EFFECT OF WIND FORCING ON BIAS IN WAVE MODEL FORECASTS

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1. INTRODUCTION

The Australian Bureau of Meteorology, as part of the input to its marine forecast and warning services, produces wind estimates from a suite of Numerical Weather Prediction (NWP) systems and wave model forecasts based on forcing from the NWP winds at horizontal scales roughly matching the wind resolution.

The Bureau of Meteorology currently runs two NWP model systems operationally. These are LAPS (Limited Area Prediction System, Puri et al. 1998), and GASP (Global Assimilation and Prediction System, Seaman et al. 1995). The former is run at a variety of resolutions and over various domains. The verifications presented in this paper focus on LAPS-375 (0.375^{o} horizontal resolution), henceforth called LAPS and the global system GASP (a spectral model currently run operationally at T239 resolution, approximately equivalent to a grid spacing at the equator of 0.75^{o}). Both systems have 29 vertical levels. The lowest level in LAPS is at approximately 10-m height while for GASP it is at approximately 70-m height.

The global system in its present operational configuration saves its state at 6-hour intervals of forecast time, while LAPS uses 3-hour intervals. In addition, winds over the ocean, interpolated to 10-m height using a boundary layer model (Hess et al. 1995), together with the derived surface stress, are saved at higher temporal resolution for forcing the wave and other ocean models. A small difference here is that GASP saves a time-average stress every 3 hours, while LAPS produces instantaneous values every hour.

The wave model used at the Bureau to forecast sea-state is WAM (Wave Model: WAMDI group 1988, Komen et al. 1994). Specific details of the current implementation can be found in Bender (1996), Greenslade (2000) and Greenslade (2001). Three versions of the wave model are currently run operationally: global, regional and mesoscale. Only the global and regional models are considered in this paper.

The global version of the wave model is forced by the 3-hourly winds from GASP, physically interpolated to 10-m height as described above. The spatial resolution of the global wave model was increased from 3^{o} to 1^{o} in April 2001.

The regional wave model spans the LAPS domain (latitudes 65S-17N, longitudes 65E-175W) and is nested inside the global wave model, that is, the global wave model provides the directional wave spectra at the boundaries of the regional model. The regional wave model is forced by hourly 10-m winds from LAPS described above. The resolution of the regional wave model was increased from 1^{o} to 0.5^{o} in August 2002.

Both the global and regional models use deep-water physics only and include the assimilation of altimeter significant wave height data.

Section 2 of this paper presents comparisons of LAPS and GASP forecast marine winds with scatterometer data during September 2001 and January 2002 plus some recent results based on GASP forecasts. Section 3 documents the results of re-running the wave model with wind forcing adjusted for bias based on the earlier results, then the effect of improvements in the surface wind forecasts from GASP on the operational wave forecasts. Results of all these experiments are summarized in Section 4.

2. VERIFICATION OF MARINE WINDS

Verification of surface marine wind forecasts has in the past been severely limited by the availability of suitable observational data for comparison. Many coastal observations are not truly representative of the marine environment because of anemometer siting and the effect of local processes such as sea breezes. Ship-based observations of wind are notoriously unreliable and buoys often have the anemometer close to the ocean surface so they are shielded by waves in strong wind conditions.

Taking the above considerations into account there are not many wind observations in the Australian region with true ocean exposure. A better source of wind observations is remotely sensed data, in particular scatterometer winds. For the purposes of comparison with models, scatterometer winds are also shown to be the most accurate, not least because they are a spatial average over a horizontal scale of about 25 km, and so are less subject to errors of representation than point measurements.

2.1 Previous Verifications of Marine Winds

A previous study (Kepert et al. 2004) presented comparisons of LAPS and GASP forecast marine winds with scatterometer data. Scatterometer wind data are ideal for such a comparison, as (i) they are available over the whole of the marine part of the model domain with high spatial and temporal density, (ii) apart from some known quality control issues such as rain contamination and directional ambiguities, they are highly accurate, and (iii) they are not currently used in the current operational LAPS and GASP systems, so provide an independent test.

The QuikSCAT instrument (JPL 2001) produces winds on an 1800-km wide swath at a horizontal spacing of 25 km, with an orbital period of 101 minutes, covering about 90% of the ice-free oceans per day. Because of the conical-scanning pencil-beam antenna used, winds near the edges and centre of the swath are of lower accuracy than in between. Also, because of the radar wavelength (Ku band), there is attenuation of the signal in heavy rain resulting in wind errors.

In this study all available QuikSCAT data from September 2001 and January 2002 were used. They were collected into 6-hourly periods centred about 00, 06, 12, and 18UTC, over the domain 70^{o}-180^{o} E, 60^{o}S - 10^{o}N. This is slightly smaller than the full LAPS domain, to avoid boundary effects in the model. Approximately 45000 observations were available at each period, or 5.6 million for the month. Modelled winds from the analysis and 6-hourly forecast intervals out to 48 hours (LAPS) and 120 hours (GASP) were interpolated to 10-m height as described in Hess et al. (1995), and horizontally to the observation point by cubic splines, and compared. The satellite overpass times are such that the analysis and 12, 24, 36 and 48-hour forecasts cover roughly the eastern half of the domain, and the 6, 18, 30 and 42-hour forecasts, the western half[1]. In the discussion, we will focus particularly on the 18 and 24-hour forecasts, since differences relatively early in the period are less likely to be due to the synoptic pattern being forecast incorrectly, and this is therefore a better diagnostic of the quality of the boundary layer physical parameterizations than a longer forecast period. As the QuikSCAT data are of high quality, and for simplicity, no additional quality control was applied except where noted below.

Two-dimensional histograms of the comparison for the LAPS 18-hour forecast during January 2002 are shown in Fig.1. In each case, the forecast wind (speed, direction, westerly and southerly components) is on the *y*-axis, and the corresponding observations on the *x*-axis. The histogram counts in each cell are contoured, with logarithmic contour spacing with a ratio of $10^{1/2}$ between contours. Thus the diagrams typically cover 3 orders of magnitude of count density. Means and standard deviations of the differences are shown, together with the slope and correlation coefficient of the line of best fit through the origin, below each panel.

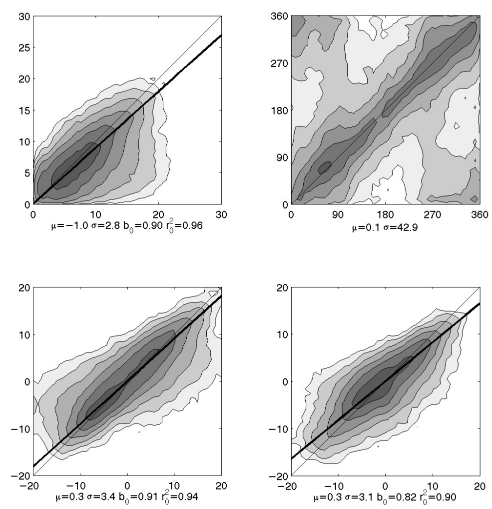

Figure 1: Contoured 2-dimensional histograms for LAPS 18-hour forecast (y-axis) against scatterometer winds during January 2002. The top left panel shows wind speed, top right shows wind direction, lower left shows the zonal wind components and lower right shows meridional components. The line *y* = *x* (light), and the line of best fit described in the text (heavy), are also shown. Contours are in geometric progression, every $10^{1/2}$. The mean μ and standard deviation σ of the model-observation difference, together with the slope b_0 and correlation parameter r_0^2 described in the text, are shown beneath each panel.

There is a slight (~ 1 m s^{-1}) negative bias of the model wind speed relative to the scatterometer-derived wind. About half of this is due to the lobe where the model winds are ~ 5 m s^{-1} but the scatterometer reports ~ 15 m s^{-1}. Careful examination of some representative cases demonstrated that many of these points are poor-quality

1 QuikSCAT is in a sun-synchronous orbit, crossing the equator at about 0600 and 1800 local standard time.

data, being either rain-affected or near the centre and edges of the swath. The remainder of the bias is because the axis of the contours lies slightly below the *x*=*y* line. The directions show little bias, apart from a consistent tendency for the model E/SE winds to be about 10^{o} more easterly than the observations.

Eliminating data where the observed and model wind speed differ by more than 5 m s^{-1} (a crude attempt at quality control of the scatterometer data), a least squares regression is performed to produce a straight line forced to go through the origin. Results of the regressions were

$$s_{\mathrm{model}} = 0.898 s_{\mathrm{obs}}$$
$$u_{\mathrm{model}} = 0.910 u_{\mathrm{obs}}$$
$$v_{\mathrm{model}} = 0.825 v_{\mathrm{obs}}$$

These fitted lines are also shown in Fig. 1. As a measure of goodness-of-fit, the analogue to the usual correlation coefficient, for a line passing through the origin, was calculated, and shown on the figure as r_0^2. This shows the strength of the linear relationship.

Similar results to those presented here for the 18-hour forecasts were obtained for the 24-hour forecast, which corresponds to the western half of the domain.

Similar calculations were carried out over the same domain for the GASP winds for those two months, and also globally for the first half of January 2002. GASP also shows a somewhat better performance in the Australian region in September than January, which is most likely a seasonal difference. The slope parameters are generally closer to unity than were obtained for LAPS. This difference is barely significant, except for the meridional component in January, where the performance of the global model over the Australian region is distinctly better.

In summary, both models tend to underestimate marine near-surface winds. In the case of GASP, the zonal component is underestimated by around 5-10%, depending on forecast period, with the meridional component having about twice the relative error. The biases in the case of LAPS were generally larger, particularly in the case of the meridional component, where it can reach 20%. In these cases there is less difference in the correlation parameter between the models, suggesting that much of the difference in performance is due to a systematic bias, rather than "random" errors in the forecast.

However, it should be pointed out that these errors, while significant, are not overwhelming. For instance, with the exception of the meridional component in LAPS, they are less than 5 knots in the presence of gale force winds. As such their major impact could be argued to be in the forcing of oceanographic models. Further, it may be that the largest errors were caused by underestimation of the pressure gradient by the system, rather than in biases in the PBL parameterizations.

2.2 Effect of Assimilation of Scatterometer Winds on Model Wind Accuracy

As part of an intended upgrade to the GASP system a parallel trial has been in progress with the operational system which includes the assimilation of scatterometer winds (GASP_TEST). To accommodate this the number of vertical levels in the model has been increased to 33 with extra levels in the boundary layer. As we are only interested in improvements in the surface winds the differences in the configuration of the models does not matter.

A similar experiment as described in Section 2.1 was carried out for the period 30-5-2004 to 14-7-2004 for the full global domain. The comparisons for the 24 hour forecast of the operational model (GASP_OPNL) are shown in Fig. 2. whilst similar comparisons for GASP_TEST are shown in Fig. 3.

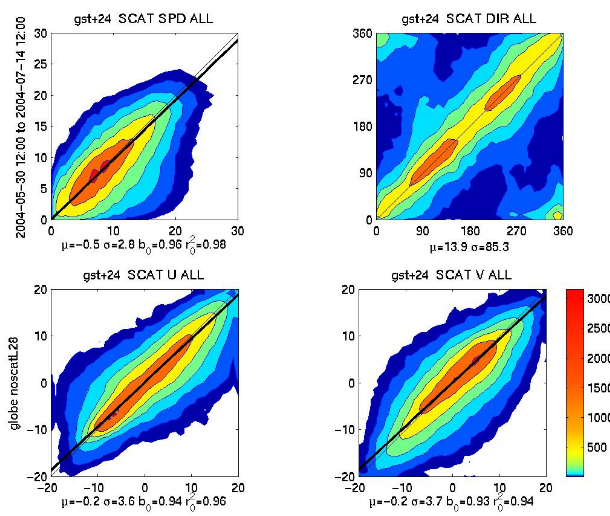

Figure 2. As for Fig. 1 for winds output from the 29-level GASP operational model for the period 30-5-2004 to 14-7-2004.

The results for the operational model are similar to those found previously. There is a small 0.5 m s^{-1} negative bias in the model wind speed when compared to the scatterometer-derived wind with a regression curve slope of 0.96.

By contrast, the results for the test model show little bias in the modeled winds and the slope of the regression curve is close to unity. The standard deviation of the model-observation difference is slightly improved on that of the operational model. Recent results, which are not shown here, in which the 33 level model is run without scatterometer assimilation indicate that the improvement is likely to come from the increased levels in the boundary layer rather than the improvements due to the scatterometer data.

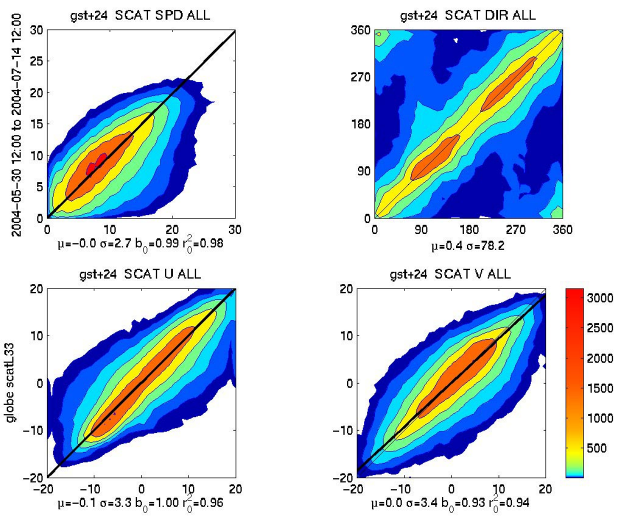

Figure 3. As for Fig. 1 for winds output from the 33-level GASP model initialised with scatterometer assimilation.

Although the errors indicated by these studies are not exceptionally large it is of interest to see what effect they have on the forcing of oceanographic models such as the wave models.

3. WAVE MODEL PERFORMANCE

In this section, verifications of Significant Wave Height (SWH) are presented. SWH is defined as:

$$SWH = 4\sqrt{E}$$

where E is the integral of the wave spectral energy over all frequencies and directions.

The National Meteorological and Oceanographic Centre (NMOC), which is the central operations centre of the Australian Bureau of Meteorology, performs ongoing verification of the wave model forecasts against observations of SWH from buoys situated around the Australian coast. Some of these buoys are indicated on Fig. 4.

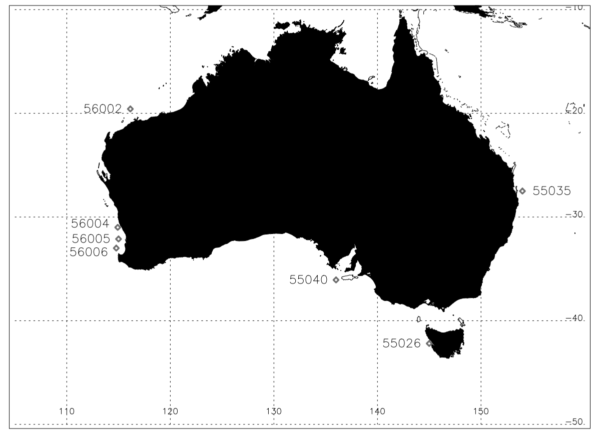

Figure 4: A portion of the waverider buoy network around the coast of Australia.

Results are published quarterly in the Quarterly Summary of the Analysis and Prediction Program published by NMOC. An example of the comparisons of the local wave models and the UK global model for comparison at Cape de Couedic (buoy 55040) is shown in Fig. 5. It is evident from this figure that most of the error in SWH is due to a negative bias.

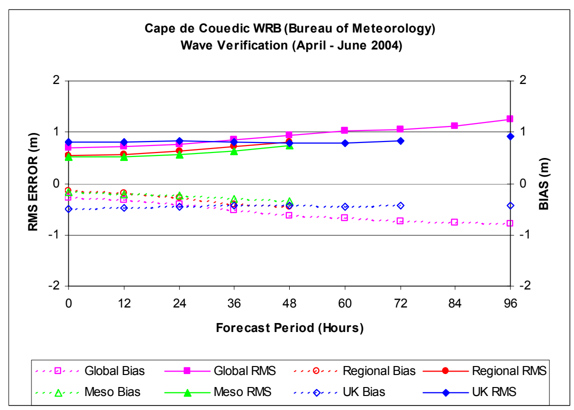

Fig. 5 Verification statistics for global, Australian Region, Australian meso-scale and UK global wave models against observations at Cape du Couedic for the period April – June 2004.

Also published are time-series of wave model forecasts and observations. An example showing the comparisons of the global wave model forecasts against observations at Cape de Couedic for July 2004 is shown in Fig.6. It can be seen that comparisons are good for lower wave heights and the phase of the forecast is good but the model tends to underpredict the higher waves. Other stations have been giving similar results.

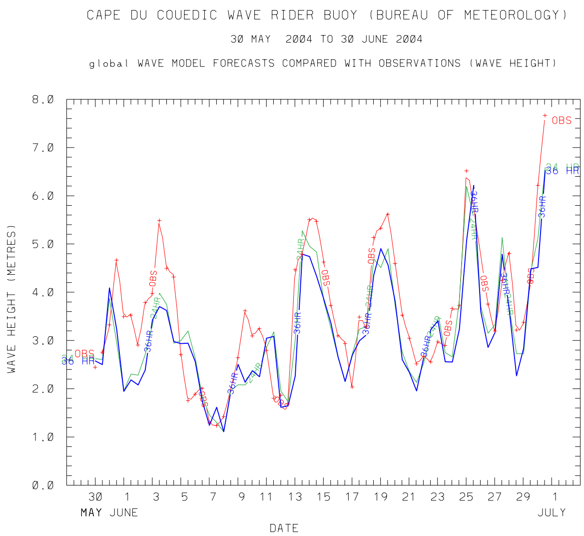

Fig.6 Time series of observations (red) of SWH at Cape de Couedic against global model forecasts. Green curve is 24-hour forecasts and blue line is 36-hour forecast.

3.1 The Impact of Statistically Corrected Winds on the Wave Models

It has been shown in this report that the LAPS surface wind speeds during January 2002 were typically underpredicted by approximately 10%. Typically, it was seen that SWH from the wave model forced by LAPS was underpredicted, and it has been suggested that this underprediction in the modelled SWH is due to the bias in the surface winds. In this section, the impact of the 10% underprediction in the LAPS wind speeds on the wave model is examined further.

For a fully developed sea-state, the equilibrium SWH is given by (Komen et al. 1994):

$$SWH = \frac{0.22U_{10}^2}{g}$$

Thus a 10% increase in U_{10} will result in a 21% increase in SWH, and the wave model can be regarded as a sensitive indicator of potential errors in the surface wind speed. Alternatively, differentiating the above equation gives:

$$\delta SWH = \frac{0.22}{g}2U_{10}\delta U_{10}$$

So for a systematic bias of 1 m s^{-1} in a mean wind speed of 7 m s^{-1}, the corresponding bias in a mean SWH of 1.1m would be 0.31m.

The above expressions are simple approximations valid for equilibrium sea-states. It is not clear how this would apply to actual modelled wave fields, where the proportion of the wave spectrum that is in equilibrium with the wind varies in time and space. So it is worthwhile to examine the impact of variations in the surface wind fields on the resulting modelled wave fields.

An experiment was run in which the wave model was forced by two sets of surface wind fields. Firstly, a run in which operational LAPS 10-m winds were used (OPNL) and secondly, a run in which the surface winds were adjusted according to the regression results in section 2.1 (ADJ). Specifically, the ADJ surface wind components were given by:

$$u_{\mathrm{adj}} = 1.11u_{\mathrm{opnl}}$$
$$v_{\mathrm{adj}} = 1.25v_{\mathrm{opnl}}$$

Operational restart files valid at Jan 1 00UTC 2002 were used for both runs. The wave model was then run over the domain of the operational regional wave model for one month, with 24-hour forecasts made every 12 hours. Identical boundary input files from the global wave model were used for both runs. No wave data assimilation was performed in order to highlight the effect of the wind adjustment. The same wind adjustment was made for each of the forecast time periods, even though the regressions shown above are based on 18-hour forecasts. However, the analysis and 24-hour forecast winds were shown to be qualitatively similar, so it is expected that slight differences in the analysis and/or 24-hour forecast winds would have little effect on the results.

Fig. 7 shows an example of the operational LAPS 10-m wind speed field, the ADJ wind speeds and the difference between the two fields for 24-hour forecasts valid at 12UTC on January 10, 2002. Over the entire month, the mean OPNL wind speed is 6.6 m s^{-1} while the mean ADJ wind speed is 7.7 m s^{-1} (17% greater). The amount by which the wind speed is increased in the ADJ fields depends on how zonal the flow is. If the wave spectra were in equilibrium with the wind, then from the above expressions, one would expect the ADJ SWH to be 36% (or 0.32m) higher than the OPNL SWH.

Modelled SWH fields valid at the same time as the wind fields in Fig. 7 are shown in Fig. 8. It can be seen that there are several regions in which the ADJ SWH is significantly greater than the OPNL SWH. The mean difference between the OPNL SWH and ADJ SWH during the entire time period is 0.42m, with the ADJ SWH being, on average, 21% higher than the OPNL SWH. Thus on the one hand the equations above underpredict the expected systematic bias, while on the other hand they overpredict the expected percent increase in SWH.

The impact of the adjusted wind forcing with respect to *in situ* wave data is now considered. The set of buoys used here is limited to those which are far enough from the coast so that interpolation from the wave model grid to the buoy location is not affected by land. In Fig. 9, the observed SWH from the buoys at 3-hourly intervals is shown. Also shown is the 24-hour forecast SWH interpolated from the model grid for each of the two model runs, OPNL and ADJ. Verification statistics are shown for each buoy. In general, the adjusted wind forcing has accounted for much of the observed bias in the wave model, and the prediction of high SWH, e.g. around day 12 at buoy 55026 is significantly improved. Results are particularly good at locations 55026, 55040 and 56006 where the *rms* error is decreased by approximately 30%.

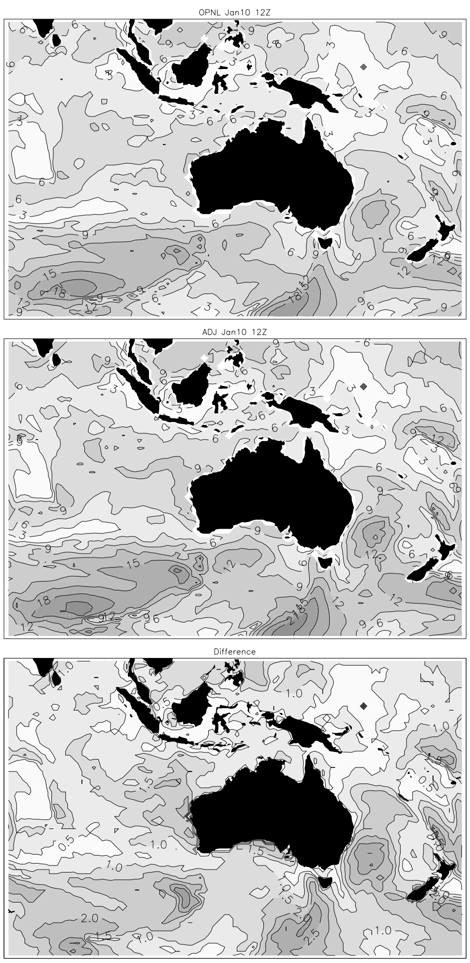

Figure 7: (a) Operational LAPS 24-hour forecast 10-m wind speeds at Jan 10 12UTC (b) Adjusted 10-m wind speeds valid at the same time and (c) Difference (m s^{-1}) between the wind fields in (a) and (b).

3.2 The Impact of Improvements in Model Forecast Winds on Wave Model Performance

As shown in Section 2.2 the GASP_TEST model (incorporating the assimilation of scatterometer winds) produces improvements in the wind fields forecast by GASP. Because the initial state of the model is different the forecast model will of course evolve differently but it is still of interest to examine the impact on the wave model performance.

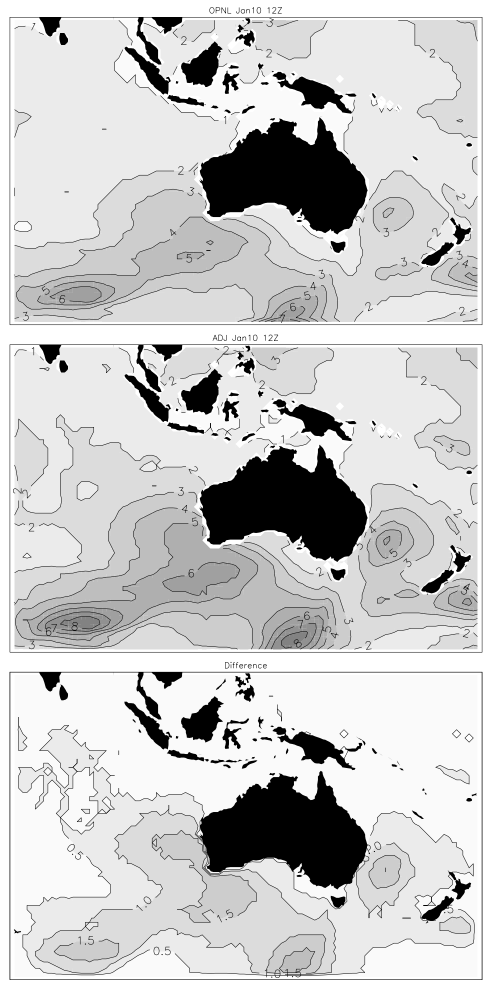

Figure 8: (a) OPNL 24-hour forecast SWH at Jan 10 12UTC. (b) ADJ SWH at the same time and (c) Difference (m) between the SWH fields in (a) and (b).

Fig. 10 shows the verification of the operational global wave model (with wind forcing from the operational 29 level GASP) and the test global wave model (with forcing from the 33 level GASP with scatterometer assimilation) at Rottnest Island[2] for the period 21-8-2004 to 20-9-2004. Both versions of the model

2 The Rottnest Island buoy is operated by the Department for Planning and Infrastructure of the Government of Western Australia

incorporate the assimilation of JASON altimeter SWH data so the only difference is the wind forcing.

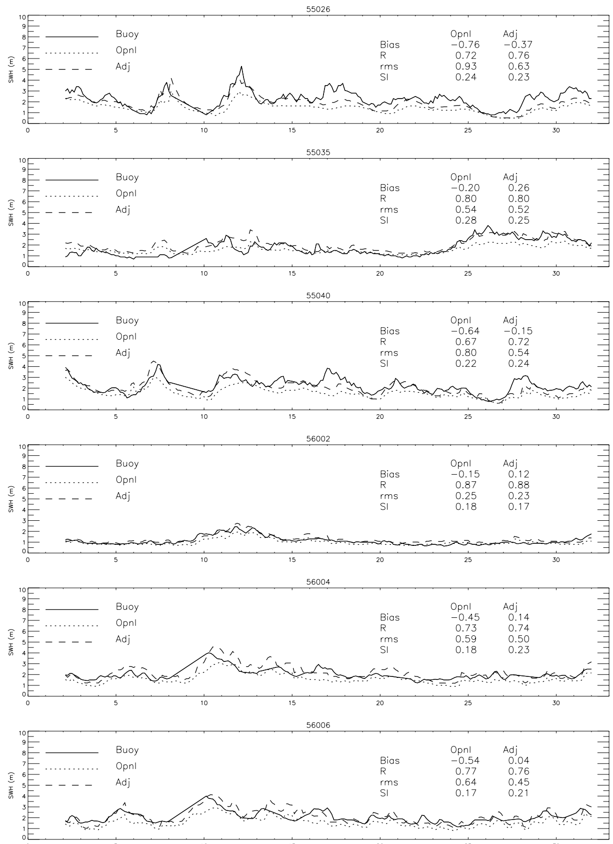

Figure 9: Observed SWH at each buoy (solid line) and 24-hour forecast SWH from the two model runs, OPNL (dotted) and ADJ (dashed) during January 2002.

The results at Brisbane[3] (buoy 55035) are shown in Fig.11. The marked differences at the two sites are mainly due to geographical effects. The Brisbane buoy is not exposed to the effects of waves generated by the storm tracks in the southern Ocean. In fact, during the period studied, conditions were quite benign with observed SWH rarely reaching 2m over the period. Results at other sites (55026 and 55040) which are exposed to the westerly regime are similar to those at Rottnest Island.

Of greater interest is the fact that there is now a small positive bias evident in the shorter term SWH forecasts from the test model given that there is negligible bias in the wind field (see Fig. 3). A negative bias still remains for the longer term forecasts but is not as great as that for the operational model. Again, this may be a geographic effect due to the fact that the major storm events in the Australian region are generated in the Southern Ocean and the high wind speeds and long fetch lengths associated with the generated waves are a factor. It may also be due to atmospheric model depiction of the intensity of individual weather systems.

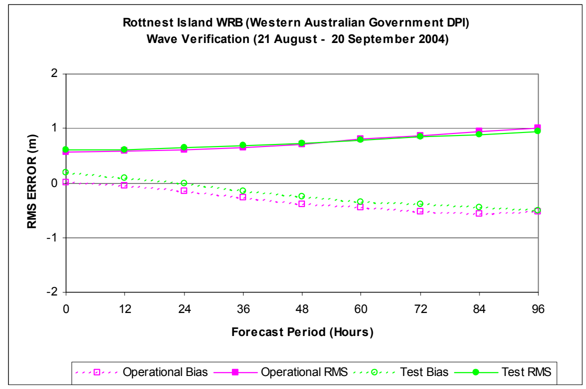

Figure 10: Verification of the operational and test global wave models forecasts of significant wave height compared to observations from the Rottnest Island buoy.

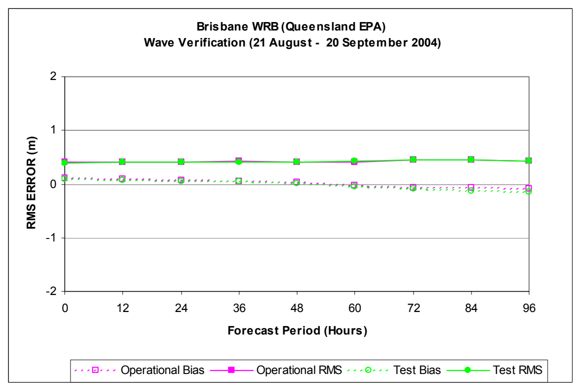

Figure11: As for Fig. 10 but for Brisbane.

Another possibility is that the characteristics of the forcing fields have changed since the original implementation of the WAM model at the Bureau of Meteorology. The source terms in the model may need re-tuning to reflect these changes. This will be examined in future work

4. SUMMARY AND CONCLUSION

It has been shown that a negative bias in the current operational wind forecasts contributes to a negative bias in the resulting wave forecasts when verified against buoys around the Australian coastline. Further, as suggested by Kepert et al (2004), a correction of the bias in the winds before being used for the wave model forcing accounts for most of the bias in the wave forecast.

3 The Brisbane buoy is operated by the Queensland Government Environmental Protection Agency

With the latest upgrade to the atmospheric models, particularly the global model considered here, this bias correction may not be necessary as the winds do not appear to have any significant bias.

There is still, however a bias evident in the wave forecasts which need further investigation. Further work will investigate whether this is a geographical effect (which would still need allowing for in operational forecasts) or whether the source terms in the wave model need tuning to account for the improvements and updates in the surface wind forecasts.

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