APPENDIX A

METEOROLOGICAL MODELING FOR THE DALLAS-FORT WORTH ATTAINMENT DEMONSTRATION STATE IMPLEMENTATION PLAN

1.1 MM5 MODELING OVERVIEW

The TCEQ is using the Fifth Generation Meteorological Model (MM5, version 3.7.4) developed jointly by the National Center for Atmospheric Research (NCAR) and Pennsylvania State University (Grell et al., 1994). This model, supported by a broad user community including the Air Force Weather Agency, national laboratories, and academia, is being used extensively for regulatory air quality modeling analyses throughout the United States. MM5 modeling was conducted for the time period listed in Table 1-1: *DFW Meteorological Modeling Episode*.

Table 1-1: DFW Meteorological Modeling Episode

Episode	All Grids Begin Date/Time (UTC)	All Grids End Date/Time (UTC)
June 2006 (2006ep0ext)	May 28, 2006 06:00	July 3, 2006 07:00

A Lambert Conformal conic map projection (LCP), with geographical coordinates defined in Table 1-2: Lambert Conformal Conic Map Projection, was used for the MM5 modeling.

Table 1-2: Lambert Conformal Conic Map Projection

First True Latitude (Alpha):	30°N
Second True Latitude (Beta):	60°N
Central Longitude (Gamma):	100°W
Projection Origin:	100°W, 40°N
Spheroid:	Perfect Sphere, Radius = 6370 km

MM5 was configured with three two-way nested outer domains (108 km, 36 km, and 12 km horizontal grid resolution) to cover the United States and regional areas of interest. A one-way 4 km fine grid domain covering the eastern half of Texas was established to focus on metropolitan areas with air quality degradation. Figure 1-1: *MM5 Modeling Domains* shows the MM5 nested domain configuration, which was established to accommodate the embedding of the CAMx nested domains with the same grid resolution, except for the MM5 36 km domain. That domain does not cover the far eastern part of the 36 km CAMx domain, so values from the MM5 108 km domain are used. Because of the distance from the Dallas-Fort Worth (DFW) area, this replacement is expected to have a minimal effect on the simulation of meteorological parameters in the 4 km domain. The easting and northing ranges for each domain are defined in Table 1-3: *MM5 Modeling Domain Definitions*.

Vertically, MM5 is structured with 43 layers from the surface to approximately 20 km (Figure 1-2: *MM5 Vertical Layer Structure*). Twenty layers are within the first 3000 meters in order to resolve boundary layer phenomena and to provide a one-to-one mapping with the first twenty layers for CAMx. The same MM5 vertical layering structure is used for all of the domains.

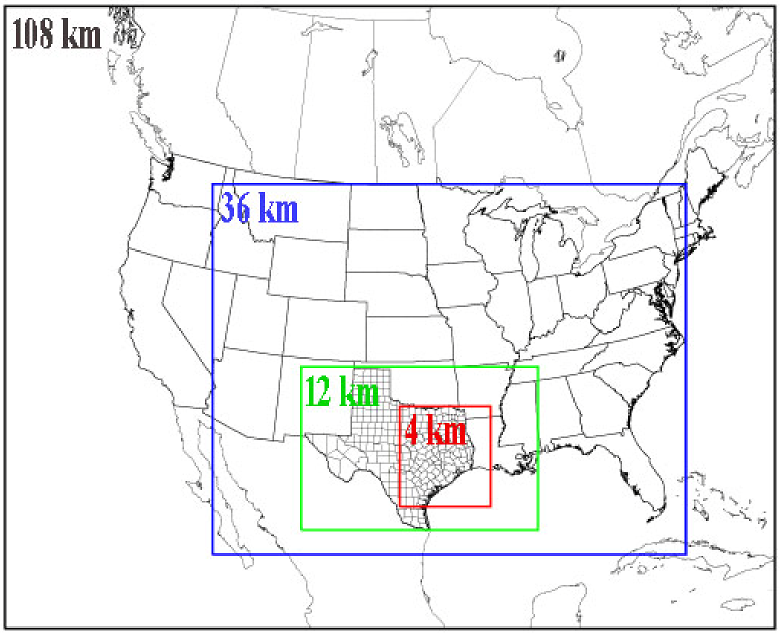


Figure 1-1: MM5 Modeling Domains

Table 1-3: MM5 Modeling Domain Definitions

Domain	Easting Range (km)	Northing Range (km)	East/West Grid Points	North/South Grid Points
108 km	(-2808, 2808)	(-2268, 2268)	53	43
36 km	(-1296, 2160)	(-1728, 972)	97	76
12 km	(-648, 1080)	(-1548, -360)	145	100
4 km	(72, 372)	(-1380, -648)	166	184

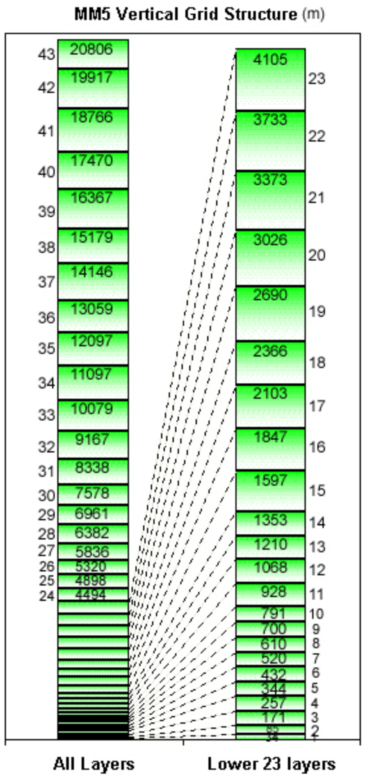


Figure 1-2: MM5 Vertical Layer Structure

1.2 MM5 CONFIGURATION

The final meteorological modeling configuration for the June 2006 episode was the result of numerous sensitivity tests, model performance evaluation, model input development, previous modeling experience, and contracted modeling. The pre-processing of the MM5 input data followed the standard program progression of TERRAIN, REGRID, and INTERPF (NCAR, 2005b). The NESTDOWN program was used to interpolate the 12 km domain output to the 4 km domain input. The following bullets feature the essential parameters that were specified for the pre-processing programs:

TERRAIN

- Central Latitude and Longitude: 40.00 ° North and -100.00 ° West
- LSMDATA=1 to create data for the land-surface model
- Updated land use and land cover (LULC), land/water mask, vegetation fraction, and soil types using satellite based data
- Further details can be found in Appendix A of (TCEQ, 2010)

REGRID

- National Center for Environmental Prediction (NCEP) North American Model (NAM) gridded output (formerly Eta model) used for model initialization (NCEP, 2009)

INTERPF

- Base state variables were set to Texas summer values: 1013 hPa sea-level pressure, a reference temperature lapse rate of 45 (K/ln p), and a 304 °K sea-level temperature

In developing the meteorological modeling of the June 2006 episode for the 2010 HGB SIP Revision, the TCEQ focused on parameterizations to improve performance of the coastal wind field (TCEQ, 2010). Land use characteristics and sea surface temperatures on all domains were updated with high resolution satellite measurements (see Attachments to Appendix A of TCEQ, 2010). In 2008, the Austin and San Antonio areas optimized the TCEQ meteorological modeling of the June 2006 episode to be more representative for central Texas (Emery et al., 2009a). Model options were chosen to remove spurious convection and improve the performance of the wind field through analysis nudging (Stauffer and Seaman, 1990; Stauffer et al., 1991; Stauffer and Seaman, 1994) on all domains using the National Center for Environmental Prediction (NCEP) North American Model (NAM) gridded output for winds, temperature, and water vapor.

The TCEQ continued this work on the June 2006 episode by contract with Environ, which resulted in an MM5 configuration that yielded good performance in the DFW and central Texas areas (Emery et al., 2009b). Observational nudging using TexAQS II radar profiler data and one-hour surface analysis nudging improved wind performance. Switching from the NOAH (NCEP Oregon State Air Force Hydrological Research Laboratory) Land-Surface Model to the five-layer soil model also improved the representation of precipitation, temperature, and planetary boundary layer (PBL) depths.

The TCEQ continued to improve upon the performance of MM5 for the June 2006 episode through a series of sensitivities. The final MM5 parameterization schemes and options selected are shown in Table 1-4: *June 2006 MM5 Configuration*. The selection of these schemes and options was based on the previous modeling experiences described above, MM5 community use, and features of the ozone episode being modeled.

Table 1-4: June 2006 MM5 Configuration

Domain	Nudging Type	PBL	Cumulus	Radiation	Land-Surface	Microphysics
108 and 36 km	3-D and Surface Analysis	MRF	Grell	RRTM / Dudhia	5-layer soil model	Simple Ice
12 km	3-D, Surface Analysis, & Obs	MRF	Grell	RRTM / Dudhia	5-layer soil model	Simple Ice
4 km	3-D, Surface Analysis, & Obs	ETA	None	RRTM / Dudhia	5-layer soil model	Simple Ice

Note: RRTM = Rapid Radiative Transfer Model

MM5 output was post-processed using the MM5CAMX version 4.8 utility to convert the MM5 meteorological fields to the Comprehensive Air Quality Model with Extensions (CAMx) grid and input format (Environ, 2010). The MM5CAMX utility was used with the Asymmetric Convective Model (ACM2) vertical diffusivity methodology, and a minimum vertical diffusivity coefficient (K_V) of 1.0. The vertical diffusivity coefficients were also modified on a land-use basis to limit the maximum within the first 200 meters of the model using the KVPATCH program (Environ, 2005).

1.3 MM5 MODEL PERFORMANCE EVALUATION (MPE) TOOLS

1.3.1 Observations

To evaluate the performance of MM5, comparisons to observed data are made. For surface data, the TCEQ Continuous Air Monitoring Stations (CAMS) are used for comparison. There were over 100 CAMS in the MM5 4 km domain and 25 in the DFW Region 4 area (*Figure 1-3: All MM5 4km TCEQ CAMS (left) and DFW Region 4 CAMS (right)*) during the 2006 modeling period. Because of the large number of CAMS monitors in the DFW region, an area wide average may smooth out smaller scale features. Eight monitors throughout the DFW area were chosen to represent smaller geographic areas as defined in Figure 1-4: *Selected DFW CAMS for MPE*. Evaluating model runs using the DFW Region area and a subset of individual monitors instead of all CAMS monitors proved to be efficient, allowing for the evaluation of more modeling sensitivities.

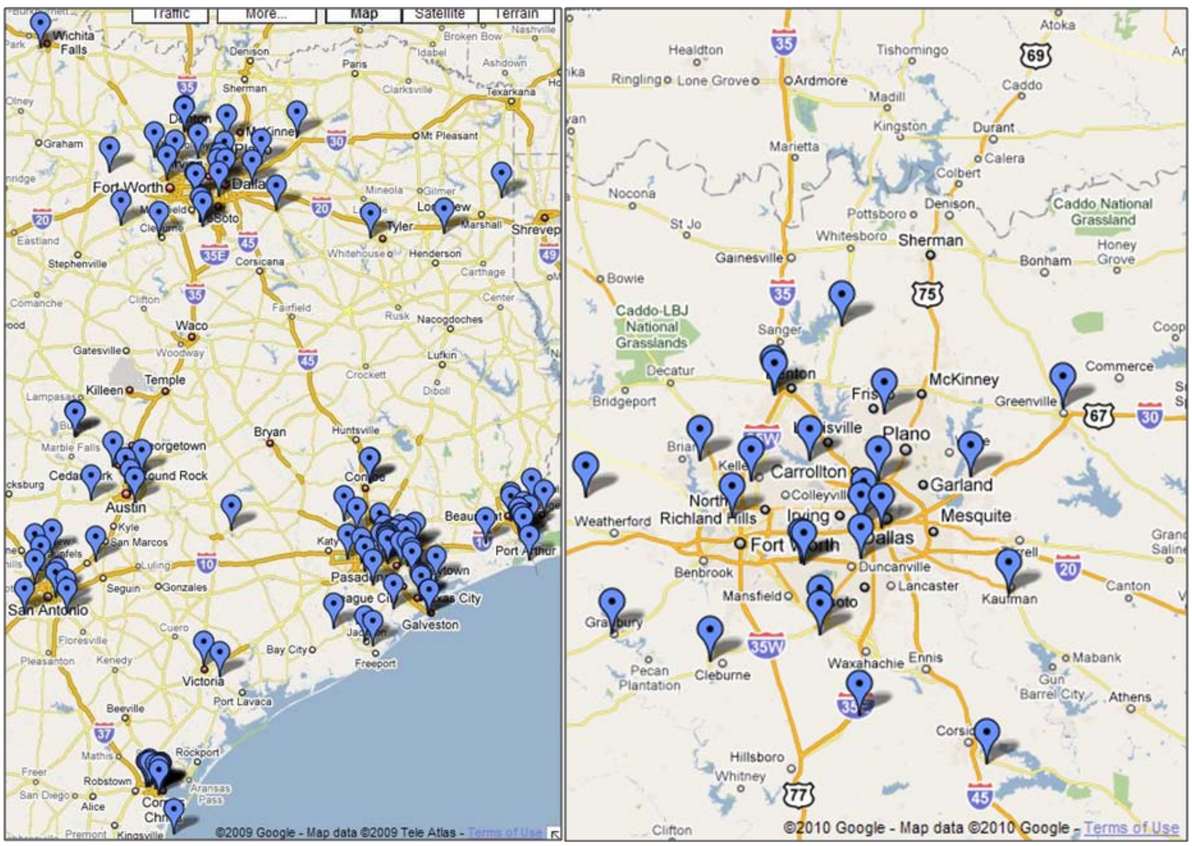


Figure 1-3: All MM5 4km TCEQ CAMS (left) and DFW Region 4 CAMS (right)

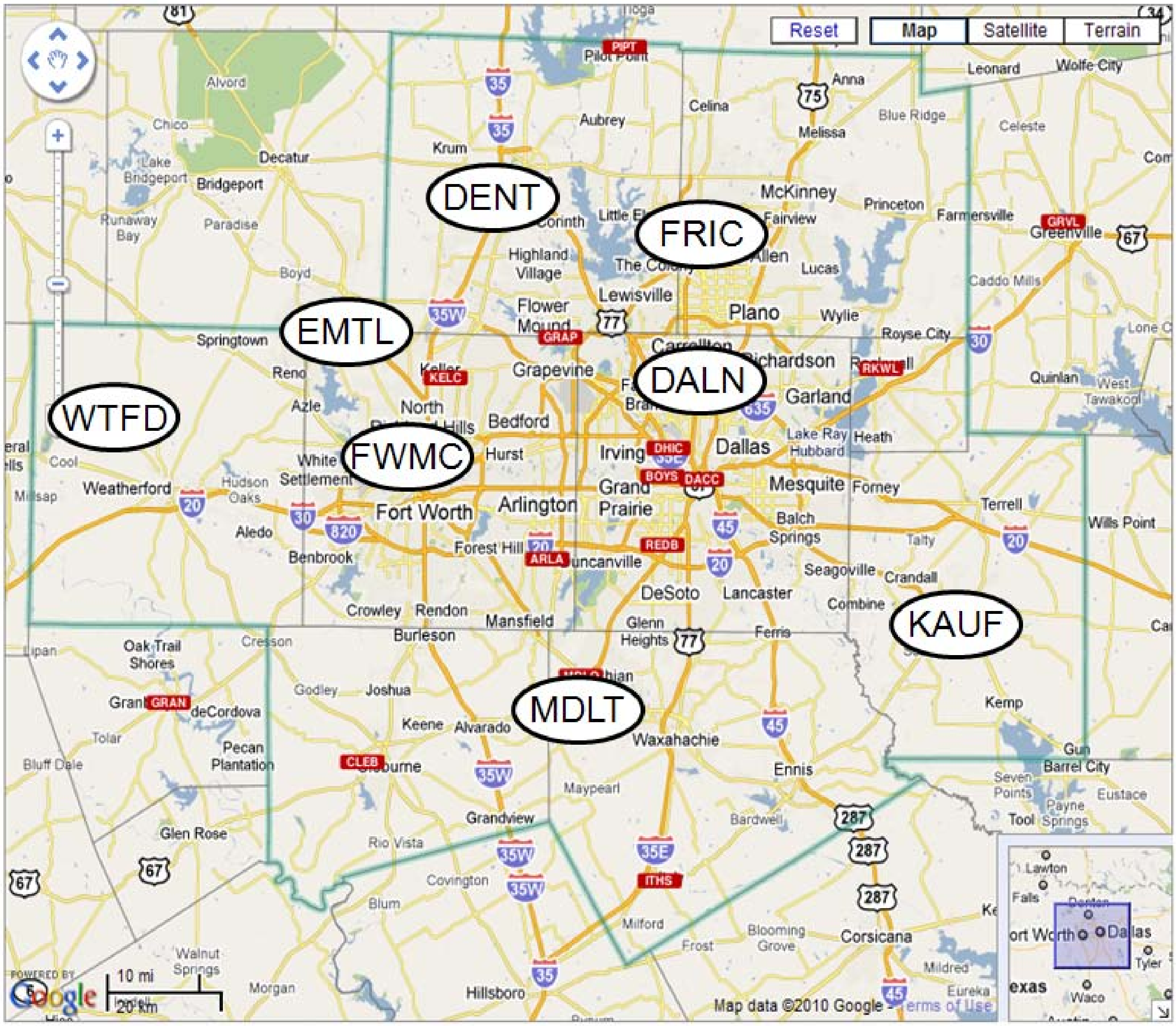


Figure 1-4: Selected DFW CAMS for MPE

The TexAQS II profiler network was used to evaluate the performance of MM5's winds above the surface layer (Figure 1-5: *Profilers in 4km MM5 domain*). Up to 15 profilers collected data during the 2006 modeling, including estimates of PBL depth.

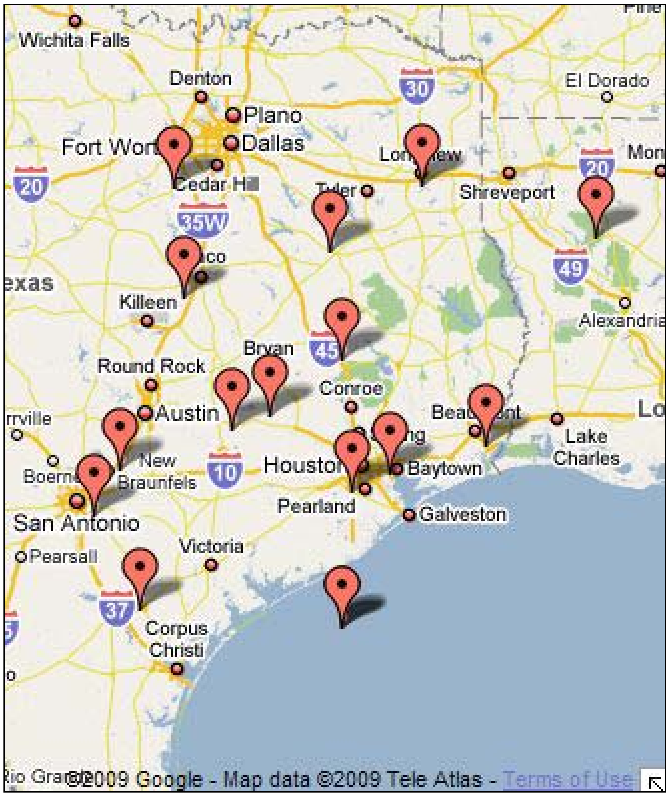


Figure 1-5: Profilers in 4km MM5 domain

1.3.2 Time Series Panel

Time series panels comparing modeled and observed CAMS surface wind direction, wind speed, and temperature were created to evaluate the model's performance over the entire episode. The observations are hourly averages of individual and grouped monitors (e.g. TCEQ Region-wide, or domain-wide). As an example of a time series panel, *Figure 1-6: Dallas Executive Airport C402 wind speed time series*, shows the time series of hourly wind speed for the Dallas Executive Airport. The X axis of the time series panels is the date and time in Central Standard Time (CST) of the modeling episode. The Y axis represents the range of values of the parameter (e.g. wind speed). The title of the panel indicates the geographic region, parameter (wind speed, temperature, etc), model and run name.

The compared model hourly values are from the monitor's corresponding model grid cell. MM5's first model layer cell value (red line – MM5) and the probe height interpolated cell value (blue line – MM5probe) are both plotted. For wind direction, the probe height and first model layer values are usually the same. For wind speed the probe height is slightly slower and for temperature the probe height is warmer than the middle of the first model layer. The first model layer values are passed to the photochemical model so they are important to evaluate. Also shown are time series of bias and mean absolute error using the model's first layer values.

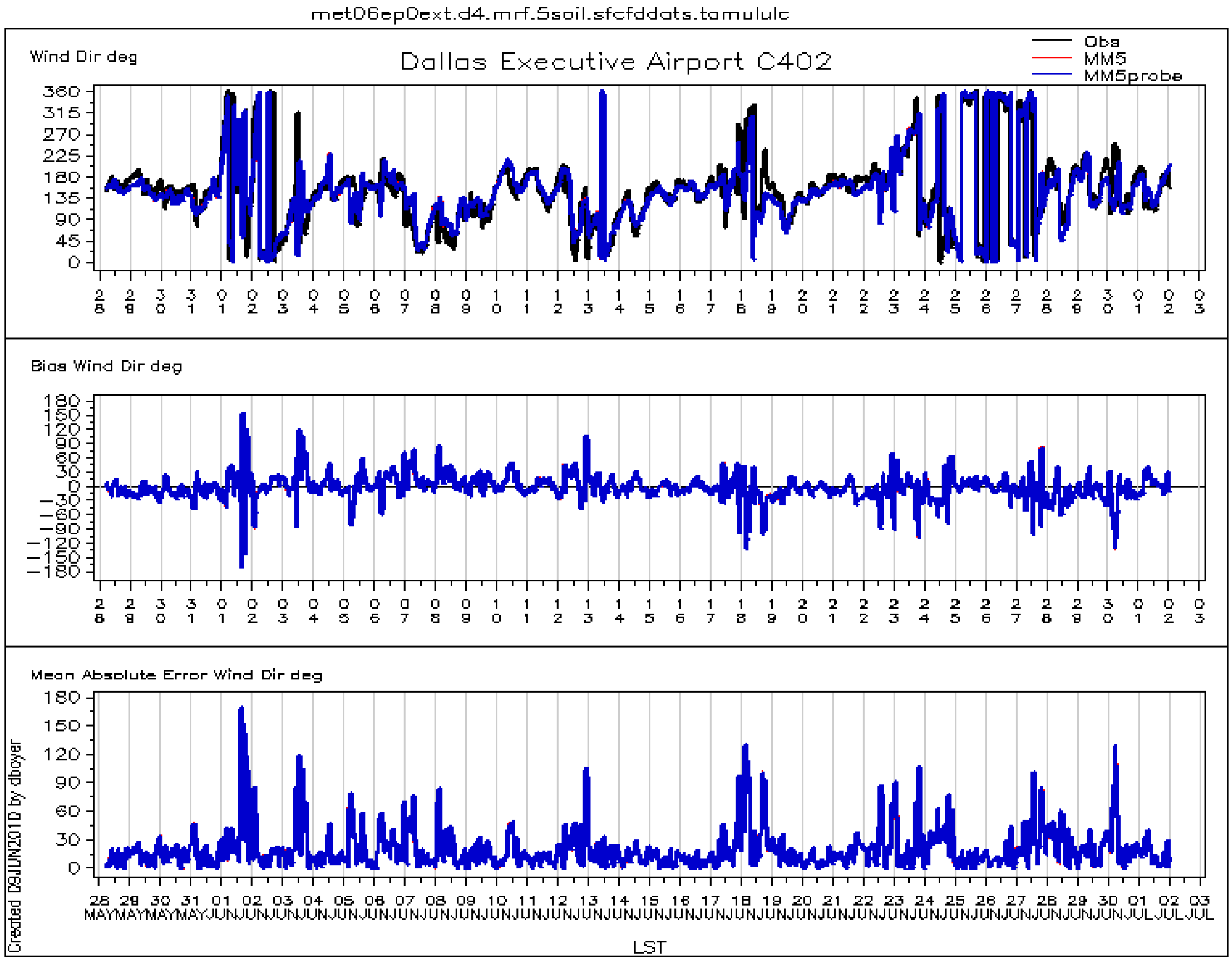


Figure 1-6: Dallas Executive Airport C402 wind speed time series

1.3.3 Scatter Plots

Scatter plots of model versus observations were created to correlate how well the model statistically performs at monitors (groups of monitors), episode days, and model layers. As with the time series, the model is compared to individual, region-wide, and domain-wide groups of monitors for every hour (per day or episode). For surface data, the observations are compared to the model's first layer values. The percent of hours (all, day, or night) where the model is within the accuracy benchmarks (e.g. wind direction less than or equal to 30 degrees or wind speed less than or equal to 2 meters per second) is depicted in the upper right of the plot. Tables of these accuracy percentages are also presented to summarize the scatter plots.

A linear regression line is fitted to the data and is shown in green. The correlation equation and coefficient of determination R^2 for the regression line is above the plot in green. For the model to perfectly fit the data the regression line would fall on the one-to-one line and the R^2 would be 1.0. The R^2 indicates how well MM5 predicts the observations, with higher values indicating better model performance. As the model is an imperfect representation of the real world and the observations have biases, errors, and limitations, a perfect fit is not expected. In fact a perfect fit (or very close to it) may be reason to suspect that MM5 is being nudged too hard (see Attachment 3: Data Assimilation). For wind direction, the regression line and R^2 are not calculated since both 0° and 360° symbolize north winds and make those statistics meaningless.

The plot titles are the same as the time series. For the scatter plots, the X axis is the observed data and the Y axis is the modeled. The total number of date-time points (hours) and observations (hour-monitor pairs) that comprise the plot are listed next to the parameter name. Figure 1-7: *Keller C17 wind speed scatter plot* shows an example of Keller C17's wind speed over the June 2006 episode.

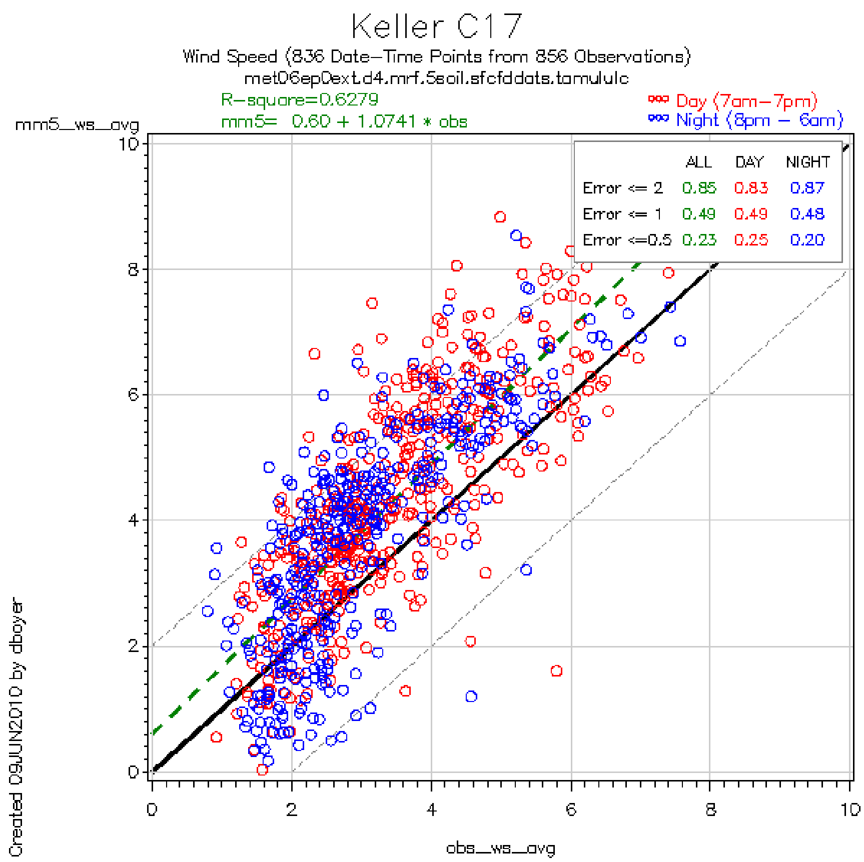


Figure 1-7: Keller C17 wind speed scatter plot

1.3.4 Time-height plots

Time-height plots represent the upper air horizontal wind conditions at profiler locations over one episode day. Vertical winds (rising or descending air) are not shown. The model winds (CAMx input) are shown as blue vectors and the observed winds (profiler) are shown as red vectors. Each hour of the episode day is depicted on the x-axis. Winds from just above the surface to 3 km are illustrated by vectors pointing in the compass direction from where the wind is blowing. A longer vector indicates faster wind speeds. The Cleburne profiler is the only profiler within the 4 km CAMx domain for DFW. In *Figure 1-8: Time-height plot example (6/2/2006 at Cleburne profiler)* below, at 4 AM CST on 6/2/2006 a southwest wind greater than 10 m/s blows at 2.5 km above the surface at the Cleburne profiler (red vector). The model predicts more southerly winds and lighter (blue vector). Observed winds were not available midnight to 3 AM and 11 PM on this day.

Also on these plots are the model (blue) and profiler (red) estimated PBL depths shown by horizontal lines between hours. The observed data is generally only available during daylight hours. At 4 PM CST in Figure 1-8 below, the model and observed PBL depth agree well but differ by 800 meters at 5 PM.

Based on Knoderer et al. (2008), the morning rise of the PBL may be more important to ozone production than the peak mixing depth. The morning rise was focused on for model performance evaluation as well as gross differences. More information regarding the derivation of mixing heights from the radar wind profiler data can be found in Knoderer and MacDonald (2007).

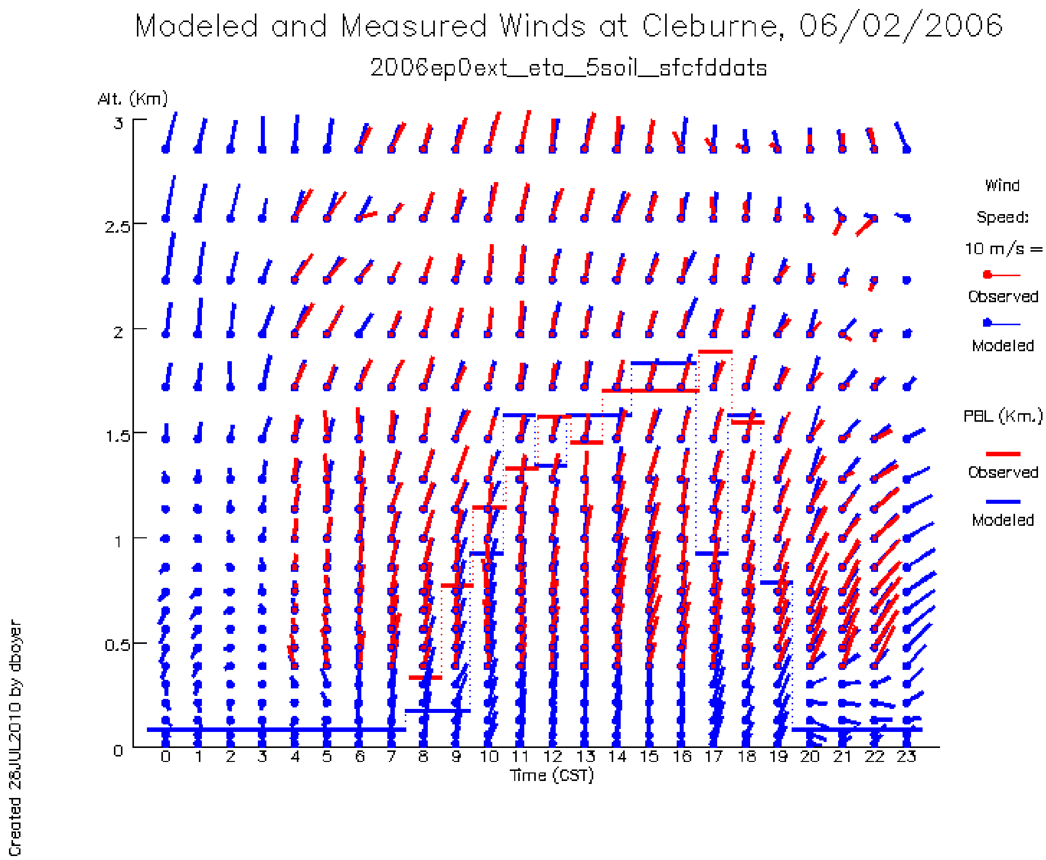


Figure 1-8: Time-height plot example (6/2/2006 at Cleburne profiler)

1.3.5 Trajectories

One of the most useful and intuitive methods for evaluating modeled wind fields is by using wind trajectories. A back trajectory shows the path that an air parcel followed before arriving at a specific location (say, a monitor). Because the trajectories inherently describe source-receptor relationships, they are especially appropriate for air-quality applications.

The TCEQ calculated back trajectories with endpoints at several locations in the DFW area (plus three in northeast Texas) for every hour of every episode day modeled using a FORTRAN program obtained from Pacific Northwest National Laboratories. This program is based on a simple kinematic model that used an inverse distance-squared weighting scheme to evaluate the u- and v-wind components of each trajectory (Berkowitz et al, 2005) Input for this program is five-minute average wind speed and direction observations from the surface meteorological sites in and around the DFW area.

The trajectory program was used to develop sets of comparable trajectories based on observational data and meteorological fields as follows: First, hourly mean modeled wind components were extracted from the meteorological data files at the location of each of the surface meteorological sites. Five-minute observations were generated by simply replicating the hourly mean wind speed and direction 12 times. Observed hourly observations were similarly used to generate five-minute averages by replicating the hourly observations 12 times each (this was done to make the comparisons between the model-based and observation-based trajectories fair). Both the modeled and measured data were formatted for input to the FORTRAN program, and trajectories were generated using each set of inputs. Trajectories were generated from the raw MM5 output files. The backward trajectories were generated for each hour of each episode day.

An example comparing model-based and observation trajectories is shown in Figure 1-9: *June 9, 2006 12-hour Backward Trajectory*. In this plot, it is easy to see the path an air parcel took over the past twelve hours. The first dot along the trajectory represents the air parcel's position one hour prior (2 PM), the next dot two hours before, etc. The larger circles represent monitoring locations, colored according to the observed peak 8-hour ozone concentration observed at that site on that day. Both sets of trajectories show light wind speeds from the southeast for most of the day. The trajectories at the Tyler and Longview monitors (east side of the domain) indicate a wind shift 10-12 hours back based on the turns in the trajectories.

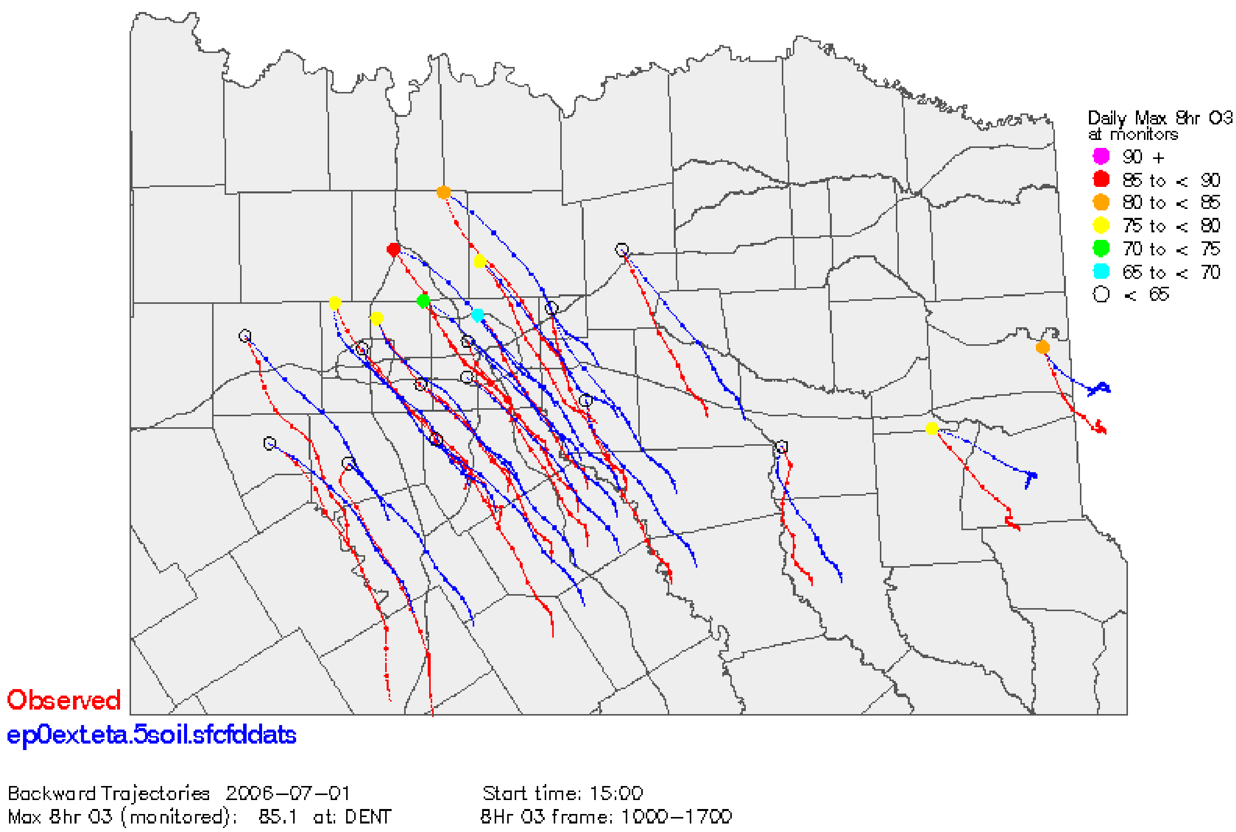


Figure 1-9: June 9, 2006 12-hour Backward Trajectory

1.4 MM5 MODELING PERFORMANCE

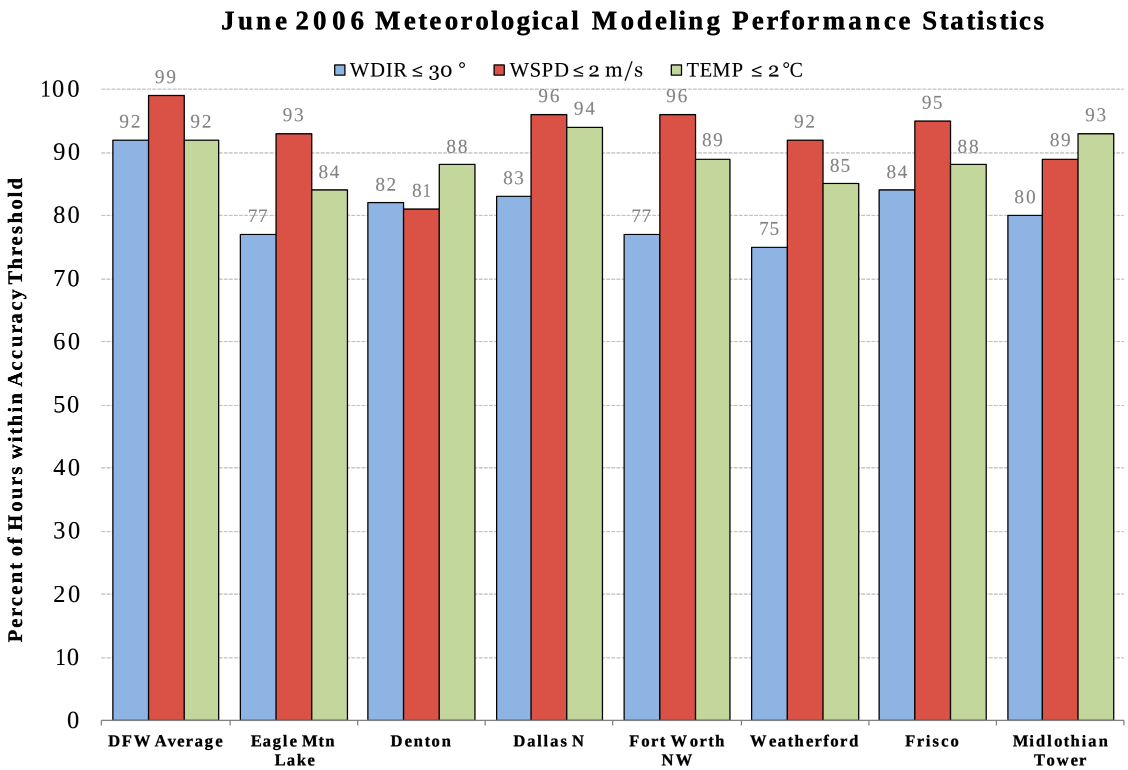
The following section describes the performance of the final MM5 modeling configuration for the June 2006 episode, as listed in Table 1-1. Due to the large number of episode days, the performance evaluation will focus on the days when high ozone and notable meteorological phenomena occurred (Knoderer et al., 2008; Nielsen-Gammon, 2007a; Nielsen-Gammon, 2007b; TCEQ, 2006). Wind field performance was deemed to be the most important for photochemical modeling input followed by temperature, PBL height, and other important features.

1.4.1 June 2006 Episode Performance Evaluation

The June 2006 episode had seventeen days (out of 33) with an observed eight-hour ozone exceedance. Eight of those days had more than five DFW monitors exceeding 84 ppb. The two highest eight-hour ozone exceedances of 2006 also occurred during this episode.

As noted in the DFW Modeling Protocol and Conceptual Model, the June 2006 episode experienced meteorological conditions similar to typical ozone exceedance days. Slow east, southeast, and south winds were observed as were clear skies with high temperatures on many days. Several frontal passages also swept through DFW, which have shown to bring stagnant conditions favorable for ozone formation (McNider, 2009).

The MM5 modeling was evaluated by comparing the hourly modeled and measured wind speed, wind direction, and temperature for all monitors in the DFW area. Figure 1-10: *June 2006 Meteorological Modeling Performance* exhibits the percent of hours for which the average absolute difference between the modeled and measured wind speed and direction, for specific monitors and a DFW area average, was within the specified accuracy benchmarks (e.g., wind speed difference less than or equal to two meters per second: WSPD ≤ 2 m/s). All performance evaluation products are available on TCEQ's ftp site (ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/DFW8H2/mm5).



Notes: WDIR = Wind Direction; WSPD = Wind Speed; TEMP = Temperature

Figure 1-10: June 2006 Meteorological Modeling Performance

As Figure 1-10 shows for the DFW area, MM5 performed very well for winds and temperature, with all benchmarks above 90%. Wind speed performance was excellent at the individual monitors noted, though wind direction errors were higher. Note that observed wind direction is less accurate when wind speeds are low, a condition often observed during ozone exceedances. Episode average temperatures were replicated well at the DFW monitors.

Table 1-5: *DFW Meteorological Modeling Percent Accuracy* provides an additional evaluation of MM5 predictions to stricter benchmarks (Emery et al., 2001). The model's ability to replicate wind direction and speed within 20 degrees and 1 m/s on average enhances the confidence in this modeling setup.

Table 1-5: DFW Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	92 / 84 / 63	99 / 85 / 48	92 / 67 / 39
Eagle Mountain Lake	77 / 67 / 40	93 / 64 / 35	84 / 56 / 29
Denton	82 / 70 / 42	81 / 45 / 25	88 / 57 / 31
Dallas North	83 / 70 / 44	96 / 62 / 32	94 / 79 / 52
Fort Worth NW	77 / 67 / 42	96 / 74 / 43	89 / 62 / 36
Weatherford	75 / 64 / 37	92 / 63 / 33	85 / 56 / 29
Frisco	84 / 71 / 48	95 / 69 / 38	88 / 55 / 28
Midlothian Tower	80 / 62 / 35	89 / 60 / 33	93 / 70 / 40

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Kaufman	76 / 62 / 34	95 / 71 / 39	90 / 62 / 33

Figure 1-11: *DFW Area Average Wind Direction and Speed Scatter Plots* present the model's prediction versus the observations for each hour of the episode for wind direction and speed. Night and daytime hours are depicted by blue and red circles, respectively. Very few hours (circles) fell outside the error benchmarks, indicating the model performed well on average.

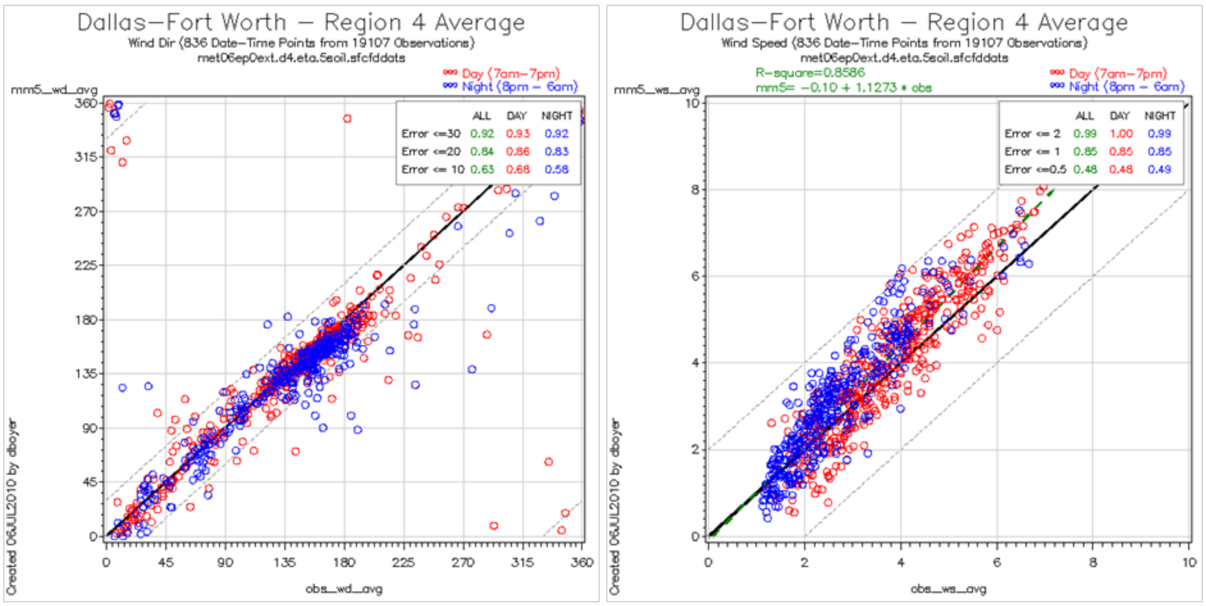


Figure 1-11: DFW Area Average Wind Direction and Speed Scatter Plots

The following three plots exhibit the wind direction, wind speed, and temperature time series of the average of all DFW monitors. MM5 follows the observations closely for almost all time periods. The wind patterns near frontal passages appear to have the highest bias and error (e.g. June 1-2, June 13-14, June 18) as shown in Figure 1-12: *DFW Average Wind Direction Time Series* and Figure 1-13: *DFW Average Wind Speed Time Series*. On most days MM5 replicated the diurnal pattern of temperature well (Figure 1-14: *DFW Average Temperature Time Series*).

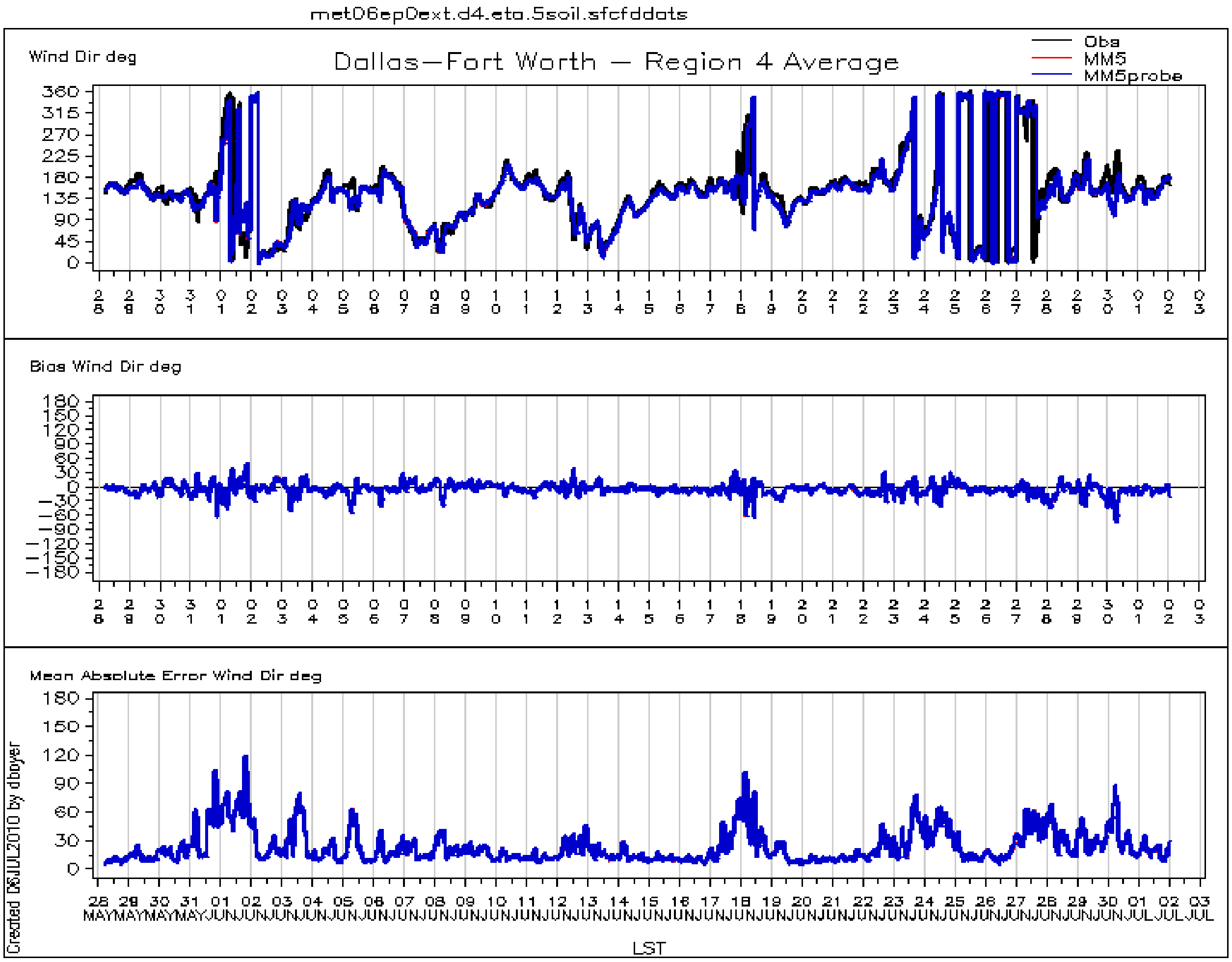


Figure 1-12: DFW Average Wind Direction Time Series

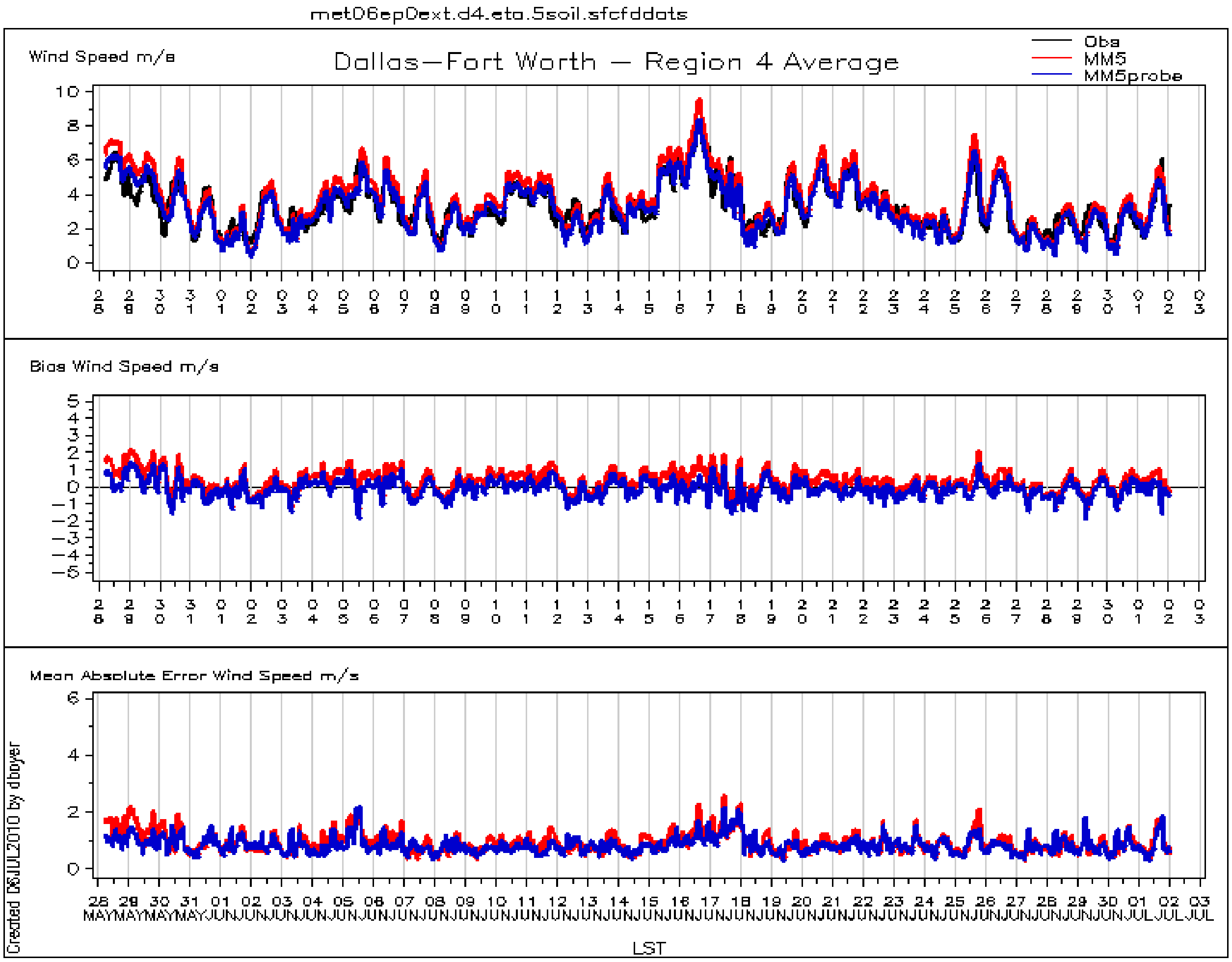


Figure 1-13: DFW Average Wind Speed Time Series

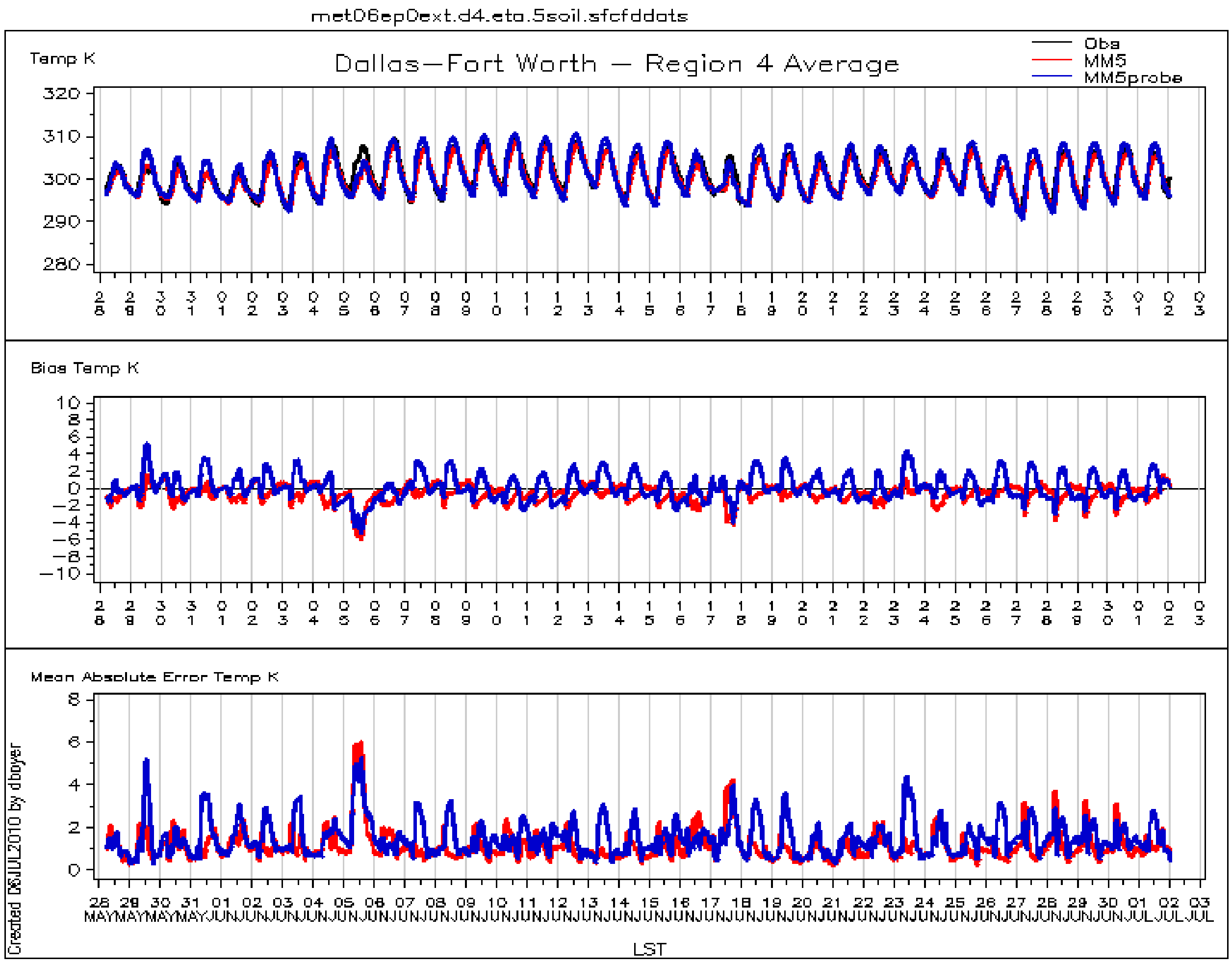


Figure 1-14: DFW Average Temperature Time Series

1.4.2 June 9, 2006 Performance Evaluation

Clear skies, high temperatures, and slow south-easterly winds contributed to the high ozone on June 9, 2006 as high pressure was centered over northern Louisiana and southern Arkansas. The peak eight-hour ozone was 106 ppb at Eagle Mountain Lake and Denton Airport. Eight monitors recorded eight-hour exceedances, all on the west and north sides of DFW. The winds were very stable on this day and the model replicated those conditions very well (Figure 1-15: *June 9, 2006 Wind Direction and Speed Scatter Plots*). Table 1-6: *June 9, 2006 Meteorological Modeling Percent Accuracy* shows that the wind direction performance for the representative monitors was similar, except for the Eagle Mountain Lake monitor. This error could be due to local conditions including a lake-breeze influence from Eagle Mountain Lake. Wind speed and temperature performance at all selected monitors was very good.

Table 1-6: June 9, 2006 Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	92 / 84 / 93	99 / 85 / 48	92 / 67 / 39
Eagle Mountain Lake	67 / 54 / 38	96 / 75 / 54	92 / 54 / 33

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Denton	93 / 58 / 38	88 / 46 / 21	92 / 58 / 17
Dallas N	100 / 88 / 50	96 / 71 / 33	100 / 83 / 71
Fort Worth NW	96 / 88 / 63	92 / 71 / 42	92 / 67 / 25
Weatherford	75 / 58 / 21	96 / 54 / 21	92 / 42 / 25
Frisco	91 / 74 / 57	100 / 87 / 43	91 / 78 / 22
Midlothian Tower	79 / 58 / 29	96 / 63 / 38	100 / 83 / 50
Kaufman	92 / 83 / 54	100 / 92 / 58	92 / 50 / 17

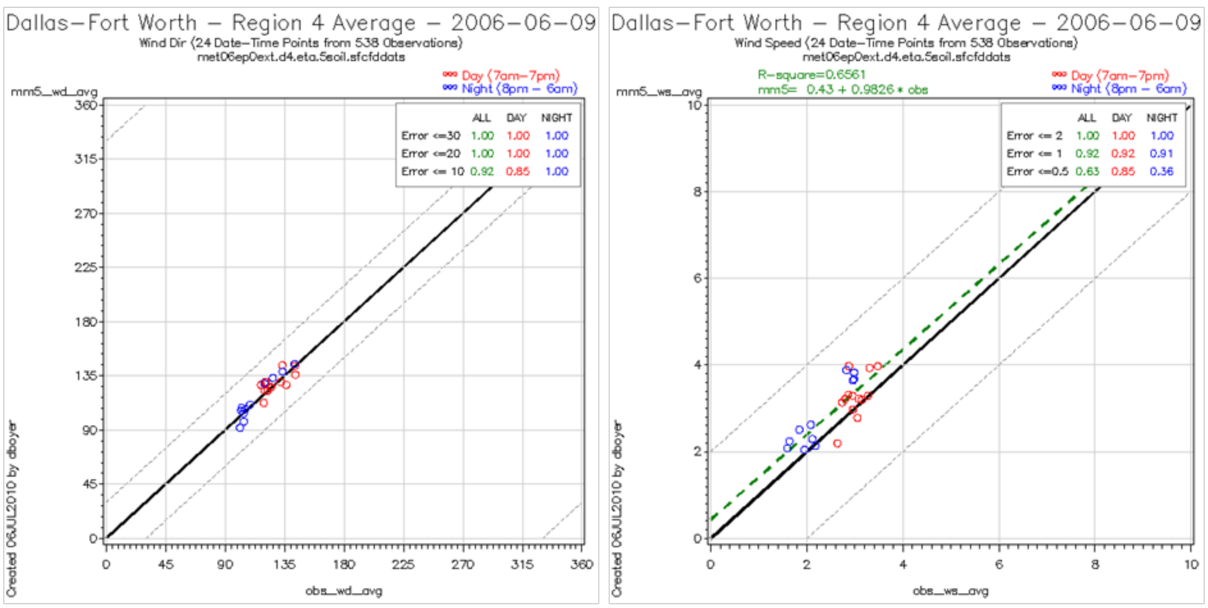


Figure 1-15: June 9, 2006 Wind Direction and Speed Scatter Plots

The back trajectories also depict how well the model replicated observed winds on this day (Figure 1-16: *June 9, 2006 12-hour Backward Trajectory*). At most monitors (receptors) the modeled and observed trajectories track closely for most of the 12-hour time frame. This indicates the photochemical modeling should advect emissions from the appropriate sources towards the monitors.

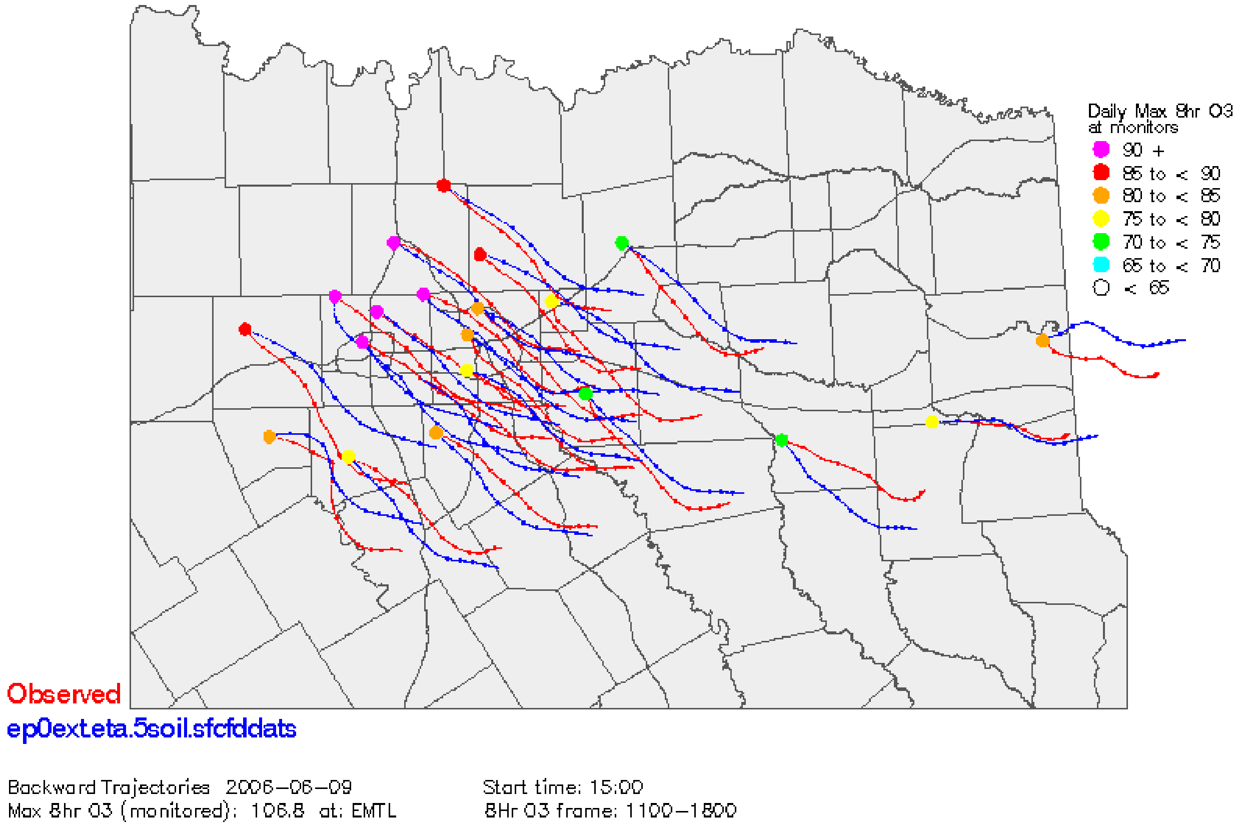


Figure 1-16: June 9, 2006 12-hour Backward Trajectory

Aloft, MM5 resolved much of the flow and PBL structure at the Cleburne profiler. As Figure 1-17: *Time-height plot for the Cleburne Profiler on June 9, 2006* exhibits, winds were generally from the southeast and 10 m/s or less above the surface. MM5 captures these winds well. The model does not capture the morning growth of the PBL from 10-12 CST but matches the afternoon peak well.

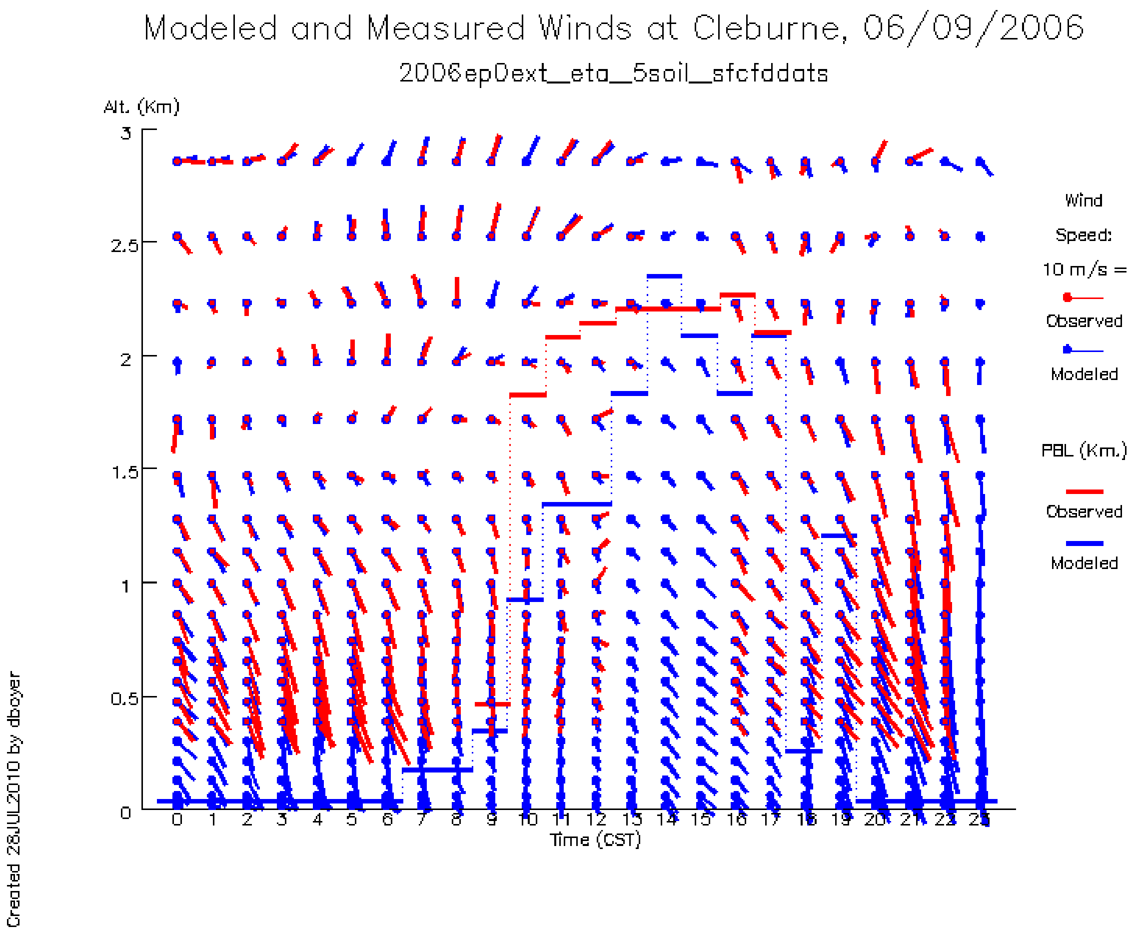


Figure 1-17: Time-height plot for the Cleburne Profiler on June 9, 2006

1.4.3 June 13, 2006 Performance Evaluation

Seven monitors recorded exceedances of the 1997 eight-hour ozone NAAQS on June 13, 2006. The peak eight-hour ozone, 98 ppb, was measured at the Cleburne and Midlothian Tower monitors on the southern side of the DFW. The major weather pattern along the Gulf of Mexico was Tropical Storm Alberto, which made landfall in northwest Florida on this day. The main flow on the northwest side of this low pressure system brought north to northeast winds towards Texas. A weak cold front had also passed through DFW, bringing northeast winds on the back side. The skies were generally clear with temperatures in the upper 80s.

MM5 did a good job replicating the wind and temperature observations on this day as the percent of hours within the error benchmarks was very high on average and at most monitors (Table 1-7: *June 13, 2006 Meteorological Modeling Percent Accuracy*). The wind direction and speed scatter plots, Figure 1-18: *June 13, 2006 Wind Direction and Speed Scatter Plots*, shows winds only from the northeast (0 – 90 degrees) at speeds less than 5 m/s. The scatter is small and almost all points fall along the one-to-one line.

Table 1-7: June 13, 2006 Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	100 / 96 / 75	100 / 88 / 50	100 / 100 / 58
Eagle Mountain Lake	91 / 83 / 35	87 / 52 / 17	100 / 70 / 39
Denton	100 / 96 / 58	100 / 63 / 50	100 / 100 / 58
Dallas N	83 / 75 /38	100 / 71 / 29	100 / 79 / 42
Fort Worth NW	75 / 67 / 50	88 / 58 / 29	100 / 92 / 54
Weatherford	100 / 95 / 77	82 / 59 / 14	100 / 86 / 55
Frisco	100 / 88 / 58	100 / 46 / 17	100 / 96 / 58
Midlothian Tower	96 / 71 / 38	96 / 54 / 33	96 / 67 / 33
Kaufman	88 / 79 / 58	100 / 83 / 25	100 / 71 / 63

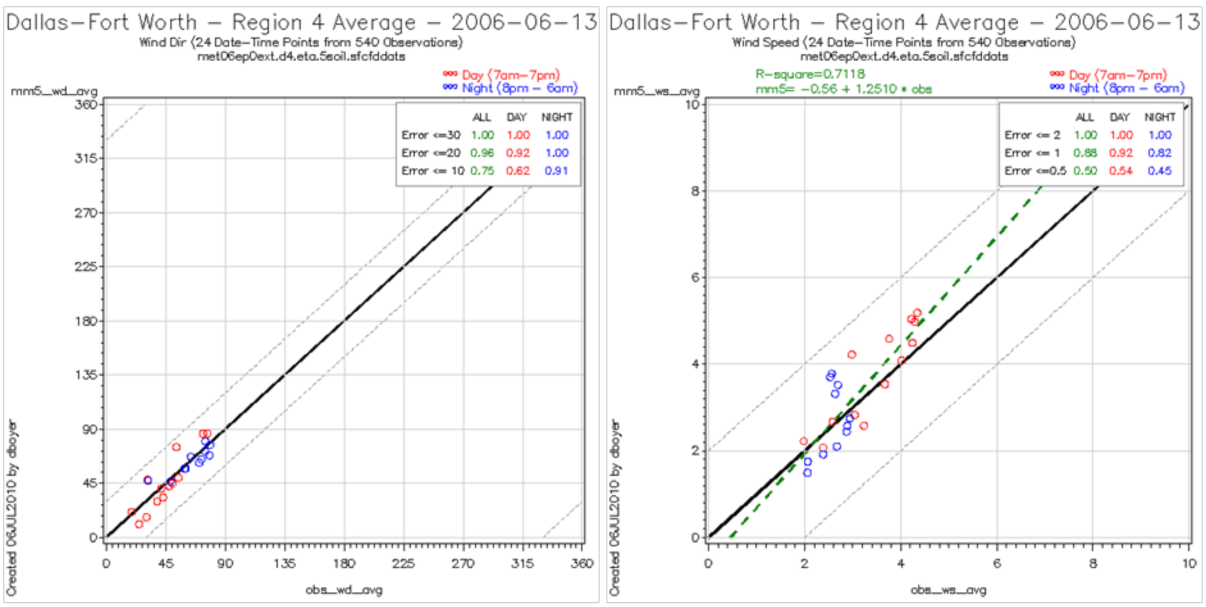


Figure 1-18: June 13, 2006 Wind Direction and Speed Scatter Plots

As with the scatter plots, the back trajectories also show good model performance (Figure 1-19: *June 13, 2006 12-hour Backward Trajectory*). About six hours back into the trajectory the winds shifted from the east to the northeast. The model's timing of this shift is off an hour or so for many of the monitors in the DFW area. This may affect the placement of the highest ozone in the domain. The lengths of the trajectories appear similar indicating the model replicated the wind speed well.

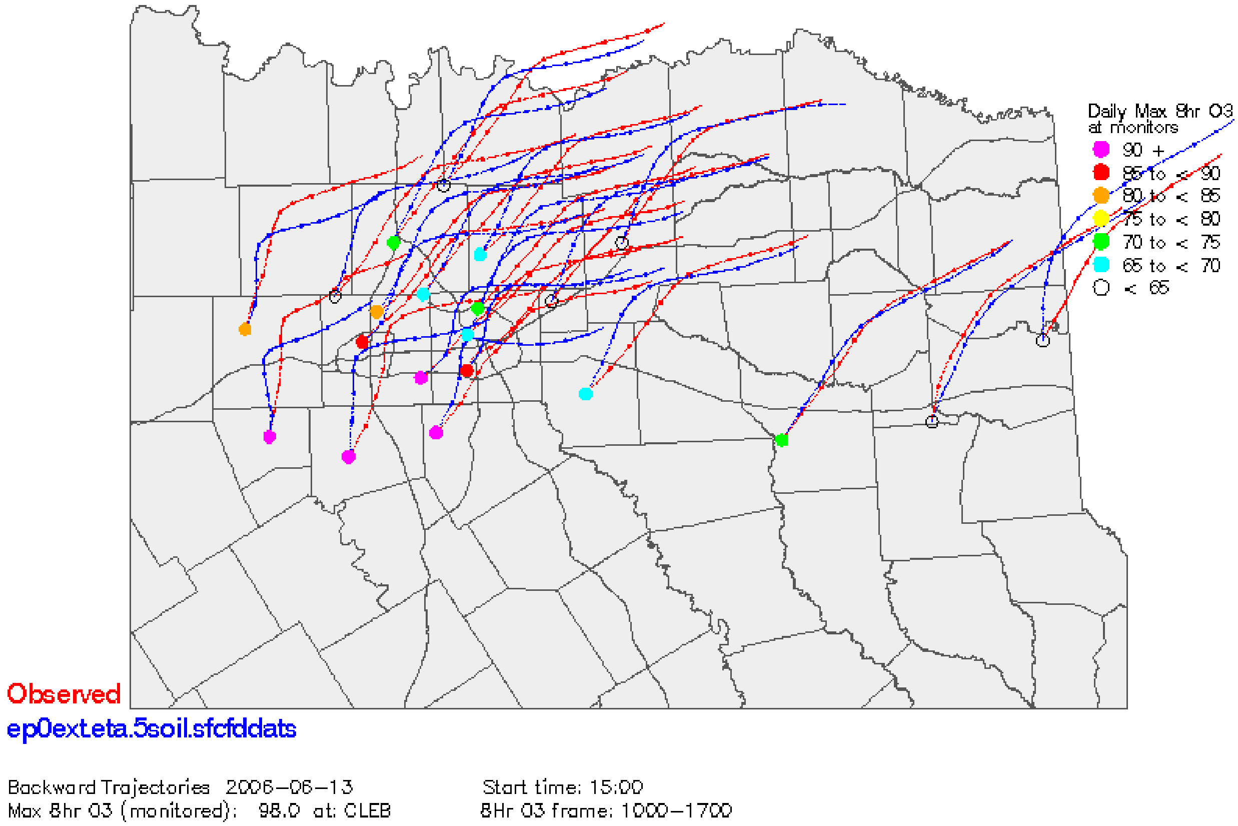


Figure 1-19: June 13, 2006 12-hour Backward Trajectory

At the Cleburne profiler, the model simulates the wind speed and direction throughout the 3 km depth of the observations very well (Figure 1-20: *Time-height plot for the Cleburne Profiler on June 13, 2006*). As the day progresses, the wind shifts aloft from the east in the morning to the northeast in the afternoon, similar to the surface trajectories. The model captures this shift well. The peak mixing depth is underestimated by about 800 meters. At 3 PM CST, the model's mixing height drops rapidly as observations end so the performance is unknown.

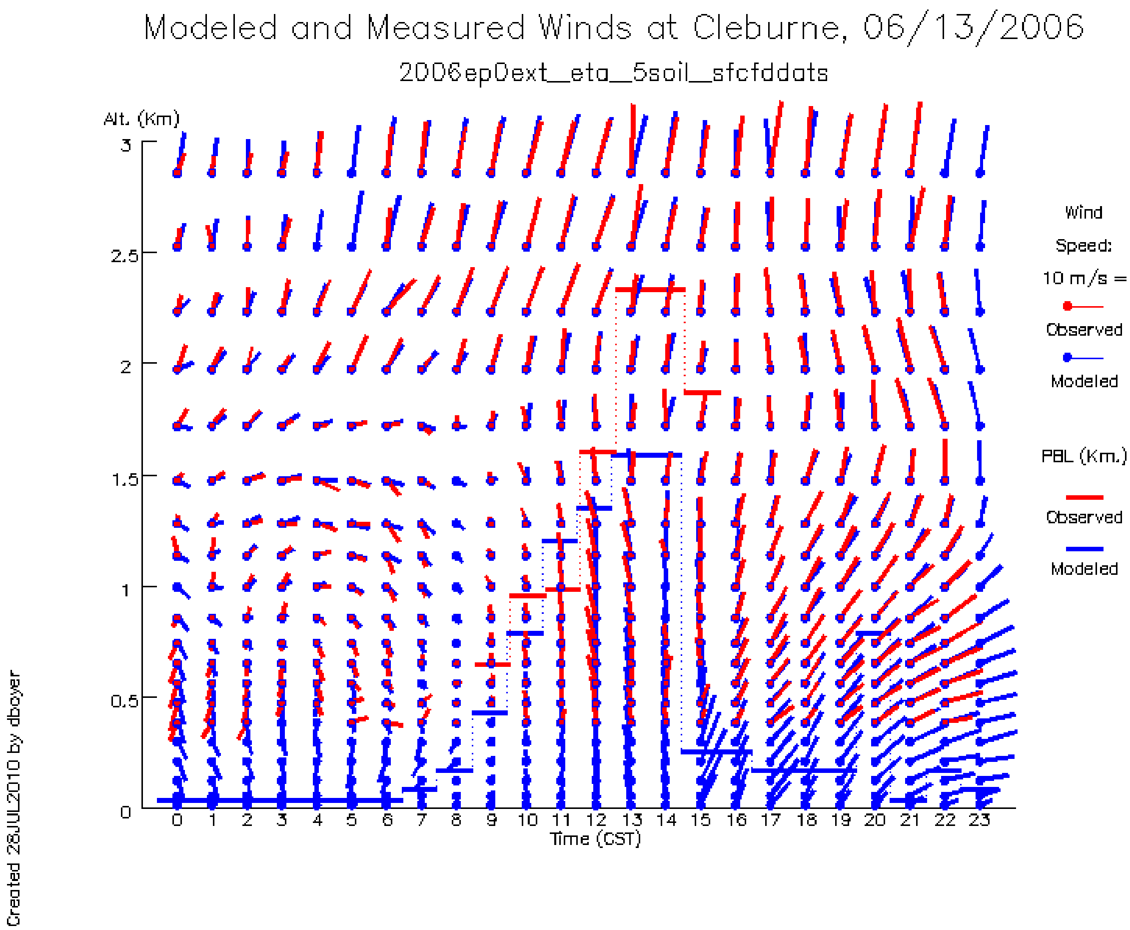


Figure 1-20: Time-height plot for the Cleburne Profiler on June 13, 2006

1.4.4 June 14, 2006 Performance Evaluation

The post-frontal regime continued on June 14, 2006 with east to southeast winds flowing for most of the day. Long range 48-hour backward trajectories (not shown) exhibit flow from the direction of the Ohio Valley. Those types of conditions can bring elevated background ozone concentrations, along with the observed clear skies and temperatures in the low 90s. Six monitors on the west side of DFW exceeded 84 ppb on this day, with a peak of 107 ppb at Eagle Mountain Lake. Wind and temperature performance on this day according to the error benchmarks were excellent (Table 1-8: *June 14, 2006 Meteorological Modeling Percent Accuracy*). The scatter plots also show the model replicated the observed wind direction and speed very well, on average (Figure 1-21: *June 14, 2006 Wind Direction and Speed Scatter Plots*).

Table 1-8: June 14, 2006 Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	100 / 100 / 96	100 / 88 / 54	100 / 71 / 54
Eagle Mountain Lake	92 / 88 / 54	100 / 92 / 50	100 / 71 / 42
Denton	92 / 83 / 54	92 / 54 / 21	96 / 63 / 33

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Dallas N	96 / 79 / 63	100 / 88/ 63	100 / 96 / 75
Fort Worth NW	100 / 83 / 54	100 / 83 / 33	100 / 88 / 42
Weatherford	100 / 92 / 38	96 / 58 / 29	100 / 50 / 21
Frisco	100 / 96 / 63	100 / 88 / 58	100 / 83 / 38
Midlothian Tower	100 / 92 / 63	92 / 75 / 50	100 / 88 / 46
Kaufman	100 / 75 / 42	96 / 75 / 38	96 / 58 / 25

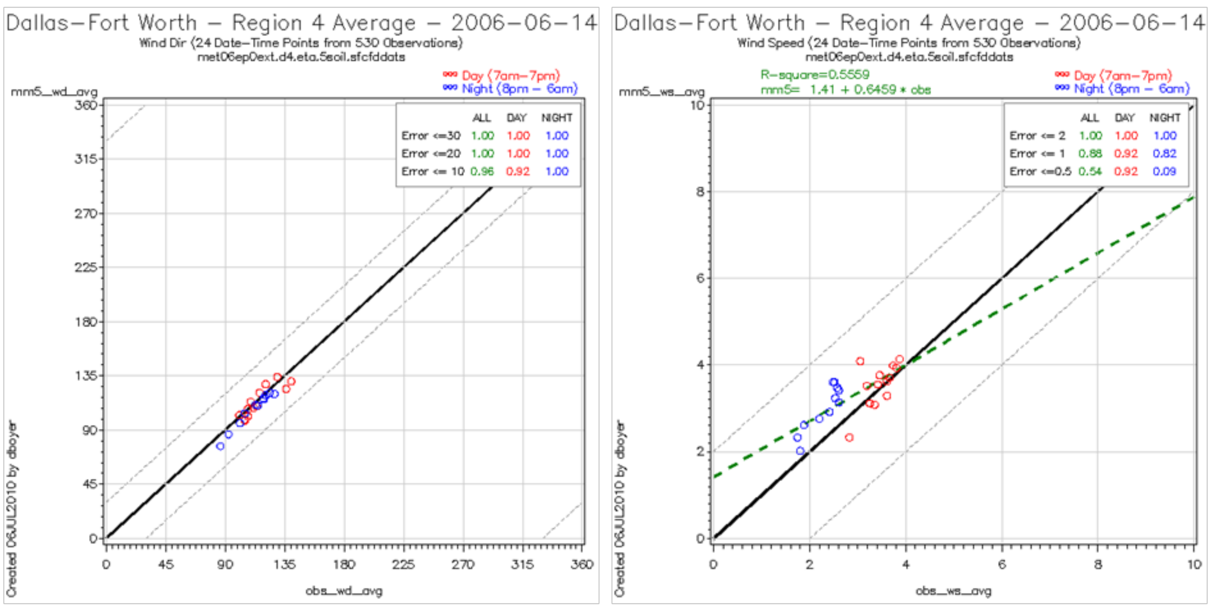


Figure 1-21: June 14, 2006 Wind Direction and Speed Scatter Plots

As with the scatter plots, the model's trajectories almost matched the observed (Figure 1-22: *June 14, 2006 12-hour Backward Trajectory*). Small wind shifts and the overall length of the trajectories were very similar. The steady flow (easterly) is a condition the model is suited to replicate well.

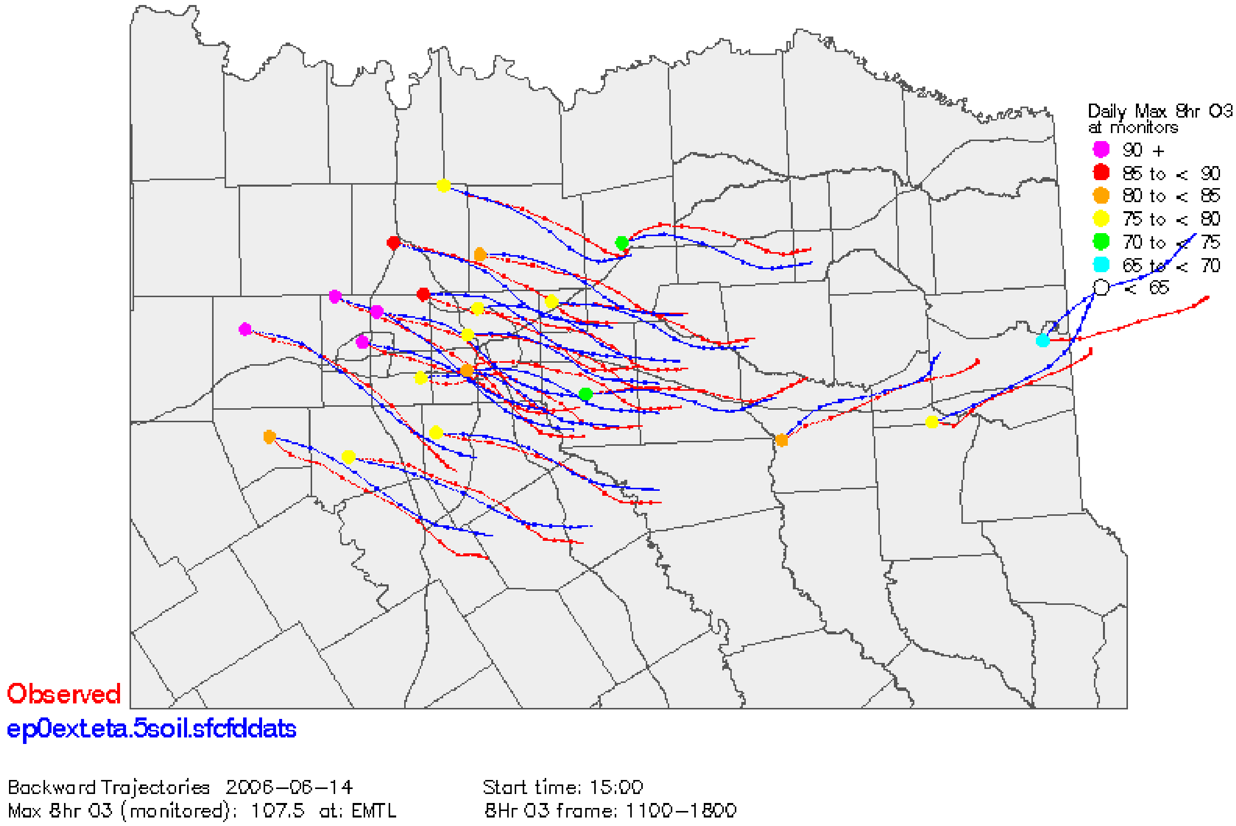


Figure 1-22: June 14, 2006 12-hour Backward Trajectory

As on June 13, 2006, MM5 replicates the upper air winds very well in comparison to the Cleburne profiler data (Figure 1-23: *Time-height plot for the Cleburne Profiler on June 14, 2006*). The atmosphere appeared uniform with south to southeast winds, a situation that the models predict well. Observations of the PBL were not available on this day.

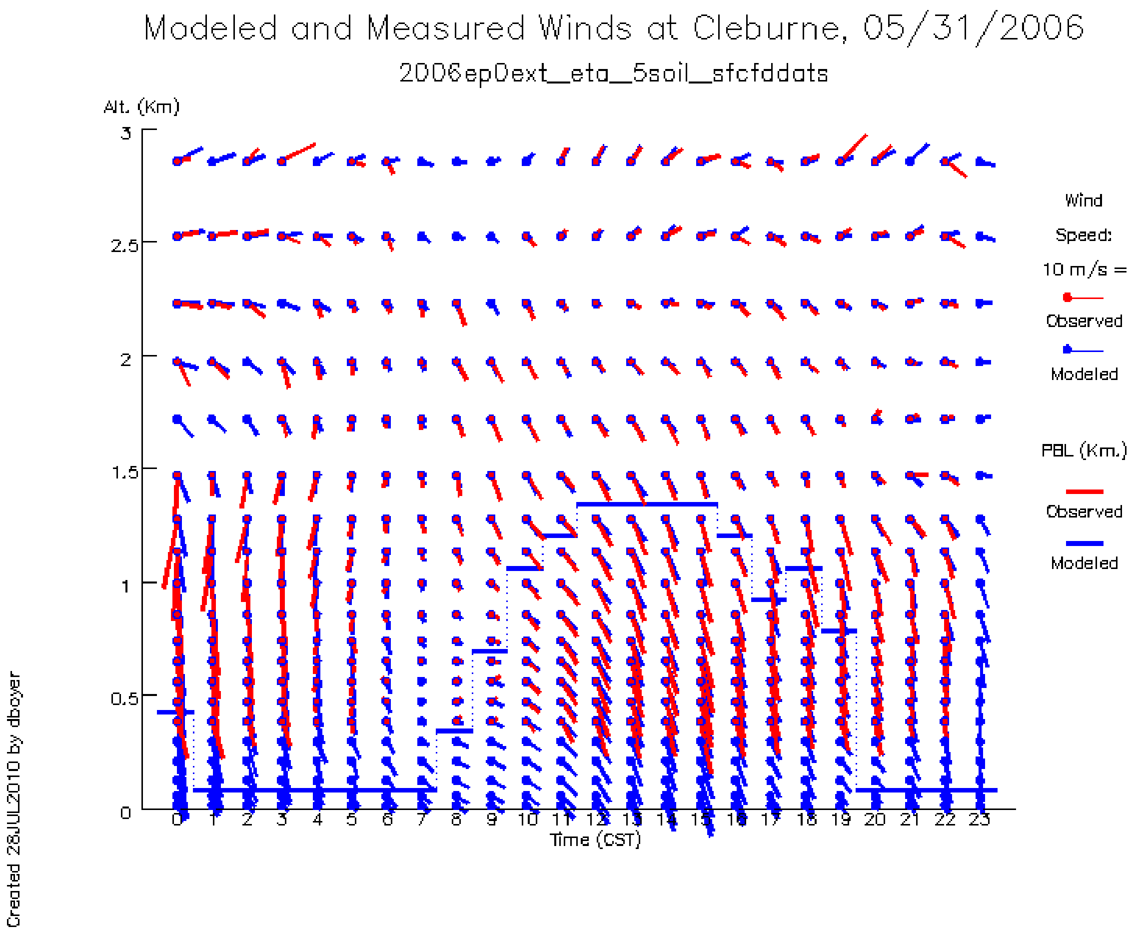


Figure 1-23: Time-height plot for the Cleburne Profiler on June 14, 2006

1.4.5 June 18, 2006 Performance Evaluation

June 18, 2006 was a difficult day for the model to replicate. The previous day had strong southerly flow with significant cloud cover. A low pressure system came through the area that brought brief northwest winds that stalled and then slowly reversed to come from the south. In the late afternoon weak southeast winds returned. Eight monitors exceeded the 84 ppb standard with the peak of 97 ppb at Denton Airport South.

As Table 1-9: *June 18, 2006 Meteorological Modeling Percent Accuracy* shows, the model had difficulty in simulating the wind directions. The wind speeds were very slow on this day (and well replicated), which should make the wind direction less important for ozone and ozone precursor transport. During some hours though, MM5's wind direction was off by more than 100 degrees (Figure 1-24: *June 18, 2006 Wind Direction and Speed Scatter Plots*).

Table 1-9: June 18, 2006 Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	75 / 54 / 29	100 / 67 / 29	100 / 75 / 46
Eagle Mountain Lake	57 / 52 / 22	91 / 70 / 57	96 / 83 / 35

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Denton	71 / 58 / 29	88 / 71 / 33	100 / 54 / 33
Dallas N	46 / 42 / 25	100 / 63 / 29	96 / 92 / 67
Fort Worth NW	58 / 46 / 29	96 / 63 / 29	92 / 75 / 46
Weatherford	54 / 42 / 21	96 / 71 / 50	92 / 75 / 33
Frisco	63 / 54 / 38	79 / 50 / 21	83 / 54 / 21
Midlothian Tower	46 / 29 / 04	88 / 71 / 42	100 / 92 / 54
Kaufman	50 / 29 / 17	88 / 58 / 08	88 / 42 / 08

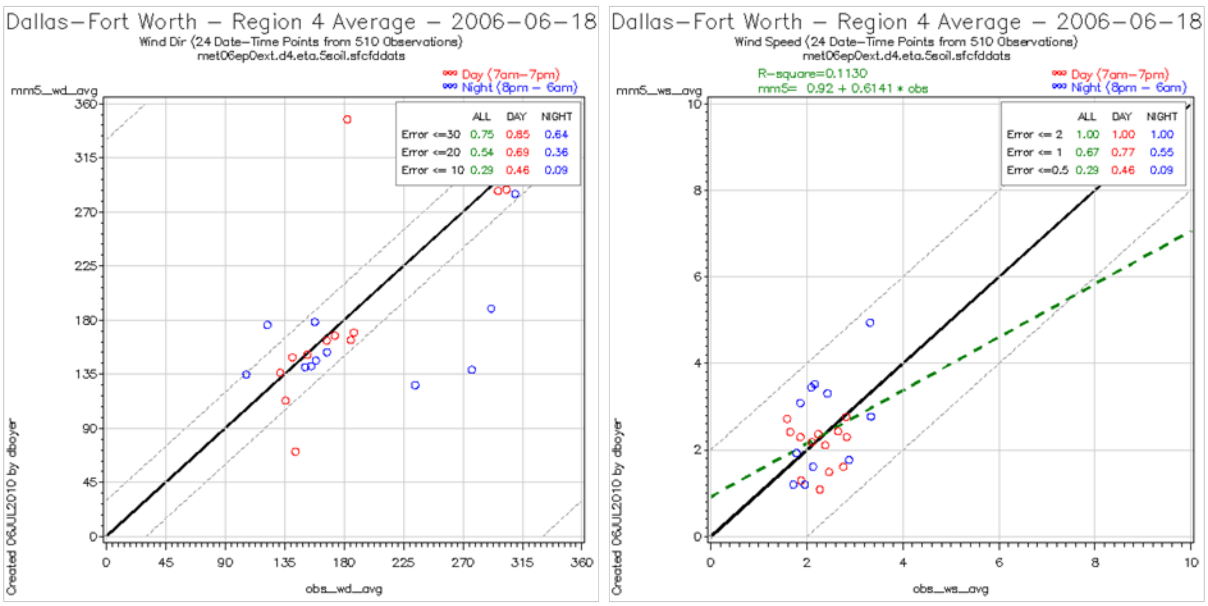


Figure 1-24: June 18, 2006 Wind Direction and Speed Scatter Plots

Figure 1-25: *June 18, 2006 12-hour Backward Trajectory* also displays the drastic wind shift and slow wind speeds via the short curvy trajectories. While the start and ending points of some of the modeled trajectories are close to the observed trajectories, the path taken is different. Other modeled trajectories deviate significantly from the observed, including those from the monitors that measured the peak ozone concentrations (magenta dots).

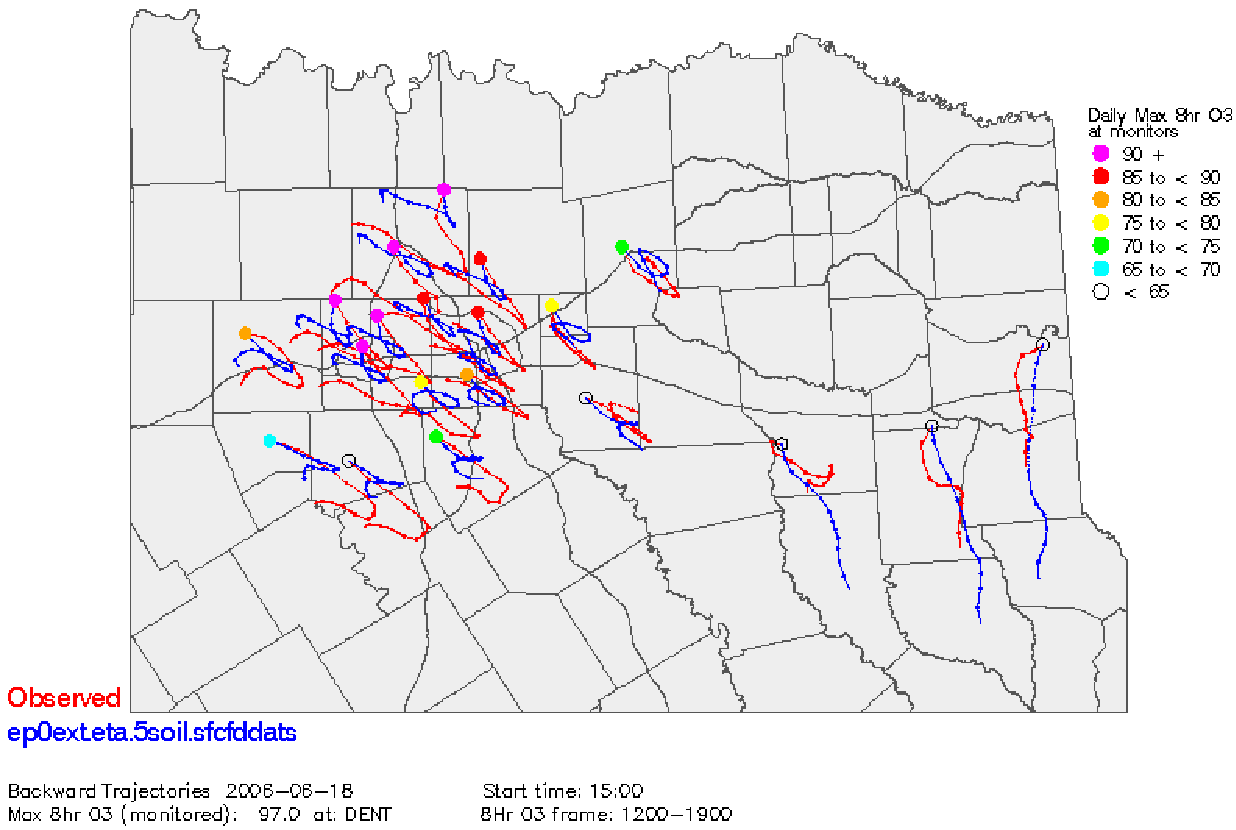


Figure 1-25: June 18, 2006 12-hour Backward Trajectory

MM5 does a respectable job of replicating the upper air winds at the Cleburne profiler, especially in the afternoon (Figure 1-26: *Time-height plot for the Cleburne Profiler on June 18, 2006*). The morning winds are not as well represented during the northeasterly flow. The model captures the growth, peak, and collapse of the PBL.

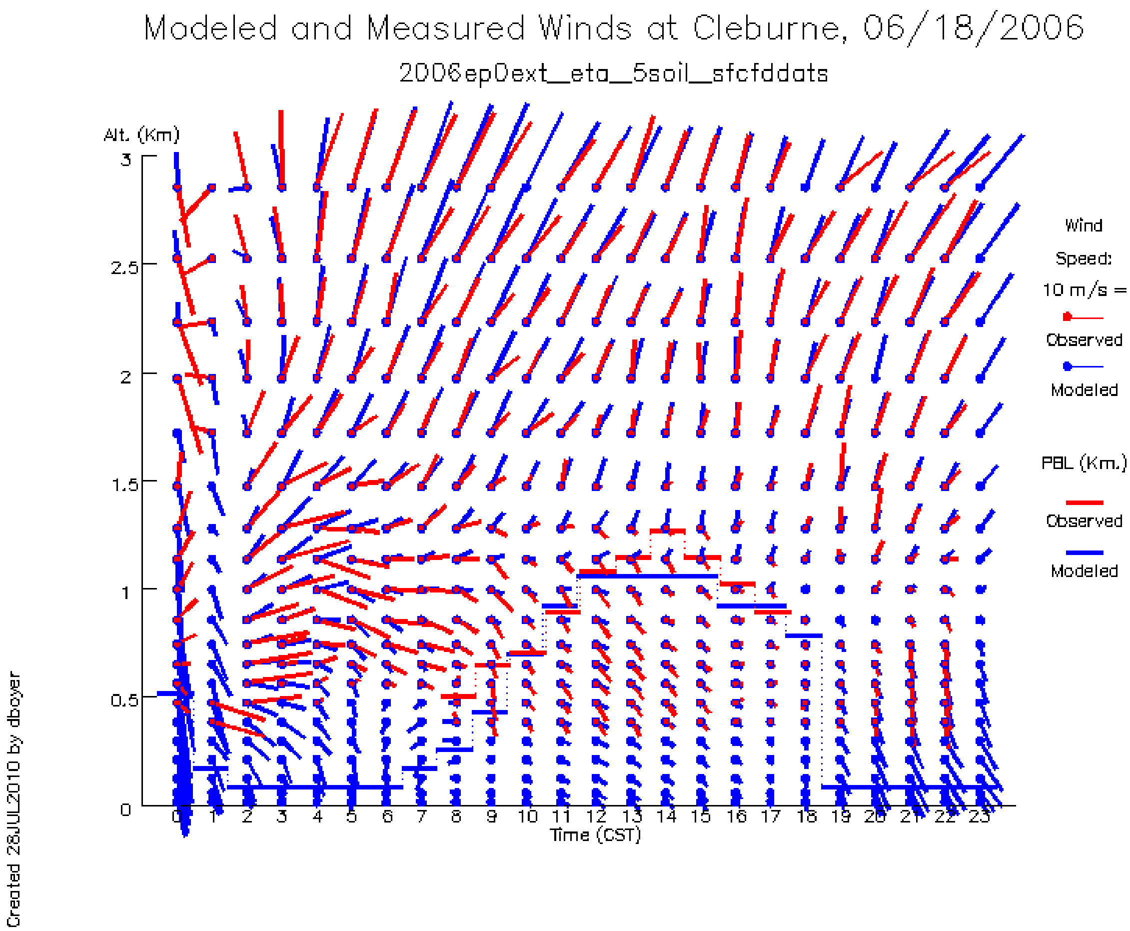


Figure 1-26: Time-height plot for the Cleburne Profiler on June 18, 2006

1.4.6 June 28, 2006 Performance Evaluation

High pressure was centered to the east of Texas on June 28, 2006, which brought light southerly winds. Skies were generally clear with temperatures in the low 90s. Six sites on the northwest and north side of DFW measured eight-hour ozone exceedances, with the peak of 98 ppb at Eagle Mountain Lake. Elevated background ozone may have contributed to the exceedances as upwind sites such as Kaufman measured 70 – 75 ppb.

MM5 replicated the overall pattern of winds on this day, though the wind direction statistics suffered somewhat due to the meandering southerly winds over the course of the day (Table 1-10: *June 28, 2006 Meteorological Modeling Percent Accuracy*; Figure 1-27: *June 28, 2006 Wind Direction and Speed Scatter Plots*). Wind speed and temperature performance was good.

Table 1-10: June 28, 2006 Meteorological Modeling Percent Accuracy

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Area Average	83 / 71 / 50	100 / 88 / 71	83 / 71 / 50
Eagle Mountain Lake	63 / 33 / 25	100 / 71 / 25	88 / 54 / 29

DFW Area	Wind Direction (°) Error ≤ 30 / 20 / 10	Wind Speed (m/s) Error ≤ 2 / 1 / 0.5	Temperature (°C) Error ≤ 2 / 1 / 0.5
Denton	67 / 46 / 25	79 / 50 / 42	88 / 63 / 33
Dallas N	80 / 53 / 40	100 / 67 / 33	94 / 88 / 81
Fort Worth NW	58 / 50 / 29	100 / 58 / 38	83 / 38 / 21
Weatherford	48 / 43 / 17	87 / 43 / 26	70 / 48 / 26
Frisco	67 / 63 / 42	96 / 63 / 46	83 / 33 / 13
Midlothian Tower	54 / 38 / 17	71 / 50 / 25	75 / 54 / 29
Kaufman	50 / 33 / 21	100 / 83 / 42	83 / 58 / 25

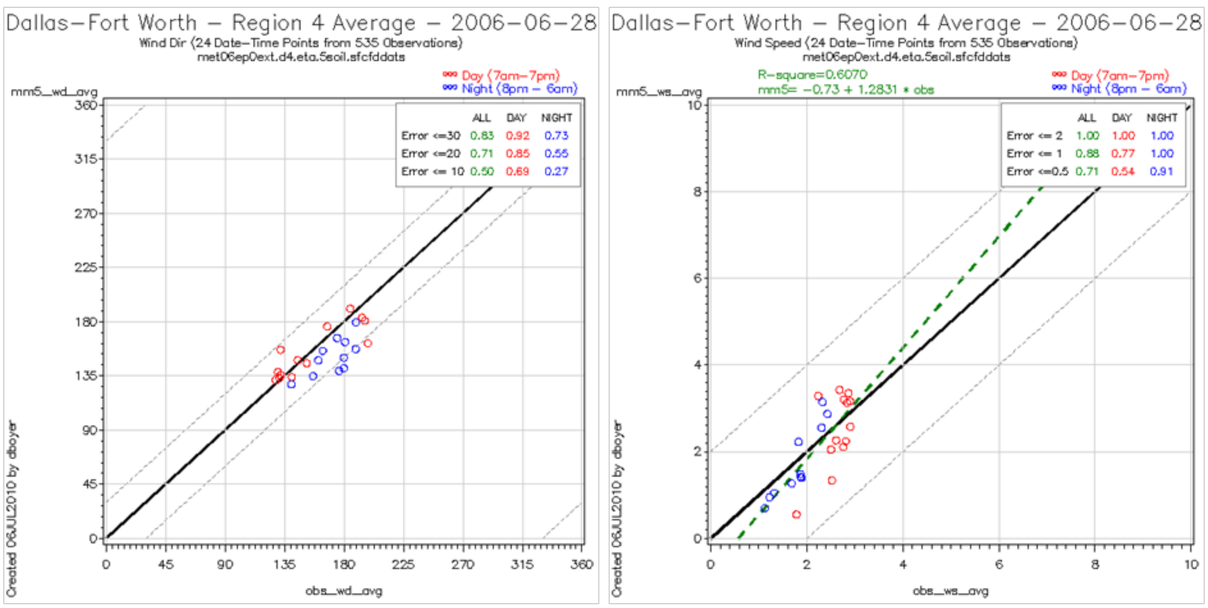


Figure 1-27: June 28, 2006 Wind Direction and Speed Scatter Plots

As Table 1-10 and Figure 1-27 showed, MM5 matched the observed wind speeds well. The back trajectories also show this as the modeled trajectories are of similar length to the observed trajectories. The difference in wind direction can be seen via some monitor's trajectories though, as the modeled and observed trajectories diverge. Overall, MM5 reproduced the wind patterns on this day.

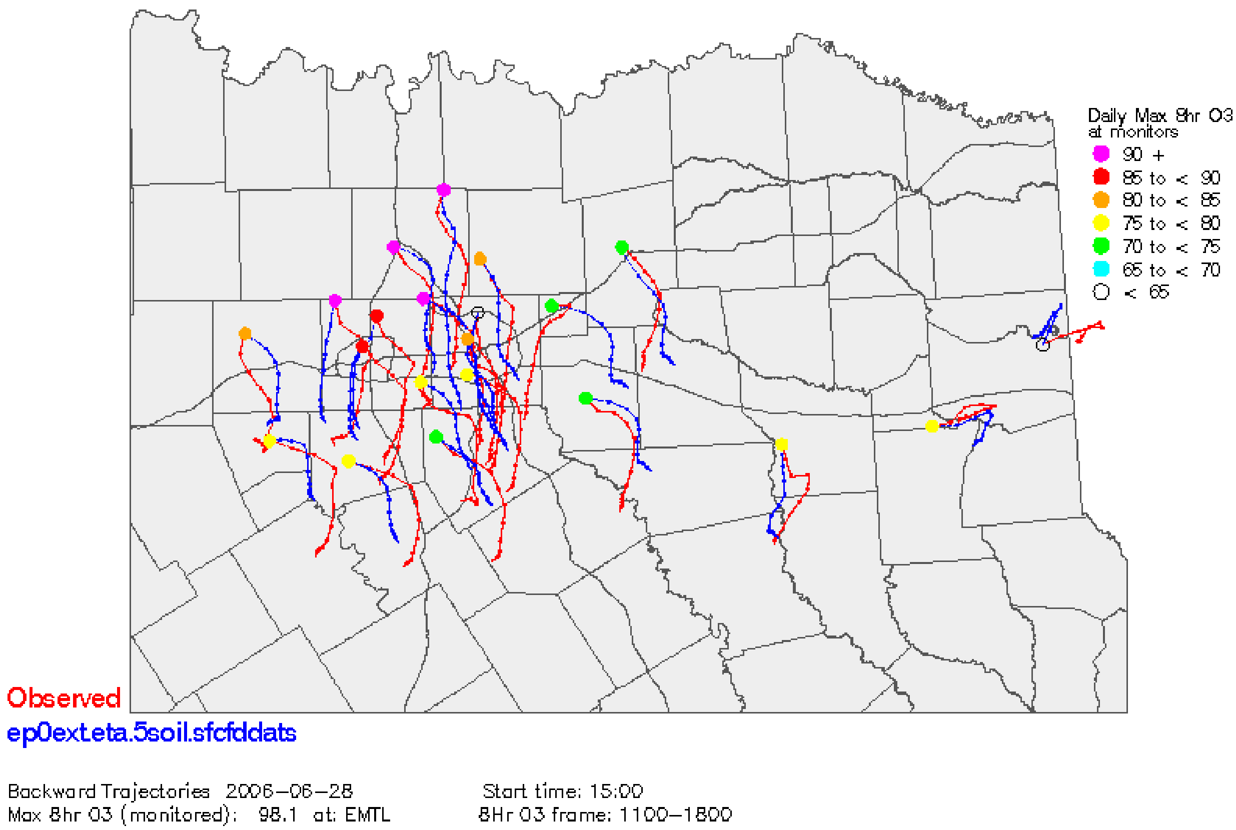


Figure 1-28: June 28, 2006 12-hour Backward Trajectory

At the Cleburne profiler, MM5 replicates the aloft winds well (Figure 1-29: *Time-height plot for the Cleburne Profiler on June 28, 2006*). The reduction in wind speeds from late morning to mid-afternoon was captured appropriately. However from 10 AM on the model underestimates the PBL height, indicating a vertical mixing problem.

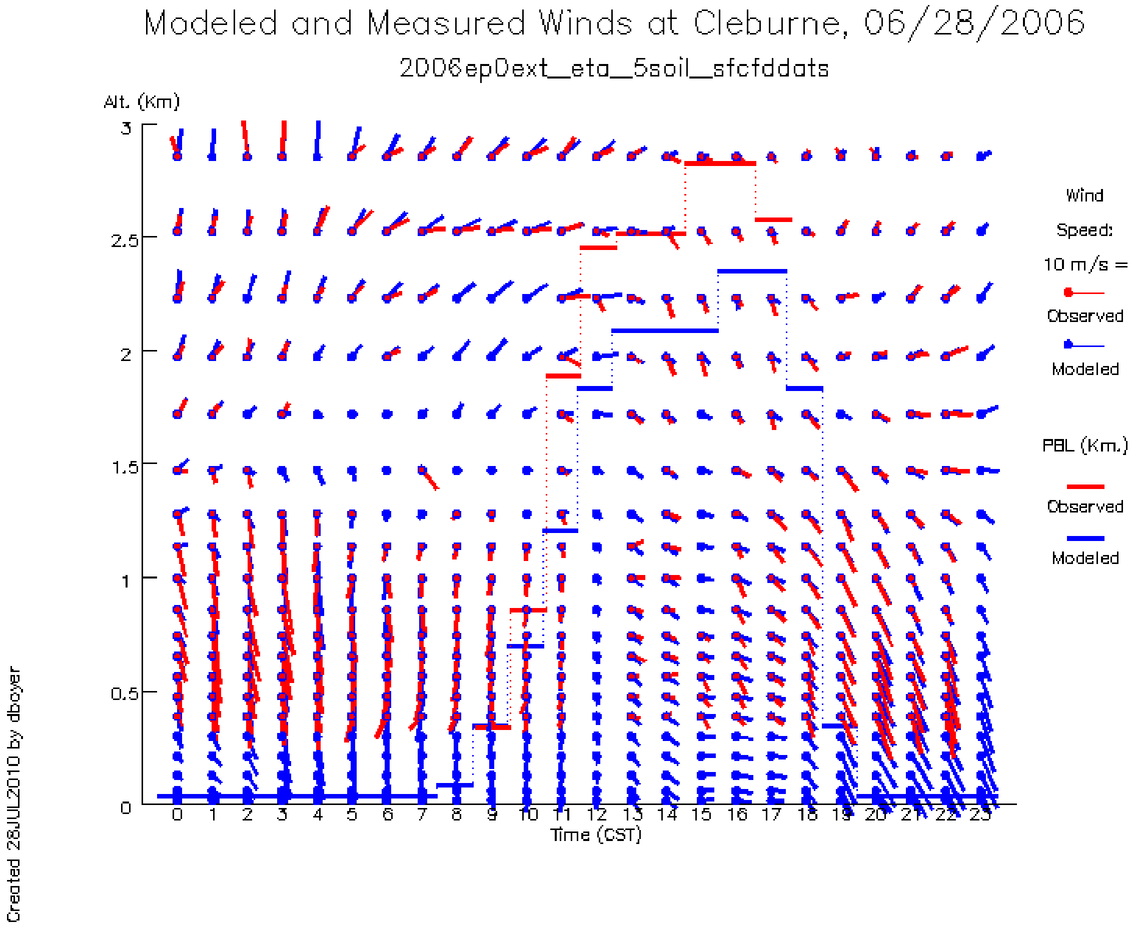


Figure 1-29: Time-height plot for the Cleburne Profiler on June 28, 2006

1.5 REFERENCES

Banta, R. M., C. J. Senff, J Nielsen-Gammon, L. S. Darby, T. B. Ryerson, R. J. Alvarez, S. P. Sandberg, E. J. Williams and M. Trainer (2005), A bad air day in Houston, *Bulletin of the American Meteorological Society*, *86*(5), 657+, 10.1175/BAMS-86-5-657

Berkowitz, C.M., Spicer, C.W., Doskey, P.V (2005), Hydrocarbon observations and ozone production rates in western Houston during the Texas 2000 air quality study. Atmospheric Environment 39 (19), 3383–3396.

Chen, F., and J. Dudhia (2001), Coupling an advanced land-surface hydrology model with the Penn State - NCAR MM5 modeling system. Part I: Model implementation and sensitivity, Mon. Wea. Rev., 129, 569–585.

Emery, C., E. Tai, and G. Yarwood (2001), Enhanced Meteorological Modeling and Performance Evaluation for Two Texas Ozone Episodes, Final Report to the Texas Natural Resource Conservation Commission under TNRCC Umbrella Contract No. 582-0-31984, Environ International Corporation, Novato, CA.

Emery, C., J. Johnson, and P. Piyachaturawat (2009a), Application of MM5 for the Austin/San Antonio Joint Meteorological Model Refinement Project. Report to the Alamo Area Council of Governments and the Capitol Area Association of Governments, April 30, 2009.

Emery, C., J. Johnson, P. Piyachaturawat, and G. Yarwood (2009b), MM5 Meteorological Modeling of Texas for June 2006, http://www.tceq.state.tx.us/assets/public/implementation/air/am/contracts/reports/mm/5820783986FY0802_June2006MM5_Final.pdf

Environ (2008), Description from MM5CAMx README file contained in mm5camx.21feb08.tar.gz archive, http://www.camx.com/files/mm5camx.21feb08.tar.gz, Environ Holdings, Inc., Last accessed May 5, 2009.

EPA (2007), Guidance on the Use of Models and Other Analyses for Demonstrating Attainment of Air Quality Goals for Ozone, PM2.5, and Regional Haze, http://www.epa.gov/scram001/guidance/guide/final-03-pm-rh-guidance.pdf, EPA-454/B-07-002, 162, Last accessed March 26, 2009.

Grell, G., J. Dudhia, and D. Stauffer (1994), A description of the Fifth Generation Penn State/NCAR Mesoscale Model (MM5), Tech. Rep. NCAR/TN-398+STR, National Center of Atmospheric Research (NCAR) Tech Note.

Janjic, Z. I. (1994), The step-mountain Eta coordinate model: Further developments of the convection, viscous sublayer, and turbulence closure schemes, Mon. Wea. Rev., 122, 927–945.

Knoderer, C. A., S. A. Bratek, C. P. MacDonald (2008), Spatial and Temporal Characteristics of Winds and Mixing During TexAQS-II, Final Report to Texas A&M University for Texas Commission on Environmental Quality Proposal under Grant Activity 582-5-64593-FY08-20, Sonoma Technology Inc, Petaluma, CA, April 2008.

McNider (2009), Stationary Front Experiment Comparison of Flight and Model Data, Final Report for Project H109 to the Houston Advanced Research Center (HARC), http://files.harc.edu/Projects/AirQuality/Projects/H109/H109FinalReport.pdf.

NCAR (2005a), Appendix C: How to Use Noah Land-Surface Model Option, PSU/NCAR Mesoscale Modeling System Tutorial Class Notes and User's Guide, http://www.mmm.ucar.edu/mm5/documents/MM5_tut_Web_notes/App-C/append-c.htm, Last accessed May 5, 2009.

NCAR (2005b), MM5 Online Tutorial Home Pages, http://www.mmm.ucar.edu/mm5/On-Line-Tutorial/teachyourself.html, Last accessed May 5, 2009.

NCEP, (2009), GCIP NCEP Eta model output, CISL RDA: ds609.2 Home Page, http://dss.ucar.edu/datasets/ds609.2/, Last accessed May 13, 2009.

Nielsen-Gammon (2007a), Preliminary Analysis of Ozone Meteorology during TexAQS-II Ozone Episodes, Interim Report to the Texas Commission on Environmental Quality under Proposal for Grant Activity 582-5-64593-FY07-21.

Nielsen-Gammon (2007b), Comprehensive meteorological analysis of TexAQS II episodes, Task 3 Deliverable for Texas Commission on Environmental Quality Proposal for Grant Activity 582-5-64593-FY07-21.

Stauffer, D. R., and N. L. Seaman (1990), Use of four-dimensional data assimilation in a limited area mesoscale model. Part I: Experiments with synoptic-scale data, Mon. Wea. Rev., 118, 1250–1277.

Stauffer, D. R., and N. L. Seaman (1994), Multiscale four-dimensional data assimilation, J. Appl. Meteor., 33, 416–434.

Stauffer, D. R., N. L. Seaman, and F. S. Binkowski (1991), Use of four-dimensional data assimilation in a limited area mesoscale model. Part II: Effects of data assimilation within the planetary boundary layer, Mon. Wea. Rev., 119, 734–754.

TCEQ (2005), 2005 Air Pollution Events, http://www.tceq.state.tx.us/airquality/monops/sigevents05.html, Texas Commission on Environmental Quality (TCEQ), Last accessed January 3, 2011.

TCEQ (2006), 2006 Air Pollution Events, http://www.tceq.state.tx.us/airquality/monops/sigevents06.html, Texas Commission on Environmental Quality (TCEQ), Last accessed January 3, 2011.

TCEQ (2009), Meteorological modeling performance evaluation products, Texas Commission on Environmental Quality (TCEQ) file transfer protocol (FTP) site, (ftp://ftp.tceq.state.tx.us/pub/OEPAA/TAD/Modeling/HGB8H2/mm5).

TCEQ, 2010. Adopted HGB Attainment Demonstration SIP Revision for the 1997 Eight-Hour Ozone Standard (2009-017-SIP-NR), Texas Commission on Environmental Quality, March 2010, http://www.tceq.state.tx.us/implementation/air/sip/texas-sip/hgb/hgb-latest-ozone.