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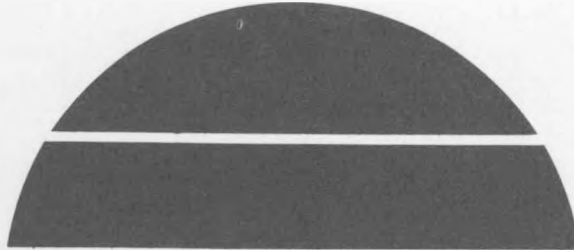
**DEVELOPMENT AND TESTING OF MODEL OUTPUT
STATISTICS FOR WIND FORECASTS AT WIND TURBINE
GENERATOR SITES**

By
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October 1980

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National Oceanic and Atmospheric Administration
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Solar Energy

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DEVELOPMENT AND TESTING OF MODEL OUTPUT
STATISTICS FOR WIND FORECASTS AT WIND
TURBINE GENERATOR SITES

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FOREWORD

The research summarized in this report is primarily a meteorological evaluation of an existing forecasting technique, Model Output Statistics (MOS), applied to the production of objective wind forecasts. Consequently, this foreword has been written by Pacific Northwest Laboratory (PNL) to orient the potential user of wind energy to the work by defining the purpose of the MOS wind forecasting evaluation, explaining the approach used, identifying the resultant limitations imposed by the approach, and describing probable follow-on work.

Electrical utilities have expressed a need for reliable wind forecasts whenever and wherever large numbers of wind turbine generators (WTGs) are used. Since the MOS technique is viewed as a state-of-the-art method of producing objective wind forecasts, it was selected for evaluation.

Several limitations were imposed upon the MOS forecasting evaluation by the nature of the available wind data. Data from the Department of Energy (DOE) candidate WTG sites were the best data set available. These data consist of a time series of hourly average wind speeds and directions. The maximum length of record available at the time of the study was 23 consecutive months. The length of the data record necessitated that only twelve months be used for forecast development and the remaining eleven months for forecast verification. Since a minimum of two years of data is recommended for MOS forecast development, the results of this study should be viewed as a lower bound on MOS wind forecasting reliability for wind energy applications.

The primary answers sought in the study were:

- the relative accuracy of MOS compared to other techniques
- the rate of decay of forecast reliability with time
- the variations in forecasting reliability with geographical and topographical setting
- the relative accuracy of MOS applied to WTG sites (windy sites) as compared to more "conventional" sites, such as air terminals.

In an attempt to answer these questions, data from nine DOE candidate sites in various topographical and geographical settings in the continental United States were used. To avoid excessive data processing, it was assumed that forecasts for every third hour were sufficient to indicate the variation of forecast accuracy with time. The wind forecasts were made in conjunction with regular production runs of the National Meteorological Center (NMC) model that generates input to the wind prediction equations. This model is run twice per day at 0000 GMT and 1200 GMT. Since it requires nearly 6 hours to collect the input weather data, run the model, and produce and disseminate the forecasts, the forecast projection times used in this report (i.e., +9, +12, +15 . . . +24, +30 h) are really only +3 to +24-h forecasts from the viewpoint of the forecast user. This fact should be kept in mind when interpreting the results of the study.

Due to limitations imposed by the input data, as well as time and money constraints, many questions could not be fully addressed. However, a large amount of data was produced and saved on magnetic tape and microfiche during the study. Current plans call for subsequent analyses of these data to:

- look at variations of accuracy with time-of-day and season
- compare more fully the forecasts produced at 0000 GMT to those produced at 1200 GMT (differences in reliability could impact the user)
- look at the implications of the verification to help determine the operational usefulness of MOS wind forecasts in general and at specific sites
- use wind predictors selected at each site to better understand the factors governing the site winds
- evaluate the reliability of the probability forecasts as a function of forecast projection time.

Questions that could not be addressed with these data and at this time are:

- How well do forecasts of hourly mean wind describe hourly WTG power output?

- How much of the observed degradation in the accuracy of the MOS forecasts is due to the small developmental data set and how much is due to the increase difficulty in forecasting winds at windy sites?
- How reliably can winds be forecast in the 0 to 3-h time frame (for use by electrical dispatchers in making minute-to-minute decisions)?

Further work is tentatively planned to address these and possibly other questions regarding MOS wind forecasts.

EXECUTIVE SUMMARY

Objective wind speed and direction forecasts for seven projections (for time frames of +9 to +30 h) were developed with the Model Output Statistics technique (MOS) for nine DOE candidate wind turbine sites in the continental United States. Forecasts were produced twice daily, at 0000 GMT and 1200 GMT, and verified against observations by statistical analyses. Though the reliability of the forecasts was degraded by the small size of the developmental data set, the technique appears sufficiently reliable to merit further investigation.

The forecast verification results show a slight tendency toward under-forecasting strong winds. In general, the forecasts perform better in the eastern portion of the country than in the West. The forecasts generally decrease in accuracy with time, except for sites having very regular diurnal wind patterns, and were markedly better at the 9-h forecast than at later times. Wind observations at the WTG site were found to be useful predictors for projections up to 15 hours after forecast time at some sites.

Both deterministic forecasts (actual speed) and probabilistic forecasts (probability of the speed being within specified intervals) were produced. The results suggest that larger developmental samples or larger speed intervals be used to develop probabilistic wind speed forecasts.

INTRODUCTION

Variations in winds throughout a 24-h period complicate the operations of utilities using Wind Turbine Generators (WTGs). Undoubtedly, the operational problems will increase as more WTGs are incorporated into electrical power grids. Reliable and accurate wind forecasts have the potential of reducing these complications.

For several years, the National Weather Service (NWS) has been producing numerical-statistical forecasts of surface winds for approximately 250 locations throughout the United States. These forecasts, made by the Model Output Statistics (MOS) technique (Glahn and Lowry 1972), serve primarily as guidance for aviation and public weather forecasters. Predictions of the wind direction and speed are given twice daily for specific valid times from 6 to 48 hours in advance. Similar forecasts of coastal winds also are provided to assist marine forecasters. These forecasts are generally regarded as "state-of-the-art" because their accuracy is comparable to that of forecasts produced subjectively by NWS field offices (Zurndorfer et al. 1979).

For a number of reasons, however, these aviation/public forecasts are not suitable help for wind turbine operations. First, they provide estimates of widely spaced (1 to 3 h) one-minute average wind speeds. For utility operations hourly-average speeds are more useful. Next, WTG sites are often located in topography different than that of most NWS airport sites and, therefore, have quite a different wind climatology. Finally, the NWS does not currently provide probability forecasts of wind speed categories. Such wind forecasts may prove important in WTG operation.

For all of these reasons, meteorologists at Pacific Northwest Laboratory decided to test MOS techniques by developing wind speed and direction forecasts for the nine current, or potential, WTG sites shown in Figure 1. Part of the data was used to develop forecasts, and the rest was used for verification.

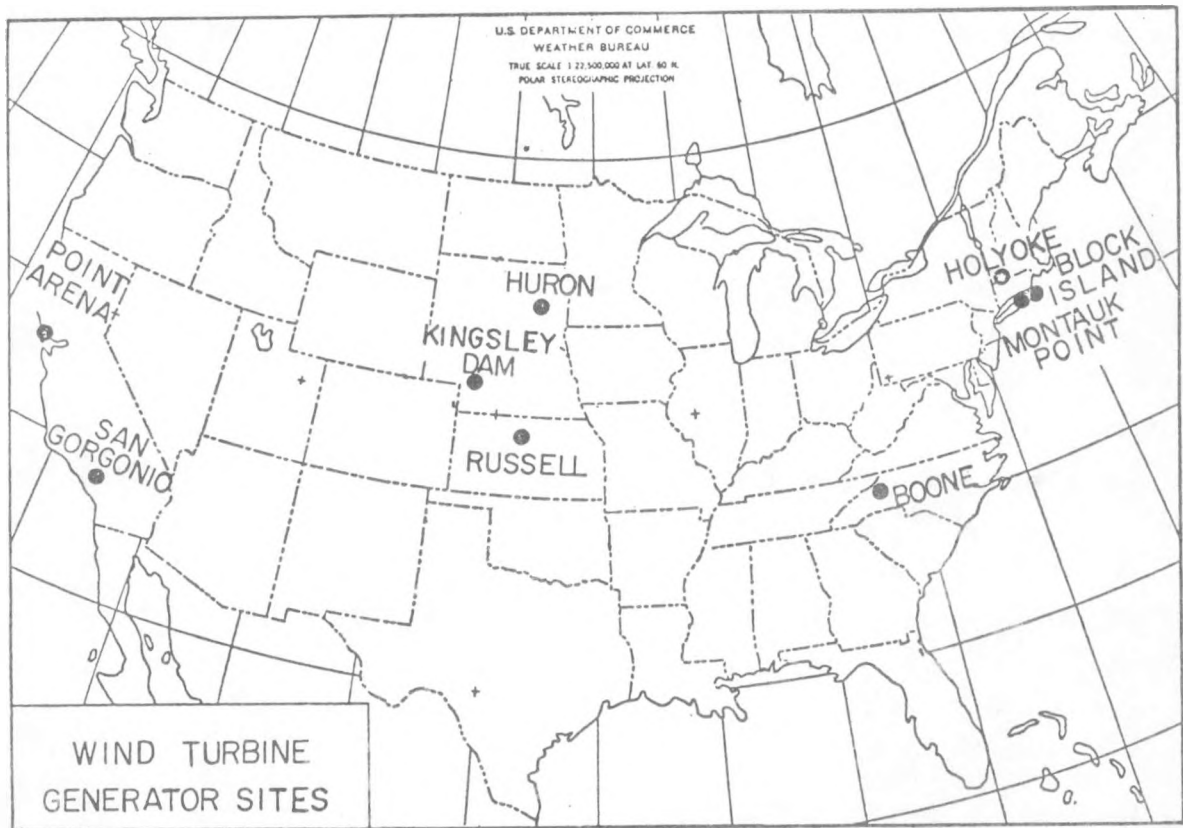


FIGURE 1. MOS Forecasts of Wind Speed and Direction were Developed for These Nine Wind Turbine Generator Sites

DEVELOPMENT OF PREDICTION EQUATIONS

The MOS forecasts are based on linear regression equations that were derived by relating wind observations (predictand data) to output from a numerical prediction model (predictor data). Separate equations were developed to forecast the U and V components and the speed. In addition, separate equations were developed to forecast the probability of the seven categories of wind speed listed in Table 1. These seven probability equations and the speed equation were derived simultaneously in order to enhance consistency between the deterministic speed estimate and the probability forecasts. The screening regression technique selects the predictor that yields the highest reduction of variance for any one of the predictands when combined with the other terms in a multiple linear regression equation. The same procedure is followed until either 10 predictors have been chosen or the additional reduction of variance is less than 0.5%. The equations for the U and V components are also derived simultaneously. The forecast wind direction is computed from forecasts of the U and V components.

TABLE 1. Definition of the Categories Used for Forecasts of Wind Speed

<u>Category</u>	<u>Wind Speed Range (m s⁻¹)</u>
1	0 to 4.00
2	4.01 to 6.00
3	6.01 to 8.00
4	8.01 to 10.00
5	10.01 to 13.00
6	13.01 to 19.00
7	<u>>19.01</u>

A serious problem of this approach has been underforecasting the speed. A separate regression equation was derived for the speed to overcome just such a problem (Carter 1975). Despite this, MOS forecasts have still underforecast

high wind speeds. Therefore, the regression estimates of wind speed are enhanced by the use of the inflation transformation.^(a)

Observed wind data for the WTG locations were available for the period December 1, 1976, through October 31, 1978. The winds were observed at the 150-ft level of towers erected at the WTG sites.

The amount of data available was divided roughly in half to form a dependent (developmental) data sample and an independent data sample. The developmental sample consisted of all dates from December 1, 1976, through November 30, 1977. Separate equations were developed for each site, each forecast cycle (0000 to 1200 GMT), and each forecast projection (+3 to +24 h). The developmental sample was not stratified according to season because of the small sample size (about 300 cases per equation).

Because of this small sample, some of the high wind speed categories were rarely observed. If any category had less than 10 cases, the regression equation to forecast the probability of that category was not derived. Tables 2 and 3 show the number of categories for which probability forecasts could be developed for 0000 and 1200 GMT, respectively.

(a) Inflation was proposed by Isadore Enger and first applied by Klein et al. (1959). The inflation estimate \hat{y}' is defined by

$$\hat{y}' = \frac{\hat{y} - \bar{y}}{R} + \bar{y},$$

where \hat{y} is the regression estimate, \bar{y} the mean of the variable in the dependent sample, and R the multiple correlation associated with the regression equation. This procedure increases the root mean square error (Glahn and Allen 1966) but gives a more desirable distribution of forecasts for wind speed prediction.

TABLE 2. The Number of Categories for which Probability Forecast Equations were Developed from 0000 GMT Model Output

<u>WTG SITE</u>	<u>HOURS AFTER 0000 GMT</u>						
	<u>09</u>	<u>12</u>	<u>15</u>	<u>18</u>	<u>21</u>	<u>24</u>	<u>30</u>
Point Arena, CA	5	5	5	5	6	6	5
San Geronio, CA	6	6	6	6	6	6	6
Huron, SD	5	5	5	6	6	6	5
Kingsley Dam, NB	6	6	6	6	6	6	6
Russell, KS	6	6	6	6	6	6	6
Boone, NC	7	6	7	6	6	6	6
Holyoke, MA	6	6	6	6	6	6	6
Montauk Point, NY	6	6	6	6	6	6	6
Block Island, RI	6	6	6	6	6	6	6

TABLE 3. The Number of Categories for which Probability Forecast Equations were Developed from 1200 GMT Model Output

<u>WTG SITE</u>	<u>HOURS AFTER 1200 GMT</u>						
	<u>09</u>	<u>12</u>	<u>15</u>	<u>18</u>	<u>21</u>	<u>24</u>	<u>30</u>
Point Arena, CA	6	6	6	5	5	5	5
San Geronio, CA	6	6	7	7	6	6	6
Huron, SD	6	6	6	5	5	5	6
Kingsley Dam, NB	6	6	6	6	6	6	6
Russell, NC	6	6	6	6	6	6	6
Boone, NC	6	6	7	7	7	6	6
Holyoke, MA	6	6	6	6	6	6	6
Montauk Point, NY	6	6	6	6	6	6	6
Block Island, RI	6	6	6	6	6	6	6

Table 4 lists the potential predictors available to forecast the tower winds. Not all the predictors are output from a numerical model. The first six predictors listed are observed wind conditions at the tower and several climatic terms. This tower wind, the hourly-averaged wind observed at 3 hours after model run time (0000 or 1200 GMT), can be a useful predictor for short-range forecasts when persistence is important. Since it was desirable to

determine the effect of the observed winds as predictors, equations were developed with and without them. When the observed winds were included in the regression run as potential predictors, the resulting equations were labeled "primary." When the observed winds were not in the predictor list, the resulting equations were labeled "backup." The harmonics of the day of year are the climatic terms that are included to help account for seasonal variations in the mean wind at the sites.

TABLE 4. Surface Observations, Climatic Terms, and LFM Output used as Potential Predictors for 18-h Wind Speed Forecasts

FIELD	SMOOTHING (POINTS)	TIME (HOURS)
Observed U, V Wind Components	--	3
Observed Wind Speed (S)	--	3
Sine Day of Year	--	--
Cosine Day of Year	--	--
Sine 2*Day of Year	--	--
Cosine 2*Day of Year	--	--
Boundary Layer U, V, S Wind	5	6, 12, 18, 24, 30
850-mb U, V, S Wind	1, 5	6, 12, 18, 24, 30
700-mb U, V, S Wind	1, 5	6, 12, 18, 24, 30
1000-mb Geostrophic U, V, S Wind	5	12, 18, 24, 30
Boundary Layer Relative Vorticity	5	12, 18, 24, 30
850-mb Relative Vorticity	5	12, 24
K Index	5	12, 24
Total Totals Index	5	12, 24
(1000-mb Temp.) - (850-mb Temp.)	1	12, 24
Mean Relative Humidity	1, 5	6, 12, 18, 24, 30
850-mb Height	5	6, 12, 18, 24, 30

The remaining predictors were forecast fields from the Limited-Area Fine Mesh (LFM) model (Gerrity 1977) that were interpolated to the WTG sites. This model has been producing forecasts from 0000 and 1200 GMT data daily since 1971. LFM-based MOS forecasts have been shown to be superior to MOS

forecasts from other numerical models (Dallavalle et al. 1979). Forecast fields from 6 to 30 hours were available as possible predictors. In addition to forecast wind fields, stability indices, vorticity at several levels, and mean relative humidity were also potential predictors. Certain fields were averaged by five points to eliminate small-scale noise. Besides being offered as continuous predictors (in their original form), some variables were also offered in binary form.

As an example, the forecast equations valid 12 hours from 1200 GMT for Boone, North Carolina, are shown in Tables 5 and 6. For this site the LFM 850-mb wind components and speed are the best predictors. Perhaps the 850-mb forecast is more correlated with the observed wind than the boundary layer forecast because of Boone's high elevation. The LFM boundary-layer wind components, the LFM 850-mb height and relative vorticity, and the site's 1500 GMT wind observation are other important characteristics. As would be expected, the relative importance of the observed predictors for most sites decreases with increasing forecast projection. Surface observations are selected for all 9-h equations, but are selected only for three sites for the 24-h forecasts.

TABLE 5. Equations for Predicting the U and V Components of the 150-ft Level Wind, 12 Hours After 1200 GMT at Boone, North Carolina. All predictors were selected in continuous form.

PREDICTORS (UNITS)	COEFFICIENTS	
	U	V
12-h LFM 850-mb V Wind ($m s^{-1}$)	-0.287	0.469
12-h LFM 850-mb U Wind ($m s^{-1}$)	0.278	-0.067
12-h LFM Boundary Layer V Wind ($m s^{-1}$)	-0.112	0.430
1500 GMT Observed U Wind ($m s^{-1}$)	0.229	-0.002
18-h LFM 850-mb U Wind ($m s^{-1}$)	0.277	-0.057
Sine Day of Year	0.230	0.917
6-h LFM 1000-mb Geostrophic Wind Speed ($m s^{-1}$)	-0.162	0.111
6-h LFM 850-mb Wind Speed ($m s^{-1}$)	0.121	-0.192
Regression Constant ($m s^{-1}$)	0.039	1.336
Standard Error of Estimate ($m s^{-1}$)	2.262	2.539
Reduction of Variance	0.852	0.788

TABLE 6. Equations for Predicting the Deterministic Wind Speed and the Probability of Each of the First Six Speed Categories, 12 Hours After 1200 GMT at Boone, North Carolina. There were not enough cases when the speed was higher than 19 m s^{-1} to derive an equation for category seven.

LFM PREDICTORS (UNITS)	SMOOTHING (POINTS)	COEFFICIENTS						
		S	CAT. 1	CAT. 2	CAT. 3	CAT. 4	CAT. 5	CAT. 6
6-h 850-mb Wind-Speed (m s^{-1})		0.3512	-0.0032	-0.0213	-0.0025	-0.0026	-0.0029	0.0292
24-h 850-mb Height (m)	5	-0.0040	-0.0002	0.0003	0.0005	0.0005	-0.0010	-0.0002
18-h 850-mb Wind Speed (m s^{-1})		0.2405	-0.0383	-0.0133	0.0242	0.0249	0.0036	-0.0014
18-h 850-mb Wind Speed $\leq 15 \text{ m s}^{-1}$		-0.6427	-0.2119	-0.0537	0.2647	0.2980	-0.1584	-0.0899
18-h 850-mb V Wind (m s^{-1})		-0.1517	0.0066	-0.0152	0.0187	0.0020	0.0009	-0.0059
12-h 850-mb Relative Vorticity (s^{-1})	5	-0.1289	0.0322	0.0003	-0.0380	0.0323	-0.0174	-0.0158
18-h Boundary Layer V Wind (m s^{-1})	5	0.0958	0.0069	0.0195	-0.0528	0.0218	-0.0003	-0.0055
12-h Boundary Layer U Wind (m s^{-1})		-0.0548	-0.0111	0.0063	0.0310	-0.0273	-0.0003	0.0091
12-h Boundary Layer Relative Vorticity $\leq 0 \text{ s}^{-1}$	5	-0.0186	0.1024	-0.0246	0.0265	0.0612	0.0283	-0.2068
18-h Boundary Layer Relative Vorticity (s^{-1})	5	-0.3076	0.0051	-0.0344	0.0036	0.0603	0.0222	-0.0619
Regression Constant (m s^{-1})		10.2500	0.8763	0.1636	-0.8796	-1.064	0.1689	0.3735
Standard Error of Estimate (m s^{-1})		2.5419	0.3404	0.3781	0.3997	0.3117	0.2924	0.2577
Reduction of Variance		0.6568	0.2012	0.1840	0.0967	0.1164	0.1274	0.3543

VERIFICATION

All deterministic forecasts of wind direction and speed were verified on independent data. The independent data sample consisted of all hours between December 1, 1977, and October 31, 1978, when the observed wind speed was greater than or equal to 2 m s^{-1} . The verification was conducted for several reasons:

1. To discover the variations in forecast accuracy between different WTG sites and forecast projections.
2. To assess the difference in accuracy between primary and backup forecasts. This helps to determine the benefit of using surface observations as predictors.
3. To discover how much the forecast accuracy deteriorates on independent data. This is especially critical since the developmental sample size is smaller than the size used in developing the aviation/public wind forecasts.

Several different verification scores were computed for both primary and backup forecasts for each WTG site and each forecast projection. Mean absolute error and root mean square error (RMSE) were computed for both wind direction and wind speed. A speed bias, which equals the mean forecast speed minus the mean observed speed, was calculated. The Appendix lists these scores for the 0000 GMT primary forecasts. In addition, forecast-observed contingency tables were constructed from these deterministic forecasts for the seven categories shown in Table 1. An example contingency table is shown in Table 7. Only a few of the verification results are shown in this report; all other results are available on microfiche.

Several figures were constructed from the data shown in the Appendix and contained on microfiche that help to summarize the verification. All figures refer to 0000 GMT forecasts. Two conclusions can be made from the Appendix itself. First, almost all of the forecasts exhibit a negative bias, which means the forecasts underestimate the observed speed. This bias, computed for all sites combined, grows as the forecast projection increases. The

reason for this bias is unclear; the aviation/public MOS forecasts have been relatively unbiased. Second, the verification scores at several of the sites show a strong diurnal variation. For example, at Boone, North Carolina, the highest wind speed errors occur for the 12-h forecasts valid at 1200 GMT. The lowest speed errors, but the highest direction errors, are observed at 1800 GMT.

TABLE 7. Contingency Table for 9-h Wind Speed Forecasts Produced from 0000 GMT Data for San Gorgonio, CA

<u>OBSERVED CATEGORY</u>	<u>FORECAST CATEGORY, NUMBER OF OCCURRENCES</u>							<u>TOTAL</u>
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	
1	50	9	16	11	2	1	0	89
2	12	6	10	5	4	1	0	38
3	11	4	5	5	3	0	0	28
4	1	4	3	3	4	2	0	17
5	1	0	9	10	19	4	0	43
6	1	1	3	4	29	50	2	90
<u>7</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>0</u>	<u>5</u>	<u>1</u>	<u>6</u>
TOTAL	76	24	46	38	61	63	3	311

Figure 2 shows the variation of RMSE for wind speed forecasts at the WTG sites. The scores for both the 9-h and 21-h forecasts are shown. The two East Coast stations show the lowest error and San Gorgonio, California, shows the highest error when the two forecast projections are considered together. Verification of the aviation/public forecasts shows a similar tendency for the forecasts to perform better in the east than in other parts of the country (Dallavalle et al. 1979). The diurnal variation at Boone also is apparent in this figure since the 21-h forecasts are more accurate than the 9-h forecasts.

The large forecast errors at San Gorgonio need some explanation. Table 7 shows the 9-h forecast-observed contingency table for San Gorgonio. Note that the distribution of wind speeds is strongly bimodal; there are many cases where the speed is less than 4 m s^{-1} or greater than 13 m s^{-1} . San Gorgonio is located in a mountain pass near Palm Springs where local temperature

differences between desert and ocean occasionally result in strong winds during the night. Though MOS forecasts exhibit an RMSE much higher than those for other sites, the forecasts do predict most of the strong winds that are observed. The distribution of the forecasts is also bimodal. Contingency tables like this one are available on microfiche for all sites and all projections.

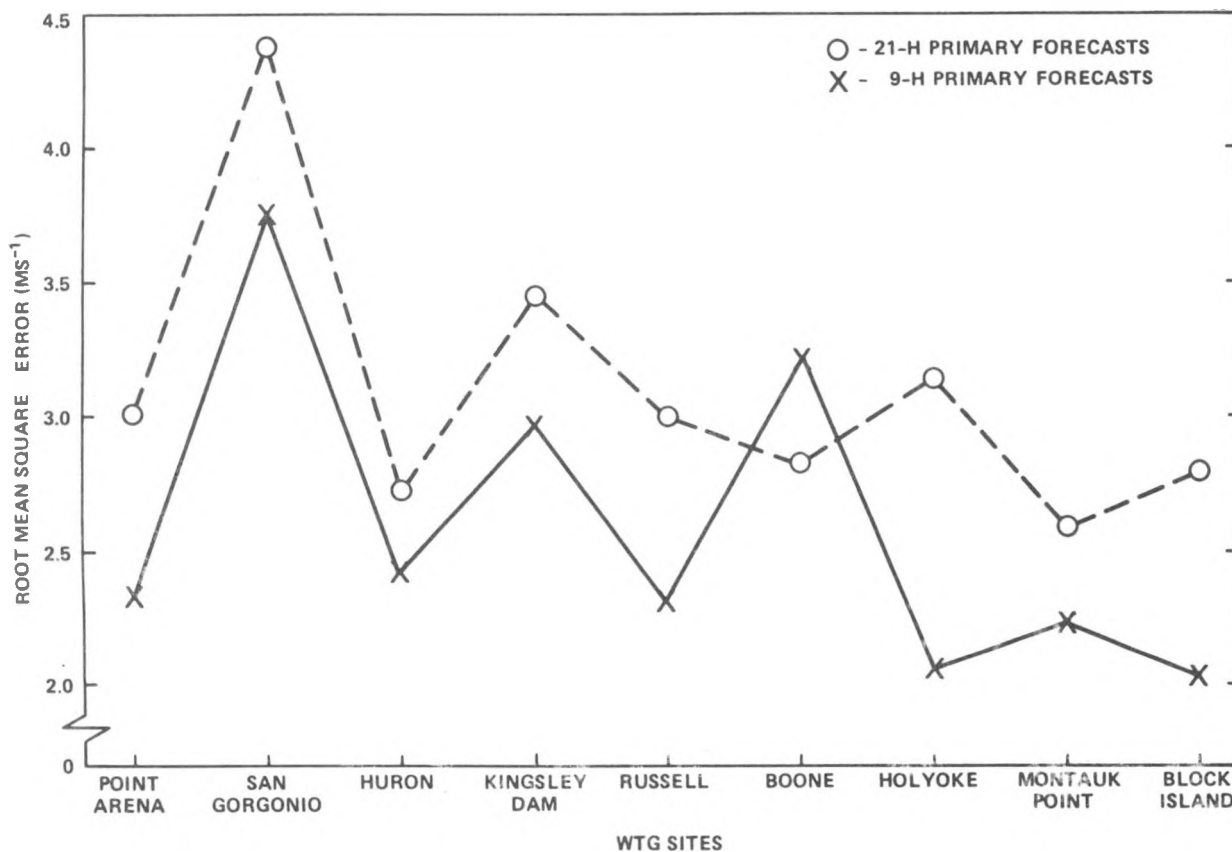


FIGURE 2. The Variation of Root Mean Square Error for 0000 GMT Wind Speed Forecasts at the WTG Sites

Figure 3 shows the difference in accuracy between primary and backup speed forecasts for all forecast projections. The verification score in this figure is the RMSE for all stations combined. The difference in RMSE between the primary and backup forecasts is about 0.3 m s^{-1} for the 9-h forecasts and becomes practically negligible by the 18-h projection. Considering the critical need for accuracy in speed forecasts, a 0.3 m s^{-1} improvement in RMSE may be operationally significant. Moreover, the difference between the primary and

backup forecasts varies considerably among the WTG sites as Figure 4 shows. The forecast improvement that results from using the site wind speed as a predictor for a 9-h forecast is greatest for the California and New England sites. Perhaps the absence of local wind circulations or the rapid movements of weather systems made the contribution of this predictor negligible for the midwestern sites.

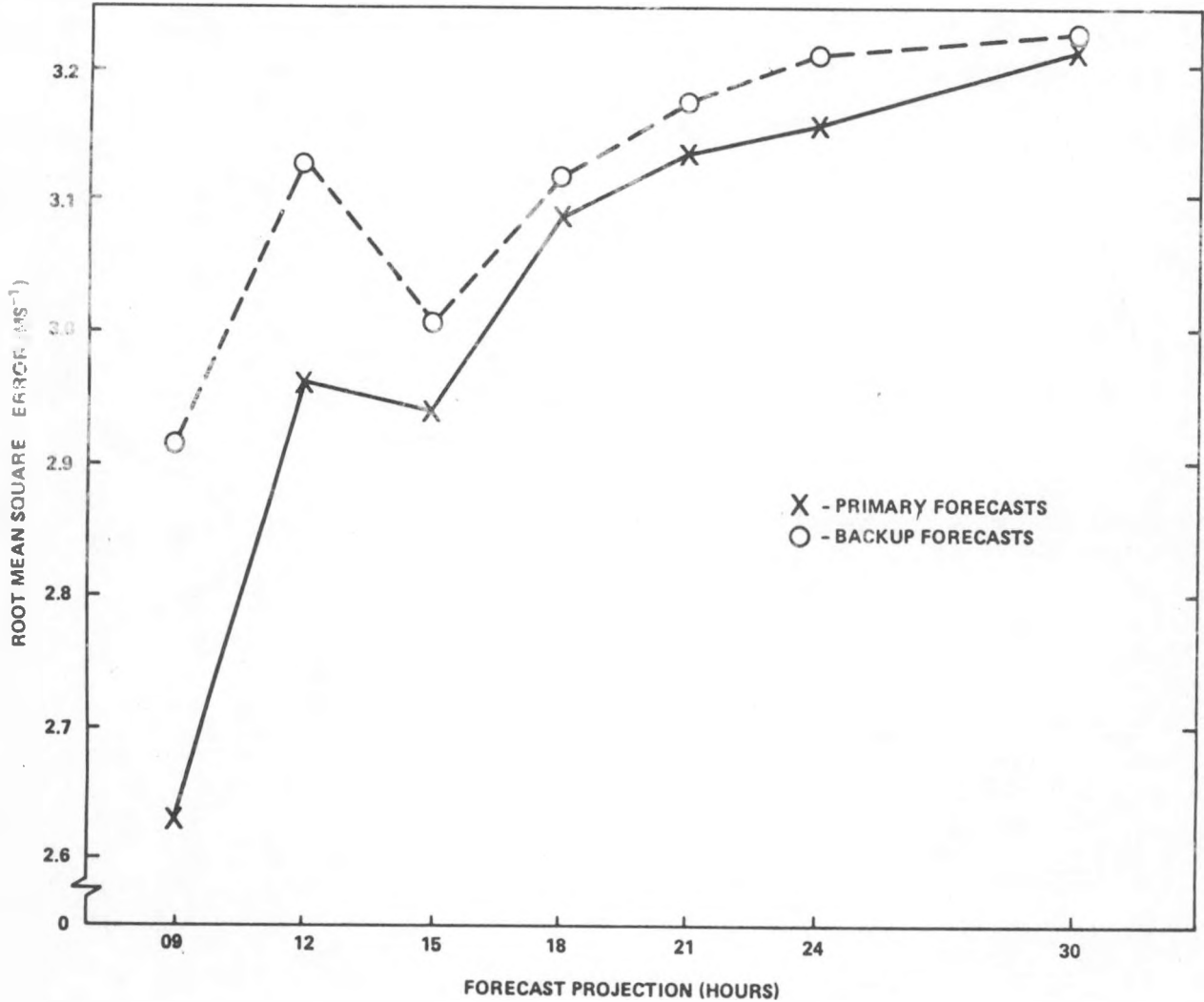


FIGURE 3. The Root Mean Square Error of Primary and Backup Speed Forecasts for 0000 GMT for all Stations Combined and all Forecast Projections

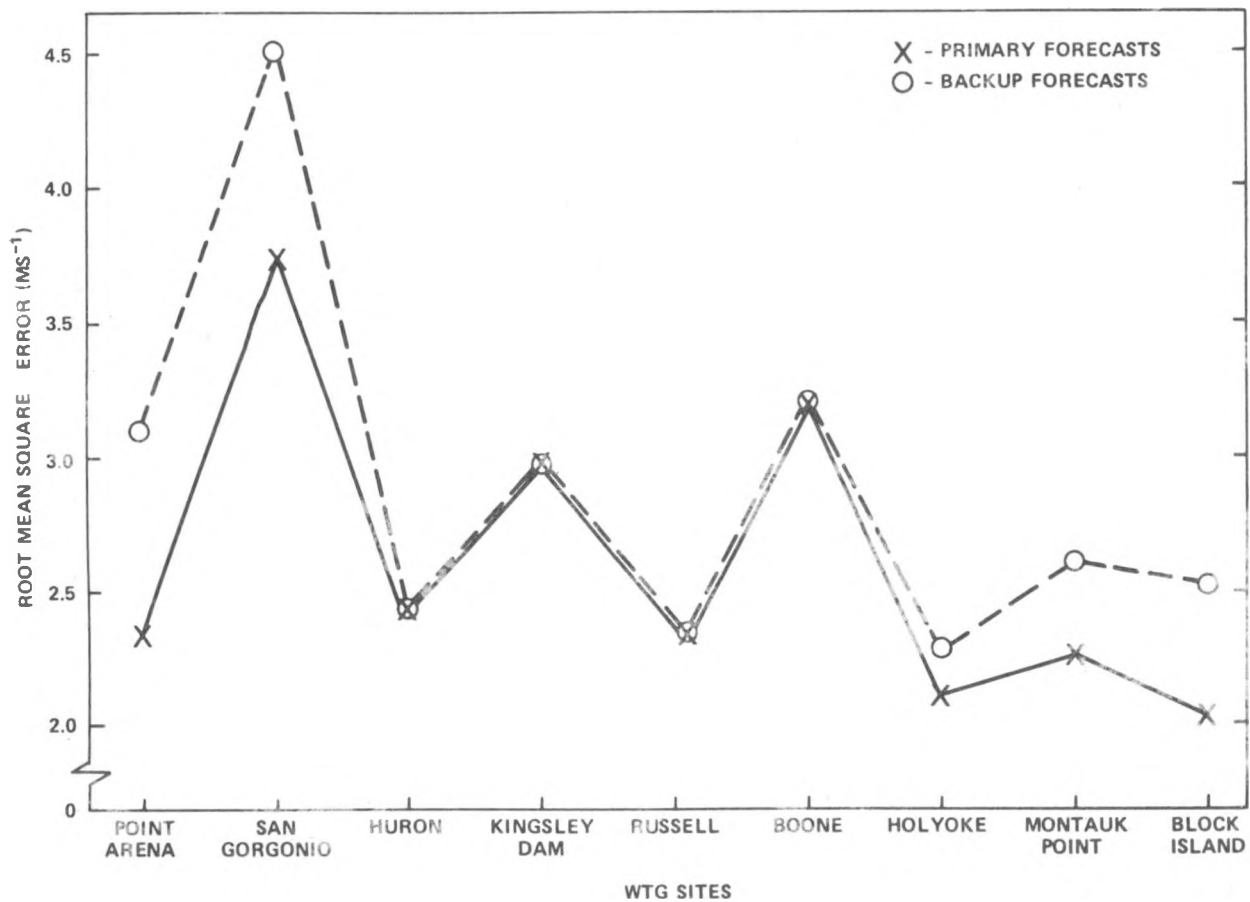


FIGURE 4. The Root Mean Square Error of the 0000 GMT 9-h Primary and Backup Speed Forecasts for all the Sites

The difference between the primary and backup forecasts of wind direction for the forecast projections is shown in Figure 5. The difference in RMSE for all the sites combined is about four degrees for the 9-h forecasts and becomes less than one degree for the 18-h and greater forecasts. Again, this difference varies considerably among the sites, but the difference is never greater than 6 degrees. Since forecasts of hourly average wind direction are not that critical for WTG operation, the benefit of using site observations may not be worth the trouble.

Table 8 shows the relative frequency of absolute wind direction errors for the 9-h forecasts at all the sites. Again, the best forecasts are produced for the eastern sites, while the worst forecasts are produced for San Gorgonio.

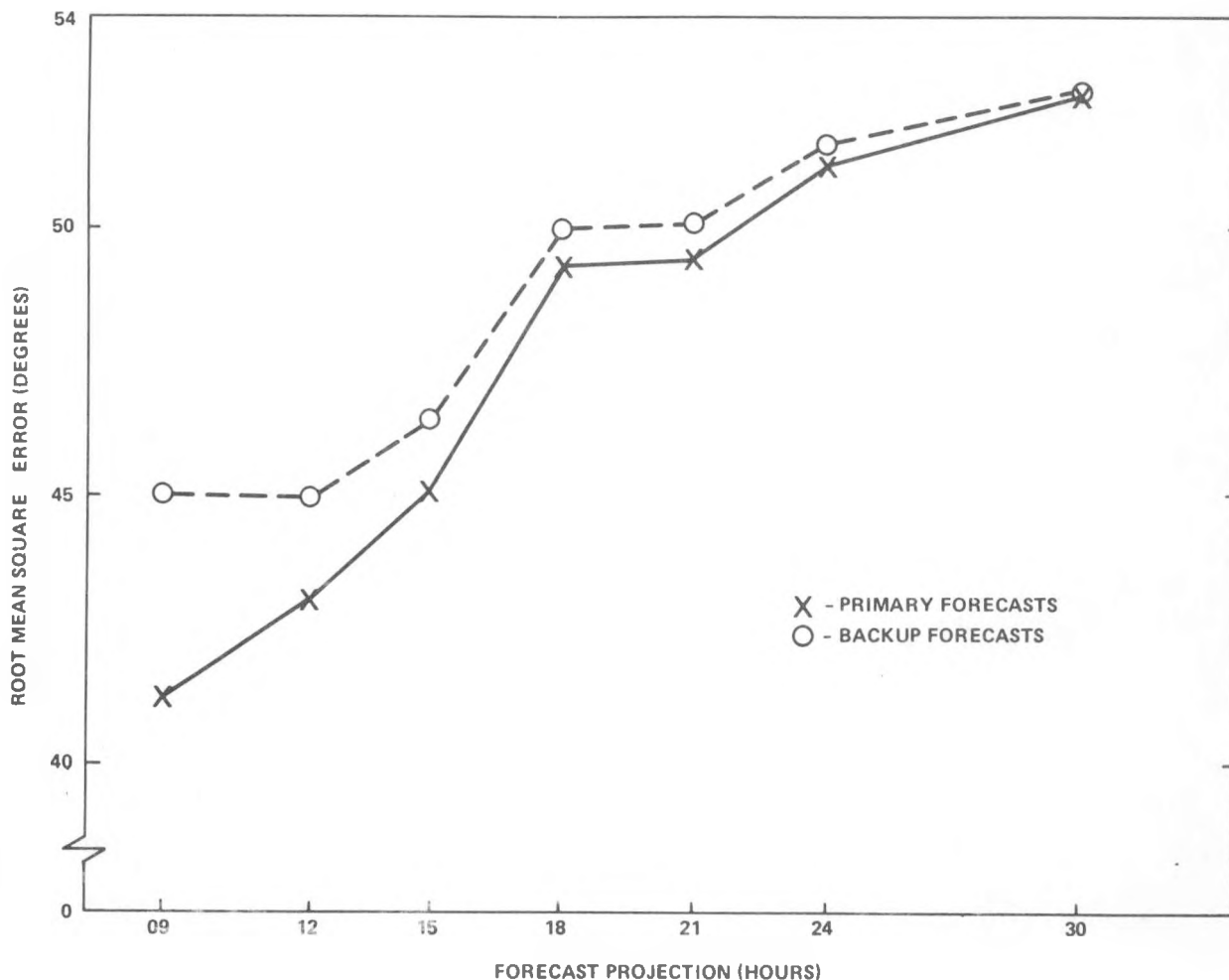


FIGURE 5. The Root Mean Square Error of the 0000 GMT Primary and Backup Wind Direction Forecasts for all Stations Combined for the Various Forecast Projections

Figure 6 shows the difference in accuracy of the 21-h speed forecasts on dependent and independent data. The RMSE on independent data is about 15% (0.4 m s^{-1}) higher than the RMSE on dependent data. This difference is somewhat higher than has been observed with some of the other MOS products, but seems realistic considering that only 1 year of development data was used.

TABLE 8. The Distribution of Absolute Errors Associated with the 0000 GMT, 9-h Forecasts of Wind Direction for the WTG Sites

WTG SITE	RELATIVE FREQUENCY OF ABSOLUTE DIRECTION ERRORS (DEG.)					
	0-30	31-60	61-90	91-120	121-150	151-180
Block Island, RI	0.76	0.13	0.06	0.03	0.02	0.01
Boone, NC	0.70	0.20	0.05	0.02	0.01	0.01
Holyoke, MA	0.77	0.15	0.04	0.03	0.01	0.00
Huron, SD	0.75	0.15	0.04	0.02	0.02	0.01
Kingsley Dam, NB	0.65	0.20	0.08	0.04	0.02	0.00
Montauk Point, NY	0.76	0.15	0.04	0.03	0.02	0.00
Point Arena, CA	0.75	0.11	0.05	0.03	0.02	0.04
Russell, KS	0.62	0.22	0.08	0.01	0.04	0.02
San Gorgonio, CA	0.65	0.15	0.09	0.05	0.04	0.03
All Stations	0.71	0.16	0.06	0.03	0.02	0.01

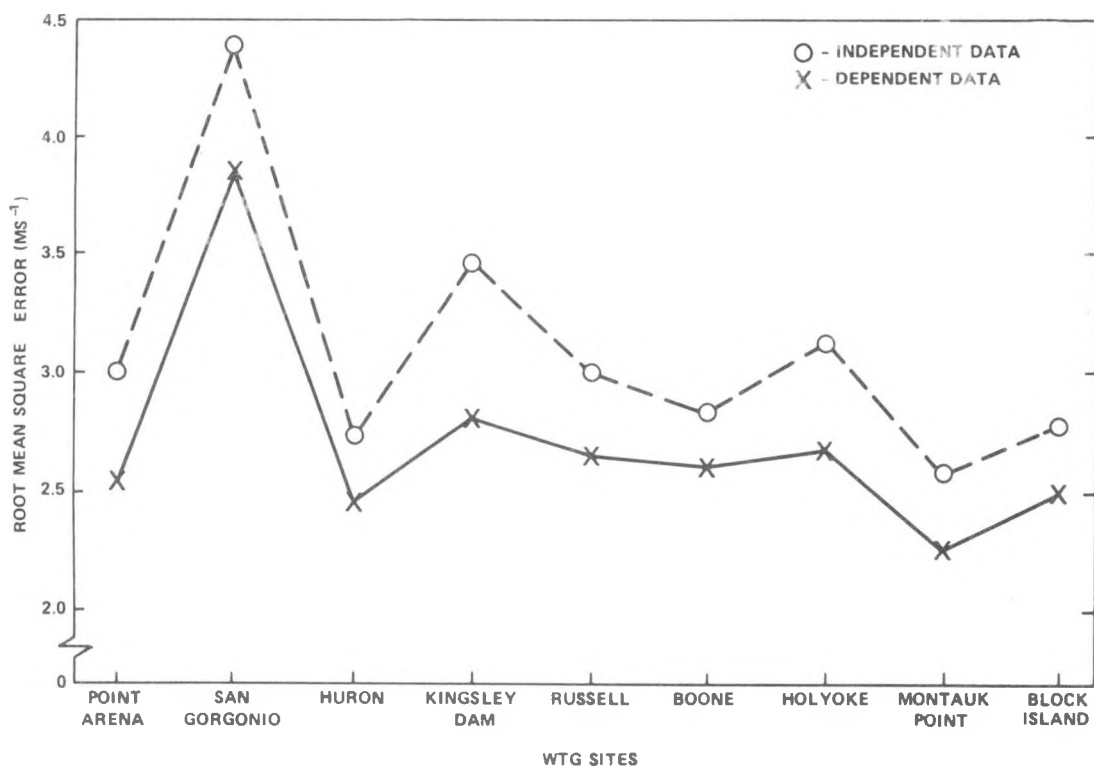


FIGURE 6. The Root Mean Square Error of the 0000 GMT 21-h Speed Forecasts on Dependent and Independent Data

MOS probability forecasts of the wind speed categories were also verified on the same independent data sample. For this verification, however, all cases were verified, not just those cases where the speed was greater than or equal to 2 m s^{-1} . A highly desirable characteristic of probability forecasts is that the probabilities be reliable. This is, when a certain probability is forecast on many occasions, the corresponding observed relative frequency of the event should not differ greatly from this probability. The reliability was determined for each speed category, each projection, and each site by computing the observed relative frequencies for several ranges of probability forecasts. Again, only a few of these results are presented here; the other results are available on microfiche.

Figures 7, 8 and 9 show plots of the reliability of three speed category forecasts for all nine WTG sites for the independent data sample. The forecast projection is nine hours. The plot for category one forecasts (Figure 7) shows good reliability, except for a small degree of overforecasting in the 30 to 70% range. In contrast, Figure 8 shows poor reliability for category three (6 to 8 m s^{-1}) forecasts. The observed relative frequency of this category is never more than 30% no matter what the forecast probability is. These poor results were not totally unexpected since the RMSE of the deterministic forecasts was 2.6 m s^{-1} and the width of the category is only 2 m s^{-1} . Figure 9 shows that category six (13 to 19 m s^{-1}) forecasts are more reliable, but the high wind speed events are underforecast when the probabilities are 30% or higher.

The verification of 1200 GMT forecasts yields the same major conclusions, but there are a few minor differences. Diurnal variations in the verification scores are more apparent at Holyoke, Massachusetts, and Russell, Kansas, than on the 0000 GMT forecasts. The RMSE of the speed and direction forecasts increases more slowly than the 0000 GMT forecasts for the 9- to 21-h projections. However, the 24- and 30-h forecasts for Kingsley Dam, Nebraska, are clearly better than backups on 1200 GMT data. No difference between the primaries and backups was observed on 0000 GMT data.

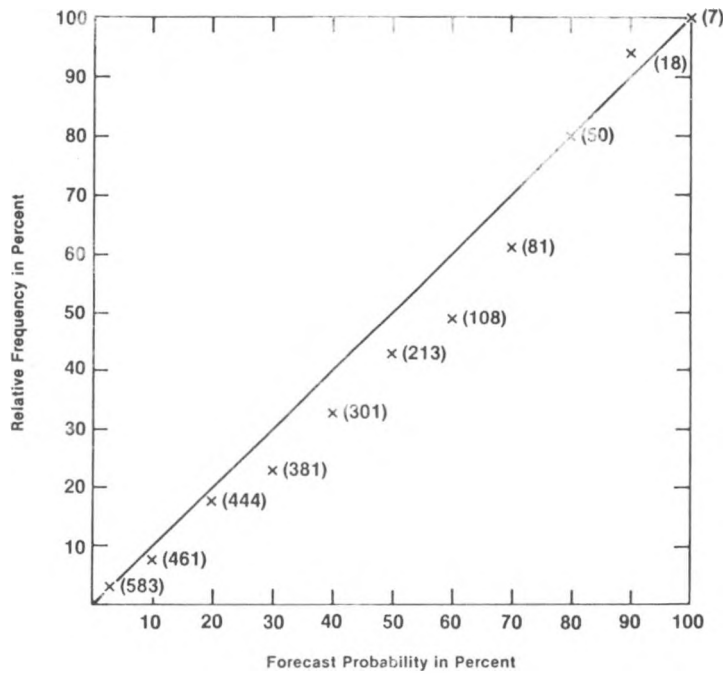


FIGURE 7. The Reliability of Category One (0 to 4 m s^{-1}) Forecasts on Independent Data for all Stations Combined. The numbers in parentheses are the sample sizes of all forecasts within $\pm 5\%$ of the plotted point.

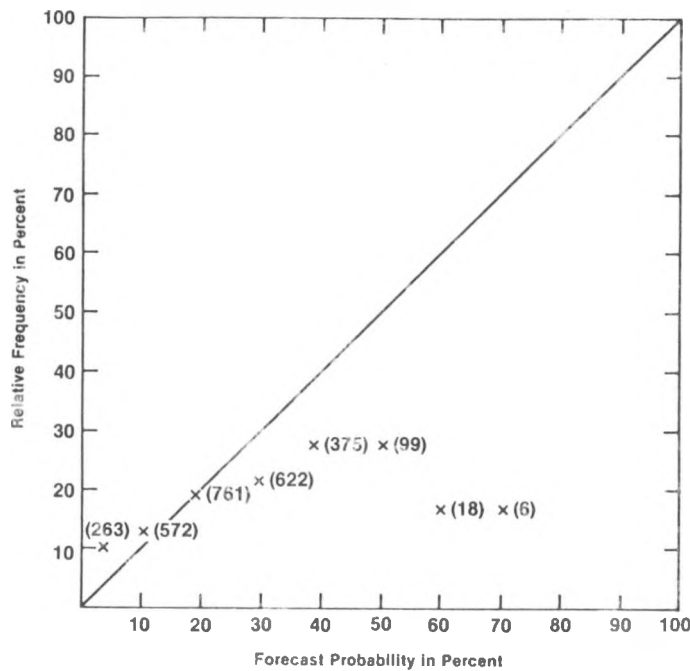


FIGURE 8. The Reliability of Category Three (6 to 8 m s^{-1}) Forecasts on Independent Data for all Stations Combined. The numbers in parentheses are the sample sizes of all forecasts within $\pm 5\%$ of the plotted point.

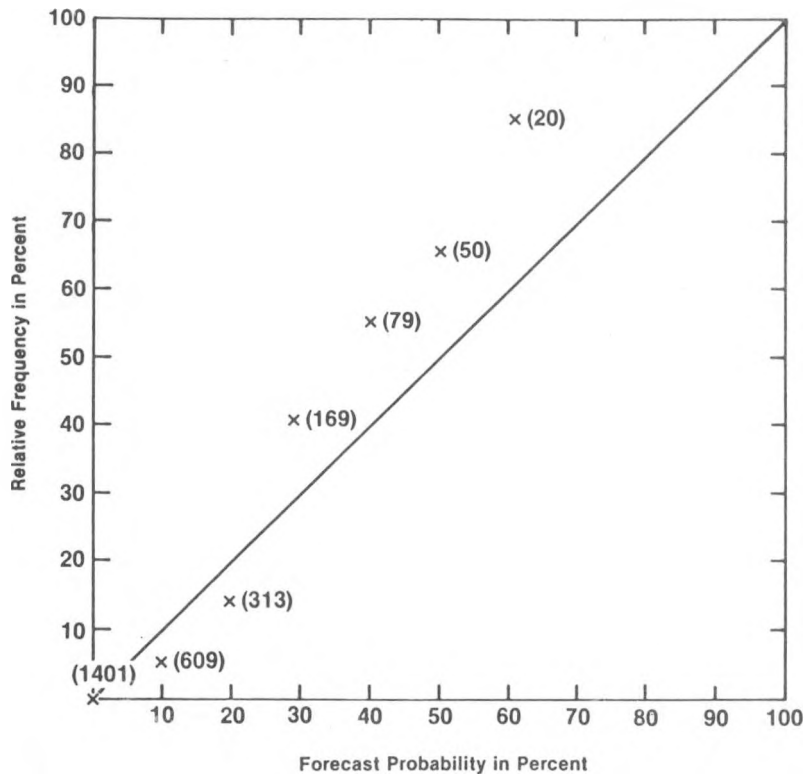


FIGURE 9. The Reliability of Category Six (13 to 19 m s^{-1}) Forecasts on Independent Data for all Stations Combined. The numbers in parentheses are the sample sizes of all forecasts within $\pm 5\%$ of the plotted point.

In future applications, making probability forecasts for fewer wind speed categories should give more reliable probabilities. Also, utility company dispatchers could become confused by the large number of probability forecasts for different categories, sites, and projections. TDLs experience with professional NWS forecasters confirms this. Reducing the number of categories could help dispatchers to use this guidance more meaningfully.

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APPENDIX

TABLE A.1. Verification of Primary Wind Direction and Speed Forecasts for the Nine WTG Sites, 0000 GMT Cycle Only, for the Period December 1977 Through October 1978. The speed bias equals the mean forecast speed minus the mean observed speed.

WTG SITE	FORECAST PROJECTION (HOURS)	DIRECTION			SPEED			NUMBER OF CASES
		MEAN ABSOLUTE ERROR (DEG)	ROOT MEAN SQUARE ERROR (DEG)	NUMBER OF CASES	MEAN ABSOLUTE ERROR (m s ⁻¹)	ROOT MEAN SQUARE ERROR (m s ⁻¹)	BIAS (m s ⁻¹)	
Point Arena, CA	9	25.6	43.2	227	1.76	2.34	-0.69	235
	12	27.9	47.8	220	2.15	2.82	-0.69	225
	15	34.2	54.4	203	2.44	3.17	-0.52	210
	18	36.1	59.5	206	2.35	3.06	-0.51	216
	21	34.8	56.3	222	2.23	3.01	-0.04	233
	24	38.6	59.2	218	2.44	3.31	-0.75	230
	30	37.8	58.9	214	2.55	3.45	-1.25	223
San Geronio, CA	9	28.7	50.4	247	3.05	3.76	-0.75	248
	12	35.3	53.9	241	3.81	4.83	-1.54	240
	15	34.6	54.1	224	3.35	4.16	-0.41	224
	18	47.8	66.9	240	3.64	4.62	-1.07	241
	21	46.7	66.0	273	3.37	4.39	-0.56	275
	24	50.3	72.0	270	3.32	4.30	-0.08	270
	30	26.5	45.8	247	3.19	4.11	-1.32	250
Huron, SD	9	25.5	38.9	252	1.97	2.43	-0.20	255
	12	25.5	38.8	243	1.93	2.54	-0.08	244
	15	27.8	42.4	240	1.93	2.53	-0.63	238
	18	27.3	38.9	245	2.18	2.70	-0.67	247
	21	27.8	41.3	253	2.18	2.73	-0.81	249
	24	30.5	46.2	258	2.34	2.92	-0.76	254
	30	34.1	48.8	255	2.35	3.03	-0.27	251
Kingsley Dam, NB	9	30.0	44.4	249	2.37	2.98	-0.65	251
	12	31.5	44.3	250	2.29	2.95	-0.58	252
	15	29.2	44.9	257	2.37	3.07	-0.57	249
	18	34.2	50.0	258	2.56	3.15	-0.78	251
	21	34.0	49.7	259	2.71	3.47	-1.20	253
	24	35.4	50.6	240	2.59	3.36	-0.75	253
	30	43.9	58.9	262	2.68	3.43	-0.62	254

TABLE A.1. (Continued)

WTG SITE	FORECAST PROJECTION (HOURS)	DIRECTION			SPEED			
		MEAN ABSOLUTE ERROR (DEG)	ROOT MEAN SQUARE ERROR (DEG)	NUMBER OF CASES	MEAN ABSOLUTE ERROR (m s ⁻¹)	ROOT MEAN SQUARE ERROR (m s ⁻¹)	BIAS (m s ⁻¹)	NUMBER OF CASES
Russell, KS	9	33.9	50.6	302	1.71	2.31	-0.25	307
	12	34.3	50.5	296	1.74	2.25	-0.10	303
	15	38.2	53.2	296	2.12	2.58	-0.48	303
	18	35.2	51.5	306	2.40	3.00	-0.94	306
	21	36.3	50.7	293	2.39	2.99	-0.88	302
	24	38.4	55.5	300	2.23	2.86	-1.07	300
	30	46.4	63.5	300	2.18	2.85	-0.33	300
Boone, NC	9	22.8	32.8	253	2.46	3.21	-0.02	255
	12	27.1	38.7	242	2.48	3.31	-0.37	249
	15	30.4	44.6	242	2.31	3.05	0.00	251
	18	34.3	50.3	263	1.96	2.55	0.09	260
	21	30.9	45.2	267	2.16	2.83	0.01	264
	24	31.9	46.3	267	2.21	2.81	-0.44	265
	30	30.9	43.4	249	2.46	3.16	-0.17	249
Holyoke, MA	9	23.8	37.3	280	1.59	2.10	-0.44	286
	12	23.7	35.6	273	1.92	2.49	-0.40	282
	15	24.6	37.0	244	2.30	2.96	-0.77	255
	18	28.1	40.9	252	2.40	3.08	-1.13	264
	21	29.8	43.9	277	2.37	3.14	-0.97	277
	24	27.3	37.9	288	2.16	2.79	-1.00	288
	30	33.0	47.7	269	2.14	2.83	-0.86	286
Montauk Point, NY	9	23.9	37.3	298	1.74	2.28	-0.55	298
	12	23.9	37.4	295	2.11	2.73	-1.04	297
	15	23.4	34.2	306	1.98	2.57	-0.59	309
	18	27.4	39.5	314	2.17	2.83	-0.77	316
	21	30.5	43.2	310	2.02	2.58	-0.60	311
	24	31.1	45.0	312	2.43	2.99	-0.89	312
	30	36.4	50.8	309	2.53	3.19	-1.19	309

TABLE A.1. (Continued)

WTG SITE	FORECAST PROJECTION (HOURS)	DIRECTION			SPEED			NUMBER OF CASES
		MEAN ABSOLUTE ERROR (DEG)	ROOT MEAN SQUARE ERROR (DEG)	NUMBER OF CASES	MEAN ABSOLUTE ERROR (m s ⁻¹)	ROOT MEAN SQUARE ERROR (m s ⁻¹)	BIAS (m s ⁻¹)	
Block Island, RI	9	22.3	32.7	296	1.56	2.04	-0.55	302
	12	25.6	39.3	295	1.76	2.32	-0.62	301
	15	25.7	39.2	291	1.82	2.42	-0.54	302
	18	29.0	43.8	296	2.01	2.58	-0.50	306
	21	30.1	44.5	301	2.15	2.78	-0.53	311
	24	30.6	43.8	306	2.18	2.91	-0.60	304
	30	35.6	49.8	308	2.30	2.91	-0.97	306
Overall	9	26.3	41.3	2404	2.00	2.63	-0.45	2437
	12	28.2	43.2	2360	2.21	2.96	-0.59	2393
	15	29.6	45.0	2303	2.26	2.95	-0.51	2341
	18	33.0	49.3	2380	2.39	3.09	-0.70	2407
	21	33.4	49.3	2455	2.39	3.14	-0.63	2475
	24	34.7	51.2	2467	2.42	3.16	-0.71	2476
	30	36.3	52.4	2413	2.47	3.21	-0.78	2428