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STATISTICAL ANALYSIS OF NUMERICAL MODEL OUTPUT USED FOR FORECASTING DURING JOINT URBAN 2003

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1. INTRODUCTION

In any experiment one must be able to control and manipulate initial conditions to test the desired hypothesis. When the laboratory is nature itself, and manipulation of the initial conditions is not possible (e.g. controlling winds entering a city), the next best option is to identify suitable conditions to conduct the experiment.

The task for forecasters during Joint Urban 2003 (JU2003) was to identify when atmospheric conditions were favorable for intensive observing periods (IOPs). The experiment plan was formulated for specific wind directions during JU2003. Thus, under appropriate conditions, atmospheric tracers were dispersed over a fixed and predetermined sampling grid. One grid, centered on due south, fanned out in a ninety-degree arc to the north to a distance of approximately 4 km, while the other was centered on southeast and fanned out to the northwest to a similar distance. The selection of which grid to deploy was entirely dependant upon the forecast of the surface wind direction. Wind speed values were also a consideration because if surface winds were too strong, the tracer concentrations might be too small to measure.

Temperature, relative humidity, and other typical atmospheric parameters had little impact on the forecasts during JU2003. Furthermore, other than unsuitable wind direction and wind speed values, the only event that could stop or delay an IOP, was convection. Lightning from thunderstorms would be dangerous for the scientists in the field, hail could potentially damage instruments, and outflow boundaries could adversely impact the tracer releases. Fortunately, convection was a minimal threat during July in Oklahoma City, nor as difficult to account for as wind direction.

A tool used by the forecasters to aid the wind speed and direction forecast was model output statistics (MOS) from three numerical weather prediction (NWP) models. This paper will briefly discuss the wind forecast process using the MOS information and the verification of the forecasts with wind observations. To accomplish the study, model forecast runs from 26 June through 1 August 2003 and surface observations from 26 June through 3 August were examined. The results of the MOS analyses are discussed for each specific model as well as the overall information provided by the forecasts.

2. BACKGROUND

2.1 *Model Output Statistics*

Introduced by Glahn and Lowry (1972), MOS has become an important component of numerical weather prediction. "[It] consists of determining a statistical relationship between the predictand and variables from the numerical model at some projection time(s)" (Glahn 1972). The predictor variables consisted of NWP output and observations; the predictand was the forecasted value at some projection time. MOS were not a direct output from a forecast model, but rather a product of multiple linear regression equations using specific variables produced by a forecast model combined with observations to generate a predictand. The regressions, created from past forecasts to adjust the variables' relation to a predictand, were used to create a forecast value. NWP output was used as predictor variables in both the development and implementation of the statistical equations (Wilks 1995). For more specific information about MOS development, see Glahn 1972.

To generate MOS, a separate regression equation must be developed for each parameter at each projection time. A further complication is that equations are also regionally dependent. Archived records of past forecasts, as well as the verification of those forecasts factor into the regression equations. Because actual observations are used in the creation and running of MOS, the climatology of a specific location factors into the MOS process. Thus, an added benefit to the MOS technique, over raw model output, is information concerning specific biases and errors with the forecast value. As such, MOS can take the specific error or bias into account, depending on the size and influence of the forecast, and produce more reasonable output (Wilks 1995).

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While NWP models have changed with time, the MOS process itself changed little. Furthermore, minor error reduction in the models impact MOS very little. However, significant changes in the NWP model, or different models all together, can critically impact the MOS regression equations, and systematic errors in forecasts require redevelopment of the regression equations (Wilks 1995). Typically, two years of stable numerical model data are required to derive appropriate MOS equations (Jacks 1990). However, if the model is rerun to forecast past events (i.e., retrospective forecasts), an adequate statistical base can be generated (Jacks 1990). Thus, MOS output can be made for evolving numerical models.

The MOS technique can be applied to any NWP model. However, the developed equations will depend on the specific NWP model that is providing the predictor values. As such, the regression equations will be different for varying NWP models.

Currently the National Center for Environment Prediction (NCEP) utilizes a suite of NWP models to forecast weather conditions at varying spatial and temporal scales: Aviation Model (AVN), Eta Model, and Nested Grid Model (NGM). MOS output for these models were used as wind guidance during JU2003, and are the foci of this study.

AVN, Eta, and NGM MOS all forecasted wind speed and direction for six to sixty hours after model initialization (0000 and 1200 UTC daily) at three hour intervals (Miller 1993; Dallavalle 2000, 2001).

The MOS for each model used in this study had regression equations for the u and v components of wind; the individual components were converted to degrees from true north for comparison with observations. In addition, MOS was available for wind speed. Typical predictors from the NGM MOS (values used in the regression equation) were: "forecasts of the 950 mb and ten meter wind components, wind at various levels up to 500 mb, vertical velocity, relative vorticity, vorticity advection, stability indices, and sinusoidal functions of each day of the year" (Jacks 1990). Wind observations at three hours after the initialization (i.e. 0300 or 1500 UTC) were also used as a predictor value (Jacks 1990). AVN MOS used similar predictors with the addition of mass divergence, "temperature differences between 1000 and 925 mb, 1000 and 850 mb, and 1000 and 700 mb, [plus] humidities for layers between 1000 and 850 mb and 850 and 700 mb" (Sfanos 2001). Furthermore, surface observations at 0300 or 1500 UTC were used in the equations for the AVN MOS (Sfanos 2001). For the Eta MOS, all predictors were the same as the AVN MOS, except for the surface observation times. Eta MOS uses wind measurements one hour after model initialization i.e., 0100 or 1300 UTC (Dallavalle 2001).

Model output statistics used in this study were acquired via the Internet

http://www.nws.noaa.gov/mdl/synop/products.shtml

for Will Rogers World Airport in Oklahoma City (KOKC). This web page, run by the Meteorological Development Lab (MDL) provides MOS output for the AVN, Eta, and NGM models used in the study (MDL 2003).

2.2 *Verification*

Hourly observations, collected by the National Weather Service's automated surface observing system (ASOS) at Will Rogers World Airport (KOKC), were used for verifying the wind forecasts, as well as compiling statistical information concerning the diurnal cycle of surface conditions at Oklahoma City. KOKC is approximately fourteen kilometers southwest of the downtown area. Thus, the measured winds at KOKC were assumed to be consistent with the entry winds for the center of Oklahoma City.

KOKC recorded the hourly observations at fifty-four minutes past the hour (e.g. 0954 UTC was the 1000 UTC observation). A wind vane and cup anemometer, atop a ten-meter mast, measured the properties of the wind. Both the wind speed and direction reports were a two-minute average of the conditions at the site. Wind speed was measured in whole knots, and wind direction was measure in ten-degree increments relative to true north (NWS 1998).

Variable wind direction reports, and missing reports, where noted in observations but did not figure into the verification of forecasts or other calculations. Errors for those times were omitted for wind direction only. Wind speed values under two knots were reported as calm (or zero) and wind direction was recorded as zero. Finally, variable winds were reported when the direction changed sixty degrees or more during the two-minute evaluation period (NWS 1998).

Observations were acquired via the Internet at

http://weather.noaa.gov/weather/current/KOKC.html

This web page, provided by the Telecommunications Operations Center (TOC), a division of the National Weather Service, displays the hourly observations in METR code and decoded format (TOC 2003).

2.3 *The diurnal cycle of wind speed and direction for Oklahoma City*

It was important to consider the diurnal cycle of wind when examining and creating forecasts. During JU2003 significant variation in wind conditions existed throughout the course of any given day. A significant portion of the variability was due to local effects as opposed to regional or synoptic-scale conditions. Furthermore, current NWP models are successful at resolving forecasts over large scales. Conversely, current NWP models often produce forecasts with greater errors for smaller scale events, especially those smaller than the model resolution. Even so, MOS can include local scale events if the frequency of the events is often enough to figure into the regression equations (Jacks 1990).

Figures 1a and 1b illustrated the average hourly wind direction and speed, during JU2003. Days that could not be used for IOPs, because of unfavorable atmospheric conditions, were removed from the analysis. Thus, twenty-seven of the thirty-eight days of the study were used.

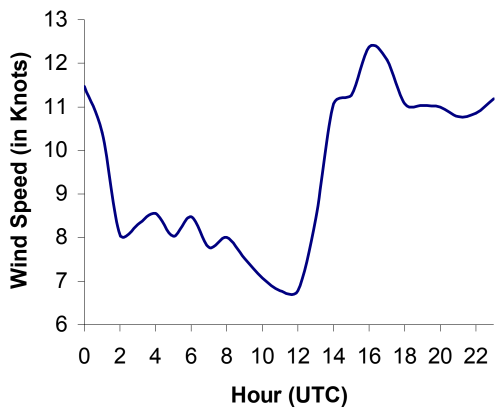

Figure 1a. Average wind speed (in Knots) per hour for KOKC during JU2003.

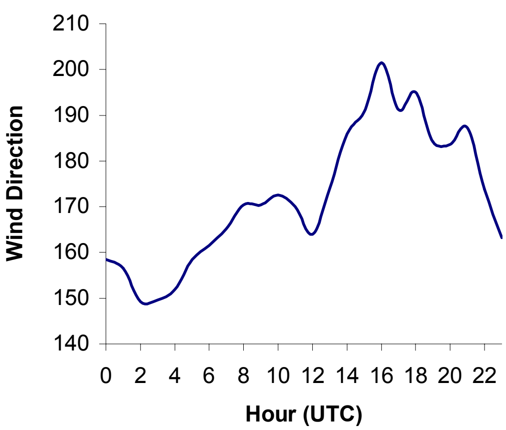

Figure 1b. Average wind direction (degrees from true north) per hour for KOKC during JU2003.

The trend for overnight conditions yielded wind directions from a southeasterly direction. However, the analysis demonstrates that typically after sunrise, (approximately 1200 UTC) the 10 m winds veered to the southwest for most of the daylight hours. Then, beginning at approximately 1600 UTC the winds backed to the southeast.

Typically during JU2003, the minimum wind speed values occurred at approximately 1200 UTC (7 AM local). However, with sunrise and subsequent convective mixing in the planetary boundary layer, the wind speed values rapidly increased until approximately 1600 UTC. Once convective mixing ceased (approximately 0000 UTC), the 10 m winds subsequently decreased.

3. ANALYSIS

In this study bias was calculated by subtracting the actual observation from the forecast value. The absolute value of the bias is the mean absolute error (MAE). As such a negative (positive) bias for wind speed denotes an underestimation (overestimation) of actual conditions by the forecast. The computation of error for wind directions posed a greater challenge. However, the convention for the wind direction error addressed the challenge and is as follows: a positive error value represents a clockwise (CW) directional error and over-forecasted value while a negative error represents a counterclockwise (CCW) error and under-forecasted values. The overall error analysis for this study incorporates values averaged over all available model runs for the experiment (approximately seventy forecast cycles for each model).

A control value was also designated for the MOS error analysis experiment. Thus, a persistence forecast (PER) was created by noting the observed conditions at a given time and extending those values for every interval within the forecast cycle. For this analysis the PER begins with the observed values at initialization (e.g., the 0000 UTC surface observations) and runs out to sixty hours at three-hour increments (i.e., observed values at t=0000 UTC are the forecasted values for t=0300 UTC, t=0600 UTC, etc.).

Model performance was calculated for the Eta, NGM, and AVN MOS, as well as a persistence forecast by comparing the observed values with the model forecasted values at specific time periods. Furthermore, the initialization periods for the MOS guidance and PER forecasts were the 0000 and 1200 UTC periods. Tables 1a - d display the wind speed bias (error) and wind direction bias (error) for each model. The models that compared the best with the observations at KOKC are noted in the far right column of each table.

The results reveal that PER forecast had the smallest bias in wind speed, while the AVN and NGM MOS had an equal number of cases over the mean forecast cycle which resulted in smallest values of MAE for wind speed. The PER example demonstrates that a small bias does not always yield a small MAE. It is likely the difference between the two calculations for PER result from a

Table 1a. Mean wind speed bias for MOS and PER per forecast projection during JU2003. Best model(s) for each projection are also noted.

	-	MOS	-		
Projection (Hours)	AVN	Eta	NGM	P	Best
6	-0.4	-1.3	-0.4	0.5	AVN/NGM
9	-1.0	-1.0	-0.9	0.4	PER
12	-1.7	-1.3	-0.5	0.2	PER
15	-1.4	-1.1	-0.6	0.1	PER
18	-0.5	-0.9	-0.3	0.3	NGM/PER
21	-0.8	-1.1	-0.5	0.5	NGM/PER
24	-1.5	-1.5	-0.9	0.3	PER
27	-1.0	-1.3	-0.9	0.2	PER
30	-1.1	-1.7	-0.4	0.4	NGM/PER
33	-1.7	-1.2	-0.6	0.4	PER
36	-1.8	-1.9	-1.1	0.4	PER
39	-1.8	-1.2	-1.1	0.0	PER
42	-1.3	-1.9	-0.8	0.1	PER
45	-1.1	-1.6	-1.1	0.3	PER
48	-2.4	-2.2	-1.6	0.2	PER
51	-1.3	-0.8	-1.5	0.0	PER
54	-2.0	-2.6	-1.1	0.1	PER
57	-1.6	-1.6	-1.0	0.4	PER
60	-2.0	-2.6	-1.2	0.3	PER
66	-1.9	-	-	-	NA
72	-1.9	-	-	-	NA

Table 1b. Mean absolute error of wind speed for MOS and PER per forecast projection during JU2003. Best model(s) for each projection are also noted.

	-	MOS	-		
Projection (Hours)	AVN	Eta	NGM	P	Best
6	1.8	2.3	2.2	4.2	AVN
9	2.3	2.2	2.4	4.7	Eta
12	2.4	2.4	2.1	4.9	NGM
15	2.7	2.7	2.1	3.3	NGM
18	2.4	2.6	2.3	3.1	NGM
21	2.5	2.5	2.6	3.1	AVN/Eta
24	2.3	2.7	2.6	2.7	AVN
27	2.1	2.7	2.2	4.6	AVN
30	2.4	2.9	2.3	4.6	NGM
33	2.9	3.0	2.7	5.2	AVN
36	2.9	3.2	2.8	5.1	NGM
39	2.9	2.8	2.5	3.8	NGM
42	2.4	3.0	2.5	3.8	AVN
45	3.0	3.1	3.0	3.8	AVN/NGM
48	3.3	3.0	3.0	3.5	Eta/NGM
51	2.5	2.8	2.8	4.4	AVN
54	2.7	3.3	2.8	4.6	AVN
57	3.0	3.2	2.9	5.2	NGM
60	2.9	3.5	3.1	5.1	AVN
66	3.0	-	-	-	NA
72	3.3	-	-	-	NA

Table 1c. Mean wind direction bias for MOS and PER per forecast projection during JU2003. Best model(s) for each projection are also noted.

	-	MOS	-		
Projection (Hours)	AVN	Eta	NGM	PER	Best
6	-3	-5	12	-18	AVN
9	-4	3	16	-6	Eta
12	-9	-3	8	-7	Eta
15	-14	-15	4	-11	NGM
18	-9	-18	7	-9	NGM
21	-4	3	8	0	PER
24	-12	-4	3	-7	NGM
27	-13	-6	-1	-5	NGM
30	-11	-11	6	-8	NGM
33	-1	-2	10	-24	AVN
36	-15	-3	4	-4	Eta
39	-21	-19	0	-18	NGM
42	-24	-13	3	-4	NGM
45	-8	-6	4	-12	NGM
48	-13	-5	0	-1	NGM
51	-16	-14	-2	1	PER
54	-18	-18	-7	-4	PER
57	-3	-16	-11	-9	AVN
60	-20	-21	-7	1	PER
66	-11	-	-	-	NA
72	-17	-	-	-	NA

Table 1d. Mean absolute error of wind direction for MOS and PER per forecast projection during JU2003. Best model(s) for each projection are also noted.

	-	MOS	-		
Projection (Hours)	AVN	Eta	NGM	PER	Best
6	17	18	22	37	AVN
9	23	21	25	35	Eta
12	24	20	24	42	Eta
15	20	21	20	51	AVN/NGM
18	23	24	25	46	AVN
21	25	24	31	48	Eta
24	27	24	31	44	Eta
27	25	26	25	54	AVN/NGM
30	26	22	30	52	Eta
33	27	25	35	55	Eta
36	32	33	33	59	AVN
39	32	32	29	63	NGM
42	36	28	32	62	Eta
45	40	33	37	65	Eta
48	40	39	33	59	NGM
51	28	33	30	62	AVN
54	29	38	33	64	AVN
57	37	43	39	67	AVN
60	36	45	35	60	NGM
66	32	-	-	-	NA
72	35	-	-	-	NA

large but balanced error per forecast over the experiment period. Finally, on average, all MOS values underestimated the wind speed while PER overestimated the wind speed.

In the case of wind direction, NGM MOS consistently had the forecast with the least bias during the forecast cycle. However, the AVN MOS had the least MAE for wind direction forecasts followed closely by the Eta MOS. This suggests that the NGM MOS might have equally overestimated and underestimated the wind direction (similarly to the PER wind speed) on varying occasions. As a result, the bias was small. On the other hand, the AVN MOS revealed a consistent bias that typically underestimated the wind direction, but with reduced absolute error compared to the NGM MOS. Finally, the overall results show that the AVN, Eta, and PER underestimated wind direction (CCW error) during JU2003 while the NGM overestimated wind direction (CW error).

The MAE for winds over the mean forecast cycle are show in Figures 2a and b. The PER Model performed poorest with the greatest MAE values for any wind speed forecast. This error varied greatly with time, which was probably a bi-product of the technique used to create the persistence forecast and the diurnal cycle of wind speed and direction. Conversely, the errors for the MOS forecasts were quite similar; the NGM and AVN revealed less error in wind speed forecasts during the period.

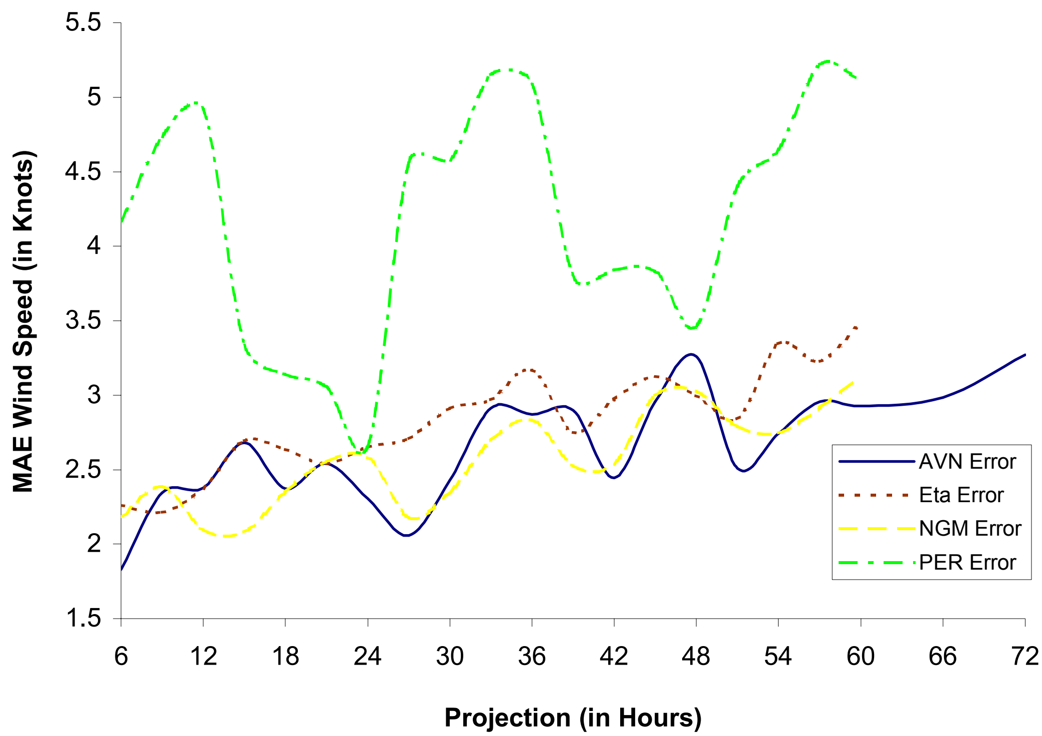

Figure 2a. Mean absolute error (MAE) for wind speed during JU2003.

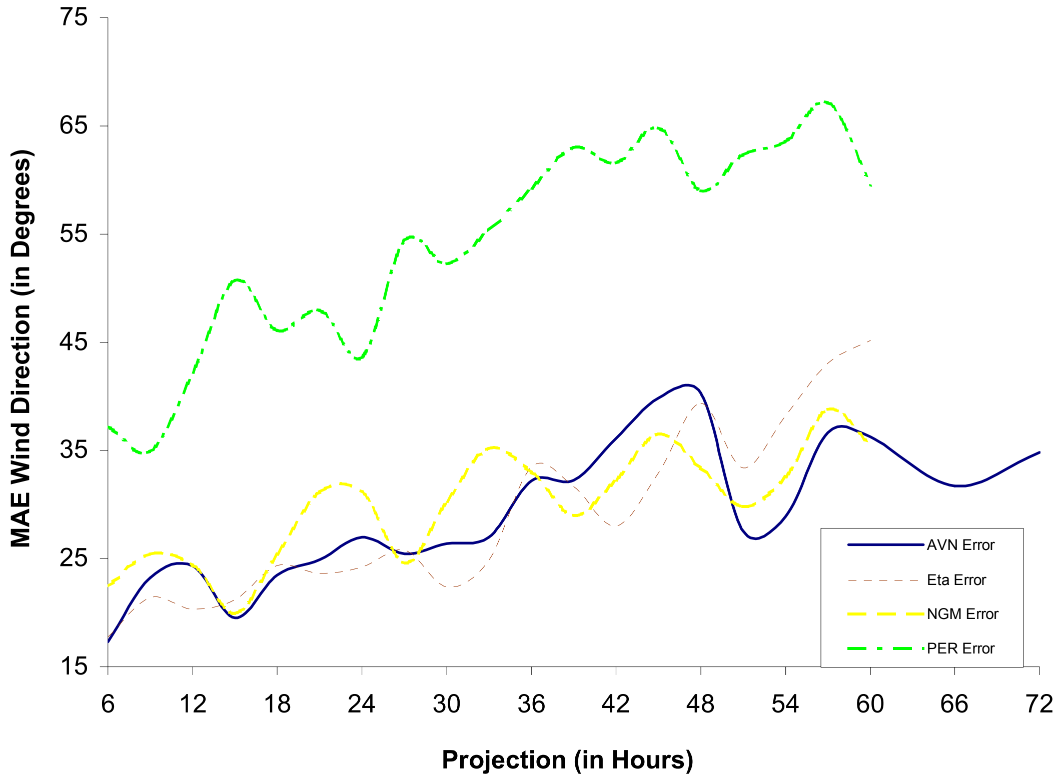

Figure 2b. Mean absolute error (MAE) of wind direction during JU2003.

While no one MOS forecast consistently produced the least MAE, the AVN, Eta, and NGM all performed in a similar manner. Conversely, MAE of the PER forecast revealed additional MAE of ten to twenty degrees greater than the MOS forecasts.

The NGM, Eta, and AVN models include observations into the computation of MOS values for each forecast run. Thus, MOS had a dependence on wind observations at the beginning of the forecast cycle and the initialization of the models.

Because wind direction was the most critical parameter to forecast during JU2003, the MAE wind direction per MOS model and cycle was examined (not shown). First, significant differences in MAE were observed between 0000 UTC and 1200 UTC forecasts for each of the models. One cause of the variability in error between forecast periods could be the diurnal oscillation of wind speed and direction. In addition, another potential cause for variability is the evolution of weather systems during JU2003. Again, however, no one model guidance proved to forecast conditions better than the others.

Finally, the 'best case' forecast error was examined. The analyses in Figures 3a and 3b use the minimum MAE values of the individual MOS forecasts to compute a composite forecast. The results of the composite forecast yields a minimum MAE of 2.3 knots at the 24-hours forecast interval and slightly greater than three knots at 36-hours. Furthermore, the composite forecast yielded a wind direction error of nearly 25 degrees at the 24-hours forecast period and over 30 degrees at the 36-hour period. Because the MAE values include the absolute value of the error, the overall result is that the "window" of error was double the MAE (i.e., 50-60 degrees for the 24-36 hour forecasts).

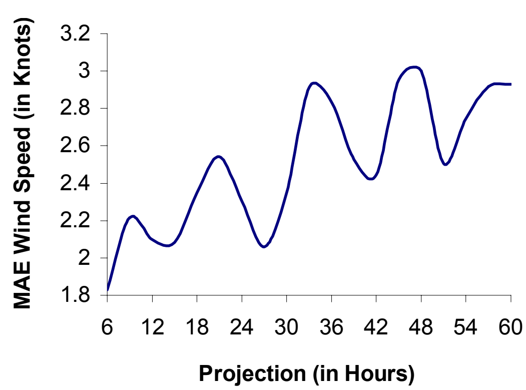

Figure 3a. 'Best Case' MAE wind speed from MOS during JU2003.

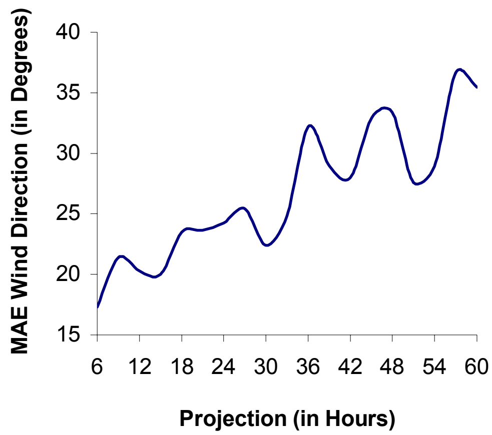

Figure 3b. 'Best Case' MAE wind direction from MOS during JU2003.

4. Conclusions

The MOS output of wind speed and direction values simulated by regional NWP models exhibited significant error during JU2003. In addition, the diurnal cycle of wind speed and direction played a critical role for the JU2003 experiment. As shown, no one MOS model out performed the others, and the persistence forecast had the largest errors of any forecast tool examined. MOS was able to forecast wind direction and speed better than persistence, but minor dependency on the diurnal cycle of winds was observed. All models revealed different errors for the 0000 and 1200 UTC forecast cycles.

The results for JU2003 seem significant. While the analyses are only valid for Oklahoma City, the inherent errors with the MOS outputs still shed new insights concerning the wind trends over a sixty-hour forecast cycle. Thus, forecasters should still use MOS as a guidance tool. However, the skill of the final forecasts must include increased understanding of the errors associated with the models for the specific location of focus. Finally, the composite analysis demonstrated that under best circumstances, the MAE associated with MOS were nearly 3 knots for wind speed and between 25-30 degrees for wind direction for the critical 24-36 hour period forecasted during JU2003.

5. ACKNOWLEDGEMENTS

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