Understanding the waves at Port Phillip Heads, Melbourne, Australia

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Abstract
Waves at Port Phillip Heads are energetic, complex, and important. Although waves arriving at the coast from the Southern Ocean are relatively uniform, in the heads they interact with tidal currents, which can exceed 3 m/s, and with complex bathymetry. This leads to a large degree of spatial and temporal variability. Port Phillip Heads are part of the approaches to the Port of Melbourne (Australia's largest container port). Wave-induced ship-motions can limit access to the port under certain conditions and the Port of Melbourne Corporation has invested heavily in wave measurement, analysis, and modelling to better understand and predict wave conditions in the shipping channel. This paper presents data and analysis achieved through the use of a range of instruments including sea-bed recorders, wave buoys, and wave radar. Key results include confirmation that, despite all the spatial complexity, most of the temporal variability in the waves measured in the shipping channel can be readily described by the 1D action balance equation. Complex wave patterns involving reflections of waves from bathymetry can be observed visually, in the wave radar, and in the measured data.

1 Introduction

Port Phillip Heads are located at the entrance to Port Phillip Bay, adjacent to the city of Melbourne, on the south coast of south eastern Australia (Figure 1). Port Phillip Bay is a large, but shallow, embayment about 1,930 km^2 in area and with an average depth of just 13 m. The bay receives little fresh water input (barely exceeding evaporation on an annual basis) and is vertically well mixed. At Port Phillip Heads the bay is constricted by rocky headlands to a width of just 3.5 km, resulting in strong tidal currents that can exceed 3 m/s during spring tides. Port Phillip Heads are exposed to Bass Strait, and energetic swell waves can propagate freely from the Southern Ocean, between King Island and the mainland, to arrive at Port Phillip Heads where they interact with the strong tidal currents and complex bathymetry to create wave conditions that vary greatly both in space and in time.

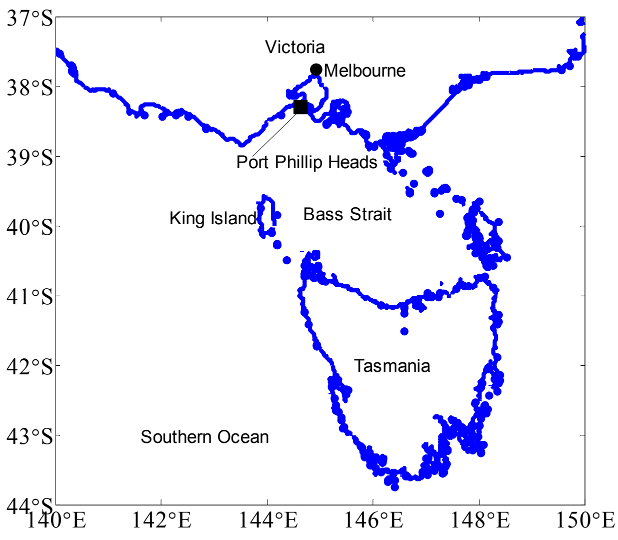

Figure 1 Location plan showing the gap between King Island and the mainland through which swell approaches Port Phillip Heads.

Port Phillip Bay is home to the Port of Melbourne, Australia's largest container port, and Port Phillip Heads are transited by several hundred deep draught vessels each year. Under certain conditions wave-induced ship-motions can limit access to the Port of Melbourne, and the Port of Melbourne Corporation is investigating the implementation of a Dynamic Underkeel Clearance (DUKC®) system (O'Brien 2002) in order to ensure that sufficient allowance is made for vessel motions during adverse conditions. As part of implementing the DUKC® system the Port of Melbourne Corporation has invested in wave measurements, analysis, and modelling to better understand and predict wave conditions in the shipping channel. This effort is now paying off, with a large quantity of high-quality data available to investigators, and has resulted in a greatly improved understanding of the processes affecting waves in Port Phillip Heads. This paper describes the data collected, and the analysis conducted in order to make detailed real-time predictions of wave spectra in Port Phillip Heads.

2 Data collected

Wave data has been collected at Port Phillip Heads for several years. Instrument types and locations have been selected to provide both reliable real-time wave data at selected critical locations for the proposed DUKC® system and a sound understanding of the spatial variations in wave conditions experienced in Port Phillip Heads.

"Offshore" wave data is collected by a group of Triaxys buoys located some 8 km southeast from the entrance in 25m water depth (Figure 2). Three wave buoys are used in rotation, with two buoys in the water at any one time in order to provide redundancy. In this location depth contours are relatively straight and parallel and waves are not significantly affected by tidal currents. Directional wave spectra (1.5D spectra) and key wave parameters are transmitted ashore from the buoys every 30 minutes and are stored in a central, remotely accessible, database along with meteorological conditions and water levels at several tide stations.

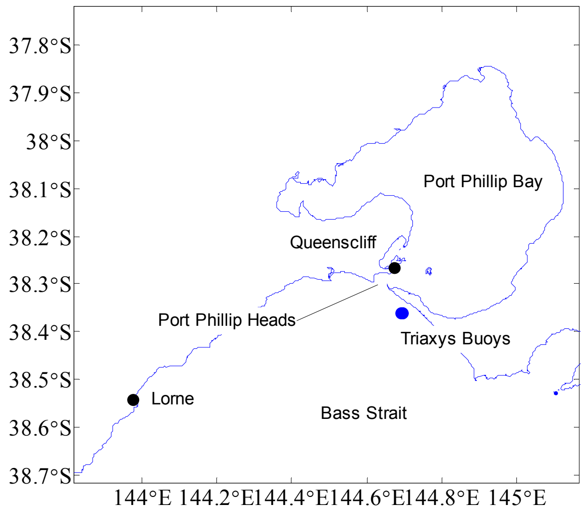

Figure 2 Map indication of Port Phillip Bay, Bass Strait, and the location the offshore Triaxys buoys. Tide gauges are located at Lorne and Queenscliff.

Environmental conditions are too extreme, and the risk of collision with vessels too high, for wave buoys to be deployed in or near the entrance channel, where the influence of tidal currents is felt. Bottom-mounted acoustic profilers (Nortek AWACs) have been deployed at three locations on the channel centreline for more than 1 year. Two instruments are used simultaneously, deployed by divers for durations of approximately 6 weeks at a time (Figure 3). The instruments are mounted in frames permanently bolted to the rocky sea floor in approximately 20 m of water. Local hollows in the rocky seabed were selected for the instruments to prevent damage by ship contact or passing debris.

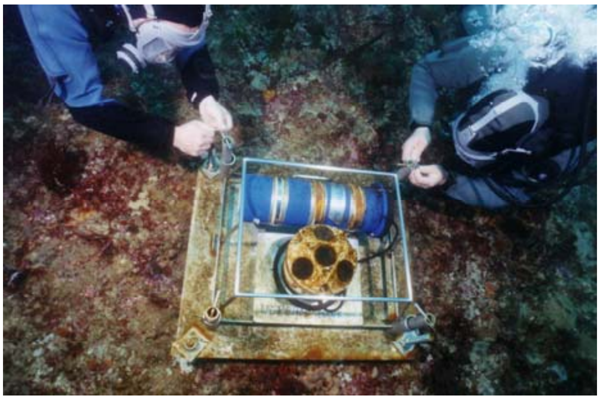

Figure 3 Divers recovering an AWAC instrument at Port Phillip Heads.

One of the advantages of using the AWAC instruments is that they include a vertical surface tracking beam which appears to be capable of providing a reasonably reliable range to surface even under the demanding conditions experienced at Port Phillip Heads. This provides a significant increase in confidence in the computed wave frequency spectra in this location where instruments which depend on pressure and/or velocity measurements for deriving wave surface elevation spectra can be unreliable due the interference of the strong tidal currents. Data from the AWAC instruments are not available in real time; they are downloaded from the instruments when removed from the water for maintenance between deployments. The locations of the AWAC deployments and indications of the complex bathymetry encountered at Port Phillip Heads are illustrated in Figure 4.

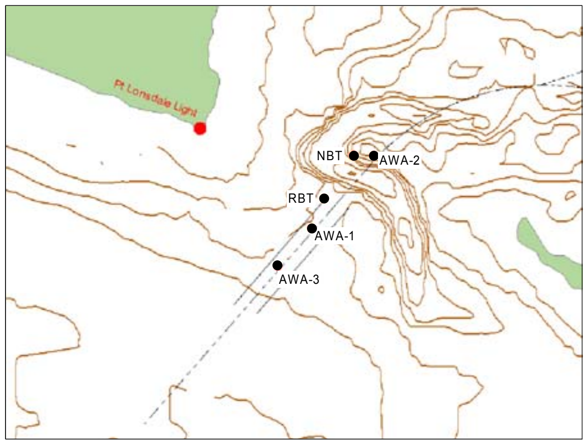

Figure 4 Port Phillip Heads indicating the complex bathymetry and the shipping channel. Locations of the AWAC deployments and the Point Lonsdale lighthouse are also included. Water depth at the AWAC instruments is approximately 20m and reaches over 90m in the submarine canyon.

This large quantity of high-quality wave data recorded simultaneously at different locations in Port Phillip Heads is extremely useful for building an understanding of the transformation of waves occurring under these complex conditions. As well as the spatial complexity in wave conditions, a significant temporal variation in wave conditions in Port Phillip Heads is also observed relative to the offshore conditions. This temporal variation is displayed in Figure 5, which presents a time series of Hm0 for both onshore and offshore locations. The lower panel shows the current phase and indicates that the variation in wave height is highly correlated with the currents in Port Phillip Heads.

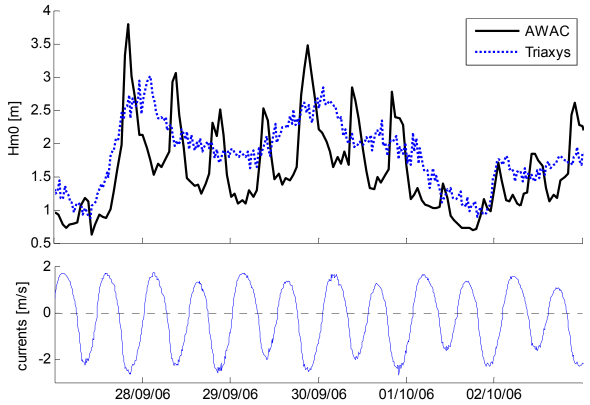

Figure 5 Timeseries of wave height and current speed (flood positive) recorded at AWA-1. Wave height recorded at offshore Triaxys buoy is included for reference. The amplification of wave height during ebb tide at this location is clearly visible.

Recently, a WaMoS wave radar (Reichert et al., 1998) has been installed at the Point Lonsdale Lighthouse, overlooking Port Phillip Heads (Figure 6). The radar has sufficient range to image waves right across the entrance channel due to preferential back-scattering of radar energy from the wave crests.

Figure 6 View of the radar antenna at Pt. Lonsdale Lighthouse

The radar back-scatter images are captured digitally at approximately 0.5 Hz and sequences of images provide clear evidence of the refraction, shoaling, and reflection that affects waves in various parts of the entrance. The WaMoS software also computes directional wave spectra and key wave parameters for individual analysis windows selected within the overall image. Advanced analysis techniques are used to derive wave spectra and surface current vectors from a sequence of backscatter images. This aspect of the WaMoS software is still undergoing calibration for local conditions.

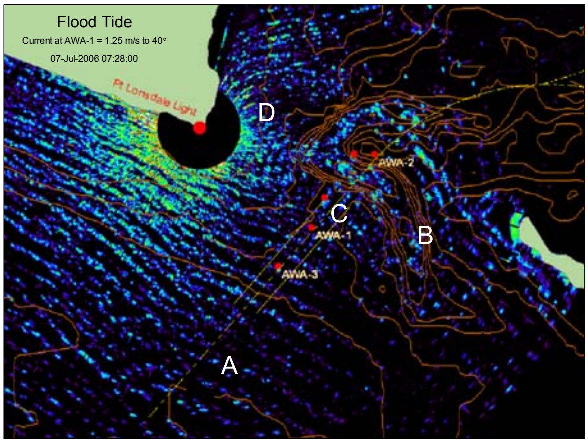

Figure 7 Example backscatter image from the WaMoS system. Lighter colours indicate higher backscatter from wave crests, or land. Labels AWA-x indicate AWAC instrument locations, letters A-D indicate locations affected by various physical processes – refer text.

An advantage of the WaMoS instrument over AWAC deployments is that WaMoS presents a spatial image enabling a view of the wave conditions over an area rather than at a single point. By analysing a sequence of WaMoS images it is possible to view individual waves propagating toward the coast and identify the refraction, shoaling and reflection that occurs as the waves interact with the bathymetry. Figure 7 shows a snapshot of a WaMoS image overlain by the coastline, bathymetry, shipping channel and AWAC locations. Offshore at location A the waves appear relatively uniform. As the waves propagate onshore refraction bends the waves toward shallower water. At location B it appears that the waves are being reflected off the steep inshore wall of the canyon cutting through Port Phillip Heads. These reflected waves can be observed travelling from east to west across Port Phillip Heads (location C), perpendicular to the waves approaching directly from the south. The reflected waves only affect a narrow band of the entrance channel, however they do pass over the old AWAC location RBT (Figure 4) close to the canyon wall, as discussed in the following paragraph. Evidence of wave refraction in the shallow water immediately adjacent to Pt Lonsdale can be clearly seen at location D, where the waves bend around the headland.

Figure 8 shows a directional-frequency wave energy spectrum recorded by and AWAC instrument at location RBT near to the edge of the canyon. The main peak of wave energy approaching from around 210° is clearly visible, however a second directional peak at similar frequencies can be seen approaching from approximately 95°.

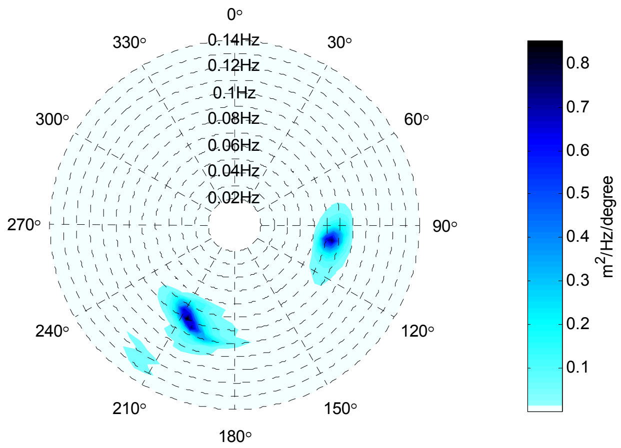

Figure 8 Directional spectra recorded by AWAC at RBT. The bimodal nature of the spectra is clearly indicating the wave energy reflected off the canyon wall and observed in the WaMoS images.

The AWAC measurements showing the bimodal spectra at RBT confirm the existence of the waves reflected by the canyon and observed by the WaMoS. The AWAC measurements also permit quantification of the amount of reflected energy for including in ship motion calculations, although the effects are minor as the duration of exposure is short. Combining data from the various instruments has enabled a better understanding of the wave conditions experienced in Port Phillip Heads. Without the WaMoS radar, the bimodal spectra observed at RBT, but nowhere else, could have been difficult to explain, but jointly they provide a thorough explanation of the wave processes and conditions occurring in the entrance channel.

3 Wave transformation algorithms

For real-time prediction and forecasting of vessel motions and underkeel clearance, the DUKC® system requires real time measurements and forecasts of the wave conditions in Port Phillip Heads. As previously noted, wave buoys cannot be installed in the shipping channel and, for this reason, a wave transformation algorithm has been developed to transform the wave spectra recorded by the Triaxys buoys to the wave conditions expected at various locations along the shipping channel within Port Phillip Heads. A further advantage of this approach is that the offshore conditions are more easily forecast as they are not affected by the semidiurnal tidal signal clearly visible in Figure 5.

An investigation of the data revealed that the temporal variation in the significant swell height in Port Phillip Heads could be explained by the 1D action balance equation with simple loss terms added to account for friction and 2D wave processes occurring within Port Phillip Heads. It is well known that when waves encounter an opposing current their wavelength decreases and their height increases, resulting in shorter steeper waves. Whereas when waves encounter a following current they become longer and lower. In Port Phillip Heads this means that the offshore wave height is amplified in the entrance channel during ebb tide and is suppressed during flood. The extent to which the waves change can be predicted, as wave "action" is conserved throughout the transformation. This is described by the 1D action balance equation (equation 1) (Smith, 1997).

$$\frac{\partial}{\partial x}\left(\frac{E\left(C_{gr}+U\right)}{\omega_r}\right)=0 \qquad (1)$$

where E is wave energy density (J/m^2), C_{gr} is group velocity of the waves relative to the current (m/s), U is the current speed in the wave direction (m/s), and ω_r is angular frequency of the waves as measured by an observer travelling with the current (rad/s).

Changes in wave height are also caused by changes in the local water depth; these changes are also included in the 1D action balance equation as any change in water depth will be reflected in an altered group velocity for the waves.

A wave transformation algorithm was developed by calculating the wave height predicted by the 1D action balance equation given the prevailing current speed and direction and then adjusting this calculated wave height using "loss" terms that were empirically fitted using measured AWAC data. These loss terms varied with offshore wave height and tidal phase and are in the range of 0.7 – 0.95 at location AWA-1. Losses are greater the further the waves penetrate into the entrance. As the DUKC® requires a wave spectrum to perform its calculations, the 1D action balance equation was applied independently to each spectral frequency bin. This is necessary because higher frequency waves are influenced more by currents than lower frequency waves, with the result that in addition to a change in wave height a change in spectral shape is observed between onshore and offshore wave spectra. This shape change is not because energy is shifting in the frequency domain, but rather because the energy density in higher frequencies is being increased (or decreased) more than in lower frequencies.

This analysis resulted in an algorithm that could accurately predict the wave conditions at various locations within in Port Phillip Heads, given the offshore wave conditions, the local current speed and direction, and the offshore and onshore water depths. Because the implementation of the algorithm in an operational system requires real time knowledge of the currents in Port Phillip Heads, and these are not measured in real time, an accurate predictor of the currents was also required.

An algorithm predicting the currents was developed based on the findings of a previous study (Lawson and Treloar, 1988.) which indicated that the current speed in Port Phillip Heads is highly correlated with the water level gradient across The Heads: taken as the difference in water level between Lorne and Queenscliff tide gauges (Figure 2). Due to effects such as inertia, bottom friction, and flow asymmetry, the current speed vs. water level gradient relationship displays a hysteresis curve with rising and falling limbs, as shown in Figure 9.

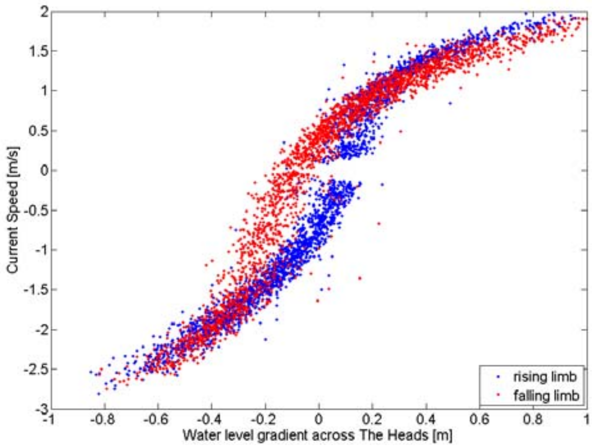

Figure 9 Illustration of the hysteresis relationship between the signed current speed (flood positive) and water level gradient across Port Phillip Head at location AWA-1.

The rising limb covers the decay of ebb currents and growth of flood currents (inward-directed gradient and acceleration), and the falling limb covers the decay of flood currents and the growth of ebb currents (outward-directed gradient and acceleration). These limbs were modelled separately and the temporal change in water level gradient was used to select between the two limbs: positive rising limb, negative falling limb. The current direction can relatively easily be established as a strong relationship exists between the signed (ebb/flood) current speed and the current direction.

The prediction of the current at various locations along the shipping channel is very successful as the scatter plot of Figure 10 indicates the results of applying the current prediction algorithm to 12 weeks of independent data. Statistics: R^2=0.9 and 90% confidence range +/- 0.27m/s. The success of the overall wave transformation algorithm, incorporating the current prediction algorithm in the wave prediction algorithm, is indicated by the scatter plot of Figure 11 which again shows validation against 12 weeks of independent data. The 90% confidence interval for predicted wave heights in Port Phillip Heads using the wave transformation algorithms is approximately +/- 0.5m under typical conditions (offshore Hs < 2m) and up to +/- 0.8m under extreme conditions. This level of uncertainty can readily be incorporated into the DUKC® system to ensure that safe UKC allowances are made without unduly affecting the efficiency of the system.

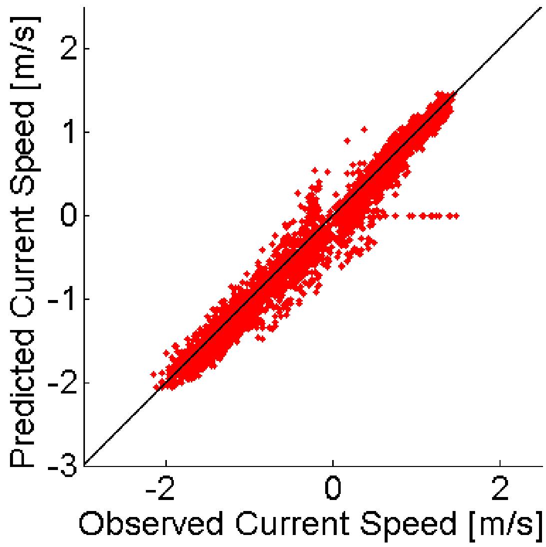

Figure 10 An example of the validation of predicted currents at AWA-3. The axes are directed flood positive.

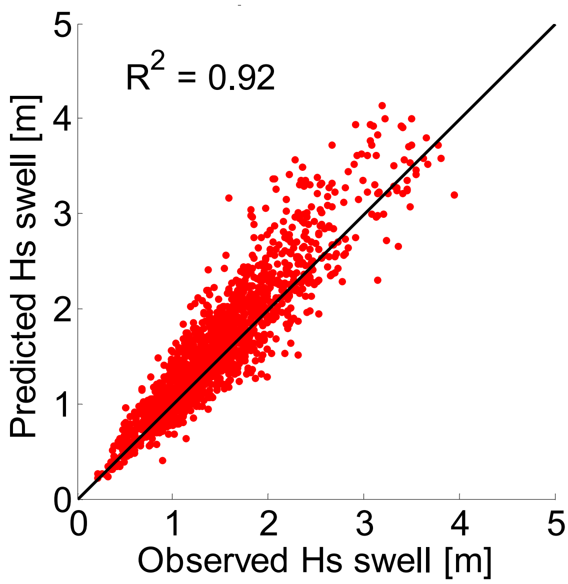

Figure 11 An example of the validation of Hm0 at AWA-3.

An example of the application of the wave transformation algorithm to wave spectra is shown in Figure 12. In this figure an offshore frequency spectrum is plotted along with a concurrent onshore frequency spectrum measured at AWA-1. The frequency spectrum predicted by the wave transformation algorithm using the offshore wave spectrum is also shown. The relatively larger growth of energy density in higher frequencies, as predicted by the 1D action balance equation, is observed and successfully predicted by the algorithm.

The importance of accurate spectral wave transformation algorithms is illustrated by the lower panel of Figure 12 which plots vessel wave response amplitude operators for pitch motions for typical Handymax and Post-Panamax sized vessels. This panel indicates the sensitivity of vessel response to the frequency of incoming energy over a range of frequencies from 0.04-0.14 Hz. Accurate prediction of the spectral distribution of energy in this range is important for accurate prediction of vessel motion.

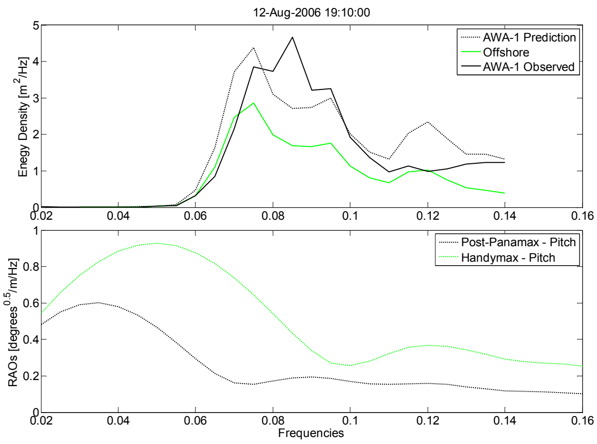

Figure 12 Transformed and measured wave spectra at location AWA-1 together with offshore measured spectra (upper panel). Vessel Response Amplitude Operators for Roll and Pitch motions for typical Handymax and Post-Panamax sized vessels.

4 Discussion / Conclusions

The waves in Port Phillip Heads have a well-earned reputation for their power and their rapid and seemingly random variation in space and time. The problem of understanding and predicting wave conditions in Port Phillip Heads has been surmounted by an extensive measuring campaign using a range of instruments combined with careful analysis of the data. Data analysis first focussed on understanding which physical processes were occurring and then, when the physical processes were qualitatively well understood, accurate prediction and forecasting of the wave conditions was achieved using well-established and relatively straightforward mathematical expressions which have been thoroughly validated against independent wave data.

This approach shows the benefit of collecting a variety of spatial (WaMoS) and point (AWAC) data and highlights some of the relative strengths of each of these two instrument types.

5 Acknowledgements

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