frac{\rho g^2}{4\pi} m_{-1} \] (14)

or more explicitly as a function of sea state parameters (Kumar and Anoop, 2015).
\[ E_f = \frac{\rho g^2}{64\pi} H_s^2 T_e \cong 0.49 H_s^2 T_e \]  

(15)

In spite of being a power formulation developed for deep water, expression (15) has been traditionally used from transitional to shallow water when only spectrally derived parameters are available. Previous research has proven that using such expression for transitional and shallow water can lead to systematic errors of up to 20% by which expression (10) was here routinely employed (Barbariol et al., 2013; Iuppa et al., 2015).

The wave energy transport per unit crest length that a WEC can actually harvest from a given sea state \( i \) defined by a particular \( H_s \) and \( T_e \), is consequently expressed by:

\[ E_{\text{sea}} = \sum_{i=1}^{j} p_i (P_{\text{WEC}})_i \]  

(16)

where \( p_i \) stands for probability of occurrence of that sea state \( i \), and \( P_{\text{WEC}} \) (kW) stands for wave energy conversion efficiency of that WEC for that sea state \( i \).

2.3 Wave energy potential and global distribution

The global wave energy resource has been estimated to be approximately 2.11 TW, to 95% confidence level, of which 4.6% is extractable with currently available technology (Gun and Stock-Williams, 2012). The generation of 850 TWh yearly from sea waves is currently sufficient to supply \( \sim 3\% \) of our global electricity needs (see Gunn and Stock-Williams, 2012). In a futuristic scenario, wave energy could potentially deliver up to 2,000 TWh yearly with fully developed wave harvesters (World Energy Council, 2013).

Wave energy is equally divided between Northern and Southern Hemispheres, with greatest wave energy resources found in regions that benefit from strong and consistent winds (Arigana and Cheung, 2012). Figure 2.4 shows that such regions are located with at mid to high latitudinal bands (temperate storm belts of both hemispheres) between 30 and 60° (Cornett, 2008; Arigana and Cheung, 2012; Gunn and Stock-Williams, 2012). The southern latitudes show, nevertheless, less seasonal variability and so average wave energy is highest between 30 and 60° south latitude (Cornett, 2008).
The southern coasts of Chile, South Africa, Australia and New Zealand are particularly well endowed, receiving annual energy flux levels of approximately 55–85 kW/m (Cornett, 2008; Gunn and Stock-Williams, 2012). The average wave energy density between latitudes 30–60° north is highest off Iceland, South Greenland and Ireland’s west coast with about 45–65 kW/m. These levels gradually decrease to 25 kW/m at 20° N. The western coast of Canada and United States are also very well exposed to relatively high wave energy levels of 35–55 kW/m annually. In equatorial waters off Northern Peru and Ecuador, wave power is typically 5–15 kW/m (Arigana and Cheung 2012; Gunn and Stock-Williams, 2012).

2.4 Wave energy offshore vs nearshore

The gross offshore wave energy resources have been traditionally documented to be far greater in offshore regions than at nearshore areas, since energy dissipation due to sheltering and bathymetric effects is still minimal or negligible (Folley and Whittaker, 2009). It has hence long been suggested that WEC devices should be deployed offshore and that nearshore regions are unlikely to reach economical viability.

However, Folley and Whittaker (2009) demonstrated that offshore gross wave energy resources account for highly energetic sea states, which comprise far greater than normal wave energy levels up to 3 MW/m. Unfortunately, such levels of wave energy are very unlikely to be harvested, since under extreme wave conditions, WEC devices have
to switched into a self-preservation mode. Additionally, Folley and Whittaker (2009) also observed that offshore waves are not directionally resolved, encompassing wave energy from all directions. Given that wave farms are comprised of WEC arrays aligned orthogonally to \( \theta_m \) (mean direction of wave propagation), wave power will be limited to several devices from specific directions.

In order to properly compare and select adequate areas for deploying wave farms, a measure more closely related with wave energy generation termed ‘exploitable wave energy resources’ has been introduced by Folley and Whittaker (2009). The exploitable wave energy resource measure discounts wave energy from unexploitable sea states exceeding WEC ratings by three to four times and only accounts for energy incident from a fixed direction orthogonal to \( \theta_m \).

Folley and Whittaker (2009) showed that whilst gross offshore wave energy levels are decreased by 30 to 50% from offshore to nearshore areas, exploitable wave energy levels are only reduced by 7–22%. They explained that refraction due to water depth variations leads to a reduction of omni-directional (or gross) wave energy from offshore to nearshore waters, but preserve wave energy travelling from more concentrated directions. In addition, refraction also acts as a filter that might lead unexploitable waves to break before reaching shallow water (Folley and Whittaker, 2009).

The loss of exploitable energy from offshore to nearshore regions is only due to bottom friction dissipation, which explains why waves travelling 0.5 to 2 km offshore carry 80 to 90% of usable energy of waves propagating further offshore. In particular areas, localised sheltering and refraction can create nearshore areas of wave energy concentration where waves can supply amounts of energy equal to those found within deep water depths (Figure 2.5). The difference between exploitable wave energy offshore and nearshore is therefore sufficiently small to suggest that other factors such as capital costs of submarine and land transmission cables, anchoring, equipment and maintenance, will be more meaningful when selecting a location for a project (Folley and Whittaker, 2009).
2.5 Sources of wave data

There are numerous sources of wave data that can be used to conduct a wave energy resource assessment, each with their differing advantages and disadvantages, which are discussed in the following sub-sections.

2.5.1 Direct measurement

The most realistic wave data is collected by in-situ instruments deployed above, at or below ocean surface. The most established and widely used instruments for purpose of wave energy resource assessments is wave rider buoys, which are well proven and very accurate, thus representing a reliable source of wave data. Alternatives to moored buoys are acoustic doppler current profilers, which are also capable of providing accurate wave measurements however these are typically only used in short-term deployments.

Waverider buoys can be directional or non-directional, depending on whether they are able to measure directional characteristics of waves. Non-directional buoys measure wave motion by using accelerometers and then integrating the measured vertical accelerations twice to arrive at a vertical displacement. The time domain record can then be
transformed into the frequency domain via fast Fourier transforms providing a spectral density function $S(f)$ from which non-directional wave parameters can be derived (Holthuijsen, 2010). Directional waverider buoys extend this by also measuring additional characteristics such as its slope of acceleration and tilt enabling the provision of full frequency-directional wave spectra. The spectrum of wave energy calculated by both directional and non-directional buoys is typically derived from sample measurements of wave conditions over acquisition periods of half an hour to one hour long (Holthuijsen, 2010).

Even though buoys provide very precise wave measurements, buoy networks worldwide are relatively scarce and have a poor spatial coverage (see Figure 2.6); particularly networks comprising directional buoys, as equipment and maintenance are expensive. Buoys also only provide measured spectra at one single point, but wave sea states can vary significantly within a few hundred meters due to wave-bottom interactions, particularly at nearshore regions with complex bottom topography. Besides, buoys are also subjected to ongoing maintenance and data transfer problems due to the harsh oceanic environment which can lead to loss of data.

![Figure 2.6 - Waverider buoy networks around the world.](image)

In spite of buoys being spatially limited and subjected to data loss, stored wave datasets from directional and non-directional buoys have been used worldwide not only to conduct analyses of wave energy resources; but also, to validate and calibrate other methods of acquiring wave data, particularly numerical wave models and satellites (e.g. Rusu and Soares, 2008; Liberti et al., 2013). Examples are provided by Vicinanza et al., (2011), Soares et al., (2014) and Wu et al., (2015). Vicinanza et al., (2011) estimated how much wave energy flux reaches Italy’s coastline, based on wave observations from
Italy’s buoy network. Soares et al., (2014) used wave observations from directional and non-directional buoy data to calibrate two wave models along Europe’s west coast (Ireland, United Kingdom France, Spain and Portugal). Wu et al., (2015) also using wave measurements from directional buoys, estimated how much wave energy is available off China’s southeast coast. In this study waverider buoy data will be used to calibrate and validate the numerical model.

2.5.2 Remotely sensed data

Remote sensing instruments are mounted on fixed or moving platforms such as ships, aircrafts and satellites, and provide wave measurements indirectly from seas either actively or passively. The most widely used remote-sensing tools for mapping ocean surface topography are spaceborn radar altimeters (Pontes et al., 2009). These have become more accurate and are definitely gainful tools for obtaining spatially broad data coverage and evaluating wave energy resources at large to medium scales.

Altimetry radar satellites are non-imaging devices that measure sea surface elevation by timing how long it takes for a pulse of microwaves to be reflected from a target sea surface and return. The backscattered signals (shape and amplitude) are later analysed to provide measurements of significant wave height $H_s$ and wind speed $U_{10}$. These are calculated, instantaneously, whilst a satellite courses over a repeat net of ground track footprints at a constant speed.

Altimetry satellites measure $H_s$ with an accuracy of a few centimetres. Through linear corrections researchers can now also correct satellite-dependent biases and also noises within measured $H_s$ data from undesired random disturbances of satellite signals. These corrections are most reliably accomplished by comparing altimeter $H_s$ datasets against long-term buoy data. It is also possible to indirectly obtain measurements of $T_z$ from altimetry satellites, with analytical neural network models that combine $H_s$ and $\sigma_o$. These algorithms calculate $T_z$ with biases inferior to 0.15 s and determination coefficients superior to 0.7 (Pontes et al., 2009).

Satellite altimeters, nevertheless, are not capable of providing directional wave data. The knowledge of $\theta_m$ is, for example, required for designing and adjusting non-axial symmetric WEC devices. Additionally, satellite data has low measurement frequency and limited spatial coverage. Satellites are set on shifted periodic orbits and thus any one location along a satellite ground track is only covered at long intervals of time be-
tween 3 and 35 days (Figure 2.7). Therefore, satellites are unlikely to capture significant sea state variations that can occur within much shorter periods of time (days to hours).

The spatial coverage is also relatively coarse (80-1300 km) and even though higher spatial coverage (with more interorbital tracks) can be acquired using lower temporal resolution (longer repeated cycles), satellites will still have large inter-track spacing exceeding 80 km (Figure 2.7). The along-track spatial resolution is also wide varying from 100 to 10 km (Pontes and Bruck, 2008). In order to achieve higher spatial and temporal coverage, various satellites tracks with complementary orbits are often combined, enabling researchers to quantify wave energy resources from large to medium spatial scales (see Cornett, 2008; Liberti et al., 2013; Rusu and Soares, 2012). Recently, Yong et al., (2015) showed a good example of that by conducting a wave energy resource evaluation for China’s seas, only based on multi-satellite merged radar altimeter data.

2.5.3 Simulated data

In view of sparse and intermittent direct or indirect wave measurements, hindcast wave data generated by numerical wave models can be employed for quantifying wave energy resources. Numerical wave models can be either phase-resolving wave models or phase-averaging wave models. The phase-resolving models attempt to represent the
time-varying water surface, by resolving both the amplitudes and phases of individual wave components. These types of wave models are very computational intensive and are typically used for modelling very small spatial domains, being impractical for regional-scale wave climate modelling such as that presented in this study. The phase-averaging wave models solve an equation termed ‘wave energy balance’ and compute directional spectra $S(f, \theta)$ as a function of time and space. First-generation spectral models exclude nonlinear wave-wave interactions, whilst second-generation models account for quadruplet nonlinear wave-wave interactions with a single parameterised form. Third-generation wave models can explicitly account for all relevant physics, without imposing any specific spectral shapes or energy levels. The simulation of wave generation, propagation and dissipation can be computed from large to very small spatial scales up to 50 m enabling estimations of wave climate statistics for whole regions. These wave models can be executed on large time frames with high spatiotemporal resolution and applied to any area. Furthermore, they are capable of simulating a greater number of variables than cannot be reliably measured. For such reasons, wave models are used worldwide to generate wave data so that wave energy resources can be more precisely evaluated.

Nowadays, wave models have been developed using different numerics, physical parameterisations and processes of data assimilation. These can be divided as global wave models and shallow water wave models. Whilst global wave models are more efficient for deep water, shallow water wave models are primarily designed required for coastal areas where shallow water physics cannot be neglected. The accuracy of wave models can be, once properly calibrated, comparable to that of buoys and satellites.

2.5.3.1 Global or basin wave models

Global wave models are usually run by meteorological organisations on a routine basis to provide forecasts for marine operations. These operational forecasting systems also enable researchers to store simulated numerical wave outputs acquired through meteorological analysis over regular periods of time. These long-term wave hindcast datasets provide groundwork for wave climatology analysis and coastal wave modeling.

These global wave models are primarily designed for deep water because they typically do not sufficiently account for most shallow water physics. In addition, global wave models have explicit finite difference numerical schemes and hence any given time-step
\[ \Delta t \text{ has to satisfy a stability criterion designated ‘Courant-Friedrichs-Lewy’ (CFL) condition (Tolman, 2001):} \]

\[ C \equiv \left| \frac{c_x \Delta t}{\Delta x} \right| + \left| \frac{c_y \Delta t}{\Delta y} \right| \leq 1 \]  \hfill (17)

Otherwise known as Courant number, \( C \), determines how steady an explicit numerical scheme is by measuring how much information crosses a computational grid cell of size \( \Delta x \) and \( \Delta y \) during a model time-step (\( \Delta t \)). In explicit numerical schemes, \( C \) is generally limited to maximum unit so that waves cannot propagate more than one grid cell during one time step at most. However, for complex coastal scenarios that require high-spatial resolution, \( \Delta x \) and \( \Delta y \) need to be relatively small and so waves will eventually propagate across more than one grid cell during each time step. Subsequently, wave propagation will become unstable and the solution will diverge.

Global-scale ocean wave forecasts have been historically generated by WaveWatch III (WW3) operated at NOAA (National Oceanic and Atmospheric Administration) and by WAve Model (WAM) run at ECMWF (European Centre for Medium-Range Weather Forecast). The historical hindcast archives from NWW3 and WAM have been used as groundwork for mapping wave energy resources from global to regional scales (Arigana and Cheung, 2011; Gunn and Stock-Williams 2012) and often used to provide wave boundary conditions for driving coastal wave models (Iglesias et al., 2009; Rusu and Soares, 2012). The latest versions of NWW3 (4.08) has been upgraded with source term packages for bottom friction dissipation and wave breaking, providing now, more realistic computations near to shore (Tolman, 2014).

2.5.3.2 Coastal or shallow water wave models

The continuous development of numerical wave models has led to high-spatial resolution transformation models that are primarily designed for finite water depth (or shallow water environments) (e.g. Booij et al., 1996). These wave models explicitly account for wave generation processes (wave growth by wind), wave propagation processes (shoaling, reflection, diffraction and also blocking), wave transformation processes (quadruplets and triad nonlinear wave-wave interactions) and wave dissipation processes (depth-induced wave breaking, whitecapping and bed friction) (Browne et al., 2006). Furthermore, transformation models have fully implicit numerical propagation schemes.
that are not limited by numerical stability conditions. Such numerical schemes are less sensitive to numerical instability and so larger values for $C$ might be tolerated (Booij et al., 1999).

Therefore, coastal wave models can be driven on high-resolution scenarios grids with reasonable stability (e.g. Bunney, 2011). These models also generally enable change of spectrum-resolution during nesting, where a higher resolution spatial domain is nested within a coarser domain. The most widely used open source shallow water wave model is Simulating WAVes Nearshore (SWAN) developed at Delft University of Technology, which will be used here to generate wave conditions (Booij et al., 1999). Examples of wave energy resource assessments conducted with SWAN are available for:

1) Portugal (Rusu and Soares, 2009; Rusu and Soares, 2012);
2) Spain (Iglesias and Carballo, 2010; Iglesias and Carballo, 2011);
3) France (Gonçalves et al., 2014);
4) Italy (Monteforte et al., 2015; Iuppa et al., 2015);
5) England (Nieuwkoop et al., 2013);
6) Ireland (Cahill and Lewis, 2013);
7) Black Sea (Soomere and Eelsalu, 2014);
8) Caspian Sea (Rusu and Onea, 2013; Hadadpour et al., 2014);
9) Mediterranean and Aegean Seas (Ayat, 2013);
10) United States of America (Stopa et al., 2011; Lenee-Bluhm et al., 2011);
11) Canada (Robertson et al., 2014);
12) China (Liang et al., 2013; Liang et al., 2014; Zhou et al., 2015);
13) South Korea (Kim et al., 2011);
14) India (Kumar and Anoop, 2015);
15) Iran (Saket and Etemad-Shahidi, 2012);
16) Australia (Hemer and Griffin, 2010);
17) Peru (López, Veigas and Iglesias, 2015)
18) Caribbean (Appendini et al., 2015)

More details about SWAN are given later within section 3.3.

2.5.3.3 Source of errors in numerical wave models

The source of errors encountered by numerical wave models can be viewed as either internal or external. Internal sources of errors are related to inadequate source term pa-
rameterisations, weak representation of complex physical processes and numerical effects induced by limitations of computational schemes (Rusu, 2011). External sources can be owing to poor input data and human errors, whilst manipulating data. Thus, a fundamental concern when modelling waves is to properly identify potential errors.

2.5.3.3.1 Numerical resolution

The description of a continuous physical process such as wave growth, propagation and dissipation with a discrete wave model can lead to significant modelling errors. The spatial grid resolution, spectral resolution (number of frequency and directional bands) and model time step are vital to accurately simulate wave features with numerical wave models (see Tolman, 2003; Rusu and Onea, 2013). Usually, time steps should be small enough to resolve any time variations of computed wave fields. It is generally enough to consider a model time step equal to that of wave and wind forcing fields (check SWAN Scientific and Technical Documentation 2008). The grid and spectral resolution must be selected small enough so that all physical processes are sufficiently resolved throughout SWAN domain (Dietrich, 2012).

The propagation of swell on a model grid with discrete directional resolution can lead to a breakup of continuous swell fields into discrete packages, a process termed Garden Sprinkler effect (Tolman, 2002). The accuracy of swell propagation can also be largely affected by highly complex seabed gradients and blockage by small archipelagos, which may not be accurately represented due to lack of spatial grid resolution (Tolman, 2003). Lack of spatial and temporal resolution might also lead to a smoothing of small intense systems, generating systematic underestimations of peak wind speeds and consequently peak wave heights (e.g. Stopa et al., 2013).

2.5.3.3.2 Input data

The quality of wave boundary condition, bathymetry and wind data can be a limiting factor for a wave model to simulate accurate wave predictions. The accuracy of wave models is critically sensitive to different wind products. These modelled winds propagate errors from atmospheric models to numerical wave models, which can often be very limiting (Teixeira et al., 2006; Feng et al., 2006). These errors are generally greater for coastal regions owing to localised wind effects, which are not resolved adequately using global scale wind models.
The resolution of wave boundary condition data can also cause degradation of model accuracy (see Rogers et al., 2005; Nieuwkoop et al., 2013). Boundary condition datasets obtained from coarse global wave model simulations can lead to a reduced intensity of strong storm systems (see Durrant et al., 2014). In coastal areas, a poor representation of highly complex seabed gradients and accentuated characteristics owing to low spatial resolution can also cause poor representation of wave transformation (Wolf et al., 2000; Rusu, 2011).

2.5.3.3.3 Model physics

Even though numerical wave models are equipped with numerous deep and shallow water source term packages, many processes are not yet completely understood. Transfers of air-sea momentum at high wind speeds, swell decay, non-linear interactions and wave diffusion are based on formulations with numerous limitations (Cavaleri et al., 2007). In addition, physical parameterisations are usually empirical and thereby wave models do not have universal range of applicability. Tuning physical formulations for application at one scale may inevitably lead to a degradation of model performance at another scale (Rogers et al., 2005). The intrinsic accuracy from a spectral approach can also have limitations. Liu et al., (2002) demonstrated that even when forcing a spectral wave model with high-quality, carefully evaluated winds, wave output parameters have a scatter that cannot be solely explained by known uncertainties of input data (Liu et al., 2002).

2.5.3.4 Computational grids

The wave action balance equation is solved by spectral models at each computational grid cell node for each time step \( \Delta t \) during a time interval \( t \). SWAN needs to be capable of solving wave propagation over coastal bathymetry that becomes progressively more complex shorewards, requiring thus a dense computational grid. The number of grid cell nodes is, however, very unlikely to be manageable by SWAN when a dense grid is used from deep water to shallow water. To avoid memory constraints of computer memory, it becomes handy to either use a grid with varying resolution (non-uniform or irregular) or a spatial refinement based on a series of nested grids. The computational grid of SWAN is generally selected based on a balance between required spatial resolution and computational effort. A good grid must be efficient over where bathymetry and wave evolution
changes rapidly requiring a higher resolution than areas where physics or depth changes less (check SWAN Scientific and Technical Documentation 2008).

2.5.3.4.1 Non-uniform grids

SWAN has a couple of different types of grids, structured (rectilinear or curvilinear) and unstructured. The number of grid cells on structured grids is four, whereas unstructured grids have typically between four and ten grid cell nodes. Therefore, unstructured grids are more flexible than structured grids, even though they require more CPU (Iuppa et al., 2015). Structured, non-uniform grids (rectangular irregular or curvilinear) are also capable of providing adequate spatial resolution offshore and high-resolution nearshore. Nevertheless, models with rectangular grids tend to be more sensitive to grid resolution than curvilinear grids as a consequence of wave modelling based on curvilinear meshes converging much faster with increasing spatial resolution (Berkhahn and Mai, 2004).

‘Nevertheless, models with rectangular grids tend to be more sensitive to grid resolution than curvilinear grids as a consequence of wave modelling based on curvilinear meshes converging much faster with increasing spatial resolution (Berkhahn and Mai, 2004).

In terms of applicability, non-uniform spatial grids appears to be more practical for simple coastal shapes (Iglesias and Carballo, 2009; Iglesias and Carballo, 2010a; Iglesias and Carballo, 2010b), whilst unstructured grids are more suitable for complex shorelines such as creeks, fjords or archipelagos (Aydoğan et al., 2013). Nested grids can be embedded on non-uniform structured grids and unstructured grids to provide a more refinement at particular areas (nesting).

2.5.3.4.2 Nesting

The spatial resolution refinement can be conducted based on a series of nested grids where finer resolution models use simulations from coarser resolution domains as wave boundary conditions (Rogers et al., 2006; Allard et al., 2007; Rusu et al., 2008; Kim et al., 2011; Liberti et al., 2012). The step size from one nesting level to another is usually reduced by a factor of 2 to 3 (see Rusu et al., 2008; Rusu and Soares, 2012; Liang et al., 2013). Nevertheless, some researchers have used larger grid steps between nesting levels (e.g. Rogers et al., 2006; Rusu and Soares, 2012; Nieuwkoop et al., 2013).
2.6 Australia’s wave energy resources

The continent of Australia spans over a land area of 7.7 million km² from 0 to 50° S and from 110 to 160° E. The southern half of Australia is endowed with consistent wave energy resources with mild to high magnitudes being considered a promising market for harvesting wave energy using current WEC technology (Behrens et al. 2015; Morim et al., 2015). Australia’s northern half has a reasonable quantity of wave energy resources, but with a low frequency of occurrence and low density, hence not being appropriate for harvesting with current technology (see Figure 2.8).

![Figure 2.8 - Spatial distribution of annual average wave energy in kW/m around Australia. The Australian transmission grid line and some wave projects (‘red circles’) are also drawn (Geoscience and ABARE, 2010).](image)

2.6.1 The south and southwestern coasts of Australia

Australia’s long, south and southwest coastlines are a huge potential source of wave energy resources. Waves generated in the southern ocean by the strong westerly wind belt travel towards Australia’s south coast delivering waves with a mean $H_s$ of 2.5 to
3.5 m and mean periods $T_m$ of 11 s. Often, fully developed unimodal spectral sea states dominated by remotely generated waves with wave periods greater than 8 s exist in this region (Hemer and Griffin, 2010). Locally generated wind seas with $H_s$ ranging from a few centimeters to approximately 2 to 3 m and periods of 2 to 8 s are also experienced (CSIRO, 2012). The seasonal variability of wave energy consists of more energetic sea states from winter to spring, due to west–east passages of strong temperate storms, and far less energetic sea states during summer–autumn, owing to local sea breezes (Hughes and Heap, 2010).

The interannual variability of wave heights and directions shows a positive correlation with positive Southern Annular Mode (SAM) phases, particularly during austral autumn and winter months (e.g. Hemer et al., 2010). The belt of westerly winds shifts towards Antarctica (during a positive SAM event) and thus waves are generated more southerly. Subsequently, northeastward swells become stronger and rotate anti-clockwise towards a more northward direction (Hemer et al., 2007; Hemer et al., 2010).

The flux of wave energy propagating off Australia’s southern coast has been examined locally based on wave buoy observations and regionally with wave transformation models. Reid and Fandry (1994) presented analyses of wave rider buoy data from Cape Sorell, located on Tasmania’s west coast. The mean wave energy flux was estimated to be about 51 kW/m. Later, Lemm et al., (1999) conducted wave energy resource analysis off Perth based on 2.5 years (1994–1996) of non-directional buoy data. The mean wave energy flux was calculated to be 48.0 kW/m at a depth of 48 m southwest of Rottnest Island.

In 2004, Sustainability Victoria (SV), commissioned a wave energy resource study for Victoria and Bass Strait (Sustainability Victoria, 2004). The transformation wave model MIKE21 SW developed by DHI (Danish Hydraulic Institute) was employed to compute wave energy resource delivery between 140–151° E and 37–42° S. (see Figure 2.9). The model was run on a flexible unstructured spatial grid with varying spatial resolution, which decreased from about 30 km offshore to about 1.5 km nearshore. MIKE21 model bathymetry was acquired from electronic digitised nautical charts provided by DHI. The MIKE21 boundary conditions were acquired from a meso-scale WAM model version of WAM for Australia and consisted of 1-year (2003), 12-hourly time series of $H_s$, $T_p$ and $\theta_m$, gridded on a 12.5 km spatial resolution (Sustainability Victoria, 2004).
Figure 2.9 shows that median wave energy delivery was observed to exceed 30 kW/m off Victoria western coast, Tasmania’s northwestern coast and King Island. The section of coast from Phillip Island to Wilson’s Promontory experienced large waves associated with storm events, but its median wave energy delivery was only 15 to 20 kW/m. The shallow effect from Tasmania was responsible for a relatively low average wave energy flux off East Gippsland with approximately 10–15 kW/m (Figure 2.9).

Hemer and Griffin (2010) published a series of wave energy resource atlas for Australia’s southern shelf, from Geraldton (WA) to South East Cape (TAS), between 110–155° E and 30–45° S (Figure 2.10). Thirty nine representative deep-water wave states, corresponding to annual and annual cycles of 10th, 50th and 90th wave energy flux percentiles, were derived from WaveWatch III (WW3) model archives managed by USA National Oceanic and Atmospheric Administration (NOAA). These archives consisted of 10-year (between 1997 and 2006), 6-hourly archives of $H_s$, $T_p$, and $\theta_m$, gridded on a 1° longitude $\times$ 1.25° latitude spatial grid resolution.

These deep-water representative sea states were later downscaled to 1 km fine resolution grids using Simulating WAves Nearshore (SWAN). The model bathymetry was acquired from Geoscience Australia (GA) with 0.01° grid resolution. Wind forcing was neglected as Hemer (2009) had previously found that wave conditions along Australia’s south coast were well described based on forcing from swell boundary conditions only.

Hemer and Griffin (2010) confirmed that Tasmania, Western Australia, South Australia and Victoria are exposed to a median wave energy flux of about 30 to 50 kW/m (Figure 2.10) depending on area. The flux of wave energy off Australia’s south coast...
was found to rarely fall below half its median and above twice its median (10%). The lowest monthly mean wave energy occurs during summer (20–45 kW/m) and largest during winter (60–85 kW/m). The total wave energy flux crossing a water depth of 25 m between Geraldton and South East Cape (VIC) was estimated to be approximately 1329 TWh/yr (Hemer and Griffin, 2010).

Figure 2.10 - Map of wave energy flux at 50\textsuperscript{th} percentile levels. Inset numbers show values at five example near-shore locations (circled). Licensed projects are also represented by blue boxes. (Adapted from Hemer and Griffin (2010) by Carnegie).

The high wave energy levels experienced along Australia’s southern continental shelf are very promising, but they still pose significant challenges for engineering design. Highly energetic sea states derived from storm wave events are likely to cause irreversible equipment damages and considerable downtime. Additionally, outside of city centres, which are situated within relatively sheltered waters, much of South Australia, Tasmania and Western Australia coastlines have a relatively low population density and consequently a small demand for electricity and heat generation. These aspects need to be considered for further deployment of wave farms.
2.6.2 The southeastern coast of Australia

The southeastern coast of Australia which extends from Eden (South of New South Wales) to Fraser Island (South of Queensland) receives moderate waves with mean $H_s$ between 1 and 2 m and with mean periods $T_m$ of 6 s. Figure 2.11 shows that Australia’s southeastern shelf receives waves from south through east to north quadrants, driven by north-easterly Trade Winds, zonal south-easterly Trade Winds and a blend of southern Tasman anti-cyclones and Tropical lows, central Tasman lows, Southern Ocean lows and Southern Tasman lows.

![Figure 2.11 - Approximate area of influence of wave producing meteorological types off Australia’s southeastern shelf based on work of Short and Trenaman (1992) and Shand et al., (2011) (Amante and Eakins, 2009).](image)

Circumpolar generated swell waves are present year round peaking during June to September, whilst northerly swells are typical for December to March, generated by North Pacific extra-tropical storms. Locally generated southeasterly trade winds typically peak during winter. The pattern of seasonal wave variability exhibits more energetic wave conditions during winter associated with heavy Southern Ocean swells and less energetic sea states during summer period owing to local sea breezes. Spring and autumn are transition seasons with moderate energetic wave conditions (Short and Trenaman, 1992; Hemer et al., 2007; Hughes and Heap, 2010).
The mean wave direction is east–southeasterly but becomes more southerly/easterly with decreasing/increasing SOI. Shifts of westerly winds associated with negative and positive SAM events (Southern Annual Mode) can also cause wave rotations. The anti-clockwise/clockwise rotation of wave direction is enhanced during periods with strong negative Interdecadal Pacific Oscillation phases (Goodwin, 2005; Hemer et al., 2007, Hemer et al., 2010).

The offshore wave energy resource along Southern Queensland and New South Wales have been determined at specific locations using buoy data and regionally using global wave models. Short and Trenaman (1992) conducted a preliminary wave energy study for Sydney, based on 20-years (1927–1990) of buoy datasets collected at a water depth of 60 m off Botany Bay. The average wave energy flux was estimated to be 27 kW/m. Statistical analyses of wave energy flux were also conducted by CSIRO (2010), based on buoy records acquired off Sydney and Eden, between 1998 and 2005. The mean wave energy flux was reported to be 14 kW/m at both locations.

In 2010, Hughes and Heap (2010) conducted a national wave energy resource study for Australia based on hindcast outputs from AusWAM (Australian WAve Model). The model was run on a regular spatial grid with 0.1° spatial resolution, which extended from 110 to 156° E and from 7 to 46° S. The model bathymetry was obtained from Geoscience Australia (GA) and gridded on a 2.25 km spatial resolution. The wave boundary conditions of AusWAM were derived from a coarser version of AusWAM, with a 0.5° spatial resolution and consisted of $H_s$, $T_m$ and $\theta_p$ at 6-hourly intervals from 1997 to 2008 (see Table 2.1).

Table 2.1 - Summary details listed for numerical wave models and hindcast data used to estimate wave energy resources around Australia.

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<thead>
<tr>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>SWAN</td>
<td>MIKE21 SW</td>
<td>AusWAM</td>
</tr>
<tr>
<td>Computational grid</td>
<td>Structured</td>
<td>Unstructured</td>
<td>Structured</td>
</tr>
<tr>
<td>Grid resolution</td>
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<td>0.3° to 0.0135°</td>
<td>0.1°</td>
</tr>
<tr>
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<td>140–151° E</td>
<td>110–156° E</td>
</tr>
<tr>
<td></td>
<td>29–44° S</td>
<td>37–42° S</td>
<td>7–46° S</td>
</tr>
<tr>
<td>Model input</td>
<td>Wave</td>
<td>Wave and Wind</td>
<td>Wave</td>
</tr>
<tr>
<td>Data source</td>
<td>Global NWW3</td>
<td>AUSWAM</td>
<td>AUSWAM</td>
</tr>
<tr>
<td>-------------</td>
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<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>Type of data</td>
<td>$H_s$, $T_p$, $\theta_m$</td>
<td>$H_s$, $T_m$, $\theta_p$</td>
<td>$H_s$, $T_m$, $\theta_p$</td>
</tr>
<tr>
<td>Spatial resolution</td>
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<td>$0.5^\circ$</td>
</tr>
<tr>
<td>Temporal resolution</td>
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<td>12-hourly</td>
<td>6-hourly</td>
</tr>
<tr>
<td>Bathymetry</td>
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<td>-</td>
<td>$0.0225^\circ$</td>
</tr>
</tbody>
</table>

Based on Hughes and Heap (2010), coastal shelf waters along Southern Queensland and New South Wales are endowed with moderate wave energy levels of 10–20 kW/m (Figure 10) with a 90th percentile of 20 to 30 kW/m, delivering a total energy of >390 GJ/m annually. These states have a consistency of wave energy delivery comparable to Australia’s southern shelf, with time average between failures of ≥1 month and failure durations of 1.5 to 2.5 days (Hughes and Heap, 2010). Figure 2.12 shows that Australia’s southeastern shelf also exhibits less seasonal and synoptic spatial variability and has a lower magnitude of extremes relative to its mean when compared to Australia’s south margin (Mortlock and Goodwin, 2015). These characteristics are advantageous as wave energy technology is traditionally designed and adjusted for moderate wave energy levels between 10 and 30 kW/m (Hughes and Heap, 2010).
2.6.2.1 Justification for the present study

There is little doubt that large shelf areas off the coast of New South Wales and Queensland have the potential for wave energy generation of up to 45 TWh/yr, representing almost 20% of Australia’s electricity generation in 2009–2010 (CSIRO, 2012). However, as recognised by Hughes and Heap (2010), wave energy developers need a more refined wave energy appraisal at a nearshore scale in order to resolve wave resource for reconnaissance, feasibility and design applications. The national-scale wave energy dataset developed by Hughes and Heap (2010) has some shortcomings and gaps that need to be resolved with further research, namely:

Figure 2.12 - Map of seasonal indices for wave energy in Australian shelf waters obtained by Hughes and Heap (2010). A value of 100 is equivalent to the annual average, values <100 indicate below the annual average and >100 indicate above the annual average.
• It is limited to offshore areas as most physical transformations that waves undergo when propagating from deep water to shallow waters were neglected (Hemer and Griffin, 2010);
• It is of limited spatial grid resolution to accurately represent wave energy delivery and redistribution for nearshore regions with complex shallow water seafloor gradients (Hughes and Heap, 2010);
• It is derived from wave hindcast conditions generated based on spectrally integrated wave parameters, which cannot accurately describe mixed wind sea and swell seas (Hemer and Griffin, 2010);
• It is derived from wave hindcast conditions acquired solely based on forcing swell boundary conditions and no wind forcing conditions (Hughes and Heap, 2010);
• It is of insufficient duration to accurately account for any interannual wave variability and its related uncertainty, which can reach up to 50% (Brooke, 2003);
• It has not been compared against wave measurements for model quality evaluation (Geoscience Australia and ABARE, 2010);

The current dissertation offers a long-term wave energy resource appraisal from deep to shallow water off from Fraser Island (South of Queensland) and down to East Gippsland (Victoria). In order to properly account for shallow water physical processes, a wave transformation model is configured and subsequently run at high spatial and temporal resolution over a period of 31 years. The model is driven using fully spectral wave boundary conditions from WaveWatch III latest version 4.08, enabling mixed wind and swell to be more accurately represented. The latest CFSR reanalysis winds are used as wind forcing fields. Nested small-scale grids are employed to provide a spatial refinement along nearshore areas of interest.

In order to find optimum numerical and physical settings, a model sensitivity analysis, calibration and validation are conducted beforehand, using wave observations from several wave buoy locations. The numerical and physical settings of greater importance are determined using qualitative and quantitative statistical analyses. The hindcast wave data is subsequently used to perform a wave energy resource assessment for Australia’s southeastern coast. The best-endowed areas with wave energy resources are determined and promising hotspots for deployment of wave farms are presented and characterized.
2.7 Wave energy conversion technology

There are currently a great number of WEC products that have been tested at open sea and many are now at R&D stage. The classification of WEC products is, however, not yet uniformly accepted (Lopez et al., 2013). There are currently many systems and each system shares subcategories of techniques and or nomenclatures. The literature review shows that wave converter devices are typically categorised based on water depth and surface orientation (Lopez et al., 2013). In Figure 2.13, wave harvesters are classified based on type, location and also working principle. For more details about wave energy transfer mechanisms, key design constraints and device configuration please see CSIRO (2012).

![Classification of wave energy converters](image)

Figure 2.13 - Classification of wave energy converters (Lopez et al., 2013).

2.7.1 Classification by location

2.7.1.1 Shoreline devices

Shoreline (or onshore) wave devices are located entirely onshore (shallow waters of <10 m) and can be placed above water or fixed to a cliff. These devices have some advantages, namely they are easy to deploy and maintain. Furthermore, shoreline devices do not need mooring systems or long underwater cables. They are also not exposed to
very high levels of wave energy and thus risks of potential damages and downtimes are reduced (Lopez et al., 2013; Fadaenejad et al., 2014).

That also means that shoreline devices harvest less energy than nearshore and offshore devices. In addition, shoreline devices cannot be designed for mass manufacturing, due to site-specific constraints such as shoreline geometry and geology and preservation of coastal landscape. Tidal range can also be challenging (Lopez et al., 2013; Fadaenejad et al., 2014).

2.7.1.2 Nearshore devices

Nearshore devices are positioned further out at a few hundred meters offshore between water depths of 10−50 m. The exploited wave energy is transformed into electricity within an onshore facility. These devices can be either fixed structures or oscillating structures. If they are fixed structures, they need to be able to handle wave-induced stress. Nevertheless, similar to shoreline devices, a disadvantage is that such devices are submitted to weaker waves with 10% less energy. Even though at nearshore areas that factor can be partially compensated by sites of wave energy concentration (Lopez et al., 2013; Fadaenejad et al., 2014).

2.7.1.3 Offshore devices

Offshore converters are deployed at water depths ranged between 40−100 m and can be either floating or submerged structures. These converters are exposed to higher levels of wave energy; however, they are also submitted to very rough sea states, which can cause irreversible equipment damage (less survivability) and substantial downtime (less reliability). They are also more complex to deploy especially due to problems associated with mooring points and underwater electrical transmissions (Fadaenejad et al., 2014).

2.7.2 Classification by surface orientation

2.7.2.1 Point Absorber

Point absorbers are usually axisymmetric about a vertical axis and have relatively small dimensions relative to the typical wavelengths ($\lambda$). The float follows the wave movement and accepts wave energy from any direction. These devices can be submerged and moved by the pressure of the wave passing overhead, or they can float on the surface and track or ‘heave’ with the movement of the sea surface. Because of their
small size, wave direction is not important for these converters (Lopez et al., 2013; Fadaeenejad et al., 2014).

2.7.2.2 Linear Absorbers or Attenuators

Attenuators lie parallel to the mean wave direction and their overall length may be large compared with the swell wavelength ($\lambda$). Nevertheless, they are also wavelength-dependent. Unlike a point absorber they need to be slack moored so that they can turn so as to maintain their principal axis normal to the oncoming waves (Lopez et al., 2013; Fadaeenejad et al., 2014).

2.7.2.3 Terminators

Terminators are designed to collect wave energy by facing waves directly. They can include passive devices like a tapered channel to focus energy from a wide section of wavefront. Examples of terminators are oscillating water column and overtopping devices (Lopez et al., 2013; Fadaeenejad et al., 2014).

2.8 Australia’s potential for wave energy technology

The potential of wave energy technology for Australian coastal waters has been assessed based on hindcast wave archives from NWW3. Behrens et al., (2012) conducted analysis of performance and cost for wave farms constituted by point absorbers, terminators and linear attenuators. These wave farms with a full capacity of 21 MW observed to operate for Australia’s south coast with a net capacity factor between 21 and 54% and a levelised cost of electricity of 78.2 to 261.0 $/MWh (Figure 2.14). The capacity factor is defined based on device power output characteristics as a function of wave period and height, and statistics of available wave energy at specific locations, as a fraction of device maximum power (Behrens et al., 2015).
The terminator farms proved to operate more efficiently for long period swells off Victoria, Western Australia and Tasmania, with mean capacity factors of 42 to 54% and a levelised costs of electricity of 78.2 to 94 $/MWh. The performance of terminator farms was observed to be highest along Tasmania’s west coast with a net capacity factor greater than 54.3%. Behrens et al., (2012) also evidenced that wave farms composed of point absorbers were more efficient for shorter period swell areas such as off Queensland and New South Wales, with mean capacity factor of 18.2–19.7% and a levelised cost of electricity between 129 and 133 $/MWh (Figure 2.14).
Later, Behrens et al., (2015) led a study on wave energy supply for Australia’s National Electricity Market (NEM) extending from Queensland to South Australia. Based on a typical terminator WEC performance, curve hourly electricity generation profiles and normalised annual wave energy capacity factors were determined and spatially distributed within ‘polygon’ of NEM. These figures were acquired for a conservative wave farm with 3.35 harvesters per km, considering environmental, marine park and general exclusion zone constraints. Behrens et al., (2015) calculated a maximum installable capacity of about 133 GW and a total generation of approximately 275 TWh annually, along almost 5,700 km of available 25 m isobath. The mean capacity factors were found to be of 10 to 15% off Southern Queensland and New South Wales and 26–44% along South Australia, Victoria and Tasmania.

There is little doubt that wave energy has potential to significantly contribute to Australia’s national electricity generation, particularly under a 100% renewable electricity scenario. Behrens et al., (2012) and Behrens et al., (2015) suggested that wave farms might operate for Australian coastal waters with capacity factors similar to that of solar and wind energy. In Australia, wind turbines typically operate with capacity factor of 25 to 35%, once fully mature, and solar plants with 20 to 25% during daylight (DHE 2006). The cost of electricity is also comparable to that of wind and solar towards more southern latitudes, which offer higher wave energy density (Behrens et al., 2012).

These preliminary findings represent a competitive edge over wind and solar, since wave technology is still relatively undeveloped and considerable maturing is yet expected. Hayward et al., (2012) proved that tuning and upgrading wave harvesters leads to a higher net capacity factor and to less intermittency of wave energy extraction. Based on Hayward et al. (2012), small capacity factor enhancements of 10% can lead to a significantly lower cost of electricity. Also, wave energy becomes viable and competitive in Australia, under a carbon price scheme and a renewable energy target policy.

Consequently, for wave energy to become more economically feasible, capital, operation and maintenance costs need to be reduced. There are currently a wide variety of converter designs being explored, so as to reduce both capital and maintenance costs. Additional research needs also to be undertaken to find a suitable economical balance between size of equipment, anchorage expenditure and number of units per wave farm.
Chapter 3

3 Methodology

3.1 Introduction

In order to accurately predict wave energy resource delivery along coastal waters of Australia’s southeastern margin over a period of 31 years (1979–2010), a high-spatial resolution SWAN model was configured. SWAN was applied on a curvilinear spatial grid using full directional spectra from CAWCR’s latest hindcast as wave boundary conditions and high-resolution winds from CFSR as wind forcing. In order to provide a more refined spatial coverage within nearshore areas of interest, a nested grid was also configured.

3.2 Area of study

The area of study extends from Queensland’s Great Sandy National Park to Victoria’s Croajingolong National Park, covering a coastal distance of approximately 1700 km along Australia’s southeastern coast and continental shelf waters up to about 80 km offshore (Figure 3.1).
The relatively high-energy, deepwater ocean wave climate acts on an extremely narrow and steep nearshore shelf profile, and so, at particular nearshore regions, 96.6% of offshore wave energy reaches shallow waters (e.g. Wright, 1976; Short and Trenaman, 1992). The exceedance probability of significant wave heights is fairly uniform from Southern Queensland to Southern New South Wales with a median (50% exceedance) between circa 1.4 and 1.7 m. Swells exceeding 6 m and waves falling under 0.5 m have a low probability of occurrence ~1% (Shand et al., 2011; Kulmar et al., 2013). Shand et al. (2011) presented exceedance probabilities for $H_s$ at several waverider buoy locations off New South Wales for 19 to 30 years of data. The study found that only 1% of waves actually exceeded 4 m (Table C.1). Also, a more recent study presented by Kulmar et al. (2013), analysed a period of approximately 30 years of wave data at several NSW buoy
sites and also found that $H_s$ exceeding 6 m have a probability of occurrence lower than ~0.1% (Table C.2). Based on Shand et al. 2010, major storms characterized by a $H_s > 5$ m along NSW are defined as ‘large, low probability extreme wave events’.

Figure 3.2 shows, however, different wave direction climates for New South Wales north, central and south coasts. For example, Byron Bay, Coffs Harbour and Crowdy Head clearly shows more wave energy arriving from east to east-southeast sector than other southern stations. In contrast, Sydney, Port Kembla and Batemans Bay show more predominant wave energy from southeast to south-southeast directions than locations up north.

Figure 3.2 - Wave roses for several wave rider buoy locations off the New South Wales coast showing latitudinal variations of $H_s$ and $\theta_m$. The buoy record lengths (years) are showed after each buoy name (Kulmar et al., 2013).

Figure 3.3 shows that seasonal variations of significant wave heights are subtle with a maximum of 0.3 m (Mortlock and Goodwin, 2015) and are more meaningful towards Byron Bay with larger swells during winter to autumn and smaller waves from spring to summer (Shand et al., 2011; Kulmar et al., 2013).
The exceedance probability of $T_p$ is fairly uniform between Southern Queensland and Victoria with a mean of 9 to 10 s (Kulmar et al., 2013). The seasonal variation is around 1.0 to 1.5 s with larger periods from autumn to winter and smaller between spring and summer. The peak wave periods typically exceed 6 s (about 90%) but rarely surpass 14 s (about 5%), which is explained by wave generation being limited to a maximum fetch of approximately 1800 km between Australia and New Zealand (Kulmar et al., 2013). Therefore, only swells formed off New Zealand’s northeast coastline during anticyclone intensifications generate larger periods (Mortlock and Goodwin, 2015).

Figure 3.2 demonstrates that mean wave direction is predominantly governed by east to southeasterly winds ranging between 120 and 135°. The mean wave direction turns somewhat more easterly towards Byron Bay (~123°) and more southerly nearby Sydney (~135°) (Figure 3.2). The seasonal variation of wave direction is about 10 to 20° having a more east-southeasterly direction from spring to summer months and a more south-southeasterly direction from autumn and winter (Figure 3.3) (Shand et al., 2011; Kulmar et al., 2013).

Figure 3.3 - Wave roses for Byron Bay, Sydney and Batemans Bay (NSW) showing seasonal variations of $H_s$ and $\theta_m$ (Kulmar et al., 2013).
3.3 The Delft3D modelling suite

Delft3D (Delft Hydraulics, 2005) is a flexible modelling software that is capable of simulating 2D and 3D current flows, sediment transport and morphology, waves, water quality and ecology, even though each specific module can be run separately. The code of SWAN was run using Delft3D-WAVE supported by a couple of flexible and robust pre-processing tools, namely RGFGRID and QUICKIN. RGFGRID is used for creating, modifying and visualising grids, whereas QUICKIN is used for generating, interpolating and manipulating grid-related parameters (bathymetry, land boundary and others).

Delft3D-WAVE has a graphical user interface that does not allow directly modifications of some model physics and parameters (e.g. rate of whitecapping dissipation) that needed to be verified. Therefore, some command lines were added to Delft3D-WAVE script by means of a batch file (Appendix A).

3.4 SWAN: theoretical background

SWAN is a semi-lagrangian, third-generation spectral wave model specifically designed to simulate random, short-crested wind-generated waves for coastal regions, bays and inlets (see Ris et al., 1997). The model has been traditionally used to transfer deep-water wave sea states to shallow waters, so that wave energy propagation and redistribution can be more accurately resolved across complex bathymetry.

The SWAN as a phase-averaging model simulates average wave field quantities by solving a spectral action balance equation, which describes the sea surface development as distribution of wave energy as a function of time and space (Holthuijsen, 2010). Due to the influence of underlying currents on the wave frequency, wave energy density is not conserved under these conditions and so the conservation of energy this equation is written in terms of the wave action density spectrum $N$ rather than the energy density spectrum $E$ which is conserved, since the wave action density is conserved under slowly varying conditions such as non-steady currents and water depth (Ris et al., 1997). The wave action density is defined as:

$$N(\sigma, \theta) = E(\sigma, \theta)/\sigma$$

(18)

where $\sigma$ is the radian frequency. The spectral wave action balance equation for Cartesian co-ordinates is given by (Ris et al., 1997):
\[
\frac{\partial}{\partial t} N + \frac{\partial}{\partial x} c_x N + \frac{\partial}{\partial y} c_y N + \frac{\partial}{\partial \sigma} c_\sigma N + \frac{\partial}{\partial \theta} c_\theta N = \frac{S(\sigma, \theta, x, y, t)}{\sigma}
\] (19)

The first term on the left-hand side of equation (19) represents the local rate of change of wave action density over time. The second and third terms are the gradients of the propagation of wave action in the geographical space, with propagation velocities \( c_x \) and \( c_y \) along the \( x \) and \( y \)-directions, respectively. The fourth term denotes the shifting of the relative frequency due to variations of water depths and currents where, \( c_\sigma \) is the propagation velocity in the \( \sigma \)-direction. The last term represents the effects of refraction and diffraction induced either by water depth variations and or currents, with propagation velocity \( c_\theta \) in the \( \theta \)-direction.

The term \( S \) on the right-hand side of equation (19) represents the sources and sinks of wave energy. The source term is composed by a sum of different physical processes:

\[
S = S_{in} + S_{ds} + S_{nl}
\]

(20)

where \( S_{in} \) represents external gains of energy due to wind generation, \( S_{nl} \) redistributions of spectral energy by nonlinear wave-wave interactions and \( S_{ds} \) energy dissipation. Similar to other transformation models, SWAN has a source term constituted by deep and shallow water components (Figure 3.4). The primary physics for deep water depths: wind-induced wave growth (\( S_{in} \)), whitecapping dissipation (\( S_{wc} \)) and quadruplet wave-wave interactions (\( S_{nl4} \)). The shallow water physics account for: bottom friction (\( S_{bfr} \)), wave breaking (\( S_{surf} \)) and triad wave-wave interactions (\( S_{nl3} \)) due to finite water depth effects. SWAN also considers reflections owing to shorelines and floating objects and partial transmission (\( S_{tr} \)). The total source of SWAN is given by (Holthuijsen, 2010):

\[
S = S_{in} + S_{wc} + S_{nl4} + S_{bfr} + S_{surf} + S_{nl3} + S_{ref} + S_{tr}
\]

(21)

The total wave energy transport per unit length of wave front (with units of \( \text{kW/m} \)) is acquired from:

\[
E_t = \sqrt{E_x^2 + E_y^2}
\]

(22)
where $E_x$ and $E_y$ are the wave energy components along $x$ and $y$-directions according to equation (10).

![Figure 3.4 - Deep and shallow water physical processes and respective influence on JONSWAP’s spectrum (Holthuijsen, 2010).](image)

### 3.4.1 Wind-induced wave growth

The transfer of wind energy to waves ($S_{in}$) is described based on a resonance mechanism (Phillips, 1957) and feedback mechanism (Miles, 1957) translated as a sum of linear and exponential growth terms of a wave component:

$$S_{in}(\sigma, \theta) = A + BE(\sigma, \theta)$$  \hspace{1cm} (23)

where $A$ is a linear wind growth term from Cavaleri and Malanotte-Rizzoli’s (1981) and $B$ an exponential wind growth parameter. The linear growth term is given by:

$$A = \frac{1.5 \times 10^{-3}}{2\pi g^2} (U_{max}[0, \cos(\theta)])^4 H$$  \hspace{1cm} (24)
where $U_f$ stands for wind friction and $H$ acts as a filter that removes wave growth for frequency bands below Pierson-Moskowitz’s spectral peak frequency (Tolman, 1992). The angle between wave propagation direction and wind vector components is given by $\theta$. The term $B$ follows a linear form adopted from an early version of WAM Cycle 3, which was proposed by Snyder et al., (1981) and later rescaled by Komen et al., (1984) as:

$$B = \max \left[ 0.025 \frac{\rho_{air}}{\rho_{water}} \left( 28 \frac{U_f}{c} \cos(\theta) - 1 \right) \right]$$  

(25)

The second equation for $B$ uses a quasi-linear wind-wave model proposed by Janssen’s (1991), based on a more recent version of WAM Cycle 4 (Komen et al., 1994):

$$B = \beta \frac{\rho_a}{\rho_w} \left( \frac{U_f}{c} \right)^2 \max[0, \cos(\theta)]^2 \sigma$$  

(26)

where $\beta$ is Miles’s (1974) constant. The wind growth formulations of Komen et al., (1984) and Janssen (1991) are coupled to a quasi-linear whitecapping dissipation model proposed by Hasselmann (1974) and solved by SWAN based on iterative method of Mastenbroek et al., (1994). The alternative equation for $B$ was proposed by Yan (1987) based on an analytical fit of experimental datasets provided by Snyder et al., (1981) and Plant (1982). The exponential wind growth rate of Yan (1987) is given by:

$$B = D \left( \frac{U_f}{c} \right)^2 \cos(\theta) + E \left( \frac{U_f}{c} \right) \cos(\theta) + F \cos(\theta) + H$$  

(27)

where $D$, $E$, $F$ and $H$ are experimental coefficients.

### 3.4.2 Whitecapping

The whitecapping dissipation sink term ($S_{ds,w}$) is simulated by SWAN based on a pulse-based model of Hasselmann (1974), reformulated by Komen et al., (1984) for finite depth:

$$S_{ds,w} = -\Gamma \frac{k}{\bar{k}} E(\sigma, \theta)$$  

(28)
where $\bar{\sigma}$ and $\bar{k}$ stand for mean frequency and mean wave number respectively. The rate of whitecapping dissipation $\Gamma$ is a steepness dependent term, which has been adapted by Günther et al., (1992) based on Janssen (1991):

$$\Gamma = C_{ds} \left( (1 - \delta) + \delta \frac{k}{\bar{k}} \right) \left( \frac{\bar{s}}{\bar{s}_{PM}} \right)^p$$

(29)

where $\bar{s}$ stands for overall wave steepness and $\bar{s}_{PM}$ is $3.02 \times 10^{-3/2}$.

The other tunable coefficients were found by Komen et al., (1984) and Janssen (1992) under idealised wave growth conditions (both for growing and fully developed wind seas) for deep water depth. The wind growth of Komen et al., (1984) uses $C_{ds} = 2.36 \times 10^{-5}$, $\delta = 0$ and $p = 4$, whilst Janssen’s (1992) wind growth formulation uses $C_{ds} = 4.10 \times 10^{-5}$, $\delta = 0.5$ and $p = 4$. Later, research conducted by Rogers et al., (2003) showed that adjusting $\delta$ from 0 and 0.5 to 1 leads to an improved prediction of wave energy at lower frequency bands, and hence, a $\delta$ of 1 has been used as default since version 40.91A.

The alternative whitecapping expression to Hasselmann’s (1974) pulse-based model is a cumulative steepness method proposed by Alkyon et al., (2002), which depends on $s$ (wave steepness) at and below a particular frequency according to:

$$S_{st} = A_m \int_0^{2\pi} \int_0^\infty k^2 |\cos(\theta - \theta_w)|^m E(\sigma, \theta) d\theta df$$

(30)

where $A_m$ is normalisation coefficient and $m$ a directional dependent coefficient. The alternative whitecapping source term is given by:

$$S_{st}^{st} = -C_{st}^{st} S_{st}(\sigma, \theta)^p E(\sigma, \theta)$$

(31)

with $C_{st}^{st}$ a tunable coefficient (default is 4) and $p$ a parameter that controls the proportionally of the dissipation rate on the steepness (default is 1).

The wind-induced wave growth term from Yan (1987) uses a nonlinear saturation-based whitecapping dissipation model adapted from Alves and Banner (2003) by Westhuysen et al., (2007). The latter is based on a relationship between wave groups and whitecapping dissipation, being specifically designed for mixed wind sea and swell conditions and also shallow water. The nonlinear saturation-based whitecapping model
is not steepness dependent and explicitly accounts for a couple of whitecapping dissipation modes, namely whitecapping owing to wave breaking and whitecapping due to non-breaking waves:

$$S_{ds,w} = f_{br}(\sigma)S_{ds,break} + [1 - f_{br}(\sigma)]S_{ds,non-break} \quad (32)$$

where $f_{br}(\sigma)$ is a weighting factor that defines when whitecapping dissipation is owing to breaking or non-breaking waves. The whitecapping dissipation owing to wave breaking is given by (Westhuysen et al., 2007; Mulligan et al., 2008):

$$S_{ds,break}(\sigma, \theta) = -C_{ds} \left( \frac{B(k)}{B_r} \right)^p \left[ \tanh(kd) \right]^{2-p} \sqrt{\frac{gkE(\sigma, \theta)}{4}} \quad (33)$$

where $B_r$ is threshold saturation level (default $1.75 \times 10^{-3}$) and $C_{ds}$ is by default $5.0 \times 10^{-5}$. The exponent $p$ takes a functional form that gradually changes from 4 to 2 as wind conditions change from a quadratic to a linear dependence on wind forcing.

The azimuthal-integrated wave spectral saturation function $B(k)$ is calculated from frequency space variable as follows (Mulligan et al., 2008):

$$B(k) = \int_0^{2\pi} \frac{dk}{d\sigma} k^3 E(\sigma, \theta) d\theta = c_g k^3 E(\sigma) \quad (34)$$

Whenever $B(k) > B_r$ wave breaking occurs owing to whitecapping and $p$ is set to a constant calibration parameter $p_0$. Whenever $B(k) \leq B_r$ waves breaking do not occurs owing to whitecapping and $p$ progressively changes to zero to account for other weaker forms of whitecapping dissipation such as turbulence and wave interactions between long and short waves using equation (29) (Mulligan et al., 2008).

### 3.4.3 Bottom friction

Depth-induced wave dissipation may be originated by bottom friction, bottom motion, percolation and by back-scattering on bottom irregularities. For continental shelf seas with sandy bottom, seabed friction is a dominant dissipation mechanism for transitional
and shallow waters (prior to wave breaking). The bottom friction sink term ($S_{bf}$) is expressed as (Holthuijsen, 2007):

$$S_{bf} = -c_b \frac{\sigma^2}{g^2 \sinh^2 kd} E(\sigma, \theta)$$  \hspace{1cm} (35)

where $c_b$ is a bottom friction (or drag) coefficient, which is by default empirically provided by Hasselmann et al., (1973) for swell dissipation based on (Holthuijsen, 2007):

$$c_b = \frac{\gamma}{g U_{rms}}$$  \hspace{1cm} (36)

with $\gamma$ equal to 0.038 m$^2$/s$^2$. For fully developed, shallow water seas, Bouws and Komen (1983) derived a more suitable $\gamma$ coefficient of 0.067 m$^2$/s$^2$. The root mean square bottom orbital velocity (m/s) is represented by (Holthuijsen, 2007):

$$U_{rms} = \int_0^{2\pi} \int_0^\infty 2 \frac{\sigma^2}{\sinh^2(kd)} E(\sigma, \theta) d\sigma d\theta$$  \hspace{1cm} (37)

The alternative formulations were proposed by Collins (1972) and Madsen et al., (1988). The non-linear drag friction model of Collins (1972) uses a bottom friction parameter directly related to bottom type substrate (Holthuijsen, 2007):

$$c_b = c_f g U_{rms}$$  \hspace{1cm} (38)

where $c_f$ is a function of bottom roughness scale (default is 0.015). The eddy-viscosity model of Madsen et al., (1988) is expressed by:

$$c_b = f_w \frac{g}{\sqrt{2}} U_{rms}$$  \hspace{1cm} (39)

where $f_w$ is a non-dimensional friction parameter (default 0.05) expressed as a function of roughness height by Jonsson’s (1966) semi-empirical model. The full parameterisations of all formulations are provided by, for example, Holthuijsen (2007).
3.4.4 Depth-induced wave breaking

The process of depth-induced wave breaking ($S_{surf}$) is modelled based on a spectral version of Battjes and Janssen’s (1978) bore-based breaker model, from Eldeberky and Battjes (1978).

$$S_{surf} = \frac{D_{tot}}{E_{tot}} E(\sigma, \theta)$$  \hspace{1cm} (40)

where $E_{tot}$ stands for total spectral energy and $D_{tot}$ stands for mean rate of energy dissipation per unit horizontal area owing to depth-induced wave breaking (Battjes and Janssen, 1978). Alternatives to Battjes and Janssen’s (1978) bore-based breaker form are proposed by Thornton and Guza (1983).

3.4.5 Non-linear wave-wave interactions

The shape and development of wind-wave spectrums are largely controlled by nonlinear wave-wave interactions, which transfer spectral energy between different frequency bands (Figure 3.4). In deep water, quadruplet wave-wave interactions ($S_{nl4}$) control:

1) The shape stabilisation of high-frequency bands;
2) The downshift of energy to lower frequency bands;
3) The frequency-dependent redistribution of $D(\theta; f)$;

The computations of quadruplet wave-wave interactions is carried out by SWAN using a discrete-interaction approximation method (DIA) of Hasselmann et al., (1985). In very shallow waters, triad wave-wave interactions ($S_{nl3}$) transfer spectral energy from lower frequency to higher frequency bands. The parameterisation of such effects is made with a lumped triad approximation (LTA) of Eldeberky (1996). The Stochastic Parametric model, based on the Boussinesq-type wave equations (SPB) is now also available.

3.5 Initial model setup

The third generation, nonstationary SWAN Cycle III version 40.72A was run on parallel mode with nautical convention and spherical coordinates, using a second-order
upwind scheme with third-order diffusion. The activated nonlinear physical processes were quadruplets and triads wave-wave interactions according to Hasselmann (1985) and Eldeberky (1996), respectively. The linear wind growth was based on Cavaleri and Malanotte-Rizzoli (1985). The exponential wind growth was that proposed by Komen et al., (1984) combined with Hasselmann’s (1974) pulse-based dissipation for whitecapping. The bottom friction dissipation was described with Hasselmann’s (1985) formulation, whilst wave breaking was based on Battjes and Janssen’s (1978) model.

The effect of tides was neglected because a study led by Mortlock et al., (2013) had previously demonstrated that providing measured hourly tide measurements to SWAN has marginal effects on its modelled wave outputs along New South Wales. The effects of currents and diffraction were also neglected.

3.5.1 Model discretisation

The directional space of SWAN was discretised using 72 equally spaced directions from 0 to 360°, with a directional resolution of \( \Delta \theta = 5^\circ \). The directional resolution was selected small enough to discretise swells with relatively small directional spreading. The frequency space of SWAN was discretised at 46 linearly spaced frequency bands, between 0.033 and 0.5 Hz at intervals of \( \Delta f = 0.1f \). The time step of SWAN was chosen to match that of wave and wind forcing fields and hence \( \Delta t = 60 \) min.

Hotstart files were used by SWAN every time when passing from one time step of simulations to another. The model spin-up time was 15 hours. The stopping convergence criterion of SWAN was its default gradient-based convergence method. The number of iterations was changed from 1 to 4 to provide superior numerical accuracy at every model time step. The hindcasted wave outputs from SWAN were requested as spectrally integrated wave parameters, written at hourly intervals for all computational grids. The nautical convention with North corresponding to 0° measured clockwise was used for directional outputs.

3.5.2 Computational grids

The computational grid of SWAN was a curvilinear orthogonal grid extending from 26° to 38° S (approximately 1700 km) and from 149.6° to 153.9° E, from 50 up to circa 80 km offshore (Figure 3.5). The coarse regional grid was designed so that each exter-
nal boundary of SWAN coincided with specific points at which spectral wave data had been previously selected from NWW3 spatial grid. Hence, no spatial interpolation of spectral wave data was necessary at open wave boundary of SWAN. The along-shore boundary was defined sufficiently far away from shore so that wave-bottom interactions did not yet affect wave propagation and to provide sufficient time for SWAN to adapt new boundary condition data to its own physics. The spatial resolution was set based on water depth and progressively decreased shoreward from a maximum $\Delta x, \Delta y$ of approximately 10 km offshore to a minimum $\Delta x, \Delta y$ of about 1 km within water depths of 0 to 100 m (Table 3.1).

Table 3.1 - The features of SWAN computational grids and wind input grid.

<table>
<thead>
<tr>
<th>Grids</th>
<th>North (°)</th>
<th>South (°)</th>
<th>East (°)</th>
<th>West (°)</th>
<th>$\Delta x - \Delta y$ (°)</th>
<th>$n_{gx} \times n_{gy} = np$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>-26.0</td>
<td>-38.3</td>
<td>153.9</td>
<td>149.6</td>
<td>0.1–0.01</td>
<td>$25 \times 288 = 6888$</td>
</tr>
<tr>
<td>Nested</td>
<td>-31.5</td>
<td>-34.1</td>
<td>153.0</td>
<td>151.0</td>
<td>0.1–0.005</td>
<td>$28 \times 379 = 1206$</td>
</tr>
<tr>
<td>Wind</td>
<td>-24.1</td>
<td>-39.8</td>
<td>155.0</td>
<td>148.1</td>
<td>0.312</td>
<td>$51 \times 23 = 1773$</td>
</tr>
</tbody>
</table>

The coarse regional grid simulations of SWAN were used as wave boundary conditions (full directional spectra) for a nested curvilinear grid defined from Port Macquarie to Sydney for water depths between 100 and 0 m (Figure 3.5). Analyses of wave energy data from Hughes and Heap (2010) suggested that such region is endowed with higher deep-water wave energy levels than other stretch of coasts from Queensland to New South Wales.
The nested grid was designed with varying spatial resolution that gradually decreased shoreward from approximately 1 km to 500 m along both x and y directions. The highest refinement factor between grid steps was defined to be 3, ensuring smooth transitions between consecutive grid steps. The grids thus supported more detailed wave simulations based on higher-resolution bathymetry that can significantly affect wave transformation processes especially in shallow waters.
3.5.3 Bathymetry data

Low quality model bathymetry has been historically reported to be a limiting factor to generate accurate computations with SWAN (Provost and Lyard, 2002). The area of study has a steep, narrow continental shelf with high-seabed gradients that needed to be properly resolved (see Webb and Kulmar, 1990). Hence, a validated, high-quality 9 arc second (~ 250 m) topobathymetric dataset was used, provided by a partnership project between Geoscience Australia and the Australia’s National Oceans Office (Whiteway, 2009). The raw xyz-scatter data was transferred to QUICKIN and bilinearly interpolated onto bottom input grids that matched SWAN computational grids (Figure 3.5), as suggested by the SWAN Manual (2008).

3.5.4 Wind forcing

The ability to generate high-quality hindcasts with SWAN has historically been limited by a lack of suitably high-resolution winds with which to force it. Consequently, selecting an accurate wind source is a necessary step to obtain reliable wave simulations. Cardno (2012) found that the most accurate representation of historical wind fields off Australia’s southeastern coast is derived from NCEP (National Centers for Environmental Prediction) Climate Forecast System Reanalysis (CFSR) database.

The recently completed CFSR reanalysis product developed by Saha et al., (2012) provided a great opportunity to drive SWAN with high spatial and temporal resolution winds. The product consisted of hourly surface winds gridded on a 0.312° spatial grid resolution between 1979 and 2010, representing a significant upgrade compared to older NCEP reanalysis datasets. It also has much finer spatial resolution as opposed to its former version (0.2°) and considers more atmospheric vertical layers (64 as opposed to 28). The hourly gridded eastward and northward wind speed components from CFSR database acquired at an elevation of 10 m were provided to SWAN on a rectangular grid with 0.312° spatial resolution (Table 3.1 and 3.2).
Table 3.2 – Different sources of wind forcing available. The chosen product is highlighted using red colour.

<table>
<thead>
<tr>
<th>Product</th>
<th>Source</th>
<th>Period</th>
<th>Spatial resolution (°)</th>
<th>Temporal Resolution (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA−40</td>
<td>ECMWF</td>
<td>1957–2002</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>ECMWF</td>
<td>1979–Present</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>NCEP1</td>
<td>NCEP/NCAR</td>
<td>1948–Present</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>NCEP2</td>
<td>NCEP/DOE</td>
<td>1979–Present</td>
<td>2.5</td>
<td>6</td>
</tr>
<tr>
<td>JRA−25</td>
<td>JMA</td>
<td>1979–Present</td>
<td>1.25</td>
<td>6</td>
</tr>
<tr>
<td>MERRA</td>
<td>NASA</td>
<td>1979–Present</td>
<td>0.5 × 0.66</td>
<td>1</td>
</tr>
<tr>
<td>CFSR</td>
<td>NCEP</td>
<td>1979–2014</td>
<td>0.312</td>
<td>1</td>
</tr>
<tr>
<td>ACCESS-R</td>
<td>BOM</td>
<td>2012–Present</td>
<td>0.11</td>
<td>6</td>
</tr>
</tbody>
</table>

3.5.5 Wave boundary conditions

The region of study experiences waves originating from a large range of directions. Hence, multi-peaked spectral sea states composed of high-frequency wind seas and low-frequency swells with different directions often subsist (Figure 3.6). These mixed sea states cannot be accurately described based on spectrally integrated wave parameters (Hemer and Griffin, 2010). For example, using $T_m$ to define a bimodal sea state might be non-sensical, as $T_m$ merges together two totally different spectral wave peaks. Several authors have stated that neglecting multimodal spectral seas by driving SWAN with synthesised spectra, as opposed to full directional spectra, leads to a reduction in model performance (Mackay et al., 2010; Robertson et al., 2014).

![Figure 3.6 – Examples of multi-peaked (left) (5/12/2009 18:00:00 PM) and bimodal (right) (14/6/2000 12:00:00 PM) directional wave spectra from NWW3 grid points with coordinates 152.8E, 32.93S and 151.2E, 35.6S respectively. The radial frequency axis goes from 0.038 Hz (center of the plot) to 0.5 Hz (outside edge of the plot).]
To better describe mixed wave sea-states, SWAN was hence forced with full spectral boundary conditions from a 30-year period wave hindcast completed by CAWCR (Centre for Australian Weather and Climate Research). The CAWCR product shows higher spatial resolution and temporal resolution compared to other accessible products (Table 3.3). The CAWCR hindcast wave dataset was obtained from NWW3 latest version 4.08, which uses a new physics package developed by Ardhuin et al., (2010). The new terms consist of a swell dissipation term and a reformed wind-wave growth formulation based on Janssen (1991). Based on Durrant et al., (2014), such data is accurate at a reasonable distance from shore, thus providing confidence to be used as wave boundary conditions to drive finer scale models such as SWAN.

Table 3.3 – Different available hindcast that provide spectral data to which to force SWAN. The chosen product is highlighted using red colour.

<table>
<thead>
<tr>
<th>Wave dataset</th>
<th>Climate Model</th>
<th>Wave Model</th>
<th>Period</th>
<th>Spatial Resolution (°)</th>
<th>Temporal resolution (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERA–40 Wave (ECMWF)</td>
<td>ERA–40 Reanalysis</td>
<td>WAM</td>
<td>1957–2002</td>
<td>1.5 × 1.5</td>
<td>6</td>
</tr>
<tr>
<td>WAVEWATCH III (NOAA-MMAB)</td>
<td>NCEP–CFSR Reanalysis</td>
<td>WW3 v2.22</td>
<td>1997–2010</td>
<td>1.25 × 1</td>
<td>6</td>
</tr>
<tr>
<td>CAWCR Hindcast (CSIRO/BOM)</td>
<td>NCEP–CFSR Reanalysis</td>
<td>WW3 v4.08</td>
<td>1979–2010</td>
<td>0.5 × 0.5</td>
<td>1</td>
</tr>
<tr>
<td>CAWCR Extension (CSIRO/BOM)</td>
<td>NCEP–CFSR v2 Forecast</td>
<td>WW3 v4.08</td>
<td>2011–2013</td>
<td>0.5 × 0.5</td>
<td>1</td>
</tr>
</tbody>
</table>

The directional spectra time series were applied to SWAN along its coarse regional grid (at 0.5° spatial resolution) at hourly intervals from February 1979 to December 2009. The raw CAWCR spectral data was discretised over 29 frequencies exponentially spaced from 0.038 Hz to 0.5 Hz and 24 directions with 15° directional resolution. The month of January 1979 is a model spin-up period and was not considered. The NWW3 grid nodes from which directional spectral outputs were extracted to force SWAN were selected based on a balance between water depth and distance to shore always attempting to reduce computational costs. The geographical locations of such points are shown in Figure 3.7. The alongshore boundary conditions of SWAN were spectral wave data
from deepwater grid nodes, whilst cross-shore boundary conditions were unavoidably taken from grid nodes located at deep and shallow water.

Figure 3.7 – The NWW3 and CFSR grid points, from which wave and wind data was selected to force SWAN.
3.5.6 Simulation process

The usage of files for spectral input takes SWAN a longer computational time compared to any other form of wave boundary input. Simulating 30 years of wave states at intervals of 1 hour requires 262,800 simulations for each computational grid of SWAN. The model had to read and process multiple spectral and wind input files with data between 1979 and 2009 in addition to writing wave output parameters on all computational grids.

Initial tests showed that was not practical to run SWAN continuously for a time period greater than 2 years, due to computer memory and processor constraints. The simulation period of 30 years was therefore divided into several shorter sub-periods of 12 weeks each requiring a computation time of 15 h each. Hence, SWAN was run for 124 sub-periods times with hot start files used every time when passing from one sub-period to another (Figure 3.8).

![Diagram of file generation and simulation process](image)

Figure 3.8 - File generation and simulation process over 31 years broken up into 124 lots of 12 weeks to overcome computer memory limitations.
Chapter 4

4 SWAN calibration & validation

4.1 Introduction

The SWAN model described during Chapter 3 was calibrated and validated against waverider buoy data from various locations off southeast Queensland and New South Wales. The calibration procedure enabled examining model sensitivity to a range of physical and numerical parameters. The calibrated SWAN was then validated against buoy measurements corresponding to a different period to that used for model calibration. The potential sources of modelling error are also identified and discussed below.
4.2 Waverider buoy data

The period of time, and number and location of points at which SWAN is calibrated and validated are determinant factors that need to be considered to build a reliable model. For example, sensitivity analyses and model calibrations conducted for only a few deep-water points might lead to misleading conclusions, particularly for nearshore shelf waters. Additionally, a model validation over a period of time where sea state variations are relatively small is also likely to give misleading indicators of model performance.

Therefore, wave measurements derived from 6 directional and 5 non-directional waverider buoys located off Southern Queensland and New South Wales were used to calibrate and validate SWAN (Table 4.1). The buoy datasets were obtained from Queensland’s Department of Science, Information Technology, Innovation and Arts and New South Wales’s Office of Environment and Heritage and were delivered by Coastal Impacts Unit-Science Delivery Division and Manly Hydraulics Laboratory, respectively. They consisted of time-series with hourly observations of significant wave height, peak period and mean wave direction, during June 2000 and December 2009 (Table 4.1).

<table>
<thead>
<tr>
<th>Buoy station</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (m)</th>
<th>Source</th>
<th>Parameters measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mooloolaba</td>
<td>26.56 S</td>
<td>153.18 E</td>
<td>33</td>
<td>DSITIA</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Brisbane</td>
<td>27.48 S</td>
<td>153.63 E</td>
<td>76</td>
<td>DSITIA</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Gold Coast</td>
<td>27.96 S</td>
<td>153.44 E</td>
<td>18</td>
<td>DSITIA</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Tweed Heads</td>
<td>28.18 S</td>
<td>153.57 E</td>
<td>23</td>
<td>DSITIA</td>
<td>$H_s, T_p$</td>
</tr>
<tr>
<td>Byron Bay</td>
<td>28.82 S</td>
<td>153.72 E</td>
<td>62</td>
<td>OEH</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Coffs Harbour</td>
<td>30.36 S</td>
<td>153.27 E</td>
<td>72</td>
<td>OEH</td>
<td>$H_s, T_p$</td>
</tr>
<tr>
<td>Crowdy Head</td>
<td>31.82 S</td>
<td>152.85 E</td>
<td>79</td>
<td>OEH</td>
<td>$H_s, T_p$</td>
</tr>
<tr>
<td>Sydney</td>
<td>33.78 S</td>
<td>151.42 E</td>
<td>85</td>
<td>OEH</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Port Kembla</td>
<td>34.47 S</td>
<td>151.02 E</td>
<td>80</td>
<td>OEH</td>
<td>$H_s, T_p$</td>
</tr>
<tr>
<td>Batemans Bay</td>
<td>35.71 S</td>
<td>150.34 E</td>
<td>73</td>
<td>OEH</td>
<td>$H_s, T_p, \theta_m$</td>
</tr>
<tr>
<td>Eden</td>
<td>37.30 S</td>
<td>150.18 E</td>
<td>100</td>
<td>OEH</td>
<td>$H_s, T_p$</td>
</tr>
</tbody>
</table>

The period of calibration (December 2009) was selected as encompassed a wide range comprised of mixed a range of sea states with $H_s$ varying between 0.5 and 3 m (low to mild wave energetic conditions) with a prevalent southeasterly direction. The period of validation (June 2000) also consisted of mixed wind sea and swell, nevertheless, with a broader variety of significant wave heights ranging between 0.5 and 6 m (low to highly energetic conditions).
These specific periods were selected because they contained a wide range of wave sea states (i.e. low energy to high energy), which mirror the range of conditions observed in the long-term wave climate off Australia’s southeastern coast (Shand et al., 2011; Kulmar et al., 2013). It is noted that extreme events have a low probability and therefore have little bearing on the long-term statistics that this thesis is focused on (cf. page 41, section 3.2). The length of calibration and validation periods was selected based on an wide literature review presented in Table 4.2.

Table 4.2 - Typical time length used by researchers to calibrate and validate wave models.

<table>
<thead>
<tr>
<th>References</th>
<th>Model</th>
<th>Region</th>
<th>Calibration (days)</th>
<th>Validation (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moeini and Etemad-Shahidi (2007)</td>
<td>SWAN</td>
<td>Lake Erie (USA)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Rusu, Pilar and Soares (2008)</td>
<td>SWAN</td>
<td>Iberian Coast</td>
<td>31</td>
<td>&lt;91</td>
</tr>
<tr>
<td>Rusu and Soares (2009)</td>
<td>SWAN</td>
<td>Portugal</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Iglesias and Carballo (2010a)</td>
<td>SWAN</td>
<td>Asturias (Spain)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Iglesias and Carballo (2010b)</td>
<td>SWAN</td>
<td>Bay of Biscay (Spain)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Iglesias and Carballo (2011)</td>
<td>SWAN</td>
<td>Galicia (Spain)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Stopa et al., (2011)</td>
<td>WRFa</td>
<td>Hawaii (USA)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Saket and Etemad-Shahidi (2012)</td>
<td>SWAN</td>
<td>Persian Gulf (Iran)</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Akpınar and Kümürcü (2013)</td>
<td>SWAN</td>
<td>Black Sea</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Ching-Piao et al. (2013)</td>
<td>SWAN</td>
<td>Taiwan</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Kamranzad et al., (2013)</td>
<td>SWAN</td>
<td>Persian Gulf (Iran)</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Zheng et al., (2013)</td>
<td>WW3</td>
<td>China</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Liang et al., (2013)</td>
<td>SWAN</td>
<td>Shandong (China)</td>
<td>&lt;62</td>
<td>&lt;62</td>
</tr>
<tr>
<td>Robertson et al., (2014)</td>
<td>WRFa</td>
<td>Vancouver (Canada)</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Pallares et al., (2014)</td>
<td>WRFa</td>
<td>Catalan Coast (Spain)</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Hadadpour et al., (2014)</td>
<td>SWAN</td>
<td>Caspian Sea</td>
<td>31</td>
<td>31</td>
</tr>
<tr>
<td>Mirzaei et al., (2015)</td>
<td>WW3</td>
<td>Malaysia</td>
<td>90</td>
<td>90</td>
</tr>
</tbody>
</table>

4.3 Calibration

The calibration of SWAN was achieved by minimising errors in $H_s$, which is consid-
ered to be a more significant parameter than wave period (Hemer and Griffin, 2010). The calibration was conducted using the regional grid to ensure that accurate boundary conditions are provided to SWAN nested grid. The sensitivity analysis comprised testing various numerical and physical parameters including:

- physical settings: wind growth, whitecapping formulation, rate of whitecapping dissipation, bottom friction, radiation stress, diffraction;
- numerical settings: numerical scheme, convergence criteria;
- wave boundary input: boundary limits, type of boundary, number of input points;
- resolution: grid resolution, regular grid, time step, directional resolution;
- computational cluster: number of computational nodes;

The sensitivity analysis simulations were compared with measurements from December 2009. The buoy moored off Batemans Bay was not considered for calibration, due to insufficient data in this period. The same variety of model fit statistics adopted by Nieuwkoop et al., (2013) was used for a quantitative evaluation of SWAN. The model bias,

\[ \text{bias} = \sum_{i=1}^{N} \frac{1}{N} (X_i - Y_i) \]  

where \( N \) stands for total number of data points, \( Y_i \) is the measured data and \( X_i \) is the simulated data. The scatter index,

\[ SI = \frac{\sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i)^2}}{\frac{1}{N} \sum_{i=1}^{N} Y_i} \times 100 \]  

and root mean square error,

\[ e_{rmse} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i)^2} \frac{1}{N} \]  

The statistical analysis of \( \theta_m \) was conducted based on \( e_{rmse} \) and absolute difference, because \( \theta_m \) is a circular parameter (Nieuwkoop et al., 2013):
\[ \text{difference} = \frac{1}{N} \sum_{i=1}^{N} 180 - |180 - |Y_i - X_i|| \]  

(44)

4.3.1 Model sensitivity to numerical settings

Initially, a sensitivity analysis of SWAN computational results to numerical settings was conducted. In order to verify a grid-independent solution a computational grid with doubled spatial resolution was tested. The spatial grid refinement marginally affected SWAN in terms of numerical accuracy, but required a significantly longer computation time. Curiously, Cardno (2012) had also observed that SWAN was not sensitive to grid refinements for spatial resolutions higher than 5 km. The SWAN original host grid was hence kept for further simulations.

Model sensitivity to temporal resolution was also tested, namely \( \Delta t = 10, 15 \) and 30 min. However, a 60 min time step was observed to be enough to resolve both wave and wind fields, since no tides or water depth time variations were considered. The directional resolution was kept as 5° (the optimal value) because lower resolutions typically yield unrealistic wave field gradients (also called ‘scintillation’ effect) (Delft Hydraulics, 2007).

4.3.2 Model sensitivity to physical settings

4.3.2.1 Wind-induced wave growth

The wind growth \( S_{in} \) was initially tested using default coefficient parameters for:

(a) Komen et al.’s., (1984) model according to equation (25).

(b) Janssen’s (1991) model according to equation (26).

(c) Yan’s (1987) model according to equation (27).

The cumulative wave steepness method of Vledder and Hurdle (2004) was not verified because it requires twice as much computational time as Komen et al.’s., (1984) equation and is hence not appropriate for long-term numerical simulations (Moeini and Etemad-Shahidi (2007). Time series comparing all different wind growth expressions against wave measurements are presented in Figure 4.1. Initial calibration runs based on
default parameters showed that Janssen’s (1991) model did not yield realistic computations and hence equation (26) was not considered for further simulations with SWAN.

Figure 4.1 - Time series of computed $H_s$ against in-situ observations various wind growth–whitecapping formulations, during calibration (December 2009). Red dashed line corresponds to Komen’s equation, green dashed line to Westhuysen’s equation (default), pink dotted line to Westhuysen’s equation with $C_{ds} = 2 \times 10^{-4}$, blue line to Westhuysen’s equation with $C_{ds} = 4 \times 10^{-4}$ and black dots to waverider buoy data.
The wind parameterisations from Komen et al., (1984) and Yan (1987) (combined with Westhuysen et al., 2007) performed similarly against wave buoy measurements. The best fit between simulated and measured data at all buoy sites was, however, provided by Yan (1987) coupled to Westhuysen et al.’s, (2007) nonlinear saturation-based model (Table 4.3). Komen et al., (1984) parameterisation led to a consistent overestimation of significant wave heights (Figure 4.1 and bias results in Table 4.3). These findings agree with previous research which showed that expression (25) over predicts wind seas when a background swell is present (Mulligan et al., 2008; Robertson et al., 2014).

Table 4.3 - Sensitivity of modelled significant wave height to choice of wind-induced wave growth-whitecapping formulation during the calibration period 1–31/12/2009.

<table>
<thead>
<tr>
<th>Buoy name</th>
<th>Komen</th>
<th>Yan-Westhuysen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bias (m)</td>
<td>SI  (%)</td>
</tr>
<tr>
<td>Mooloolaba (N = 744)</td>
<td>0.22</td>
<td>25.4</td>
</tr>
<tr>
<td>Brisbane (N = 707)</td>
<td>0.33</td>
<td>36.6</td>
</tr>
<tr>
<td>Gold Coast (N = 742)</td>
<td>0.07</td>
<td>17.6</td>
</tr>
<tr>
<td>Tweed Heads (N = 742)</td>
<td>0.10</td>
<td>18.1</td>
</tr>
<tr>
<td>Byron Bay (N = 406)</td>
<td>0.34</td>
<td>38.2</td>
</tr>
<tr>
<td>Coffs Harbour (N = 590)</td>
<td>0.25</td>
<td>28.0</td>
</tr>
<tr>
<td>Crowdys Head (N = 667)</td>
<td>0.05</td>
<td>27.9</td>
</tr>
<tr>
<td>Sydney (N = 671)</td>
<td>0.16</td>
<td>27.5</td>
</tr>
<tr>
<td>Port Kembla (N = 586)</td>
<td>0.17</td>
<td>25.9</td>
</tr>
<tr>
<td>Eden (N = 743)</td>
<td>0.25</td>
<td>30.6</td>
</tr>
<tr>
<td>Mean</td>
<td>0.27</td>
<td>27.6</td>
</tr>
</tbody>
</table>

Mulligan et al., (2008) observed that Komen et al.’s., (1984) whitecapping dissipation term (25) is strongly weighted by $\vec{k}$ (spectrally mean wave number) and hence swell energy has a great effect on dissipation of wind seas (Mulligan et al., 2008). In contrast, Westhuysen et al.’s., (2007) saturation-based model treats whitecapping of wind seas locally (spectrally local wave number) and so high-frequency waves are no longer affected by low-frequency swells (Mulligan et al., 2008). The nonlinear saturation-based equation was thus selected to carry further simulations with SWAN.

4.3.2.2 Whitecapping dissipation

The nonlinear saturation-based whitecapping dissipation model was tuned by adjust-
ing \( C_{ds} \), which has proven to be successful at calibrating wave height simulations with SWAN (e.g. Yang et al., 2011; Rusu and Onea, 2013). The rate of whitecapping dissipation was enhanced by means of a larger proportionally coefficient to increase energy dissipation at high and low frequency bands. In order to ensure that a reasonable rate of whitecapping dissipation was used, two proportionality coefficients that lead to a \( \Gamma \) consistent with Komen et al.’s, (1984) function were tested, namely \( 2 \times 10^{-4} \) and \( 4 \times 10^{-4} \):

\[
\Gamma = C_{ds} \left( \frac{\bar{s}}{\overline{s_{PM}}} \right)^4
\]  

(45)

In comparison, Yang et al., (2011) used a value of \( 2 \times 10^{-4} \) for similar wave conditions. The increase of white-capping dissipation due to a greater proportionally coefficient led to a superior fit between simulated and measured data. The qualitative effects of both modifications are presented in Figure 4.1. Table 4.4 shows that both values lead to very similar error metrics (equal average metrics), however, a coefficient of \( 4 \times 10^{-4} \) yielded slightly better simulated results and was adopted for further simulations.

<table>
<thead>
<tr>
<th>Site</th>
<th>( C_{ds} = 2 \times 10^{-4} )</th>
<th>( C_{ds} = 4 \times 10^{-4} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bias</td>
<td>SI</td>
</tr>
<tr>
<td>Mooloolaba (N = 744)</td>
<td>0.01</td>
<td>17.2</td>
</tr>
<tr>
<td>Brisbane (N = 707)</td>
<td>0.04</td>
<td>24.8</td>
</tr>
<tr>
<td>Gold Coast (N = 742)</td>
<td>-0.08</td>
<td>17.1</td>
</tr>
<tr>
<td>Tweed Heads (N = 742)</td>
<td>-0.05</td>
<td>15.1</td>
</tr>
<tr>
<td>Byron Bay (N = 406)</td>
<td>0.13</td>
<td>26.4</td>
</tr>
<tr>
<td>Coffs Harbour (N = 590)</td>
<td>0.04</td>
<td>18.4</td>
</tr>
<tr>
<td>Crowdy Head (N = 667)</td>
<td>-0.10</td>
<td>27.1</td>
</tr>
<tr>
<td>Sydney (N = 671)</td>
<td>-0.07</td>
<td>24.0</td>
</tr>
<tr>
<td>Port Kembla (N = 586)</td>
<td>-0.06</td>
<td>21.6</td>
</tr>
<tr>
<td>Eden (N = 743)</td>
<td>-0.01</td>
<td>22.5</td>
</tr>
<tr>
<td>Mean</td>
<td>21.4</td>
<td>0.28</td>
</tr>
</tbody>
</table>

### 4.3.2.3 Bottom friction

The bottom friction dissipation \( S_{bot} \) was tested based on equation (35) with:

(a) Hasselmann’s (1973) bottom friction coefficient (36).
(b) Collins’s (1972) bottom friction coefficient (37).
(c) Madsen’s (1988) bottom friction coefficient (38).

Table 4.5 - Sensitivity of modelled significant wave height ($H_s$) to choice of bottom friction dissipation during the calibration period 1-31/12/2009.

<table>
<thead>
<tr>
<th>Buoy name</th>
<th>Hasselmann</th>
<th></th>
<th></th>
<th></th>
<th>Collins</th>
<th></th>
<th></th>
<th>Madsen</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>bias (m)</td>
<td>SI (%)</td>
<td>ermse (m)</td>
<td></td>
<td>bias (m)</td>
<td>SI (%)</td>
<td>ermse (m)</td>
<td>bias (m)</td>
<td>SI (%)</td>
<td>ermse (m)</td>
</tr>
<tr>
<td>Mooloolaba (N = 744)</td>
<td>0.00</td>
<td>17.2</td>
<td>0.19</td>
<td></td>
<td>0.02</td>
<td>17.3</td>
<td>0.19</td>
<td>0.00</td>
<td>17.2</td>
<td>0.19</td>
</tr>
<tr>
<td>Gold Coast (N = 742)</td>
<td>-0.09</td>
<td>17.4</td>
<td>0.17</td>
<td></td>
<td>-0.07</td>
<td>16.3</td>
<td>0.16</td>
<td>-0.12</td>
<td>19.5</td>
<td>0.19</td>
</tr>
<tr>
<td>Tweed Heads (N = 742)</td>
<td>-0.06</td>
<td>15.5</td>
<td>0.16</td>
<td></td>
<td>-0.03</td>
<td>14.8</td>
<td>0.15</td>
<td>-0.14</td>
<td>20.2</td>
<td>0.21</td>
</tr>
<tr>
<td>Mean</td>
<td>16.7</td>
<td>0.17</td>
<td>16.1</td>
<td>0.17</td>
<td>19.0</td>
<td>0.20</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The bottom friction is considered to be a transitional to shallow water physical process, and thus only Mooloolaba, Gold Coast and Tweed Heads buoys were used for assessing model performance. The different proposed bottom friction coefficients were observed to have marginal effects on SWAN simulated wave heights simulations (Figure 4.2). The best comparison for simulated $H_s$ were yet was obtained with using Collins’s (1972) coefficient according to equation (37), which was hence kept used for further simulations with SWAN (Table 4.5). No further optimisation of friction coefficients was performed.
Figure 4.2 - Time series of computed $H_s$ against in-situ observations for transitional and shallow water sites using three bottom friction formulations, during calibration (December 2009). Blue line corresponds to Hasselmann’s equation, red dashed line to Collins’s equation, green dashed line to Madsen’s equation and black dots to waverider buoy data.

4.4 Summary of calibrated model parameters

Model calibration and sensitivity analysis were conducted by comparing simulated significant wave heights against observations from multiple inner and mid-shelf wave rider buoys. The model was observed to be most sensitive to the choice wind growth and whitecapping dissipation formulations and also the rate of whitecapping dissipation, in agreement with previous studies (e.g. Moeini and Etemad-Shahidi, 2007; Saket and Etemad-Shahidi, 2012; Kamranzad et al., 2013; Hadadpour and Etemad-Shahidi, 2014).

The wind growth of Yan (1987) coupled with Westhuysen et al.’s, (2007) nonlinear saturation-based whitecapping model was observed to provide the best results. The rate
of whitecapping dissipation was tuned using a proportionally coefficient to obtain the best-fit agreement between simulated and measure datasets. Consistent with Cardno (2012) and Mortlock et al., (2012), SWAN was largely insensitive to bottom friction with the formulation of Collins (1972) providing the best results.

### 4.5 Model validation

The calibrated model was validated against buoy data for the month of June 2000 (Figure 4.3). The buoy off Crowdy Head was excluded from validation due to insufficient data during this period. The calibrated model provided reasonable agreement with measured $H_s$ data, only underestimating measurements by only a few per cent (Table 4.6). The statistical errors obtained suggest that SWAN performed somewhat marginally better during calibration than during validation, especially for nearshore buoy locations (Table 4.6 and Table 4.7).

<table>
<thead>
<tr>
<th>Buoy name</th>
<th>Bias ($m$)</th>
<th>SI (%)</th>
<th>ermse ($m$)</th>
<th>Bias ($s$)</th>
<th>SI (%)</th>
<th>ermse ($s$)</th>
<th>diff. ($^\circ$)</th>
<th>ermse ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mooloolaba ($N = 718$)</td>
<td>-0.02</td>
<td>22.9</td>
<td>0.29</td>
<td>0.11</td>
<td>22.1</td>
<td>2.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brisbane ($N = 719$)</td>
<td>-0.03</td>
<td>24.1</td>
<td>0.39</td>
<td>0.02</td>
<td>17.9</td>
<td>1.70</td>
<td>20.4</td>
<td>24.7</td>
</tr>
<tr>
<td>Gold Coast ($N = 721$)</td>
<td>0.02</td>
<td>27.5</td>
<td>0.25</td>
<td>-0.02</td>
<td>22.5</td>
<td>2.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tweed Heads ($N = 718$)</td>
<td>-0.04</td>
<td>22.0</td>
<td>0.26</td>
<td>0.16</td>
<td>18.9</td>
<td>1.83</td>
<td>11.4</td>
<td>14.3</td>
</tr>
<tr>
<td>Byron Bay ($N = 620$)</td>
<td>-0.00</td>
<td>25.8</td>
<td>0.43</td>
<td>-0.25</td>
<td>15.4</td>
<td>1.47</td>
<td>19.8</td>
<td>28.0</td>
</tr>
<tr>
<td>Coffs Harbour ($N = 718$)</td>
<td>-0.09</td>
<td>24.4</td>
<td>0.41</td>
<td>-0.06</td>
<td>18.7</td>
<td>1.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney ($N = 684$)</td>
<td>-0.02</td>
<td>21.4</td>
<td>0.30</td>
<td>-0.73</td>
<td>24.5</td>
<td>2.58</td>
<td>32.7</td>
<td>32.7</td>
</tr>
<tr>
<td>Port Kembla ($N = 696$)</td>
<td>-0.00</td>
<td>24.7</td>
<td>0.32</td>
<td>-0.72</td>
<td>22.0</td>
<td>2.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batemans Bay ($N = 718$)</td>
<td>-0.06</td>
<td>29.6</td>
<td>0.39</td>
<td>-0.64</td>
<td>22.2</td>
<td>2.28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eden ($N = 673$)</td>
<td>-0.10</td>
<td>25.9</td>
<td>0.40</td>
<td>-0.33</td>
<td>26.3</td>
<td>2.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>24.9</td>
<td>0.34</td>
<td>21.0</td>
<td>2.09</td>
<td>18.2</td>
<td>24.9</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.7 – Summary of statistical errors in the model-data comparison for the calibration period: 1-31/12/2009.

<table>
<thead>
<tr>
<th>Buoy name</th>
<th>Bias ($m$)</th>
<th>SI (%)</th>
<th>ermse ($m$)</th>
<th>Bias ($s$)</th>
<th>SI (%)</th>
<th>ermse ($s$)</th>
<th>diff. ($^\circ$)</th>
<th>ermse ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mooloolaba ($N = 744$)</td>
<td>0.02</td>
<td>17.3</td>
<td>0.19</td>
<td>0.24</td>
<td>24.6</td>
<td>1.94</td>
<td>17.0</td>
<td>22.5</td>
</tr>
<tr>
<td>Location</td>
<td>N</td>
<td>$H_s$ (m)</td>
<td>$H_{sp}$ (m)</td>
<td>$H_s - H_{sp}$ (m)</td>
<td>$H_s$ (m)</td>
<td>$H_{sp}$ (m)</td>
<td>$H_s - H_{sp}$ (m)</td>
<td>$H_s$ (m)</td>
</tr>
<tr>
<td>------------------------</td>
<td>-----</td>
<td>-----------</td>
<td>--------------</td>
<td>---------------------</td>
<td>-----------</td>
<td>--------------</td>
<td>---------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Brisbane (N = 707)</td>
<td>0.02</td>
<td>24.2</td>
<td>0.31</td>
<td>-0.16</td>
<td>19.5</td>
<td>1.67</td>
<td>20.1</td>
<td>28.1</td>
</tr>
<tr>
<td>Gold Coast (N = 742)</td>
<td>-0.07</td>
<td>16.3</td>
<td>0.16</td>
<td>0.07</td>
<td>22.9</td>
<td>1.92</td>
<td>14.2</td>
<td>18.3</td>
</tr>
<tr>
<td>Tweed Heads (N = 742)</td>
<td>-0.03</td>
<td>14.8</td>
<td>0.15</td>
<td>0.41</td>
<td>22.3</td>
<td>1.84</td>
<td>16.9</td>
<td>22.5</td>
</tr>
<tr>
<td>Byron Bay (N = 406)</td>
<td>0.11</td>
<td>25.6</td>
<td>0.32</td>
<td>0.14</td>
<td>25.6</td>
<td>2.09</td>
<td>20.1</td>
<td>28.1</td>
</tr>
<tr>
<td>Coffs Harbour (N = 590)</td>
<td>0.03</td>
<td>17.9</td>
<td>0.23</td>
<td>0.12</td>
<td>24.2</td>
<td>1.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crowdy Head (N = 667)</td>
<td>-0.01</td>
<td>27.1</td>
<td>0.41</td>
<td>0.00</td>
<td>22.7</td>
<td>1.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sydney (N = 671)</td>
<td>-0.09</td>
<td>24.1</td>
<td>0.35</td>
<td>-0.03</td>
<td>23.5</td>
<td>1.95</td>
<td>39.0</td>
<td>49.0</td>
</tr>
<tr>
<td>Port Kembla (N = 586)</td>
<td>-0.07</td>
<td>21.5</td>
<td>0.31</td>
<td>-0.06</td>
<td>23.6</td>
<td>1.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eden (N = 743)</td>
<td>-0.03</td>
<td>22.1</td>
<td>0.31</td>
<td>-0.04</td>
<td>25.1</td>
<td>2.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>19.1</td>
<td>0.27</td>
<td>23.4</td>
<td>1.93</td>
<td>21.2</td>
<td>28.1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.3 - Time series of computed $H_s$ against in-situ observations using the calibrated set during validation (June 2000).
4.6 Discussion

The significant wave height and timing of swells were observed to be simulated competently by SWAN. The simulated $H_s$ exhibited a very small bias of less than 11 cm at deep and transitional buoy locations and less than 9 cm at nearshore locations. The other error metrics were also relatively good and showed greater model accuracy for nearshore sites than for deep-water sites, even though nearshore sites are closer to land, and so errors owing to wind input, shallow water processes, wave-current interactions and water level variations, are more likely to happen.

At offshore locations, SWAN simulated $H_s$ with a scatter index of 18–29% and a rmse of 0.23 to 0.41 m, whilst at nearshore buoy locations SWAN simulated wave heights more competently, showing a scatter index of 15 to 27% and of root mean squared error of 0.15 to 0.29 m. These statistical metrics compare well to findings of Komen et al., (1994), who suggested that a scatter index between 10 and 20% is the minimum scatter index that can be reached due to the randomness of the wind forcing field (Nieuwkoop et al., 2013). They also compare relatively well with Mortlock et al., (2012), who built and calibrated a nearshore SWAN model at Wamberal, NSW (with buoy data collected at 12 m water depth) reporting a bias of about 0.1 m and root mean squared error of 0.25 m in $H_s$.

The peak wave period was observed to be simulated competently by SWAN during June 2000 and December 2009. The measures of error were fairly similar at offshore and nearshore areas, exhibiting a bias from 0.02 to 0.7 s and a scatter index from 15 to 25% (Table 4.7). The mean wave direction was modelled with absolute differences between 18 and 21° and a root mean square error of 24 to 28°. These statistics also agree relatively well to those presented by Mortlock et al., (2014).

The error metrics estimated for wave height, peak period and mean wave direction are, by way of comparison, of similar quality to those of other wave hindcasts conducted for mixed multimodal sea states over periods of similar length (e.g. Rusu and Soares, 2008; Stopa et al., 2011; Liang et al., 2013; Appendini et al., 2015). Folley et al., (2012) suggests that the maximum allowable root mean square error ($H_s$ and $T_p$) for the purpose of site reconnaissance and project feasibility is 30%.

It is worth mentioning that a month of model calibration and validation was too short to properly capture extreme wave events and, even though such events are contained within CAWCR’s spectral data, SWAN may be less accurate when simulating swells with large wave heights and peak periods as suggested by Figure 4.1 and Figure...
4.3. However, such extreme events have, by definition, a low frequency of occurrence they will have negligible effects on long-term wave energy statistics which are the focus of this study (Kulmar et al., 2013; Mortlock and Goodwin, 2015). In addition, wave energy converters are not designed to operate efficiently during highly energetic seas and may even reduce to zero efficiency when devices enter survival mode (Cahill and Lewis, 2013).

Figure 4.4 - Time series of computed mean wave direction against observations using various wind growth-whitecapping parameters, during calibration (December 2009).

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4.7 Source of inaccuracy

4.7.1 Wind forcing

The CFSR reanalysis wind forcing data was examined as a possible source of error using measured wind speed and direction from three coastal weather stations acquired for both calibration and validation periods (Table 4.8). The measured wind speeds were transferred to an elevation above mean sea level of 10 m based on a wind profile power law used by Wood et al., (2007):

\[ U_{10} = U_z \left( \frac{10}{z} \right)^K \]  

(46)

where \( U_{10} \) stands for wind speed at 10 m elevation, \( U_z \) stands for wind speed at a given elevation \( z \) and \( K \) was assumed to be 1/7 for neutral atmospheric stability conditions. The comparison between CFSR reanalysis winds and observational winds from weather stations was done after spatial interpolation. The standard oceanographic convention was used for wind direction.

Table 4.8 - Coastal weather stations used to evaluate modelled CFSR winds. Distance denotes distance to the closest CFSR grid node and Method denotes method used to interpolate the CFSR grid data to the observation location. The source of data was BOM.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Lat (°)</th>
<th>Lon (°)</th>
<th>Height (m)</th>
<th>Distance (m)</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brisbane Aero</td>
<td>27.39 S</td>
<td>153.13 E</td>
<td>5</td>
<td>140</td>
<td>Nearest-neighbour</td>
</tr>
<tr>
<td>Gold Coast Seaway</td>
<td>27.93 S</td>
<td>153.42 E</td>
<td>4.2</td>
<td>1,272</td>
<td>Nearest-neighbour</td>
</tr>
<tr>
<td>Cape Byron AWS</td>
<td>28.63 S</td>
<td>153.63 E</td>
<td>95</td>
<td>13,540</td>
<td>Bilinear</td>
</tr>
<tr>
<td>Ballina Airport AWS</td>
<td>28.84 S</td>
<td>153.56 E</td>
<td>1.3</td>
<td>19,000</td>
<td>Bilinear</td>
</tr>
</tbody>
</table>

Figure 4.5 and Figure 4.6 shows that observed wind speed and direction were not properly represented by NCEP CFSR reanalysis surface winds displaying differences greater than 3 m/s and 50°, respectively. The statistical error derived from comparisons between reanalysis winds and wind observations for both hindcast periods are presented in Table 4.9. The range of errors from Table 4.9 is comparable to that reported by Chawla et al., (2013) for coastal areas. Based on Chawla et al., (2013), reanalysis winds
provided by CFSR display unresolved coastal topographic features and use linear spatial interpolations not being capable of properly accounting for land-sea transitions.

Table 4.9 - Statistical errors for wind speed (m/s) and wind direction (°) – reanalysis winds versus observed winds for 1-31/12/2009 and 1-30/06/2000.

<table>
<thead>
<tr>
<th>Station name</th>
<th>Wind speed</th>
<th>Wind direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias (m/s)</td>
<td>ermse (m/s)</td>
</tr>
<tr>
<td>Period: 1-31/12/2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brisbane Aero</td>
<td>-2.01</td>
<td>3.82</td>
</tr>
<tr>
<td>Gold Coast Seaway</td>
<td>-0.61</td>
<td>3.29</td>
</tr>
<tr>
<td>Cape Byron AWS</td>
<td>0.75</td>
<td>2.59</td>
</tr>
<tr>
<td>Period: 1-30/06/2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brisbane Aero</td>
<td>0.39</td>
<td>2.20</td>
</tr>
<tr>
<td>Gold Coast Seaway</td>
<td>1.76</td>
<td>2.98</td>
</tr>
<tr>
<td>Ballina Airport AWS</td>
<td>1.57</td>
<td>3.21</td>
</tr>
</tbody>
</table>

Kinsela et al. (2015) also suggested that reanalysis surface winds from NCEP CFSR suffer from reduced wind speed by 20% within 30 km from shore. The underestimation of wind speed is possibly linked to some under estimations of peak significant wave heights from larger wave events (Figure 4.3). Kinsela (2015) also confirmed that CFSR reanalysis wind lead to too much higher frequency wave energy, causing a systematic under prediction of wave periods (by around 0.5 to 1 second). In terms of wind direction Mortlock et al., (2012) demonstrated that reanalysis winds from NCEP CFSR have directional divergences compared to measured wind direction, carrying a directional wave bias.
Figure 4.5 - Comparison of wind speed (left) and direction (right) between weather stations and CFSR reanalysis product for December 2009 (oceanographic convention – direction towards which atmospheric winds are travelling with units of degrees clockwise from true North).

Figure 4.5 and Figure 4.6 also demonstrated that modeled wind speeds by CFSR were smoother than observed wind speeds. It is known that within close proximity from shore, wind fields are strongly disturbed by orographic land features and locally generated winds, with high spatial and temporal variability. Wood et al., (2012) showed that wind reanalysis products represented winds observed off Sydney (3 km offshore) poorly, not resolving variability for winds with a frequency of less than 2 days. The aforementioned smoothness is therefore possibly (to a limited extent) owing to CFSR reanalysis winds having a smoother temporal variation than observational winds, possibly neglecting short episodic locally generated winds. Research of Brown et al., (2013) proved that considering local wind variability on a sub-hourly time scale has great effect upon wave height simulations (difference of up to 35%) and modelled wave powers (difference of up to 56%).
Figure 4.6 - Comparison of wind speed (left) and direction (right) between weather stations and CFSR reanalysis product for June 2000 (oceanographic convention – direction towards which atmospheric winds are travelling with units of degrees clockwise from true North).

4.7.2 Wave forcing

The 31-year global wave hindcast used as wave boundary conditions had been validated against deepwater wave measurements and altimetry remote-sensed data by Dur rant et al., (2014). The buoys are maintained and owned by SOPAC and moored nearby Fiji. Table 4.10 shows a range of statistical errors derived from direct comparisons between model and buoy data. These errors demonstrate broad-scale agreement with those obtained by Durrant et al., (2014) from model and altimeter satellite comparisons along Australia’s southeast coast. Based on Table 4.10, wave parameters were hence acquired with model accuracy comparable to that of its wave boundary conditions suggesting that a forcing error of similar magnitude to that of Table 14 was expected.
Table 4.10 – Statistical errors for CAWCR $H_s$ and $T_p$ data (Durrant et al., 2014).

<table>
<thead>
<tr>
<th>Buoy station</th>
<th>bias (m)</th>
<th>ermse (m)</th>
<th>Buoy station</th>
<th>bias (s)</th>
<th>ermse (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>37 (N=2966)</td>
<td>-0.27</td>
<td>0.39</td>
<td>37 (N=2338)</td>
<td>0.24</td>
<td>2.35</td>
</tr>
<tr>
<td>152 (N=1052)</td>
<td>0.07</td>
<td>0.31</td>
<td>152 (N=944)</td>
<td>0.77</td>
<td>2.86</td>
</tr>
<tr>
<td>16 (N=6642)</td>
<td>-0.07</td>
<td>0.42</td>
<td>16 (N=1453)</td>
<td>1.89</td>
<td>3.50</td>
</tr>
<tr>
<td>32 (N=6360)</td>
<td>-0.27</td>
<td>0.42</td>
<td>32 (N=4785)</td>
<td>2.54</td>
<td>4.04</td>
</tr>
<tr>
<td>33 (N=4558)</td>
<td>-0.41</td>
<td>0.47</td>
<td>33 (N=4028)</td>
<td>1.26</td>
<td>3.34</td>
</tr>
<tr>
<td>41 (N=5563)</td>
<td>0.10</td>
<td>0.36</td>
<td>41 (N=4394)</td>
<td>2.00</td>
<td>3.89</td>
</tr>
<tr>
<td>52200 (N=50160)</td>
<td>-0.11</td>
<td>0.24</td>
<td>52200 (N=50038)</td>
<td>0.46</td>
<td>1.74</td>
</tr>
</tbody>
</table>
Chapter 5

5 Results and discussion

5.1 Introduction

The spatial and temporal distributions of wave energy resources were determined and analysed based on maps of wave energy resource magnitude, variability and reliability. These were derived from hourly time series of wave conditions hindcasted by SWAN between 1979 and 2010. The mapping of wave energy distribution helped to determine which region has most consistent wave energy resources.

The results from SWAN nested grid was used to map nearshore wave power potential and identify promising hotspots for deploying WEC farms. The wave power potential was characterized using:
- Box and whisker plots of $E_f$;
- Cumulative probability distribution of annual and seasonal $E_f$;
- Bivariate probability distribution of $E_f$ against $T_e$;
- Seasonal and annual mean wave power roses of $E_f$ against $\theta_m$;

5.2 Regional coarse model results

5.2.1 Distribution of annual mean wave power

Figure 5.1 shows us that Southeastern Queensland and New South Wales are exposed to annual mean wave powers between approximately 6 and 12 kW/m. It can also be clearly deduced that such wave powers are associated and transported by sea waves from a directional sector between approximately 110–160°. The highest annual mean wave powers are observed along central New South Wales from Sydney up to nearby Crowdy Head with approximately 8 to 12 kW/m.

Figure 5.1 - Maps of annual mean wave power (left) and annual mean wave direction (right) for Australia’s southeast shelf. The bathymetric contour of 100 water depth is also depicted as a dashed line and major population centres denoted with a black dot. Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.1 to 0.01°.
The wave power is transported by southeasterly-orientated waves coming from between 130 and 140º. This conclusion is based on annual mean wave power roses presented in page 113, section 5.4.4.1 that clearly show that most wave power is delivered by southeasterly-oriented waves. These findings are consistent with those of other authors who have suggested that central New South Wales is a convergence of cyclonic wave generating regions, hence experiencing a more energetic wave climate than any other coastal area (see Short and Trenaman 1992).

Annual mean wave powers for New South Wales north coast from Crowdy Head to Byron Bay are approximately 8 to 9 kW/m (Figure 5.1). The relatively smaller annual mean wave power compared to that of central New South Wales are owing to waves with more easterly orientated directions between approximately 115 and 130º. The coastal areas further north of Cape Byron also experience mild yearly mean wave powers, but between 6 and 9 kW/m. These zones are partially shadowed from southerly swell events due to refraction and shoreline geometry and also more exposed to waves formed northeast of New Zealand. Therefore and as evidenced in Figure 5.1, waves propagate towards shore from a more easterly oriented direction between 100 and 120º (see also Mortlock and Goodwin, 2015).

The lowest annual mean wave powers are observed along New South Wales south coast from Eden to Jervis Bay, with approximately 5 and 8 kW/m. These coastal regions are also less exposed to southerly-orientated swells, as a result of a combination of landmass sheltering effects from Victoria and Tasmania with wind variations (Coghlan et al., 2011). The east-southeasterly mean wave direction between 110 and 120º for New South Wales south coast sector suggests that lower degree of exposure to powerful southerly swell events (Figure 5.1).

The distribution of annual mean wave powers presented shows decent agreement, as expected, with that described by Hughes and Heap (2010). The presented wave energy resource maps are, however, and by way of comparison, more conservative with annual mean wave energy resources displaying on average less approximately 2 to 4 kW/m. For example, Hughes and Heap (2010) found approximately 13.61 kW/m for Seal Rocks (32.5º S, 152.5º E), whilst a mean wave power of 10.74 kW/m was here observed (approximately 21% less). There are a few aspects that have certainly contributed to such discrepancy and are addressed below.

Firstly, Hughes and Heap’s (2010) national wave energy resource maps have not accounted for energy dissipation processes such as refraction, bottom friction and wave breaking, whilst such transformation processes were considered here. These processes
can have substantial effects on wave energy calculations, particularly within nearshore areas where wave farms are usually deployed. It has been recognised that bottom friction dissipates approximately 10% of wave energy from deep to shallow waters (Folley and Whittaker, 2009).

Secondly, such wave energy maps were derived from model wave hindcast outputs over periods of ten years which are not long enough to properly account for wind-wave climate variability and consequent aleatory uncertainty. Australia’s southeastern coast exhibits a high level of wave variability from year to year. Interannual variability for wave height has been found to be 5–10% for Australia’s southeast coast, but can reach up to 35% for Queensland during monsoons (Hemer et al., 2007).

In conclusion, annual mean wave powers exhibit a degree of synoptic spatial variability, however, such variability is relatively low when compared, for example, to that of Australia’s southern coast (Hemer and Griffin, 2010). The greatest annual mean wave powers are concentrated along New South Wales central coast with approximately 8 to 12 kW/m, followed by northern New South Wales with 8 to 9 kW/m. The coastal sectors south and north from these regions are more sheltered from southerly swells and hence are endowed with annual mean wave powers of about 6 kW/m. The directionality of wave power and associated synoptic wave generating systems will be discussed in detail in section 5.4.4.

5.2.2 Seasonal variability

The mean wave power and direction exhibit clear seasonal variability. Figure 5.2–5.3 show that seasonal mean wave powers are highest during winter to the south of Byron Bay. In winter, mean wave directions rotate towards a more southerly orientated direction with waves providing approximately 9 to 15 kW/m between New South Wales central and north coasts. Along the Queensland and southern New South Wales coasts, winter mean wave powers are relatively lower with only 5 to 10 kW/m. Based on Figure 5.2 and consistent with what previously discussed during section 5.2.1, these regions are partially sheltered from powerful southerly swells, as evidenced by a prevalence of a more easterly mean wave direction (Figure 5.3).

In spring, mean wave powers range from 5 to 9 kW/m and the mean wave direction experiences a counter-clockwise rotation of approximately 10 to 20° from north to south, as also observed by Kulmar et al., (2013). The largest mean wave powers during spring are observed along New South Wales central coast sector (up to 9kW/m). These
months are clearly a seasonal transition between stronger winter wave powers and lower wave powers that will prevail during summer period. The seasonal distribution of wave energy presented agrees well with Hughes and Heap (2010).

Figure 5.2 – Map of seasonal mean wave power for Australia’s southeast shelf. The bathymetric contour of 100 water depth is also depicted as a dashed line and major population centres denoted with a black dote. Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.1 to 0.01º.

The lowest mean wave powers are observed during summer period from south to central New South Wales with approximately 4 and 7 kW/m derived from waves with mean wave directions between approximately 110 and 130º. There is nevertheless greater wave power during summer than spring period for regions located north of Byron Bay, which suggests a more frequent and stronger activity of northeasterly winds originated by high-pressure systems. In autumn, mean wave directions turns clockwise by up to 20º towards a more southerly direction and mean wave powers become greater
compared to spring and summer ranging between 8 and 12 kW/m (Figure 5.2). The rotation of mean wave direction suggests that waves generation is occurring more frequently from southeast mid-latitude cyclones.

In conclusion, winter and autumn seasons are endowed with greater mean wave powers associated with more southerly directions, whilst lower wave powers are observed during spring and summer period resultant from more easterly orientated waves. The seasonal wave power variability is low, with winter only showing mean wave powers twice as large as summer. The seasonal distribution of mean wave power presented above is consistent with that described by Short and Trenaman (1992), Hughes and Heap (2010), and Mortlock and Goodwin (2015).

Figure 5.3 - Map of seasonal mean wave direction for Australia’s southeast shelf. The bathymetric contour of 100 water depth is also depicted as a dashed line and major population centres denoted with a black dot. Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.1 to 0.01º.
The variability of wave power on a seasonal time scale is a necessary aspect to consider when choosing potential sites for sitting a wave farm. For example, areas with a moderate and steady wave power may well prove to be more attractive than areas where wave power is higher but also more unsteady and hence less consistent. Therefore, to provide a high fidelity understanding of wave power variability on a seasonal scale, a seasonal variability index proposed by Cornett (2008) was applied,

\[ SV = \frac{E_{\text{max}} - E_{\text{min}}}{E_{\text{annual}}} \]  \hspace{1cm} (47)

where \( E_{\text{max}} \) stands for the mean wave power for the most energetic season, and \( E_{\text{min}} \) is the mean wave power for the least energetic season. Moderate seasonal variability occurs when a seasonal variability index exceeds 1.

Figure 5.4 demonstrates that wave energy resources show a small seasonal variability, as evident by seasonal variability coefficients of 0.3 to 0.8. It can be clearly observed that seasonal wave power variations are more significant for Victoria and Queensland and less significant for south and central New South Wales. Based on Figure 5.4, seasonal variability in wave power is more significant across mid and outer shelf zones.

The aforementioned results are consistent with those of Cornett (2008), who suggested seasonal variability indexes between 0.25 and 0.75 for Australia’s southeast margin. It also concurs with a study of Reguero et al., (2011) which calculated a seasonal variability index ranging between 0.25 and 0.5 for Southeastern Queensland and New South Wales.
Figure 5.4 - Map of seasonal variability index for Australia’s southeast shelf. The bathymetric contour of 100 water depth is also depicted as a dashed line and major population centres denoted with a black dot. Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.1 to 0.01°.

5.2.3 Consistency of wave energy resource delivery

It is recognised that many wave energy converters are tuned for particular wave heights and cannot generate electricity when waves fall below a critical value. To investigate the consistency of wave power delivery on a year round, a significant wave height threshold for conversion failure was adopted so that mean time between failures and mean duration of failures could be mapped.

The threshold for failure was assumed to be, for demonstrative purposes, equal to that of a cylindrical energy transfer oscillator (Figure 2.13), which starts operating for waves of approximately 1 m between 25 and 50 m water depths. The threshold of a CETO is considered to be a good representation of a critical limit for wave conversion, given that point absorbers are more likely to be chosen for deployment along Queensland and New South Wales (see Behrens et al. 2012). Failures due to wave power exceeding threshold
levels for safe operation were disregarded since waves above 6 m (survivability threshold) display a probability of occurrence of less than 0.01% (Kulmar et al., 2013).

The maps of mean time between failures and mean duration of failures are given in Figure 5.5. The consistency of wave power delivery is stable and consistent along Australia’s southeastern coast, with short periods of failures and relatively long periods between failures. The greatest consistency can be observed along north and central New South Wales and nearby Victoria where electricity can be continuously generated up to 22 days. New South Wales and Queensland show a comparatively less consistent wave power with only up to 14 days of non-failures (Figure 5.5).

Figure 5.5 - Mean time between failures (days) (left) and mean duration of failures (days) (right) for Southern Queensland and New South Wales, where failure is defined as occurring when ($H_s < 1$ m). The bathymetric contour of 100 water depth is also depicted as a dashed line and major population centers denoted with a black dot.

Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.1 to 0.01°.

Figure 5.5 also suggests that wave power is more reliably delivered within offshore areas than closer to shore, as wave powers have had relatively little exposure to energy dissipated processes and sheltering effects. The mean duration of each failure period is relatively short showing that a cylindrical energy transfer oscillator fails to work, during
a continued period of 2.5 days (see Figure 5.5). The exception is Moreton Bay where mean durations of failures are greater than 10 days owing to its sheltered nature. These results are consistent with findings of Hughes and Heap (2010), which suggested a mean time between failure of up to 31 days and a mean period of failure of up to 2.5 days.

5.3 Nested model: Central coast of New South Wales

5.3.1 Distribution of annual mean wave power

The best wave energy resources are distributed along the central New South Wales coast between Sydney and Crowdy Head (Figure 5.6). The relatively high annual mean wave power and low seasonal variability suggest that such areas are likely to be more economically viable and appealing for generating electricity using wave technology.

Figure 5.6 - Maps of annual mean wave power (left) and mean wave directions (right) for from central New South Wales nested model. The hotspots are marked with circles and locations with a black dot. Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.01 to 0.005°.

Figure 5.6 shows that annual mean wave powers from Sydney to Crowdy Head range between approximately 7 and 11 kW/m and are associated with southeasterly orientated waves. Annual mean wave powers display a progressive decrease as water depth de-
creases towards shore. In shallow waters, complex bathymetric features can create zones of energy concentration and dispersion by means of refraction and localized diffraction and so shallow-water wave powers show a higher degree of spatial variability.

These nearshore spatial variations can be observed in Figure 5.6, which shows that wave energy is more concentrated near headlands and more dispersed along or close to coastal embayments and shadow zones behind islands. Figure 5.6 also suggest that southeasterly orientated waves need relatively less directional dispersion to reach particular regions off central New South Wales as a result of shoreline orientation.

Energy dissipation occurs from deep to shallow waters due to bottom friction, but mean wave powers are somewhat conserved, which suggests that only a relatively small percentage of exploitable wave power is dissipated. These features are in line with the study conducted by Wright (1992) showing that only 3.4% of exploitable wave power is dissipated due to bed friction. Based on Wright (1992) and Short and Trenaman (1992), the central coast of New South Wales has a narrow steep continental shelf and so waves rapidly shoal with small energy dissipation upon transformation (see Mortlock and Goodwin, 2015).

The geographical distribution of annual mean wave powers presented shows a decent agreement with wave climatological analysis conducted based on long-term buoy measurements (see Shand et al., 2011 and Kulmar et al., 2013). Figure 30 appears to be, nevertheless, more conservative compared to buoy-derived mean wave power magnitudes, which are under predicted by approximately 20% (Table 5.1). There are a few aspects that might have contributed to such discrepancy, namely:

1) Interannual wave variability: wave energy resource was hindcasted during a longer period of time when compared to that period over which wave buoy measurements are available for comparison (Hemer et al., 2007);
2) Model wave boundary conditions: which had rmse of approximately 37–45 cm for significant wave height and given that wave power and wave height are not linearly correlated, a low rmse can lead to a significant wave power discrepancy;
3) Model wind forcing: which suffer from diminishing wind speeds especially within 30 km from shore and required to be revised by 20%. These winds also lead to too much higher frequency spectral energy causing a systematic under prediction of wave periods by around 0.5 to 1 s.
Table 5.1 – Comparison between buoy-derived and hindcasted wave energy.

<table>
<thead>
<tr>
<th>Buoy name</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (m)</th>
<th>Buoy Model</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crowdy Head</td>
<td>31.82 S</td>
<td>152.85 E</td>
<td>79</td>
<td>11.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Sydney</td>
<td>33.78 S</td>
<td>151.42 E</td>
<td>85</td>
<td>11.3</td>
<td>8.5</td>
</tr>
</tbody>
</table>

New South Wales central coast exhibits a wave energy resource potential comparable to other regions where wave energy resources have been considered adequate for harvesting. Table 16 shows a summary of annual mean wave power magnitudes documented for other overseas nearshore regions. It can be observed that central coast New South Wales displays a mean wave power similar to that of Gran Canaria, which has been considered a zone with potential for wave energy exploitation (Gonçalves et al. 2014). The wave energy resource potential of central New South Wales seems also comparable to that of some wave projects operating with medium and full-commercial wave farms (see Lopez et al., 2013).

Table 5.2 – Characteristics of other foreigner areas where wave energy resource evaluations have been conducted.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Period (years)</th>
<th>Country or Region</th>
<th>Depth (m)</th>
<th>Mean wave power (kW/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liang et al. (2014)</td>
<td>22</td>
<td>Galway Bay (Ireland)</td>
<td>25</td>
<td>10.0</td>
</tr>
<tr>
<td>Kumar and Anoop (2015)</td>
<td>34</td>
<td>South of India</td>
<td>150</td>
<td>11.3</td>
</tr>
<tr>
<td>Wu et al. (2015)</td>
<td>2</td>
<td>East China (Zhejiang)</td>
<td>63</td>
<td>14.4</td>
</tr>
<tr>
<td>Mirzaei et al. (2014)</td>
<td>31</td>
<td>East Malaysia</td>
<td>17</td>
<td>4.60</td>
</tr>
<tr>
<td>Liang et al. (2013)</td>
<td>16</td>
<td>China (Shandong)</td>
<td>20</td>
<td>4.00</td>
</tr>
<tr>
<td>Mirzaei et al. (2015)</td>
<td>31</td>
<td>Philippines (Palawan)</td>
<td>42</td>
<td>6.30</td>
</tr>
<tr>
<td>Gonçalves et al. (2014)</td>
<td>3</td>
<td>West France (Le Croisic)</td>
<td>32</td>
<td>14.9</td>
</tr>
<tr>
<td>Monteforte et al. (2015)</td>
<td>10</td>
<td>Italy (Sicily)</td>
<td>15</td>
<td>5.60</td>
</tr>
<tr>
<td>Vicinanza et al. (2013)</td>
<td>22</td>
<td>Italy (Sardinia)</td>
<td>20-50</td>
<td>10.9</td>
</tr>
<tr>
<td>Gonçalves et al. (2014)</td>
<td>3</td>
<td>Spain (Grand Canaria)</td>
<td>42</td>
<td>8.59</td>
</tr>
<tr>
<td>Gleizon and Woolf (2013)</td>
<td>1</td>
<td>Scotland (Orkney Islands)</td>
<td>20</td>
<td>16.0</td>
</tr>
<tr>
<td>Nieuwkoop et al. (2013)</td>
<td>23</td>
<td>UK (Cornish Coast)</td>
<td>50</td>
<td>18.0</td>
</tr>
<tr>
<td>Robertson et al. (2014)</td>
<td>7</td>
<td>Canada (Vancouver)</td>
<td>27</td>
<td>27.8</td>
</tr>
</tbody>
</table>
5.3.2 Seasonal variability

The seasonal distribution of wave power along the central New South Wales coast is consistent to what was previously explained during section 5.2.2 (Figure 5.2–5.3). Figure 5.7 shows that winter has larger mean wave powers between approximately 9 and 15 kW/m followed by autumn with approximately 9 to 12 kW/m. The smallest mean wave powers are observed during summer and spring with up to approximately 6 to 8 kW/m.

The seasonal variability of mean wave power is relatively small as evident by a small seasonal variability coefficient between 0.3 and 0.6 (Figure 5.8). Summer and spring show seasonal mean wave powers only approximately 15% to 20% below annual averages and winter and autumn only approximately 20% to 30% above the annual average. The small seasonal variability of wave powers expresses a wave climate that is predominantly driven by proximal winds that blow across a fetch-limited length (Mortlock and Goodwin, 2015).

Figure 5.7 - Maps of seasonal mean wave power for central New South Wales. Hindcast wave data for February 1979 to December 2011. Grid cell size is 0.01 to 0.005°.
5.3.3 Consistency of wave energy resource delivery

The wave power resource delivery is more consistent northward from Seal Rocks with a mean period between failures ($H_s < 1 \text{ m}$, see section 5.2.3) of approximately 12 to 17 days. In areas south of Seal Rocks wave power resource delivery is less reliable, with a shorter period between failures of 6 to 12 days. The mean period of failures along central coast New South Wales ranges between 1 and 2 days, with coastal bays showing a somewhat greater mean period of failures up to 2 days (Figure 5.9). It can also be observed that the mean wave powers are relatively less reliable towards shore, as a result of coastline sheltering effects that begin to dissipate remote swells since a depth of 50 to 60 m (Soomere and Eelsalu, 2014).

These findings suggest that the wave energy resource in this area is reliable, particularly north of Newcastle. There is also a reasonable window of 1 to 2 days where wave powers are not harvestable but remain at sufficiently low levels which permit a given set of marine operations to be made safely. The durations, starting time and number of occurrences of ‘maintenance’ windows are recognized to be fundamental for planning management purposes.
Figure 5.9 - Mean time between failures (days) (left) and mean duration of failures (days) (right) for central New South Wales, where failure is defined as occurring when \( (H_s < 1 \text{ m}) \). Hindcast wave data from February 1979 to December 2011. Grid cell size is 0.01 to 0.005°.

5.4 Potential wave energy ‘hotspots’

The hotspots were selected by considering not only wave energy resource availability but also other relevant aspects that are fundamental when determining potential sites for deploying a wave energy project facility. The following site selection criteria were used:

- The wave energy resource potential;
- The distance to shore;
- The closeness to urban centers or ports;

The distance to shore plays a key role when developing and or deploying a wave energy project facility as projects closer from shore will obviously require less lengthy and costly submarine cables and can be more easily accessed for operation, maintenance and repairs. Furthermore, nearshore regions require relatively less costly mooring cables. The costs of bringing energy ashore can be decisive for a wave project to be economically feasible. The hotspots chosen for analyses ranged in distances from shore between 60 m and 5 km (Table 5.1).

The closeness to urban centers can also be determinant for a project to become economically viable and profitable. These regions will need less costly overland transmission lines that might show substantial power losses when transmitting energy over long
distances. They will also be certainly closer to cable landing points and grid connectivity access points so less infrastructures needs to be built. For that reason, only hotspots adjacent to population centers were selected. The principal geographical features of each hotspot analysed are available within Table 5.1.

Table 5.1 shows that annual mean wave power magnitudes range between 75 and 92 kW/m. The hotspot with largest annual mean wave power magnitude is H2 with 10.7 kW/m followed by H3 and H4 with 10 kW/m. At location H2, 60 m off Seal Rocks, approximately 1 GWh/year of electricity can be potentially generated with a generic wave energy conversion system with 20% efficiency and 50 m capture length. The electricity generated by a wave farm with ten such units will be sufficient to supply 41 houses of Seals Rocks with a typical monthly consumption of 2 MWh.

The difference of recoverable annual wave power between hotspots appears to be nevertheless sufficiently small to suggest that other variables may become more decisive when selecting a hotspot over another. In fact, relatively lower annual mean wave powers do not necessarily signify that a certain hotspot is less adequate for harvesting wave energy, as wave farms and particularly some WECs can be tuned to operate more efficiently for a given set of climatic conditions.

In terms of consistency of wave power delivery, H1 and H2 display shorter mean failure durations and longer mean time between failures, suggesting a greater reliability of wave power resource delivery. The mean time between failures for both hotspots is almost twice as long as those observed for the other hotspots. The mean failure durations are also approximately 50% shorter. The seasonal variability of wave power is low and is similar between hotspots even though wave powers are somewhat less variable for H7 to H9 (Table 5.1).
Table 5.3 – The principal characteristics of each selected hotspot.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Water depth (m)</th>
<th>Distance to shore (m)</th>
<th>Coordinates (°)</th>
<th>Closest population</th>
<th>Annual energy delivery (MWh/m/year)</th>
<th>Mean wave power (kW/m)</th>
<th>MFD&lt;sup&gt;1&lt;/sup&gt; (days)</th>
<th>MTBF&lt;sup&gt;2&lt;/sup&gt; (days)</th>
<th>SV&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>18.2</td>
<td>1550</td>
<td>152.80 E, 31.75 S</td>
<td>Crowdy Head</td>
<td>83.01</td>
<td>9.47</td>
<td>1.07</td>
<td>13.70</td>
<td>0.42</td>
</tr>
<tr>
<td>H2</td>
<td>10.2</td>
<td>60</td>
<td>152.54 E, 32.44 S</td>
<td>Seals Rock</td>
<td>91.69</td>
<td>10.76</td>
<td>1.06</td>
<td>12.28</td>
<td>0.42</td>
</tr>
<tr>
<td>H3</td>
<td>19.2</td>
<td>5000</td>
<td>152.33 E, 32.62 S</td>
<td>Broughton Island</td>
<td>87.13</td>
<td>9.94</td>
<td>1.46</td>
<td>7.25</td>
<td>0.44</td>
</tr>
<tr>
<td>H4</td>
<td>17.7</td>
<td>1370</td>
<td>152.21 E, 32.76 S</td>
<td>Fingal Bay</td>
<td>90.28</td>
<td>10.03</td>
<td>1.15</td>
<td>7.85</td>
<td>0.42</td>
</tr>
<tr>
<td>H5</td>
<td>12.2</td>
<td>820</td>
<td>152.12 E, 32.79 S</td>
<td>Boat Harbor</td>
<td>82.83</td>
<td>9.45</td>
<td>1.73</td>
<td>5.15</td>
<td>0.43</td>
</tr>
<tr>
<td>H6</td>
<td>22.0</td>
<td>4180</td>
<td>151.85 E, 32.90 S</td>
<td>Newcastle</td>
<td>77.13</td>
<td>8.80</td>
<td>1.78</td>
<td>5.23</td>
<td>0.41</td>
</tr>
<tr>
<td>H7</td>
<td>4.50</td>
<td>510</td>
<td>151.57 E, 33.29 S</td>
<td>Norah Head</td>
<td>80.55</td>
<td>9.19</td>
<td>1.42</td>
<td>6.81</td>
<td>0.33</td>
</tr>
<tr>
<td>H8</td>
<td>8.20</td>
<td>2610</td>
<td>151.45 E, 33.51 S</td>
<td>Macmasters Beach</td>
<td>75.42</td>
<td>8.61</td>
<td>1.45</td>
<td>6.88</td>
<td>0.29</td>
</tr>
<tr>
<td>H9</td>
<td>11.7</td>
<td>1550</td>
<td>151.30 E, 33.88 S</td>
<td>Sydney</td>
<td>76.26</td>
<td>8.70</td>
<td>1.46</td>
<td>7.51</td>
<td>0.32</td>
</tr>
</tbody>
</table>

<sup>1</sup>Mean duration of failures.

<sup>2</sup>Mean time between failures.

<sup>3</sup>Seasonal variability index.
5.4.1 Whisker-box plots of wave power

In order to further investigate how wave power is distributed on seasonal and annual cycles, whisker-box plots were generated for each hotspot. These diagrams are very alike displaying similar wave power distributions and trends. Figure 5.10 displays that median wave powers are clearly lower during summer and spring and are higher during winter and autumn as shown by red middle quartile marks. Interquartile ranges are larger during autumn and winter particularly and shorter during spring and summer. These features suggest that winter and autumn show a larger range of wave powers between about 5 and 17 kW/m, almost twice as large as those of summer and spring period. During summer and spring, the relatively small range of wave power hence demonstrates that median values represent a good measure of wave power availability in those seasons.

Figure 5.10 also shows that that autumn and winter have a greater range between maximum and minimum values with 15 and 17 kW/m up to 35 and 40 kW/m during autumn and winter respectively. In comparison, the range is from a minimum of 12 kW/m up to maximum of 25 kW/m during summer and spring periods. These features shows that wave powers on a year round are always below standard survivability thresholds as well as extreme energy events display a relatively small magnitude relative to median wave powers.

In summary, all considered hotspots display a relatively small seasonal wave power variability ranging between approximately 2 and 3 kW/m. The annual wave power ranges between approximately 5 and 15 kW/m but with a greater change of exceeding 15 kW/m up to 30 kW/m than falling below approximately 5 kW/m. These findings demonstrate that these hotspots are more reliable than other areas where wave powers are greater but unsteadier. The reliability of wave energy resources can be often more vital than wave energy resource magnitudes. By way of comparison, Strahan a town located on Tasmania’s mid-west coast (about 145.2° E and 42.4° S) has a larger median wave power baseline of nearly 20 kW/m, but also faces (25% of time) much larger extreme power events up to 800 kW/m.
5.4.2 Cumulative probability distribution

Figure 5.11 shows cumulative probability distributions of annual mean wave powers for selected hotspots. It can be observed that about 90% of sea states show annual mean wave powers at or below 25 kW/m. The proportion of sea states with a wave power of less than 5 kW/m ranges between 30 and 45%; and with less than 10 kW/m, between 60 and 72%. It can also be observed that all cumulative probability curves are similar,
which suggests that such hotspots are subjected to similar wave power conditions. Consistent with Table 5.1, Seal Rocks displays a cumulative probability distribution curve that falls distinctly below all other curves indicating a more abundant annual wave energy resource.

Figure 5.11 - Cumulative probability distribution of annual mean wave power for all hotspots considered, for power up to 50 kW/m.

Figure 5.12 shows cumulative probability distributions of annual and seasonal mean wave power for Seal Rocks for wave power up to 50 kW/m. It can be inferred that, as expected, winter and autumn period deliver greater wave powers than summer and spring. In winter and autumn only 55% of wave powers falls below 10 kW/m, whilst during spring and summer months that probability rises up to 70%. In winter and autumn, the cumulative probability distribution is about 5 to 20% smaller than during summer and spring for wave powers above 5 kW/m.
5.4.3 Bivariate probability distributions

The bivariate distribution diagrams were constructed using energy bin sizes of 1 s ($\Delta T_e$) by 0.5 m ($\Delta H_s$) and determined for each hotspot. Figure 5.13 shows a combined probability distribution of frequency of occurrence (number of hours per year) and cumulative energy (energy per year) for H2. The frequency of occurrence of each sea state is presented as a number within each sea state bin, while color codes specify how much energy is delivered yearly by each different sea state. Isolines representing wave power density obtained with equation (15) are also drawn.
Figure 5.13 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Seal Rocks (H2). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.

At all sites (see Appendix B), the greatest contribution to total annual energy is delivered by sea state bins with energy periods between 8 and 9 s and wave heights between 1.5 and 2 m. The sea states bins with energy periods between 7 and 10 s and significant wave heights between 1 and 2.5 m also deliver a significant portion of energy. The bivariate probability distributions determined for H5 and H7 show a greater peak energy that falls away faster as demonstrated by dark red colours transitioning quickly to cooler colors. These distributions suggest that H5 and H7 have larger concentrations of exploitable wave power, within a narrower range of wave sea states (see Figure 5.14). The concentration of wave power within a few energy bins means that conversion devices can be tuned to operate at maximum capacity for longer periods of time.

Interestingly, sea state bins with greatest contribution to total annual energy show a considerably lower occurrence than sea state with smaller energy contribution. The sea states with greatest frequency of occurrence (700 or more hours yearly) contribute more often to annual energy but with less significance as a result of smaller significant wave heights and energy periods. In contrast, sea state bins with largest significant wave heights and energy periods do not deliver much energy yearly, as a result of occurring at most, for only a few hours or days.
The probability of occurrence of sea states with largest significant wave height is, however, essential when considering risk of equipment breakdown owing to fatigue, wear and extreme wave events. It can be observed that dangerous sea states between 4.5 and 5.5 m are very rare, only occurring for a few hours over a year, showing that most hotspots only exhibit operational wave sea state conditions considering a standard band of operation between 1–5 m. These results are not surprising as all hotspots are located very close to shore at shallow water depths.

In conclusion, for each hotspot, most of the exploitable energy will come from relatively moderate wave heights (1 to 2.5 m) and wave energy periods (7–10 s), which is typical of far but fetch-limited Tasman southeasterly waves. The fetch-limited nature of Tasman generated waves means that energy periods are rarely sustained above 12–13 s. In terms of reliability and survivability, WECs have a low probability of having to cope with extreme loading scenarios given a significant wave height of 6 m as a hypothetical survivability threshold. Interestingly, Figure 5.14 (H7) displays a combined probability distribution where most of annual wave energy comes from a range of wave sea states that occurs more frequently.

Figure 5.14 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Norah Head (H7). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.
Hence, engineers can possibly combine both efficiency and consistency. It must be also stated that wave power matrices can be often misleading for resonant wave energy devices, which are sensitive to particular sea power spectrums and various spectral shapes, with similar wave heights and energy periods. The use of a power matrix provides a computationally simple method for power output evaluation with an error not exceeding that introduced due to assumptions behind financial calculations (Teillant et al., 2012).

5.4.4 Wave power roses

5.4.4.1 Annual roses

The wave power roses for each hotspot were generated based on 1-hourly consecutive wave energy transport and mean wave period time sequences from 1979 to 2010. Seasonal and annual power roses were determined for each hotspot and plotted using directional bins of 10º width. The annual wave power roses are given in Figure 5.15 where the length of each colored bar shows how often wave power comes from a particular direction, where each concentric circle shows a different frequency of occurrence. The colour-coded bands of each spike show different wave power classes separated by a power band width of 5 kW/m.

The annual power roses presented for each hotspot are similar with wave power coming from the south through to the east-northeast. The greatest share of annual mean wave power comes from the southeasterly and south-southeasterly quadrants between approximately 135 and 170º. A high percentage of waves from these directions provide wave power above 10 kW/m. In contrast, east-southeasterly and east-northeasterly waves exhibit a much lower percentage of occurrence than more southerly oriented waves; and rarely provide wave powers greater than 10 kW/m. These features suggest a dominance of persistent southerly swells from extra-tropical Tasman cyclones (Harley et al., 2010).

Interestingly, some hotspots display annual wave power roses where wave power comes from a narrower directional range. Figure 5.15 clearly suggest that mean wave powers are overall more uniform directionally at shallower water hotspots and less uniform for deeper waters owing to wave refraction (Folley and Whittaker, 2009; Lenee-Bluhm et al., 2011). The degree of exposure of each hotspot to different wave directions owing to shoreline geometry and orientation can also explain why particular hotspots receive wave powers from a wider directional range than others.
The greatest percentage of occurrence of southerly waves can be observed at H3 and H4 with approximately 20%; whereas easterly waves occur most often at H8 and H9, with 12 and 10% respectively. The highest frequency of south-southeasterly waves are observed at H5 and H6 (about 20%) and of southeasterly waves at H7 and H8 with 20 and 25%. Interestingly, east-northeasterly waves can only be seen at H1 and H2 and further down for H8 and H9 suggesting that H3–H7 are sheltered from such directions.

Figure 5.15 - Directional distribution of annual mean wave powers for each hotspot considered. Results of simulations with SWAN during 1979 to 2010.

5.4.4.2 Seasonal roses

The seasonal wave power roses are more or less the same. Winter has a much greater frequency of occurrence of more-powerful south-southeasterly and southeasterly waves with lower frequency of occurrence of less-powerful east-southeasterly and easterly
waves, compared to other seasons. These percentages are a result of a blend between long-period waves originating between a Tasman Sea high-pressure system and a Southern Ocean low with swells associated with Southern Tasman Low formations (Mortlock and Goodwin, 2015).

The domination of powerful southeasterly to south-southeasterly waves weakens during spring with a much lower percentage of wave power above 25 kW/m compared to winter. The subtropical ridge progresses southwards and quasi-stable high pressure systems block northward progressions of southeast mid-latitude cyclones, which causes a natural decline of long-period southerly oriented swells (Goodwin, 2005). There is subsequently a greater occurrence of less-powerful waves from east-southeast to east and a gradual shift of wave powers counterclockwise that will continue towards summer (Figure 5.16).

![Directional distribution of annual mean wave powers for each hotspot considered. Results of simulations with SWAN during 1979 to 2010.](image)

The smallest percentage of more-powerful southerly to southeasterly waves and greatest percentage of less-powerful east-southeasterly and east-northeasterly waves occurs during summer. During summer, the subtropical ridge moves southwards leading to a significant-reduction of southeasterly waves and providing conditions for regular development of northeasterly sea breezes that can persist for long periods. Summer northeast
tropical cy-clones and zonal easterly Trade Winds are also observed which contribute to a directional shift of wave powers to east-northeast.

The subtropical ridge shifts northwards during autumn and several types of low-pressure systems start to govern namely, southeast mid-latitude cyclones and east coast cyclones. It can observed in Figure 5.16 that less-powerful easterly and northeasterly waves give way to more powerful southeasterly waves as evidenced by a rotation of dominant wave power towards a more southerly oriented direction.

The seasonal directionality of wave energy resource presented suggests that wave power conversion systems need to be aligned for directions between southeast to south-southeast depending on hotspot. It also means that non-axially symmetric wave devices will need to undergo some directional tuning between seasons to follow directional wave power shifts. Therefore, since wave power resources are only moderate, axially symmetric wave energy systems that are not sensitive to wave direction may be more adequate.
Chapter 6

6 Conclusions and future work

Australia’s southeastern shelf has been documented as being suitable for wave energy harnessing. Nevertheless, existing wave energy databases for this area are only adequate for deep water, whilst wave energy conversion systems are typically positioned within water depths of 10–50 m. In addition, such databases are of limited spatial and temporal resolution and do not provide applicable deliverables for the purpose of wave energy resource harvesting. Therefore, a robust study devoted to coastal and nearshore mapping of wave energy resources at high resolution that supports selecting areas for wave farm deployment was required.

The current dissertation provides a contribution to our existing knowledge by unfolding a comprehensive wave energy resource appraisal for Australia’s southeastern shelf, with emphasis on nearshore areas and potential sites for locating WEC farms. The present research used SWAN to transfer the wave energy field from deep to shallow waters
and at hourly time steps for 31 years from 1979 to 2010. The model accounted for both deep and shallow water wave transformation and was driven using full directional spectra boundary conditions from NWW3 (version 4.08) and high-resolution surface winds from CFSR. The SWAN model was successfully calibrated and validated against wave rider buoy observations from eleven locations along Australia’s southeastern coast. The calibration of SWAN was achieved based on minimising various error metrics for wave height and model validation was examined based on error metrics for wave height, period and direction. It must be noted that extreme wave events seemed not to be accurately modelled with SWAN underestimating peak wave heights.

The calibration analysis process established that the model results were more sensitive to the choice of wind growth and whitecapping dissipation physics formulations. The most appropriate wind input/whitecapping model was found to be that of Westhuysen et al.’s., (2007), which outperformed the Komen et al.’s., (1994) and Janssen’s (1991) models. Increasing the whitecapping dissipation by using a higher proportionally coefficient $C_{ds}$ led to a better fit between measured and modelled wave heights.

The model validation then demonstrated that the calibrated model was capable of simulating wave heights with a mean bias of less than 1 cm and an overall average root square error of approximately 30 cm. The peak periods were modelled with a mean bias of less 0.5 s and an overall average root mean square error of approximately 2 s, respectively. These statistical errors are consistent with a range of other wave energy evaluations from around the world. The amount of error reported was partially owing to a lack of spatial and temporal resolution of the CFSR reanalysis winds limiting its ability to describe short-episodic locally generated coastal winds. Existing inaccuracies in the wave forcing boundary conditions (NWW3) were also a source of modelling error. In future work, it is suggested that the assimilation of observed surface winds from coastal weather stations with modeled winds might improve model results by more accurately accounting for locally generated winds and land-sea transitions.

The hourly numerical wave hindcast spectral outputs enabled access to a wide variety of wave field parameters, which were processed and used to generate a set of specific deliverables sought by wave energy developers, namely:

1) maps of wave energy resource availability, variability and reliability at a spatial resolution down to 1 km for Australia’s southeast coast;
2) maps of nearshore wave energy resource availability, variability and reliability at a spatial resolution up to 500 m for central New South Wales;
3) detailed analyses of nine ‘hotspots’ based on power matrices, whisker-box plots, probability distributions and power directional roses;
4) a 31-year database of multiple wave field variables for more than 12,000 grid cells extending out to a distance of 80 km from shore;

These specific deliverables were subsequently used to draw conclusions on wave energy resource potential for wave farm deployment. Australia’s southeast coast has a low to moderate wave energy resource potential between approximately 6 and 12 kW/m with relatively low synoptic spatial variability. It also exhibits a relatively low seasonal variability of the wave power resource with winter and autumn months having higher mean wave powers than those of spring and summer. The consistency of wave resource delivery is similar to that seen along Australia’s south coast, with short failure durations and relatively long periods between failures.

The largest wave energy resource is concentrated along the central coastline of New South Wales, whereas coastal regions further north and south are comparatively more sheltered and are hence less endowed. Detailed analysis of nine locations in this area provided the following results:

1) The nearshore regions with best exploitable recoverable wave energy resources for commercial wave farm projects are available along central coast New South Wales with approximately 7 to 11 kW/m;
2) The nearshore hotspot with best exploitable wave energy resource for the deployment of commercial wave farms is located offshore from Seal Rocks with nearly 11 kW/m;
3) The selection of wave energy devices should target for maximum power efficiency between 1 and 2.5 m for significant wave heights and between 7 and 10 s for wave energy periods;
4) The wave energy resource is usually delivered under a survivability threshold of $H_s = 6$ m, which means that wave converters could be employed with a low risk of failing to operate due to excessive amount of energy.
5) Directionally dependent or non-axially symmetric WECs should be deployed for a predominant wave direction between south-southeast and southeast;

This demonstrated that the wave energy resource vary significantly over distances as short as a few hundred meters up to a few kilometers not only alongshore but also cross-
shore due to wave refraction and other sheltering effects. The usage of a high-resolution wave transformation model allowed resolving such variability, which had never been captured before.

It can be also concluded that, by analysing the power distribution among different sea states, additional elements of spatial variability clearly emerge even between hotspots apparently homogenous in terms of wave energy potential. From this perspective, even though mean wave powers expected for a certain geographical location are unquestionably an important resource metric, an analysis solely based on such metric for determining suitable locations for commercial wave farms can be misleading. It is hence recommended to select and compare potential sites for WEC deployment using scatter energy diagrams, box plots, cumulative probability functions and wave directional roses.

The present dissertation represents another step towards proving the wave energy feasibility for Australia’s southeast coast, particularly for nearshore regions of central coast New South Wales. It clearly opens up a new range of applications for modelling wave energy device’s performance and productivity as well as conducting economical evaluations of projects.
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Appendix A

Figure A.1 - Commands lines added to Delft3D-WAVE through a script to change some physics and numerics.
Appendix B

Figure B.1 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Crowdy Head (H1).

Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.

Figure B.2 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Broughton Island (H3).

Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.
Figure B.3 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Fingal Bay (H4). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.

Figure B.4 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Boat Harbor (H5). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.
Figure B.5 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Newcastle (H6). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.

Figure B.6 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Macmasters Beach (H8). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.
Figure B.7 - Bivariate probability distribution of occurrence and wave energy, for sea states defined by significant wave height and energy period, at Sydney (H8). Numbers show how many hours a particular sea state occurs annually, while color codes show how much total annual wave energy is given by each sea state. Isolines represent wave energy density levels.
Appendix C

Table C.1 - Descriptive $H_s$ statistics for NSW waverider buoys. Adapted from Shand et al. 2011.

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<th>$H_{sig}$ (m)</th>
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<th>Crowdy Head (%)</th>
<th>Sydney (%)</th>
<th>Port Kembia (%)</th>
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Table C.2 – Probability of exceedance of $H_s$ for NSW waverider buoys. Data from Kulmar et al. 2013.