RESULTS OF THE APPLICATION OF THE CANADIAN UPDATEABLE MODEL OUTPUT STATISTICS SYSTEM TO THE GREAT LAKES MARINE FORECAST PROBLEM

Syd Peel*, Laurence J. Wilson, Marcel Vallée
Meteorological Research Branch/RPN
Meteorological Service of Canada

1. INTRODUCTION

The Canadian Updateable Model Output Statistics (UMOS) system, described in Wilson and Vallée (2003, 2002), has been producing forecasts of the marine winds for the Great Lakes in real time, on an experimental basis, since December of 2002. This paper will briefly describe UMOS, focussing on those modifications of the operational implementation required for its adaptation to the Great Lakes marine forecast problem. To that end the desired predictands are defined, and those model predictors introduced specifically for the application of UMOS to the Great Lakes forecast are listed.

Comparisons of the UMOS forecasts against the direct model output of the regional Global Environmental Multiscale (GEM) model which supplied the predictors for the regression, the official marine forecast issued by the Ontario region of the Meteorological Service of Canada (MSC), and the perfect prog forecasts of the National Weather Service (NWS) of the United States are presented.

In May, 2003 the Meteorological Development Lab of the NWS announced the operational implementation of a new Model Output Statistics (MOS) (Glahn and Lowry, 1972) system encompassing the observational network maintained by the National Data Buoy Centre (NDBC) of the American National Oceanic and Atmospheric Administration (NOAA), (McAloon, 2003) including those weather buoys moored on the Great Lakes supplying observations used in the UMOS regressions. Solutions from the UMOS and the MDL MOS systems are compared at those sites on the Great Lakes at which both of these systems produce forecasts.

Finally, we examine the problem of capturing the seasonal dependence of the windspeed on the Great Lakes. Resolution of the strong seasonal signal in this predictand is complicated by the incomplete observational programme in place to monitor the Great Lakes. Removal of the buoys each fall, and their subsequent re-deployment in the spring, obscures this signal in the regression. We touch upon this feature of the problem, and on a possible approach to guarantee the faithful reproduction of the seasonal trend in the regression solutions.

2. UMOS

In March of 2001 the Canadian UMOS system, inspired by ideas presented by Ross (1989, 1987), was implemented operationally at the Canadian Meteorological Centre (CMC), providing guidance to the forecast centres of the MSC across Canada. The system is based upon a MOS formulation for constructing the regression equations used to obtain forecasts of the desired predictands. However, as its name suggests, UMOS has the capacity to automatically update these regression equations with any desired frequency.

Furthermore, UMOS can quickly adapt to changes in the numerical weather prediction (NWP) model which supplies the predictors to the regression equations. UMOS permits the assignment of different weights to the predictor samples from the old and new NWP models. A judicious choice of these weights can accelerate the acclimatization of the statistical model to the biases inherent to the new NWP model, without introducing unacceptable instabilities into the regression solutions during the course of the transition from the old NWP model to the new one.

As a statistical post-processing system intended to refine the guidance available for the MSC environmental forecast programmes, it was designed to function efficiently and robustly in an operational NWP computing environment, possessing extensive configurability and a fairly high degree of portability across UNIX/Linux platforms. These characteristics, along with the promising results reported by Wilson and Vallée (2003), strongly recommended the application of UMOS to the problem of forecasting marine winds on the Great Lakes.

3. PREDICTANDS

The smallest forecast region in the MSC marine forecast for the Great Lakes is half a lake, the lakes being split east-west, with the exception of Lake Huron and Georgian Bay, which are split north-south, and Whitefish Bay and Lake St. Clair, which are too small to be split. Thus the buoys displayed in Fig. 1 monitor all of the regions in the MSC marine forecast programme on the Great Lakes except for Whitefish Bay and that segment of the St. Lawrence River which flows

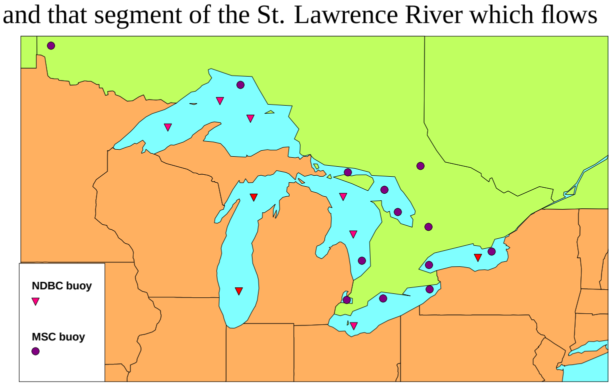

Figure 1. Weather buoys in the Great Lakes basin.

through the province of Ontario.

*Syd.Peel@ec.gc.ca, 4905 Dufferin St., Toronto, Ontario, Canada M3H 5T4

Lake Michigan falls outside of the MSC Great Lakes programme, so the buoys on this lake were excluded from consideration. Furthermore, UMOS requires approximately 325 sample points in order to obtain stable regession equations for forecasting the wind (Wilson and Vallée, 2002), so several of the buoys were eliminated because their observational records weren't sufficiently long.* The buoys originally considered in this project, shown in Figure 2, cover both halves of all of the major lakes.

The predictands employed in the regression consist of the windspeed, along with the zonal and meridional wind components, observed at these buoys. Since the anemometers on most of these buoys are situated less than 5 metres above the surface of the water, the windspeeds reported by these instruments were corrected to the standard 10 metre reference level, using Bridget Thomas' implementation (Thomas, 1972) of J. L. Walmsley's (Walmsley, 1988) algorithm for adjusting windspeed to different heights. The archived model forecasts supplying the predictors for the regression were only available at the synoptic hours. The maximum windspeed observed in the 6-hour period centred on the synoptic hours was therefore employed as a predictand. For the wind direction, the predictands for a particular synoptic hour were given by the wind components obtained from the wind with the maximum windspeed in the 6-hour interval bracketing the synoptic hour. In contrast to the 17 forecast projections of wind speed and direction produced in the operational implementation of UMOS (Wilson and Vallée, 2003), only 9 forecast projections (every 6 hours from 0 to 48 h) are generated by the version of UMOS adapted to the Great Lakes forecast.

4. PREDICTORS

The version of UMOS in operational use draws the predictors for the regression equations from a large pool of variables derived from the meteorological fields forecast by the GEM model - including persistance variables there are a total of 177 potential predictors available to the operational implementation of UMOS. This wide selection of predictors notwithstanding, a number of additional quantities deemed particularly pertinent to the marine forecast problem were added to the original UMOS set, including isallobaric and curvature terms, variables representing the instability of the marine atmosphere in the lower layers, and second-order terms coupling the mean instability in these layers with the winds at the top of the layer.

In order to capture any climatological signals in the predictands the Julian day is available in the original set of UMOS predictors. Inspired by the perfect prog system developed by the NWS for Great Lakes winds, the first harmonics of the Julian day † were added to this predictor set. ‡

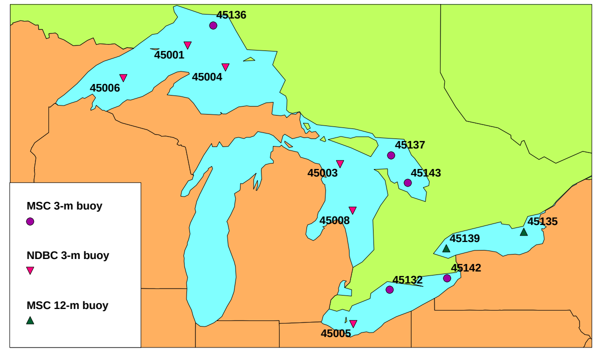

Figure 2. Weather buoys considered for this study.

The entire collection of predictors offered to the forward-stepwise multivariate linear regression (MLR) algorithm (Draper and Smith, 1966; IMSL User's Manual, 1989) employed by UMOS in the forecast of continuous predictands, is presented in Table 1. Those variables displayed in red were added to the original set available to the version of UMOS currently in operational service.

5. TESTS

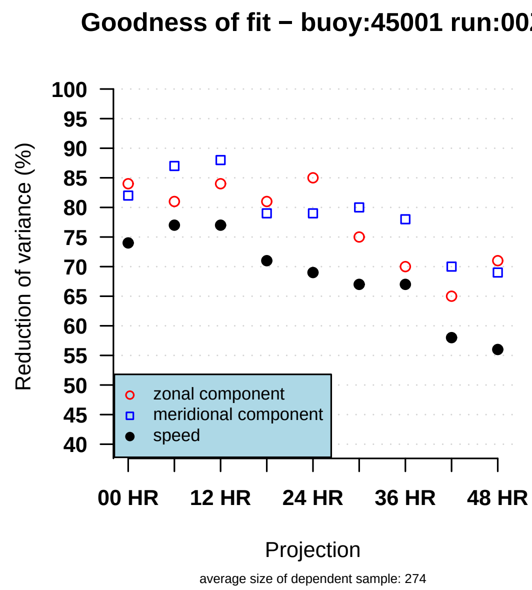

Figure 3. Fit of UMOS equations for the central Superior buoy.

The results for the UMOS forecasts of the wind at the NDBC's central Superior buoy (45001), displayed in Figs 3 - 6, are generally representative of its performance on the Great Lakes. In Fig. 3 the fits for the components of the wind peak at an adjusted reduction of variance neighbouring 85% as the regional GEM model spins up. The fit then begins to deteriorate with increasing forecast projection as the skill of the GEM

*Specifically, the watchkeeper buoys deployed in the fall of 1999 by the MSC on some of the smaller bodies of water in Ontario, namely Lake of the Woods, Lake Nipissing, the North Channel, and Lake Simcoe. The buoy deployed by the NDBC in Lake Ontario in 2001 was omitted for the same reason, although its data could be pooled with that of the two Lake Ontario buoys maintained by the MSC.

†The second harmonics, which are also employed by the NWS in their statistical models, were not used.

‡Faucher et al. (1999) also discuss the possible utility of the first harmonics of the Julian day, but used only the Julian day itself as a climatological predictor in their statistical model.

Model Predictor	**Level(s)**	**Label**
Zonal and meridional wind components	Surface, 1000, 925, 850, 700, 500	UU,VV
Wind speed derived from UU,VV	Surface, 1000, 925, 850, 700, 500	UV
Geostrophic wind components	Surface, 1000, 925, 850, 700, 500	UG,VG
Vertical velocity	1000, 925, 850, 700, 500	WW
Curvature of the MSL pressure field	Surface	K_n,K_i
Surface pressure tendency	Surface	D3
Gradients of the surface pressure tendency	Surface	**DD3X,DD3Y**
Laplacian of the surface pressure tendency	Surface	LT
Divergence	Surface, 1000, 925, 850, 700	DI
Meridional shear of the zonal wind component	1000, 925, 850, 700	UY
Zonal shear of the meridional wind component	1000, 925, 850, 700	VX
Temperature	Surface, 1000, 925, 850, 700	TT
Zonal and meridional temperature gradients	Surface, 1000, 925, 850, 700	TX, TY
Vertical temperature gradient	Surface,1000,925,850,700	TZ
Temperature advection	Surface, 1000, 925, 850, 700	AT
Water temperature		**TM**
Water-air temperature difference	Surface, 1000, 925, 850, 700	**TMTT**
Zonal, meridional gradients of dewpoint depression	Surface, 1000, 925, 850, 700	DX,DY
Vorticity advection	Surface, 1000, 925, 850, 700, 500	ZA
Second order terms coupling TZ with upper level winds	1000, 925, 850	**UVT,UUT,VVT**
Second order terms coupling TZ with upper level geostrophic winds	1000, 925, 850	**WGT,UGT,VGT**
Julian day		JULIAN
First harmonics of Julian day		**COS_JUL,SIN_JUL**

Table 1: Potential predictors derived from GEM forecast fields

forecast wanes. The fit for the windspeed exhibits similar behaviour, but the reduction of variance is anywhere from 5 to 15% lower than that achieved for the wind components. The UMOS model manifests very little bias, as is evident in Fig. 4, which is to be expected from a regression model.

As can be seen in Fig. 5, UMOS reduces the mean absolute error in the model windspeed at all projections, with corrections of as much as 1 knot or more. In Fig. 6 we can see that the direction of the wind is generally improved on average by approximately $5°$. Additional results on the performance of this adaptation of UMOS to the Great Lakes marine forecast can be found in Peel et al. (2002).

Comparisons against the official forecast issued by the Ontario Region of the MSC necessitated the parsing of the MAFOR, a highly structured, codified version of the marine forecast for the St. Lawrence Seaway. The MAFOR classifies windspeed forecasts into the categories listed in Table 2.

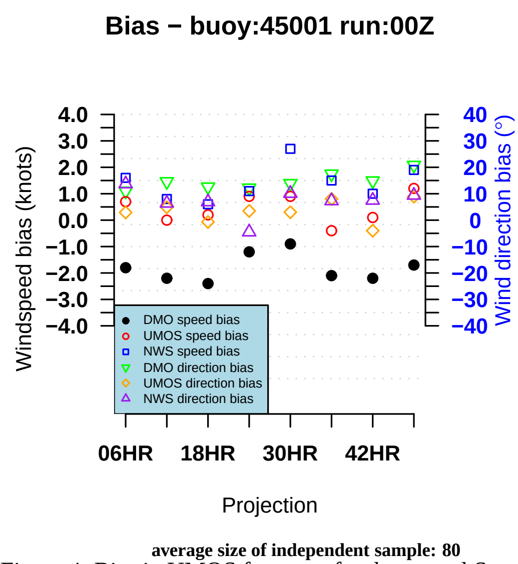

Figure 4. Bias in UMOS forecasts for the central Superior buoy.

ing elements in the table for the official MSC forecast in all windspeed categories except the lowest.

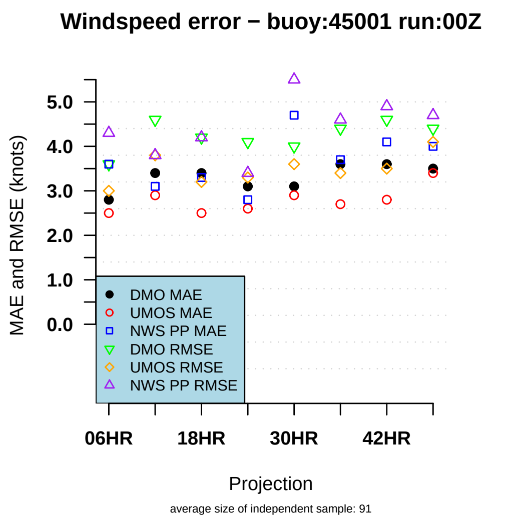

Figure 5. Windspeed error at the central Superior buoy.

MAFOR windspeed class	windspeed range (knots)
0	0 - 10
1	11 - 16
2	17 - 21
3	22 - 27
4	28 - 33
5	34 - 40
6	41 - 47
7	48 - 55
8	56 - 63
9	> 63

Table 2. MAFOR wind speed classes.

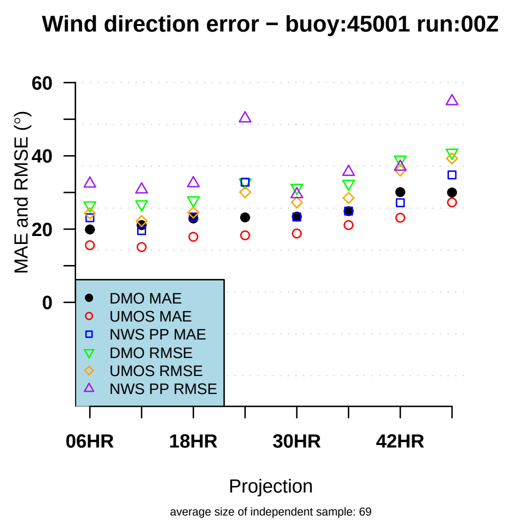

Figure 6. Wind direction error at the central Superior buoy.

Verification of the forecast systems, employing this categorization of the windspeed, results in 9×9 contingency tables such as those presented in Tables 3 - 5. The contingency table for a perfect forecast system would consist of a diagonal matrix, and the relative size of the diagonal elements for the corresponding column from each of the contingency tables affords an initial impression of the comparative quality of the forecasts of wind speed in that forecast range. On this basis it can be seen that UMOS improves on GEM model output for all windspeed categories except the lowest two. The elements on the principal diagonal of the contingency table for the UMOS forecasts are markedly larger than the correspond-

Forecast biases in each windspeed range are given by the ratio of the total number of forecasts for that range, which is found in the "totals" column at the right for the row corresponding to the desired windspeed range, to the total number of buoy reports falling into that range, given in the matching column of the "totals" row at the bottom. Hence it can be seen from Table 4 that UMOS greatly underforecasts winds in the lowest speed category, possessing a bias of $\frac{234}{989}$. Conversely, UMOS overforecasts winds in the second-lowest windspeed category, with a bias of $\frac{1240}{676}$. This over-forecasting bias persists for the rest of the windspeed classes, but relaxes with increasing windspeed to near unity at the upper end of the windspeed spectrum, where the UMOS forecasts exhibit a bias of $\frac{36}{33}$ for gales.

This behaviour in the UMOS forecasts results from the tendency of regression solutions to forecast towards the mean. Windspeed follows a Weibull distribution (Somerville and Bean, 1979), which is positively skewed. Hence, while inspection of the column totals in Tables 3 - 5 reveals that the mode of the distribution of windspeeds reported at the buoys occurs in the lowest range, the mean falls in the second-lowest windspeed category.

The biases resulting from the UMOS equations discernible in Table 4 are mirrored in Tables 6 and 7, which tabulate the Probability of Detection (POD) and False Alarm Ratio (FAR) for the thresholds separating each of the adjacent windspeed categories. These tables demonstrate that while UMOS scores PODs comparable to those achieved by the official MSC forecast for all thresholds, the UMOS FARs are near, and for some thresholds below, half of the corresponding FARs of the official forecasts.

		Observed										
		0	1	2	3	4	5	6	7	8	9	totals
	0	**0562**	0133	0023	0002	0000	0000	0000	0000	0000	0000	0720
F	1	0383	**0413**	0225	0017	0000	0000	0000	0000	0000	0000	1038
o	2	0037	0119	**0299**	0097	0007	0000	0000	0000	0000	0000	0559
r	3	0007	0010	0077	**0128**	0023	0002	0000	0000	0000	0000	0247
e	4	0000	0001	0004	0019	**0029**	0016	0000	0000	0000	0000	0069
c	5	0000	0000	0000	0001	0010	**0014**	0000	0000	0000	0000	0025
a	6	0000	0000	0000	0000	0001	0001	**0000**	0000	0000	0000	0002
s	7	0000	0000	0000	0000	0000	0000	0000	**0000**	0000	0000	0000
t	8	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000	0000
	9	0000	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000
	totals	0989	0676	0628	0264	0070	0033	0000	0000	0000	0000	2660

Table 3. Verification of regional GEM forecasts at all projections

		Observed										
		0	1	2	3	4	5	6	7	8	9	totals
	0	**0213**	0020	0001	0000	0000	0000	0000	0000	0000	0000	0234
F	1	0688	**0408**	0137	0007	0000	0000	0000	0000	0000	0000	1240
o	2	0081	0222	**0343**	0056	0003	0000	0000	0000	0000	0000	0705
r	3	0006	0024	0143	**0165**	0017	0003	0000	0000	0000	0000	0358
e	4	0001	0002	0003	0034	**0038**	0006	0000	0000	0000	0000	0084
c	5	0000	0000	0001	0002	0012	**0021**	0000	0000	0000	0000	0036
a	6	0000	0000	0000	0000	0000	0003	**0000**	0000	0000	0000	0003
s	7	0000	0000	0000	0000	0000	0000	0000	**0000**	0000	0000	0000
t	8	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000	0000
	9	0000	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000
	totals	0989	0676	0628	0264	0070	0033	0000	0000	0000	0000	2660

Table 4. Verification of UMOS forecasts at all projections

		Observed										
		0	1	2	3	4	5	6	7	8	9	totals
	0	**0338**	0106	0020	0002	0000	0000	0000	0000	0000	0000	0466
F	1	0400	**0255**	0129	0012	0000	0000	0000	0000	0000	0000	0796
o	2	0188	0210	**0207**	0045	0001	0000	0000	0000	0000	0000	0651
r	3	0052	0084	0187	**0099**	0012	0003	0000	0000	0000	0000	0437
e	4	0007	0018	0070	0063	**0012**	0002	0000	0000	0000	0000	0172
c	5	0003	0003	0014	0041	0029	**0012**	0000	0000	0000	0000	0102
a	6	0000	0000	0000	0000	0013	0006	**0000**	0000	0000	0000	0019
s	7	0000	0000	0001	0002	0003	0010	0000	**0000**	0000	0000	0016
t	8	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000	0000
	9	0000	0000	0000	0000	0000	0000	0000	0000	0000	**0000**	0000
	totals	0989	0676	0628	0264	0070	0033	0000	0000	0000	0000	2660

Table 5. Verification of official MSC forecasts at all projections

forecast	threshold				
	class 0-class 1	class 1-class 2 light-moderate	class 2-class 3 moderate-strong	class 3-class 4 strong-near gale	class 4-class 5 near gale-gale
DMO	0.91	0.73	0.66	0.69	0.45
UMOS	0.99	0.85	0.82	0.78	0.73
FPCN20	0.92	0.84	0.84	0.84	0.85

Table 6. Comparison of probabilities of detection.

forecast	threshold				
	class 0-class 1	class 1-class 2 light-moderate	class 2-class 3 moderate-strong	class 3-class 4 strong-near gale	class 4-class 5 near gale-gale
DMO	0.22	0.19	0.29	0.26	0.44
UMOS	0.32	0.28	0.37	0.35	0.38
FPCN20	0.30	0.40	0.59	0.72	0.80

Table 7. Comparison of false alarm ratios.

While these statistics provide a measure of the cumulative performance of the forecast systems considered, it is also interesting to examine individual cases. On October 14, 2003 a deepening low pressure system crossed the lower Great Lakes, triggering storm warnings for Lake Ontario. Fig. 7 displays the UMOS and regional GEM wind forecasts at the eastern Ontario buoy (45135), based on the initialization of the GEM model at 00Z on October 13. UMOS forecast a windspeed (red squares) of 45 knots with a lead time of 42 hours, which was corroborated by a reported windspeed of 47 knots observed at the anemometer on 45135 (solid black line). UMOS consistently forecast a windspeed in this range with each subsequent integration of the model.

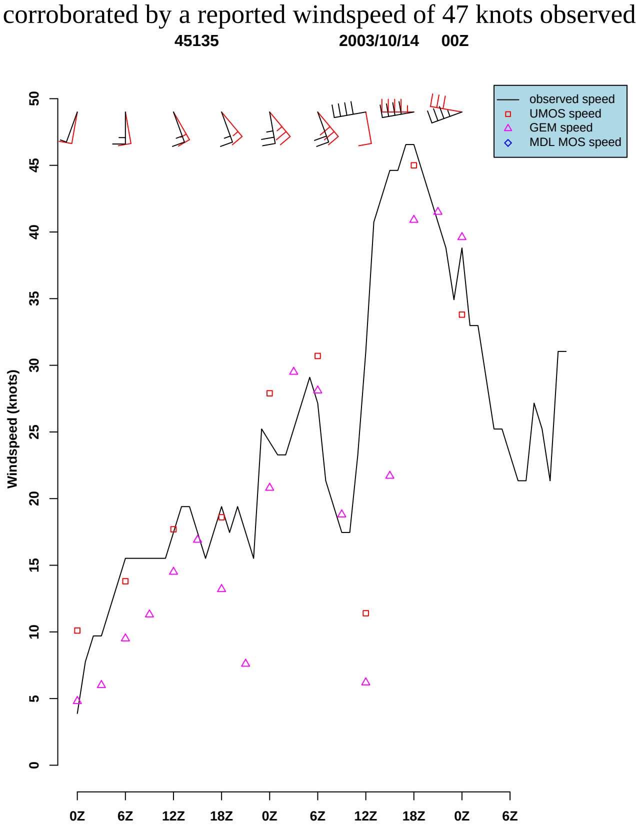

Figure 7. Verification of UMOS and GEM forecasts for a storm event on Lake Ontario.

The UMOS forecasts for the direction of the wind (red wind barbs near the top of the figure) were in fairly good agreement with the buoy reports (black wind barbs) except for the 36 hour forecast valid at 12Z October 15. The 90° discrepancy between the UMOS forecast of south-southeasterly winds and the west-southwesterly winds observed at the buoy is simply a phasing error, as the model is a few hours slow bringing the cold front through eastern Lake Ontario. The concomitant lag of the UMOS windspeeds behind those observed by the buoy corresponds to the delay in the displacement of a stable southerly flow with an unstable westerly one.

MDL MOS Forecasts for the Great Lakes became available early in May of 2003. This system produces forecasts for 6 sites at which UMOS also generates forecasts, namely the NDBC buoys in Superior, Huron, and western Erie. The predictors for the MDL system are obtained from the NWS GFS NWP model, which is integrated every 6 hours. Moreover, the MDL system provides forecasts every 3 hours (McAloon, 2003). In order to compare against UMOS only those forecasts on the synoptic hours were used, and the preliminary results reported here where obtained from the forecasts of model runs initialized at 00Z.

Forecasts of the wind direction are in quite good agreement, as can be seen in Figure 8. Comparison of the windspeed forecasts (Fig. 9) is complicated by the fact that the predictand for the UMOS windspeed forecasts is the maximum windspeed observed over the 6-hour interval bracketing the synoptic hour. Thus the forecasts were compared to the maximum wind speed observed in these 6 hour intervals. Since the MDL system produces forecasts at 3-hour intervals, for each synoptic hour the largest of: the MDL windpseed forecast on the synoptic hour, the MDL forecast for 3 hours before the synoptic hour, and the forecast for 3 hours after the hour, was taken as the MDL forecast at the synoptic hour *.

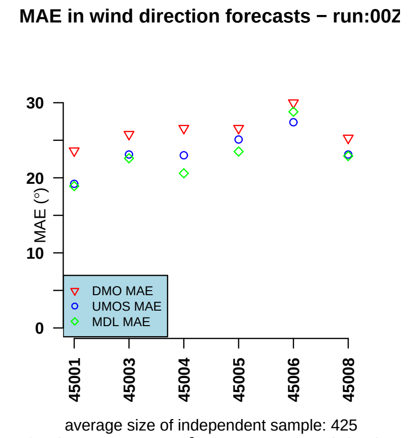

Figure 8. Comparison of errors in UMOS, GEM, and MDL forecasts of wind direction.

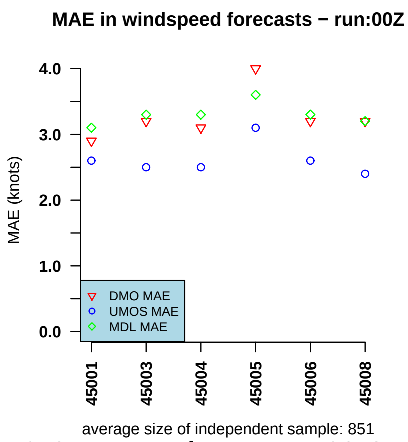

Figure 9. Comparison of errors in UMOS, GEM, and MDL forecasts of windspeed.

6. SEASONAL SIGNAL IN THE WINDSPEED

Plots of the windspeed observed at the anemometer on the eastern Ontario buoy (45135), along with the low-level stability of the atmosphere as determined by the difference between the surface air temperature and the temperature of the water in the lake, are displayed in Fig. 10 for the period extending from late 1998 through the end of 2002. The eastern Ontario buoy is a 12-metre discus buoy which normally remains in the lake throughout the year.

However, the other buoys monitoring conditions on the Great Lakes are removed from the water every fall, to be re-deployed each spring. The annual entry of the buoys into the water roughly coincides with the minimum in the instability of the marine atmosphere which results from the cooling of the lakes to near the freezing mark over the winter, along with the northward retreat of the arctic airmass. The corresponding minimum in the windspeed is due in part to the dampening effect of the strong marine inversion prevalent in this very stable atmosphere. The retrieval of the buoys in the fall occurs just prior to the annual peak in the low-level instability, as cold air periodically invades the Great Lakes basin with the passage of synoptic disturbances while lake temperatures only slowly recede from their late summer maxima.

Employing only the Julian day as a climatological predictor could therefore introduce significant errors into the windspeed forecasts for the winter months due to an incorrect extrapolation by the statistical model. The trace of the time-series for the windspeed would be more accurately modelled by a term in the cosine of the Julian day, and this term does appear frequently in the regression equations for the windspeed at several of the buoys on the upper lakes. At these locations spring arrives later, and winter earlier, so that the minima and maxima in the windspeed trends, apparent in Fig. 10, fall within the observational record of the buoys, and therefore influence the regressions. On the lower lakes these minima and maxima may be absent from the observational record, resulting in a better fit to either the Julian day or its sine.

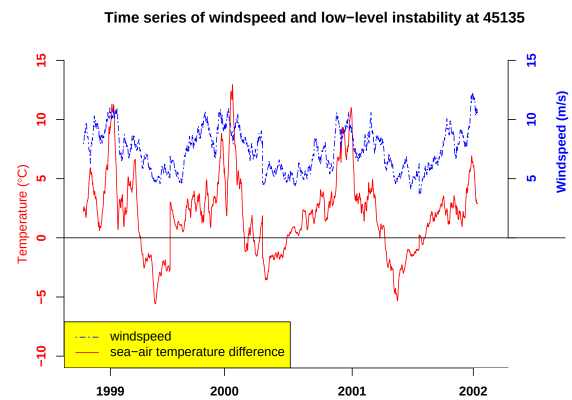

Figure 10. Seasonal trend in windspeed and low-level instability at the eastern Ontario buoy.

7. DISCUSSION AND CONCLUSIONS

The UMOS forecasts of marine winds on the Great Lakes certainly improve on the GEM model guidance. This appears to hold especially for forecasts of windspeed at the higher end of the spectrum, at the price of a significant over-forecasting bias at the lower end of the windspeed spectrum. Preliminary results of a comparison of UMOS to the NWS MOS forecasts indicate fairly good agreement for wind direction. UMOS windspeed forecasts, which are essentially forecasts of the maximum speed over a 6-hour interval, are generally stronger than the NWS solutions.

Several of the predictors introduced expressly to model marine winds did appear frequently in the regression equations, in particular the second-order terms coupling winds aloft to the low-level instability, as well as terms modelling the instability alone, and the isallobaric terms. The curvature terms could probably be omitted without serious consequences, consistent with the findings reported in Faucher et al. (1999) and Burrows et al. (1998) for their reconstruction of a wind climate at the west coast buoys.

*For the 6-hour projection only two MDL forecasts were available: at the hour and three hours ahead.

With regard to the climatological predictors, reliance solely on the Julian day may result in extrapolation errors for those months during which the buoys are not in the water. One possible recourse would be to deny the Julian day to the regressions for the windspeed, while at the same time possibly forcing the inclusion in the regression equations of a term in the cosine of the Julian day.

The MDL system circumvents such extrapolation errors (McAloon, 2003) arising from the interruption in the observation programme on the lakes by generating equations for the buoy locations in Lakes Superior and Huron from pooled samples including data from Coastal Marine Automated Network (C-MAN) stations (see Fig. 11). The C-MAN stations, typically located on lighthouses, monitor marine conditions on the lakes year-round. Forecasts using the C-MAN data are not currently available in UMOS because the observational data was not available at CMC in the format required for ingestion into UMOS. It will be interesting to compare the forecasts from the MDL and UMOS systems after the buoys are withdrawn from the water to see if the MDL strategy produces forecasts significantly different from those of UMOS.

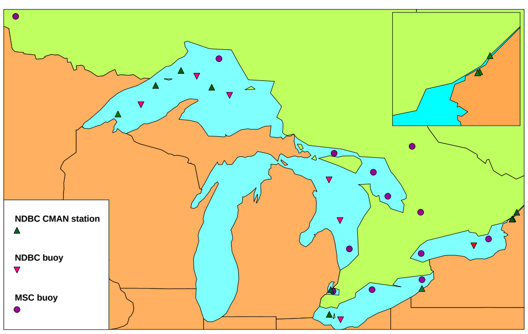

Figure 11. Observation platforms in the Great Lakes basin.

8. ACKNOWLEDGEMENTS

This work was financed in part by the Search and Rescue Secretariat of the Government of Canada.

The corresponding author would like to convey his gratitude to Chris McAloon and Kathryn Hughes of the Meteorological Development Lab at the National Weather Service, for the information which they provided about the MOS system developed at the MDL.

This author would also like to acknowledge Bridget Thomas of the Climate Research Branch of Environment Canada - Atlantic Region for her contribution of the code used to correct the observed winds to the 10-m reference level, Nelson Shum of the Meteorological Service of Canada for the code he supplied for the automated file transfer of the realtime UMOS forecasts, and Dr. William Burrows at the Meteorological Research Branch of the MSC for his advice through the course of this project.

The graphs were produced in R (Ihaka and Gentlemen, 1996), and code from the RadioSonde package written by Tim Hoar, Eric Gilleland, and Doug Nychka of NCAR/UCAR was adapted to the production of the windbarbs appearing in Fig 3.

This document was typeset in LaTeX.

9. REFERENCES

Burrows, W. R., J. Walmsley, J. Montpetit, and M. Faucher: 1998, CART-Neuro-Fuzzy Statistical data modelling Part 2: Results. *Preprints of the 14th Conference on Probability and Statistics in Atmospheric Sciences, Phoenix, AZ*, Amer. Meteor. Soc., 160–167.

Draper, N. R. and H. Smith: 1966, *Applied Regression Analysis*. John Wiley and Sons, second edition., 709 pp.

Faucher, M., W. R. Burrows, and L. Pandoflo: 1999, Empirical-statistical reconstruction of surface marine winds along the western coast of Canada. *Clim Res*, **11**, 173–190.

Glahn, H. and D. A. Lowry: 1972, The use of model output statistics (MOS) in objective weather forecasting. *J. Appl. Meteor.*, **11**, 1203–1211.

Ihaka, R. and R. Gentlemen: 1996, R: A Language for Data Analysis and Graphics. *Journal of Computational and Graphical Statistics*, **5**, 299–314.

IMSL User's Manual: 1989, *STAT/LIBRARY - FORTRAN Subroutines for Statistical Analysis*. IMSL, Inc., 1231 pp.

McAloon, C. M.: 2003, GFS-BASED MOS WIND GUIDANCE FOR MARINE LOCATIONS IN THE UNITED STATES.

Peel, S., L. J. Wilson, and M. Vallée: 2002, ADAPTATION OF THE CANADIAN UPDATEABLE MODEL OUTPUT SYSTEM TO FORECASTING MARINE WINDS ON THE GREAT LAKES. *Preprints of the 19th Conference on Weather Analysis and Forecasting, Amer. Meteor. Soc., San Antonio, TX*, Amer. Meteor. Soc., 391–394.

Ross, G. H.: 1987, An Updateable Model Output Statistics Scheme. *World Meteorological Organization, Programme on short- and medium range weather prediction, PSMP Report Series No. 25*, 45–48.

— 1989, Model output statistics - an updateable scheme. *Preprints of the 11th Conference on Probability and Statistics in Atmospheric Sciences, Boston, MA*, Amer. Meteor. Soc., 93–97.

Somerville, P. N. and S. J. Bean: 1979, Probability modeling of weather elements. *Preprints of the 6th Conference on Probability and Statistics in Atmospheric Sciences, Banff, CANADA*, Amer. Meteor. Soc., Boston, MA, 173–175.

Thomas, B.: 1972, Comparison of methods to adjust marine wind speeds in the vertical.

Walmsley, J. L.: 1988, On theoretical wind speed and temperature profiles over the sea with applications to data from Sable Island, Nova Scotia. *Atmosphere-Ocean*, **26**, 203–233.

Wilson, L. J. and M. Vallée: 2002, The Canadian Updateable Model Output Statistics (UMOS) System: Design and Development Tests. *Weather and Forecasting*, **17**, 206–222.

— 2003, The Canadian Updateable Model Output Statistics (UMOS) System: Validation against Perfect Prog. *Weather and Forecasting*, **18**, 288–302.