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Meteorological Modeling of 2002 using Penn State/NCAR 5th Generation Mesoscale Model (MM5)

Bureau of Air Quality Analysis and Research

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January 10, 2008

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Version 3.6 of MM5 was used to generate annual 2002 meteorology for the Mid-Atlantic Northeast Visibility Union (MANE-VU) through the Modeling Committee of Ozone Transport Commission (OTC). Prof. Dalin Zhang of the University of Maryland (UMD) performed the MM5 simulations in consultation with NYSDEC staffs. The model was applied in Lambert conformal map projection and utilized MPP Version developed for clusters. The two-way nested domain consisted of a coarse (36km) and fine (12km) mesh corresponding to 149x129 and 175x175 grids, respectively, in this application (see Figure 1).

The Lambert projection used in this work followed the Regional Planning Organization (RPO) national domain setup with the center at (40°N, 97°W) and parallels at 33°N and 45°N. Map projection parameters in reference to the projection center point are as follows: Southwest corner for the 36 km grid is at (-2664km, -2304km) and the northeast corner at (2664km, 2304km). In the case of the 12km grid, the southwest corner is at (252km, -900km) and the northeast corner at (2340km, 1188km). In the vertical direction, the terrain following σ-coordinate system was used with the pressure at each σ-level determined from a reference state that is estimated using the hydrostatic equation from a given sea-level pressure and temperature with a standard lapse rate. There are 30 unevenly spaced σ levels, giving 29 vertical layers, with higher resolution within the planetary boundary layer (PBL). The σ levels are:

1.0000, 0.9974, 0.9940, 0.8980, 0.9820, 0.9720, 0.9590, 0.9430, 0.9230, 0.8990, 0.8710, 0.8390, 0.8030, 0.7630, 0.7180, 0.6680, 0.6180, 0.5680, 0.5180, 0.4680, 0.3680, 0.3180, 0.2680, 0.2180, 0.1680, 0.1230, 0.0800, 0.0400, 0.0000

The surface layer was set at about 10m, the level at which surface winds were typically observed, and the model top was set at 50hPa with a radiative top boundary condition. The time steps for the 36km and 12km domains were 75 and 25 seconds, respectively.

The important model physics options used for this MM5 simulation include:

- Kain-Fritsch (1993) convective scheme for both 36- and 12-km domains
- Explicit moisture scheme (without the mixed phase) containing prognostic equations for cloud water (ice) and rainwater (snow) (Dudhia 1989; Zhang 1989)
- Modified version of the Blackadar planetary boundary layer (PBL) scheme (Zhang and Anthes 1982; Zhang and Zheng 2004)
- Simple radiative cooling scheme (Grell et al. 1994)
- Multi-layer soil model to predict land surface temperatures using the surface energy budget equation (Dudhia 1996)

Note that the Blackadar PBL scheme has been modified in order to correct the phase shift of surface wind speed and temperature diurnal cycle, following a study that compared five different PBL schemes: the Gayno-Seaman TKE scheme (Shafran et al. 2000), Burk-

Thompson (1989), Blackadar (Zhang and Anthes 1982), MRF (Hong and Pan 1996), and Mellor-Yamada-Jajic (Mellor and Yamada 1974; Jajic 1990, 1994). The details of the study can be found at Zhang and Zheng (2004).

Nudging Processes

The MM5 provides options for nudging observations for each domain during the model integration process (Stauffer and Seaman, 1990; Stauffer et al. 1991). The Eta analyses of upper-air winds, temperature and water-vapor mixing ratio as well as their associated surface fields were used for nudging every 6 hours, and the Eta surface wind fields blended with surface wind observations were used to nudge every 3 hours. While only the surface winds were nudged, their influences could extend into the PBL as well (see Stauffer et al. 1991). Based on UMD's prior experience in numerical experiments, the following nudging coefficients have been used:

- Upper-air wind fields: 5. 0E-4s^{-1} for Domain 1 (36km), and 2. 5E-4s^{-1} for Domain 2 (12km);
- Upper-air temperature fields: 1.0E-5s^{-1} for both Domains;
- Surface winds: 5. 0s^{-1}E-4s^{-1} for Domain 1, and 2.5E-4s^{-1} for Domain 2; and
- Surface temperature and moisture: not nudged due to instability consideration.

ASSESSMENT

National Weather Service (NWS) and CASTNet data – Surface temperature, Wind Speed, and Humidity

NWS (TDL) and CASTNet (www.epa.gov/castnet/) surface measurements of temperature, wind speed, and humidity (note there were no humidity measurements for CASTNet) were used to compare with the MM5 outputs. The evaluation was performed with METSTAT program developed by Environ Corporation (www.camx.com/files/metstat.15feb05.tar.gz) When comparing to NWS data, the METSTAT interpolates the first layer MM5 (at 10m height) temperature and humidity data to a height of 2m, the level that corresponds to the NWS measurement of these parameters, but no interpolation was made for wind speed and direction. In the case of CASTNet surface measurements, no interpolations were made as CASTNet data were reported at 10m height. In this analysis, no exclusion was made for calm conditions. The reported calm winds (zero wind speed measured) were treated *as is* in this evaluation effort. The METSTAT calculated standard statistical measures – average, bias, error and index of agreement between the measured and predicted parameters. Table 1 summarizes the MM5 average bias for each month for wind speed, wind direction, temperature, and humidity by comparing data from NWS and CASTNet networks. The humidity data is only available for NWS network. In general, there is no systematic bias between winter and summer seasons for MM5 in terms of wind speed, wind direction and temperature. However, MM5 showed dry bias in the summer and wet bias in the winter when compared with humidity data from NWS.

Figure 2a and 2b display the time series comparison of wind speed between MM5 and measured data from NWS and CASTNet networks for winter months (January, February and December) and summer months (June, July and August), respectively. MM5 underpredicted NWS and overpredicted CASTNet daytime peak wind speed, while MM5 appears to track quite well the nighttime wind speed minimum for CASTNet and overpredicted nighttime wind speed minimum for the NWS data. MM5 performed quite well in capturing magnitude and diurnal timing for temperature from both NWS and CASTNet data (Figures 3a and 3b). It should be pointed out that there are differences in how the meteorological information is collected and reported by the two networks and as computed in MM5. The CASTNet measurements are based on hourly averaged wind speed while NWS reports 2min average at 10min before the hour, whereas MM5 predictions are reflective of the last time-step of the hour of computation. In the case of humidity (Figure 4), MM5 tracked the NWS observed humidity trend well, but exhibits dry bias for summer season and wet bias for winter season and misses the observed semi-diurnal cycles. Comparisons for the whole year of 2002 including bias and root mean square error from both NWS and CASTNet are available on request from NYSDEC.

The above assessment is based on domain-wide averages to provide an overall response of the model. Another way of assessing the model is to examine the spatial distribution of correlation between the measured and predicted parameters at each monitor. Figures 5a and 5b display such a comparison for wind speed and temperature over winter months and summer months, respectively. For the wind speed (Figure 5a), the correlation is in the range of 0.8 to 0.9 for winter months and 0.7 to 0.8 for summer months. For the temperature (Figure 5b), the correlation is above 0.95 for summer months, slightly higher than winter months. The correlation for humidity (Figure 5c) is in the range of 0.8 to 0.9 for both winter and summer months. These correlations indicate that MM5 simulation has captured both the diurnal and synoptic scale variations. Detailed plots of this comparison are available on request from NYSDEC.

Vertical Profiler – Winds

The Wind-Profiler network measurements along the U. S. East Coast (www.madis-fsl.org/cap) were used to evaluate the vertical profiles from MM5. There are twelve wind-profiler measurement stations from which data were available for comparison. For convenience of comparison, the wind-profiler measurements were interpolated to the MM5 vertical levels. The approach used was simple interpolation between two adjacent wind-profiler layers to the MM5 vertical level, and was limited to that reported by the profiler measurement. The focus of the comparison was to assess if MM5 was able to capture the measured vertical structure, and for this we used the observed Low Level Jet (LLJ) as an indicator. The comparison was performed for June, July and August 2002. In general it is found that MM5 captures the profiler measured vertical wind field structure reasonably well. Figure 6 displays an example of the MM5 and wind profiler comparison for the August 2002 episode at Richmond, VA and Concord, NH. MM5 predicted weaker LLJ winds compared to those based on the wind-profiler measurements. The detailed plots of this comparison are available on request from NYSDEC.

Cloud Cover – Satellite cloud image

Cloud information derived from satellite image data (www.atmos.umd.edu/~srb/gcip/webgcip.htm) were used to assess the MM5 prediction of cloud cover. The 0.5^o by 0.5^o resolution of the satellite data were interpolated into the 12km MM5 grid for comparison. The MM5 total cloud fraction was estimated by MCIP based on the MM5's low cloud, middle cloud and high cloud predictions. In general, MM5 seems to capture the satellite cloud pattern well but underestimates the satellite cloud fraction (see Figure 7a and 7b as examples), which may in part be due to the coarse resolution of the satellite cloud data.

Precipitation comparison

The monthly total observed precipitation data were constructed from 1/8-degree daily precipitation analysis data (http://data.eol.ucar.edu/codiac/dss/id=21.093) produced by Climate Prediction Center, based on 7,000-8,000 hourly/6-hourly gauge reports and radar). The MM5 monthly total precipitation was estimated from the MM5 predicted convective and non-convective rainfall and summed up for each month. In general, MM5 captured the observed spatial patterns (see examples of Figures 8a and 8b). For winter months, MM5 performed well for February (Figure 8a) but underpredicted for November. For the summer months, MM5 performed well for May and September, but no so well for June, July and August (See Figure 8b), that may reflect the summertime convective rain activities are not captured by MM5.

Calm Conditions

Calm conditions are defined as observed wind speed of zero knots and wind direction as 0^o. It would be useful to assess how MM5 performs under observed calm conditions, because of potential pollutant buildup that could occur under such conditions. Table 2a and 2b list the summary of the percentage of calm condition at each hour for the February and August 2002, respectively from the NWS data within the 12km domain. It is apparent from the Table that the calm conditions occur primarily during the night and early morning hours, from 23Z (7 p.m. EDT) to 15Z (11 a.m. EDT) with a peak at around 10Z (6 a.m. EDT). August had much higher percentage of calm condition than February. To assess MM5 performance, the observed and MM5 predicted wind speeds were divided into calm and non-calm according to observed wind speed. In general MM5 underpredicted the observed non-calm conditions for both February and August (Table 2a and 2b). Figure 9 displays such a comparison of the MM5 predicted wind speed to the observed wind speed under the calm and non-calm conditions for the month of August 2002. For the "calm" group, the average wind speed for MM5 varies from 1 m/s during the night and early morning hours and over 1.5 m/s during the day. MM5 is over-predicting during observed calm wind conditions. There are local minima every 3 hours, due to the surface observed wind speed nudging in MM5. In contrast under the non-calm conditions, MM5 underpredicts by about 0.5 m/s for all hours with noticeable local maximum happening at the nudging hours. The MM5 nudging process would pull predictions toward the measured data, while the underprediction of MM5 for the non-calm conditions may due to the adopted PBL scheme in this simulation.

Summary

In this study, we performed an assessment of the MM5 simulation to measured data, both with the surface measurement networks as well as with information from the vertical wind profilers and satellite cloud images. While there are no specific recommended procedures identified for this assessment, similar approaches have been used elsewhere (Dolwick 2005, Baker 2004, and Johnson 2004). Traditionally, the NWS surface measurements are used for such a comparison. Since NWS data had been used through nudging processes in developing the MM5 simulation, the comparisons should not be far removed from each other. In this study, we extended the evaluation by using CASTNet measurements that were not used in the nudging of MM5 simulation. Thus comparison with CASTNet data provides for an independent assessment and should complement the comparison with NWS data. We also compared the MM5 results with the wind profiler data and cloud data derived from satellite images to diagnose if the MM5 simulation is yielding the right dynamics in the vertical. The analyses shows that in general, the performance of the MM5 is reasonable both at the surface and in the vertical, thereby providing confidence in the use of these data in the CMAQ simulations.

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Table 1: Average bias of wind speed, wind direction, temperature, and humidity of MM5 in comparing with observed data from TDL and CASTNet networks for each *month* in 2002

Month	Wind Speed (TDL / CASTNet)	Wind Direction (TDL / CASTNet)	Temperature (TDL / CASTNet)	Humidity TDL
January	-0.53 / 0.34	3.12 / 2.54	-1.18 / -1.25	0.45
February	-0.56 / 0.31	3.31 / 0.88	-1.00 / -0.65	0.48
March	-0.59 / 0.31	3.48 / 1.93	-0.72 / -0.35	0.52
April	-0.55 / 0.38	3.61 / 2.49	-0.48 / -0.52	0.52
May	-0.52 / 0.44	3.53 / 2.33	-0.18 / 0.67	-0.02
June	-0.56 / 0.28	3.89 / 3.33	-0.12 / 1.03	-0.33
July	-0.58 / 0.31	3.62 / 1.44	-0.34 / 0.34	-0.55
August	-0.61 / 0.24	2.74 / 2.34	-0.42 / 0.32	-0.23
September	-0.54 / 0.30	3.31 / 3.01	-0.54 / 0.76	0.03
October	-0.56 / 0.32	2.81 / 1.39	-0.79 / -0.56	0.15
November	-0.57 / 0.37	2.28 / 2.35	-1.35 / -1.25	0.34
December	-0.59 / 0.39	3.41 / 2.69	-1.20 / -1.17	0.34

Table 2a: Measured calm and non-calm occurrences over the modeling domain during *February* 2002 based on NWS data

Hour (UTC)	Obs Not Calm	Obs Calm	Obs Total	Percent Calm (%)	TDL Avg WinSpd Not Calm	MM5 Avg WinSpd Not Calm
0	17266	2711	19977	13.6	4.28	3.84
1	17270	3324	20594	16.1	4.30	3.82
2	17051	3421	20472	16.7	4.30	3.75
3	16878	3499	20377	17.2	4.32	3.79
4	16401	3513	19914	17.6	4.33	3.78
5	16127	3532	19659	18.0	4.28	3.75
6	15914	3645	19559	18.6	4.26	3.81
7	15841	3703	19544	18.9	4.23	3.75
8	15784	3783	19567	19.3	4.20	3.71
9	15752	3857	19609	19.7	4.19	3.73
10	15630	3932	19562	20.1	4.18	3.70
11	15911	4020	19931	**20.2**	4.16	3.72
12	16451	4104	20555	20.0	4.21	3.82
13	16844	3891	20735	18.8	4.28	3.86
14	17779	2945	20724	14.2	4.62	4.00
15	18741	1822	20563	8.9	4.98	4.37
16	18740	1337	20077	6.7	5.21	4.66
17	19079	1106	20185	5.5	5.38	4.83
18	19158	954	20112	4.7	5.46	4.93
19	19380	880	20260	4.3	5.49	4.91
20	19545	883	20428	4.3	5.47	4.75
21	19648	859	20507	4.2	5.33	4.46
22	19576	1027	20603	5.0	5.03	4.02
23	18941	1772	20713	8.6	4.57	3.79

Table 2b: Measured calm and non-calm occurrences over the modeling domain during *August* 2002 based on NWS data

Hour (UTC)	Obs Not Calm	Obs Calm	Obs Total	Percent Calm (%)	TDL Avg WinSpd Not Calm	MM5 Avg WinSpd Not Calm
0	18209	3924	22133	17.7	3.14	2.56
1	16531	6026	22557	26.7	2.85	2.45
2	15604	6929	22533	30.8	2.79	2.33
3	14983	7245	22228	32.6	2.81	2.33
4	14309	7540	21849	34.5	2.80	2.28
5	14073	7735	21808	35.5	2.79	2.24
6	13934	7949	21883	36.3	2.78	2.29
7	13792	8040	21832	36.8	2.76	2.23
8	13542	8273	21815	37.9	2.75	2.22
9	13542	8385	21927	38.2	2.74	2.28
10	13708	8591	22299	**38.5**	2.72	2.25
11	14139	8693	22832	38.1	2.74	2.25
12	15297	7690	22987	33.5	2.89	2.33
13	17336	5192	22528	23.0	3.14	2.41
14	18522	3439	21961	15.7	3.39	2.63
15	18755	2617	21372	12.2	3.60	2.98
16	19169	2015	21184	9.5	3.79	3.15
17	19555	1617	21172	7.6	3.97	3.22
18	19982	1430	21412	6.7	4.08	3.38
19	20149	1389	21538	6.4	4.16	3.43
20	20565	1288	21853	5.9	4.14	3.41
21	20518	1383	21901	6.3	4.06	3.41
22	20672	1556	22228	7.0	3.88	3.12
23	20231	2292	22523	10.2	3.56	2.74

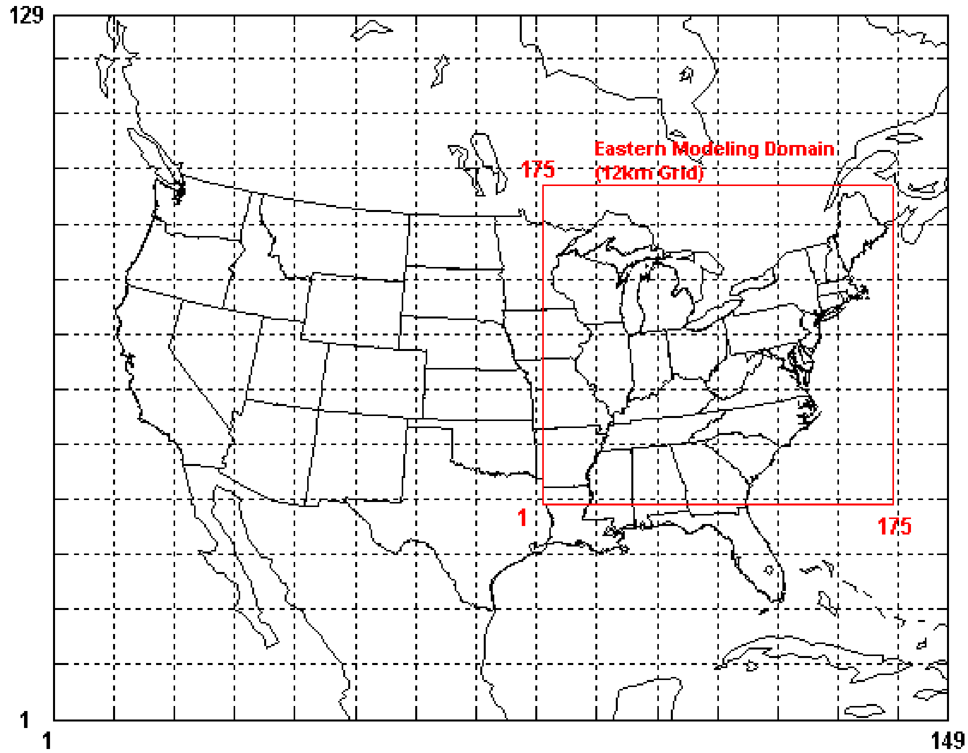


Figure 1: OTC MM5 modeling domain with areal extent of 12km and 36km grids

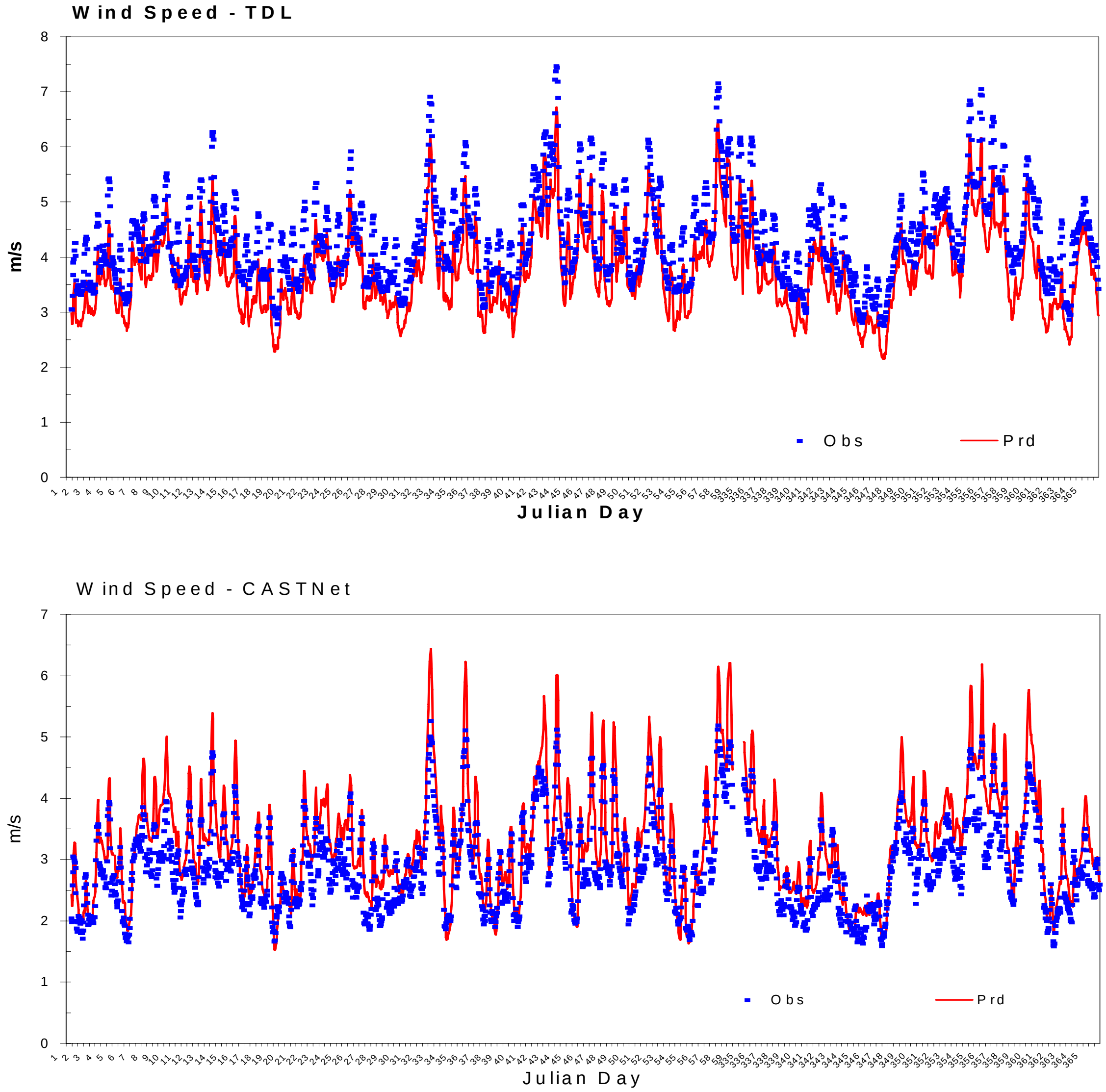
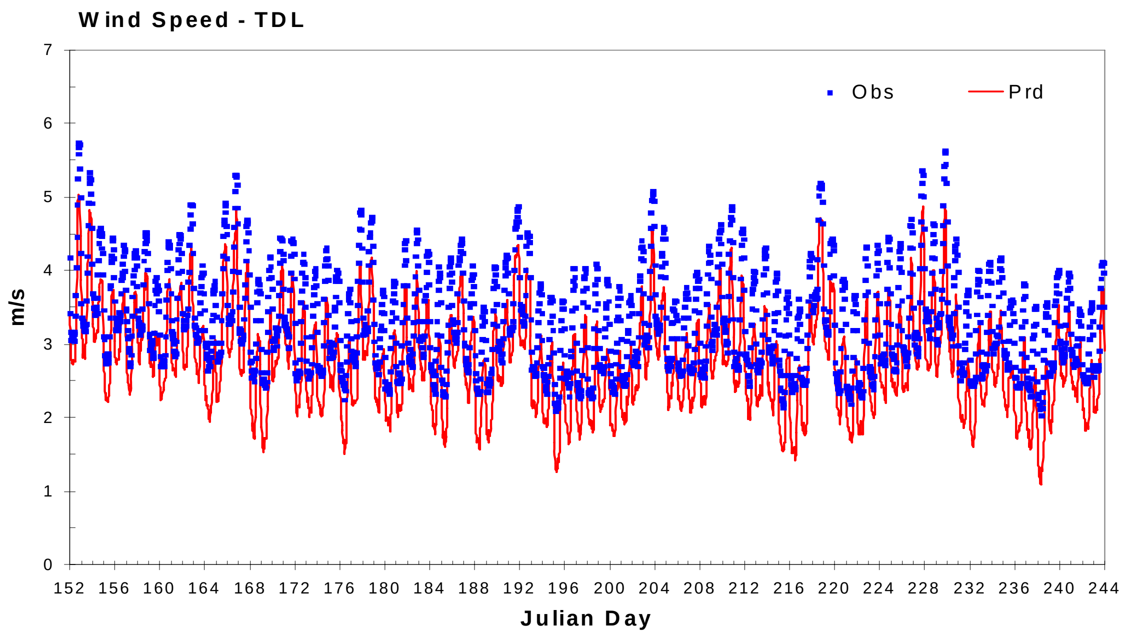


Figure 2a: Wind speed comparison for winter months - January, February, and December, 2002. The upper panel is the comparison between MM5 and NWS data, and the lower panel is the comparison between MM5 and CASTNet data.



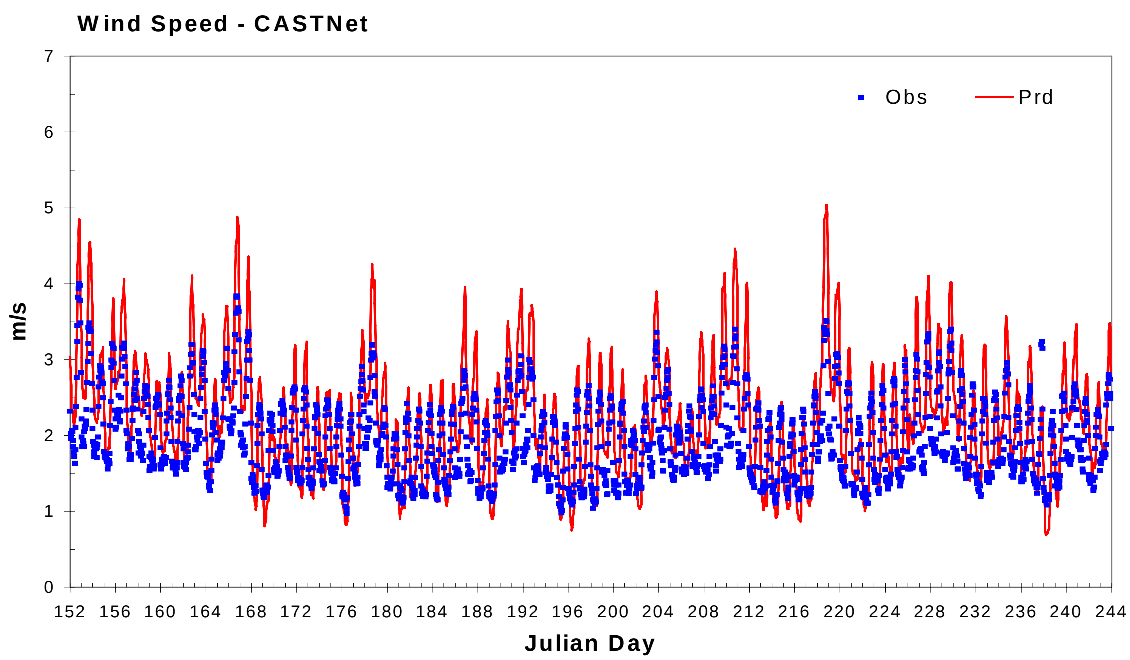
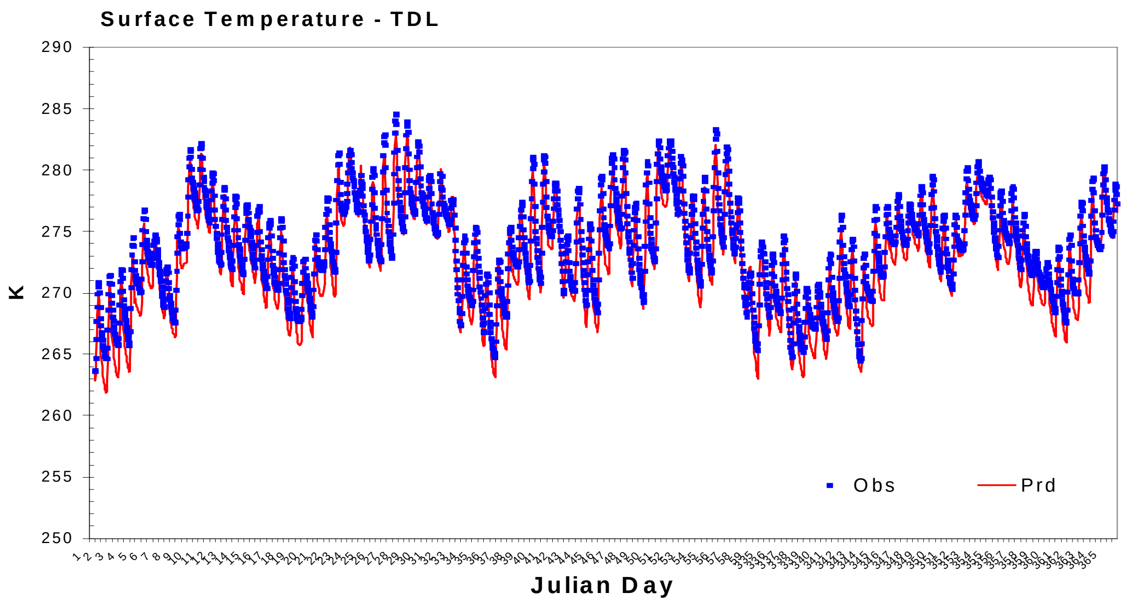


Figure 2b: Wind speed comparison for summer months - June, July, and August, 2002. The upper panel is the comparison between MM5 and NWS data, and the lower panel is the comparison between MM5 and CASTNet data.



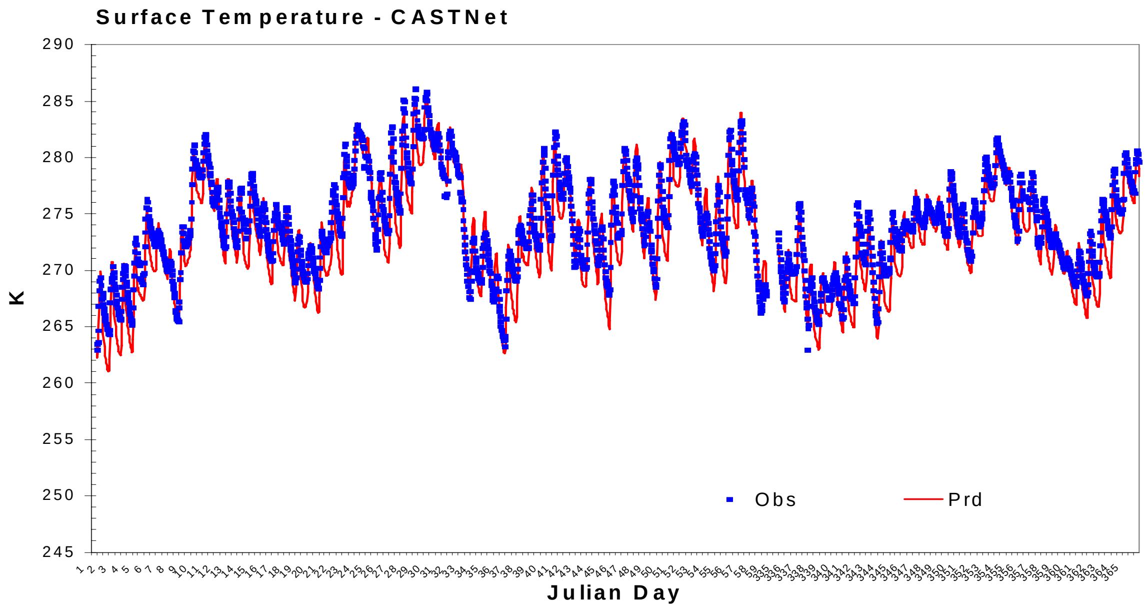
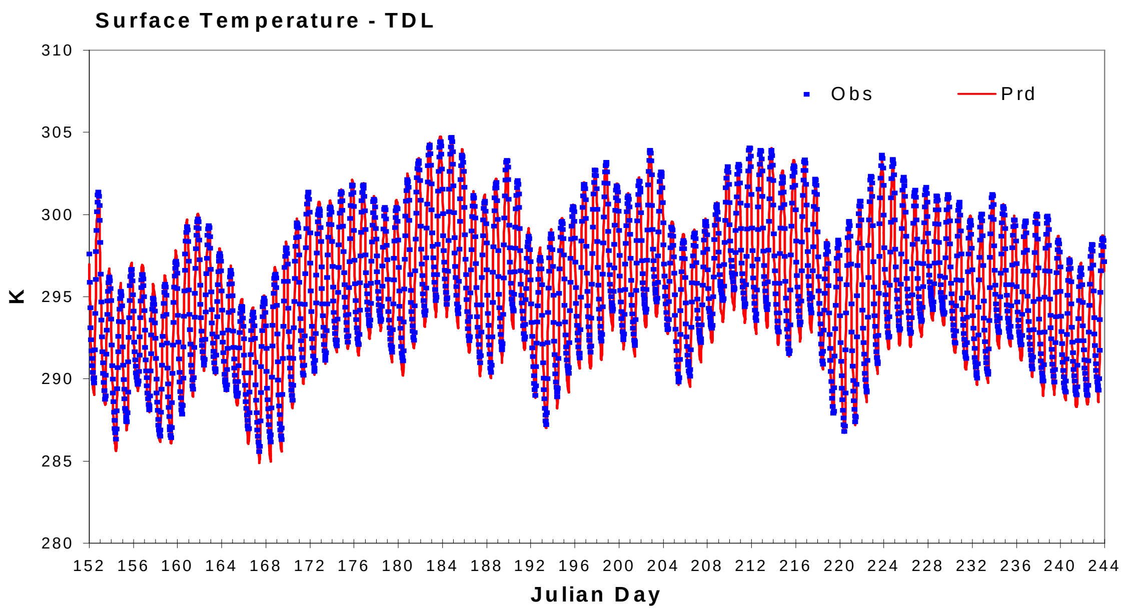


Figure 3a: Temperature comparison for winter months - January, February, and December, 2002. Upper panel is the comparison between MM5 and NWS data, and the lower panel is the comparison between MM5 and CASTNet data.



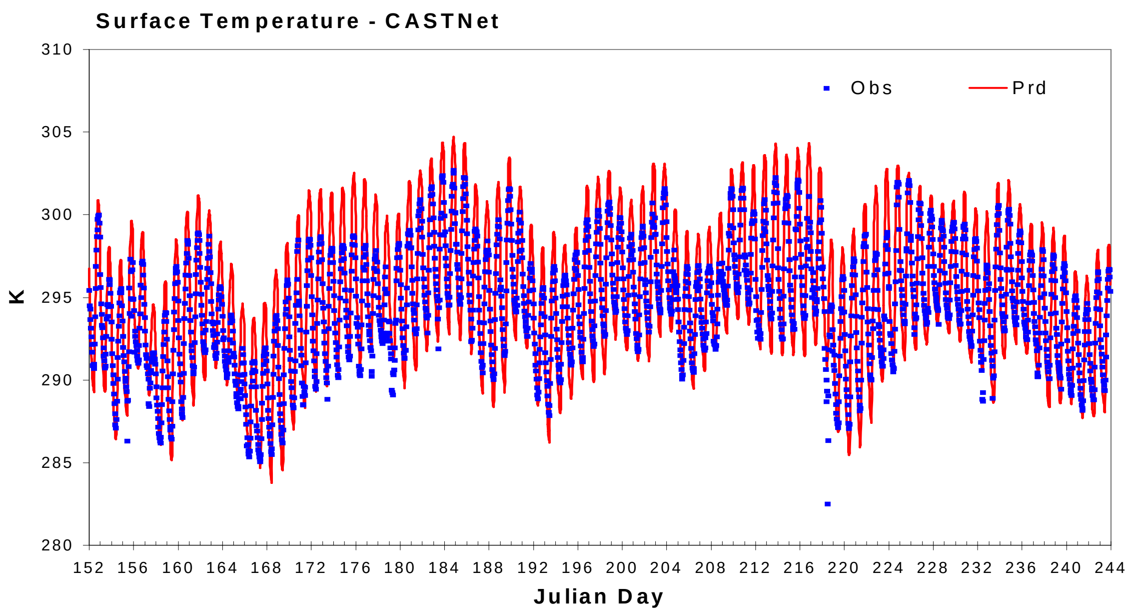
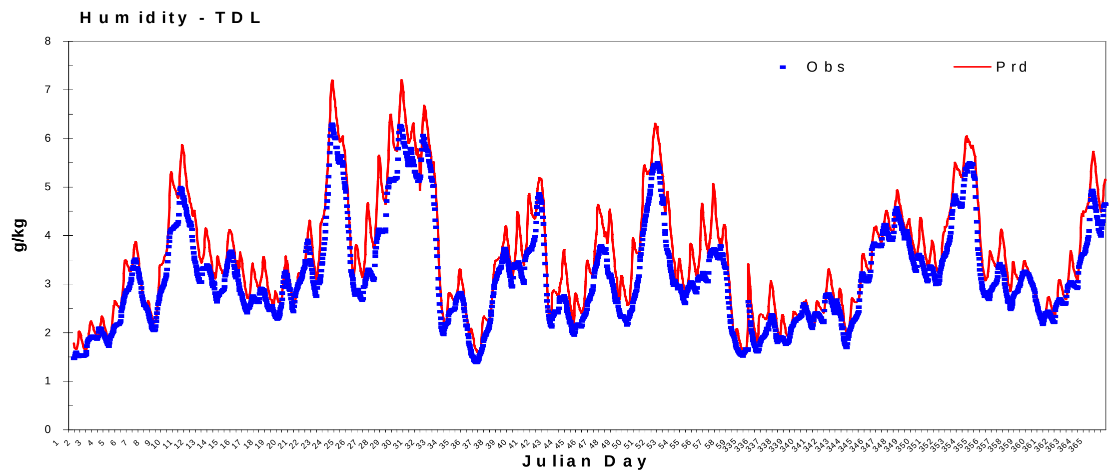


Figure 3b: Temperature comparison for summer months - June, July, and August, 2002. The upper panel is the comparison between MM5 and NWS data, and the lower panel is thew comparison between MM5 and CASTNet data.



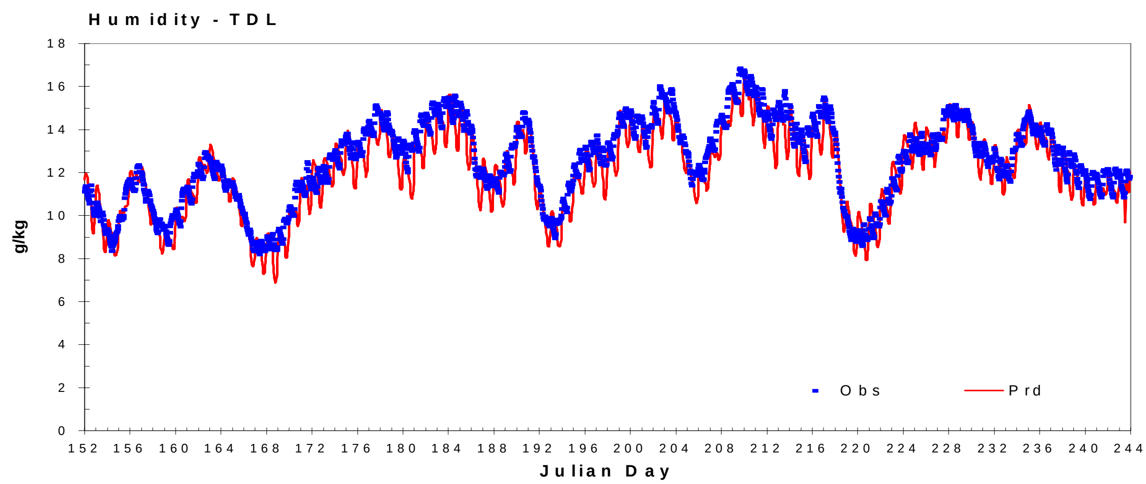


Figure 4: Humidity comparison for winter months - January, February, and December, 2002, (top panel), and summer months - June, July, and August, 2002 (bottom panel).

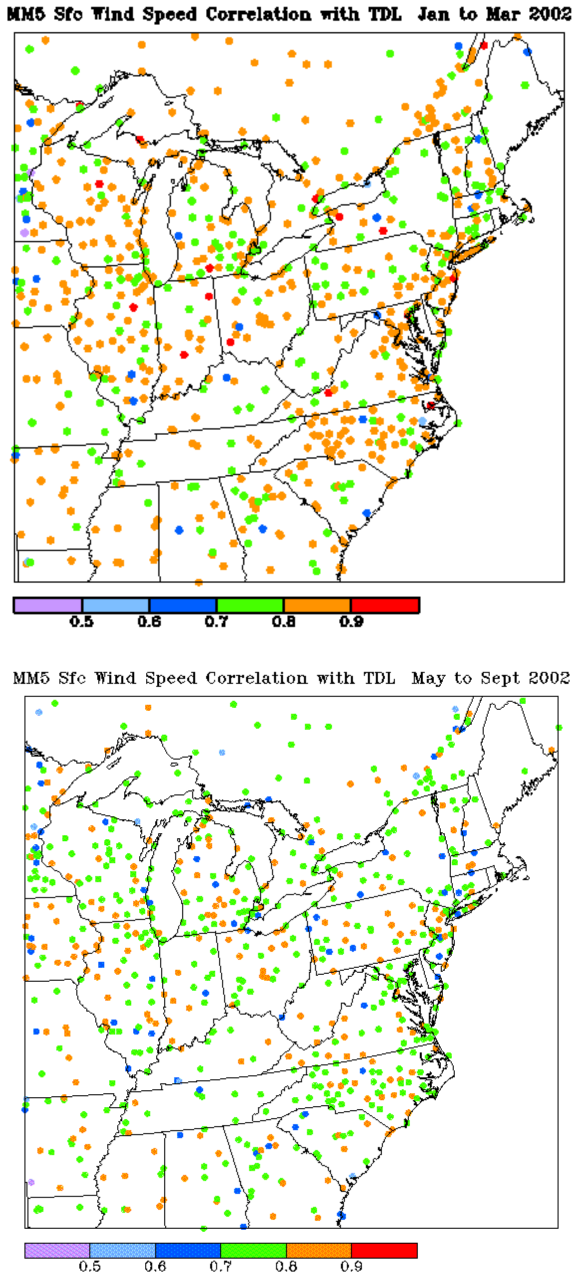
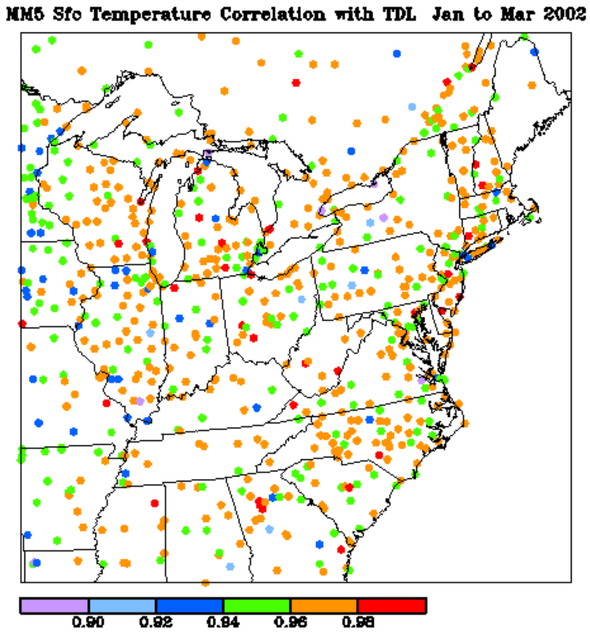


Figure 5a: Spatial correlation estimates between MM5 and NWS data for wind speed for winter months – January to March, 2002 (top panel) and summer months - May to September, 2002 (bottom panel).



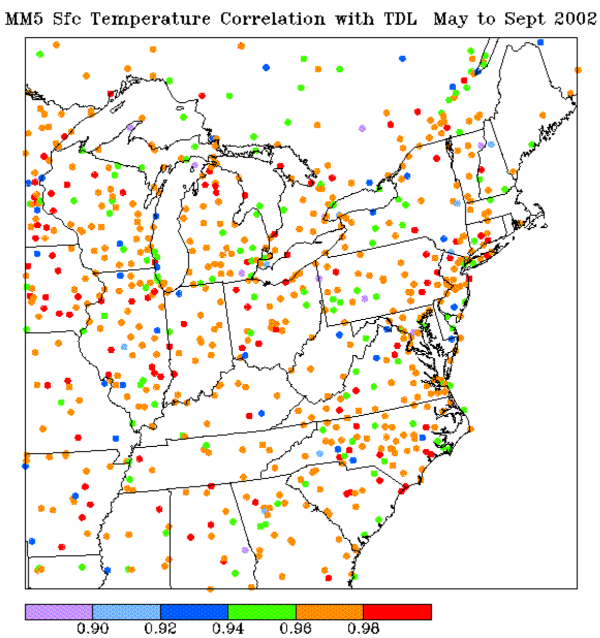
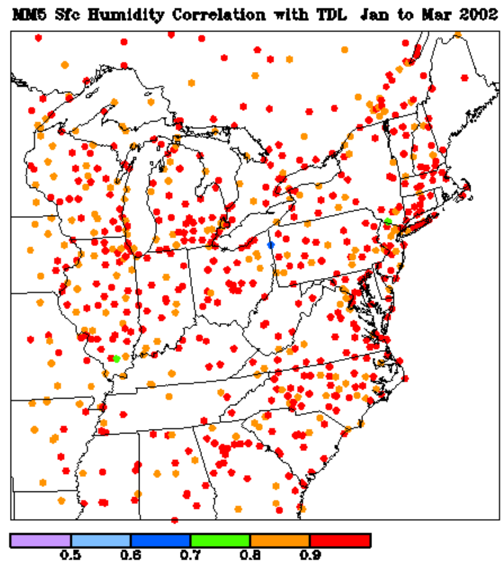


Figure 5b: Spatial distribution of correlation coefficients for Temperature between MM5 and NWS data for winter months – January to March, 2002 (top panel), and summer months - May to September, 2002 (bottom panel).



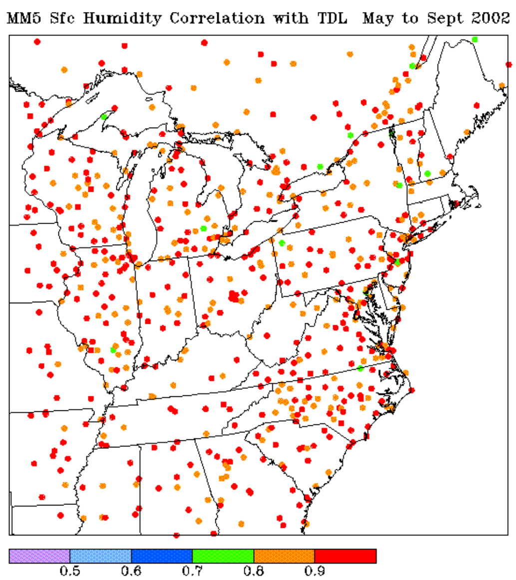
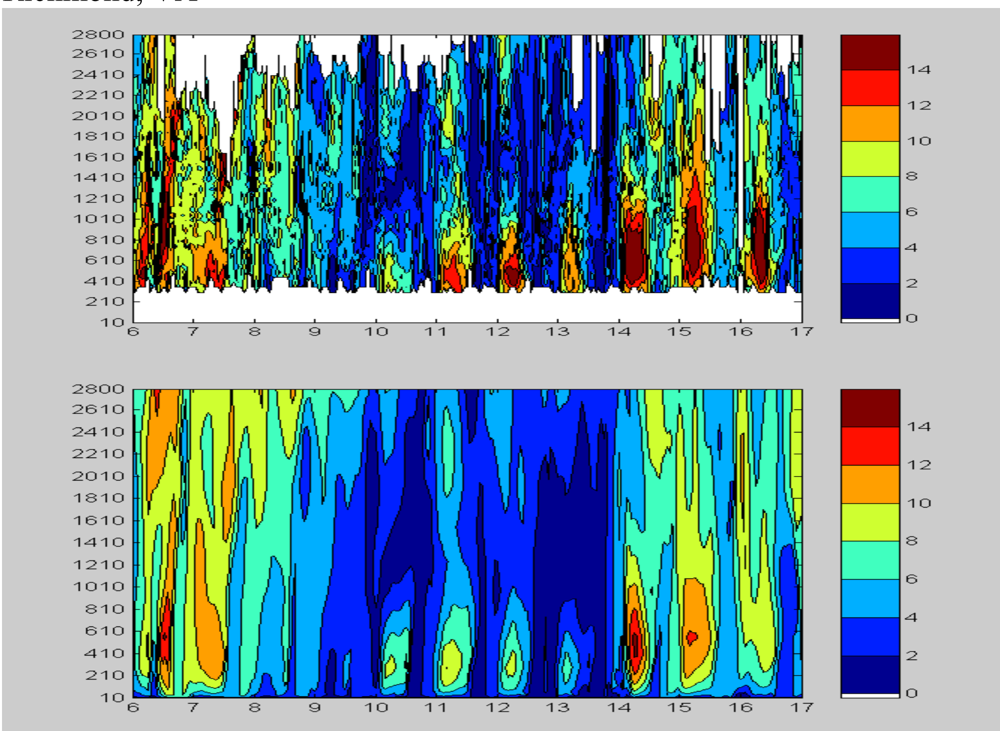


Figure 5c: Spatial distribution of correlation coefficients for Humidity between MM5 and NWS data for winter months – January to March, 2002 (top panel), and summer months - May to September, 2002 (bottom panel).

Richmond, VA



Concord, NH

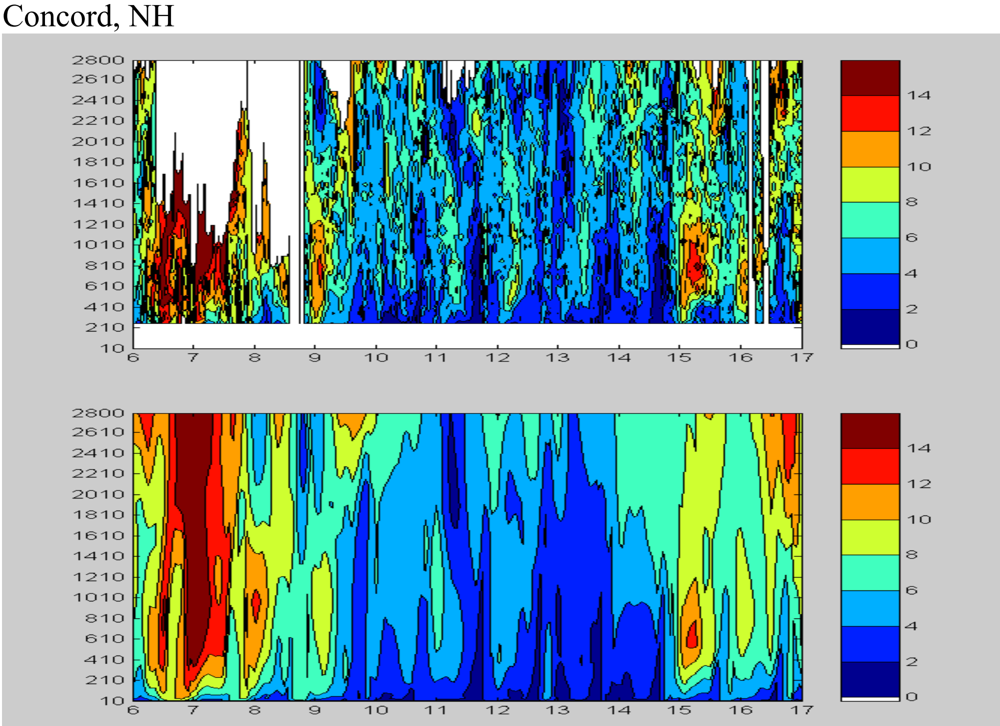


Figure 6: MM5 and Wind profiler comparison for August 6 to 17, 2002 at Richmond, VA and Concord, NH. The upper and lower panes at each station are for MM5 and profiler, respectively. The abscissa represents day and the ordinate the height (m).

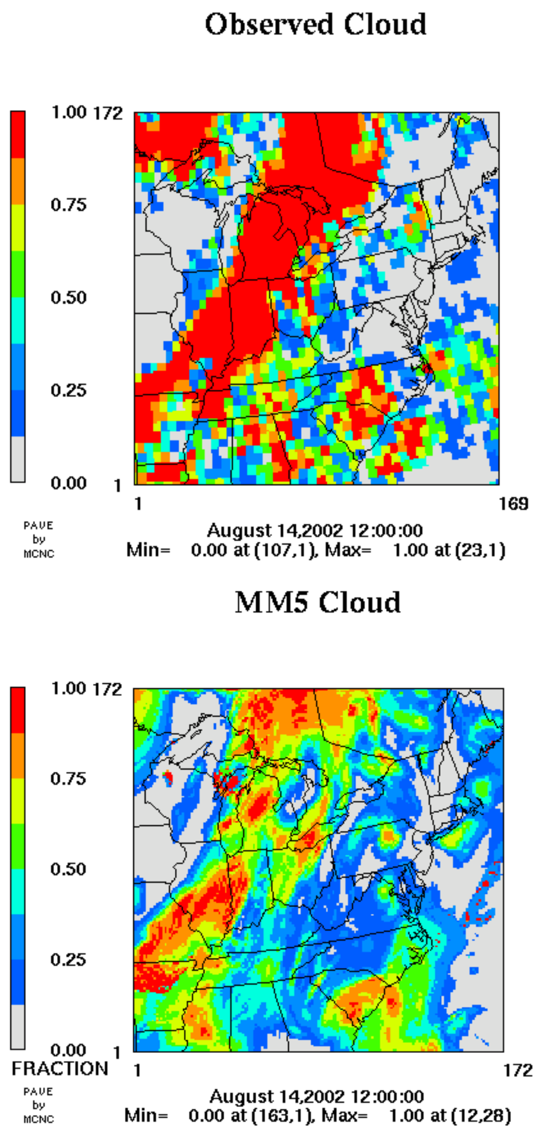
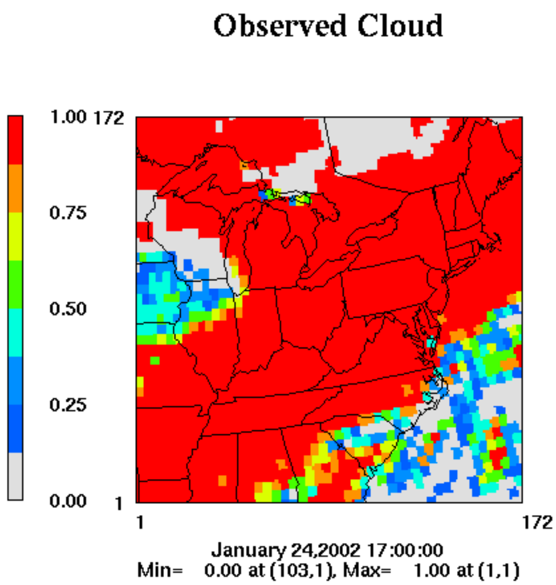


Figure 7a: Observed Satellite and MM5 cloud images for *August* 14, 2002 at 0700 EST



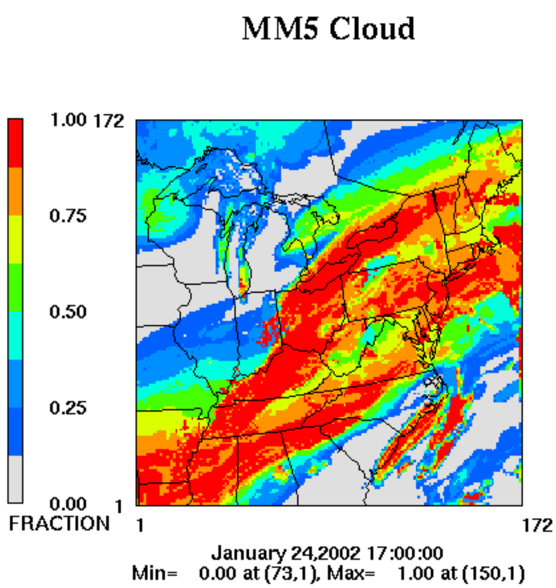


Figure 7b: Observed Satellite and MM5 cloud images for *January* 24, 2002 at 1200 EST

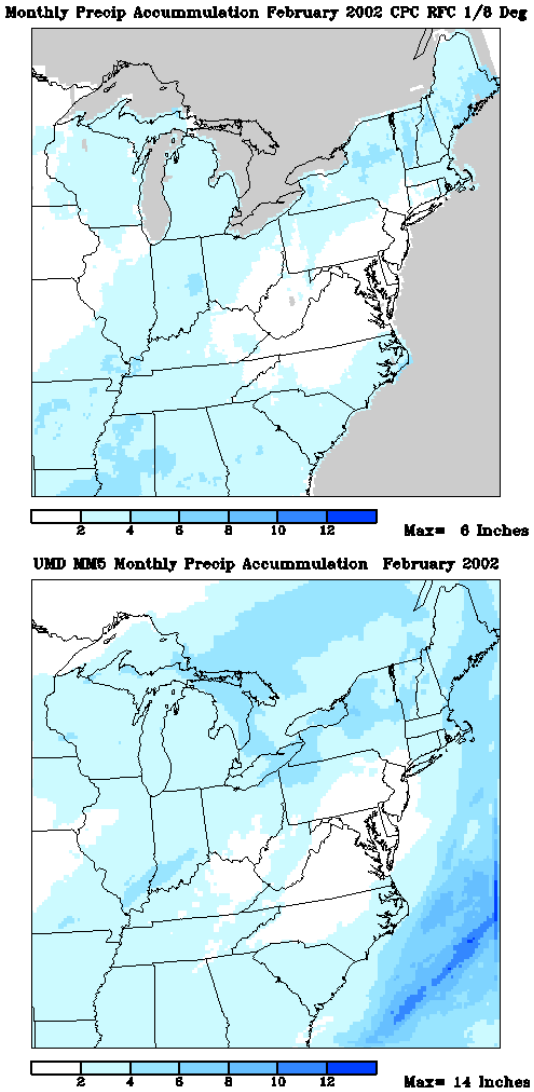
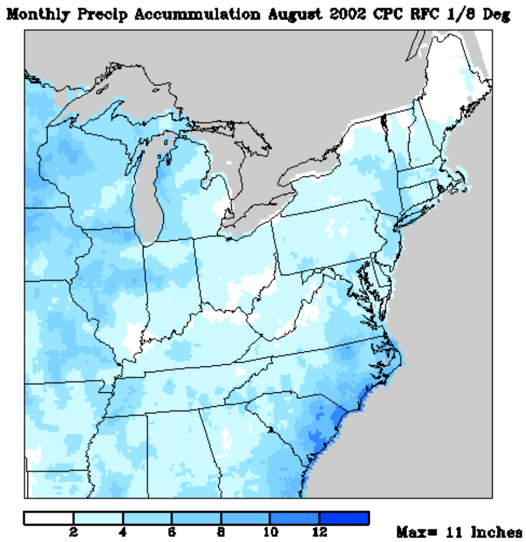


Figure 8a: Measured and MM5 predicted precipitation over the domain for the month of *February* 2002.



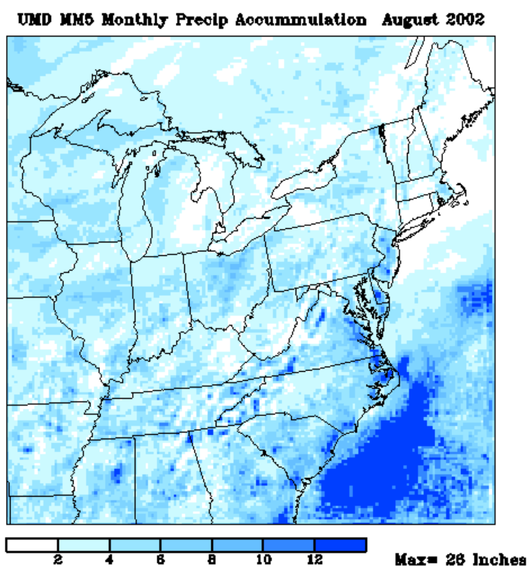


Figure 8b: Measured and MM5 predicted precipitation over the domain for the month of *August* 2002

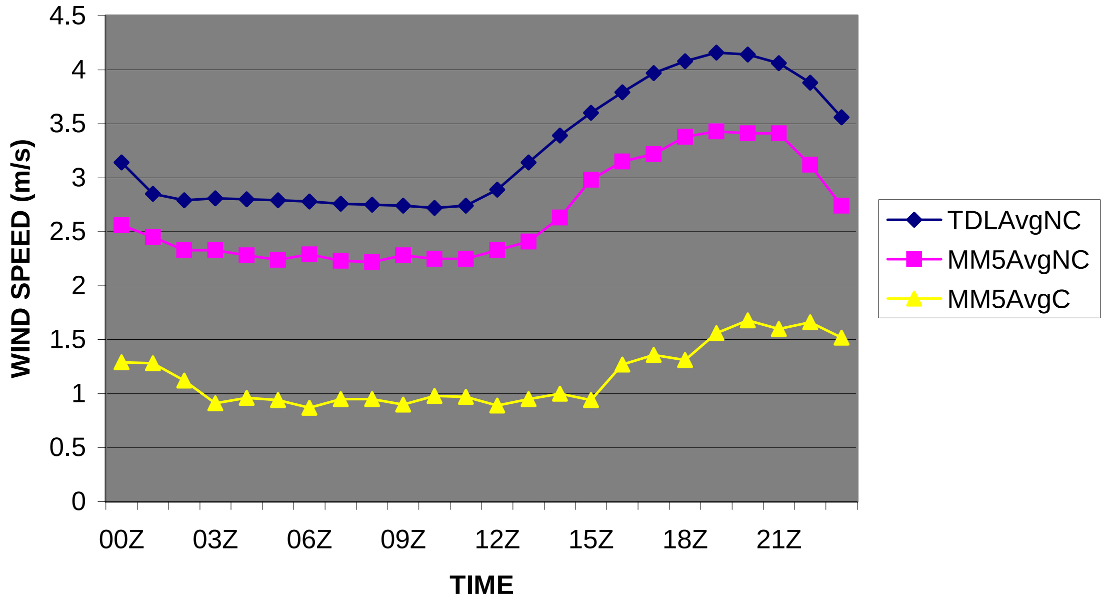


Figure 9: Comparison of averaged wind speed between MM5 and observed under calm (C) and non-calm (NC) conditions.