Spectral characterisation of nearshore wave energy during the sea-breeze cycle

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Abstract

From in situ measurements taken over several sea-breeze cycles off a beach in SW Australia, the evolution of the one-dimensional spectrum of wave energy is observed to have an unexpected spectral shape. Low rates of dissipation of wave energy are seen at high frequencies compared to mid-range frequencies above the windsea peak frequency. The SWAN model performed a simulation of waves and produced the same spectral evolution as seen in the observations. The performance of whitecapping schemes available in SWAN is assessed. Duration-limited and fetch-limited situations are investigated for the different wave conditions. From examination of the modelled two-dimensional spectra it is found that quadruplet interactions play a key role in spreading high-frequency wave energy in frequency and direction space.

Introduction

Wave growth due to increasing wind is relatively well understood since the JONSWAP experiment (Hasselmann et al. 1973), and the JONSWAP wave energy spectrum for deep-water wind-generated waves has a shape that has been well established. Young (1999) gives a complete description of the state of understanding of the processes governing spectral evolution. Essentially, a developing wind-sea has a well-defined spectral shape above the peak frequency that is maintained by nonlinear transfer by quadruplet interactions and whitecapping. In the absence of wind, the spectral shape is maintained by quadruplet interactions and whitecapping.

Whitecapping has been extensively studied (Ardhuin et al, 2010; Cavaleri et al, 2007; Donelan & Yuan, 1994), and is one of the least understood processes that is parameterized in spectral wave models. Model studies have mainly been aimed at understanding the dissipation through whitecapping (Banner & Young, 1994) and Rogers et al (2003) using SWAN. Young & Verhagen (1996a, 1996b, 1996c), from measurements in a long lake, examined the processes affecting the frequency and directional spectra of wind-generated waves in shallow water.
There has been less study of the spectral response to changes in both wind speed and direction. Young & Van Agthoven (1998), in a numerical study, showed how following an increase in wind speed, the nonlinear interactions act to stabilize the frequency spectrum. For changes in wind directions, Young et al. (1987) showed how for sudden wind shifts of less than ninety degrees, the turning wind-sea peak was smoothed out rather than creating a secondary peak.

As part of the Bluelink 2 project, a field experiment at Secret Harbour measured waves and currents at Secret Harbour, a longshore-uniform beach in Southwest Australia (see figure 1). Wave energy spectra were recorded over several intense sea-breeze cycles during summer (see figure 2).

To investigate and understand the evolution of the wave energy spectrum, a spectral wave model (SWAN) simulated wave condition over the region during the sea-breeze cycles. Wave energy dissipation is an important component of the model, and several parameterisations of whitecapping were investigated. Here we focus on the SWAN simulation of one sea-breeze/land-breeze event. Analysis of the modelled two-dimensional spectra at various locations reveals the processes at play in SWAN affecting the spectral and directional distribution of wave energy near the coast.
Figure 1: Bathymetry around Secret Harbour [115.73 E, 32.40 S]. This is the extent of the fine (30m res) grid used in SWAN. The AWAC location is denoted by A, along with other locations where wave energy spectra from SWAN were also analysed.

**Observations**

An AWAC (Acoustic Wave And Current profiler) was situated 1000 metres offshore (hereafter denoted location A, shown in figure 1) in 8.9 metres water depth. As well as spectra, hourly measurements of integrated wave parameters and bottom pressure were recorded from the 10th to the 28th February 2009 (see figure 2). Wind measurements were also recorded at the shore radar station.
The observed 1-D spectra on 19–20 Feb show growing windsea in the late afternoon due to a strong southwesterly wind (see figure 3, left) reaching a maximum in the early evening at 0.25 Hz. Swell (peak 0.08 Hz) from the west persisted throughout the daily cycle. The windsea decays during the morning hours in the presence of a moderate southeasterly wind switching to northeasterly. During the decay phase as wave energy decreased at all frequencies above the swell peak, there was a slower decay of wave energy at \( f > 0.5 \text{ Hz} \) as can be seen in figure 2. A spectral trough at 0.4-0.5 Hz appears at about 00:10 and deepens with time and the corresponding spectral peak to the right of the trough decays more slowly initially and shifts to higher frequency with time.

The spectral shape of the growing windsea is consistent with results from previous studies. However the evolution of the spectral shape during the decay phase showed a behaviour that was not readily explainable.
Figure 3: The one-dimensional wave energy spectrum at two-hourly intervals measured by the AWAC during the growth (left) and the decay (right) phase of the sea-breeze cycle on the 19 and 20 February 2009 at Secret Harbour [115.73 E, 32.40 S]. Frequency tails are $f^{-5}$ (dashed) and $f^{-3}$ (dash-dot).

The SWAN model

A realistic wind field is required to model the wave conditions accurately. It was not known *a priori* how far offshore the sea-breeze/land-breeze atmospheric circulation cell extends. A series of nested model runs (16km – 8km – 4km resolution) of the RAMS (Regional Atmospheric Modelling System) model were performed in order to capture the full wind-sea signal that is generated over a sea-breeze cycle. The modelled wind speed and direction compared well with observed values at the experiment site (see figure 2) and at Rottnest Island (50 km to the north).

SWAN is spectral wave model (Booij et al, 1999; Ris et al, 1999), which evolves the
wave action density $N(\sigma, \theta; x, y, t)$ (defined as wave energy density divided by intrinsic frequency, $E/\sigma$), in frequency, direction, space and time according to

$$N(\sigma, \theta; x, y, t)$$

where $c_g$ is the group velocity, and $S \approx S_{in} + S_{nl} + S_{diss}$, is the sum of source/sink terms. $S_{in}$ represents wind generation of wave energy, $S_{nl}(f, \theta)$ represents nonlinear wave-wave interactions, and $S_{diss}(f, \theta)$ represents dissipation through whitecapping, bottom friction and depth-induced breaking. For the high-frequency wave energy that will be considered here, $S_{diss}$ is dominated by whitecapping.

The details of the formulation of the source/sink terms used in SWAN may be found in Holthuijsen (2007). The expression of the wind input term is important for later analysis, in SWAN the wind input term is of the form (Holthuijsen, 2007)

where the initial wave growth term is given by

$$S_{in}(f, \theta)$$

where $u_f$ is the friction velocity. The coefficient for exponential growth is of the form

$$S_{diss}(f, \theta)$$

where $c$ is the phase speed. Note that for shallow water waves, $u_f$. Hence, the size of the wind input term may be sensitive to the depth as well as wind speed.

SWAN, at version 40.81, was run over the region forced by hourly winds. Three nested model runs (2000m – 400m – 30m resolution) were implemented, the coarsest extending out into the Indian Ocean and south of Western Australia. The smallest domain is shown in figure 1. The swell peak seen in figure 2 is from distant wave energy generated in the Roaring Forties region. An estimate of the swell parameters [$H_s=2m$, $T_p=13s$, $Dir=40^o$ (Cartesian)] was added as a boundary condition to the coarsest model run.
Figure 4: The one-dimensional wave energy spectrum at location A, at two-hourly intervals modelled by SWAN during the growth (left) and the decay (right) phase of the sea-breeze cycle on the 19 and 20 February 2009. Frequency tails are $f^{-5}$ (dashed) and $f^{-3}$ (dash-dot).

Figure 4 shows the modelled 1-D spectra at the same location and times as in Figure 3. SWAN has captured the spectral response of waves at location A through the sea-breeze cycle. Although the timing of the onset of wave growth is different between AWAC and SWAN due to the RAMS winds having slight differences in the timing of the sea-breeze (see figure 2f).

The root-mean-square difference between the 1-D spectra from the AWAC and from SWAN is shown in figure 5. Largest errors occur around the time of onset of the sea-breeze due to the different timing between RAMS and the observed winds. Also, the errors are large around the frequencies in the neighbourhood of the peak of the wind-sea at its maximum ($0.2 - 0.3 \text{ Hz}$).
The behaviour of the growth and decay of the wave energy was found to be quite sensitive to the choice of whitecapping parametrization used. Figure 5 compares the performance of three different whitecapping parametrizations used in SWAN; Ko (Komen et al, 1984, the default scheme for SWAN), BJ (Battjes & Janssen, 1978) and AB (van de Westhuysen et al, 2007, based on the work of Alves & Banner, 2003).

Komen overestimates wave energy at high frequencies ($f > 0.5 \text{ Hz}$). The Ko scheme is known to have reduced dissipation at high frequencies in the presence of swell (van de Westhuysen et al, 2007; Rogers et al, 2003). The BJ scheme appears to underestimates the growth, during early evening, of the windsea peak for $0.2 < f < 0.3 \text{ Hz}$. Both these schemes employ measures of the mean spectral wavenumber and steepness to calculate the whitecapping dissipation at a given frequency. These mean quantities can be influenced by the presence of a swell peak at low frequencies, when estimating the
whitecapping dissipation at high frequencies.

The AB scheme uses a saturation-based expression to calculate the whitecapping dissipation that essentially computes whitecapping dissipation locally in wavenumber space (see van de Westhuysen et al, 2007, and Alves & Banner, 2003, for more details). This scheme was found to produce wave energy frequency dependence most similar to the observations.

Non-dimensional fetch

The evolution of the wind-sea can be investigated in terms of its equivalent fetch, to be either a fetch-limited or a duration-limited situation. This can be shown by calculating the non-dimensional peak frequency, \( \eta \), non-dimensional fetch, \( x \), and non-dimensional duration, \( \tau \), where \( x \) is the fetch, \( t \) is the duration for which the wind blows, and \( \eta \) is the peak frequency of the wind-sea, calculated from the one-dimensional energy spectra by, according to Young & Verhagen (1996a),

\[
\eta = \frac{\text{peak frequency of wind-sea}}{\text{fetch}}
\]

From examining a number of previous studies, Young (1999) proposed the following empirical relationship between non-dimensional peak frequency and fetch,

\[
\frac{x}{\eta^2} = C
\]  
(4)

Selecting values of \( \eta \) and \( x \), at hourly intervals between 14:00 and 18:00 on February 19\textsuperscript{th},

we calculated \( \zeta, \nu, \) and hence \( \chi \) using the above relationship. Plotting \( \chi \) against \( \eta \) (see figure 6) gives an indication of whether the situation is fetch-limited or duration-limited. Young (1999) proposed a relationship for the separation between fetch-limited and duration-limited growth that is shown by the line in figure 6. Hence the growing wind-sea on the afternoon of February 19\textsuperscript{th} is a duration-limited fetch situation.
During the morning of February 20th the wind veers to the east and becomes a land-breeze for several hours (see figure 2). As the wind is directly offshore, the fetch is limited to 1000 metres at the location of the AWAC so there is no wind input in the direction of the wind. Spectra were selected, at hourly intervals from 04:00 to 07:00, from SWAN over this period at several points further offshore from A, in a downwind land-breeze direction. These are stations B, C and D as shown in figure 1. Wind-sea growth does occur at these stations over the morning. Knowing the actual fetch and duration, the non-dimensional fetch and duration were calculated and are shown in figure 6. Hence these wind-sea peaks are in a fetch-limited situation.

The non-dimensional peak frequency was also calculated from these SWAN spectra. Figure 7 shows the empirical relationship between non-dimensional peak frequency and fetch, equation (4) [with accuracy limits given by Young (1999) reflecting the variation

Figure 6: Relationship between non-dimensional fetch, $\chi$, and non-dimensional duration, $\varsigma$.

The line is from Young (1999), equation (5.48). Cases above the line represent duration-limited situations, cases below the line represent fetch-limited situations.
among the various experimental datasets used]. Also shown are the non-dimensional values calculated from the modelled spectra at B, C, and D on the morning of February 20th. Hence the modelled values fall within the limits of empirical relationship.

**Figure 7:** Non-dimensional peak frequency, $\nu$, against non-dimensional fetch, $\chi$, at three offshore locations at hourly intervals between 04:00 and 07:00 on February 20th. Also show is the relationship according to equation (4) with accuracy limits from Young (1999).

At all of the stations used in the above fetch analysis, where is the peak wavenumber, and the water depth. That is, these situations involve deep water waves, and an analysis in terms of non-dimensional depth is not necessary.
Analysis of modelled two-dimensional spectra

Figure 8 shows the modelled two-dimensional wave energy spectrum at the AWAC location, at 18:00 on February 19th, the time of the maximum wind-sea peak. Also shown are the most significant source/sink terms in equation (1). That is, wind input ($S_{\text{wind}}$), dissipation through whitecapping ($S_{\text{cap}}$), and quadruplet wave-wave interactions ($S_{n4}$), along with the local wind vector. One can see that the zone of high wind input is also where energy is lost to whitecapping and spread through wave-wave interactions (figures 8c and 8d).

![Figure 8](image)

**Figure 8:** At location A, Two-dimensional (frequency, direction) spectra of (a) log(Wave action density) (b) Input by wind and value of wind speed, $U_{10}$, (c) dissipation by whitecapping, and (d) spreading by quadruplet interactions. The local wind is indicated by the white arrow.

The generated windsea has significant amounts of energy travelling in directions away from the peak windsea direction (Figure 8a). This is mainly due to quadruplet interactions (Figure 8d) enabling energy in various wave bins to interact and add energy to wave bins at other frequencies and directions. Also, the Swind source term puts energy into
direction bins up to +/- ninety degrees according to a cosine power relation.

Over the next thirty hours, the wind veers southerly and then intensifies into an easterly land-breeze. Figure 9 shows the two-dimensional energy and source/sink terms at 3:00 on February 20th. The rate of turning of the wind is slow enough to allow the wind-sea peak to smooth in the direction of turning without creating a separate high frequency peak (Young, 1999; Young et al. 1987).

**Figure 9:** As figure 8, but at 3:00 February 20th.

Figure 10 shows the two-dimensional energy and source/sink terms at 11:00 on February 20th. Here the scales for the source/sink terms are greatly reduced to show the extremely low levels of wind growth, whitecapping, and wave-wave interactions. As the source/sink terms are very low, the peaks of wave energy seen at this time (figure 9a) are due to advection of wave energy into this location by the local group velocity, according to equation (1).
Figure 10: As figure 8, but at 11:00 February 20th. Note different scales.

From figure 10, apparent in the wave energy are four localized peaks frequency-direction space. There is the swell peak and the windsea peak from the previous afternoon heading in a northeasterly direction. Two other peaks are evident, both at higher frequencies (0.6 – 0.8 Hz), but travelling in opposite directions that align with the angle of the shoreline nearby. The presence of these latter peaks create the apparently faster decay of wave energy at mid-frequencies (0.4 – 0.5 Hz) seen in the one-dimensional spectra (figures 3 and 4).

The localized peaks of high-frequency wave energy are advected into this location from source regions in both longshore directions. The peak that is travelling in a northward direction is from wind-sea generated, to the south, during the turning wind field as seen in figure 9.

SWAN spectra were sampled at other locations alongshore from A, at the same distance from shore (1000 m). At site E to the north (see figure 1), there is significant input from the term due to the local wind as can be figure 11.
Comparing the wind input at these two locations at this time, there are two main differences between conditions at the A and E locations, water depth (8.9 m, 6.3 m, respectively) and wind speed (4.8 m/s, 5.3 m/s, respectively). Equation (3) shows that the coefficient of exponential growth may have depth dependence through the phase velocity. However, at both these depths the phase speed is for deep water waves, , for frequencies above 0.4 Hz. Equation (2) shows that the initial growth term has a dependence on . Thus the 10% difference in wind speed translates to a 50% increase in the initial growth term at the E location.

The terms and spread the windsea energy in direction-space. Hence, some high-frequency energy from the vicinity of location E propagates southward to location A, appearing as the southward travelling peak in figure 10a.

The notion that it is the presence of the strong land-breeze, during the night and morning of the 20th, that causes the two high-frequency peaks in longshore directions as seen in figure 5a was tested by running SWAN over the 19th and 20th, turning off all wind at
20:00 on the 19th. The resulting energy spectrum at 11:00 on the 20th is shown in figure 12.

![Energy Spectrum](image)

**Figure 12**: Two-dimensional energy spectrum at location A, at 11:00 on the 20th, for the SWAN run where wind is turned off at 20:00 on the 19th.

Comparing this plot to the energy spectrum at the same time and location in SWAN when the land-breeze has been blowing (figure 10a) we can see that, in the absence of the veering southerly wind followed by an easterly land-breeze, the two localized high-frequency peaks travelling in longshore directions are not present. The wind-sea at higher frequencies propagating from the southwest, from the previous sea-breeze has a frequency dependence similar to a JONSWAP spectrum, that is with an or dependence, which is quite different to the frequency dependence when the land breeze is present.

In the absence of wind forcing, the energy at high frequencies is maintained by the balance between loss due to whitecapping and gain by quadruplet interactions, or the shape stabilizing effect of the nonlinear term (Young, 1999). When a turning or opposing wind occurs, the quadruplet interactions act to distribute the energy in directional space, and the gain of energy at high frequencies is transferred to a different part of the directional spectrum.

**Discussion and Conclusions**

The implementation of SWAN using realistic winds over a sea-breeze/land-breeze cycle was able to successfully simulate the observed spectral evolution of wave energy. The
roles of wind-growth, whitecapping and quadruplet interactions were able to be explored, to offer insight into how the wave energy spectrum evolved. We focussed on the conditions during the sea-breeze of the evening of February 19th, followed by the land breeze of the morning of February 20th.

The SWAN simulations were found to be dependent on the choice of whitecapping scheme. The Alves-Banner scheme was found to produce wave energy frequency dependence more similar to that observed by the AWAC, compared to the Komen, and Battjes-Janssen schemes.

The non-dimensional fetch, peak frequency and duration were calculated from SWAN spectra, and showed consistency with the empirical relationships of Young (1999). These results showed that during the sea-breeze the wind-sea peak was for a duration-limited situation, and during the land-breeze the wind-sea peak was for a fetch-limited situation.

Wave growth from wind input during the land breeze was found to be dependent on distance from shore and wind speed. At offshore locations, with the same distance from land, wind-growth was sensitive to variations in wind speed through the initial growth term dependence on wind speed. Wave energy appears at high frequencies in the longshore directions, either propagating from earlier times while the wind was turning from the sea-breeze, or propagating from nearby locations where the wind was slightly stronger allowing wind growth.

In this case of sea breeze conditions turning and becoming land breeze conditions over several hours, the wind-sea peak is able to smoothly follow the wind direction. A consequence of this is that the quadruplet interactions, which act to remove energy from the wind-sea peak and add energy to high frequencies, tend to add energy to the waves being generated by the turning wind. Hence the whitecapping dissipation acting on the older windssea has more effect in when the wind turns. If the wind is turned off after the sea breeze duration, the wind-sea at high frequencies evolves keeping a stable JONSWAP-like shape due to the balance between whitecapping and quadruplet interactions.

Previous observation or modelling studies have not shown this longshore propagation of wave energy at high frequencies, in the presence of an offshore wind at fetch-limited locations. This study shows that SWAN is quite capable of capturing the behaviour of several peaks of wave energy with varied peak frequencies and directions, arising from quite varied histories. These conclusions about the spreading of wave energy at high frequencies, in cases that are both fetch-limited and duration-limited, have well tested the performance of the SWAN model.
References


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