The effect of improved marine wind forecasts on wave forecasts from WAM

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1. Introduction

Results from high resolution field campaigns have often led to the conclusion that wind field errors are the single largest source of errors in wave model output. Since the wave models are very sensitive to the wind input, it follows that improvements to the wind input would be most likely to translate to significant improvements in wave simulations, both hindcasts and forecasts.

This paper describes work that is in progress to improve the wind field data that is available in real-time to drive the operational wave forecast model. Improvement is particularly needed in the operational real-time analysis and forecast context, since the data available to the wind analysis in real time is more limited than may be available in retrospective (hindcast) studies. Improvements in wave analysis and forecast capability are of obvious importance for the safety of marine operations of all types.

2. Data and methods

a) Statistical wind equation development

With relatively little high quality observational data routinely available over the marine areas bordering Canada, the surface wind analysis available to the wave model is understandably at relatively low resolution, and relies heavily on the trial field supplied by the atmospheric model GEM. One way of correcting surface wind analyses and forecasts that has been successfully applied to the correction of wind forecasts at land stations is model output statistics (MOS – Glahn and Lowry, 1972). MOS involves statistically matching forecasts and observations at observation locations, using a historical dataset of observations (the "predictand") and model forecast variables valid at the observation times (the "predictors"). Then, the resulting equations can be used in predictive mode by feeding forecast information from the latest model run into the statistical equations to predict the surface variables at projections which correspond to those used in equation development. For example, 24h forecasts of marine surface winds can be matched with observed winds for the valid time of the forecast. The resulting statistical equation can then be used with forecast data from the current model run to obtain 24 h forecasts of the surface winds at the same observation locations. Equations may be built for individual stations separately, or, if the physical relationships between the forecast variables and the surface winds are considered to be constant over an area, then the data can be grouped over several observation locations. For the most part, we used single station equation development in this study.

The statistical equations are developed using multiple linear regression. Non-linearities in the relationship are accounted for by transforming the model predictor variables to linearize the relationship as much as possible with respect to the predictand observation data.

We were able to take advantage of an existing statistical development package called "UMOS" (Updateable Model Output Statistics - Wilson and Vallée, 2002) which was built for MOS equation development for land stations, based on the output of the regional and global versions of the operational atmospheric model GEM. This package was applied to develop MOS equations for individual buoy locations in East and West Coast Canadian waters, and on the Great Lakes. Since the available development dataset was stationary (The model didn't change during the period), we did not need to use the updating features of UMOS.

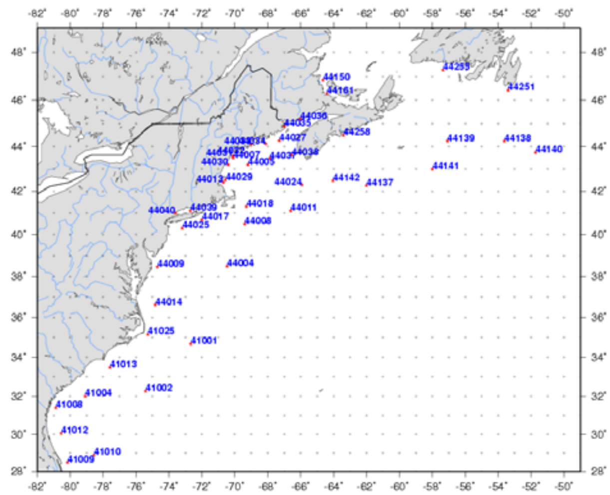
The predictands for wind include earth-oriented UU (west) and **VV** (south) wind components as well as wind speed UV observed at buoy level. The wind direction is predicted by using the UU- and VV- wind components. Wind speed is used as a separate predictand because the statistical estimates of speed from the UU and VV components lead to an underforecasting bias in the speeds.

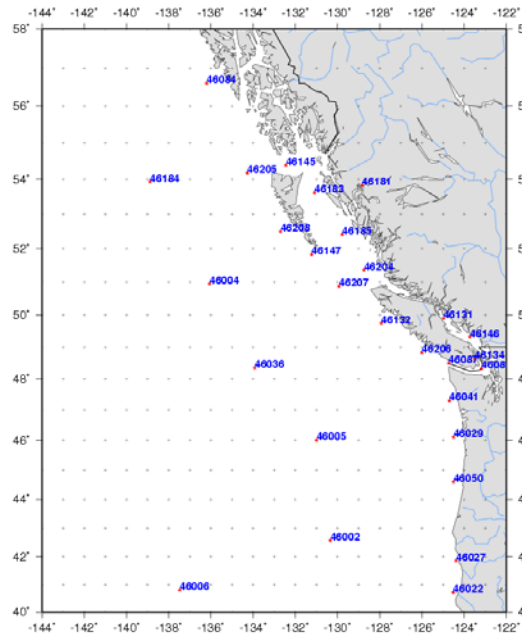
Buoy anemometers are not usually at the height of 10 m. However, the heights of the anemometers can be obtained from the data providers. Although the wave model requires heights at 10 m, results of experiments suggested that the best quality statistically corrected wind could be obtained by developing equations with respect to the buoy observations at their reported height, normally about 5 m.

We therefore produce the statistical forecasts at the anemometer level. They are then corrected assuming that, on average, the wind profile in the planetary boundary layer is neutral, as described in Bidlot et al. (2002). In case of strong winds, the neutral wind profile is usually appropriate. It might be less appropriate for low wind speeds when the boundary layer is stably stratified and decoupled.

Available predictors for the development of forecast equations originate, generally, from three possible sources: numerical model variables interpolated to the stations, prior surface observations, and climatic variables. For marine wind forecasts we used the same full set of predictors designed to be used for all surface weather elements (Wilson and Vallée, 2002). Predictors which correlate the highest with any of the predictands, when combined with the other already selected predictors, are chosen as terms in the regression equation. Predictors are chosen until none contributes more than 0.5 % to the total reduction of variance.

Predictands and predictors data have been collected for the period January 2001 – July 2006. This period was separated in two parts: a development sample for the period January 2001 – December 2003 and an independent test sample for the period January 2004 – July 2006. Data was collected for all the available buoys of the 4 areas shown in Fig. 1. For development, all predictors were interpolated from the GEM grid to the buoy locations. Equations were developed for each buoy location and for each 6 h forecast projection to 48 h.





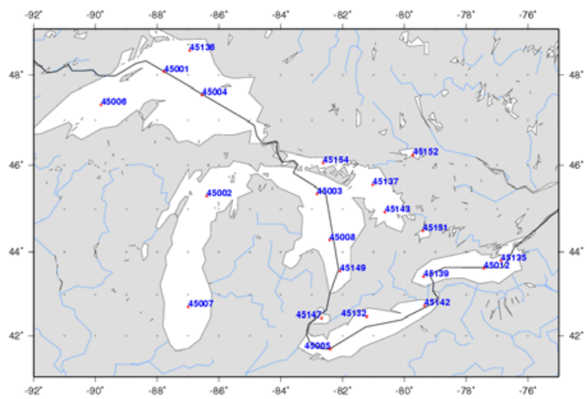


FIG. 1. Maps showing the three domains for which UMOS equations were developed, from top left, east coast, west coast and Great Lakes. Locations of all buoys are plotted.

Results of independent tests have been completed for all domains shown in Fig. 1, and are positive, in the sense that the wind speed is improved with respect to the direct model output at all projection times for all locations. For wind direction, the improvement is smaller. In this paper we show only the results for L. Erie, since the procedure for input of the statistical winds to the wave model is still being built for the other domains.

Fig. 2 shows the L. Erie domain of the wave model, which extends from 41.30 N – 43.00 N and from 83.60 W to 78.40 W. The resolution is 0.05 x 0.05 degree. There are 3430 total points and 1172 Sea Points. The UMOS equations for the 4 L. Erie buoys were applied for all days during the test period and the forecast was verified against observations, at the buoy level. Verification results for wind speed – bias, RMSE and Reduction of Variance – are shown in Fig. 3.

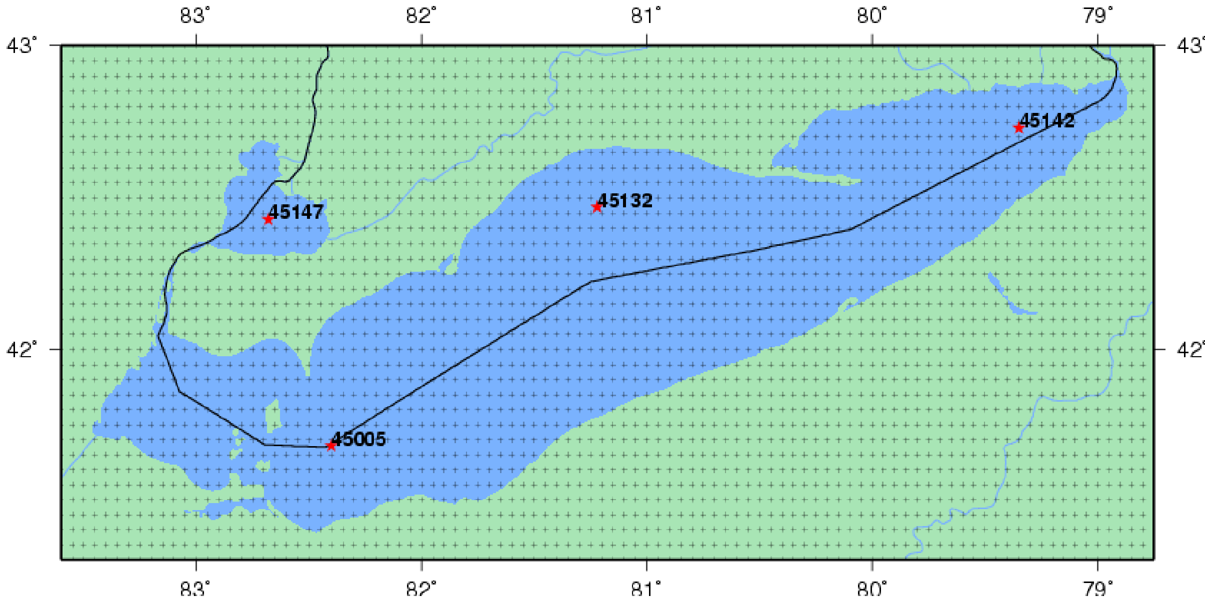
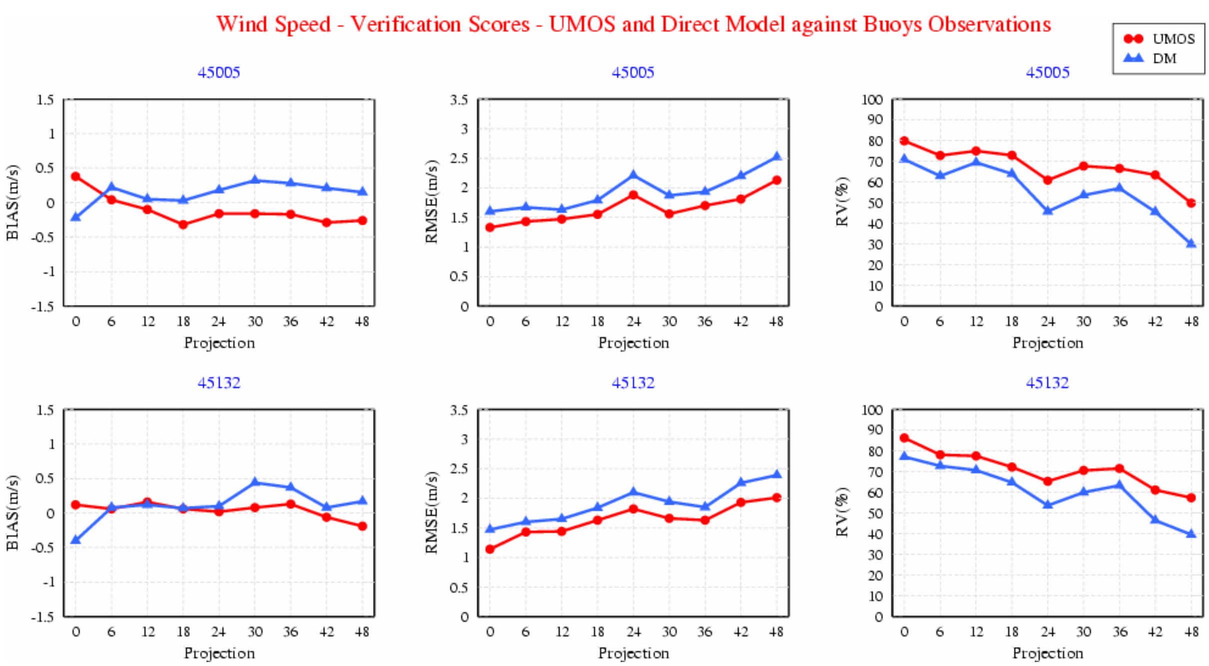


FIG. 2. WAM domain over Erie Lake showing the locations of the 4 buoys and the grid .



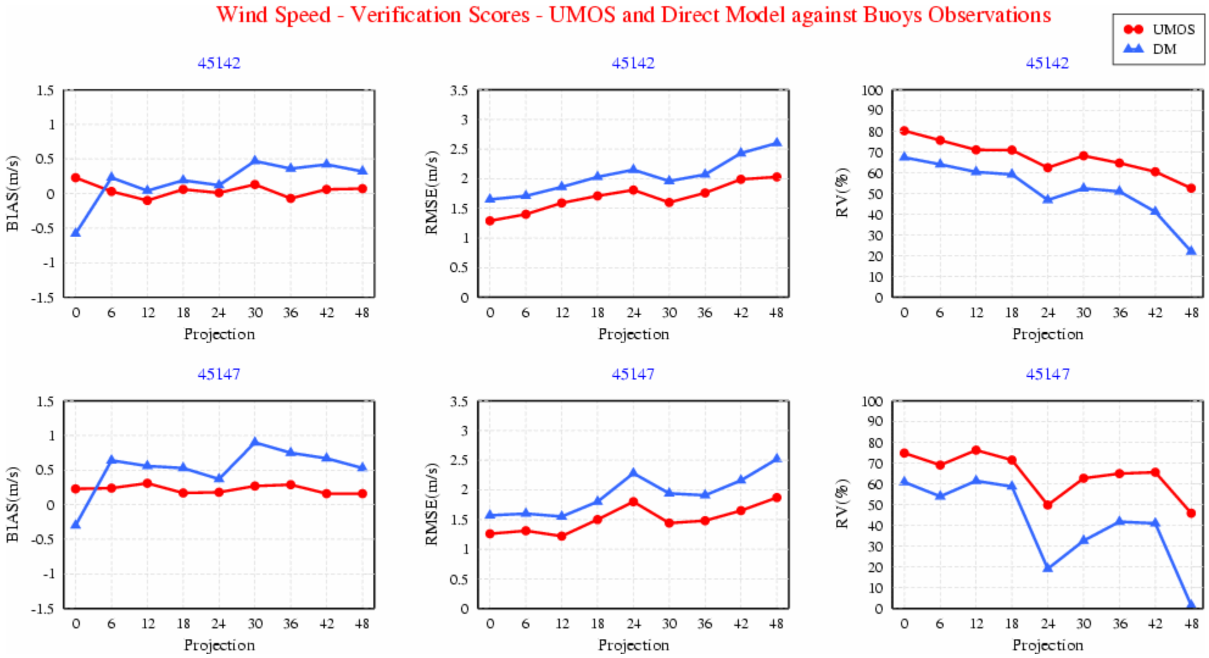


FIG. 3. Comparison of bias (left), RMSE (center) and reduction of variance (right) scores for the 4 buoy locations of the L. Erie domain, as a function of forecast projection in h. Independent sample of about 2.5 years. Statistical wind forecasts are in red and direct model output forecasts are in blue. All are valid at buoy height.

b) Gridding the MOS forecasts for input to the wave model

The output of the statistical package produces forecasts at the specific buoy locations where data is available (Fig. 1 and 2). The wave model requires wind input on a regular grid. On the assumption that the boundary layer physics relating the model output to the buoy locations does not change much with location over the open ocean, the equations developed for buoy locations were used to prepare the gridded wind fields required for input to the wave model.

The procedure was performed in 3 steps:

1. The statistical equations from each buoy and each time projection were applied at each grid point, using the specific predictors for that point. At the end of this step we have obtained a number of forecasts equal to the number of buoy-equations. This step is performed for UV, UU and VV parameters. For L. Erie, this step yields 4 estimates of wind speed and direction at all the grid points of interest, for each forecast projection.
2. The forecasts were combined, into one final forecast for each parameter : UU, VV and UV, at each grid point.
3. The three components UU, VV and UV from step 2 were transformed into UU and VV components This step is necessary once again so that unbiased wind speed forecasts from the statistical method are carried over to the UU and VV components needed by WAM.

The method used to combine the forecasts in step 2 is “IDW – Inverse distance weighting” - a simple method for curve fitting. It’s a process of assigning values to unknown locations by using values from known locations. In our application, we start with wind estimates that are valid at each grid point, because predictor values are calculated for each grid point.

However, we cannot assume that all the estimates, based on equations developed for buoy locations at various distances from the grid point, are equally valid. Some kind of weighting procedure is needed, which is a function of distance.

A simple IDW weighting factor is:

$$w_{d_w} = \frac{1}{d^p}$$

where w_d is the weighting factor applied to a known value, d is the distance from the known value to the unknown value, and p is a user-selected power factor. Here weight decreases as distance increases from the interpolated points. Greater values of p assign greater influence to values closest to the interpolated point. The most common value of p, and the value used here is 2.

A general form of interpolating a value using IDW is:

$$UV = \frac{\sum_{i=1}^{N} \frac{UV_i}{d_i^p}}{\sum_{i=1}^{N} \frac{1}{d_i^p}}$$

where UV is the value of the interpolated point, UV_i is a known value, and N is a total number of points used in the interpolation.

In order to do this we have constructed a distance field d_i assigned to each buoy. The distances were computed as a real distance on the sphere. Figures 4 and 5 show examples of the distance-weighting field for two of the buoys on L. Erie.

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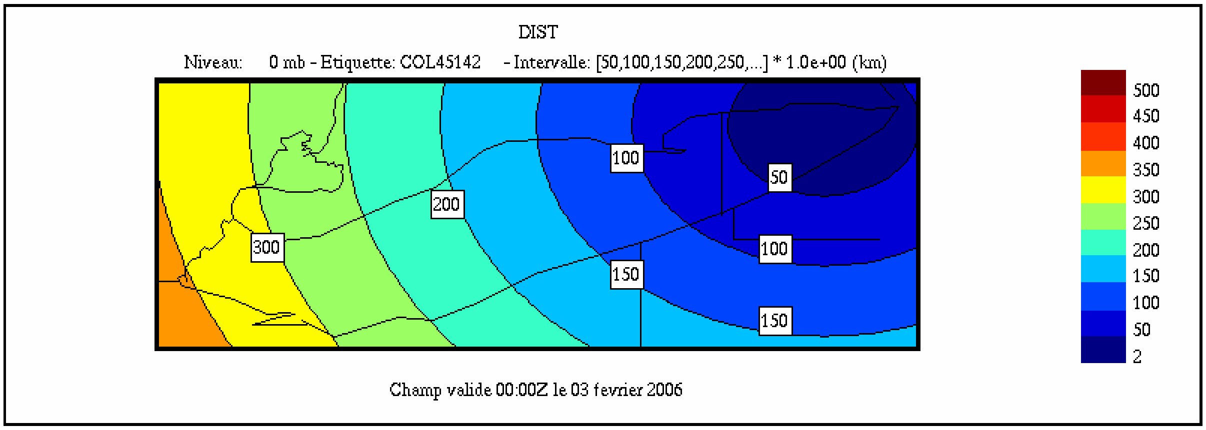


FIG. 4. The distance field from the Buoy 45142

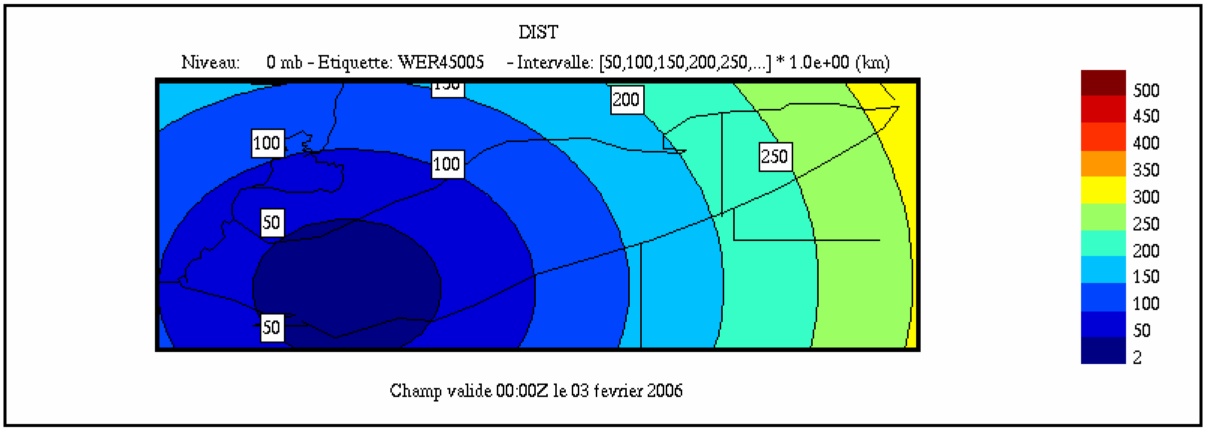


FIG. 5. The distance field from the Buoy 45005

3. Preliminary results for L. Erie

a) Verification of gridded wind speed forecasts against GEM model analysis at 10m height.

The gridded statistical wind speed forecasts were verified against the GEM analysis. Since the MOS winds are valid at the buoy elevation and the analysis is considered to be valid at the standard height of 10 m, it was first necessary to convert the statistical forecasts to 10 m. For the wind speed height adjustment, we used the WMO standard method, which is based on the power law wind profile (Hsu et al, 1994)

$$u_2 = u_1 \left(\frac{z_2}{z_1} \right)^{0.11}$$

where u_1 and u_2 are the forecast wind speed before and after the correction, respectively; z_1 and z_2 are the original observation height and the adjustment height (10m), respectively; and the power of 0.11 is a constant derived empirically from near-neutral conditions over water.

Verification of the MOS forecast wind speed was done for the 00 UTC cycle only. The UMOS wind forecasts were compared to the GEM model output, which is considered to be at 10 m. The verification scores were calculated over all water-points and for 3 months periods, from January 2004 until June 2006. Results are shown for autumn 2005 only in Fig. 6, the bias and the RMSE are averaged over all points. Results for other seasons and other parts of the domain were similar in character.

Fig. 6 indicates that the diurnal variation of bias and corresponding RMSE is very prominent. Bias and RMSE of the GEM forecasts at time 0 is essentially 0 because this is the analysis against which the forecasts are compared. Biases in both sets of forecasts are positive and highest in the middle of the night local time, when the assumption of neutral stability is least likely to hold over the lake. The bias and RMSE of UMOS forecasts are smaller than the model bias and RMSE at all forecast projections. The model forecasts seem to show an increased bias on day 2, which has been corrected by the statistical forecasts.

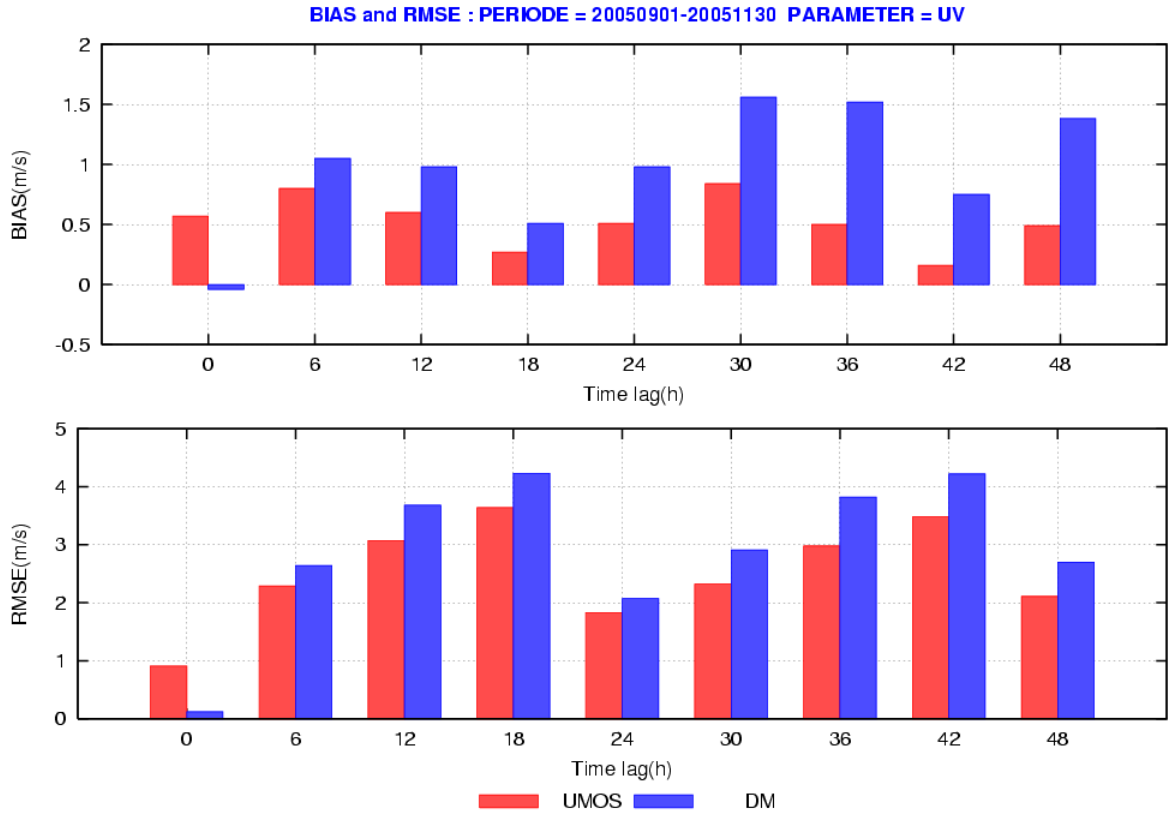


FIG. 6. Overall bias (top) and RMSE(bottom) for UMOS (red) and GEM (blue) 10 m wind speed forecasts for the Autumn season 2005, for L. Erie. Verification is against the GEM analysis.

b) Verification of WAM output fields against buoy observations

To evaluate the impact of the modified wind forecasts on the wave forecasts, the gridded winds were used as input to a test run of WAM, after adjustment to 10 m. Information on the current operational version of WAM can be found in Lalbeharry et al (2004). Since the necessary data for running the wave model retrospectively was most readily available for L. Erie, we began by examining some cases for this domain. The test period chosen was 21 – 25 August, 2006. For this 5 day period, most of the time, there was little difference between the wave field produced from the model winds and the wave field produced from the statistical winds, but there were a couple of exceptions. These cases were singled out for further examination; results are shown below.

Case 1: 24 august 2006, 42 hour forecast

In this case, shown in Figs. 7, 8, and 9 , the wave heights produced by WAM with GEM winds are as much as 0.5 m higher than those produced by WAM with statistical winds, in the Northeastern part of the lake.

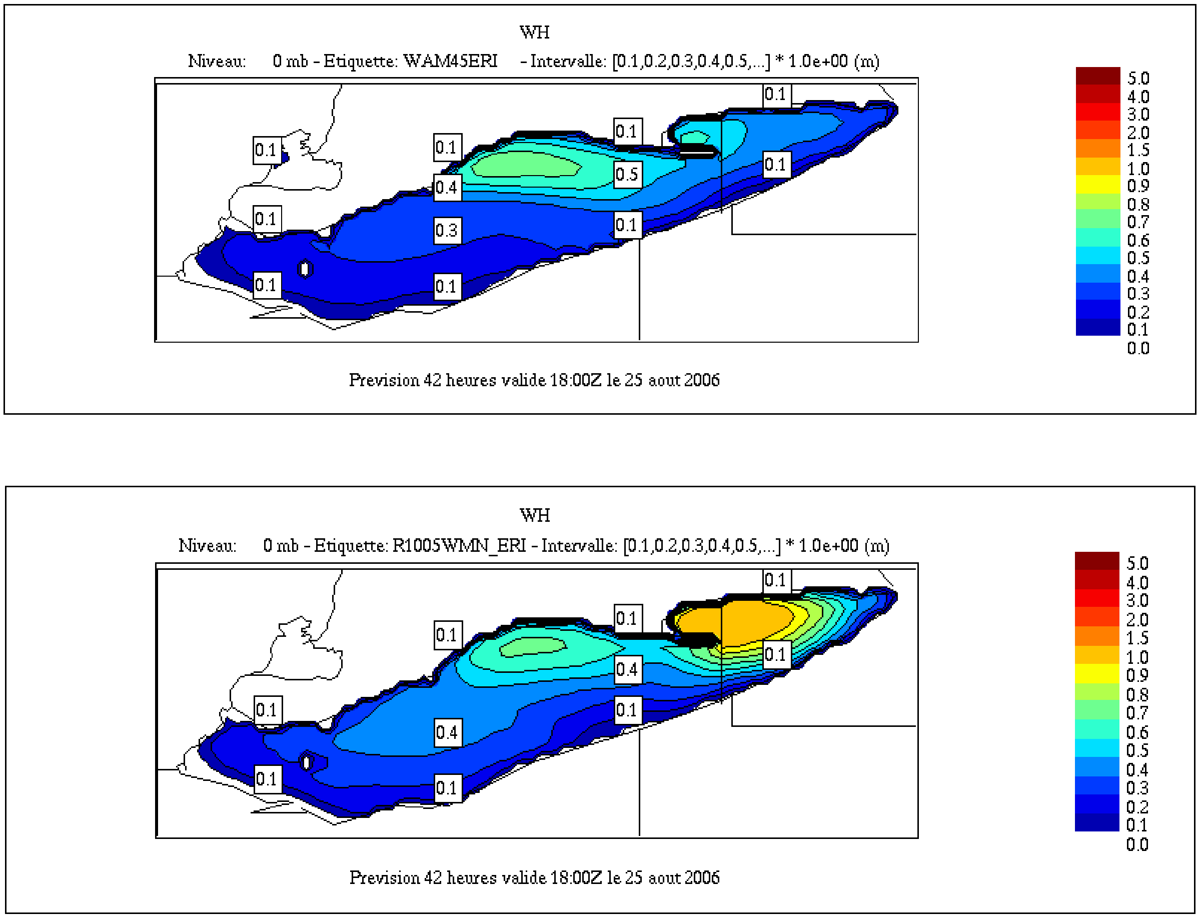


FIG. 7. 42 h forecast of the significant wave height field for L. Erie in m, using statistical winds (top) and model winds (bottom)

If we compare with the respective forecast wind fields (Fig. 8), it can be seen that the wind speed produced by GEM was almost twice the wind speed from UMOS in that part of the lake. Unfortunately we don't have a buoy located in the "core" of that region but the buoy 45142 is close enough to verify this difference.

Fig. 9 shows the forecast time series of winds and waves at buoy 45142, along with the corresponding observations. The wind speed produced by GEM was higher than the observation starting 24 august 21 UTC, with a maximum at 24 August + 42 h. UMOS produced a smoother wind speed time series and the forecast values were closer to those observed. The wave height reported by the buoy was 0.2m, which compares to a forecast of 0.4 m from WAM driven by UMOS winds and 0.8m from WAM driven by GEM winds. The over forecast GEM winds have led to an over forecast of the wave heights in this case, which is reduced in the WAM forecasts run from UMOS winds.

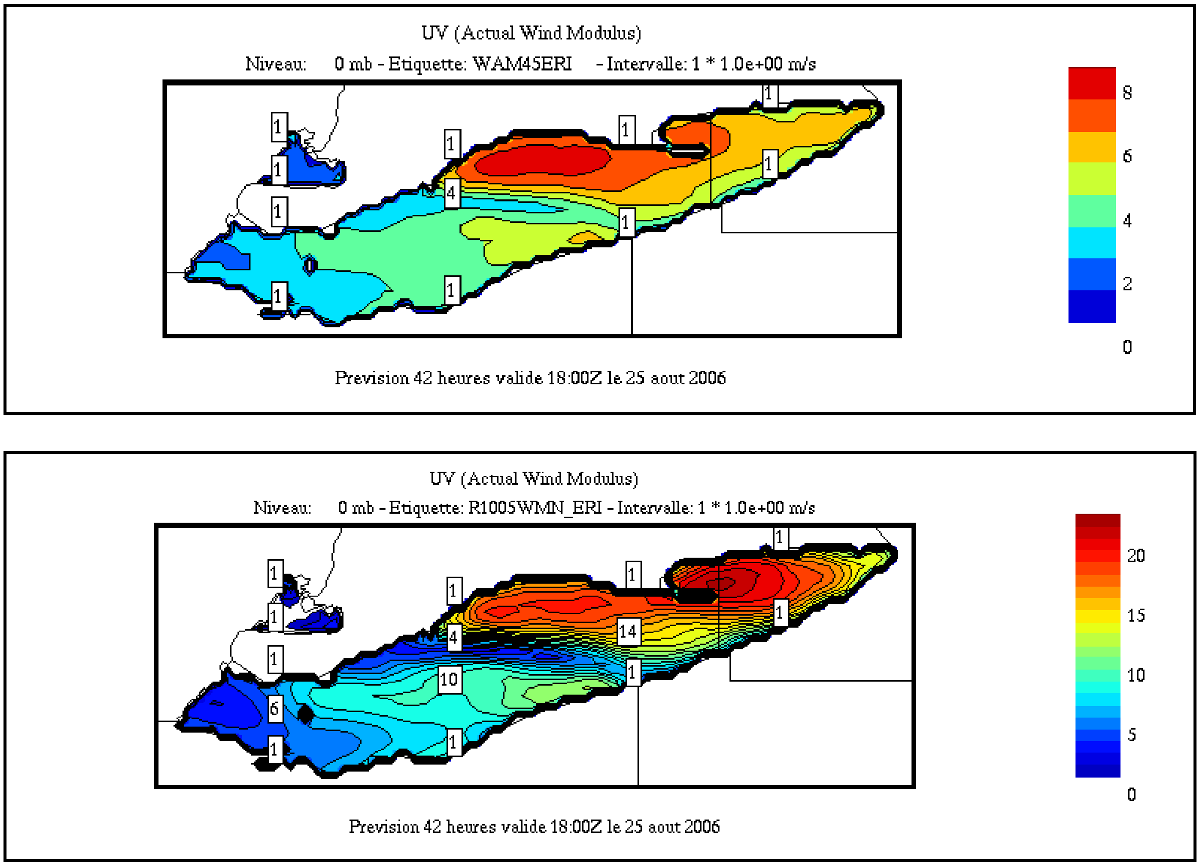


FIG. 8. 42 h forecast wind field from UMOS (top) and from GEM (bottom) for L. Erie

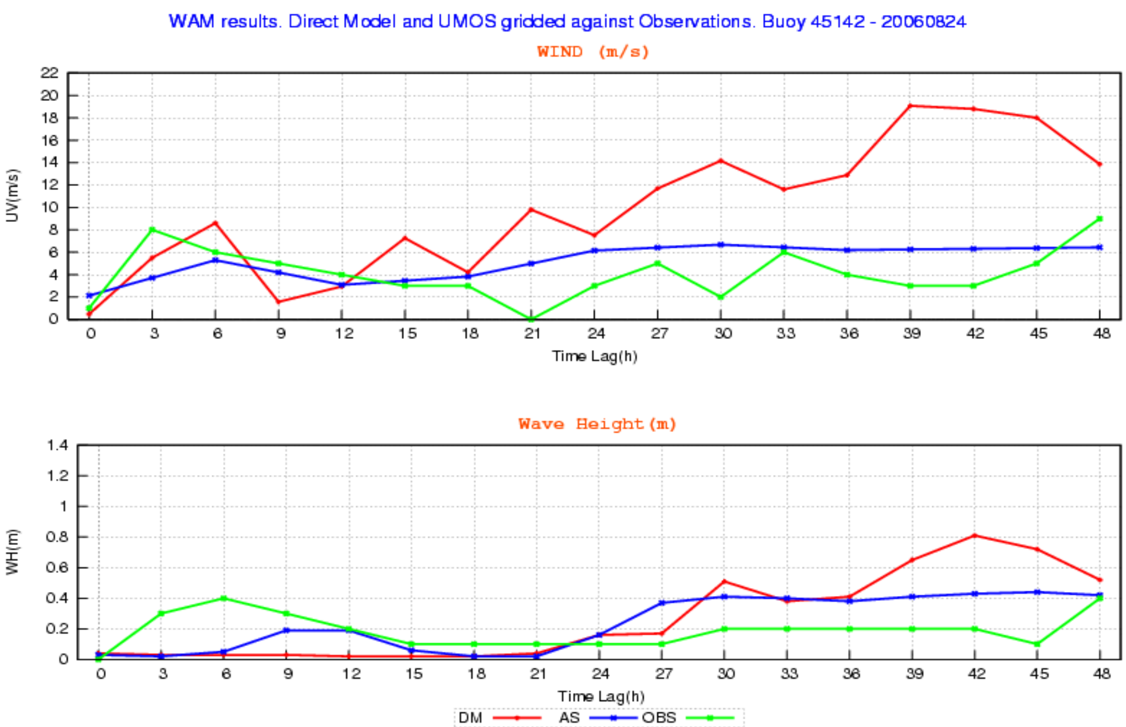
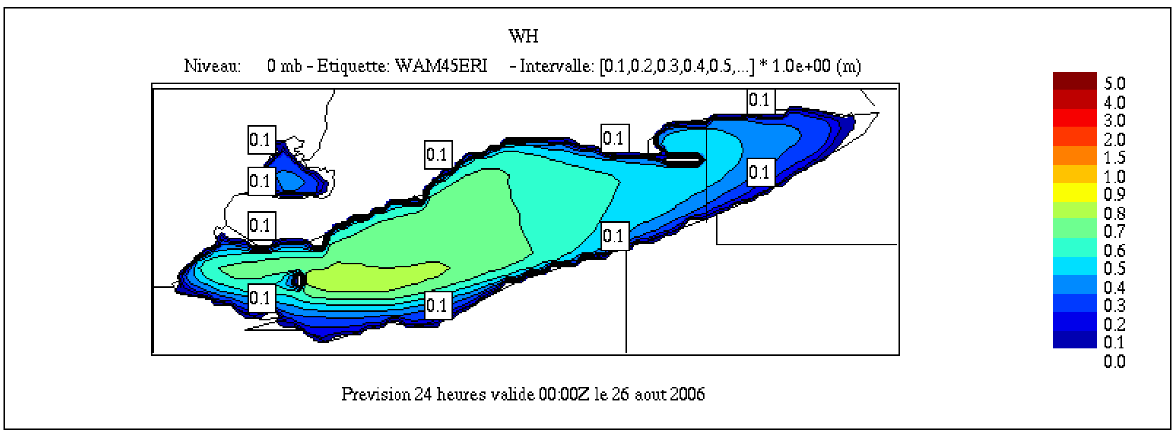


FIG. 9. Predicted and observed time series evolution of Wave height (bottom) and Wind speed (top) for the period 24 august 2006 – 00 UTC to 26 august 00 UTC. GEM winds results in red, UMOS results in blue and observations in green.

Case 2: 25 august 2006

In this case the differences between the two models started at 24 h. Results are shown in Figs. 10 – 13. Generally, (Fig.10) the forecast wave fields have the same shape, but the maximum wave height is located in the central part pf the Lake for GEM wind-driven waves, and in the southwest part for UMOS wind-driven waves **. T**he significant wave height is twice as large using GEM winds as it is using UMOS winds**.** The wind field distribution (Fig. 11) shows that the wind speed maximum corresponds to the wave height maximum, and the magnitude of the GEM wind maximum is also nearly double that for the UMOS winds. For this case, two buoy observations, 45005 and 45132 were used for validation.

At buoy 45005 (Fig. 12), UMOS has predicted the wind speed quite well throughout the 48 h run, while GEM winds overpredict, especially at 24 and 48 h. Nevertheless, WAM has underestimated the maximum wave height using both sets of winds; the GEM winds produce wave heights slightly closer to the peak. WAM seems to be a little over responsive to the winds in this case – the forecast maximum wave height precedes the observed maximum wave height by about 12 h.



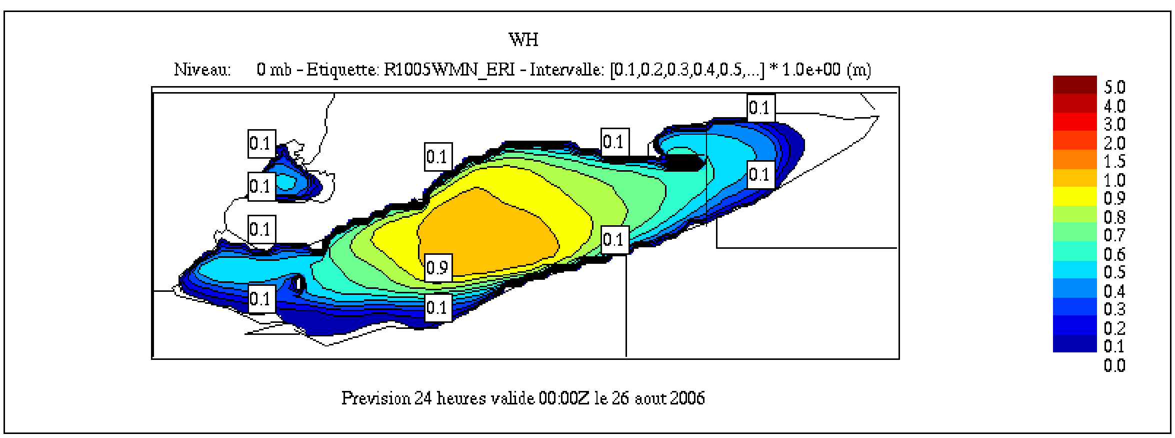


FIG. 10. 24 h forecast of Significant wave height for WAM driven by UMOS winds (top) and by GEM winds (bottom).

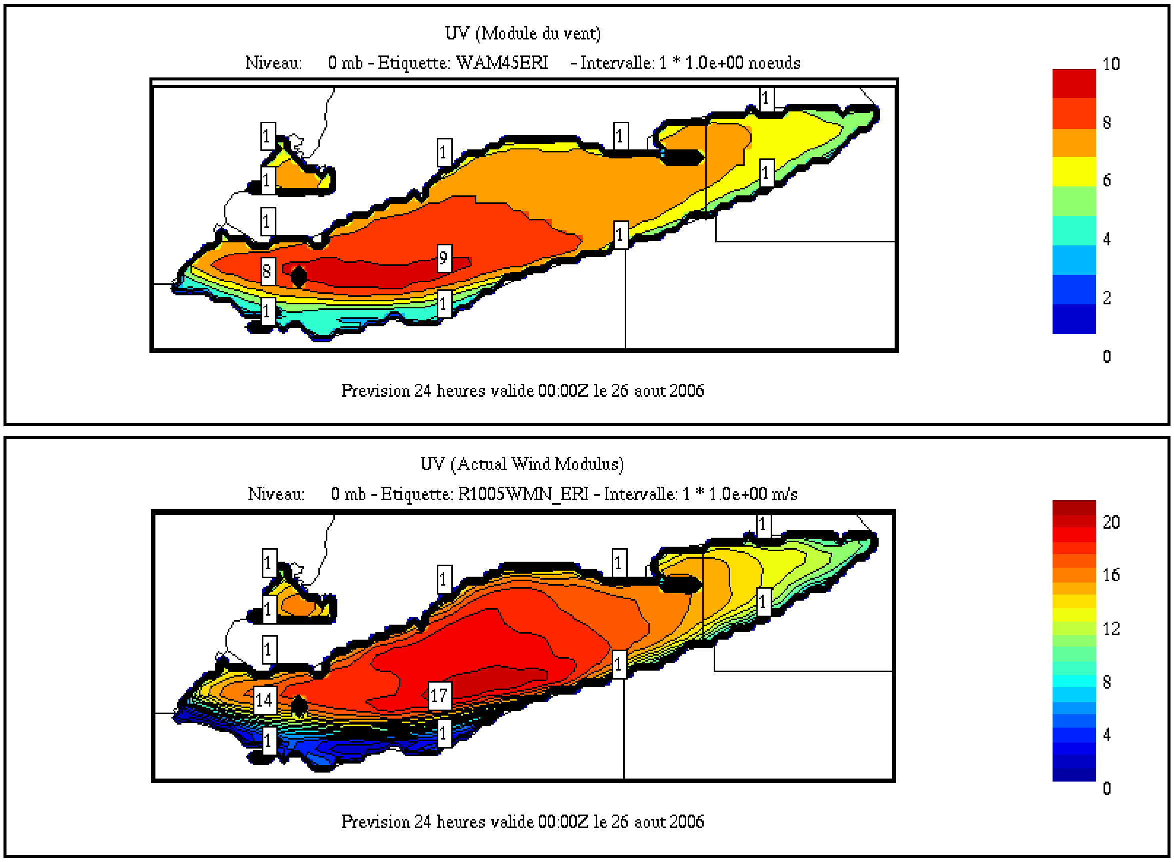


FIG. 11. 24 h wind speed forecast valid 26 August 06, 00UTC, produced by UMOS winds (top) and GEM winds (bottom)

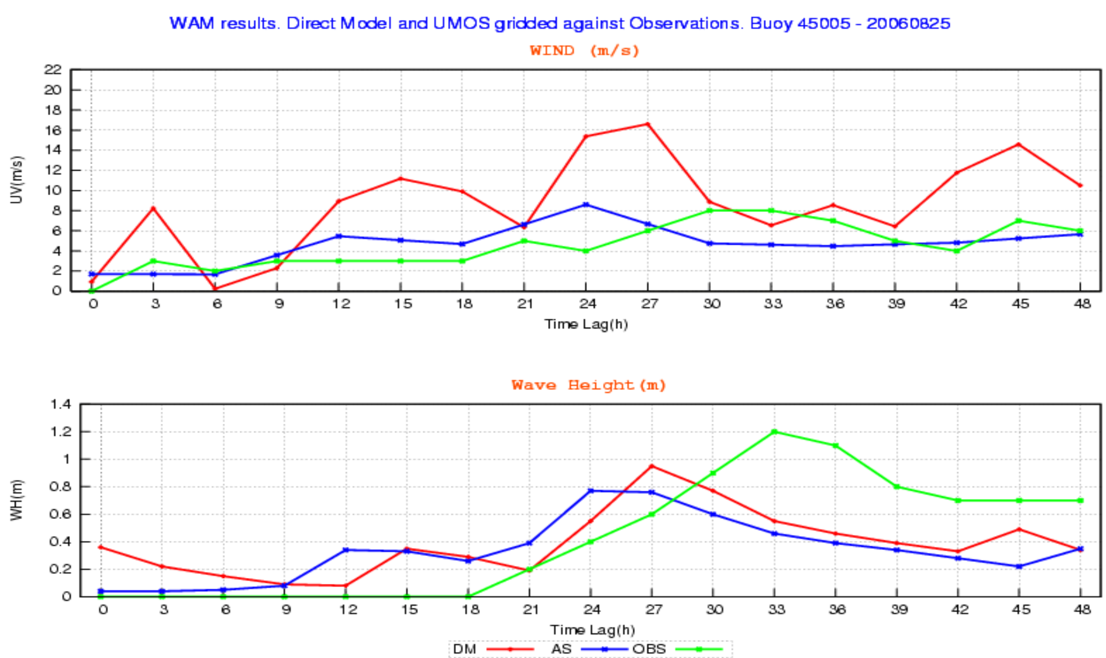


FIG. 12. Predicted and observed time series evolution of wave height (bottom) and wind speed (top) for the period 25 august 2006 – 00 UTC – 27 august 00 UTC. Buoy 45005 *GEM winds results in red, UMOS results in blue and observations in green.*

At the other buoy, which is closer to the GEM wind maximum location, (Fig. 13) the GEM winds have evidently significantly overpredicted the wind speed for a period of more than 24 h, while the MOS winds are rather accurate overall. The overpredicted GEM winds lead to maximum wave heights which are close to those observed, but again the peak is 6 to 12 h early. The MOS winds, which slightly underpredict from 27 h on, result in a maximum wave height about 30% too low, and also early compared to the observed maximum.

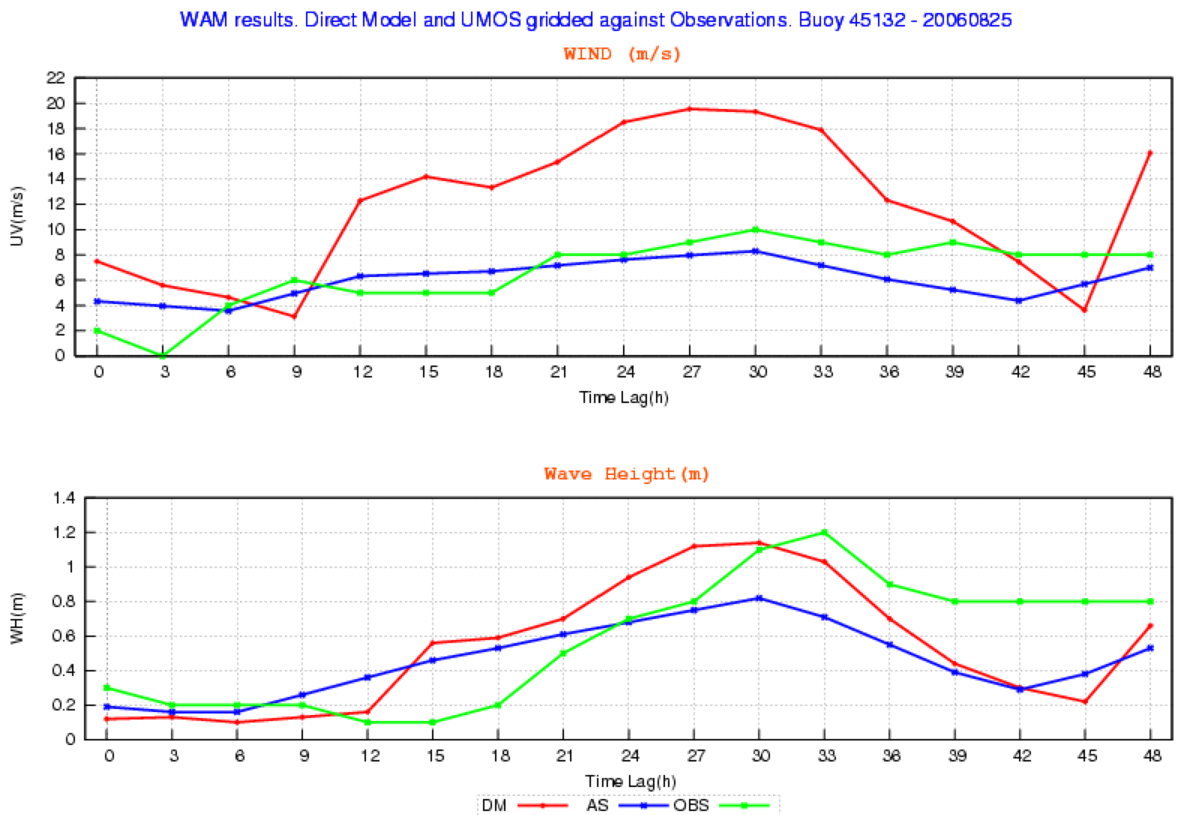


FIG. 13. Predicted and observed time series evolution of wave height (bottom) and wind speed (top) for the period 25 august 2006 – 00 UTC – 27 august 00 UTC.. Buoy 45132. *GEM winds results in red, UMOS results in blue and observations in green.*

These results show some interesting characteristics which warrant further examination. If it is true that getting the winds correct leads to an underforecasting of the waves, then this points to inadequacies in the wave model or in the correction of the winds to the 10 m level that must be examined.

4. Discussion

MOS wind forecasts have been developed for all the buoys for which data was available over the east coast, west coast and Great Lakes waters. In independent tests (not shown here), forecasts from these equations, applied to the output of the GEM model, have indicated consistent improvement over the direct model output winds. We have begun to assess the degree to which this improvement can be transmitted to improvements in wave analyses and forecasts.

In this preliminary study, an inverse distance weighting scheme was used to blend wind speed estimates from the UMOS winds into a single estimate for each wave model grid point over L. Erie. Then the UMOS winds were converted to 10 m and input to the operational version of WAM for a 5-day test period. The wind and wave forecast results over this period were compared with those from the operational WAM using operationally available winds from GEM.

The following points can be made based on an assessment of the results:

1. Three months of comparison of the wind forecasts against the GEM analysis indicate that all the forecast winds are biased high, and this bias is reduced by UMOS.
2. Compared to the buoy winds, the UMOS winds are quite accurate while the GEM winds are high, based on the 5- day study and consistent with the 3-month results.
3. The accurate UMOS winds do not necessarily result in improved wave forecasts. At least the evidence of this is not yet clear after one study.
4. There is some evidence that the wave model in L. Erie is over responsive to the winds – building waves too quickly and allowing the waves to subside too quickly. This is based on one case only however.

The next major step in this project is to apply the MOS winds to WAM runs in the Atlantic and Pacific domains. These are much larger, and will require further assumptions about the applicability of the MOS equations for the offshore areas over large areas of open ocean. The inverse weighting scheme will be adapted to this situation. As results from further runs of WAM are collected, summary statistics will be produced to assess the overall performance of WAM with UMOS winds compared to WAM with GEM winds.

The case study shown here involved maximum observed wave heights of only 1.2 m. The adaptation to east and west coasts will permit case studies of important extreme storms.

If we can confirm that the statistical interpretation of model output winds can improve wave forecasts, then the scheme will eventually be implemented. The UMOS marine wind forecasts are already in the process of being implemented at CMC, and will form part of the UMOS guidance package for regional offices which has been in operations for several years.

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