7.3 EVALUATION OF THE NELSON DEAD FUEL MOISTURE MODEL IN A FORECAST ENVIRONMENT

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1. INTRODUCTION

The “Nelson model” for dead fuel moisture (Nelson, 2000) is a numerical model which was originally developed in the 1990s by Ralph Nelson (USDA Forest Service, retired) to take advantage of frequent weather observations from automated weather monitoring stations. This new dead fuel moisture model is targeted for inclusion in the next-generation National Fire Danger Rating System (NFDRS) of the USDA Forest Service. The current dead fuel moisture algorithms in NFDRS (Bradshaw *et al.*, 1983) have remained virtually unchanged since the 1970s.

In a companion paper P1.5 (Carlson *et al.*, 2005) from this symposium, the Nelson model was evaluated against field observations from Oklahoma over a 21-month period using weather observations from the Oklahoma Mesonet, the state’s automated weather station monitoring network (Brock *et al.*, 1995). This paper also compared the performance of the older NFDRS dead fuel moisture algorithms against the observational data; the Nelson model outperformed the NFDRS predictions in every size fuel class.

In addition to using observational data, it is anticipated that the Nelson model will also be run in a mid-range forecast environment, as the next-generation NFDRS will incorporate several-day numerical output from an operational mid-range forecast model of the National Centers for Environmental Prediction (NCEP). Thus, it is also important to see how the Nelson model performs in such a forecast environment.

As part of a funded project between the Missoula Fire Sciences Lab (Rocky Mountain Research Station, USDA Forest Service) and Oklahoma State University, the Nelson model was evaluated in a forecast environment covering the state of Oklahoma during the year 2004. The forecast model utilized was the 32-km version of the NCEP Eta model (Black, 1994). Forecast output included both 00Z and 12Z runs, and covered an 84-hour prediction period.

This paper analyzes the performance of the Nelson model over an 84-hour period for each size dead fuel class (1-, 10-, 100-, and 1000-hour). Two months from 2004 (a wet and a dry month) were chosen for the present analysis.

2. OPERATIONAL PROCEDURES

In the present study the Nelson model was run using both observational data from the Oklahoma Mesonet and forecast data from the Eta model. The methodology used in integrating these two sources of weather data into the Nelson model for purposes of this study is now discussed.

The two sources of 2004 weather data for use with the Nelson model consisted of (1) historical 15-minute observational data from the Oklahoma Mesonet, and (2) historical hourly forecast data from available archived Eta forecasts.

With respect to the Eta forecast data, 3-hourly GRIB (gridded binary) data files going 84 hours into the future from both the 00Z and 12Z runs of the 32-km Eta model were obtained when possible (during 2004 the successful download of Eta forecasts at the Oklahoma Climatological Survey was intermittent at best). From these 3-hourly files, the relevant weather data was then interpolated from the Eta 32-km grid to the locations of the Mesonet stations using bilinear interpolation. Linear interpolation in time was used to create hourly forecast data. This procedure resulted in forecast data files of the same structure as those in the Mesonet environment (data at each Mesonet site, rather than on a rectangular grid).

As discussed in the companion paper (P1.5), separate sets of model parameters have been developed for use with 15-minute weather data and for use with hourly data. In this study, when the Nelson

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model was run using Mesonet data, the “15-minute” parameter set was utilized; when run using Eta data, the “hourly” parameter set was utilized.

In this research study the Nelson model was first run at all Mesonet sites using historical 15-minute data from the Oklahoma Mesonet for the year 2004. The site-specific output was archived, as were the “initialization” data files needed to numerically step the model from one 15-minute period to the next.

When a specific 84-hour Eta forecast was run, the Mesonet-based Nelson initialization files were used to initialize the Nelson model at either 00Z or 12Z (start of the forecast run). The Nelson model was then run through the 84-hour period using hourly data from the Eta model, beginning with the 01Z or 13Z data, respectively. The site-specific output at each forecast hour throughout the 84-hour period was archived.

3. ANALYSIS METHODOLOGY

Given 116 Mesonet sites and the extensive amount of work that would be involved in analyzing all sites, it was decided to concentrate on 11 sites spaced evenly throughout the state (Figure 1). The four-letter abbreviations associated with these stations are shown on the map.

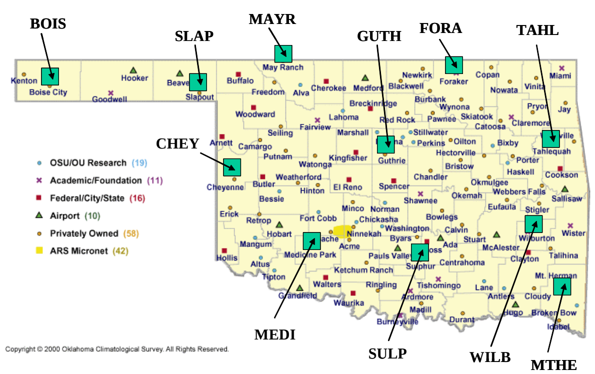

Figure 1. *Eleven Mesonet sites selected for the present analysis.*

The months selected for analysis were April and May 2004. The choice was partially based on having enough archived Eta forecasts with which to work (there were 25 available in each month - about 40% of all that occurred). The other factor was monthly rainfall; we wished to choose both a wet month and a dry month. April 2004 had an average rainfall (considering only these 11 Mesonet stations) of 103 mm (4.06"). In contrast, May 2004 was the driest May on record (since 1892); the average rainfall of the 11 stations was 30 mm (1.18") in a month which is normally Oklahoma’s wettest (132 mm; 5.21").

The statistical analyses to be later described were performed separately for April and May on (1) each of the 11 individual sites and (2) all 11 sites combined. Because of the large volume of data in these analyses, only set (2) will be the focus of the present paper.

To test the Nelson model in the Eta forecast environment, we evaluated the Nelson dead fuel moisture (DFM) output every 6 hours throughout the 84-hour forecast period, starting with the 3-hour forecast. Comparisons were made with the Mesonet-based Nelson DFM output at the respective forecast validation times (when the observational weather data had “caught up” with the various forecast validation times). The comparison against Mesonet-based Nelson DFM values was chosen because, in contrast to the study reported in companion paper P1.5, we had no observational DFM data in 2004 to serve as “ground truth”. Thus, Mesonet-based Nelson model DFM output at the forecast validation times served as the basis for comparison.

When evaluating forecast results at a given forecast verification time in the following section, we present statistics from two data sets: (1) the original data set (“Total Sample”) and (2) a data set where a 90% filter has been applied (“90% Filter”). The original data set contains all the forecast DFM data points for the combined 11 Mesonet sites at a given forecast verification time, along with their Mesonet-based DFM counterparts. The filtered data set is the original data set minus that 10% of the data having the largest values of absolute difference between the forecast and the Mesonet-based DFM values. Forecast errors in rainfall timing/amount and relative humidity can lead to large discrepancies between forecast Nelson DFM and Mesonet-based Nelson DFM; it was seen that removing 10% of the data points having the largest discrepancies substantially improved the statistics. Using the “90% Filter” statistics, one can thus estimate how the Nelson model will perform 90% of the time.

In some sense, the results of this study constitute a referendum on the accuracy of the Eta forecast for these months (perfect forecasts would give perfect comparisons). However, any forecast is going to have inaccuracies and observing how the Nelson dead fuel moisture model performs in such an environment says something about the model’s sensitivity to less than perfect forecast data and its ability to still produce useful results for wildland fire management over, in this case, an 84-hour forecast period.

4. RESULTS

4.1 *Weather and Dead Fuel Moisture Conditions*

Tables 1 and 2 present an overall picture of the weather and dead fuel moisture conditions experienced by the 11 Mesonet sites during the months of April and May 2004. Air temperature (TAIR), 1-hour rainfall (RAIN_1h), and solar radiation (SRAD) were taken from the Mesonet observations, while 1-hour (FM1), 10-hour (FM10), 100-hour (FM100), and 1000-hour (FM1000) dead fuel moisture (DFM) were calculated by the Nelson model using 15-minute Mesonet data. As mentioned earlier, these DFM values are the closest we have to “ground truth” for this analysis since no DFM field observations were taken during 2004.

Table 1. Weather and dead fuel moisture conditions at 11 Mesonet sites during April 2004.

	BOIS	SLAP	CHEY	MAYR	MEDI	GUTH	SULP	FOR A	WILB	TAHL	MTHE	ALL 11 SITES
TAIR (C)												
Average	10.8	13.1	14.5	13.8	16.1	15.7	16.6	14.9	16.5	15.3	16.3	14.9
Maximum	28	31.5	31.9	33.2	29.9	29.4	27.6	29.9	26.9	25.4	26.1	33.2
Minimum	-6.9	-4.9	-1.9	-1.9	1.1	0.2	-1	0.5	0.1	-1.1	0.4	-6.9
Range	34.9	36.4	33.8	35.1	28.8	29.2	28.6	29.4	26.8	26.5	25.7	40.1
RAIN_1h (mm)												
Maximum	7.11	56.1	12.95	20.83	9.91	12.19	9.91	14.22	34.29	29.72	28.19	56.1
Monthly Rainfall	61.72	112.78	65.28	91.69	67.56	57.15	55.88	96.01	164.34	202.44	156.97	102.89
SRAD (W/m2)												
Maximum	1098	1032	995	1088	1155	1024	1077	1035	1054	993	1019	1155
FM1 (%)												
Average	18.8	18.4	18.3	17.9	17.8	17.3	16.9	18.7	18.6	20.1	19.6	18.4
Maximum	85	85	85	85	85	85	85	85	85	85	85	85
Minimum	2.3	2.8	2.9	3	4.7	6	6	5.6	6.2	6.3	5.4	2.3
Range	82.7	82.2	82.1	82	80.3	79	79	79.4	78.8	78.7	79.6	82.7
FM10 (%)												
Average	14.9	15.4	15.3	15.2	16.1	15.1	15.3	16	16.5	18.1	18.5	16
Maximum	50.5	44.2	52	50.1	47	49.9	53.1	48.8	55.9	60	60	60
Minimum	5.9	5.6	5.3	5.8	6.8	7	7.3	7.1	7.5	7.8	8	5.3
Range	44.6	38.5	46.7	44.4	40.1	42.8	45.8	41.7	48.3	52.2	52	54.7
FM100 (%)												
Average	14.4	14.3	14	13.8	14.6	14.2	13.8	15	15.2	16.2	16.2	14.7
Maximum	23.9	24.4	21.7	24.8	22	24	23.4	26.5	28.3	32.2	28.5	32.2
Minimum	8.8	9.7	9.7	9.6	9.7	10.1	9.4	10.2	10.4	10.3	10.5	8.8
Range	15.2	14.7	12	15.2	12.3	13.9	14	16.2	17.9	21.9	18	23.4
FM1000 (%)												
Average	7.5	10.7	11.7	10.8	12.1	11.9	11.9	13.7	12.4	14.2	15.4	12
Maximum	11	13.9	14.7	13.6	15.2	14.9	14.8	15.9	15.3	17.5	18.1	18.1
Minimum	6.3	8.9	10.2	9.4	10.4	10.6	10.4	12	11	12.2	13.8	6.3
Range	4.7	4.9	4.5	4.2	4.8	4.3	4.4	3.9	4.3	5.3	4.3	11.8

Table 2. Weather and dead fuel moisture conditions at 11 Mesonet sites during May 2004.

	BOIS	SLAP	CHEY	MAYR	MEDI	GUTH	SULP	FOR A	WILB	TAHL	MTHE	ALL 11 SITES
TAIR (C)												
Average	19.4	21.4	21.6	21.6	21.8	22.2	21.6	20.5	21.9	20.7	20.9	21.2
Maximum	35.4	39.2	36.3	38	35.3	33.8	32.1	30.8	31.8	30	29.6	39.2
Minimum	0.2	2.2	5.7	3.3	6.4	4.3	2.2	3.8	3.8	1.7	3.6	0.2
Range	35.2	37	30.6	34.7	28.9	29.5	29.9	27	28	28.3	26	39
RAIN_1h (mm)												
Maximum	8.13	1.02	1.52	5.59	1.02	53.09	3.56	6.35	4.57	41.4	18	53.09
Monthly Rainfall	8.89	1.27	1.52	11.94	4.57	60.96	9.65	46.99	21.34	75.44	86.87	29.95
SRAD (W/m2)												
Maximum	1128	1066	1021	1019	1105	1026	1083	1039	1130	1057	1133	1133
FM1 (%)												
Average	10.2	11.6	13.3	13.7	15.9	15.1	16.7	19	17.5	19	22.7	15.9
Maximum	48.7	37.6	85	76.5	85	85	85	85	85	85	85	85
Minimum	2.1	2.1	3	2.5	3.7	4.5	4.1	6.3	5.1	7.2	5.8	2.1
Range	46.6	35.4	82	73.9	81.3	80.5	80.9	78.7	79.9	77.8	79.2	82.9
FM10 (%)												
Average	9.5	10.6	12.2	12.6	14.7	14.5	16.2	17.4	16.3	18	20.4	14.8
Maximum	29.3	21	24.9	35	28	40.1	43.5	57.2	41.3	54.3	60	60
Minimum	4.6	4.4	5	5.3	4.5	5.7	6.2	6.4	6.7	8	8.1	4.4
Range	24.7	16.6	19.9	29.7	23.5	34.3	37.3	50.8	34.5	46.3	51.9	55.6
FM100 (%)												
Average	9.1	9.1	10.1	10.7	12.4	12.3	13.4	14.4	14.1	15.5	16.9	12.5
Maximum	16.5	13.3	13.5	16.7	19.8	20.2	19.2	27.5	25.7	26.5	30.8	30.8
Minimum	6.6	5.9	7.5	7.3	8.8	8.8	10.3	10.2	10	11	10.9	5.9
Range	9.8	7.4	6	9.3	11	11.4	8.9	17.3	15.7	15.5	19.9	24.9
FM1000 (%)												
Average	7.9	9.1	8.7	9	9.3	10.4	10.9	12.3	11	12.3	13.9	10.4
Maximum	10.9	11.7	11.2	11.2	11.8	14.9	13.5	15.8	15.5	17.1	17.3	17.3
Minimum	6.4	6.9	6.6	7	7.1	8.2	9	9.7	8.9	9.6	12.1	6.4
Range	4.5	4.8	4.6	4.2	4.7	6.7	4.5	6	6.6	7.4	5.2	10.9

April 2004 represents the "wet" month of the study, with individual monthly rainfall totals ranging from 55.9 mm (2.20") at Sulphur (SULP) to 202.4 mm (7.97") at Tahlequah (TAHL). Highest 1-hour rainfall was 34.3 mm (1.34") at Wilburton (WILB). Average April temperature was 14.9C (59F) with extremes ranging from -6.9C (20F) at Boise City (BOIS) to 33.2C (92F) at May Ranch (MAYR).

May 2004 represents the "dry" month of the study, with individual monthly rainfall totals ranging from only 1.3 mm (0.05") at Slapout (SLAP) to 86.9 mm (3.42") at Mt. Herman (MTHE). Highest 1-hour rainfall was 53.1 mm (2.09") at Guthrie (GUTH). Average May temperature was 21.2C (70F) with extremes ranging from 0.2C (32F) at BOIS to 39.2C (103F) at SLAP.

Dead fuel moisture (DFM) reflects the climatic gradient across Oklahoma, with average DFM values generally lowest in the drier western areas of the state and highest in the wetter eastern areas (the order of stations in Tables 1 and 2 is generally arranged from west to east).

Average 1-hour dead fuel moisture (FM1) during the wet month of April was 18.4%, with extremes of 2.3% and 85% (the upper limit of the Nelson model for FM1 under rainy conditions). During the dry month of May, average FM1 was 15.9%, with extremes of 2.1% and 85%.

Average 10-hour dead fuel moisture (FM10) during April was 16%, with extremes of 5.3% and 60% (the upper limit of the Nelson model for FM10 under rainy conditions). During May average FM10 was 14.8%, with extremes of 4.4% and 60%.

Average 100-hour dead fuel moisture (FM100) during April was 14.7%, with extremes of 8.8% and 32.2% (Nelson model upper limit for FM100 is 40%). During May average FM100 was 12.5%, with extremes of 5.9% and 30.8%.

Finally, average 1000-hour dead fuel moisture (FM1000) during April was 12%, with extremes of 6.3% and 18.1% (Nelson model upper limit for FM1000 is 32%). During May average FM1000 was 10.4%, with extremes of 6.4% and 17.3%.

Over the two-month period, the Nelson model thus encountered a wide range of weather conditions with temperatures ranging from -6.9C to 39.2C, and monthly rainfall totals ranging from only 1.3 mm to as much as 202.4 mm. It is against this background that we now evaluate the Nelson model in a forecast environment.

4.2 *Analysis of Forecasted Dead Fuel Moisture*

We now come to the major focus of this paper - that is, the analysis of how the 1-, 10-, 100-, and 1000-hour dead fuel moisture (DFM) values generated by the Nelson model using Eta model input compare with the DFM values generated by the Nelson model using Mesonet data, the latter DFM values being considered "ground truth" inasmuch as we have no observed field values of DFM at these times.

a. **<u>1-hour dead fuel moisture</u>**

We begin with 1-hour (fine fuel) dead fuel moisture (FM1). The Nelson model for 1-hour fuels is highly sensitive to rainfall, rising frequently to values of 85% during rainfall events. Thus, it should not be surprising, given the difficulties of forecasting rainfall (location, timing, and amount) that large deviations in FM1 can occur during such events (e.g., Eta model predicting rainfall when Mesonet does not measure any, or conversely). These high deviations in such cases greatly influence the overall statistics for FM1 (that is why the 90% filter greatly improves statistics).

Other complications (in the analysis) arise from the use of 15-minute data with Mesonet and 1-hour data with the Eta model. Consider the case where it rains sometime during the first 15 to 45 minutes of a given hour, but not during the last 15 minutes. Since the Nelson model with Mesonet input is run with 15-minute data, on the whole hour it would see "no rain" during its last calculation period for FM1. The Nelson model in the forecast mode, however, uses hourly data, so at that same whole hour it would see "rain" during the time interval and calculate FM1 accordingly. Since we are comparing Eta to Mesonet results at "whole" hours (e.g., 0300, 0900), these complications affect the statistics as well.

Proceeding now to the analysis for FM1, we first look at the r2 values describing the relationship between the Eta forecast and Mesonet FM1 values over the 84-hour forecast period. Figure 2 presents the r2 values over the forecast period for both the April and May total sample data sets and the 90% filter data sets.

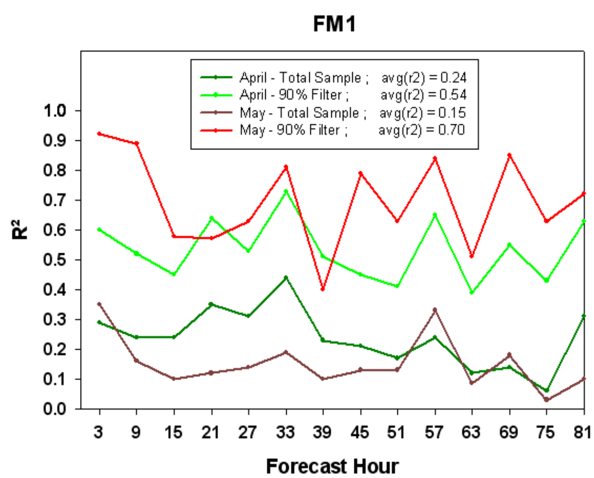

Figure 2. *R2 values for 1-hour dead fuel moisture over the 84-hour forecast period.*

Considering all the forecast points (total sample), the r2 plots show poor correlation between the Eta and Mesonet FM1 values for both April and May, with all r2 values being below 0.5 during the entire forecast period and showing a slow decline in skill with increasing forecast hour. During the dry month of May, these poor correlations are often related to poor relative humidity forecasts. With the 90% filter, the statistics improve greatly, with most May r2 values lying well above 0.5 (average r2 of 0.70). April's statistics improve as well, but not as markedly (due to the greater frequency of rain events), with most r2 values hovering about 0.5 (average r2 of 0.54). With both months there is only a very slight decline in skill over the forecast period.

We now inspect the standard deviation of the difference between the forecast FM1 value and the Mesonet FM1 value (the forecast "error") for these four data sets. Figure 3 presents this information.

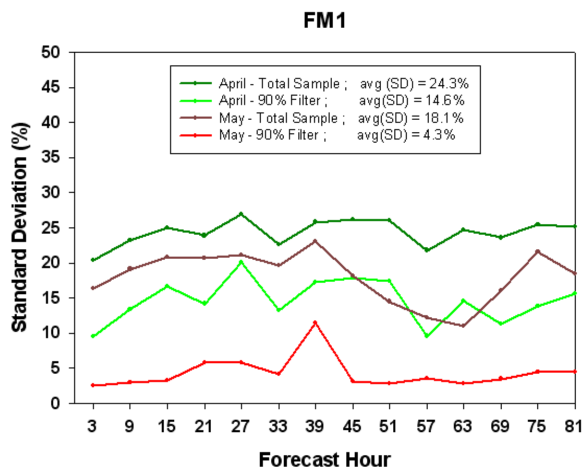

Figure 3. *Standard deviation (%) of the difference between forecast and Mesonet 1-hour dead fuel moisture over the 84-hour forecast period.*

The standard deviation of the forecast error is greater in April for both the total sample and 90% filter data sets; this can be explained by the greater frequency of rain in April as compared to May. The plots show that forecast error is more or less constant over the 84-hour period. For the total sample, the April average value is 24.3% while May's average is 18.1%. Again, the 90% filter improves the statistics, with the average value for April falling to 18.1% and May's value falling greatly to only 4.3%. These results imply that during April the forecast FM1 was generally within 18.1% of the Mesonet ("true") value during 90% of the time, while for May it was generally within 4.3% of the Mesonet value during 90% of the time.

Table 3 presents some descriptive FM1 statistics for April and May averaged over the 84-hour period for the two data sets. N represents the average number of data points per forecast time available in the total sample for a given month; the 90% filter would thus contain 90% of those points. This table shows the great improvement in average r2 and standard deviation (SD) in forecast error as one applies the 90% filter. April's r2 values improve from 0.24 to 0.54, and May values, from 0.15 to 0.7. April's SD values fall from 24.3% to 14.6%, while May values fall from 18.1% to 4.3%. The median values of forecast error are negative, and, for a given month, have nearly the same value. A median forecast underprediction of FM1 (from the Mesonet "true" value) in the range of 1-1.5% for April and 2-2.5% for May is indicated.

Table 3. Descriptive statistics for 1-hour dead fuel moisture averaged over the 84-hour forecast period.

FM1 (%)		Apr-04	May-04
Total Sample	N	260	259
	r2	0.24	0.15
90% Filter	r2	0.54	0.7
Difference (%) [Forecast - Mesonet]			
Total Sample			
	Median	-1.1	-2.3
	Mean	7.3	1.2
	Std. Deviation	24.3	18.1
	Skewness	1.5	2.4
	Maximum	78.6	80.3
	Minimum	-77.9	-81.9
90% Filter			
	Median	-1.4	-2.5
	Mean	1.6	-2.4
	Std. Deviation	14.6	4.3
	Skewness	2.3	0.8
	Maximum	64.2	57
	Minimum	-57.7	-29.2

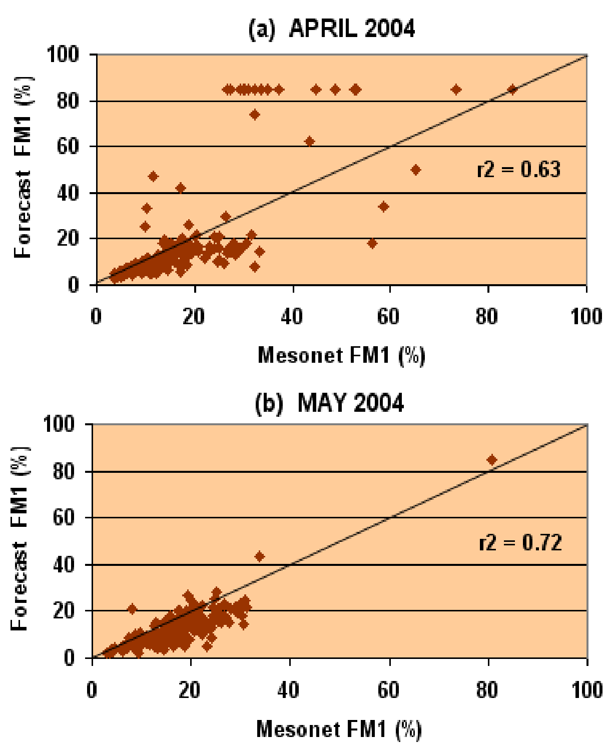

Figure 4. *Scatterplots of forecast versus Mesonet-based 1-hour dead fuel moisture at 81 hours from the 90% filter data sets for (a) April 2004 and (b) May 2004. The solid line represents the x=y line for reference.*

Finally, we conclude our discussion of 1-hr DFM with reference to some scatterplots at the 81-hour forecast time (the latest forecast time analyzed). The performance of the Nelson model at 81 hours is similar to that at other forecast times, but being toward the very end of the 84-hour period, could be viewed as a "worst case" scenario. Figure 4 presents scatterplots of forecast FM1 versus Mesonet FM1 from the 90% filter data sets for April (a) and May (b). Both months have most data points near the x=y line in the FM1 < 30% range (which is good, considering most fuel types have moisture of extinctions 30% or less). However, the wet month of April also has a sizeable number of forecast misses, even with the 90% filter, resulting in some large overpredictions (data points well above the x=y line) and some large underpredictions (data points well below the x=y line).

b. <u>10-hour dead fuel moisture</u>

The 10-hour Nelson model, like the 1-hour, is fairly responsive to rainfall, although 10-hour dead fuel moisture (FM10) is limited to 60%. Again, difficulties in forecasting rainfall (as well as the use of 15-minute versus 1-hour rainfall) can lead to large deviations in DFM. However, it will be seen that with each increase in fuel size, the effects of rainfall decrease and statistics improve.

Proceeding to the analysis of FM10 over the forecast period, we first look at the r2 values. Figure 5 presents the r2 values over the forecast period for both the April and May total sample and 90% filter data sets.

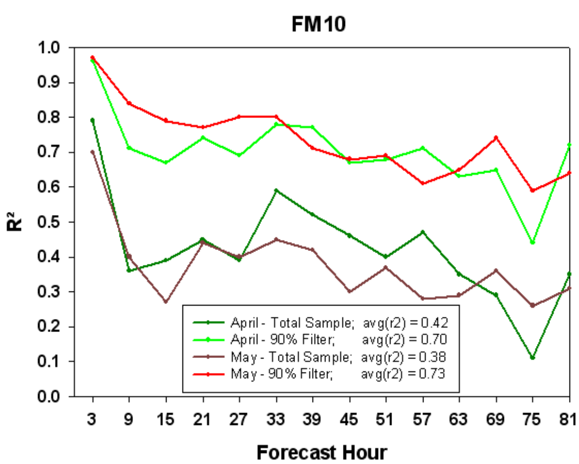

Figure 5. *R2 values for 10-hour dead fuel moisture over the 84-hour forecast period.*

The total sample plots for both April and May show poor correlation between the Eta and Mesonet FM10 values, with most r2 values lying below 0.5 for the period and showing a decline in skill with increasing time. However, with the 90% filter, the statistics improve greatly, with most values lying above 0.7 during the period; the decline in skill with increasing forecast hour continues.

Figure 6 presents the standard deviation of the difference between the forecast FM10 values and the Mesonet-based FM10 values for these four data sets.

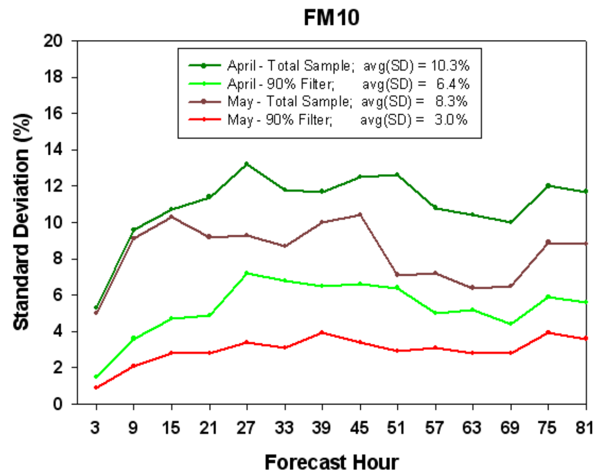

Figure 6. *Standard deviation (%) of the difference between forecast and Mesonet 10-hour dead fuel moisture over the 84-hour forecast period.*

As with FM1, the standard deviation (SD) of forecast error is greater in April for both data sets than it is in May. This, again, can be attributed to the greater frequency of rain in April. The plots also show that, aside from a rise in error during the first 27 hours, the forecast error is more or less constant through the rest of the forecast period. Again, the 90% filter improves the statistics, with an average April SD of 6.4% and an average May SD of 3.0%. These results imply that during 90% of the time, the forecast FM10 values were generally within 6.4% of the Mesonet ("true") values in April and within 3.0% of the Mesonet values in May.

Table 4 presents the FM10 descriptive statistics for April and May averaged over the 84-hour forecast period. With the application of the 90% filter, April r2 values improve from 0.42 to 0.7, and May r2 values, from 0.38 to 0.73 . Standard deviations of the forecast error fall from 11% to 5.3%, and May values, from 8.3% to 3%. The median values of forecast error are, like the FM1 case, negative and, for a given month, of similar magnitude. A median forecast underprediction of FM10 (from the Mesonet "true" value) of around 1% for April and 2.3% for May is indicated.

Similar to the FM1 discussion, we conclude our FM10 analysis with reference to some scatterplots at the 81-hour forecast time. Figure 7 presents scatterplots of forecast FM10 versus Mesonet FM10 from the 90% filter data sets for April (a) and May (b). Most of the points lie near the x=y line in the FM10 < 30% range. April, however, shows a greater frequency of larger deviations of forecast FM10 from Mesonet FM10 due to the greater frequency of rain in that month.

Table 4. Descriptive statistics for 10-hour dead fuel moisture averaged over the 84-hour forecast period.

FM10 (%)		Apr-04	May-04
Total Sample	N	260	259
	r2	0.42	0.38
90% Filter	r2	0.7	0.73
Difference (%) [Forecast - Mesonet]			
Total Sample			
	Median	-1.1	-2.3
	Mean	1.6	-1.1
	Std. Deviation	11	8.3
	Skewness	1.7	2.7
	Maximum	50.8	53.2
	Minimum	-43.9	-44
90% Filter			
	Median	-1.2	-2.3
	Mean	-0.7	-2.4
	Std. Deviation	5.3	3
	Skewness	1.1	0.8
	Maximum	26.3	13.6
	Minimum	-24.6	-14.1

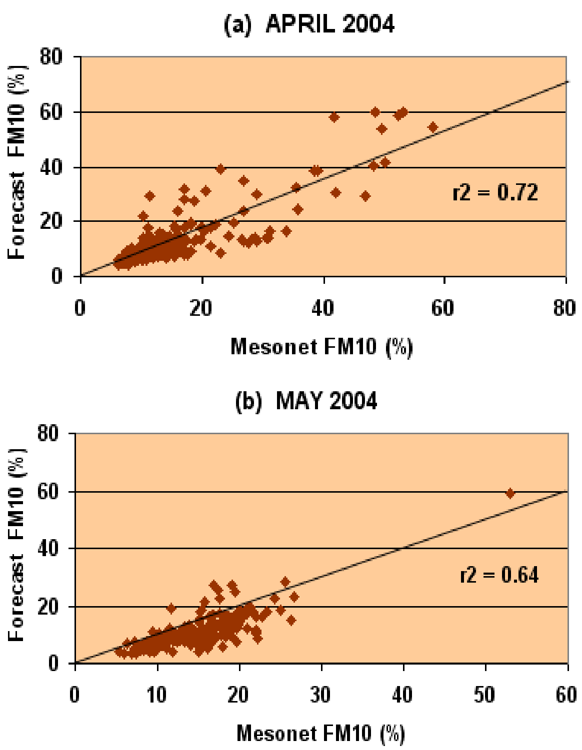

Figure 7. *Scatterplots of forecast versus Mesonet-based 10-hour dead fuel moisture at 81 hours from the 90% filter data sets for (a) April 2004 and (b) May 2004. The solid line represents the x=y line for reference.*

c. <u>100-hour dead fuel moisture</u>

Statistics continue to improve with 100-hour dead fuel moisture (FM100). Figure 8 presents the r2 values over the forecast period for FM100.

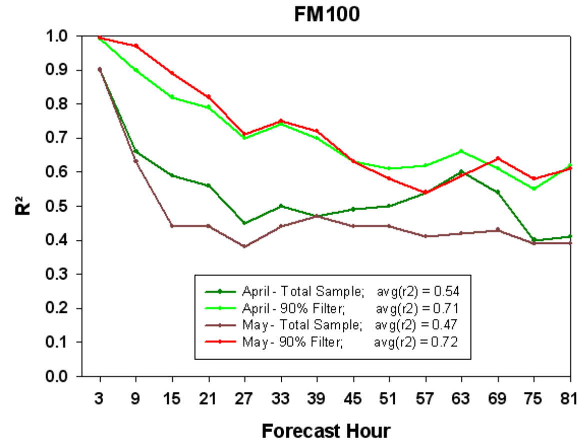

Figure 8. *R2 values for 100-hour dead fuel moisture over the 84-hour forecast period.*

Considerable improvement for both months still exists upon applying the 90% filter. With this filter, the r2 plots for both months are nearly identical, with an average r2 over the forecast period of 0.71-0.72. A decline in skill is seen over time, with r2 values near 1.0 initially and falling to near 0.6 at the end of the period.

Figure 9 presents the standard deviation of the FM100 "forecast error" over the 84-hour period. While not as pronounced as with smaller fuels, the standard deviation (SD) of forecast error is still slightly greater in April for both data sets than it is in May. SD values continue to decrease in magnitude, being smaller than those associated with FM10 and FM1. Similar to the case with FM10, after an initial rise in SD during the first 27 hours or so, the forecast error is more or less constant through the rest of the period.

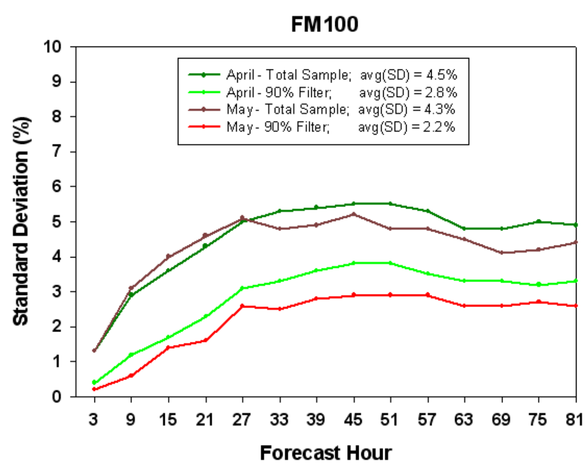

Figure 9. *Standard deviation (%) of the difference between forecast and Mesonet 100-hour dead fuel moisture over the 84-hour forecast period.*

Table 5. Descriptive statistics for 100-hour dead fuel moisture averaged over the 84-hour forecast period.

FM100 (%)		Apr-04	May-04
Total Sample	N	260	259
	r2	0.54	0.47
90% Filter	r2	0.71	0.72
Difference (%) [Forecast - Mesonet]			
Total Sample			
	Median	-0.1	-0.7
	Mean	1.8	0.6
	Std. Deviation	4.5	4.3
	Skewness	1.6	2.2
	Maximum	25.4	22.1
	Minimum	-14.3	-12.2
90% Filter			
	Median	-0.3	-0.8
	Mean	0.7	-0.3
	Std. Deviation	2.8	2.2
	Skewness	1	1.4
	Maximum	11.5	10
	Minimum	-9.8	-9.6

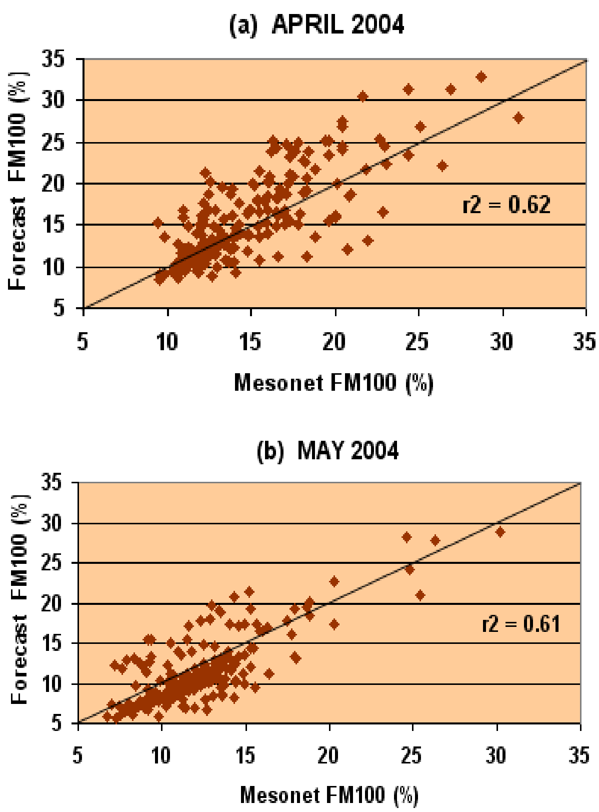

Figure 10. *Scatterplots of forecast versus Mesonet-based 100-hour dead fuel moisture at 81 hours from the 90% filter data sets for (a) April 2004 and (b) May 2004. The solid line represents the x=y line for reference.*

Table 5 presents the FM100 descriptive statistics for April and May averaged over the 84-hour forecast period. With the application of the 90% filter, April r2 values improve from 0.54 to 0.71, and May r2 values, from 0.47 to 0.72. Standard deviations of the forecast error fall from 4.5% to 2.8% for April, and from 4.3% to 2.2% for May. Median forecast errors are only slightly negative, with an median underprediction of less than 1%.

We conclude our discussion of FM100 with reference to the 81-hour scatterplots (Figure 10). Most of the points lie near the x=y line in the FM100 <25% range. As with the other fuel sizes, however, April shows a greater frequency of larger deviations due to the more frequent rainfall that month.

d. 1000-hour dead fuel moisture

In terms of forecast to Mesonet-based Nelson model comparison, the best statistics occur with the 1000-hour Nelson model.

Figure 11 presents the r2 plots for both months over the forecast period. For FM1000, the two months have nearly identical traces for both the total sample and the 90% filter sets. With the 90% filter, r2 values decrease with time from near 1.0 at the start of the period to near 0.75 at the end. The average value over forecast period for both months is above 0.8, by far the best of any size fuel.

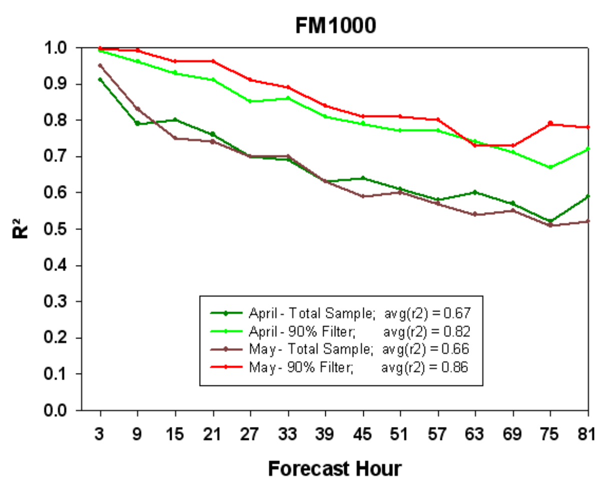

Figure 11. *R2 values for 1000-hour dead fuel moisture over the 84-hour forecast period.*

Figure 12 presents the standard deviation (SD) in forecast error for FM1000. As with FM100, SD values are still slightly greater for both data sets in April than in May. SD values are smaller than for FM100, continuing the trend for larger size fuels. However, in contrast to the SD behavior of FM1, FM10, and FM100 over time, the standard deviations show a gradual quasi-linear increase with time.

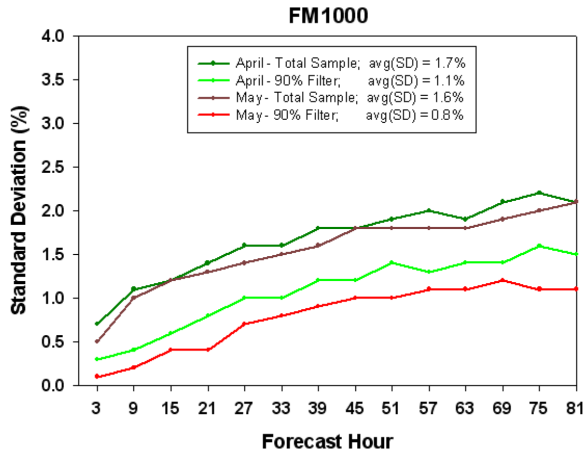

Figure 12. *Standard deviation (%) of the difference between forecast and Mesonet 1000-hour dead fuel moisture over the 84-hour forecast period.*

Table 6 presents the FM1000 descriptive statistics for April and May averaged over the 84-hour forecast period. With the application of the 90% filter, r2 values improve from 0.67 to 0.82 in April, and from 0.66 to 0.86 in May. Standard deviations of the forecast error fall slightly from 1.7% to 1.1% in April, and from 1.5% to 0.8% in May. The median values of forecast error are essentially zero.

Finally, Figure 13 presents the 81-hour scatterplots. Most of the points lie near the x=y line in the FM1000 < 15-20% range. While not as noticeable as with the smaller size fuels, April still shows a greater frequency of larger deviations than May.

Table 6. Descriptive statistics for 1000-hour dead fuel moisture averaged over the 84-hour forecast period.

FM1000 (%)		Apr-04	May-04
Total Sample	N	260	259
	r2	0.67	0.66
90% Filter	r2	0.82	0.86
Difference (%) [Forecast - Mesonet]			
Total Sample			
	Median	0.1	-0.1
	Mean	0.8	0.5
	Std. Deviation	1.7	1.5
	Skewness	1.6	2.2
	Maximum	11.5	8.8
	Minimum	-4.3	-3.7
90% Filter			
	Median	0	-0.1
	Mean	0.4	0.1
	Std. Deviation	1.1	0.8
	Skewness	0.8	1
	Maximum	4.5	3.7
	Minimum	-4	-3.4

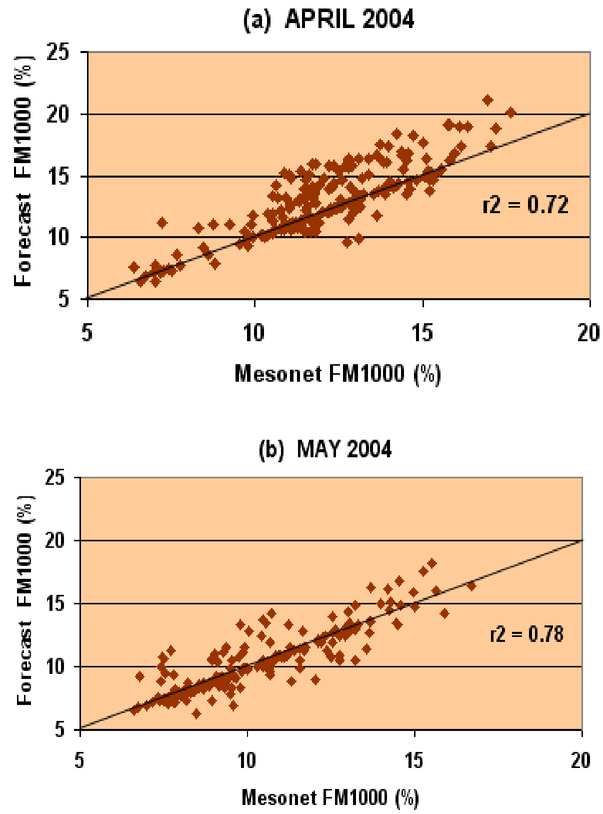

Figure 13. *Scatterplots of forecast versus Mesonet-based 1000-hour dead fuel moisture at 81 hours from the 90% filter data sets for (a) April 2004 and (b) May 2004. The solid line represents the x=y line for reference.*

e. Comparisons between dead fuel classes

Table 7 presents a comparison of the Nelson model performance over the 84-hour forecast period for the four different fuel size classes. Averages over the forecast period are shown. The results presented in this table are from the 90% filter data sets. Again, the comparison is of the forecast-based dead fuel moisture (DFM) against the Mesonet-based DFM, which for this analysis is considered "ground truth" due to lack of DFM field observations.

The effect of the wetter month of April 2004 is clearly seen in these results, with lower r2 values and higher standard deviations (SD) for each size fuel class when compared to the May counterparts. The differences are most pronounced for 1-hour fuels, which is the fuel most sensitive to rainfall and thus most sensitive to forecast rainfall misses on the spatial and temporal scales. For FM1, r2 values improve from 0.54 (April) to 0.70 (May); SD values decrease (improve) from 14.6% (April) to 4.3% (May). For FM10 through FM1000, the differences between April and May are minimal and of the same order of magnitude.

The other obvious trend, true for either month, is an improvement in Nelson model performance over the forecast period as one considers larger size fuels. For April the r2 values improve from 0.54 (FM1) to 0.82 (FM1000); SD values decrease (improve) from 14.6% (FM1) to 1.1% (FM1000). In May the r2 values improve from 0.70 (FM1) to 0.86 (FM1000); SD values decrease from 4.3% to 0.8%.

Looking at the median values, a tendency toward underprediction of the "true" Mesonet DFM value can be seen. The median decreases in magnitude in each month as one considers larger size fuels. In April the median "forecast error" drops from -1.4% (FM1) to 0.0% (FM1000); in May, the median drops from -2.5% (FM1) to -0.1 (%). The higher (more negative) medians in May for each size fuel can, in part, be attributed to forecast relative humidity errors. May tends to be a humid month in Oklahoma (even with the lack of rain in 2004) and forecast underpredictions of relative humidity were noted, leading to lower DFM forecast values.

Table 7. Nelson model performance over the 84-hour forecast period for four different fuel size classes. Average values over the forecast period from the 90% filter data sets are presented.

Forecast vs. Mesonet DFM	Apr-04	May-04
r2		
FM1	0.54	0.70
FM10	0.70	0.73
FM100	0.71	0.72
FM1000	0.82	0.86
Forecast - Mesonet DFM		
Standard Deviation (%)		
FM1	14.6	4.3
FM10	5.3	3.0
FM100	2.8	2.2
FM1000	1.1	0.8
Median (%)		
FM1	-1.4	-2.5
FM10	-1.2	-2.3
FM100	-0.3	-0.8
FM1000	0.0	-0.1

4.3 *Examples of Some Specific 84-Hour Forecasts*

We conclude with two examples of specific Eta 84-hour forecasts to see how the Nelson model behaves over two specific 84-hour periods. The first forecast covers a dry and sunny period at Slapout, OK toward the end of May 2004. The second example, in contrast, covers a rainy period at Tahlequah, OK during April 2004. The plots compare the Eta-forecast solar radiation, rainfall, temperature, and relative humidity with that later measured by the Oklahoma Mesonet. Also the Eta-based Nelson model dead fuel moisture values (FM1, FM10, FM100, and FM1000) are compared with those calculated by the Nelson model using Mesonet data.

a. <u>Dry 84-hour period (Slapout, OK)</u>

The first example is of a dry, sunny, and hot period at Slapout during the end of May 2004. The Eta forecast used was the 84-hour forecast issued at 0Z on May 29.

Figure 14a shows the Eta-forecast (Solar_F) and Mesonet-measured (Solar_M) solar radiation values during the 84-hour forecast period. Date/time is based on Central Standard Time (CST) and hourly data values are plotted. The correspondence between forecast solar radiation and that which actually occurred is particularly close in this example.

Figure 14b shows the Eta forecast (_F) and Mesonet measured (_M) temperature and relative humidity during this period. Temperature correspondence is particularly close; this hot period featured temperatures as high as 36.4C (98F).

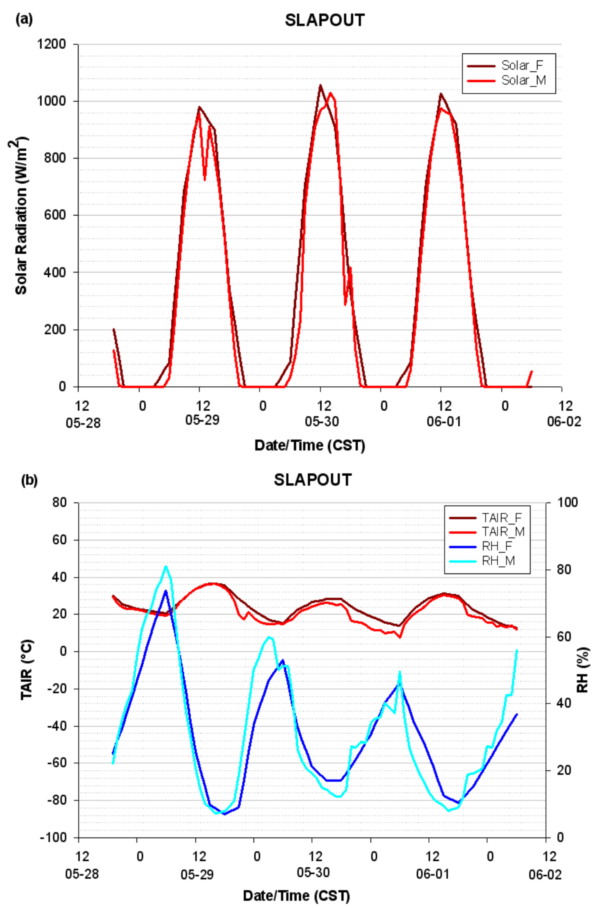

Figure 14. *0Z May 29 2004 Eta 84-hour forecast for Slapout for (a) solar radiation (Solar_F), and (b) air temperature (TAIR_F) and relative humidity (RH_F). The corresponding Mesonet measured values (_M) are also plotted.*

Considering the difficulty of predicting relative humidity (RH), correspondence between the Eta forecast and Mesonet observations is quite good, although the forecast underpredicted the RH maxima during the first two mornings of the period.

Figure 15a shows the 1-hour (FM1) and 10-hour (FM10) dead fuel moisture (DFM) as calculated by the Nelson model using Eta forecast input (_F) and using Mesonet data (_M). The lower levels of relative humidity forecasted during the first two mornings result in an underprediction of FM1 and FM10. Aside from these discrepancies, the forecast and Mesonet-based DFM plots track quite close to each other. Note that the Nelson model captures the diurnal cycle of DFM and that the average values for FM1 and FM10 decrease throughout the 84-hour forecast period, due to the good drying weather.

Figure 15b depicts the 100-hour (FM100) and 1000-hour (FM1000) dead fuel moisture. The correspondence between the forecast and Mesonet-based DFM is excellent, with the largest discrepancies only on the order of 0.25% in the case of FM100. Similar to the case with FM1 and FM10, the diurnal cycle is captured and the average DFM values decrease during the forecast period, although less so for FM1000.

b. <u>Wet 84-hour period (Tahlequah, OK)</u>

This second example is of a mild and very wet period at Tahlequah, OK during mid-April 2004. The Eta forecast used was the 84-hour forecast issued at 0Z on April 21. Mesonet-measured rainfall during this 84-hour period was 160.78 mm (6.33").

Figure 16a shows the Eta-forecast (Solar_F) and Mesonet-measured (Solar_M) solar radiation values during the 84-hour forecast period, as well as the hourly rainfall values (RAIN_M and RAIN_F). Note that there were three major episodes of rainfall, the first two falling during the overnight hours, so that solar radiation

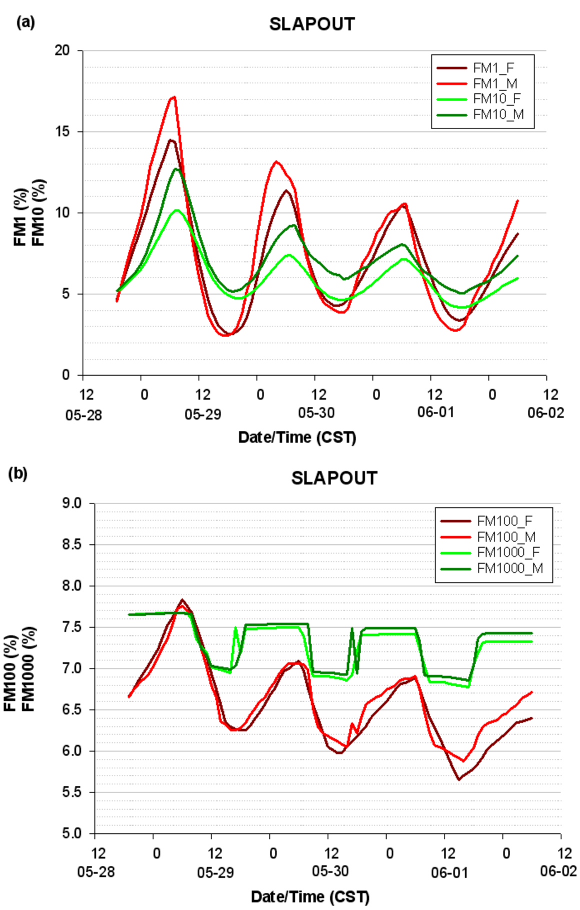

Figure 15. *0Z May 29 2004 Eta 84-hour forecast for Slapout for (a) Eta-based 1-hour DFM (FM1_F) and 10-hour DFM (FM10_F), and (b) Eta-based 100-hour DFM (FM100_F) and 1000-hour DFM (FM1000_F). The corresponding Mesonet-based dead fuel moisture values (_M) are also plotted.*

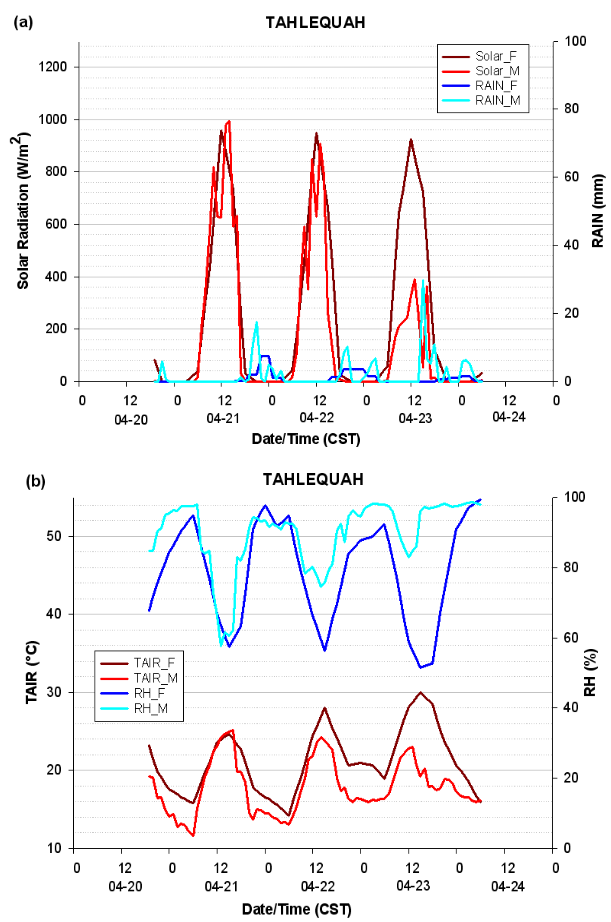

Figure 16. *0Z April 21 2004 Eta 84-hour forecast for Tahlequah for (a) solar radiation (Solar_F) and hourly rainfall (RAIN_F), and (b) air temperature (TAIR_F) and relative humidity (RH_F). The corresponding Mesonet-measured values (_M) are also plotted.*

correspondence was excellent during the first two days. The third rainfall episode was the most intense and occurred during the afternoon of April 23 through the early morning hours of April 24. In the first hour of this episode, 52.58 mm (2.07") of rainfall fell, with 29.72 mm (1.17") of it falling in the first 15 minutes. The Eta forecast missed this large rainfall event and, correspondingly, its solar radiation prediction on April 23 greatly overestimated the levels of solar radiation measured.

Figure 16b shows the Eta-forecast (_F) and Mesonet-measured (_M) air temperature and relative humidity during this period. Temperature differences between forecast and Mesonet are greatest during the third rainfall episode and the hours leading up to it. Due to the lower amounts of forecast cloud cover (see Fig. 16a) and rainfall on April 23, temperatures are

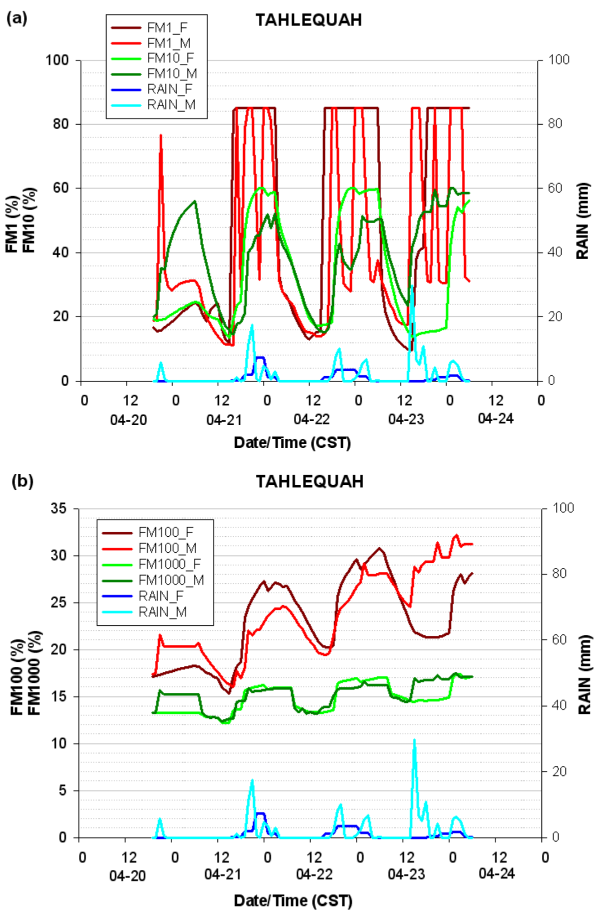

Figure 17. *0Z May 29 2004 Eta 84-hour forecast for Tahlequah for (a) Eta-based 1-hour DFM (FM1_F) and 10-hour DFM (FM10_F), and (b) Eta-based 100-hour DFM (FM100_F) and 1000-hour DFM (FM1000_F). The corresponding Mesonet-based dead fuel moisture values (_M) are also plotted, as are the Mesonet-measured and forecast hourly rainfalls for reference.*

greatly overpredicted. Correspondence of RH is good through sunrise on April 22, but begins to break down after that. Forecast RH values are much lower during the daylight hours of April 22-23. During the day of April 22, the forecast underestimated the influx of moisture associated with the second rain event, and during April 23, the higher solar radiation and temperatures led to an underestimate of RH.

Figure 17a shows the 1-hour (FM1) and 10-hour (FM10) dead fuel moisture (DFM) as calculated by the Nelson model using Eta forecast input (_F) and using Mesonet data (_M). The brief spike of rainfall (not captured by the forecast) at the beginning of the 84-hour period results in abrupt rises in Mesonet-based FM1 and FM10 not reflected in the forecast DFM values. The first and second major rainfall episodes show fairly good correspondence for both FM1 and FM10, although the Mesonet-based DFM values show more fluctuations, especially for FM1, due to the use of 15-minute data. Note that the model maxima of 85% (FM1) and 60% (FM10) are reached a number of times during this 84-hour period. The correspondence is not as good during the last rainfall episode, due to the forecast missing the timing and intensity of this major rain event. Finally, one can detect a general rise in average FM10 values during this wet 84-hour period.

Figure 17b depicts the corresponding 100-hour (FM100) and 1000-hour (FM1000) dead fuel moisture during this period. As with FM1 and FM10, the initial spike in rainfall at the beginning of the period results in abrupt rises (relative to their fuel sizes) in FM100 and FM1000 not captured by the forecast values. The correspondence is fairly good during the first and second major rain episodes, but not good during the last one due to causes already mentioned. Note a general rise in average FM100 and FM100 during this wet 84-hour period.

5. SUMMARY

In this study the Nelson model for dead fuel moisture was evaluated in an 84-hour forecast environment using the NCEP Eta model. All four dead fuel classes (1-, 10-, 100-, and 1000-hour) were included in the study, which for the present analysis included a wet month (April 2004) and a dry month (May 2004). Since we had no dead fuel moisture (DFM) field measurements to serve as “ground truth” during 2004, the comparison of forecast Nelson model DFM results in this study was to DFM values generated by the Nelson model using observed weather data from the Oklahoma Mesonet, Oklahoma’s automated weather station network.

As seen in Section 4.1, a wide range of weather conditions were encountered by the Nelson model during April and May 2004. Over the two-month period, temperatures ranged from -6.9 to 39.2C and monthly rainfalls, from only 1.3 mm to as much as 202.4 mm. Eleven Mesonet sites (Figure 1) were studied in the analysis, but only the combined results from all sites are reported in this paper.

For a given forecast verification time, the analysis utilized two data sets: (1) the original data set ("Total Sample") of all paired data points (forecast DFM, Mesonet DFM) and (2) a data set where a 90% filter had been applied ("90% Filter"). The latter data set removed that 10% of the data from the original data set having the largest discrepancies between forecast and Mesonet DFM. It was seen that application of this 90% filter greatly improved the statistics, which are summarized below, especially for smaller size fuels and during the wet month of April when rainfall forecast errors (in timing, location, and amount) often led to large discrepancies between forecast and Mesonet DFM.

As was mentioned earlier, in some sense the results of this study constitute a referendum on the accuracy of the Eta model during these two months (perfect forecasts would give perfect comparisons). However, any forecast is going to have inaccuracies and our results have demonstrated that the Nelson model is reliable over a forecast period of up to 3-4 days despite less than perfect forecasts.

In our analysis it was seen that, over the 84-hour forecast period, the Nelson model performs more accurately as fuel size increases and also as rainfall frequency and amounts decrease (statistics were better for May than April). This is due to the sensitivity of dead fuels, especially 1- and 10-hour fuels, to rainfall and relative humidity; errors in forecasting these variables decrease model performance.

Table 7 presents a good summary of the results from the 90% filter data sets. For a given size fuel, improvements in average r2 values are noted from April (wet month) to May (dry month), although the improvements are minimal for the larger size fuels. What is notable is that, with the exception of 1-hour dead fuel moisture for April, the average r2 values over the 84-hour period for all size fuels and months are 0.70 or better. R2 values generally improve with increasing fuel size, with 1-hour fuels having the lowest r2 values and 1000-hour fuels, the highest. Over the 84 hours, all size fuels (Figures 2, 5, 8, 11) show a general decrease in r2 with time for the 90% filter data sets. Over the two months, r2 values near the end of the forecast period fall to 0.6-0.7 in the case of 1-, 10-, and 100-hour fuels, and to 0.7-0.8 for 1000-hour fuels.

The average standard deviation (SD) in "forecast error" for the 90% filter data sets also improves from April to May, and decreases within a given month as fuel size increases (Table 7). Over the two-month period, the average SD in dead fuel moisture (DFM) for 1-hour fuels (FM1) lies between 4 and 14% ; for 10-hour fuels (FM10), the average SD value lies in the 3-6% range; for 100-hour fuels (FM100), it lies in the 2-3% range; and for 1000-hour fuels (FM1000), the average SD is near 1%. Over the 84 hours, SD values are more or less constant with time for 1-hour fuels (Figure 3). For 10- and 100-hour fuels (Figures 6, 9), after an initial rise through the first 27 hours or so, SD values level off and are quasi-constant through the remainder of the forecast period. For 1000-hour fuels (Figure 12), SD values show a quasi-linear increase with time. Near the end of the forecast period, SD values (considering both months) are in the 4-16% range for FM1, in the 3-6% range for FM10, in the 2-4% range for FM100, and in the 1-2% range for FM1000. These values represent the average "forecast errors" in dead fuel moisture that one can expect 90% of the time near the end of a 3.5 day forecast period.

Despite the inaccuracies of mid-range forecasts, our evaluation has shown that 90% of the time, over an 84-hour forecast period, the Nelson model performs well in comparison to the Mesonet-generated values of dead fuel moisture. The Nelson model can thus be expected to provide useful dead fuel moisture guidance to wildland fire managers over the mid-range forecast time frame.

By the end of 2005, the Nelson model is scheduled to replace the dead fuel moisture algorithms in the Oklahoma Fire Danger Model (Carlson *et al.*, 2003; Carlson *et al.*, 2002), Oklahoma's operational fire danger model based on the National Fire Danger Rating System. In addition, a mid-range forecast component will be added to the fire danger model through incorporation of 84-hour output from the Eta model.

6. ACKNOWLEDGEMENTS

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