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OBJECTIVE WIND FORECASTING AND VERIFICATION ON THE GREAT LAKES

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ABSTRACT. *The Techniques Development Laboratory of the National Weather Service has developed an automated objective wind forecast scheme. The forecasts are currently being transmitted twice daily for the five Great Lakes. Wind forecasts are made for 12 locations on the lakes by the Model Output Statistics technique. Mean absolute errors in wind speed, for the various forecast periods, range from 5 to 8 knots (2.6 to 4.1 m sec^{-1}). Mean absolute errors in direction are as low as 20 degrees for the short-term forecasts (6- to 12-hour periods) to as high as 70 degrees for the longer term forecasts (30 to 36 hours).*

INTRODUCTION

Weather service for the Great Lakes was one of the original functions of the United States Meteorological Service. The Army's Signal Service, in 1870, was assigned the responsibility for issuing weather warnings under the direction of Colonel A. J. Myer. On November 8, 1870, Colonel Myer requested Professor I. A. Lapham to assume responsibility for the Great Lakes area. Lapham issued the first storm warning the same day with a forecast of high winds at Chicago and Milwaukee, barometer falling and thermometer rising at Chicago, Detroit, Toledo, Cleveland, Buffalo, and Rochester, and high winds probable along the lakes. This forecast was made by considering weather conditions at 20 stations which reported by telegraph (Whitnah 1961). Today the National Weather Service (NWS) continues to have the responsibility for providing forecasts and warnings on the Great Lakes. This service is of great importance to fishing, marine recreational activities, industrial operations and, in particular, to commercial shipping interests.

Commercial shipping activities, from the time they were started in 1815, have been plagued by the destructive action of severe storms and waves. In terms of the number of lives lost and the number of ships that sank, the storm of November 9, 1913 was the worst. Ten ships were sunk and 20 others were driven ashore with a loss of 235 lives. Winds were measured at 65 miles per hour (29 m sec^{-1}) with gusts to over 70 miles per hour (31 m sec^{-1}). Waves were estimated at 35 feet (10.7 m) following each other in rapid succession.

The most recent sinking of a large ship on the Great Lakes was that of the *Edmund Fitzgerald* during a severe storm on November 10, 1975. The 729-foot *Fitzgerald,* which was carrying 26,216 tons of taconite ore pellets, sank in eastern Lake Superior, northwest of Whitefish Point. Winds in the area were from the WNW at 50-60 knots (26-31 m sec^{-1}) with gusts reported to 75 knots (39 m sec^{-1}). Significant wave height was likely to have been about 9 m (Liu 1977).

This paper describes the development by the Techniques Development Laboratory (TDL) of a wind forecast guidance product which helps support the NWS Great Lakes mission, viz. automated, objective, wind and wave forecasts.

Automated wind forecasts for the Great Lakes were implemented in December 1969. These forecasts were for Lake Erie and Lake Ontario and were based upon 1000-mb geostrophic wind and sea-level pressure forecasts from the NWS Subsynoptic Advection Model for eight cities near the two lakes (Barrientos 1971). Resio and Vincent (1977) have shown how it is possible to estimate winds over the Great Lakes if the winds over adjacent land are known. The method is based upon

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a land wind transformation. While the method is of value for long range planning and design applications, its use as an operational forecast tool is limited by the fact that a forecast must first be made of the overland winds. On the other hand, numerical models may be used to directly forecast the over water wind on a day to day basis. The present automated Great Lakes forecast method is based on the Model Output Statistics (MOS) technique (Feit and Barrientos 1974). The predictors are the various forecast elements computed by the National Meteorological Center's Primitive Equation (PE) model. Wind forecasts are available for transmission twice daily to 36 hours in advance at 6-hour intervals for the 12 areas of the Great Lakes as shown in Figure 1. In addition, these wind forecasts are used as input to an objective wave forecast procedure.

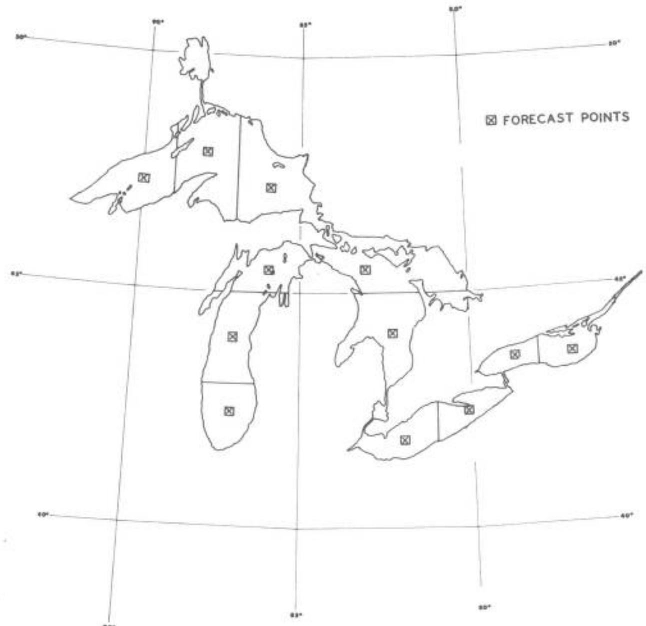

FIG. 1. Locations of wind forecast areas.

PROCEDURE

The method used was a linear regression technique where numerical model output (predictors) were matched with marine observations (predictands) and a forecast equation derived (Feit and Barrientos 1974).

The predictors used were the fields computed by the PE model. These forecast fields are saved on the TDL tape library for grid points in the United States. The PE model is run twice daily with origin times of 0000 GMT and 1200 GMT. The predictors were stratified by these times and separate systems developed for each. The forecasts saved are those for 6-hour intervals out to 48 hours.

Basic PE predictor elements were chosen as potential predictors based on their relevance to the predictand. From this basic set a computed set was developed (Table 1). Since these predictors are at grid points, they were interpolated to the forecast locations shown in Figure 1. A biquadratic interpolation scheme was used. This scheme fits, by least squares, a quadratic curve successively in two dimensions.

Marine observations (MAOBS) are regularly taken by anemometer-equipped vessels participating in the Great Lakes marine observation program. The wind observations are taken at some height above the water (on the order of 15 meters) and are not modified to represent a wind at the water surface. These MAOBS are collected by the National Climatic Center. These data were stratified by season; the winter season consisted of the months of October to December and the summer season the months of April to September. January through March are months of little or no Great Lakes activity due to ice, hence no data were used from this period, although forecasts continue to be made during those months. Table 2 shows the total numbers of observations used in developing the forecast equations.

Each lake was divided into two or three sections of approximately equal size. The observations were then separated according to the lake section in which they were taken. Since, in any given section, there might be several simultaneous observations, the observation of highest wind was picked as representative of the wind in the lake section. And since the MAOBS by agreement are taken no closer to the shore than 5 miles, they should be representative of the over-water wind condition. By picking the highest wind of simultaneous observations we tend to bias the wind forecasts to the higher winds. For our purposes this is quite desirable because the derived regression equation would normally have a tendency to underforecast the higher wind speeds.

The forecast equations were derived using a stepwise multiple regression program. At each step, the variable (predictor) entered into the regression equation is the one explaining the greatest amount of variance between it and the dependent variable (predictand) plus the previously picked predictor.

To have as large a data sample as possible, the predictors and predictands were arranged so that a generalized operator approach could be used (Russo, Enger, and Merriman 1966). Using this

TABLE 1. Basic and computed Primitive Equation model predictors.

	Variable	Valid Time (Hours) 06	12	18	24	30	36
Basic	1000 mb Heights	X	X	X	X		X
	850 mb Heights	X	X	X	X		X
	500 mb Heights				X		
	1000 mb Temperatures		X		X		X
	850 mb Temperatures		X		X		X
	700 mb Temperatures				X		
	500 mb Temperatures				X		
	P* Surface Pressure		X		X		X
	Boundary Layer U Component	X	X	X	X		X
	Boundary Layer V Component	X	X	X	X		X
	850 mb U Component				X		
	850 mb V Component				X		
	700 mb U Component				X		
	700 mb V Component				X		
	500 mb U Component				X		
	500 mb V Component				X		
Computed	Boundary Layer Wind Speed	X	X	X	X		X
	850 mb Wind Speed				X		
	1000 mb - 850 mb Temperature		X		X		X
	850 mb - Boundary Layer Wind Speed				X		
	(1000 mb - 850 mb) Temperatures / (850 mb - Boundary Layer) Wind Speed				X		
	700 mb Wind Speed				X		
	500 mb Wind Speed				X		
	(850 - 1000 mb) Hgts - (500 - 850 mb) Hgts / (500 mb - Boundary Layer) Wind Speed				X		
	P*12 - P*36 (Surface Pressure Change)						
	P*12 - P*24 (Surface Pressure Change)						

method, the data are pooled so that no distinction is made between individual lakes or lake sections. The equations derived are considered general in nature and are applied at each of the 12 forecast points. Although there is some loss of predictability since local conditions are not well accounted for, there are the advantages of increased sample size and the derivation of fewer equations.

Separate equations were derived for each of six forecast times (6-, 12-, 18-, 24-, 30-, and 36-hr forecasts). For each forecast time three equations were derived: a V-component equation (north-south), a U-component equation (east-west), and a wind speed (S) equation. The U- and V-component equations are used to forecast the wind direction. They are not used to forecast wind speed because simple vector addition of these components would result in an underestimation of this element (Glahn 1970).

The screening regression program resulted in forecast equations of the following form:

$$Y = C_0 + C_1 X_1 + C_2 X_2 + \ldots + C_n X_n$$

where Y is the predictand,
C_0 is a constant,
C_n are coefficients, and
X_n are predictors.

In actual operational use, the predictors are obtained by interpolating the PE grid point fields to the forecast point of each lake sector so that a different wind forecast is made for each location.

Figure 2 shows the dependent data multiple correlation coefficients by forecast projections, PE origin times, and seasons. The correlation generally decreases with projection time. The summer season, however, does show a departure from this trend and will be discussed further in the verification section of this paper.

TABLE 2. The numbers of observations used in the development of wind forecast equations.

	Summer PE Origin Times		Winter PE Origin Times	
Fcst Pd	OOZ	12Z	OOZ	12Z
06	1896	1845	967	1001
12	1880	1738	892	957
18	1875	1856	955	1007
24	1833	1879	919	857
30	1950	1840	945	903
36	1904	1308	878	964

The wind forecasts are also used to produce forecasts of wave height and period. These forecasts are based upon the method of Bretschneider (1970) and are made at 64 specific forecast points spread about the lakes. Details of this method along with verification will be discussed in a future paper.

THE FORECAST MESSAGE

The Great Lakes wind forecast system is run twice daily after the 0000 GMT and 1200 GMT PE model runs. A sample bulletin is shown in Figure 3. In this message the forecasts were made following the 0000 GMT PE run on the 10th of the month. This is indicated by the group 100000 of the heading line. The wind forecasts are made out to 36 hours. The wind forecasts are made for each of the 12 forecast locations (Figure 1) and are given in the format ddff, where dd is the direction in ten's of degrees and ff is the speed in knots.

VERIFICATION

The operational forecasts were compared with ac-

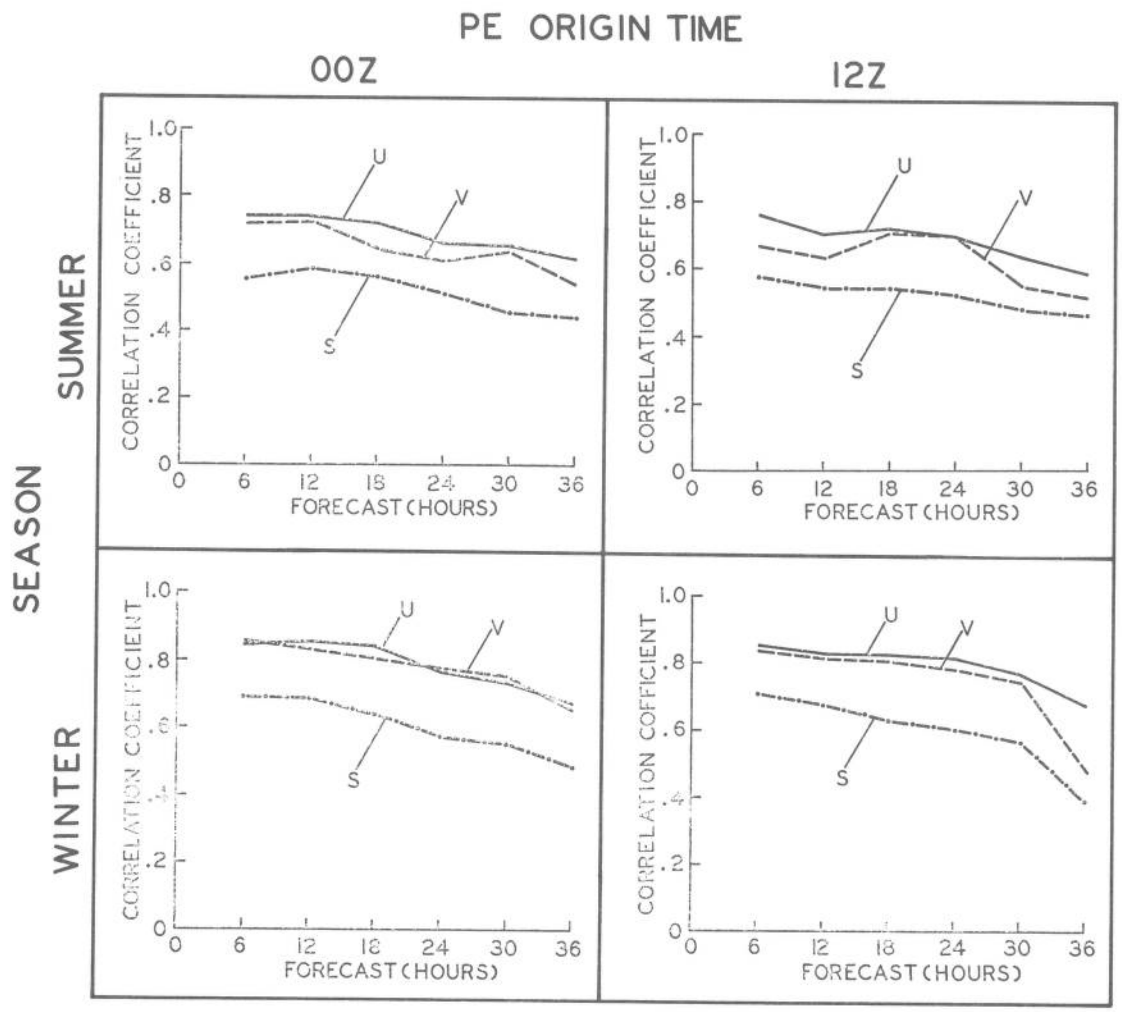

FIG. 2. Dependent data multiple correlation coefficients as a function of projection time for winter and summer seasons and 0000 GMT and 1200 GMT origin times. U is the east wind component where positive values are toward the east. V is the north wind component where positive values are towards north. S is the wind speed.

FZUS4 KWBC 100000

WIND FORECASTS FOR THE GREAT LAKES

LOCATION	06Z	12Z	18Z	00Z	06Z	12Z
EAST ONTARIO	1920	1728	2131	2429	2627	2422
WEST ONTARIO	1822	1829	2231	2329	2624	2019
EAST ERIE	1822	2028	2331	2328	2620	1916
WEST ERIE	1926	2132	2331	2527	2720	2615
SOUTH HURON	1825	2136	2435	2531	2725	2318
NORTH HURON	1625	2135	2433	2632	2728	2620
SOUTH MICHIGAN	2135	2437	2630	2929	3022	3118
CENTRAL MICHIGAN	2132	2539	2733	2832	2925	2920
NORTH MICHIGAN	1827	2435	2732	2833	2928	2821
EAST SUPERIOR	1425	2330	2826	2931	2927	3021
CENTRAL SUPERIOR	1323	3024	3023	2928	3022	2918
WEST SUPERIOR	1717	3123	3029	2827	2816	2614

FIG. 3. Sample transmitted teletypewriter bulletin. The winds are expressed as DDFF, where DD is direction in tens of degrees and FF is speed in knots.

tual marine observations, and various types of errors were computed. The comparison was made by season and PE origin time for 1974. The marine observations were chosen for verification the same way they were chosen in the development, i.e. if there were several simultaneous observations in a given lake section the observation with the highest wind was picked.

Figure 4 shows the errors in wind speed and direction, for the lakes in general, as the forecast projection period increases. This is shown for both the winter and summer seasons, and for the 0000 GMT and 1200 GMT PE origin times. Mean absolute error in wind speed (ABSERR) is defined as:

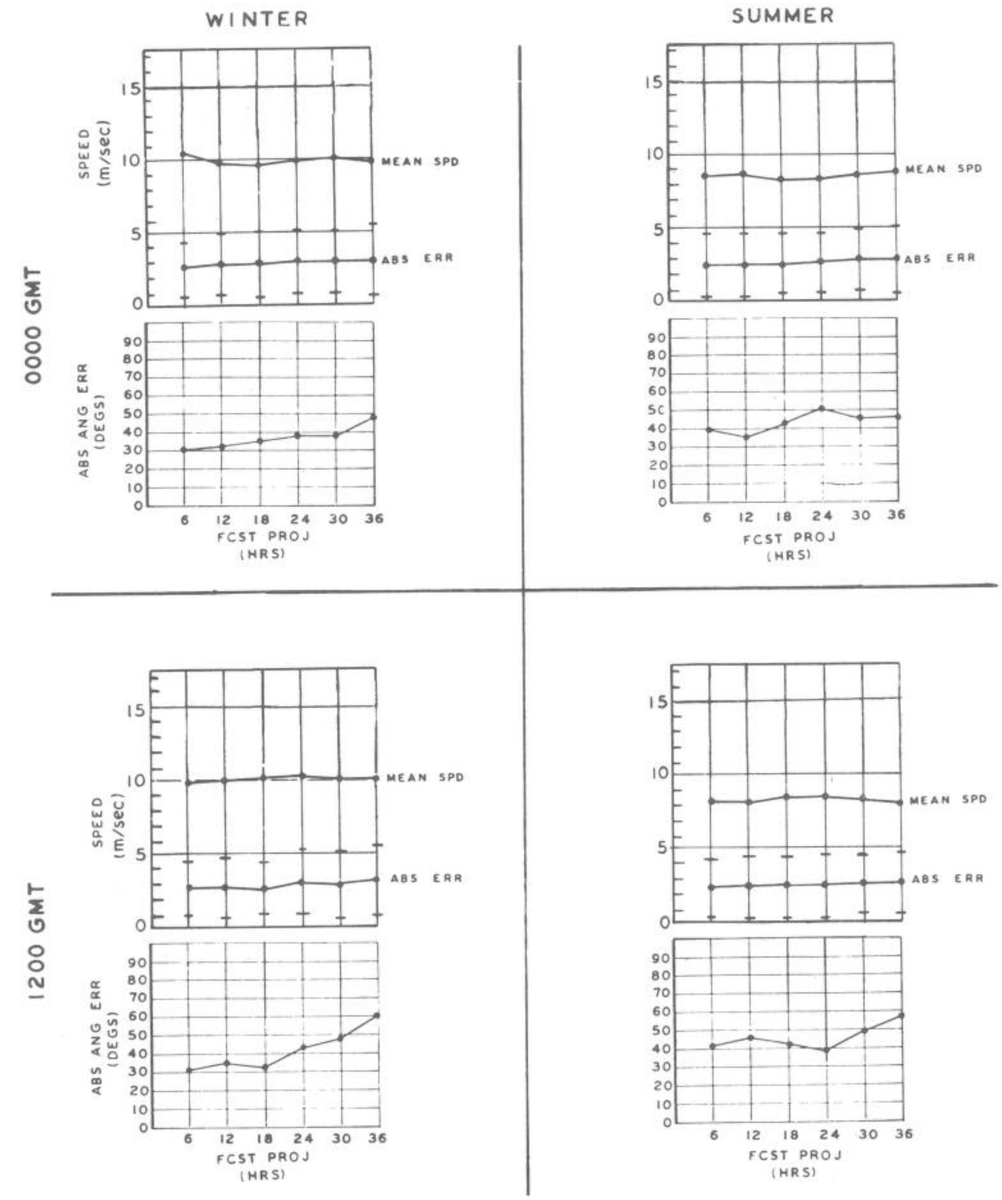

FIG. 4. Errors in wind speed and direction for each season and each PE origin time. The tick marks are the standard deviations about the mean absolute error.

$$\frac{\sum_{i=1}^{N} |S_{Fi} - S_{oi}|}{N}$$

where N = number of cases,
S_{Fi} = forecast wind speed
and S_{oi} = observed wind speed.

The tick marks above and below the ABSERR indicate the limits of the standard deviation of the ABSERR. Mean Speed (Mean Spd) is the observed speed, averaged for each of the six projection times.

Absolute angular error is defined as:

$$\frac{\sum_{i=1}^{N} |D_{Fi} - D_{oi}|}{N}$$

where N is the number of cases,
D_{Fi} is forecast wind direction (Deg), and
D_{oi} is observed wind direction (Deg).

Figure 5 is the same as Figure 4 except that only wind observations greater than or equal to 12.5

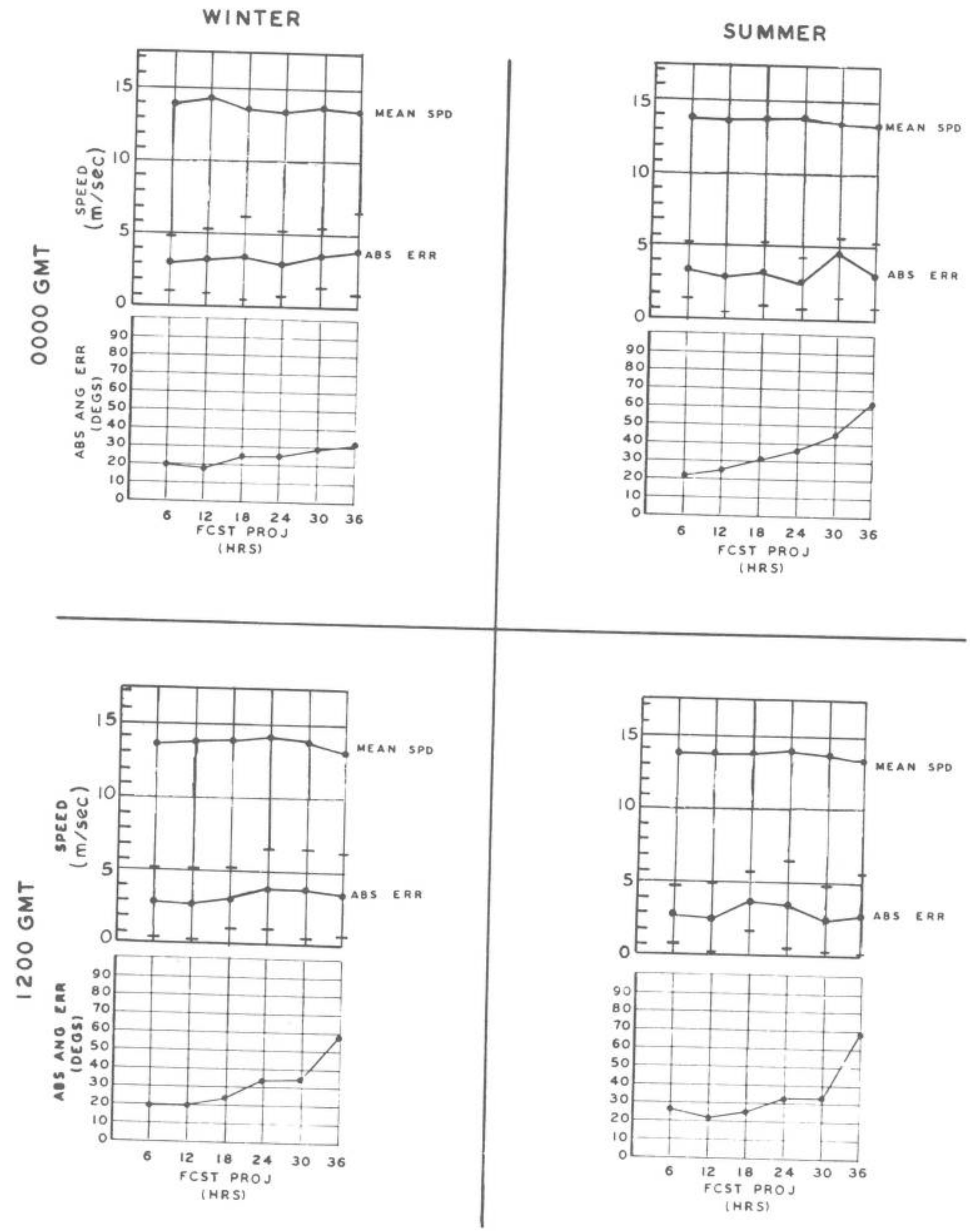

FIG. 5. Errors in wind speed and direction for each season and each PE origin time for those forecasts 12.5 m/sec or greater.

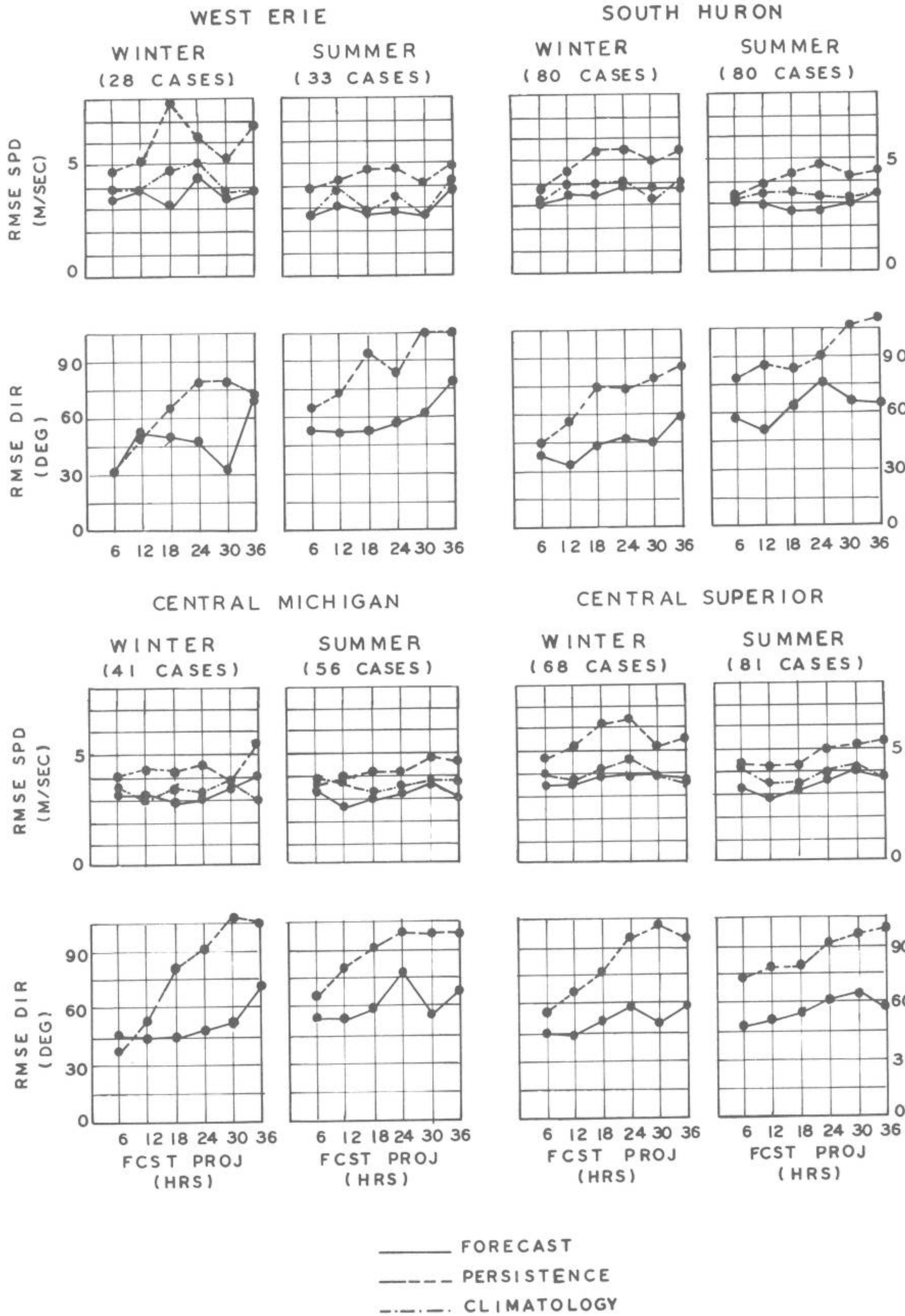

FIG. 6. Comparison of root mean square errors of wind speed and direction for sample forecast locations.

m sec^{-1} were considered. Note that wind direction errors are considerably smaller when these higher wind speeds are observed.

Since forecasts are being made by lake sector it is logical that the forecast errors by lake sector be evaluated. For this evaluation two comparisons were made:

(1) The wind observation (direction and speed) at the PE origin time was used as a persistence forecast for the following 36 hours. The root mean square errors (RMSE) of these forecasts were computed.

(2) The standard deviation of the observed wind speed for each projection time for the summer and winter season was computed.

Standard deviation of observed wind =

$$\left[\frac{\sum_{i=1}^{N} (X_{oi} - \overline{X}_{oi})^2}{N}\right]^{1/2}$$

where N is the number of observations,
X_{oi} is the wind speed observation at a given projection, and
$\overline{X}_{oi}$ is the average wind speed observation at a given projection for a given season.

If we consider $\overline{X}_{oi}$ as a forecast, the equation gives the RMSE of a quasi-climatic forecast. This was compared to the RMSE of the operational objective forecasts:

$$\text{RMSE forecast} = \left[\frac{\sum_{i=1}^{N} (X_{oi} - X_{fi})^2}{N}\right]^{1/2}$$

where N is the number of observations,
X_{oi} is the wind speed observation at a given projection, and
X_{fi} is the wind speed forecast at a given projection.

Figure 6 shows the comparison of root mean square errors for sample lake sections. The automated forecasts consistently do better than using persistence as a forecast for both speed and direction, and consistently do better than using a quasi-climatic forecast, except for projections beyond 24 hours during the winter. Other lake sections exhibit similar error properties.

Figure 7 compares the Lake Michigan 0000 GMT, summer, RMSE of wind speed and direction with 1200 GMT RMSE for the same period. The errors are plotted as a function of local time. Note that, although independently derived, there is a tendency for the maximum and minimum errors for both origin times to align themselves at specific times of the day. Thus, decreases in error occur during the nighttime hours and increases during the daytime. During the summer, in the daytime, it is expected that the diurnal lake breeze would distort the gradient wind field. The MAOBS would then include a measure of the lake breeze along with the gradient wind. Because this distortion is on a scale smaller than can be predicted by the PE model, it does not show up in the PE predictors. During nighttime the lake breeze ceases so that the observations over the water more nearly represent

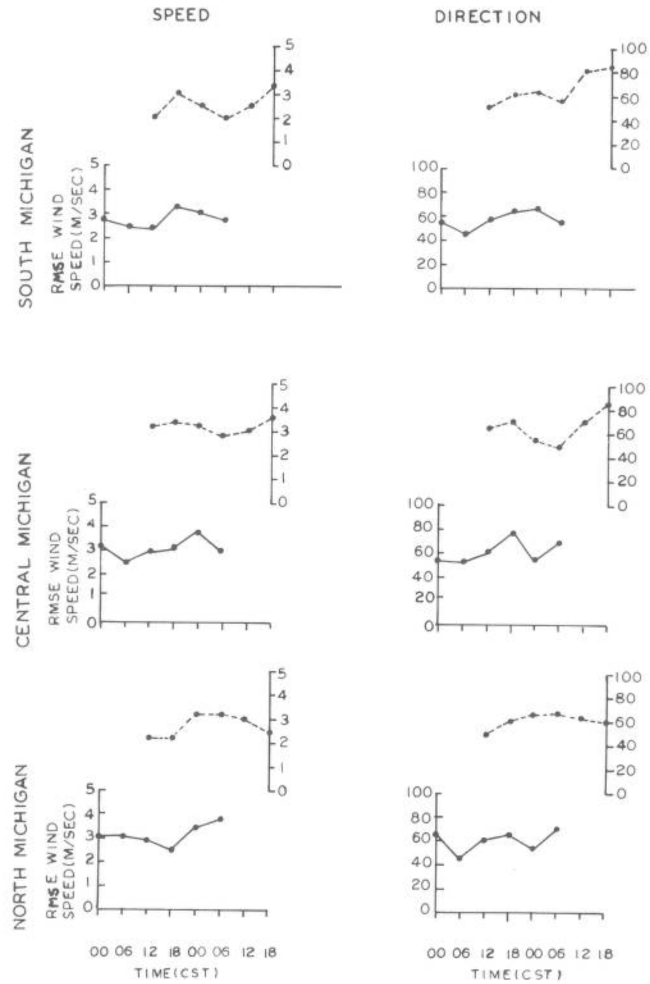

FIG. 7. Comparison of 0000 GMT, summer, RMSE of wind speed and direction with 1200 GMT RMSE for the same period for Lake Michigan. The solid curves are based on forecasts of 0000 GMT origin times. The dashed curves are based on origin times of 1200 GMT.

the large scale gradient wind pattern, the pattern predicted by the PE model. The errors during this time are hence diminished. This effect is particularly evident in the direction RMSE.

FUTURE WORK

Future work will concentrate in the two main areas of modification and redevelopment of the system using output from finer scale models, such as the NMC limited area fine mesh model, and modification of the wind forecasts using some measure of stability so that the wind input to the wave forecast program is more representative of the wind at the surface of the water.

ACKNOWLEDGMENTS

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