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A Comparative Study of Prognostic MM5 Meteorological Modeling with Aircraft, Wind Profiler, Lidar, Tethered Balloon and RASS Data over Philadelphia during a 1999 Summer Episode

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Abstract. This study presents a comparative evaluation of the prognostic meteorological Fifth Generation NCAR Pennsylvania State University Mesoscale Model (MM5) using data from the Northeast Oxidant and Particle Study (NE-OPS) research program collected over Philadelphia, PA during a summer episode in 1999. A set of model simulations utilizing a nested grid of 36 km, 12 km and 4 km horizontal resolutions with 21 layers in the vertical direction was performed for a period of 101 h from July 15, 1999; 12 UTC to July 19, 1999; 17 UTC. The model predictions obtained with 4 km horizontal grid resolution were compared with the NE-OPS observations. Comparisons of model temperature with aircraft data revealed that the model exhibited slight underestimation as noted by previous investigators. Comparisons of model temperature with aircraft and tethered balloon data indicate that the mean absolute error varied up to 1.5 °C. The comparisons of model relative humidity with aircraft and tethered balloon indicate that the mean relative error varied from −11% to −22% for the tethered balloon and from −5% to −30% for the aircraft data. The mean relative error for water vapor mixing ratio with respect to the lidar data exhibited a negative bias consistent with the humidity bias corresponding to aircraft and tethered balloon data. The tendency of MM5 to produce estimates of very low wind speeds, especially in the early-mid afternoon hours, as noted by earlier investigators, is seen in this study also. It is indeed true that the initial fields as well as the fields utilized in the data assimilation also contribute to some of the differences between the model and observations. Studies such as these which compare the grid averaged mean state variables with observations have inherent difficulties. Despite the above limitations, the results of the present study broadly conform to the general traits of MM5 as noted by earlier investigators.

Key words: aircraft, lidar, MM5, NE-OPS, RASS, tethered balloon, wind profiler

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1. Introduction

1.1. RATIONALE

Regional prognostic mesoscale meteorological models are essential in many applications, including the development of accurate meteorological inputs for three-dimensional photochemical modeling systems. These photochemical models are the primary tools used by state and federal agencies for developing emission control strategies to reduce ambient ozone concentrations, particulate matter concentrations, and ultimately population exposures to these contaminants. An important requirement for a regional mesoscale meteorological model is its ability to simulate the mesoscale circulations in a realistic manner, consistent with observations. Hence, there is a need to compare the mesoscale meteorological model results with field observations in order to understand the limitations as well as strengths of these models.

The North American Research Strategy for Tropospheric Ozone – Northeast – Oxidant and Particle Study (NARSTO-NE-OPS) [1] has pursued an observational field campaign that provided meteorological data from a variety of platforms, such as instrumented aircraft, wind profiler, Radio Acoustic Sounding System (RASS), lidar, and tethered balloon sondes. The present work describes a comparison of the Fifth Generation NCAR Pennsylvania State University Mesoscale Model (MM5) with NE-OPS observations collected during a major ozone episode which occurred during the summer of 1999 over Philadelphia, PA.

1.2. OBJECTIVE

The primary objective of this research effort was to perform an evaluation of MM5 by comparing its predictions with observations obtained from aircraft, wind profiler, RASS, lidar and tethered balloon during the NE-OPS campaign of 1999 over Philadelphia, PA, during a major ozone episode.

1.3. BACKGROUND

Mesoscale meteorological models have been evaluated in some earlier studies [2, 3] using both qualitative and quantitative assessments. The latter have utilized traditional statistical measures while the former involved graphical comparison of observed and simulated fields of wind and temperature. In general, the evaluation of the meteorological models has limitations due to the fact that the observed and the predicted meteorological fields are not independent as a consequence of the use of four-dimensional data assimilation (4DDA). Hence, it is difficult to establish clear-cut criteria for assessing the performance of meteorological models used in air quality predictions. Also, comparisons between observations and model predictions are not straightforward since observations are primarily point measurements while model predictions are gridded values of Reynolds average mean state variables.

Cox *et al.* [4] compared four mesoscale models: the Regional Atmospheric Modeling System (RAMS), MM5, the Navy Operational Regional Prediction System Version 6 (NORAPS6) and the Relocatable Window Model (RWM) for quality of forecasts in different climatic regions in the world. Cox *et al.* [4] found that both MM5 and RAMS performed better than the other two models. The Texas Natural Resources Conservation Commission (TNRCC) [5] performed MM5 and RAMS simulations over the Houston area for the September 8–11, 1993 ozone episode and found that MM5 did not exhibit the tendency for the nighttime cold temperature bias which was exhibited by RAMS. The 4 km MM5 simulation results indicated that the water vapor was underestimated almost throughout the entire simulation period with the mean absolute error varying from 1.3 g kg^{-1} to 3.5 g kg^{-1} [5]. The average absolute error for water vapor over the entire simulation period was about 2.3 g kg^{-1} [5]. The 4 km MM5 simulation results also indicated that the temperature was underestimated with mean absolute error varying from 1 °C to 4 °C with an average absolute error of about 2.5 °C over the entire simulation period.

The TNRCC [6] performed high resolution (1.33 km) MM5 simulations over the Houston area for the September 8–11, 1993 ozone episode with different MM5 parameterizations to investigate causes of undesirable features in MM5 applications. Hogrefe *et al.* [7] recently introduced the concept of scale analysis and successfully applied it to an evaluation of MM5 and RAMS3b. Sistla *et al.* [8] investigated the performance of two coupled meteorological and regional scale photochemical systems, namely the RAMS/Urban Airshed Model-Variable Grid Version (RAMS/UAM-V) and the MM5/San Joaquin Valley Air Quality Model (MM5/SAQM) over the eastern United States during the summer of 1995 and found that the performances of both modeling systems (RAMS/UAM-V and MM5/SAQM) in predicting observed ozone concentrations were comparable when the model outputs were averaged over all simulated days.

Fast *et al.* [9] studied the effect of regional-scale transport on the dynamics of oxidants in the vicinity of Philadelphia for the period July 15–August 4, 1999 by utilizing a coupled meteorological and chemical modeling system, the Pacific Northwest National Laboratory (PNNL) Eulerian Gas and Aerosols Scalability Unified System (PEGASUS) [10]. The meteorological model results were evaluated with radar wind profiler and radiosonde data while the chemical transport model results were evaluated with aircraft, ozonesonde and surface monitoring data collected during the NE-OPS campaign. The results indicated little model bias in the simulated model wind speed as compared to the wind profilers but the simulated wind directions were more westerly by about 15 degrees. The mixing layer temperature and specific humidity predictions were within 1–2 K and 1–2 g kg^{-1} of the corresponding observed values.

An assessment of the effect of different parameterizations (Blackadar PBL; a hybrid local (stable regime) and non-local (convective regime) mixing scheme; and the Gaynor-Seaman PBL, a turbulent kinetic energy based eddy diffusion scheme) on the PBL evolution was carried out using the MM5V3 model for July 15–20, 1999 by Zhang *et al.* [11]. The results of the above study indicate that there are substantial differences between the PBL structures and the PBL evolutions simulated by the above mentioned different schemes. The comparison of results with observations seems to support the non-local mixing mechanism over the layer-to-layer eddy diffusion in the convective PBL.

Buckley *et al.* [12] quantitatively compared the RAMS results with surface observations of temperature, wind speed, wind direction and turbulent intensity for the southeastern United States for a two year period (1998–2000) by utililizing various statistical measures. The results of Buckley *et al.* [12] indicated that the temperature errors are higher during the cooler months for inland stations suggesting difficulties with the surface energy budget in the model. Buckley *et al.* [12] also noticed the appearance of large errors in the temperature and moisture fields coinciding with the transition from day-time to nocturnal conditions. For mesoscale systems generated by surface inhomogenities in surface heating, Pielke *et al.* [13] provide the horizontal resolution requirement for adequately resolving the lower tropospheric profiling by a network of profilers. Pielke *et al.* [13] conclude from their analysis that to directly monitor the horizontal/vertical wind field, it is necessary to have considerably higher spatial resolution of the profiler network. Pielke *et al.* [13] caution that a stringent data initialization requirement would result if one were to insert mesoscale resolution profiler derived temperature or wind data into a model. Even with a profiler network of 10 km horizontal resolution, a fictitious acceleration of the order of 1 m s^{-1} h^{-1} would result, even if the relative errors in the temperature measurements were as low as 0.24 °C through a depth of about 2 km [13].

Although the present study utilized 4DDA, it was decided to refrain from using the NE-OPS observations in 4DDA; hence a comparison of the mesoscale meteorological model with NE-OPS observations is indeed possible. MM5 has in fact been evaluated in earlier studies using a variety of observations (surface, sounding, aircraft etc.), but the authors are not aware of another study where MM5 is evaluated using a wide-ranging array of advanced measurement platforms (aircraft, RASS, profiler, lidar and tethered balloon); such a multifaceted evaluation is presented here.

1.4. A BRIEF OVERVIEW OF NARSTO-NE-OPS

The NARSTO-NE-OPS is a multi-institutional collaborative research program set up under a USEPA initiative aiming to improve the current understanding of the causes underlying the occurrence of high ozone and fine particle concentrations in the northeastern United States. Various advanced meteorological and air chemistry measurements were made in the vicinity of Philadelphia, PA during a field campaign conducted in the summer of 1999 [1]. The site preparation for the main summer intensive NE-OPS program at the Baxter Water Treatment Plant, Philadelphia, PA (40.0764° N, 75.0119° W) began on June 15, 1999 and the site was fully operational from June 28–August 19, 1999. During this two-month campaign, eight pollution episodes occurred over Philadelphia (July 3–5; July 8–10; July 16–21; July 23–24; July 27–August 1; August 7–8; August 11–13; and August 15–17), all of which resulted in measurements of high ozone concentrations over Philadelphia. All of the above episodes were monitored continuously during the NE-OPS campaign which yielded a variety of diverse meteorological and air quality data of high vertical and temporal resolutions. The strongest episode, culminating in a major ozone event, occurred during the period of July 16–21, 1999 over Philadelphia. Radar wind profiler/RASS were operated at the Baxter Water Treatment Plant (by Pennsylvania State University) and West Chester (by PNNL) sites, while a radar wind profiler operated by Argonne National Laboratory (ANL) was stationed at Centerton, New Jersey. The Pennsylvania State University Lidar, referred to as LAPS (Lidar Atmospheric Profile Sensor), was used to obtain vertical profiles of ozone, water vapor, temperature and extinction coefficients during the NE-OPS field campaign. Millersville University deployed two tethered balloons to obtain detailed temporal and vertical profiles of fine particles, O_3 concentrations, and meteorological variables [14]. The University of Maryland collected data on the distribution of PM, chemical species, and meteorological variables by performing instrumented flights with Cessna and Aztec aircraft over Philadelphia Airport (PNE) (40.0819° N, 75.0105° W) and Tipton Airport, Ft. Meade, MD (FME) (39.0846° N, 76.7599° W) [15]. Temperature and relative humidity data were collected by these aircraft at different pressure altitude levels in the atmosphere. The radar wind profiler provided profiles for all three wind velocity components while the RASS provided profiles of the virtual temperature and vertical velocity. The tethered balloons provided profiles of dry and wet bulb temperature, atmospheric pressure, wind speed and direction, and O_3 concentration, while temperature, humidity, ozone and extinction data were provided by lidar.

The present study focused primarily on a major ozone episode that took place in July 1999 over the Philadelphia region, in order to perform a comparison of MM5 [16]. Figure 1 provides the location of Baxter, Centerton, and West Chester instrumentation sites during the NE-OPS program, along with the flight paths of the University of Maryland aircraft. Table I presents details of the various observation data (including date and time period) utilized in this study.

1.5. OBSERVED SYNOPTIC FEATURES OF THE JULY 15–19 EPISODE

The entire eastern United States was under the influence of a high-pressure system over land during the period of July 15–19, 1999. The Appalachian lee trough [17],

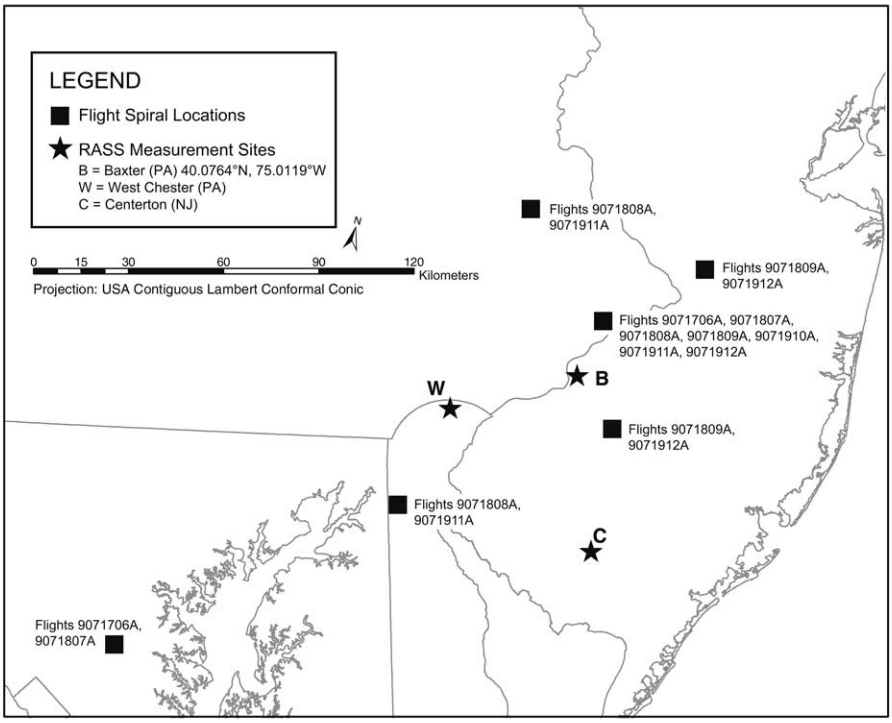

Figure 1. Locations of the Baxter, Centerton and West Chester RASS measurement sites during the NE-OPS program along with locations of the flight spirals of the University of Maryland aircraft.

persisted for three days and was especially pronounced on July 17–18. Southwesterly flow from the mid-Atlantic region to the northeast U.S. was caused by the presence of a lee trough along the Atlantic seaboard. Also, the low-level westerly flow from the midwest to the northeast U.S. was duly supported by the presence of large north-south pressure gradients above 37° N latitude. The above mentioned pattern (conducive to a high ozone episode) persisted until a cold front passed through the eastern U.S. on July 19 [11].

2. Prognostic Meteorological Modeling: Approach

The present study utilized MM5 Version 3.4 [16]. Twenty one layers in the vertical direction and three levels of nested domains were used with grid resolutions of 36 km for the outermost domains, 12 km for the intermediate domain and 4 km for the innermost domain for a period from July 15, 1999; 12 UTC to July 19, 1999; 17 UTC. The outermost domain encompasses the entire eastern U.S. while the inner domain is centered over northern New Jersey (Figure 2). The number of grid cells in the east-west and north-south directions are 75×69, 91×76 and 124×148 at the 36, 12 and 4 km resolutions, respectively. Table II provides details of

Table I. List of the various observational data (with date and time) used in this study.

S. No	Instrument	Date	Time period	Variable
1.	Aircraft	07/17/99	1956–2028 UTC	Temperature, rel. humidity
2.	Aircraft	07/18/99	1943–2000 UTC	Temperature, rel. humidity
3.	Aircraft	07/19/99	0145–0220 UTC	Temperature, rel. humidity
4.	Aircraft	07/19/99	1555–1620 UTC	Temperature, rel. humidity
5.	RASS	07/19/99	0000–0004 UTC	Virtual temperature
6.	RASS	07/19/99	0601–0605 UTC	Virtual temperature
7.	RASS	07/19/99	1200–1204 UTC	Virtual temperature
8.	RASS	07/19/99	1700–1704 UTC	Virtual temperature
9.	Profiler	07/16/99	0035–0100 UTC	u, v velocity components
10.	Profiler	07/17/99	0335–0400 UTC	u, v velocity components
11.	Profiler	07/18/99	0035–0100 UTC	u, v velocity components
12.	Profiler	07/19/99	0535–0600 UTC	u, v velocity components
13.	Lidar	07/16/99	0148–0217 UTC	Temperature, mixing ratio
14.	Lidar	07/16/99	0334–0403 UTC	Temperature, mixing ratio
15.	Lidar	07/17/99	0347–0417 UTC	Temperature, mixing ratio
16.	Lidar	07/17/99	0648–0717 UTC	Temperature, mixing ratio
17.	Tethered balloon	07/15/99	1400–1435 UTC	Temperature, rel. humidity, wind speed, and direction
18.	Tethered balloon	07/15/99	2024–2111 UTC	Temperature, rel. humidity, wind speed, and direction
19.	Tethered balloon	07/16/99	0145–0205 UTC	Temperature, rel. humidity, wind speed, and direction
20.	Tethered balloon	07/16/99	0440–0610 UTC	Temperature, rel. humidity, wind speed, and direction
21.	Tethered balloon	07/16/99	1348–1500 UTC	Temperature, rel. humidity, wind speed, and direction

the vertical structure used in the MM5v3 simulations listing the non-dimensional pressure (sigma) levels, pressure, mid-layer height, layer thickness, and the ratio of adjacent layers, for the 21 layers in the vertical direction. The study utilized the high resolution Blackadar scheme for Planetary Boundary Layer (PBL), the Grell scheme for cumulus parameterization (except for the 4 km domain), the mixed phase (Reisner) scheme for explicit moisture, a cloud radiation scheme and a force restore (Blackadar) scheme for ground temperature. Initial, boundary, and nudging data are a combination of outputs from the gridded European Center for Medium Range Weather Forecast (ECMWF) global analysis, blended with surface and upper air observations. The ECMWF gridded fields are available at 2.5 degree horizontal resolution and a time resolution of 12 h. The observations (both surface and upper air) are blended with the gridded data using the Cressman objective

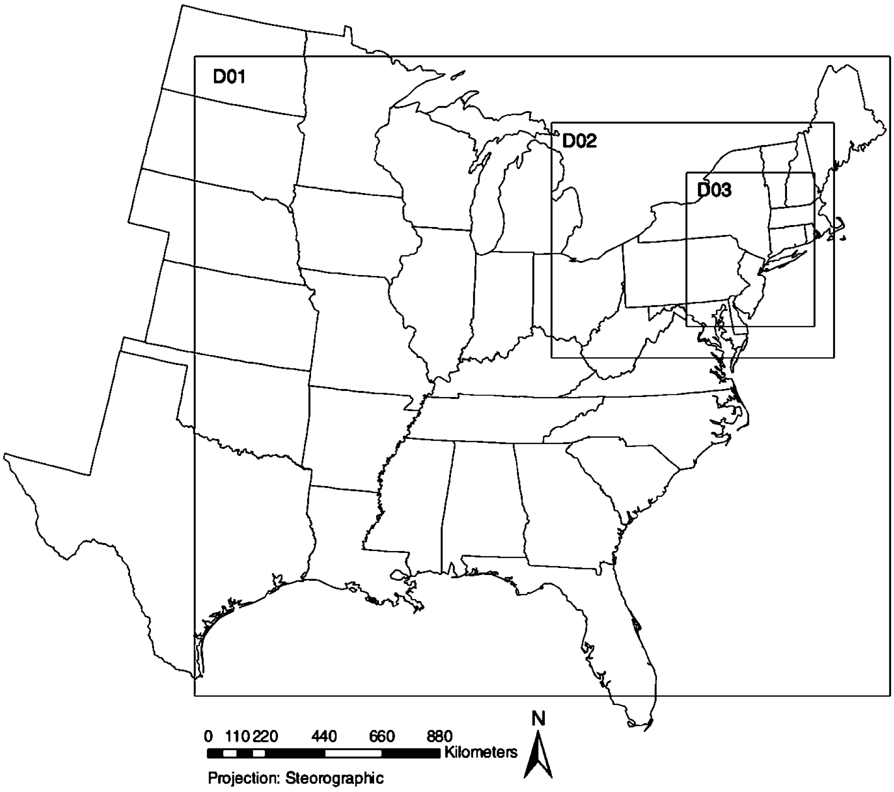

Figure 2. The triply nested MM5 modeling domain using 21 layers in the vertical direction with the 36 km (D01), 12 km (D02) and 4 km (D03) horizontal grid structure. The projection shown above is Lambert Conformal projection, with the 1st and 2nd parallels being 30° and 60° and the reference longitude and latitude being 84.36° W and 37.34° N.

analysis on pressure levels. Model predictions for wind, temperature and water vapor were nudged towards these blended input fields in the free atmosphere. In the atmospheric boundary layer (ABL), the temperature and water vapor were not nudged, while only the winds were nudged towards the blended input fields. A one-way nesting approach was utilized in these simulations.

3. Results and Discussion

3.1. COMPARISON OF MM5 SIMULATIONS WITH NE-OPS OBSERVATIONS

In order to assess the performance of MM5 with 21 layers in the vertical direction, a comparison of the model results with NE-OPS observations was undertaken. All the MM5 results (comparisons with NE-OPS observations) depicted in this study correspond to the 4 km MM5 simulation runs. This study employed 4DDA with the global analysis gridded data as well as with the upper air rawinsonde and surface observations. The 4 km domain encompasses 4 upper air stations and 100 surface

Table II. The vertical structure used for the MM5v3 simulations with 21 layers in the vertical direction. The non-dimensional pressure σ levels, approximate pressure (hPa), approximate height (meters above ground level (AGL)), approximate layer thickness (meters), and ratio of adjacent layer thickness are shown.

Model level	σ level	Pressure (hPa)	Approx. mid-layer height (m AGL)	Layer thickness dz (m)	Ratio of dz
21	0.9975	994	18	36	1.00
20	0.9925	990	54	36	1.00
19	0.9875	986	90	36	1.00
18	0.9825	982	127	36	1.51
17	0.975	976	181	55	1.34
16	0.965	968	255	74	1.26
15	0.9525	958	348	93	1.21
14	0.9375	945	460	112	1.18
13	0.92	931	593	133	1.16
12	0.9	914	747	154	1.14
11	0.8775	896	923	176	1.13
10	0.8525	875	1123	200	1.76
9	0.81	840	1475	352	1.73
8	0.74	782	2084	609	1.39
7	0.65	707	2930	846	1.23
6	0.55	623	3966	1036	1.13
5	0.45	538	5135	1170	1.16
4	0.35	452	6487	1351	1.19
3	0.25	365	8096	1609	1.25
2	0.15	276	10107	2011	1.38
1	0.05	185	12877	2771	N/A

stations. The following subsections provide the comparison of the MM5 model simulations with NE-OPS observations.

3.1.1. *Comparison of MM5 Simulations with Aircraft Data*

In 1999 the University of Maryland aircraft were utilized day and night, from near surface (10 m above ground level) to 2.7 km above mean sea level at an average climb rate of 100 m min^{-1}, in 52 spirals and 21 flybys of the Baxter surface site during the operational period between July 4 and August 17. In situ observations of GPS position, standard meteorological parameters (temperature, relative humidity at different pressure altitude levels), and important atmospheric chemical tracers such as O_3 and CO were made from the instrumented aircraft. Since MM5 output can be available every hour, it was decided to compare the model output with the

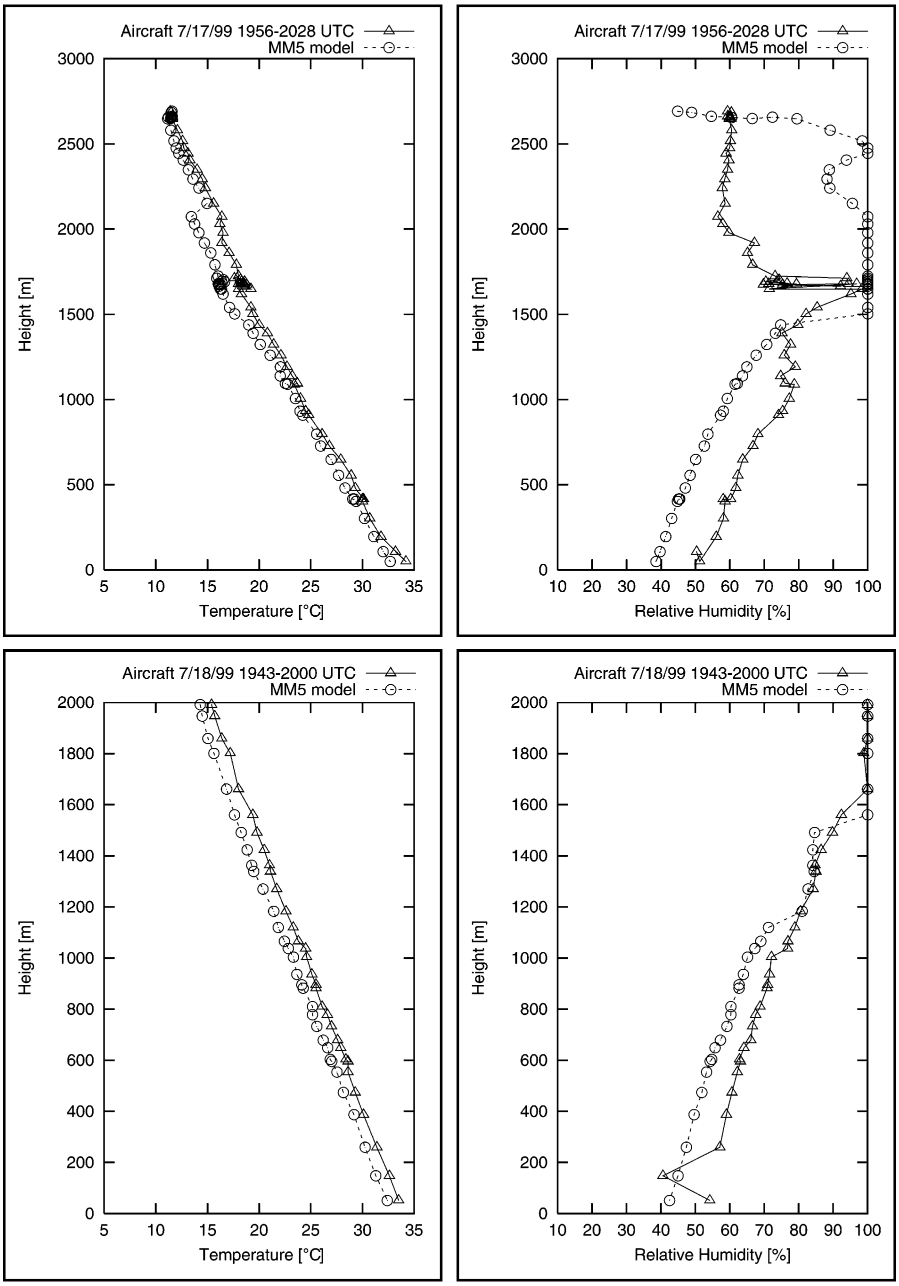

Figure 3. Comparison of aircraft observations with MM5 4 km model results over Philadelphia for temperature and relative humidity for July 17, 1999; 20 UTC (upper panels) and for July 18, 1999; 20 UTC (lower panels).

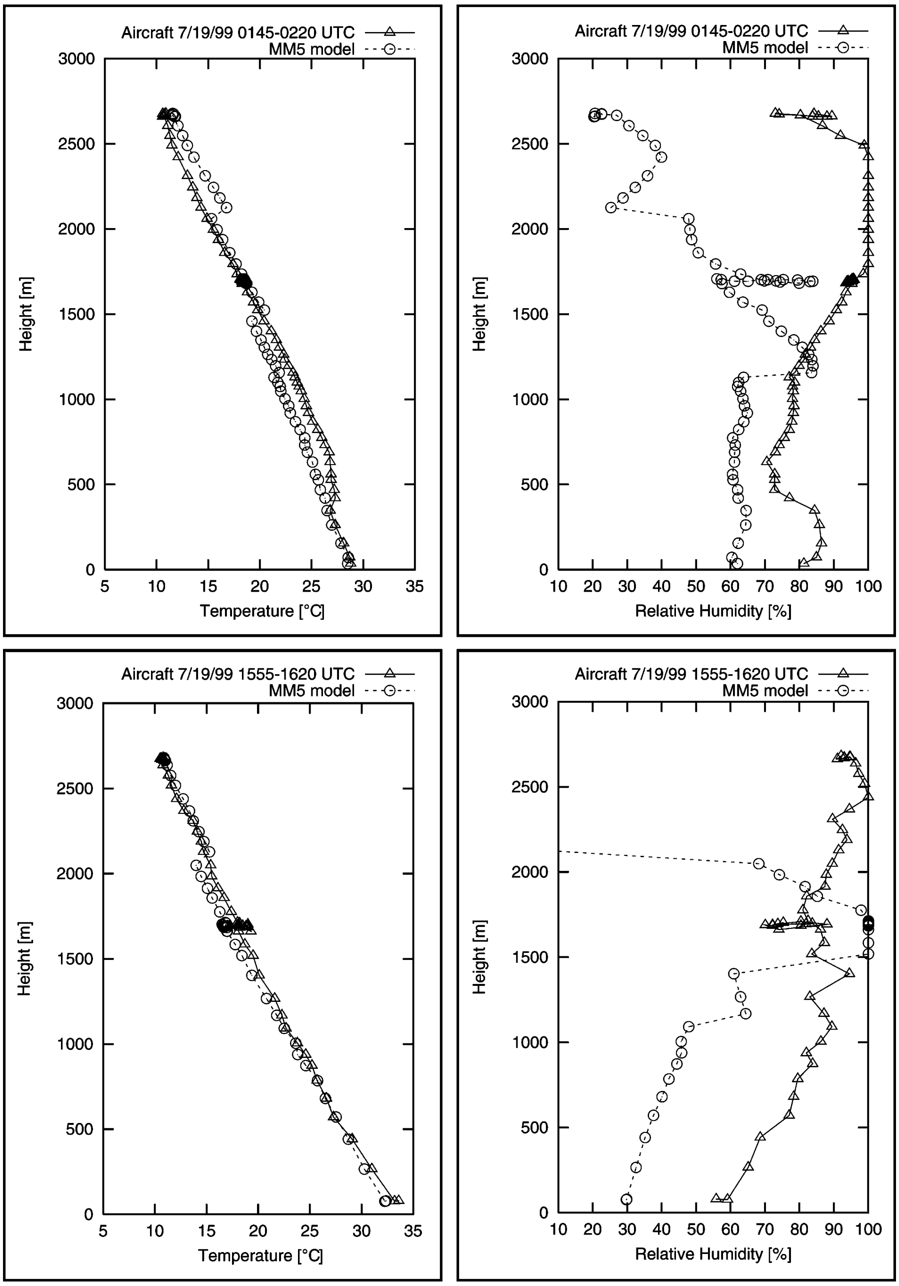

Figure 4. Comparison of aircraft observations with MM5 4 km model results over Philadelphia for temperature and relative humidity for July 19, 1999; 02 UTC (upper panels) and for July 19, 1999; 16 UTC (lower panels).

aircraft observations when the latter was in one of its spiral paths, either descending or ascending, and coinciding with the model output time. All the aircraft data were available at altitudes above mean sea level (msl). Utilizing the postprocessor GRAPH module of MM5, the temperature and relative humidity values at the aircraft locations were obtained. All heights mentioned in the following figures refer to height above msl. The comparisons of aircraft observations with 4 km MM5 model results are shown in Figures 3 (July 17, 1999; 20 UTC and July 18, 1999; 20 UTC) and 4 (July 19, 1999; 02 and 16 UTC) for both temperature and relative humidity. Twenty-one spirals and eleven flybys were performed by University of Maryland aircraft during the period of July 15–19, 1999. The mean relative error, mean absolute error and the standard deviation of the difference [12] were calculated over Philadelphia at different times by using the observation in the vertical direction. The model temperatures were lower compared to the aircraft observation, with the mean relative error varying from -0.18 °C to -1.35 °C. This is consistent with the earlier results of TNRCC investigators [5]. The mean absolute error varied from 0.74 °C to 1.35 °C while the standard deviation of the difference varied from 0.76 °C to 1.2 °C. The mean absolute error was within the desired forecast accuracy of 2 °C [4]. The 4 km MM5 model, as reported by previous investigators [5], simulates lower values of moisture with the mean relative error of water vapor mixing ratio varying from 0 to -3.5 g kg^{-1} with the average over all times of the order of -2 g kg^{-1}. The model relative humidity predictions were lower than the aircraft observations with the mean relative error varying from -5% to -30%. The mean absolute error as well as the standard deviation of the difference for relative humidity varied from 5% to 43%. Though earlier investigators also obtained results where the moisture was underestimated [5], the magnitude of underestimation is slightly higher in this study. Despite the model underestimating the humidity values, there is general agreement on the trend in height of the model-generated vertical profiles of relative humidity with aircraft observations. This study did not utilize a land surface model or actual soil moisture fields. However, according to other studies (e.g., [5]), utilization of actual soil moisture could improve the moisture verification.

3.1.2. *Comparison of MM5 Simulations with RASS Data*

Comparisons of virtual temperature obtained from RASS with the 4 km MM5 simulation results are shown in Figure 5, for July 19, 1999; 00, 06, 12 and 17 UTC. RASS units are usually collocated with a profiler system and are used in conjunction with the profiler to provide the virtual temperature profile. The above mentioned RASS and wind profiler were operated at the Baxter Water Treatment Plant site. Angevine *et al.* [18], while comparing the wind profiler and RASS measurements with 450 m tower measurements, observed that the virtual temperature as measured by RASS was only accurate to about 0.5 °C. Since MM5 simulates lower moisture values and slightly lower temperature values it should underestimate the virtual temperature values. The 4 km MM5 application does predict lower values of

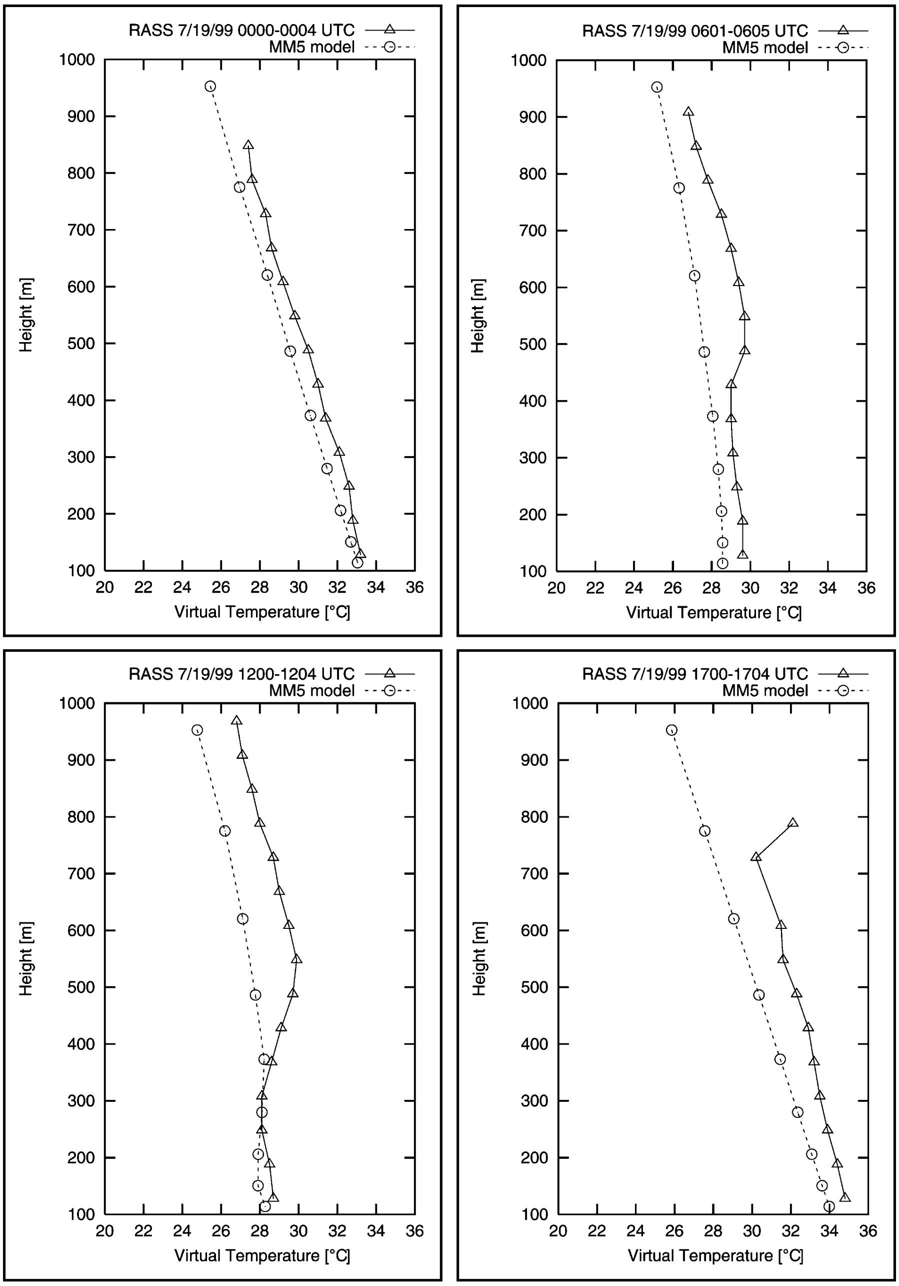

Figure 5. Comparison of RASS observations with MM5 4 km model results over Philadelphia for virtual temperature for July 19, 1999; 00 and 06 UTC (upper panels) and for July 19, 1999; 12 and 17 UTC (lower panels).

virtual temperature with the mean relative error varying from −0.6 °C to −1.7 °C. The deviation between MM5 and RASS measurement of virtual temperature appears larger at higher elevations for some cases only and is especially prominent on July 19, 1999; 12 UTC (lower left hand panel of Figure 5). Models are known to have difficulty in accurately predicting moisture at higher levels and generally predict humidity fields much better on surface for the simple reason that more data exists [4]. The above argument could provide a plausible explanation for the supposed larger deviation between the model and RASS measurement of virtual temperature at higher levels in some cases.

3.1.3. *Comparison of MM5 Simulations with Wind Profiler Data*

As mentioned in the previous subsection, RASS units are usually collocated with a profiler system to provide information on the three wind components as well as the virtual temperature. Hence, the above combined system is also known as RASS profiler [11] as well as Radar-RASS [1]. Comparisons of the horizontal wind components obtained from the wind profiler with the 4 km MM5 results are shown in Figure 6 for July 16, 1999; 01 UTC (top panels) and for July 17, 1999; 04 UTC (bottom panels). Figure 7 is similar to Figure 6 except that the comparison is for July 18, 1999; 01 UTC (top panels) and for July 19, 1999; 06 UTC (bottom panels). The presence of low level jets (LLJs), which play an important role in the transport of water vapor and pollutants, is clearly seen in the wind profiler observations in Figures 6 and 7. The strongest LLJ occurred on July 17, 1999; 04 UTC over Philadelphia during the major ozone episode period of July 15–20, 1999. The LLJs are seen between heights of 600 and 1000 m above ground level (AGL) and are typically westerly/southwesterly. MM5 reasonably simulates the LLJs as seen in Figures 6 and 7. Zhang *et al.* [11] investigated the nocturnal LLJs in the northeastern U.S. during July 15–20, 1999 by utilizing two different planetary boundary layer (PBL) parameterization schemes (Blackadar scheme and Gayno-Seaman scheme) in MM5 and found that both PBL schemes produced LLJs which were weaker and which occurred at times different from the NE-OPS profiler observation. Zhang *et al.* [11] then limited the 4DDA to regions above the PBL and also allowed the convective energy computation to all PBL regimes. The above modifications produced LLJs with improvements in timing as well as in the strength of the jet. However, Zhang *et al.* [11] found that both the PBL schemes still failed to reproduce the sharp vertical gradients near the jet core and attributed the above to the fact that the model vertical resolution was inadequate, since the layer thickness in the vertical direction was about 200 m around the jet core region of 400–600 m. In the present study, the layer thickness of the MM5 application in the vertical direction was 112 m around 500 m. Also, unlike Zhang *et al.* [11], in the present study 4DDA was restricted to above the PBL only for temperature and moisture, and hence 4DDA was utilized to nudge the PBL horizontal wind components. Also, in the present study, 4DDA utilized twice-a-day rawinsonde observations and global analysis data at 00 and 12 UTC. While Zhang *et al.* [11]

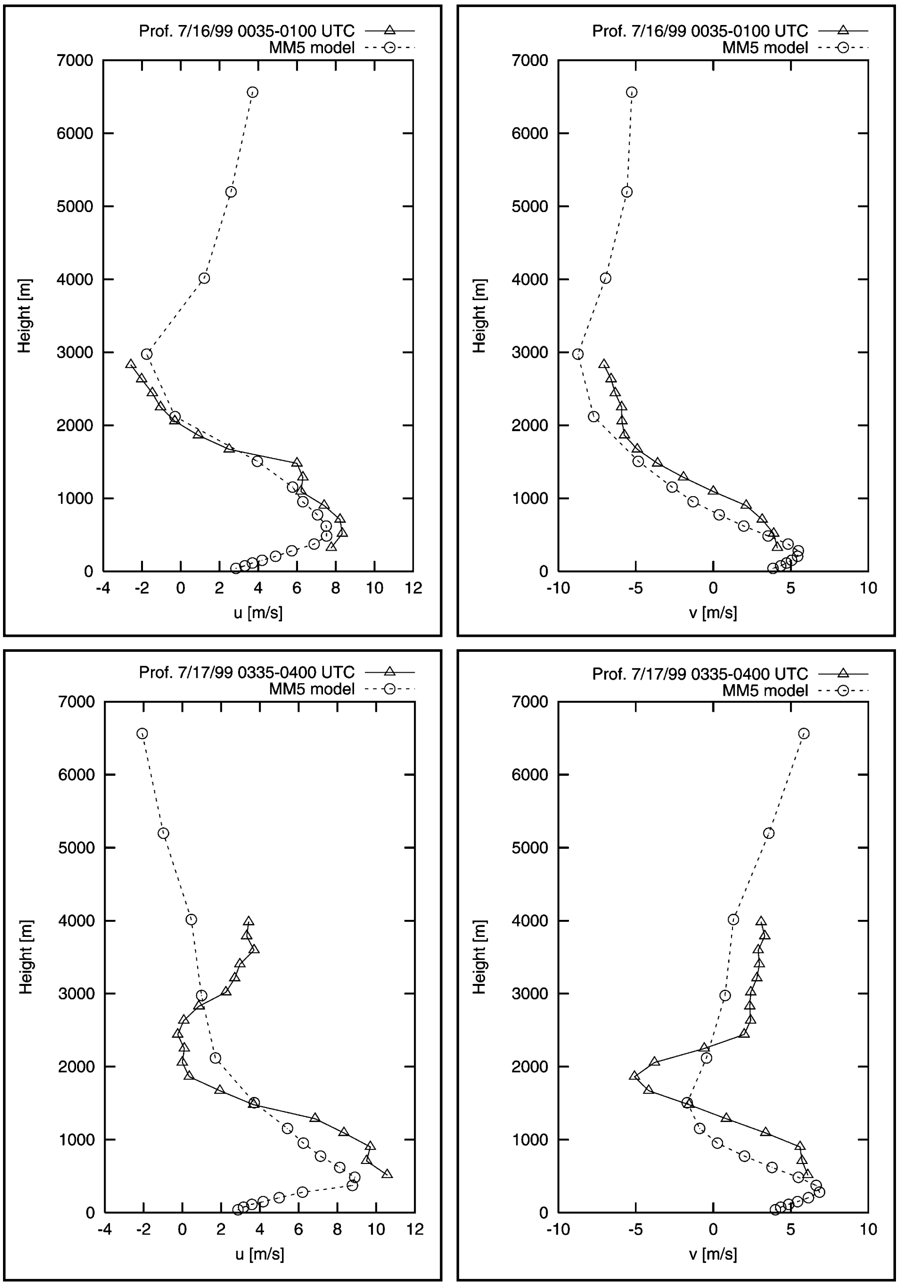

Figure 6. Comparison of wind profiler observations with MM5 4 km model results over Philadelphia for *u* and *v* component of velocity for July 16, 1999; 01 UTC (upper panels) and for July 17, 1999; 04 UTC (lower panels).

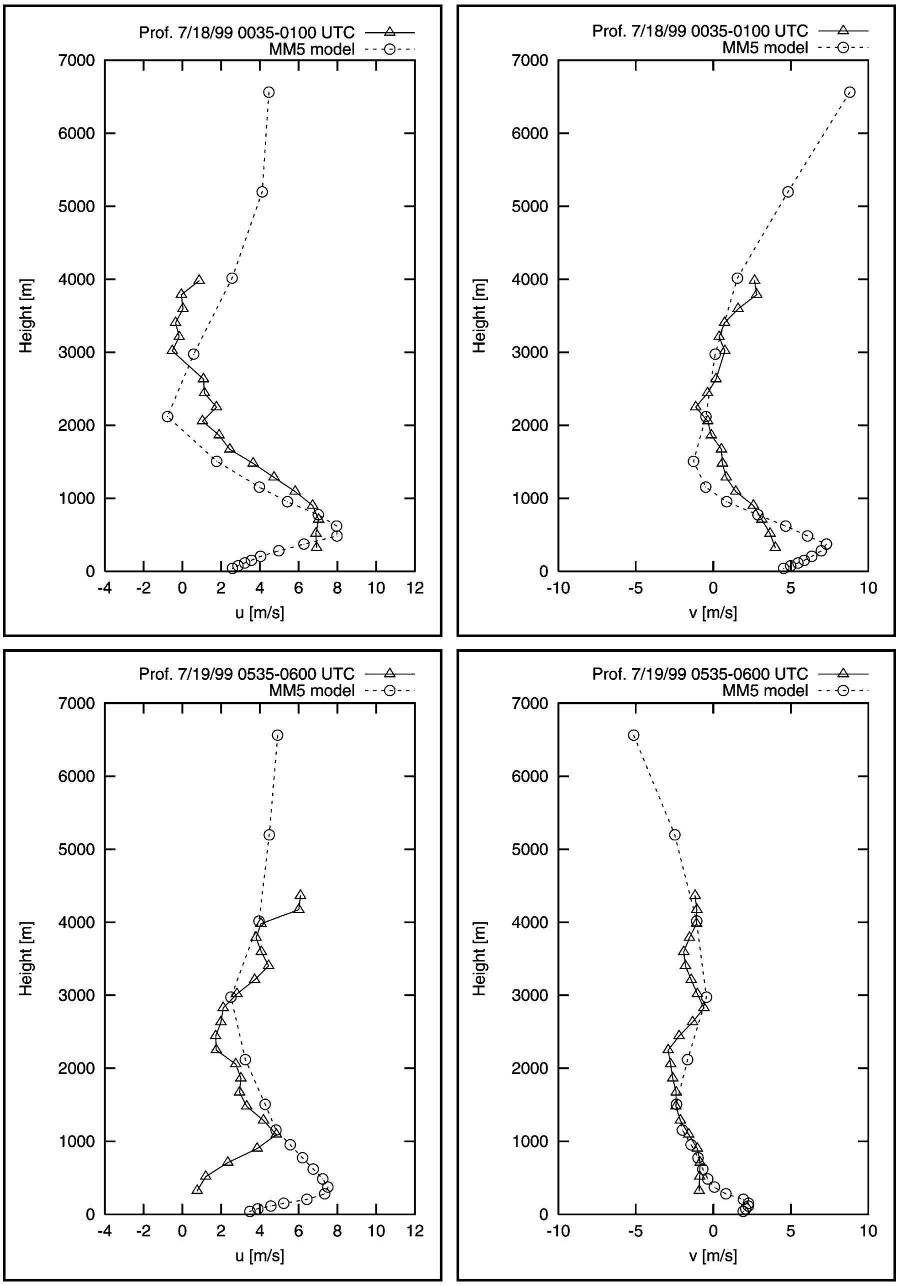

Figure 7. Comparison of wind profiler observations with MM5 4 km model results over Philadelphia for *u* and *v* component of velocity for July 18, 1999; 01 UTC (upper panels) and for July 19, 1999; 06 UTC (lower panels).

failed to reproduce the sharp vertical gradients near the jet core, the present study appears to successfully simulate the sharp gradients. In fact the simulation of the nocturnal LLJ for July 16, 1999; 01 UTC (top panels of Figure 6) is indeed very good. The simulation of LLJs for July 17, 1999; 04 UTC (bottom panels of Figure 6) and for July 18, 1999; 01 UTC (top panels of Figure 7) are also reasonable. Since 4DDA utilized twice-a-day rawinsonde observations and global analysis data at 00 and 12 UTC, nudging the PBL horizontal wind components may not necessarily provide adequate temporal resolution to delineate the evolution of the LLJ. In fact, nudging horizontal wind components may be responsible for some of the model results, where there is very good agreement with observations at heights above 1000 m with less agreement at lower levels (meridional component for July 18, 1999; 01 UTC and zonal component for July 19, 1999; 06 UTC, as seen in Figure 7). Though the model overestimated the LLJ on July 19, 1999; 06 UTC (mean relative error of the zonal and meridional components of the velocity being 0.46 m s^{-1} and 0.72 m s^{-1}), the mean relative error for the other LLJs are negative. The mean absolute error and the standard deviation of the difference for the u and v velocity components vary from 1.0 to 2.0 m s^{-1} and 0.9 to 2.5 m s^{-1}. The TNRCC investigators [5] also provide evidence for MM5 simulating lower wind speeds close to 00 UTC with an average absolute error of about 1.5 m s^{-1} spread over the entire simulation period. Cox *et al.* [4] has proposed a desired forecast accuracy of 2.5 m s^{-1} for wind speeds greater than 10 m s^{-1} and an accuracy of 1.0 m s^{-1} otherwise. The results of the present study satisfy, to a great extent, the above requirement, which is reasonable given that MM5 was not utilized in a forecasting mode.

3.1.4. *Comparison of MM5 Simulations with Lidar Data*

The lidar provides raw data at 75 m resolution at 1 min timesteps, and a smoother is utilized to integrate the data either for 5 min with 1 min timesteps or for 30 min using 5 min timesteps. All 1999 temperature data were filtered using a 3-point Hanning filter from 1.5 km to 3 km and 5-point Hanning filter above 3 km. Comparisons of the temperature and water vapor mixing ratio values obtained from the lidar with MM5 predictions are shown in Figure 8 for July 16, 1999; 02 and 04 UTC and in Figure 9 for July 17, 1999; 04 and 07 UTC. For the lidar observations from the LAPS instrument, the median value of every five observations is depicted in these figures for convenience. All the lidar observations depicted in Figures 8 and 9 utilized 30 min integration times. The TNRCC investigators [5] found that the 4 km MM5 application simulated lower values of water vapor with the mean relative error varying up to −3.5 g kg^{-1}. The average relative error of water vapor mixing ratio is about −2.3 g kg^{-1} over the entire simulation period [5]. The mean relative error for water vapor mixing ratio, when compared to lidar data, varied between −0.5 g kg^{-1} and −1.2 g kg^{-1} while the mean absolute error and the standard deviation of difference varied between 0.7 g kg^{-1} and 1.8 g kg^{-1}. However, the mean relative error of temperature with respect to the lidar data varied from 7.5 °C

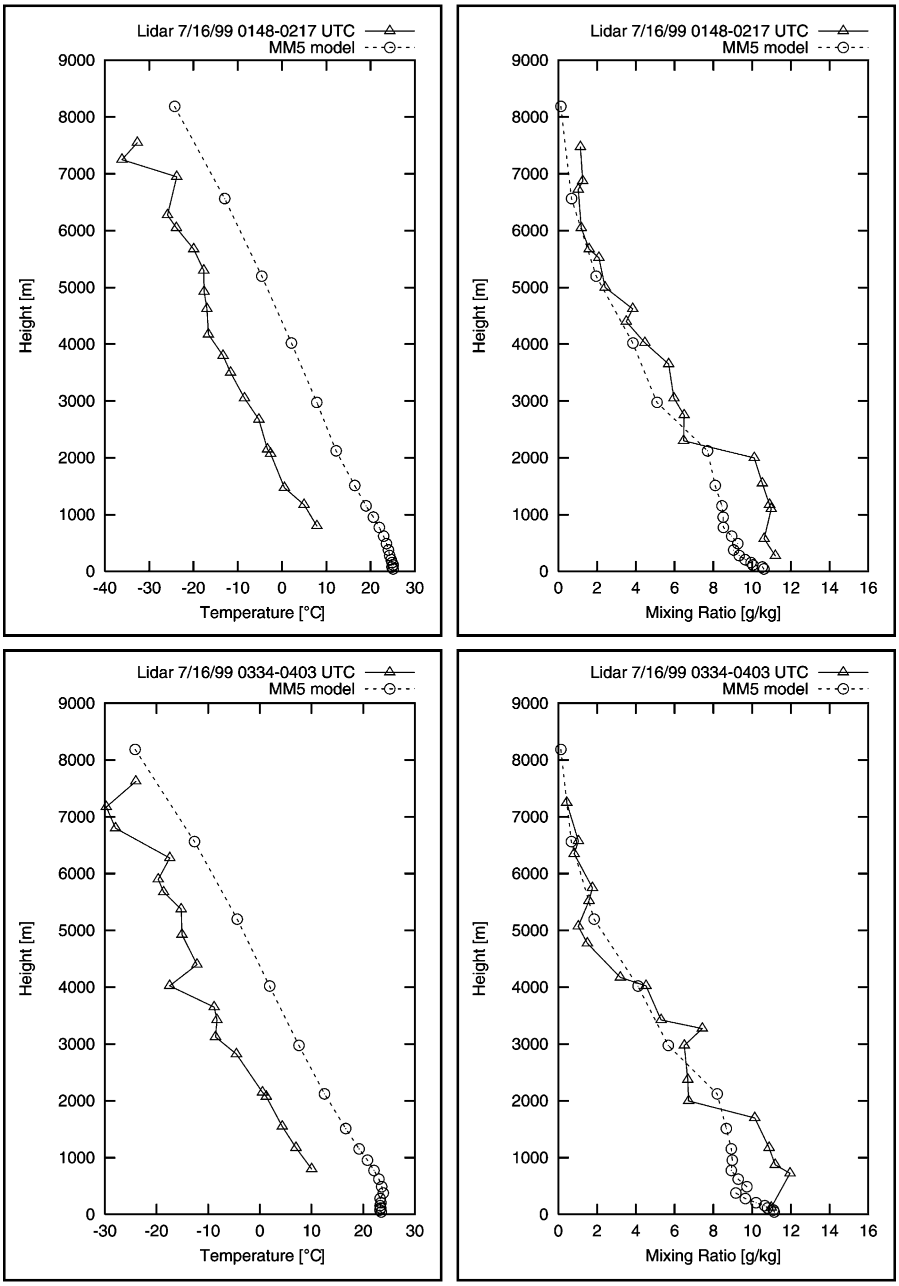

Figure 8. Comparison of lidar observations with MM5 4 km model results over Philadelphia for temperature and mixing ratio for July 16, 1999; 02 UTC (upper panels) and for July 16, 1999; 04 UTC (lower panels).

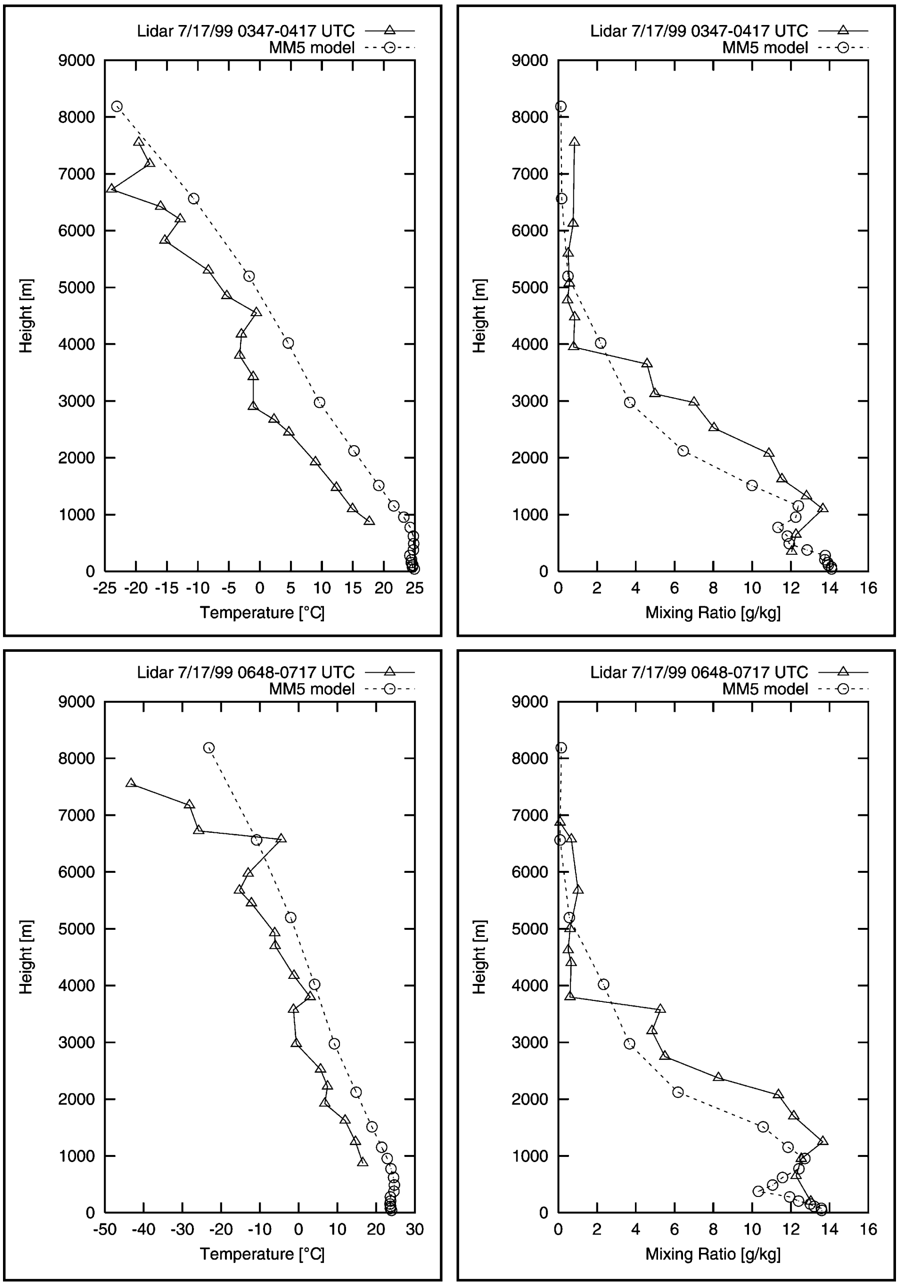

Figure 9. Comparison of lidar observations with MM5 4 km model results over Philadelphia for temperature and mixing ratio for July 17, 1999; 04 UTC (upper panels) and for July 17, 1999; 07 UTC (lower panels).

to 15.1 °C. The above large overestimations of temperature may be due to errors in the temperature lidar data on the above mentioned dates.

3.1.5. *Comparison of MM5 Simulations with Tethered Balloon Data*

The small tethered balloon was utilized in a series of ascent/descent soundings to an altitude of 300 m at a rate of approximately 0.15–0.2 m s^{-1}. Typically one vertical profile was obtained every 30 min with a vertical resolution of 1-3 m. During the period of July 15–19, 1999, thirty-eight vertical profiles were obtained. Comparisons of the model-predicted meteorological variables with the tethered balloon data are shown for July 15, 1999; 14 UTC (Figure 10) and 21 UTC (Figure 11) and for July 16, 1999; 02 UTC (Figure 12), 06 UTC (Figure 13) and 15 UTC (Figure 14). The median value of every five observations is depicted in these figures for convenience. The mean relative error for relative humidity has negative values varying from -11% to -22%. The mean absolute error for relative humidity has a similar range. The above behavior (underestimation of moisture) is in conformity with previous studies [5]. The mean relative error for temperature varied from 0.69 °C to 1.53 °C and is within the desired forecast accuracy of 2 °C [4]. MM5 is known to exhibit a bias towards very low wind speeds, especially in the early-mid afternoon hours [5]. The above feature is very clearly manifested in Figure 11 (July 15, 1999; 21 UTC) (mean relative error for wind speed is -4.73 m sec^{-1}) and somewhat moderately in Figure 14 (July 16, 1999; 15 UTC). A southwesterly jet-like feature is seen in Figures 12 and 13 (July 16, 1999; 02 and 06 UTC). The wind profiler data clearly show the presence of a southwesterly LLJ on July 16, 1999; 01 UTC with the jet core between 400–600 m. Since the tethered balloon data were available only for up to a height of 300 m, the jet core region is not seen in Figures 12 and 13. The mean absolute errors for wind speeds are found to vary between 1.2 m s^{-1} to 4.7 m s^{-1} while the same for wind direction varied between 10° and 39°. Cox *et al.* [4] have suggested a desired forecast accuracy of 30° in the wind direction, which is satisfied, to a large extent, in this study; this is reasonable since the MM5 model was utilized here in a hindcast mode.

4. Conclusions

This study presented a comparative evaluation of the prognostic MM5 meteorological mesoscale model predictions with data from the Northeast Oxidant and Particle Study (NE-OPS) research program over Philadelphia, PA during a summer ozone episode in 1999. The comparison of model temperature with aircraft data revealed that the model exhibits a negative bias in the mean relative errors for temperature, as also noted by earlier investigators. While the model slightly overestimates temperature values when compared to the tethered balloon data, it severely overestimates them when compared with lidar data. The comparisons of model relative humidity with aircraft and tethered balloon data indicate that the mean relative error varied from -5% to -30%. The underestimation of water

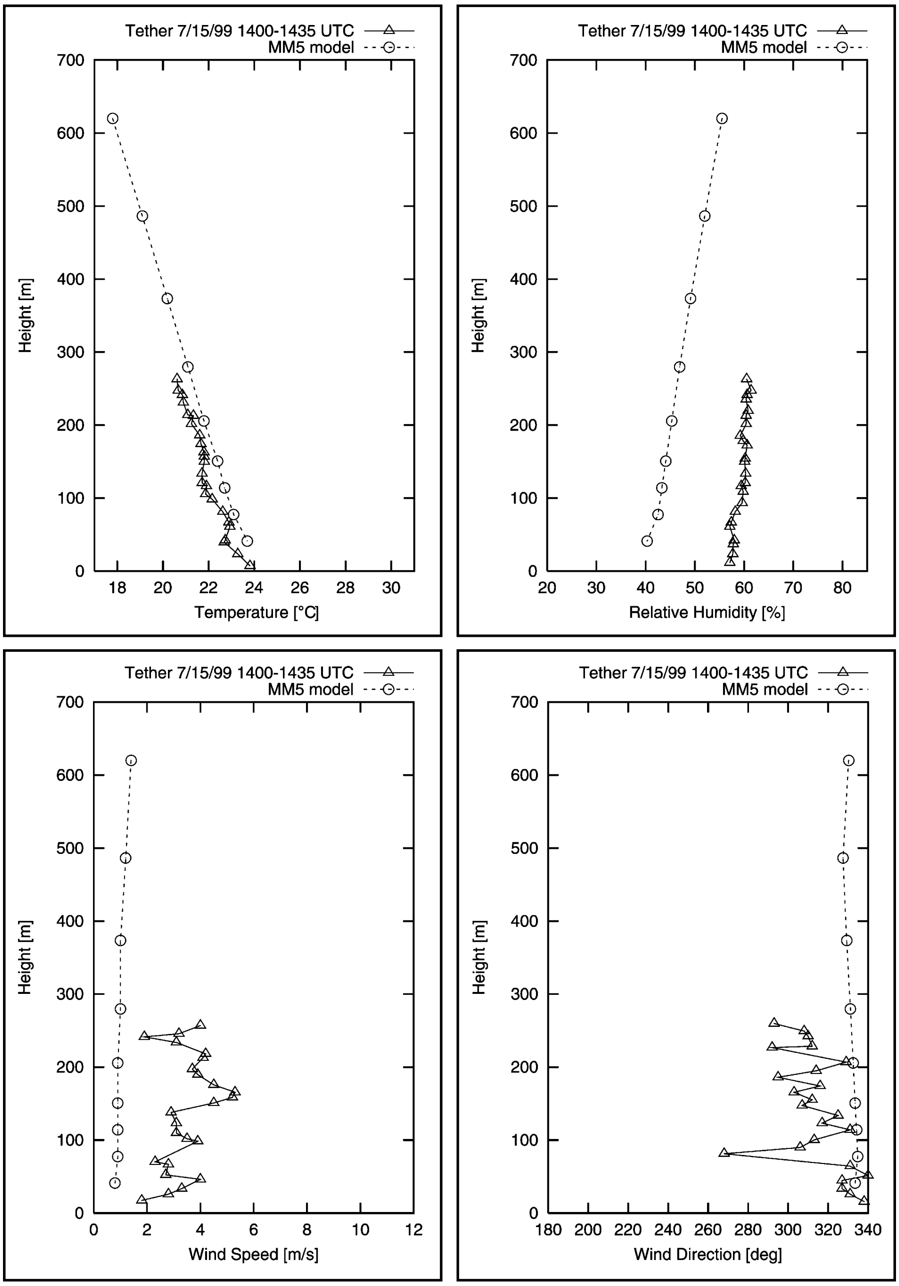

Figure 10. Comparison of tethered balloon observations with MM5 4 km model results over Philadelphia for July 15, 1999; 14 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

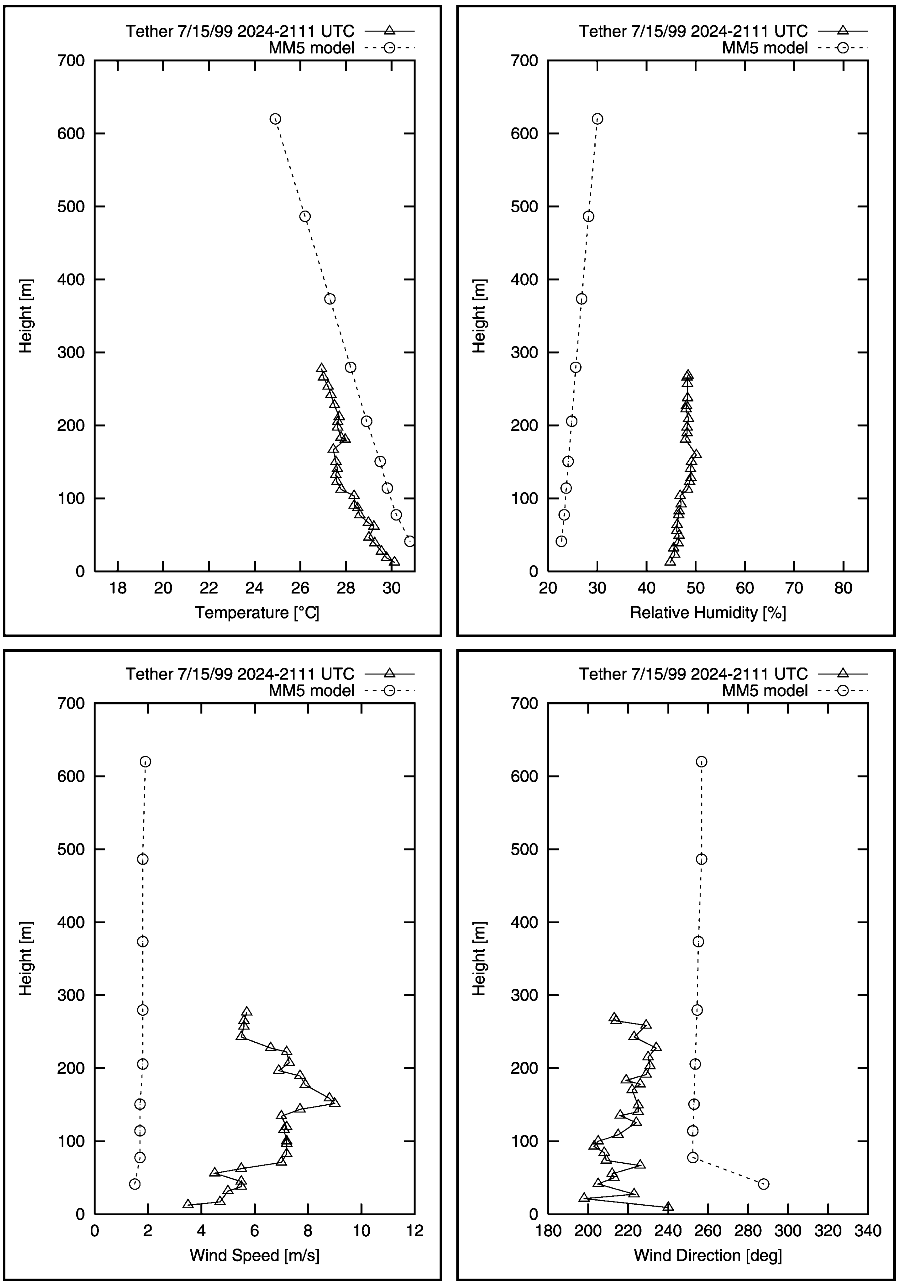

Figure 11. Comparison of tethered balloon observations with MM5 4 km model results over Philadelphia for July 15, 1999; 21 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

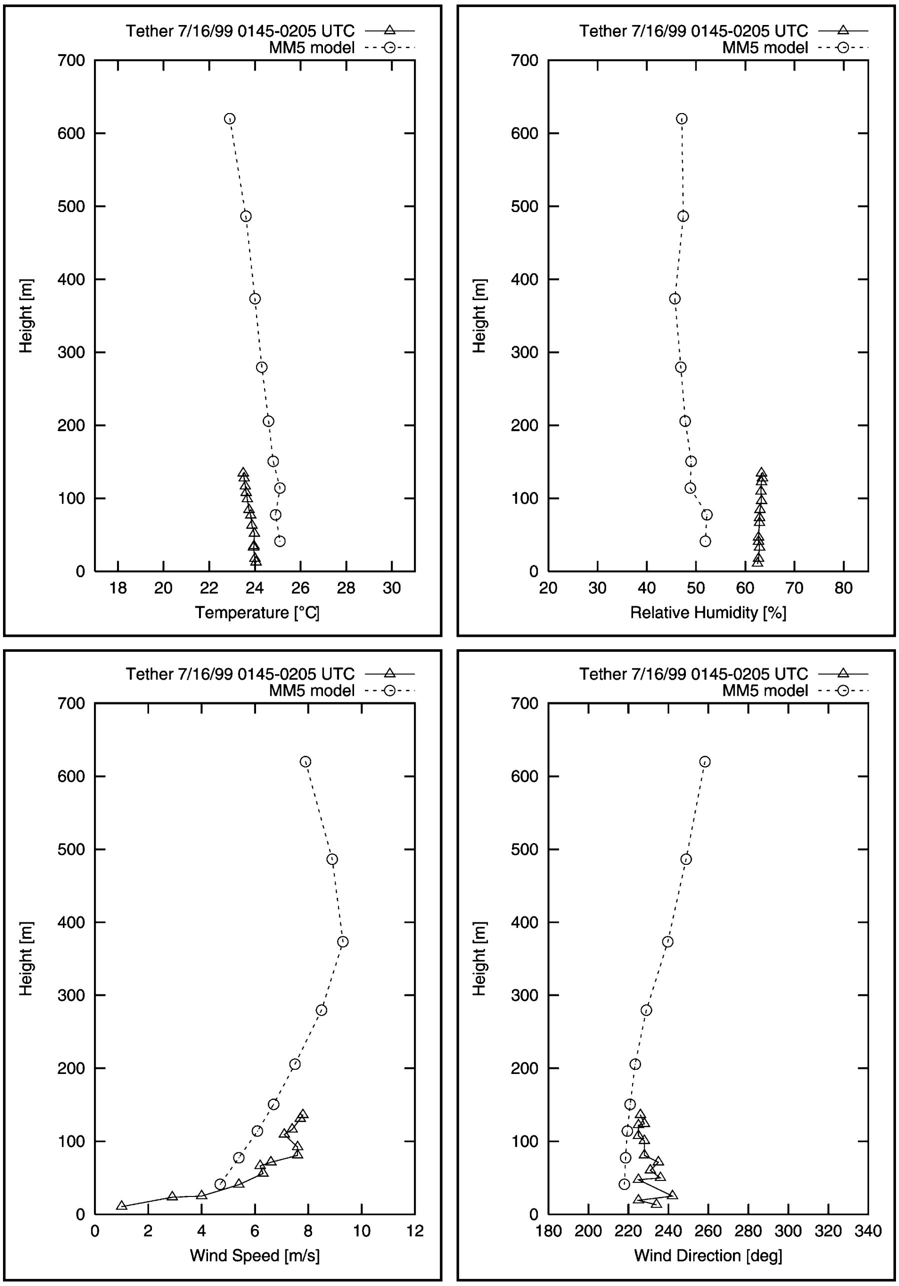

Figure 12. Comparison of tethered balloon observations with MM5 4 km model results over Philadelphia for July 16, 1999; 02 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

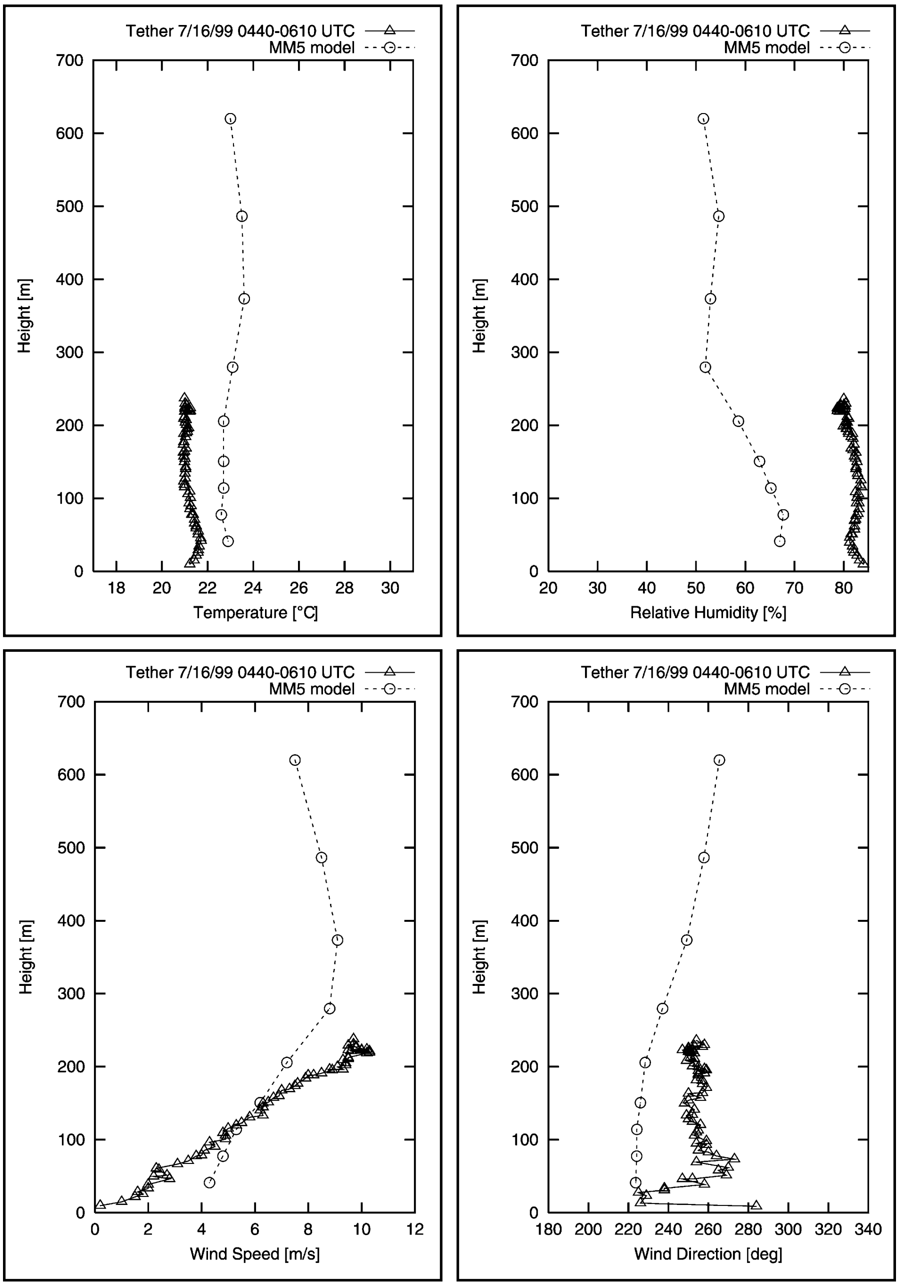

Figure 13. Comparison of tethered balloon observations with MM5 4 km model results over Philadelphia for July 16, 1999; 06 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

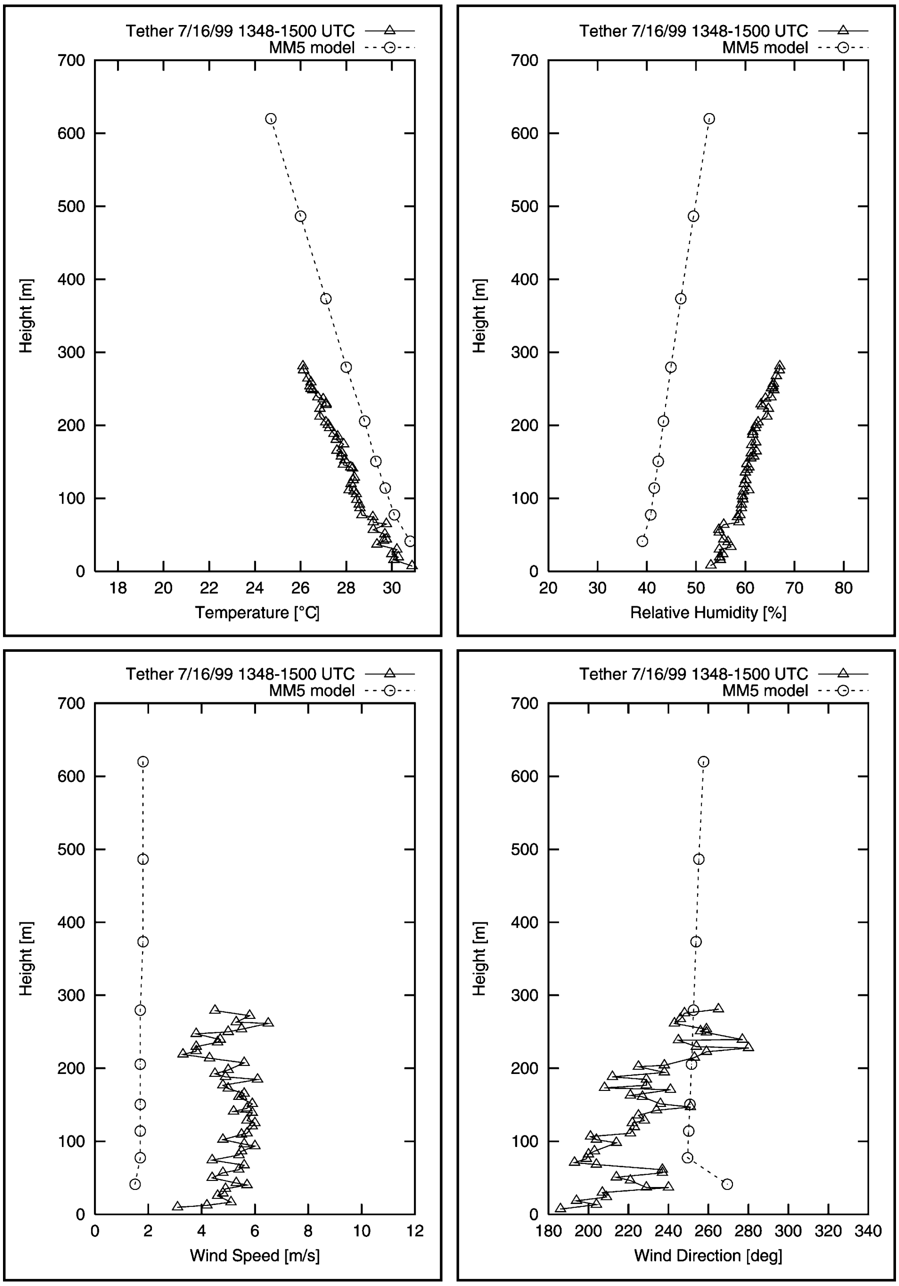

Figure 14. Comparison of tethered balloon observations with MM5 4 km model results over Philadelphia for July 16, 1999; 15 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

vapor mixing ratio with respect to the lidar data (mean relative error varying from -0.5 g kg^{-1} to -1.23 g kg^{-1}), is consistent with the underestimation of the relative humidity with respect to the aircraft and tethered balloon data. Earlier investigators have found that MM5 underestimates the moisture field and the results of this study corroborate these findings. Earlier investigators have found that MM5 exhibited a tendency towards very low wind speeds in the early-mid afternoon hours and the above feature was also seen in this study. MM5 could also successfully simulate the sharp gradients of the horizontal velocity components seen in the wind profiler data. It appears that the temperature data obtained from the lidar have some errors for some of the time periods considered in this study. The differences between the model results and observations are also in part due to the initial fields and the fields utilized in the data assimilation, as MM5 has been employed in this study in a hindcasting and not in a forecasting mode. Finally, despite the inherent limitations of a comparison study such as this, the results of the present study broadly conform to the general traits of MM5 predictions, as noted in earlier investigations.

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References

1. Philbrick, C.R., Ryan, W.F., Clark, R.D., Doddridge, B.G., Dickerson, R.R., Koutrakis, P., Allen, G., McDow, S.R., Rao, S.T., Hopke, P.K., Eatough, D.J., Dasgupta, P.K., Tollerud, D.J., Georgopoulos, P., Kleinman, L.I., Daum, P., Nunnermacker, L., Dennis, R., Schere, K., McClenny, W., Gaffney, J., Marley, N., Coulter, R., Fast, J., Doren, C. and Mueller, P.K.: 2002, Overview of the NARSTO-NE-OPS Program. In: *Proceedings of the Fourth Conference on Atmospheric Chemistry: Urban, Regional, and Global-Scale Impacts of Air Pollutants*, pp. 107–114, American Meteorological Society, Orlando, FL.
2. Hanna, S.T.: 1994, Mesoscale meteorological model evaluation techniques with emphasis on needs of air quality models. In: R.A. Pielke and R.P. Pearce (eds.), *Mesoscale Modeling of the Atmosphere*, Vol. 25, pp. 47–58, American Meteorological Society, Boston, MA.
3. Lyons, W.A., Tremback, C.J. and Pielke, R.A.: 1995, Applications of the Regional Atmospheric Modeling System (RAMS) to provide input to photochemical grid models for the Lake Michigan Ozone Study (LMOS), *J. Appl. Meteorol.* **34**, 1762–1786.

4. Cox, R., Bauer, B.L. and Smith, T.: 1998, A mesoscale model intercomparison, *Bull. Amer. Meteorol. Soc.* **79**, 265–283.
5. TNRCC: 2001, MM5/RAMS *Fine Grid Meteorological Modeling for September 8–11, 1993 Ozone Episode*, pp. 36 (www.tnrcc.state.tx.us/air/aqp/airquality_contracts.html#met02), TNRCC Report No. 31984-12.
6. TNRCC: 2002, *High Resolution (1.33 km) MM5 Modeling of the September 1993 COAST Episode: Sensitivity to Model Configuration and Performance Optimization*, p. 58 (www.tnrcc.state.tx.us/air/aqp/airquality_contracts.html#met11), TNRCC Report No. 31984-18.
7. Hogrefe, C., Rao, S.T., Kasibhatla, P., Kallos, G., Tremback, C.J., Hao, W., Olerud, D., Xiu, A., McHenry, J. and Alapaty, K.: 2001a, Evaluating the performance of regional-scale photochemical modeling systems: Part I – meteorological predictions, *Atmos. Environ.* **35**, 4159–4174.
8. Sistla, G., Hao, W., Ku, J.Y., Kallos, G., Zhang, K.S., Mao, H.T. and Rao, S.T.: 2001, An operational evaluation of two regional-scale ozone air quality modeling systems over the eastern United States, *Bull. Amer. Meteorol. Soc.* **82**, 945–964.
9. Fast, J.D., Zaveri, R.A., Bian, X., Chapman, E.G. and Easter, R.C.: 2002, The effect of regional-scale transport on oxidants in the vicinity of Philadelphia during the 1999 NE-OPS field campaign, *J. Geophys. Res.* **107**, 10.1029/2001JD000980.
10. Fast, J.D., Doran, J.C., Shaw, W.J., Coulter, R.L. and Martin, T.J.: 2000, The evolution of the boundary layer and its effect on air chemistry in the Phoenix area, *J. Geophys. Res.* **105**, 22833–22848.
11. Zhang, K., Mao, H., Civerolo, K., Berman, S., Ku, J.Y., Rao, S.T., Doddridge, B.G., Philbrick, C.R. and Clark, R.D.: 2001, Numerical investigation of boundary-layer evolution and nocturnal low-level jets: Local versus non-local PBL schemes, *Environ. Fluid Mech.* **1**, 171–208.
12. Buckley, R.L., Weber, A.H. and Weber, J.H., 2001: Statistical comparison of forecast meteorology with observations using the Regional Atmospheric Modeling System, pp. 9 (www.srs.gov/general/pubs/fulltext/ms2001678/ms2001678.html), WSRC-MS-2001-00678.
13. Pielke, R.A., Kallos, G. and Segal, M.: 1989, Horizontal resolution needs for adequate lower tropospheric profiling involved with atmospheric systems forced by horizontal gradients in surface heating, *J. Atmos. Oceanic Technol.* **6**, 741–758.
14. Clark, R.D., Philbrick, C.R. and Doddridge, B.G.: 2002, The effects of local and regional scale circulations on air pollutants during NARSTO-NEOPS 1999–2001. In: *Proceedings of the Fourth Conference on Atmospheric Chemistry: Urban, Regional, and Global-Scale Impacts of Air Pollutants*, pp. 125–132, American Meteorological Society, Orlando, FL.
15. Doddridge, B.G.: 2000, An airborne study of chemistry and fine particles over the U.S. Mid-Atlantic region. In: *Proceedings of the PM2000: Particulate Matter and Health Conference*, pp. 4–5, Air and Waste Management Association, Charleston, SC.
16. Grell, G.A., Dudhia, J. and Stauffer, D.R.: 1994, *A Description of the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5)*, NCAR Technical Note TN-398 + STR. National Center for Atmospheric Research, Boulder, CO.
17. Pagnotti, V.: 1987, A mesoscale meteorological feature associated with high ozone concentrations in the northeastern United States, *J. Air Pollut. Control Assoc.* **37**, 720–722.
18. Angevine, W.M., Bakwin, P.S. and Davis, K.J.: 1998, Wind profiler and RASS measurements compared with measurements from a 450-m-tall tower, *J. Atmos. Oceanic Technol.* **15**, 818–825.