ENSEMBLE TURNING-POINT WATER LEVEL PREDICTIONS FOR UNCERTAINTY ESTIMATION FOR SHORT-HORIZON PLANNING AND RISK ASSESSMENT

BURAK USLU[1], GREGORY K. HIBBERT[1], GILES LESSER[1], JENNIFER PENTON[2]

1OMC INTERNATIONAL PTY LTD, MELBOURNE, AUSTRALIA; B.USLU@OMCINTERNATIONAL.COM

2 UNIVERSITY OF WESTERN AUSTRALIA, PERTH, AUSTRALIA

ABSTRACT

This paper describes a probabilistic approach to achieving improved water level predictions, designed for use in ship movement planning. The short-horizon prediction of water levels and storm surge anomaly can have significant economic implications for port shipping operations. Accurate assessment of the uncertainty in the water level predictions, particularly around tidal high water turning points, can enhance the prediction of maximum sailing drafts and improve the reliability of predicted windows of opportunity for safe transit through depth-constrained shipping channels. In the presence of tidal oscillations and storm-surge anomalies, this approach for estimating water levels uses the astronomically determined turning points (i.e. at local high and low waters) as the reference points for comparison with observed water levels. The apparent time-shift (lag) and height offset (residual) of the observations compared to the astronomical time series are used to determine climatic distributions. Together with a persistence model, these distributions are then used to generate a time-series ensemble to span the risk assessment forecast horizon, typically six to 96 hours. The data model has been designed to be able to incorporate external predictors such as those produced by numerical models. Included in this paper is a description of the principles of the methodology and a case study of its application to the Port of Weipa in Queensland, Australia.

Keywords: Tides, storm surges, forecasting, uncertainty, under-keel clearance

1 INTRODUCTION

Planning and executing shipping movements in depth-constrained channels depends on multiple factors which include physical, economic and natural constraints. For deep draft vessels transiting a port, one of the major constraints for planning the vessel movements is under keel clearance (UKC). Under-keel clearance is the vertical distance between the vessel's keel and the sea bed. Insufficient UKC can lead to vessel grounding events through either direct bottom touch events or indirectly due to the loss of manoeuvrability. As a vessel's draft increases, its UKC is decreased assuming all other factors are held constant. To ensure planned transits are safe, ports mandate UKC limits that must be maintained.

Generally speaking, this can take two distinct forms: i) a gross or static allowance for UKC which makes a fixed UKC allowance to safely cover all factors that influence UKC, or ii) a dynamic UKC approach which mandates a fixed net UKC allowance but determines on a case by case basis the UKC allowances required for each specific sailing.

This paper will focus on the latter approach to UKC management. In particular, utilising the Dynamic Under Keel Clearance (DUKC®) methodology as pioneered by OMC International and implemented at a several Australian and overseas ports.

Operationally, planning the maximum safe sailing draft of a vessel utilising DUKC® requires an accurate determination of the UKC anticipated along the scheduled sailing route in space and time. Accurate prediction of UKC requires combining numerical modelling with data including vessel characteristics (particulars and planned loading state including draft), transit characteristics (e.g. channel depths and planned manoeuvre speeds) and environmental conditions predicted for the time of sailing (wave, tides, and currents).

Given that planning decisions for sailing drafts must be made many hours prior to transit, forecasts are required to allow for change in environmental conditions over the prediction period from prevailing measured conditions. As such, reducing the uncertainty of water level forecasts can directly increase the target draft for loading operations, therefore yielding significant economic throughput benefits.

Specifically, at the Port of Weipa on the north-west coast of Cape York Peninsula in north Queensland, shipping operations are primarily concerned with the export of bauxite. Approximately 25 million tons of this product is exported through the port in 2012, on board 475 [1] capsize bulk cargo vessels. On these large vessels a 1 cm increase in vessel sailing draft translates to approximately 80 tons of additional cargo transported. That implies that, for the port of Weipa, if average sailing drafts could be increased by 10 cm, then the annual bauxite exports could be transported on approximately 7 fewer vessels, resulting in significant freight and environmental savings for the same throughput.

Tides are primarily a result of gravitational forces from the moon and the sun, and in Australia astronomical predictions for most ports can be obtained from the National Tidal Centre [2].

However these predictions based on harmonic analysis cannot account for the short-term meteorological and oceanographic effects that cause water levels to deviate from the astronomical predictions.

The improvements to water level predictions need to account not only for improved accuracy but also to improve the stability and self-consistency of forecasts through successively issued predictions. While forecasts which react to short-term changes in conditions may produce more accurate estimates, the changeability of such predictions can burden port operations with uncertainty on the final sailing outcome and as a result force the occasional sailing cancellation. Conversely, predictions based only on astronomical tides may produce perfectly stable water level estimates at the cost of accuracy, forcing the operations to conservatively plan on lower sailing drafts to allow for the greater uncertainty. Thus a key requirement of an improved prediction regime is to balance the trade-off between accuracy and stability, adapted to suit the port operations. Good predictions will not only provide economic benefits and safer shipping, but by reducing the likelihood of accidental vessel groundings the improvements can also have a beneficial environmental impact.

2 PORT OPERATIONS

The DUKC® at Port of Weipa makes initial predictions of maximum sailing draft approximately 24 hours prior to sailing time. This information is used to set the initial draft target for the loaders. This initial draft amount has a conservative margin of safety subtracted from the DUKC® calculated maximum draft. Typically a vessel will be loaded to less than 85% of the target draft before a second draft prediction is made, approximately 8 hours prior to sailing time. This second prediction is used to set the sailing draft. A final draft check is made two hours before planned sailing time, when a final determination of whether it is safe for the vessel to sail given the actual vessel draft and prevailing environmental conditions (e.g. tide anomaly).

Most bulk export ports including Weipa do not have unloading facilities, so if the vessel has been loaded to a draft that exceeds the final check, the sailing must be cancelled and the vessel waits for the next higher tide [3]. Cancelling a departure is an extremely expensive exercise, with the laden vessel tying up the loading berth and preventing other vessel movements, so it is important that the water level predictions used in the first two draft predictions are sufficiently conservative. Conversely, overly conservative forecasts will reduce the sailing's draft efficiency, as previously discussed.

Instability or inconsistency (termed nervousness in this paper), is another undesirable feature of water level forecasts used for draft planning. Jumps in water level forecast values between subsequent forecasts cause consequential jumps in maximum draft which reduces user confidence in the system.

2.1 MOTIVATIONS

The main objective for developing this water level prediction method is to reduce the nervousness (instability/inconsistency) of water level predictions used for port operations while maintaining or improving accuracy.

Specifically the model aims to:

- Improve the benefit of DUKC® advice, through reducing draft-related sailing cancelations and increasing the stability of predictions, thereby allowing improved integration with port operations.
-
- Improve the accuracy of the forecast, and thereby reduce the average conservatism required. Currently at Weipa, water level predictions for draft planning are used 8 hours prior to transit and are, on average, 18 cm lower than those measured at sailing time.

2.2 TIDES IN WEIPA PORT

Weipa experiences diurnal tides with a high astronomical tide (HAT) of 3.38 m [4]. During the wet season, observed water levels can exceed this value and the highest water level of 4.27 m is recorded near Embley River [5]. This study analysed both continuous observations and astronomical tide predictions from October 2006 until January 2011.

3 METHOD

A statistical analysis indicates that water level deviations from astronomical predictions can persist through multiple tide cycles. For instance, the local excess water build-up caused by a major storm surge (e.g. due to tropical cyclone activity) typically will not fall to normal level within 24 hours. Table 1 demonstrates this persistence in auto-correlations between the residual (local level anomaly) at successive tide turning points. In comparison, the lag (temporal shift of the turning point) does not demonstrate much statistical persistence. The statistics for high and low waters turning points (HW and LW respectively) were calculated separately.

Table 1. Correlation coefficients between turning points for lags and residuals from Weipa tide analysis for 2007-2014 are listed below.

Correlation Coefficients						
Turning Points	0	1	2	3	4	5
Residual HW	1.000	0.74	0.56	0.53	0.45	0.36
Residual LW	1.000	0.75	0.57	0.53	0.42	0.34
Lags HW	1.000	0.29	0.07	0.00	0.00	0.02
Lags LW	1.000	0.44	0.25	0.19	0.11	0.05

The model approach takes advantage of the persistence of successive turning point lag and residual anomaly to construct a statistically consistent ensemble of potential future water levels using a Monte Carlo approach.

First an analysis phase produces the statistical models for the algorithm. This analysis is performed over a historic data set and includes identifying the time of each high and low water measurements, computing all residuals, determining correlations between each high and low water measurements with their lags and residuals and producing statistical distributions (see Table 2 and

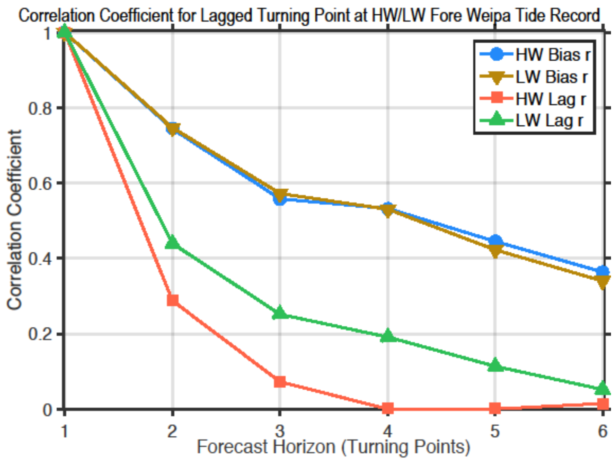

Figure 1). At Weipa, the time between sucessive local high and low waters can be inconsistent due to the phase of separate tidal components with similar amplitudes converging and diverging over time. This has been problematic for planning ship movements based on high waters, since the "significant" high water can sometimes be ambiguous. The analysis & evaluation statistics throughout this report rely on only the higher HW from each cycle (see Figure 2).

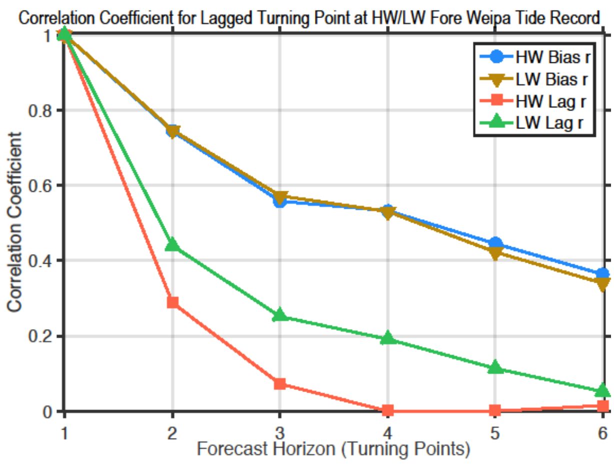

Figure 1. Correlation between turning points for lags and biases are shown above.

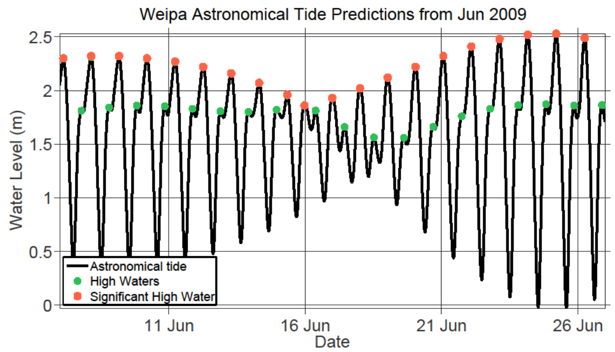

Figure 2 - High Waters & "Significant" High Waters.

Water level predictions are generated by shifting the astronomical prediction turning points and mid-points to those identified by the sampled lag and residual values. Then a coherent time series is created by linearly "stretching" or "shrinking" (vertically and horizontally) the intermediate points.

Table 2 – Statistical distributions for bias and lag for Weipa for 2007-2014 are listed below.

Parameter	Mean	St. Dev
HW residual	0.07 m	0.14 m
LW residual	0.06 m	0.15 m
HW lag	-3.9 min	21.9 min
LW lag	-0.1 min	11.5 min
High Freq. HW	-0.003 m	0.03 m
High Freq. LW	-0.006 m	0.003 m
High Freq. Mid Point	-0.01 m	0.055 m

The prediction algorithm deconstructs recent measurements into their turning points and residuals, and then predicts the water level distributions for the future turning points based on the modelled statistics. Ensemble members are then generated by combining a sample of random predictions for each turning point from the predicted distributions. These turning point predictions are converted into a time series by stretching the astronomical tide predictions to join them. These ensemble members are consolidated into a time series statistical distribution and this time series can evaluate a future water level at a desired conservatism levels. Figure 3 shows an example prediction for 6 Sep, 2008 illustrating turning point predictions and resultant ensemble generated.

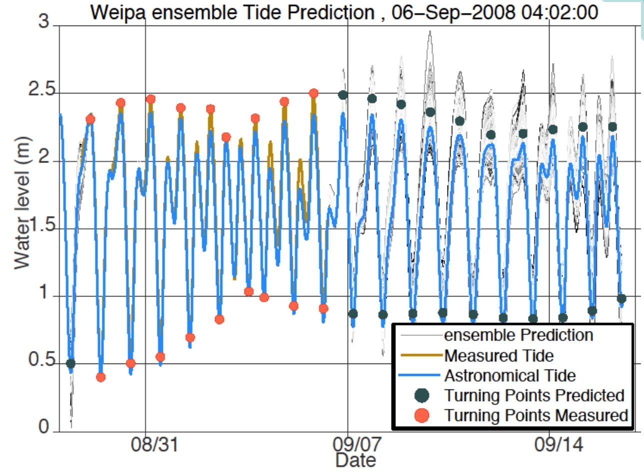

Figure 3. An ensemble prediction for 6 Sep, 2008 for a sample duration.

3.1 COMBINING MULTIPLE FORECAST SOURCES

[6] introduced an optimum method for combining multiple forecasts that includes ensemble prediction, measurements and any other forecast models that are available. This procedure includes minimising RMS error from each source over an historical record with a method adapted from [7] and [8]. The ultimate forecast S_{cf} is composed of the best two available forecast sources (i and j) for the current prediction, scaled by the weighting factor β_{ij}:

$$S_{cf} = (\beta_{ij} S_{f,i} + (1-\beta_{ij}) S_{f,i}) \qquad (1)$$

Since the astronomical residual from the most recent measurement is a strong indicator of the near future anomaly (irrespective of the point in the tide cycle), a persistent water level forecast is made by holding this residual constant into the future. A weighting factor between this persistence forecast and the ensemble prediction is computed for the near future where autocorrelation statistics remain high. An example prediction for 14 September, 2011 shows how the weighting factor blends multiple forecasts in Figure 4.

3.2 ANALYSIS OF MODEL PERFORMANCE

In order to evaluate the operational impact of the model, a series of evaluation parameters were derived in consideration of the Port of Weipa's loading and shipping operations:

- **Over-loading**: Percentage of draft predictions higher than actual at time of transit (major over-loading > 5 cm),
- **Under-loading**: Percentage of draft predictions lower than actual at time of transit (major under-loading > 15 cm),
- **Average Under-loading (AU)**: Mean conservatism of predictions,
- **Sailing Tide Exceedance**: Locked-in 8 hour draft cannot sail (>4cm threshold),
- **Short Term Variability (STV)**: Nervousness near sailing time. RMSE Mean and RMSE from the forecast trend.

Figure 5 illustrates the significance of the parameters relative to max draft advice and the time to sailing.

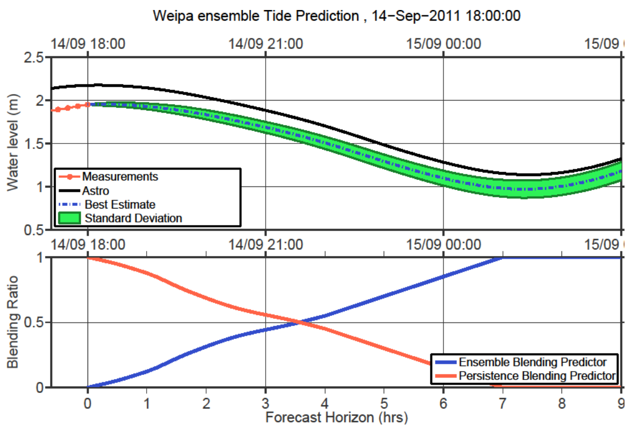

Figure 4. An example prediction showing persistence and ensemble blending for 14-Sep, 2011. Lower panel shows the blending factors used in the prediction.

4 RESULTS

Tide predictions for Weipa were assessed using statistics based on operationally critical horizons. **Error! Reference source not found.** shows the evolution of statistics at 25, 24, 12, 8, 2 and 1 hour(s) prior to sailing time. For this study all sailing times are assumed to be around high water, as is typical at Weipa. Predictions were generated for the period between 08-Aug-2009 and 26-Sep-2010, including 413 significant high water turning points.

The approach is able to maintain a target conservatism percentile throughout the forecast horizon, while assimilating measurements and ensemble member predictions. This is illustrated in **Error! Reference source not found.** where a 95th percentile lower bound was targeted. This is configurable, as Figure 7 shows where a 60th percentile non-exceedance results in only 3 cm conservatism, whereas a 23 cm average under-loading was required to predict to a 99th percentile non-exceedance water level. This configurable conservatism level can be used to address the different logistical and planning needs of individual port operations, or even adjusted on a transit by transit basis depending on the particular scenario, i.e. subsequent tides trending towards neaps or springs.

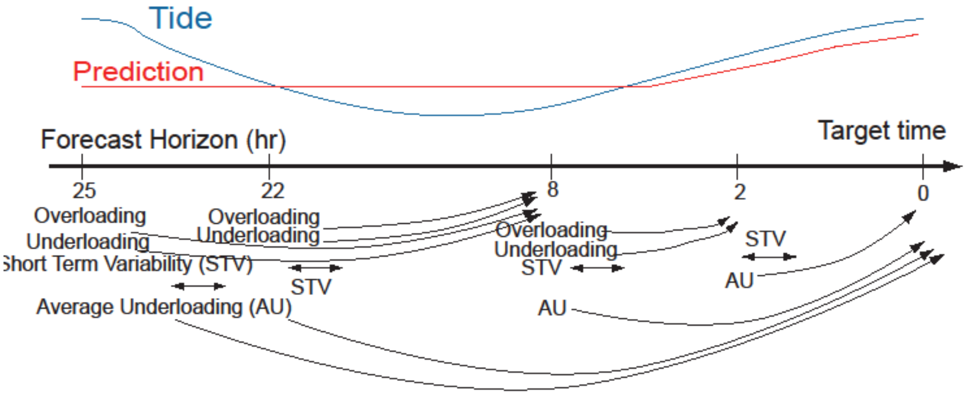

Figure 5. Operational evaluation parameters derived for assessing tide forecast impact on Weipa port operations.

The operational evaluation statistics listed in **Error! Reference source not found.** show that the model (when configured for a 95th percentile conservatism) produced over-loading scenarios 2% of the time, while under-loading for 14% of scenarios for the 8-hour draft lock-in horizon. It produced these predictions with a conservatism "sacrificing" an average of 15 cm of under-load (lost opportunity) at 8 hours.

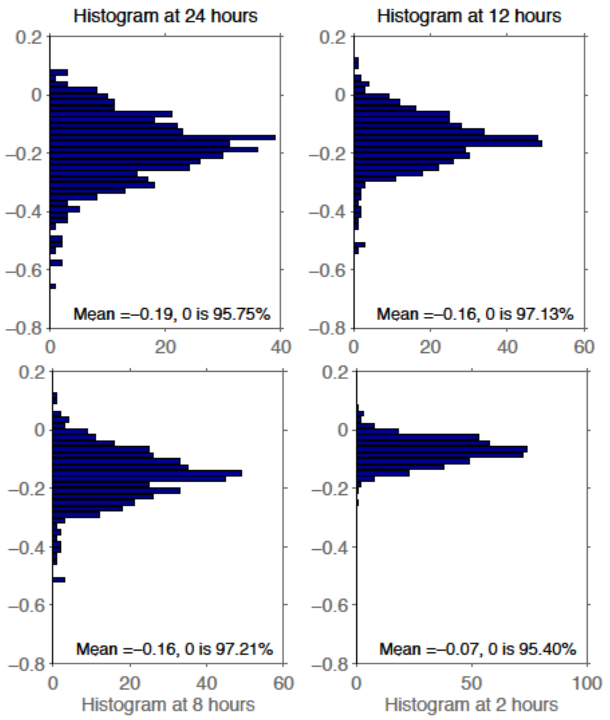

Figure 6. Evolution of conservatism in water level predictions with forecast horizon for 413 sailing times.

Sailing Tide Exceedance is an important statistic which indicates how many sailings would have to be cancelled after the drafts are locked-in at 8 hours prior to sailing time. The new model predictions resulted in an estimated 1% sailing cancelations over the analysis period, a significant reduction from the 4% produced by the existing method. At the same time the new model reduces the critical average 8 hr conservatism from 18 cm to 15 cm, equivalent to approximately extra 240 tons of cargo per vessel.

Table 3 – Evaluation of model prediction statistics relative to forecast horizon.

Forecast Horizon	Over-loading (> 5cm)	Under-loading (>15cm)	Average Under-load	Sailing Tide Non-Exceedance (>4cm)
25 hrs.	9%	3%	18 cm	
8 hrs.	2%	14%	15 cm	
2 hrs.			7 cm	1%

5 DISCUSSION & CONCLUSIONS

The water level prediction approach discussed in this paper promises to improve the efficiency of the port operations at Weipa by both reducing the lost opportunity due to overly conservative or fluctuating forecasts and reducing the risk of overloading. This approach has the potential to be applied to other locations.

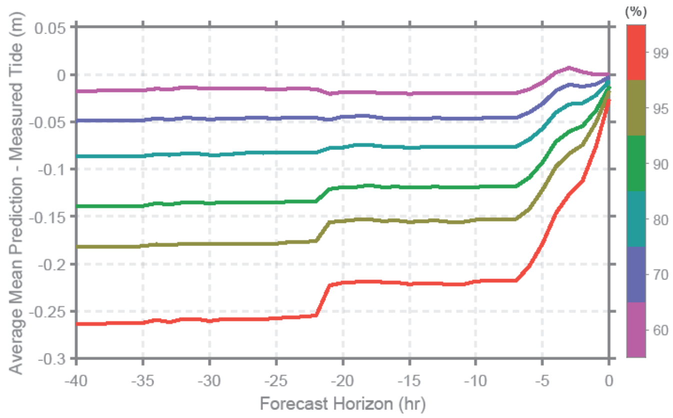

Figure 7. Average under-loading depending on conservatism level is shown.

This study finds that implementing an operational water level predictor is beneficial for port operations where tidal anomaly variations can significantly impact shipping operations. For the

Figure 8. Operational evaluation parameters derived for assessing tide forecast impact on Weipa port operations.

Port of Weipa, the present average under-loading of approximately 18 cm could be reduced by 3 cm while also significantly reducing delays due to occasional vessel overloading.

6 FUTURE RECOMMENDATIONS

The positive results from this study indicate that the proposed tide forecasting approach has the potential to benefit other port operations using DUKC® systems and should be evaluated at other locations which are subject to different tide and residual regimes.

The model described in this report is fundamentally a "persistence" model, in that it relies on climate statistics and recent measurements to predict forward in time. However, the approach was designed to accommodate the possibility of incorporating the skill of external forecasts [6] such as those produced by [9] and [10]. Further development of the model should consider the assimilation of similar operational forecast sources.

7 ACKNOWLEDGEMENT

Authors wish to thank the Port of Weipa for providing the data for this investigation and Andy Taylor of the Bureau of Meteorology for his collaborative contributions.

8 REFERENES

[1] Port of Weipa, the present average under-loading of approximately 18 cm could be reduced by 3 cm while also significantly reducing delays due to occasional vessel overloading.

[2] Australian Bureau of Meteorology, "National Tidal Centre," 2015.

[3] R. Saunders, Interviewee, *Personal Communications.* [Interview]. 2014.

[4] The positive results from this study indicate that the proposed tide forecasting approach has the potential to benefit other port operations using DUKC® systems and should be evaluated at other locations which are subject to different tide and residual regimes.

[5] Department of Transport and Main Roads, "Port Procedures and Information for shipping Port of Weipa," Maritime Safety Queensland, 2013.

[6] The model described in this report is fundamentally a "persistence" model, in that it relies on climate statistics and recent measurements to predict forward in time. However, the approach was designed to accommodate the possibility of incorporating the skill of external forecasts [6] such as those produced by [9] and [10]. Further development of the model should consider the assimilation of similar operational forecast sources.

[7] O. Talagrand, "Assimilation of Observations, and Introductions," *Journal of the Meteorological Society of Japan,* vol. 75, pp. 191-209, 1997

[8] O. Talagrand, "On the mathematics of data assimilation," *Tellus,* vol. 33, no. 4, pp. 321-339, 1981.

[9] Authors wish to thank the Port of Weipa for providing the data for this investigation and Andy Taylor of the Bureau of Meteorology for his collaborative contributions.

[10] G. B. Brassington, "Multicycle ensemble forecasting of sea surface temperature," *Geophys. Res. Lett.,* vol. 40, no. 23, p. 6191–6195, 2013.