Spectral wave prediction with imperfect forecasts

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Abstract

The short-term prediction of wave conditions can have significant economic implications for port shipping operations. Better prediction accuracy can potentially increase loading drafts while also increasing the probability of the loaded vessel being able to safely traverse port harbor channel. This paper describes a new approach to achieving improved swell predictions for use in ship movement planning.

With no ideal forecast source for swell conditions available, a method of combining multiple forecast sources was investigated to determine a best-estimate swell forecast. Numerical wave forecasting models can provide forecasts of wave states for specified locations, however for many locations the forecast quality can be insufficient for ship loading and movement planning. Nevertheless, forecasts at various locations from such numerical models display significant skill for different parts of the wave spectra. The Wave Spectral Predictor (WaSP) takes advantage of such sources by combining them with other available information, including recent wave measurements at the target port and other locations, to derive a prediction of the wave conditions at a targeted sailing location and time. Uncertainties in the predictions are managed in both time and frequency domain in order to allow for the sensitivity of vessel wave response to changes in swell frequencies.

Included in this paper is a description of the principles of the WaSP methodology and a case study of its application at a port in North West Australia.

1 Introduction

Regional wave condition forecasting can have significant implications for port operations planning. The advent of readily available forecasts from numerical models means that these results can now be incorporated into under-keel clearance (UKC) calculations to forecast loading drafts and sailing windows. Experience shows that this can reduce risk to the operators, increase loading drafts and extend tidal sailing windows and useful planning periods when compared to making estimates based on the statistical growth of locally measured swell conditions.

Exploratory studies performed for the implementation of such a scheme at a port in Dampier, on the North West Shelf of Australia, showed that the available numerical model forecasts did not by themselves display the required level of reliability for the scheduling of major shipping operations. Issues such as the time resolution of the forecasts, the model output locations available and the variable quality of the forecasts meant that they required processing (similar to the forecast ‘production line’ suggested by Guddal, 1999) before they could be utilised operationally.

While techniques for error forecasting in numerical model forecasts have been explored previously (Babovic *et. al*, 2005), these methods can be complex and tend to focus on parameters such as a significant wave height and/or peak/mean period as opposed to full spectra. A specific requirement of this analysis was the prediction of longer period swells, which are poorly correlated with the local wind fields.

The analysis detailed in this paper was completed for the Pilbara Iron port in Dampier (WA) using WAve Model (WAM) output point forecasts. These forecasts were provided by the Bureau of Meteorology’s ‘meso-scale’ third generation WAM model (WAMDI, 1988). The resulting method (dubbed the Wave Spectral Predictor, WaSP) was found to be portable enough for implementation anywhere that measures wave data and has sufficiently accurate forecasts available. In order to successfully implement the WaSP method, forecast accuracy needs to be evaluated over a historical period of at least six months.

2 Analysis of Wave Forecasts

The initial aim of this study was to determine the usefulness of the available forecasts, compared with using wave measurements and allowing for swell growth. To aid in this process, a parameterisation technique was developed to encapsulate key properties of wave spectra over long time periods.

2.1 Parameterisation of Spectra

The accurate prediction of energy in a range of wave periods (i.e. wave spectra) is necessary as ship wave response is sensitive to wave frequency as well as height, to the point where simply predicting a significant swell height and period (such as HsSwell, TpSwell) is insufficient for the purposes of draft forecasting in UKC calculations. Spectral predictions of the swell band are therefore required. However, this makes initial forecast evaluation difficult due to the complexity of comparing large amounts of three-dimensional data (time, frequency, energy density) which may have different time and frequency bases. In order to simplify the problem, a technique of summarising the wave spectra into wave-height parameters based on spectral bands is utilised.

The parameter definitions include transitional regions in frequency space as shown in Figure 2-1, based on the observation that measured spectral modes tend to move across frequency bins, so spectral parameters can only be semi-independent.

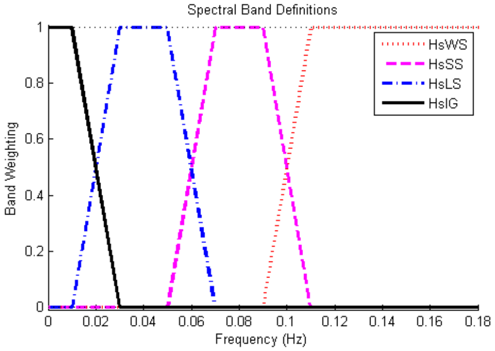

Figure 2-1 Spectral Band Pass Filter definitions for parameterised wave spectra

The transition regions were selected to minimise the noise introduced by this movement of energy. The parameter band definitions were defined as:

- HsWS – local wind sea waves
    - Frequency Band: ∞-0.11-0.09 Hz (approx. 0-10s)
- HsSS - short swell waves
    - Frequency Band: 0.11-0.09-0.07-0.05 Hz (approx 10-17s)
- HsLS - long swell waves
    - Frequency Band: 0.07-0.05-0.03-0.01 Hz (approx. 17-50s)
- HsIG - infra-gravity waves
    - Frequency Band: 0.03-0.01-0 Hz (approx. 50s+)

The band parameters were selected such that HsSS and HsLS were good indicators of the wave-induced roll and pitch motions for the type of the vessels under consideration (bulk carriers) respectively. The equations for the calculation of these parameters are shown in Eq. 1 and 2:

$$HsXX \approx Hm_0XX = 4\sqrt{m_0XX} \qquad (1)$$

$$m_0XX = \int S(f)B_{XX}(f)df \qquad (2)$$

Where B_{XX} is the band-pass filter weighting of the parameter XX as indicated in Figure 2-1; and S is the wave spectral energy density as a function of frequency.

These parameters allow multiple WAM output points to be quantitatively compared with measured data from the target location for different spectral bands.

2.2 Forecast Evaluation

In order to evaluate the WAM forecast data, a matrix of correlations for the WAM forecasts against measurement data was generated (see Table 2-1). The data correlations vary with time and forecast horizon as can be seen in Figure 2-2. Measured data autocorrelations were also generated in order to evaluate wave condition ‘persistence’. More persistent wave conditions reduce the value of forecasts, since they indicate relatively static wave states.

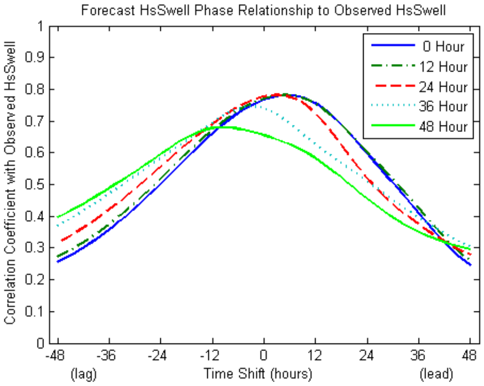

Figure 2-2 Correlation diagram for Dampier WAM output point forecasts (vs. measured data) (Hs[7-25s])

The correlations shown in Table 2-1 were generated for a 4-month set of synchronous data in order to directly compare the WAM output points shown in Figure 2-3. Longer correlation periods up to 18 months for individual points did not deviate significantly from these values. No correlations for HsIG are available since the WAM outputs do not extend to these frequencies.

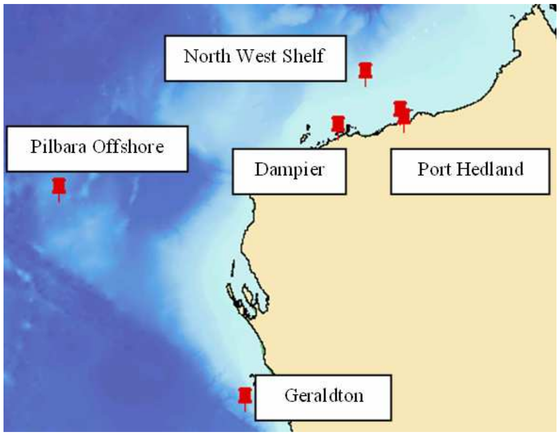

Figure 2-3 Output points for the WAM model around the North-West Shelf of Australia

Table 2-1 Dampier Parameter Correlations Matrix (against measured data 25 May to 25 September 2006)

	Bureau of Meteorology WAM Points, 12 hour forecast horizon					Auto-Correlations	
Parameter	**Geraldton**	**Pilbara Offshore**	**North-West Shelf**	**Dampier**	**Port Hedland**	**12hr**	**24hr**
HsWS (m)	-0.2	-0.1	0.55	0.66	0.46	0.83	0.77
HsSS (m)	0.58	0.53	0.71	0.55	0.65	0.76	0.6
HsLS (m)	0.67	0.75	0.69	0.49	0.48	0.76	0.48
HsIG (m)	n/a	n/a	n/a	n/a	n/a	0.42	0.52
HsSwell (m)	0.43	0.41	0.61	0.47	0.5	0.73	0.54
Dominant Time Shift (hours)	+24	+24	-8	+9	-10	+12	+24

Table 2-1 shows the peak WAM forecast correlations when time-adjusted for maximum correlations. Positive time shifts indicate that the signal tends to 'lead' measured events, and the negatives 'lag'.

WAM output points in deeper water and to the west of the target location show better correlations with the short and long swell wave energies observed than the Dampier output point situated closer to the measurement location. To compensate for the deficiencies in the local forecasts, data from these less regional points is included in the construction of an 'overall' forecast for the output location.

A simple magnitude transformation using a mean-matching scaling factor was chosen to transform these different WAM output points to the target location (along with time-adjusting). The scale and time shift adjustments were chosen independently for each band. These lightweight transformations were chosen with real-time operation and limited computational overhead requirements in mind.

3 Integration of multiple forecast sources

Including multiple data sources in the predictions requires a method for choosing and combining optimal sources for each band. This aggregation is used for both producing an 'overall' forecast from multiple forecast sources as well as creating a 'prediction' which combines the current measured wave state with the 'overall' forecast.

3.1 Combining forecast sources

Pairs of sources are combined according to minimising RMS error in each parameter over the historical record and ranked accordingly. The recombination occurs spectrally as in Eq. 3.

$$S_{cf} = \sum_{XX}^{N} B_{XX}\left(\beta_{ij,XX} S_{f,i} + (1-\beta_{ij,XX}) S_{f,j}\right) \tag{3}$$

Where S_f is a forecast wave energy spectrum; S_{cf} is the combined forecast spectral energy; i and j are the best two available forecast sources for the current XX band; N is the number of bands; and $\beta_{ij,XX}$ is the weighting coefficient for the two forecast sources i and j for band XX.

Combining pairs of WAM outputs produces superior results compared to using single forecasts per band, because local WAM points sometimes forecast local events (e.g. cyclones) that the overall better correlated but more distant points do not. Multiple combination options are available in order to allow for forecast unavailability.

The elementary combination method shown here may be extended in the future to use more sources per band and to use more discerning source choosing techniques. The β weightings at Dampier are shown in Table 3-1.

Table 3-1 β weighting coefficients between pairs of WAM forecast output points for Dampier

β_{WS}	i	**Pilbara Offshore**	**NW Shelf**	**Dampier**	**Port Hedland**
j		5	3	2	4
Geraldton	4	0	0	0	0
Pilbara Offshore	3		0	0	0
NW Shelf	2	1		0.15	0.94
Dampier	1	1	0.85		1

β_{SS}	i	**Pilbara Offshore**	**NW Shelf**	**Dampier**	**Port Hedland**
j		2	3	4	5
Geraldton	3	0.48	0.31	0.67	0.71
Pilbara Offshore	1		0.31	0.66	0.70
NW Shelf	2	0.69		1	1
Dampier	4	0.34	0		0.66

β_{LS}	I	**Pilbara Offshore**	**NW Shelf**	**Dampier**	**Port Hedland**
j		2	3	4	5
Geraldton	3	0.21	0.38	0.79	0.80
Pilbara Offshore	1		0.70	0.93	0.93
NW Shelf	2	0.30		1	1
Dampier	4	0.07	0		0.99

E.g. if the best sources available for band WS are 'NW Shelf' and 'Port Hedland', the 'NW Shelf' spectrum is weighted by $\beta_{24,WS}$ = 0.94 and 'Port Hedland' by 0.06.

In this way, a series of best ‘overall’ forecasts can be assembled as a combination of many, as demonstrated in Figure 3-1 and Figure 3-2.

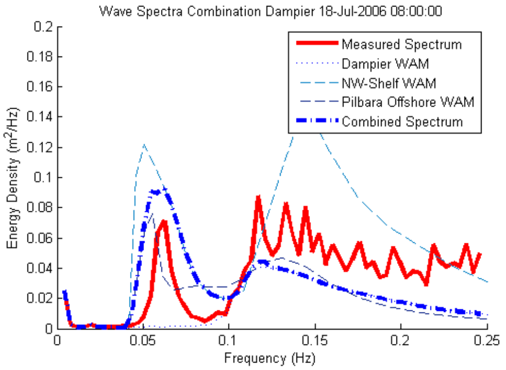

Figure 3-1 Spectral combination of different WAM forecasts against measured spectrum (example 1)

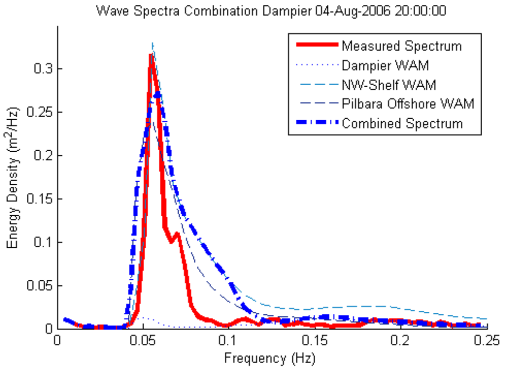

Figure 3-2 Spectral combination of different WAM forecasts against measured spectrum (example 2)

For Dampier, the source that consistently combined to produce the lowest RMS error in HsWS was the ‘Dampier’ WAM output point, as expected. However for HsSS, ‘Pilbara Offshore’ was the preferred source followed by ‘North-West Shelf’, and interestingly the inverse was found for HsLS.

3.2 Combining forecasts with measured data

Due to wave persistence, measured wave spectra are useful as indicators of near future wave spectra, as demonstrated by the autocorrelation values of the correlations matrix (Table 2-1). However this usefulness decreases as forecast horizon (time lag) increases, and varies with frequency band. Predictions are therefore made as a weighted combination of the combined forecast from WAM and other sources and the most recent measured wave as shown in Eq. 4.

$$S_{pr} = \sum_{XX}^{N} B_{XX}\left(\alpha_{XX} S_m + (1-\alpha_{XX}) S_{cf}\right) \qquad (4)$$

Where S_{pr} is the predicted wave spectrum; S_m is the most recent measured wave spectrum; and α_{XX} is the weighting coefficient for band XX at the selected forecast horizon.

The weightings applied to the locally measured waves against the overall forecast are dependant on the interaction between forecast accuracy and the wave condition persistence. The value of each can be seen in Figure 3-3 and Figure 3-4, where the ‘prediction’ tracks the measured data better as a result of combining the forecast and the latest measurements.

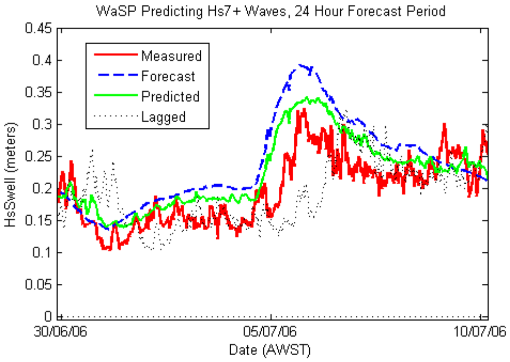

Figure 3-3 Comparison of Predicted and Measured HsSwell at Dampier (10 day period)

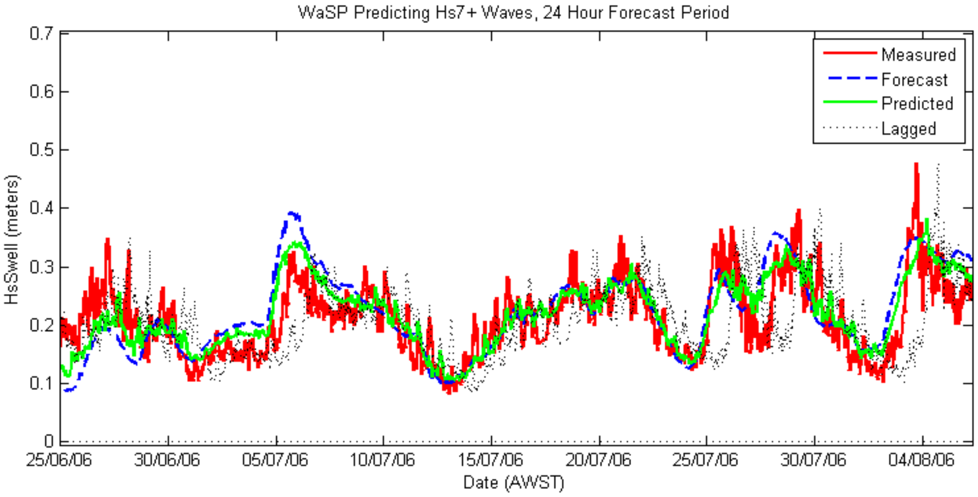

Figure 3-4 Comparison of Predicted and Measured HsSwell at Dampier (42 day period)

The α weighting coefficients are determined by finding the optimal combinations of the measured and forecast spectra by minimising spectral RMS error over time as a function of forecast horizon. Different α values are chosen for different parameter bands.

The resulting weighting relationships for Dampier are graphed as seen in Figure 3-5.

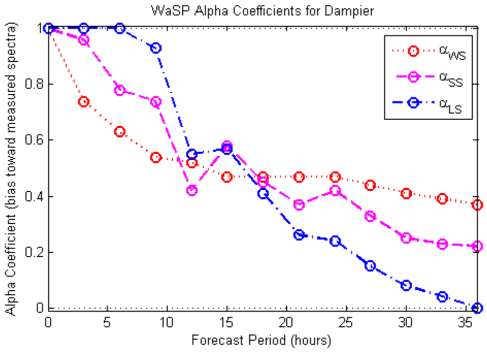

Figure 3-5 α coefficients for Dampier – predictions biased toward measurements for forecast horizons up to 15 hours

By contrast, a target location near the Heads of Port Phillip Bay demonstrates a much clearer benefit from using numerical model forecasts, as seen in Figure 3-6.

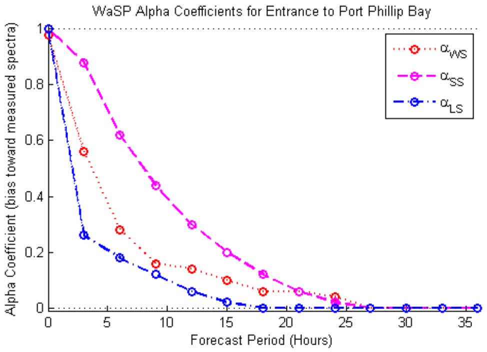

Figure 3-6 α coefficients for Melbourne – predictions biased toward measurements for forecast horizons up to 3 hours for HsLS, and 9 hours for HsSS

4 Allowing for uncertainty

Since the art of swell forecasting is imperfect, a method of allowing for errors is an extremely important aspect for utilising WaSP predictions in port operations, such as at Dampier where a prediction of the upper limit of swell conditions is required. Therefore, conservatism is added to the spectral estimates in order to cover a specified percentage of under-predicted wave conditions. The predictions get closer to reality as the forecast horizon reduces, so less conservatism need be added for the same level of risk. The desirable implication for shipping operators is that draft yields typically improve as the forecast horizon decreases.

A method for adding the conservatism spectrally is utilised through the analysis of historical error in the predictions. This historical error is generated by back-simulating a series of predictions against the measured spectra. Conservative error spectra are then applied to the predictions using a tunable method which enables the resulting conservative predictions to suit the port operation's needs. This tuning requires the careful balancing of:

- the risk of wave response predictions being exceeded (resulting in a no-sail situation for the forecast sailing draft)
- maximising average economic sailing draft (which increases with lower predicted swell waves)
- self-consistency (explained below)

If predictions are requested at several different occasions for the same transit time, and if either measured conditions or forecasts have deteriorated more rapidly than allowed for by conservatism between those two times, then the forecast sailing draft will be reduced. This can occur even when the initial prediction was similar to the ultimate sailing draft, due to changes in forecast and/or measured conditions in the meantime.

The effect of such occurrences is to decrease user confidence in the system and increasing the risk to port operations when guaranteeing sailing drafts. The behaviour of the conservative predictions must therefore be tuned to minimise the occurrence of these events in accordance with the end user's needs, such that predicted drafts typically increase as the forecast horizon decreases.

5 Results

In order to evaluate the benefits of using the WaSP methodology, vessel wave response motions were simulated for a 7-month period with 200 sets of different vessel stability data for comparison against the swell growth model (SGM). The WaSP was tuned to deliver a reduced but similar exceedence probability compared to a traditional SGM implementation.

As a result of improved swell wave prediction (including conservative allowances), the WaSP showed that a marginal average draft gain of 5cm was possible for the 12-hour forecast horizon at Dampier, along with a marginally reduced probability of exceedence. However for longer forecast horizons the gains were much greater, with average draft benefits of 30cm for the 24-hour forecast horizon and 60cm for the 36-hour forecasts. Figures 5-1 to 5-4 show the improvement in predicted vertical wave response achieved for various forecast horizons. The plots display residual error distributions for a typical bulk carrier over a 7-month period at Dampier.

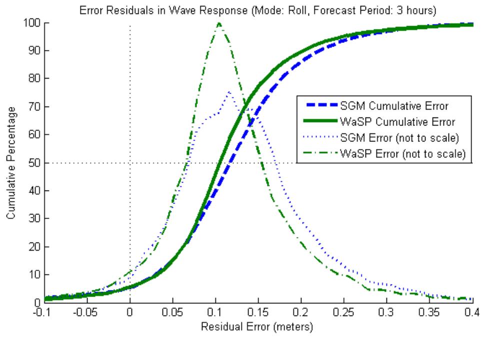

Figure 5-1 Over-prediction of (maximum) vessel wave response, 3-hour forecast horizon

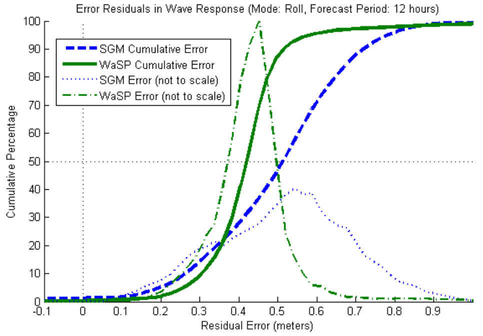

Figure 5-2 Over-prediction of (maximum) vessel wave response, 12-hour forecast horizon

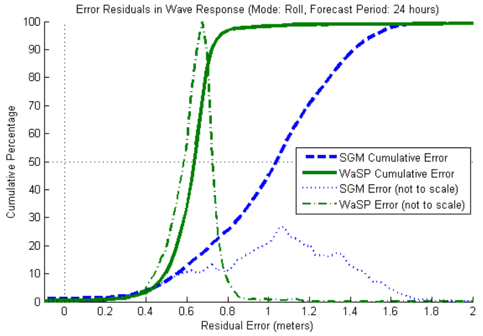

Figure 5-3 Over-prediction of (maximum) vessel wave response, 24-hour forecast horizon

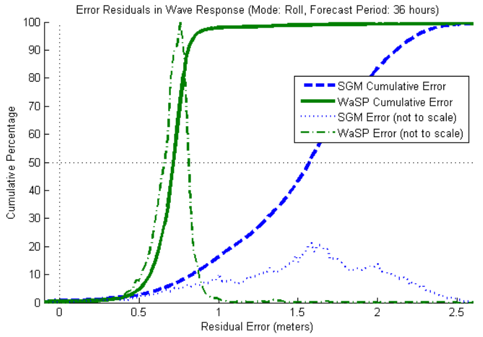

Figure 5-4 Over-prediction of vessel wave response, 36-hour forecast horizon

Only modest gains were possible for forecast horizons shorter than 12 hours, but improved rapidly for longer horizons due to increasingly tight error distributions compared to the SGM implementation.

During exploratory analyses, similar or better results have been realised for other locations around Australia where the accuracy of the WAM forecasts matched or exceeded the accuracy of the Dampier forecasts.

6 Conclusions

The benefits of including swell forecasts from numerical models in port operations planning tools are significant, potentially improving economic draft yields and sailing windows as well as extending useful sailing planning periods by increasing the accuracy of UKC predictions. These benefits can be quickly and simply implemented using the WaSP method, enabling data fusion in a flexible manner so that multiple forecast sources can be assimilated with minimal computational overheads.

Far from being limited to WAM model outputs, the WaSP methodology is designed to accept inputs from generic forecast sources such as nested SWAN models and in-situ wave measurements from offshore wave buoys, platforms or nearby ports.

7 Future Directions

Future directions for extension and improvement of the WaSP method include:

- more advanced and/or dynamic data assimilation techniques for determining α and β coefficients (e.g. the Local Linear Model, Babovic et. al, 2005), and
- the utilisation of directional wave data in order to expand the WaSP outputs from 1D to 1.5D or 2D wave spectra.

8 Acknowledgements

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9 References

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