A Comparative Study of Prognostic MM5 Meteorological Model 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 MM5 meteorological mesoscale model using data from the North East Oxidant and Particle Study (NE-OPS) research program collected over Philadelphia, PA during a summer episode in 1999. Also, this study presents a comparative evaluation of MM5 applications employing different numbers of layers in the vertical direction (21 and 14) assessing the performance of the alternate simulations with NE-OPS observations. A first set of model simulations was performed with 21 layers in the vertical direction for a period of 101 hours from July 15, 1999; 12 UTC to July 19, 1999; 17 UTC. A second set of MM5 model simulations was performed with 14 layers in the vertical direction for a two week period from July 11, 1999; 00 UTC to July 25, 1999; 11 UTC, corresponding to the field study days for NE-OPS. The results indicate that the 14 layer model is able to capture the atmospheric mesoscale structure as well as the 21 layer model. The comparison with aircraft data reveals that temperature values are reasonably well predicted while the relative humidity values are underestimated by both model set-ups. The virtual temperature profiles predicted by both simulations compares favorably with RASS data. Both the MM5 applications successfuly simulate the low level jets seen over Philadelphia during the period July 16-19, 1999. In fact, both the MM5 applications reasonably reproduce the sharp gradients in the horizontal wind components seen near the jet core. The mixing ratio profiles obtained from the lidar instrument compare reasonably well with predictions from both simulations. While both applications compare reasonably well with the lidar temperature data for some instances, they seem to over predict the temperature for other occasions. The model predicted temperature profiles are in reasonable agreement with the tethered balloon observations while the relative humidity and wind speed are somewhat underestimated. The largest root mean square (rms) errors obtained from the 36 km resolution MM5 model results and the regular upper air rawinsonde stations are associated with the relative humidity values for both simulations. The largest rms errors for any variable are all associated with the upper atmosphere while the smallest rms errors are associated with the lower troposphere.

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

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1. Introduction

1.1. Rationale

Highlighting the importance of regional mesoscale meteorological models in providing accurate meteorological inputs necessary to perform simulations of the current three dimensional photochemical modeling systems is hardly necessary. The photochemical models are the primary tools available to 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 as close to observations as possible. Hence, there is a need to perform extensive evaluations of available mesoscale meteorological models with field observations in order to understand the limitations as well as strengths of these models.

Even with the advent of faster computing machines, the computational costs of running a three dimensional mesoscale meteorological model is quite high and there is a real need to explore ways and means of reducing the computational requirements especially when one is dealing with simulations over relatively extended periods. Most past applications involved mesoscale meteorological and subsequently photochemical modeling over periods of a few days; current applications focus mostly on two to four week periods while there is a well-established regulatory need for seasonal and even annual simulations, especially in relation to strategies for meeting the ambient PM standard. One of the options available for reducing the computational requirements is to perform simulations with the atmosphere being divided into relatively fewer layers in the vertical direction. Of course, in such a case it is important to ensure that the Planetary Boundary Layer (PBL) is well represented in terms of vertical resolution.

The North American Research Strategy for Tropospheric Ozone - North-East - Oxidant and Particle Study (NARSTO-NE-OPS) [29] has pursued an observational field campaign that provide meteorological data from a variety of platforms such as instrumented aircraft, wind profiler, rass, lidar and tethered balloon sondes. In the present work an extensive evaluation of the MM5 model with NE-OPS observations is undertaken during a major ozone episode which occured during the summer of 1999 over Philadelphia.

1.2. Objectives

The primary objectives of this research effort are :

1. to perform an evaluation of the MM5 meteorological model 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 during a major ozone episode.

2. to perform a comparative evaluation of MM5 applications that utilize different numbers of layers in the vertical direction and to compare the performances of these alternative simulations with NE-OPS observations.

1.3. Background

A large number of studies have shown that prognostic mesoscale meteorological models can successfully provide the meteorological inputs necessary to perform simulations with comprehensive three dimensional photochemical modeling systems [30, 19]. However, uncertainties in the meteorological inputs can cause unrealistic air quality predictions, thus affecting the development of appropriate emission control strategies [33]. Hence, there is a critical need to perform extensive evaluations of mesoscale meteorological models with observations in order to understand the limitations and strengths of these models.

Mesoscale meteorological models used in air quality assessment modeling have been evaluated in some earlier studies [14, 22, 25] 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 a four-dimensional data assimilation (4DDA). Hence, it is difficult to establish clearcut 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. Oncley and Dudhia (1995) [26] evaluated the MM5 model by comparing model output with direct observations of surface fluxes of momentum, sensible and latent heat. Oncley and Dudhia [26] utilized meteorological towers and aircraft to obtain observations of the above surface fluxes. The results of that comparison revealed that the MM5 model flux parameterizations worked well when appropriate values of the roughness length and the moisture availability parameter were chosen. Dosio et al. (2001) investigated the typical features of a summer smog episode in a highly complex terrain of the Province of Bolzano, Northern Italy through numerical modeling (MM5 and TVM) as well as through an intensive measurement campaign. The latter included ground-based monitoring stations as well as vertical profiling with two sodars and an ultra-light aircraft. A comparison of the field data with both the simulation results yielded satisfactory agreement, thus providing evidence of the suitability of the MM5 and TVM models to simulate meteorological conditions in complex terrain. Michelson and Seaman (2000) [24] successfully assimilated the Next-Generation Radar Velocity Azimuth Display (NEXRAD-VAD) winds over the Northeastern United States into the MM5 model for summertime meteorological simulations for the year 1995. The NEXRAD-VAD winds were available at ten sites in the Northeastern United States and these formed part of the North American Research Strategy on Tropospheric Ozone - Northeast field study for the summer of 1995. The MM5 simulations with the assimilation of NEXRAD-VAD were then evaluated using independent experimental data and it was found that this caused a significant decrease in the model wind errors. Guo et al. (2000) performed various assimilation experiments by utilizing MM5 with a four dimensional variational data assimilation (4DVAR) system utilizing a full physics adjoint. The above 4DVAR system assimilated wind profiler, hourly rainfall, surface dew point and ground based GPS precipitable water vapor data. The assimilation experiments were then evaluated against independent observations and the results revealed that the 4DVAR system successfully reproduced the observed rainfall and substantially reduced model errors. Spangenberg et al. (1997) [35] utilized the MM5 model to simulate details of the upper tropospheric relative humidity (UTRH) fields. Because upper tropospheric radiosonde measurements of relative humidity were not reliable, Spangenberg et al. (1997) [35] utilized the satellite GOES 6.7 μm water vapor observations to evaluate the MM5 simulations of UTRH. The MM5 simulated clear-sky 6.7 μm brightness temperature were compared with the GOES satellite observations resulting in an average correlation coefficient of 0.80. Siebert et al. (2000) investigated the ozone situation in the Eastern Alps during the south foehn period during May 1997, by utilizing measurements (surface, soundings including mobile sodar, a stationary ozone lidar, and aircraft) of meteorological and chemical parameters as well as through models (MM5 and a chemistry transport model). Hogrefe et al. (2001a) [17] recently introduced the concept of scale analysis and successfully applied it to evaluate two popular mesoscale meteorological models, namely MM5 and RAMS3b. The second part [18] of the above work dealt with ozone predictions while the third part [2] was confined to precursor predictions. Sistla et al. (2001) [34] investigated the performance of two regional scale photochemical systems, namely the Regional Atmospheric Modeling System/Urban Airshed Model-Variable Grid Version (RAMS/UAM-V) and the Fifth Generation NCAR- Penn State Mesoscale Model/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 in fact comparable when the model outputs were averaged over all simulated days. Recently, Hanna and Young (2001) [15] compared the mesoscale simulations of near-surface winds, temperature gradients, and mixing depths from four mesoscale meteorological models (MM5 being one of the models) with boundary layer observations.

Also recently Chen and Dudhia (2001) [3] conducted several simulations using the MM5 model coupled with an advanced land surface model (LSM), alongside simulations where the MM5 model was coupled with a simple slab model. Both the above sets of simulations (MM5-LSM and MM5-SLAB) were evaluated using observations. Chen and Dudhia (2001) [3] found that the MM5-LSM simulations yielded surface temperatures and humidity values closer to FIFE observations, compared to MM5-SLAB model runs. Also, precipitation forecasts from the MM5 model were evaluated for the Pacific Northwest region during the winter/spring season of 1996-1997 [4] and 1997-1999 [6] using National Weather Service precipitation sites, to study the effects of increased horizontal resolution and to document spatial variations in the model skill. The model verification score (model skill) is derived by using a contingency table approach from which it is possible to define bias and equitable threat scores [6]. While the above mentioned bias and equitable threat scores measure model accuracy based on the frequency of occurrence at or above the precipitation threshold, quantitative precipitation errors are calculated using root mean square errors [6].Colle et al. (1999, 2000) [4, 6] found a noticeable improvement in the precipitation forecast skill as horizontal resolution is increased from 36 to 12 km. However, they found improvement in the precipitation forecast skill from 12 to 4 km to occur only during heavy precipitation events. A study (including both observational and numerical aspects) of a cold front interacting with the Olympus mountains during the Coastal Observations and Simulation with Topography (COAST) field program was undertaken [5]. The numerical part of the above study utilized the MM5 model while the observational part utilized NOAA P-3 aircraft which provided flight level data, radar reflectivity and Doppler winds. Roswintiarti et al. (2001) [31] utilized the MM5 model for the March 5-7, 1999 period over the tropical Indian Ocean during the Indian Ocean Experiment (INDOEX). The model simulations were then evaluated against analysis for large-scale characteristics as well as with GPS sonde vertical soundings. The results indicated that the MM5 model simulations were in good agreement with both dynamical and thermodynamical fields over the INDOEX domain. The impact 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 has recently been carried out using the MM5V3 model for July 15-20, 1999 by Zhang et al., 2001 [36]. 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. Ku et al., (2001) [20] investigated the effects of the above mentioned PBL schemes on the predicted ozone (O_3) concentrations using the MODELS-3/CMAQ photochemical model for the July 12-17, 1999 period. Ku et al., (2001) [20] utilized CMAQ with 12 km horizontal resolution and 163 x 145 grid cells in the east-west and north-south directions, covering a large portion of the Eastern United States.

It is well known that numerical weather prediction (NWP) models are being used to provide inputs of various meteorological fields to atmospheric dispersion models. Most evaluations of NWP models have been confined to predictions on weather related parameters such as rainfall, etc. Hanna et al. (2000) [16] recently proposed an evaluation methodology which is primarily focused on the needs of atmospheric dispersion models. Hanna et al. (2000) [16] tested the above mentioned evaluation methodology with two NWP models (MM5 and RAMS) for a typical light wind period in the United States during 1995 and obtained estimates for root mean square errors in wind speed and wind direction. Recently, Mass et al. (2002) [23] studied the effects of increasing horizontal resolution on the forecast skill by examining the results of two years of the University of Washington Real-Time MM5 Modeling and Verification System over the Pacific Northwest and found that decreasing grid spacing does improve the realism of the results but does not necessarily significantly improve the skill accuracy of the forecasts.

Even though the present study has utilized four dimensional data assimilation (4DDA), we have refrained from using the NE-OPS observations in 4DDA and hence an extensive evaluation of the mesoscale meteorological model with NE-OPS observations is indeed possible. Even though the MM5 model has been evaluated in earlier studies using a variety of observations (surface, sounding, aircraft etc.); the authors are not aware of a study where the MM5 model is evaluated using a wide-ranging array of advanced measurement platforms (aircraft, rass, profiler, lidar and tethered balloon) as is being attemped in this study.

1.4. Meteorological Modeling

In order to develop the meteorological inputs for modeling the air quality of the Philadelphia region during a major summer ozone episode in 1999, the MM5 model with 21 layers in the vertical directions and three levels of nested domains (36 km, 12 km and 4 km grid resolutions) was applied for the July 15-19, 1999 period. Since the ultimate concern is to assess regional population exposures to ozone and particulate matter (PM) there is a need for meteorology/air quality simulations over periods of substantial length. Due to the computational requirements involved in medium to long durations of simulation it is useful to evaluate a more computationally efficient "set-up" of the MM5 model i.e. a simulation with a reduced number of layers in the vertical directions. Hence, the MM5 model with 14 layers in the vertical direction and three levels of nested domains (36 km, 12 km and 4 km grid resolutions) was applied for the July 11-25, 1999 period. The MM5 model predictions utilizing 14 and 21 layers in the vertical direction were then compared with one another and also with aircraft, wind profiler, rass, lidar and tethered balloon data from the NE-OPS observations over Philadelphia during that period.

1.5. A brief overview of NARSTO-NE-OPS

The North American Research Strategy for Tropospheric Ozone - NorthEast - Oxidant and Particle Study (NARSTO-NE-OPS) is a multi institutional collaborative research program set up to improve current understanding of the underlying causes for the occurence of high ozone concentrations and increased levels of fine particles in the north-eastern United States. Various advanced meteorological and air chemistry measurements were made in the vicinity of Philadelphia, PA during two field campaigns conducted in the summers of 1998 and 1999 [29]. The campaign during the summer of 1998 constituted the pilot study while the periods of 1999 and 2001 comprised the main NE-OPS observation program. The site preparation for the main summer intensive NE-OPS program at the Baxter Water Treatment Plant, Philadelphia, PA (40.0764^{o}N, 75.0119^{o}W) began on June 15, 1999 and the site was fully operational from June 28 to August 19, 1999. During the above mentioned two month campaign eight pollution episodes occured over Philadelphia (July 3-5; July 8-10; July 16-21; July 23-24; July 27-August 1; August 7-8; August 11-13; August 15-17, 1999) all of them resulting to measurements of high ozone concentration over Philadelphia. All of the above episodes were monitored continously 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 occured during the period July 16-21, 1999 over Philadelphia. The University of Maryland provided information on the distribution of PM, chemical species and meteorologcal variables by operating the instrumented flights with Cessna and Aztec aircrafts over Philadelphia airport (PNE) and Tipton Airport, Ft. Meade, MD (FME) [8]. Radar wind profiler/RASS sounder were operated at the Baxter Water Treatment Plant site and West Chester (Pacific Northwest National Laboratory, PNNL) sites while a radar wind profiler was stationed at Centerton, New Jersey (Argonne National Laboratory, ANL). The Pennsylvania State University Lidar, referred to as LAPS (Lidar Atmospheric Profile Sensor), was utilized to obtain vertical profiles of ozone, water vapor, temperature and extinction during the summers of 1998 and 1999. The LAPS instrument uses multi-channel photon counting detection to measure several wavelengths of Raman scattered signals which ultimately yields vertical profiles of atmospheric properties [21, 28]. Millersville University deployed two tethered balloons during the summers of 1998 and 1999 to obtain detailed temporal and vertical profiles of fine particles, O_3 concentrations and meteorological variables [7]. In addition to the above aircraft measurements (Brookhaven National Laboratory), ozonesondes (PNNL), rawinsondes (PNNL, ANL) and ground based measurements of particle/chemical samples (Harvard University School of Public Health, Drexel University and Bringham Young University) were conducted. Brookaven National Laboratory performed 19 regional flights between July 25 to August 11, 1999 using the instrumented DOE-G1 aircraft to sample chemical species and particle characterization. The Pacific Northwest National Lab (PNNL) released 61 radiosonde balloons and 10 ozonesonde balloons between July 23 and August 10, 1999 from the Philadelphia site to obtain vertical profiles of wind direction, speed, temperature, humidity and ozone concentrations. Also, PNNL operated a Radar/RASS sounder at West Chester, PA, located 30 miles west from the Baxter site from July 23 to August 11, 1999. Argonne National Laboratory (ANL) operated a mobile chemistry laboratory and a Radar/SODAR sounder at Centerton NJ, (30 miles south of the Philadelphia site) during the period July 24 to August 11, 1999. Also ANL released 56 radiosonde balloons at the above site during the campaign duration. Bringham Young University utilized three instruments to measure the volatile and semi-volatile mass and species of particles during the period July 2-30, 1999. Temperature and relative humidity data were provided by University of Maryland instrumented aircraft at different pressure and altitude levels in the atmosphere. The radar wind profiler provided the profiles for all three velocity components while the RASS (Radio Acoustic Sounding System) sounder provided profiles of the virtual temperature and vertical velocity respectively. 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 investigation was primarily focused on a major ozone episode that took place in July 1999 over the Philadelphia region, to perform an extensive evaluation of the MM5 [12] meteorological model. In recent years, starting from 1999, there has been a significant increase in the number of continous (i.e., reporting hourly average concentrations) monitors for $PM_{2.5}$ that complement the already extensive ozone. Figure 1 presents the air quality monitoring stations and flight tracks in the vicinity of the NE-OPS Baxter site. Also depicted in the same figure in purple is the area representing urban Philadelphia, the region representing the focus of a comprehensive population exposure study for Ozone and fine Particulate Matter during the summer period of 1999 [11]. The two circles indicated in Figure 1 correspond to a radii of 50 km and 100 km with the Baxter site, Philadelphia, PA at the center. The flight tracks depicted in

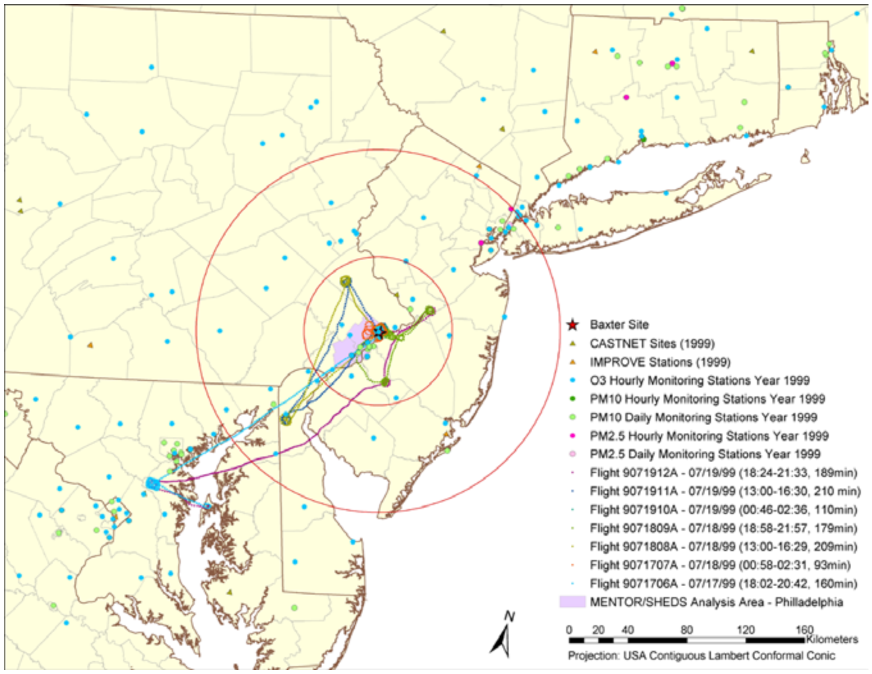

Figure 1. Air quality monitoring stations and flight tracks in the vicinity of NE-OPS: area in purple (urban Philadelphia) represents focus of the MENTOR/SHEDS analysis of population exposures to Ozone and fine PM during summer 1999 utilizing NE-OPS data. The circles indicated in the figure correspond to a radius of 50 Km and 100 Km with the Baxter NE-OPS site at the center

Figure 1 correspond to the University of Maryland flights during the period July 17-19, 1999. A field campaign during October 2000 focused on the vertical transport and mixing (VTMX) in the Salt Lake Valley area and like the NE-OPS field campaign utilized various advanced measurement platforms such as RASS, lidars, tethered balloons, rawinsondes, sonic anemometers, sodars and radar profilers [9].

1.6. 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 July 15-19, 1999. The Mid-atlantic and Northeastern U.S. regions were characterized by high temperatures, very strong short-wave radiation and a dominant westerly flow. The above mentioned conditions are known to be favorable for the transport of pollutants from the Midwest to the East as well as the in-situ formation of ozone and other secondary pollutants [36]. The Appalachian lee trough [27], a typical pressure pattern for high ozone episodes and for the occurence of Low Level Jets

(LLJ) in the Northeastern U.S. persisted for three days from July 16-19, 1999. Southwesterly flow from the Mid-Atlantic region to the Northeastern 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, 1999.

2. Prognostic Meteorological Modeling: Approach

2.1. MM5 model using 21 layers in the vertical direction

The present study utilized the Fifth Generation Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) Version 3.4 [12]. Twenty one layers in the vertical direction (centered at σ = 0.9975, 0.9925, 0.9875, 0.9825, 0.975, 0.965, 0.9525, 0.9375, 0.92, 0.9, 0.8775, 0.8525, 0.81, 0.74, 0.65, 0.55, 0.45, 0.35, 0.25, 0.15 and 0.05) 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. The outermost domain encompasses the entire Eastern United States while the inner domain is centered over Northern New Jersey (left panel of Figure 2). The number of grid cells in the east-west and north-south directions are 75 x 69, 91 x 76 and 124 x 148 at the 36, 12 and 4 km resolutions, respectively. Table I provides for the vertical structure used in the MM5V3 simulations and provides 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, the mixed phase (Reisner) scheme for explicit moisture, a cloud radiation scheme and a force restore (Blackadar) scheme for ground temperature. In addition to surface and rawinsonde observations, the ECMWF global analysis data at 2.5 degree resolution were utilized. A one way nesting approach was chosen. The four dimensional data assimilation option was utilized in the free atmosphere. In the atmospheric boundary layer (ABL) the winds were nudged using the surface data. Model simulations were performed for the July 15, 1999; 12 UTC to July 19, 1999; 17 UTC period.

2.2. MM5 model using 14 layers in the vertical direction

In order to evaluate the performance of a more computationally efficient "set-up" of MM5, a version with the number of layers in the vertical direction

Table I. 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)	Approximate 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

reduced from 21 to 14 and the number of grid cells in the east-west and north-south directions reduced by a factor of two for the 12 and 4 Km domains, respectively was run for the period July 11, 1999; 00 UTC to July 25, 1999; 11 UTC. The layers were centered at σ = 0.9975, 0.9925, 0.985, 0.9725, 0.955, 0.9325, 0.9, 0.84, 0.75, 0.65, 0.525, 0.375, 0.225 and 0.075,respectively. Table II provides the same information as Table I for the 14 layer MM5 simulations in the vertical direction. The number of grid cells in the east-west and north-south directions for the 36 Km domain were unchanged while the same number for the 12 Km domain was changed to 52 x 52 and for the 4 Km domain changed to 67 x 76. The above 4 Km domain just encompassed the Phildelphia and New Jersey region (right panel of Figure 2).

Figure 2. The triply nested MM5 modeling domain using 21 layers in the vertical direction (left panel) and using 14 layers in the vertical direction (right panel) with the 36km (D01), 12km (D02) and 4km (D03) horizontal grid structure The projection shown above is Lambert Conformal projection, with the 1st & 2nd parallels being 30^o and 60^o and the reference longitude and latitude being 84.35865^o W and 37.34498^o N

Table II. The vertical structure used for the MM5V3 simulation with 14 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)	Approximate mid-layer height (m AGL)	Layer thickness dz(m)	Ratio of dz
14	0.9975	994	18	36	1.00
13	0.9925	990	54	36	1.51
12	0.985	984	109	55	1.68
11	0.9725	974	201	92	1.42
10	0.955	959	331	130	1.31
9	0.9325	941	500	170	1.48
8	0.9	914	751	251	1.93
7	0.84	864	1235	484	1.60
6	0.75	789	2007	772	1.21
5	0.65	705	2942	935	1.44
4	0.525	600	4285	1344	1.42
3	0.375	472	6196	1910	1.30
2	0.225	342	8674	2478	1.50
1	0.075	208	12390	3717	N/A

3. Results and Discussion

3.1. Comparison of MM5 simulations with NE-OPS observations

In order to assess the performance of MM5 model with 14 layers in the vertical direction vis a vis the 21 layers in the vertical direction results, a comparison of the corresponding results and the observations was undertaken. In 1998, C-172 light aircraft was operational between August 14-22, and conducted 12 research flights over six operational flight days for a total of 26 flight hours. During the pilot study in 1998, 27 survey spirals were acquired day and night generally 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 1999 both C-172 as well as Aztec aircrafts were utilized day and night in 52 spirals and 21 flybys during the operational period between July 4 to August 17, 1999. In situ observations of GPS position, standard meteorological (temperature, relative humidity at different pressure and altitude levels) and important atmospheric chemical tracers such as O_3 and CO were made from the instrumented aircraft. Since MM5 output is typically available every hour (0, 1, 2 UTC etc), it was decided to compare the model output with the aircraft observations when the latter is in one of its spiral paths, either descending or ascending, and coinciding with the model output time. All the aircraft meteorological observations (temperature, relative humidity) were available at altitudes above mean sea level. Also the latitude and longitude of the aircraft position was available at various altitudes above mean sea level in its ascending or descending spiral paths. Utilizing the postprocessor GRAPH module of the MM5 model, the temperature and dew point temperature profiles at the aircraft locations were obtained and relative humidity calculated from the temperature and dew point temperature values. Next the grid cell closest to the latitude and longitude of aircraft location was identified and the terrain heights as well as the half sigma level heights were added to provide for the heights of the model levels above mean sea level at the aircraft locations. The temperature and relative humidity values of that model level closest to the aircraft altitude were extracted and assigned the appropriate height above mean sea level of that model level. The above mentioned procedure was repeated for the 14 layers in the vertical direction model results as well. All heights referred in the following figures refer to height above mean sea level. Also all the MM5 model results (comparisons with NE-OPS observations) depicted in this study correspond to the 4 km MM5 simulation runs. This study employed four-dimensional data assimilation (4DDA) with the global analysis gridded data as well as with the upper air rawinsonde and surface observations. The 36 Km MM5 domain considered in this study, which happens to be identical for both the applications with 21 and 14 layers in the vertical direction, encompasses about 40 upper air stations and about a thousand surface stations. The 12 Km domain with the 21 layers in the vertical direction encompasses 10 upper air stations and 700 surface stations. The 4 Km domain with the 21 layers in the vertical direction encompasses 4 upper air stations and one hundred surface stations. For the application with 14 layers in the vertical direction, the 12 Km domain encompasses three upper air stations and 120 surface stations while the 4 Km domain encompasses only one upper air station and 30 surface stations. Figure 3 depict the MM5 simulations for NE-OPS 99 for the 4 Km domain and for both applications with 21 and 14 layers in the vertical direction for July 16, 1999; 18 UTC. The above figure depict the wind vector field (upper panels) and the temperature field (lower panels) at the lowest sigma level above the ground surface. Since the lowest sigma level above the surface ($\sigma = 0.9975$) is the same for both the applications with 21 and 14 layers in the vertical direction it was decided to depict the fields at this level. It is clear from the above figures that westerly flows are dominating the Mid-Atlantic and NorthEast United States, and the temperature pattern is characterized by high temperatures. Both the above are characteristic of the occurence of an ozone event over NorthEast United States.

3.1.1. *Comparison of MM5 simulations with aircraft data*

The comparison of aircraft observations with both 4 km MM5 model results using 21 layers and 14 layers in the vertical direction are depicted in Figures 4 (July 17, 1999; 20 UTC and July 18, 1999; 20 UTC) and 5 (July 19, 1999; 02 and 16 UTC) for both temperature and relative humidity. All the above cases are for aircraft in its descending spiral path and correspond to cases when an aircraft spiral occurs during the course of an hour (i.e 0, 1, 2 UTC etc). It is obvious from the above figures that temperature values are more or less robustly simulated by the MM5 applications. The temperature predictions by the application with 21 layers in the vertical direction is slightly nearer to the aircraft observation as compared with the application with 14 layers in the vertical direction. It turns out that the best comparison for temperature occurs on July 19, 1999 at 16 UTC (Figure 5) with both 21 layers and 14 layers simulations results fairly close to their observational values. Several shallow inversions, as can be seen from aircraft observations for July 17, 1999; 20 UTC, July 18, 1999; 20 UTC (Figure 4) and July 19, 1999; 16 UTC (Figure 5) occured between 1700 m to 2200 m. The above aircraft observations suggest that the mixed layer height for the above indicated times ranged from about 1.7 to 2.2 km. The above inferences of mixed height are in agreement with Zhang et al., 2001 [36]. A sharp inversion around 400 m characterizes the aircraft temperature profile on July 19, 1999; 02 UTC. The corresponding relative humidity aircraft profile shows evidence of sharp gradients around 400-600 m and is characterized by low relative humidity values at 500 m.

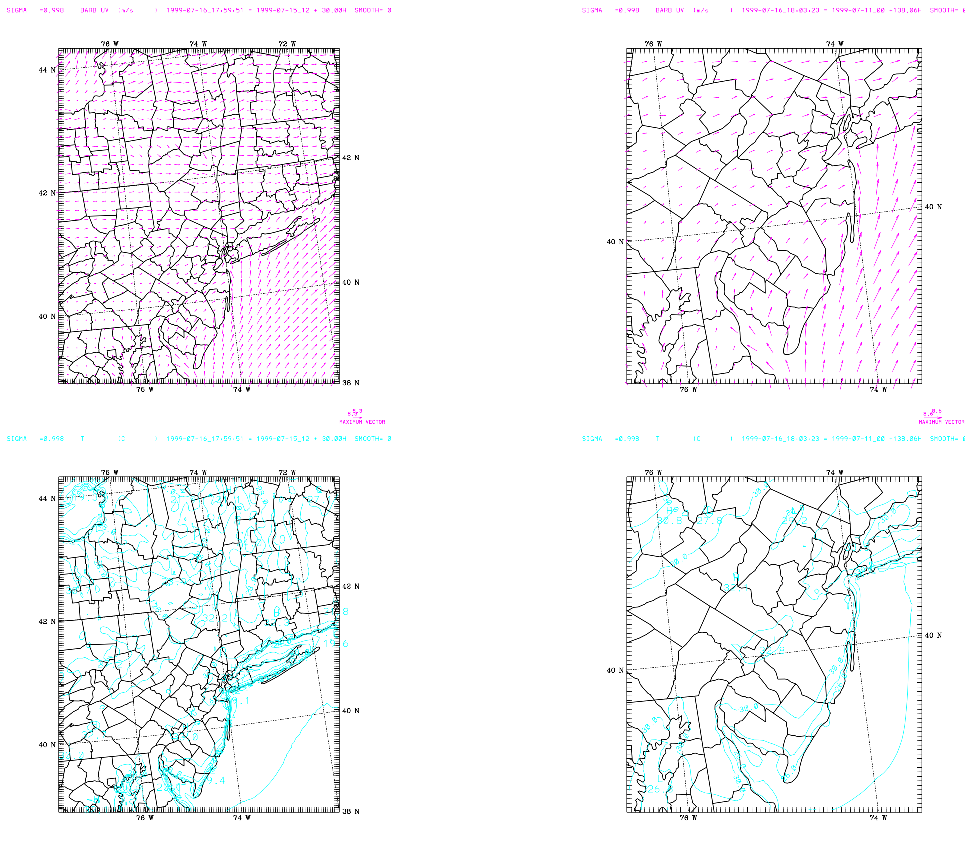

Figure 3. MM5 simulations at the lowest layer (σ=0.9975) above surface for the 4 km domain with both 21 and 14 layers in the vertical direction on July 16, 1999; 18 UTC for wind vector (upper panels) and temperature (lower panels)

The above mentioned pattern indicates that the mixed layer (found between 400-500 m for this time) separates the relatively warm and moist air found at lower levels with the colder and drier air above.

The MM5 simulations with both 21 and 14 layers in the vertical direction appear to underestimate the relative humidity values especially in the lower atmosphere with the 14 layers application results being at times surprisingly closer to the observations (especially on July 19, 1999; 16 UTC (Figure 5)). The applications with the 21 layers in the vertical direction simulates accurately the very high humidity values at heights between 1.5 km to 2 km on July 18, 1999; 20 UTC (Figure 4). While there appeared a slight but distinct improvement in the temperature prediction of the aircraft data with the 21 layers in the vertical direction, the same cannot be said of the relative humidity prediction of the aircraft data for the application with 21 layers in the vertical direction. Both the MM5 applications appear to be unable to

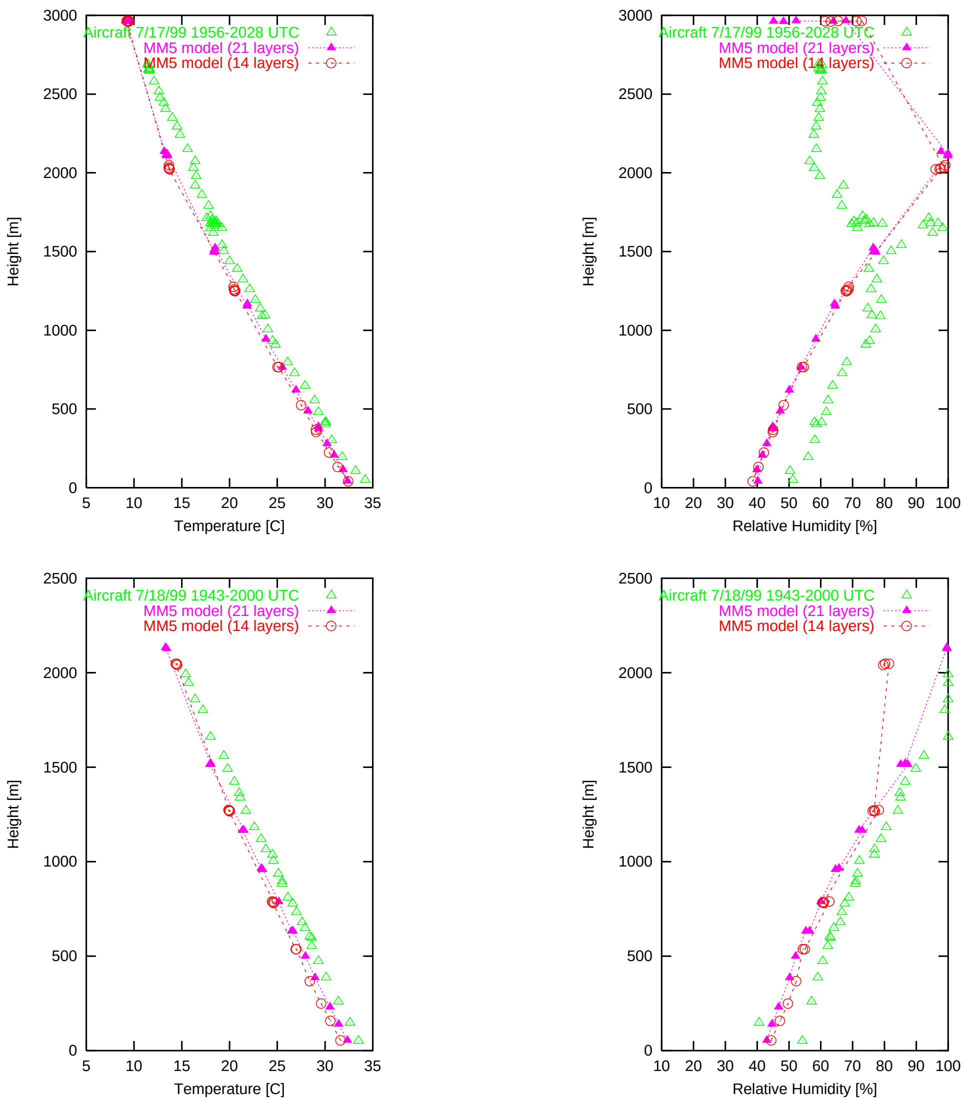

Figure 4. Comparison of aircraft observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for temperature and relative humidity for July 17, 1999; 20 UTC (upper panels) and for July 18, 1999; 20 UTC (lower panels)

accurately simulate the sharp gradients in the relative humidity profile for July 19, 1999; 02 UTC (Figure 5). Also, the sharp gradient seen around 500 m in the temperature profile for July 19, 1999; 02 UTC (Figure 5) is not well simulated by both the MM5 applications. The grid cell size in the vertical direction for both the MM5 applications around 500 m is 112 m and 170 m for 21 and 14 layers in the vertical direction. The sharp gradients in

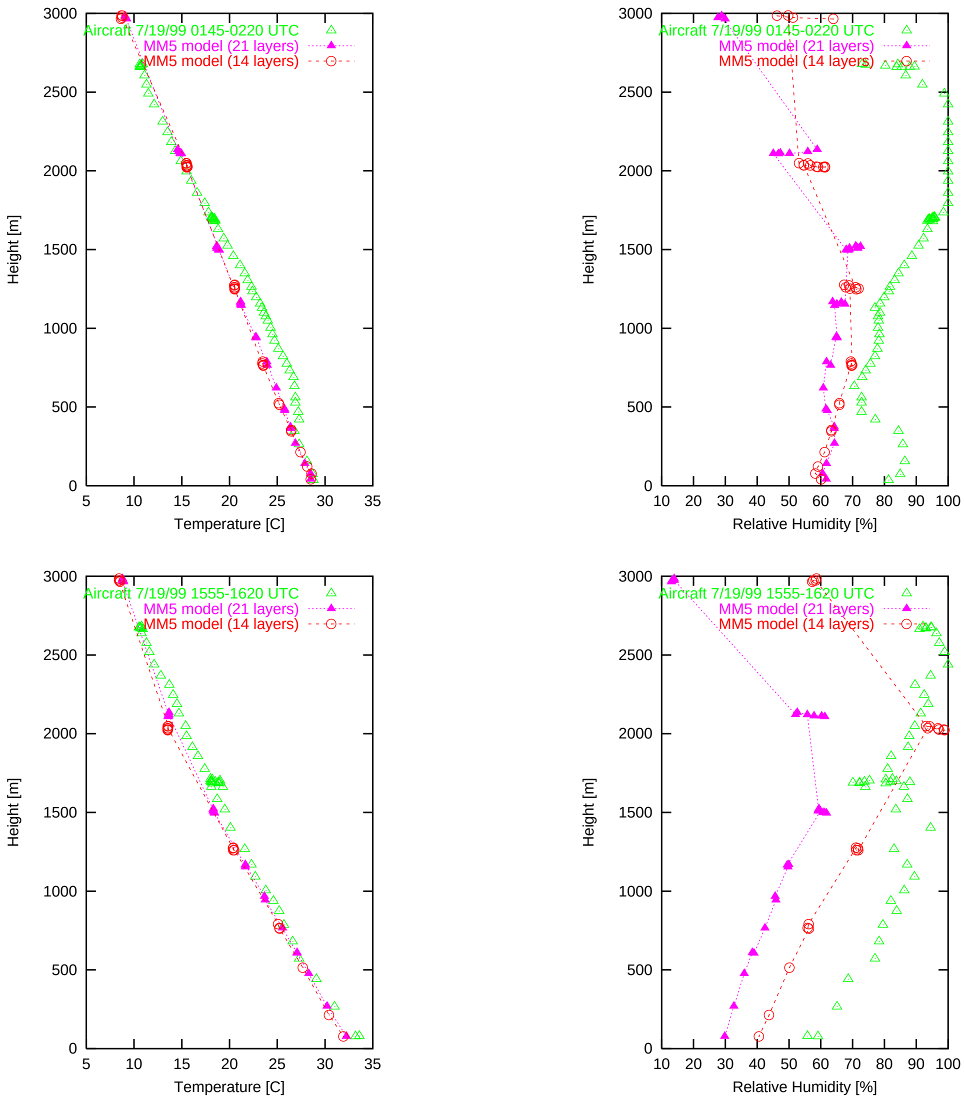

Figure 5. Comparison of aircraft observations with MM5 4 km model results (both 21 vertical layers and 14 vertical layers) over Philadelphia for temperature and relative humidity for July 19, 1999; 02 UTC (upper panels) and for July 19, 1999; 16 UTC (lower panels)

the temperature profile for July 19, 1999; 02 UTC (Figure 5) extend over a depth of 50-75 m in the vertical direction. The above indicates that both the applications may be unable to accurately simulate the sharp gradients in the temperature profile for July 19, 1999; 02 UTC due to the coarseness of the grid in the vertical direction. Despite the model underestimating the humidity values, there is good agreement on the trend of the model generated vertical profiles of relative humidity with aircraft observations.

3.1.2. *Comparison of MM5 simulations with RASS data*

The comparison of virtual temperature obtained from RASS with both 4 km MM5 simulation results with 21 layers in the vertical direction and 14 layers in the vertical direction are depicted in Figure 6. The comparison data with RASS are shown only on and after July 19, 1999 for the following reason. Due to initial setup conditions the instrument may only represent authentic data on and after July 19, 1999 and hence the comparison of virtual temperature data from MM5 model with RASS data is restricted only to July 19, 1999. Figure 6 depicts the comparison for 00, 06, 12 and 17 UTC. A similar procedure was employed here as well except that unlike the aircraft case, one dealt with a single latitude longitude position of the RASS system here. RASS units are usually colocated with a profiler system and are used in conjunction with profiler to provide the virtual temperature profile. RASS unit sends an acoustic wave in the vertical direction whose propagation speed depends on temperature and moisture and hence on the virtual temperature. The profiler then sends out its own pulse which backscatters off of the RASS acoustical wave. The velocity of propagation of the acoustic wave can be obtained from information of its Doppler shift in frequency and the virtual temperature in turn can be determined from the former. By and large the comparison of virtual temperature model results with RASS observations is pretty good except possibly for some differences at heights above 400 m for 06 and 12 UTC. The virtual temperature profiles obtained from the RASS sounder is characterized by sharp gradients close to 400 m for 06 UTC and around 300 m for 12 UTC. Both the MM5 applications appear unable to accurately simulate the sharp gradients in the virtual temperature profile for 06 and 12 UTC. The grid cell size in the vertical direction for both MM5 applications is 93 m and 130 m (21 and 14 layers) around 300 m and is 112 m and 170 m (21 and 14 layers) around 400-500 m. The relatively coarse grid size could possibly be responsible for the inability of both the MM5 applications in accurately simulating the sharp gradients seen in the observed virtual temperature profile. Also, the results of the simulation with 14 layers in the vertical direction compares very favorably with the simulation results with 21 layers in the vertical direction and observations as far as the virtual temperature is concerned. The above mentioned RASS sounder with wind profiler were operated at the Baxter Water Treatment Plant site. Angevine et al.[1], while comparing the wind profiler and RASS measurements with a 450 m tall tower measurements, observed that the virtual temperature as measured by RASS is only accurate to about 0.5^o C. Also Zhang et al., (2001) [36] discuss about the uncertainties arising among the different measurement platforms and provide evidence (Figure 8 of their paper) of differences of

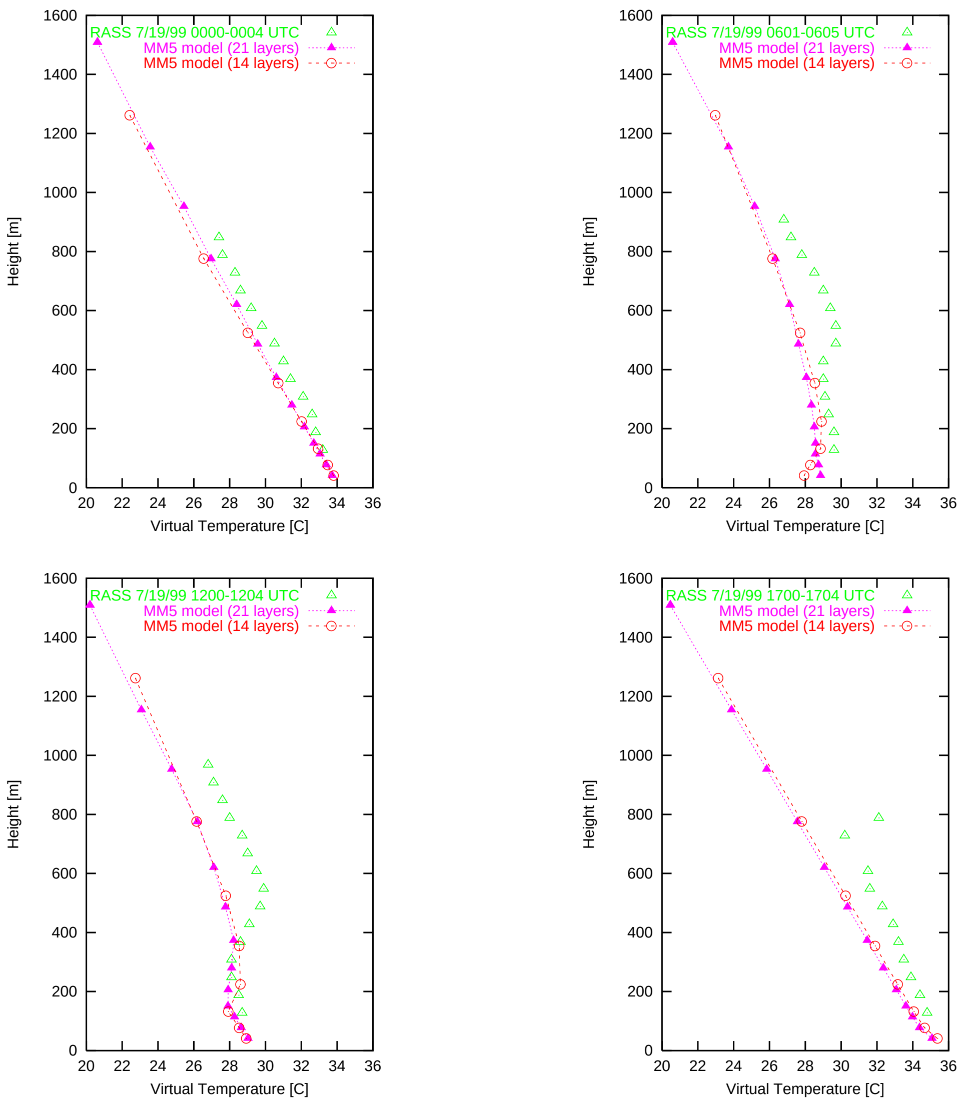

Figure 6. Comparison of RASS observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for virtual temperature for July 19, 1999; 00 and 06 UTC (upper panels) and for July 19, 1999; 12 and 17 UTC (lower panels)

$1 - 2^o$ C in the virtual temperature profile between the aircraft, tethered balloon and RASS measurements during the NE-OPS campaign around July 17, 1999; 20 UTC. Zhang et al., (2001) [36], while comparing the NE-OPS RASS measurements to NE-OPS tower based measurements, found the mean bias and standard deviation of the biases to be about 1^o C.

3.1.3. *Comparison of MM5 simulations with Wind Profiler data*

Usually, RASS units are colocated 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 [36] as well as by Radar-RASS [29]. The comparison of the horizontal wind components obtained from the wind profiler with the 4 km MM5 applications for both 21 layers in the vertical direction and 14 layers in the vertical direction are depicted in Figures 7 and 8. The comparison of the model results with wind profiler data are provided for July 16, 1999; 01 UTC and for July 17, 1999; 04 UTC (top and bottom panels of Figure 7) and for July 18, 1999; 01 UTC and for July 19, 1999; 06 UTC (top and bottom panels of Figure 8). The presence of low level jets (LLJ) which play an important role in the transport of water vapor and pollutants are clearly seen in the wind profiler observations in Figures 7 and 8. The strongest low level jet occured on July 17, 1999; 04 UTC over Philadelphia during the major ozone period July 15-20, 1999. The low level jets are seen between heights of 600-1000 m and are typicaly westerly/south-westerly. Except for the jet seen on July 19, 1999; 06 UTC (bottom panel of Figure 8), the other jets occur earlier, around 01 UTC (upper panels of Figures 7 and 8) and around 04 UTC (lower panel of Figure 7). Both the MM5 applications with 14 and 21 layers in the vertical direction reasonably simulate the low level jets seen in Figures 7 and 8. Zhang et al. (2001) [36] investigated the nocturnal low level jets in the northeastern United States during July 15-20, 1999 by utilizing two different planetary boundary layer (PBL) parameterization schemes (Blackadar scheme and Gayno-Seaman scheme) in MM5. Zhang et al. (2001) [36] found that both PBL schemes produced low level jets which were weaker and which occured at times different from the NE-OPS profiler observation. Zhang et al. (2001) [36] then restricted the four dimensional data assimilation (FDDA) to regions above the PBL and also allowed the convective energy computation to all PBL regimes. The above modifications produced low level jets with improvements in timing as well as in the strength of the jet. However, Zhang et al. (2001) [36] found that both the PBL schemes still failed to reproduce the sharp vertical gradients near the jet core. Zhang et al. (2001) [36] 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 in the vertical direction for the MM5 application was 112 m around 500 m (for 21 layers) and 170 m around 500 m (for 14 layers). Also, unlike Zhang et al. (2001) [36], in the present study FDDA was restricted to above the PBL only for temperature and moisture, and hence FDDA was utilized to nudge the PBL horizontal wind components. Also, in the present study, FDDA utilized twice-a-day rawinsonde observations and global analysis data at 00 and 12 UTC. While Zhang et al. (2001) [36] failed to reproduce the sharp vertical gradients near the jet core, both the MM5 applications seem to successfully simulate the sharp gradients. In fact the simulation of the nocturnal low level jet for July 16, 1999; 01 UTC (top panels of Figure 7) is indeed very good. The simulation of low level jets for July 17, 1999; 04 UTC (bottom panels of Figure 7) and for July 18, 1999; 01 UTC (top panels of Figure 8) are also reasonable. Since FDDA 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 for 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 (Figure 8)). Also, both the MM5 applications with 21 and 14 layers in the vertical direction do not differ much from one another (refer Figures 7 and 8).

3.1.4. *Comparison of MM5 simulations with Lidar data*

The Lidar Atmospheric Profiles Sensor (LAPS) instrument, developed by the Penn State University was utilized as the lidar instrument during the NE-OPS field campaign. Incidentally, the LAPS instrument happens to be the fifth generation Raman lidar instrument developed by the Penn State University. It is well known that Raman scattering occurs when optical radiation is scattered from the molecules of the atmosphere. The LAPS instrument utilizes Raman scattering techniques to determine profiles of the meteorological and optical properties of the lower atmosphere. Also, the vibrational Raman scattering provides for distinct wavelength shifts for species specific vibrational energy states of the molecules while the rotational Raman scattering provides a signal with a variation in the wavelength that depends mainly upon the atmospheric temperature. Hence, the LAPS instrument can directly use the rotational Raman scatter to measure atmospheric temperature while utilizing the vibrational Raman scatter to measure profiles of atmospheric properties like water vapor and ozone and to measure optical properties like optical extinction. The integration times for 1999 water vapor lidar data are 5 minutes as well as 30 minutes. No filtering is present in the water vapor data files. All temperature lidar data in 1999 below 600 m is invalid due to an unresolved problem with vignetting in the detector system. The temperature data for 1999 uses 5 minute integration at 1 minute timesteps as well as 30 minute integrations at 5 minute timesteps. All 1999 temperature data is filtered using a 3 point Hanning filter from 1.5 km to 3 km and 5 point Hanning filter above 3 km. The comparison of the temperature and mixing ratio values obtained from the lidar with both MM5 applications with 21 layers in the vertical direction and 14 layers in the vertical direction are depicted in Figures 9 and 10. The above figures provide the comparison for July 16, 1999; 02 and 04 UTC

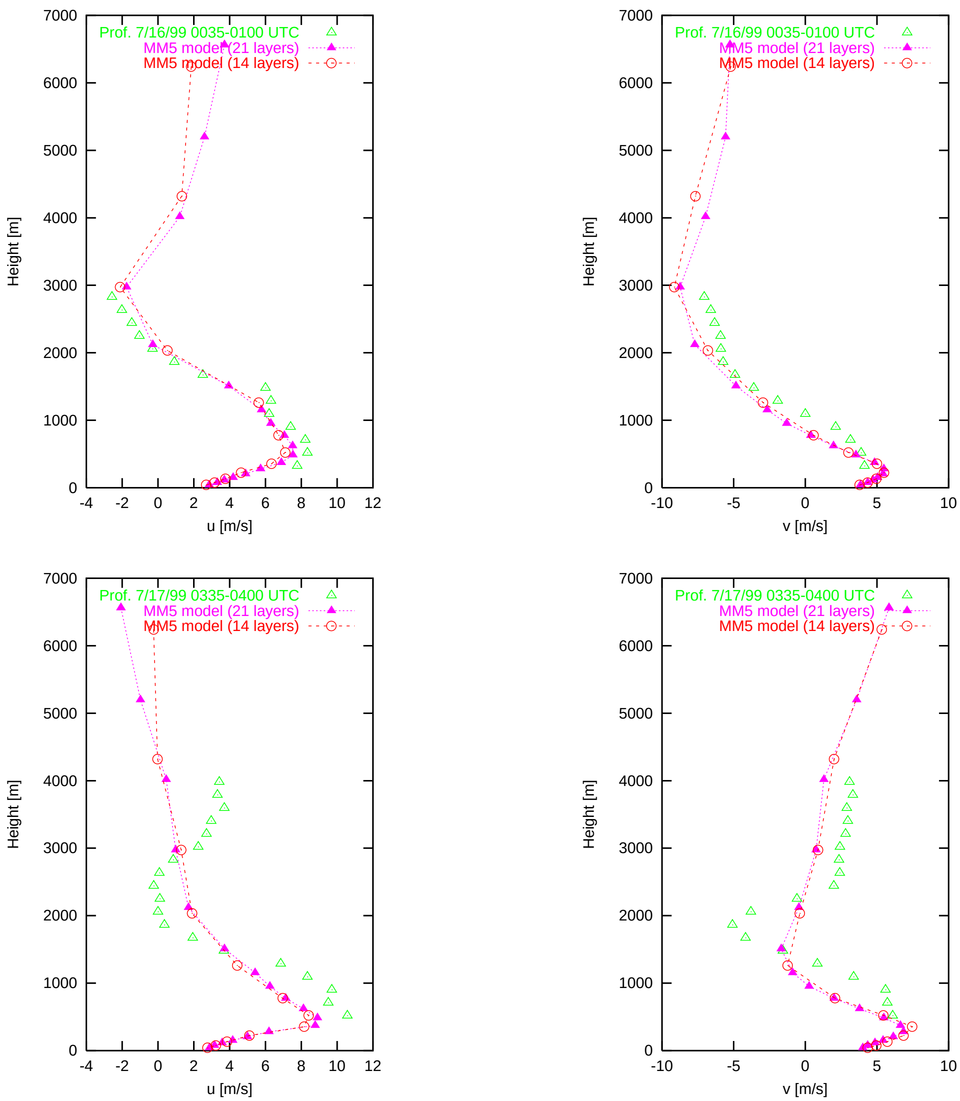

Figure 7. Comparison of wind profiler observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for u and v component of velocity for July 16, 1999; 01 UTC (upper panels) and for July 17, 1999; 04 UTC (lower panels)

(Figure 9) and for July 17, 1999; 04 and 07 UTC (Figure 10), respectively. In the above figures for the lidar observations from LAPS instrument, the median value of every five observations is depicted for convenience. All the lidar observations depicted in Figures 9 and 10 utilized 30 minute integration times. Both the MM5 applications with 21 layers in the vertical direction and 14 layers in the vertical direction compare reasonably well with the lidar

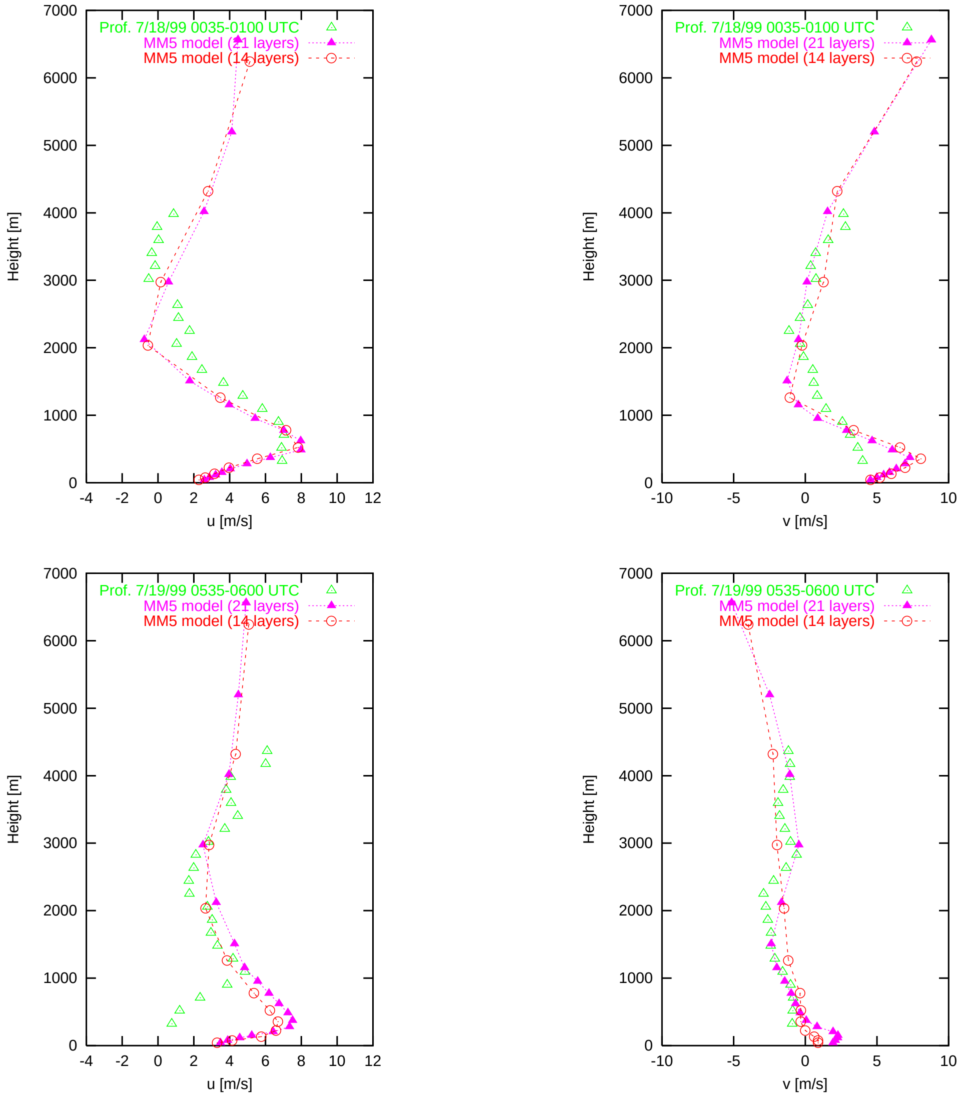

Figure 8. Comparison of wind profiler observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for u and v component of velocity for July 18, 1999; 01 UTC (upper panels) and for July 19, 1999; 06 UTC (lower panels)

temperature observations on July 17, 1999; 04 and 07 UTC. However, the lidar observations of temperature on July 16, 1999; 02 and 04 UTC appear to be consistently lower as compared with the temperature predictions with both the applications with 21 layers in the vertical direction and 14 layers in the vertical direction. The temperature prediction of the 14 layers in the vertical direction is as good as the temperature prediction of the 21 layers in the vertical direction. The mixing ratio profiles obtained from the lidar instrument compares reasonably well with both the MM5 simulation results with 21 and 14 layers in the vertical direction, except for some underestimation by the application with 21 layers in the vertical direction in the lower atmosphere on July 16, 1999; 02 and 04 UTC (Figure 9). Surprisingly, the simulation with 14 layers in the vertical direction is closer to the mixing ratio lidar observations in the lower atmosphere on July 16, 1999; 02 and 04 UTC (Figure 9). The mixing ratio profiles on July 17, 1999; 04 and 07 UTC (Figure 10) are characterized by relatively higher values (12 - 14 g kg^{-1}) at heights close to 1.5 km. However, both the MM5 simulations with 21 and 14 layers in the vertical direction are not able to accurately predict these high values.

3.1.5. *Comparison of MM5 simulations with Tethered balloon data*

Two tethered balloons were deployed by Millersville University during the NE-OPS program. The small 7 m^3 balloon carried two sensor packages; one which recorded meteorological variables such as dry and wet bulb temperature, atmospheric pressure, wind speed and direction and another to measure O_3 concentrations using the KI-oxidation method. The small 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 sec^{-1}. Typically one vertical profile was obtained every 30 minutes with a vertical resolution of 1-3 m. The large 100 m^3 balloon with a free-lift capacity of 50 kg was utilized to suspend samples at nearly constant altitudes (75, 150, 225, 300 m) for a duration of 10 hours. The large 100 m^3 balloon collected the impaction samples for analysis of accumulated $PM_{2.5}$ dry mass, canister samples for analysis of 55 toxics and measurements of $PM_{2.5}$ concentrations using laser scatterometry. The large 100 m^3 balloon was utilized for two ten hour periods per day (10:00 - 20:00 Local Time; 22:00 - 08:00 Local time). The above times were chosen to clearly isolate the daytime and nighttime boundary layer regimes. During the period between July- August 1999, 449 vertical profiles were obtained. The comparison of the model predicted (both 21 and 14 layers in the vertical direction) meteorological variables with the tethered balloon data are depicted in Figures 11 to 15. The above figures provide the comparison for July 15, 1999; 14 (Figure 11) and 21 UTC (Figure 12) and for July 16, 1999; 02 (Figure 13), 06 (Figure 14)and 15 UTC (Figure 15), respectively. In the above figures for the tethered balloon observations, the median value of every five observations is depicted for convenience. The model predicted temperature profiles are in reasonable agreement with the tethered balloon observations while the relative humidity and wind speed are somewhat underestimated. Despite the underestimation of humidity by both the MM5 applications, there is good agreement on the trend of the model generated vertical profiles of humidity with the tethered balloon observations. There is a perceptible im-

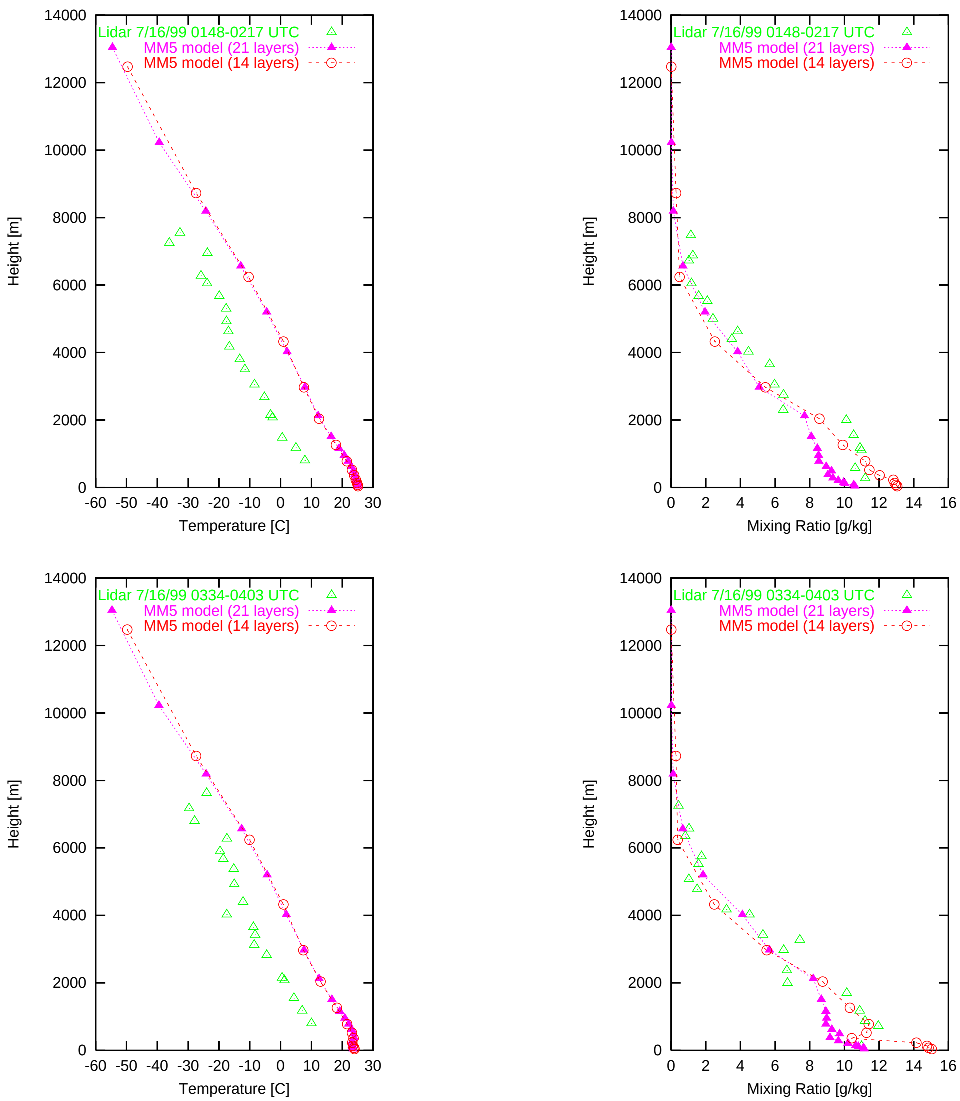

Figure 9. Comparison of lidar observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for temperature and mixing ratio for July 16, 1999; 02 UTC (upper panels) and for July 16, 1999; 04 UTC (lower panels)

provement in the simulation of the meteorological variables on July 15, 1999; 14 UTC (Figure 11) with the 21 layers in the vertical direction more closer to tethered balloon observations as compared to the simulation with 14 layers in the vertical direction. However, both the applications underestimate the relative humidity and the wind speed values on July 15, 1999; 14 UTC (Figure 11). The situation for July 15, 1999; 21 UTC (Figure 12) is altered

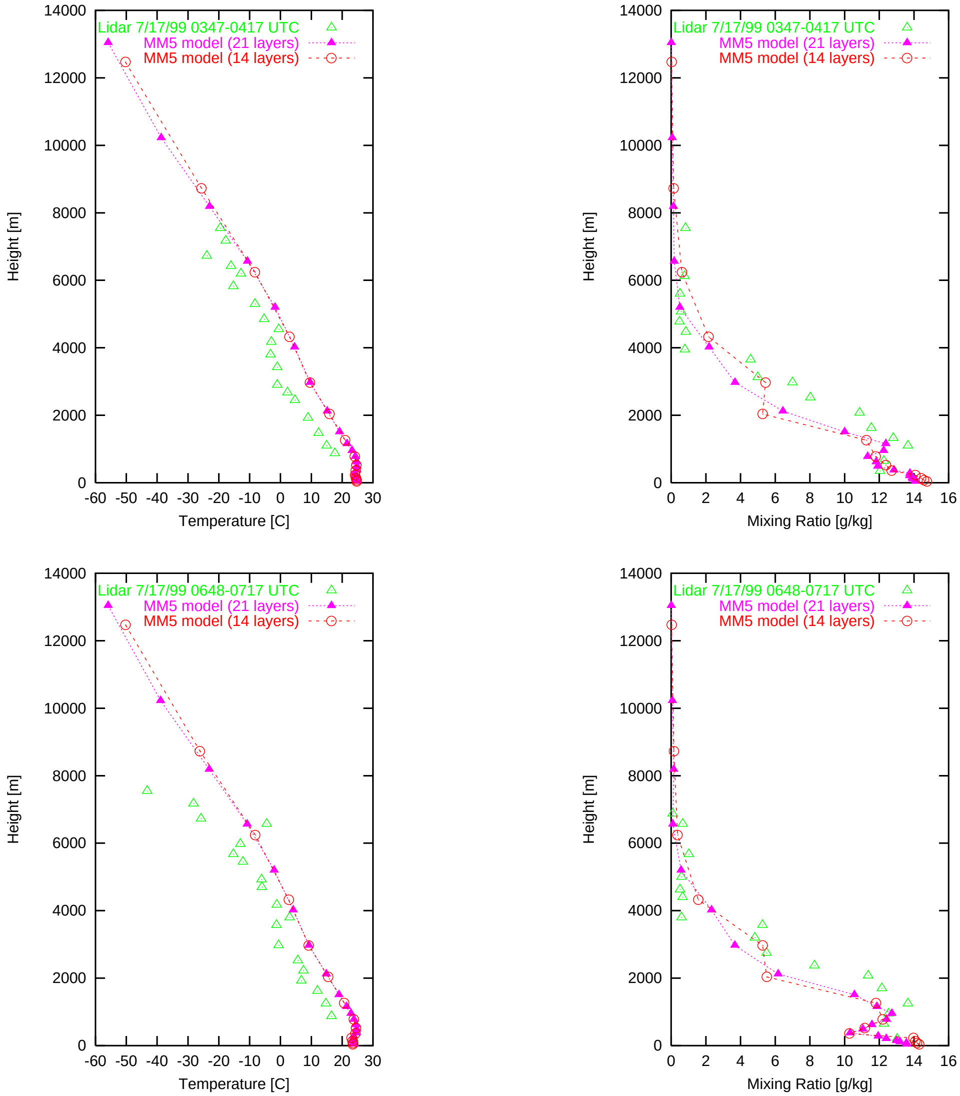

Figure 10. Comparison of lidar observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for temperature and mixing ratio for July 17, 1999; 04 UTC (upper panels) and for July 17, 1999; 07 UTC (lower panels)

with the 14 layers in the vertical direction simulation performing slightly better compared with the 21 layer simulation. However, underestimation of the relative humidity and the wind speed values by both the simulations is seen on July 15, 1999; 21 UTC (Figure 12). A south-westerly jet like feature is seen in Figures 13 and 14 (July 16, 1999; 02 and 06 UTC). The wind profiler data clearly shows the presence of a south-westerly low level jet on July 16, 1999; 01 UTC with the jet core between 400-600 m. Since the tethered balloon data were available only up to a height of 300 m, the jet core region is not seen in Figures 13 and 14. Wind speeds corresponding to the jet like features are reasonably well simulated by both the MM5 applications for July 16, 1999; 02 and 06 UTC (Figures 13 and 14). There seems to be perceptible differences (relative humidity profiles for July 15, 1999; 14 UTC (Figure 11) and for July 16, 1999; 02 and 06 UTC (Figures 13 and 14) and wind direction profiles for July 15, 1999; 14 and 21 UTC (Figures 11 and 12)) in the results for applications with 21 and 14 layer in the vertical direction with the former predicting the meteorological variables better in some instances (July 15, 1999; 14 UTC (Figure 11)) and vice versa (July 15, 1999; 21 UTC (Figure 12)).

3.2. Root mean square errors of MM5 simulations with rawinsonde observations

In order to obtain quantitative estimates of the performance of the MM5 model (both 14 and 21 layers in the vertical direction) with observations, the following strategy was employed. Since the D1 domains (refer Figure 2) with both 14 and 21 layers in the vertical direction are identical, the D1 domain was utilized to estimate the performance of the MM5 model. Also, the D1 domain has the largest horizontal extent and also encompasses about 45 rawinsonde stations within it. In order to obtain a robust quantitative estimate of the performance of the MM5 model it is more appropriate to compare its results with the rawinsonde observations spread over the standard upper air observational network in United States of America than to compare it with vertical profiles obtained over a single Philadelphia site during the NE-OPS campaign. The model forecast soundings (vertical profiles of the horizontal wind components, temperature and relative humidity) were extracted from the MM5 model results at the rawinsonde station locations using the post-processor GRAPH. All the above mentioned meteorological variables were then interpolated through log pressure interpolation to the standard meteorological levels 1000, 850, 700, 500, 400, 300 and 250 hPa using the following expression.

$$\mathrm{var}(k) = \mathrm{var}(k-a) + \ln\left(\frac{\mathrm{prs}(k)}{\mathrm{prs}(k-a)}\right)\left(\frac{\mathrm{var}(k+b)-\mathrm{var}(k-a)}{\ln[\mathrm{prs}(k+b)/\mathrm{prs}(k-a)]}\right) \quad (1)$$

where $\mathrm{var}(k)$ is the missing value being calculated, $\mathrm{prs}(k)$ is pressure at a specified vertical level and $\mathrm{var}(k-a)$ and $\mathrm{var}(k+b)$ are values immediately below and above the missing value level.

The root mean square applied to the horizontal wind components, temperature and relative humidity were calculated by using the following expres-

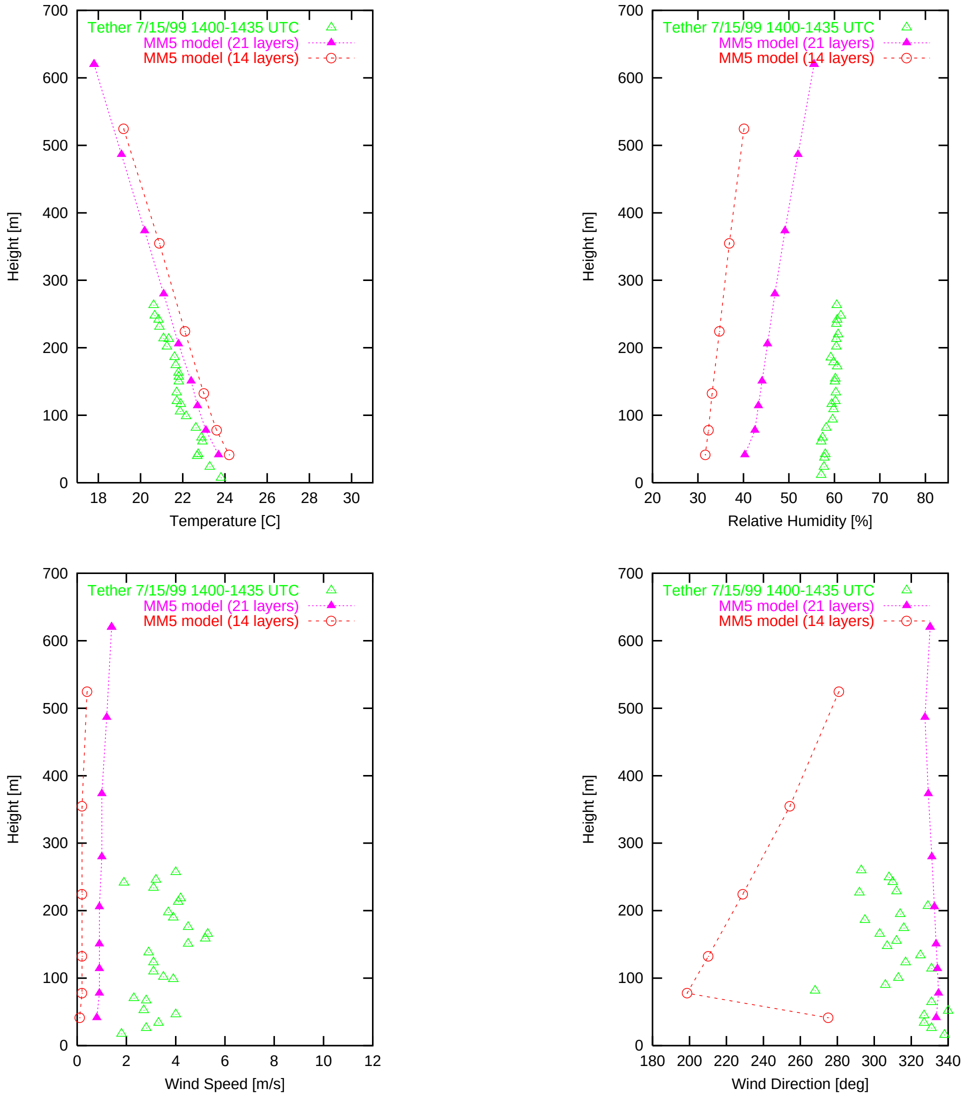

Figure 11. Comparison of tethered balloon observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for July 15, 1999; 14 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels)

sion.

$$RMSE_{var} = \left(\frac{\sum_{k=1}^{k_z} \sum_{s=1}^{S_n} [\mathrm{var}_{obs}(s,k) - \mathrm{var}_{pred}(s,k)]^2}{S_n k_z} \right)^{1/2} \qquad (2)$$

where S_n is the number of rawinsonde stations and k_z is the number of standard meteorological pressure levels.

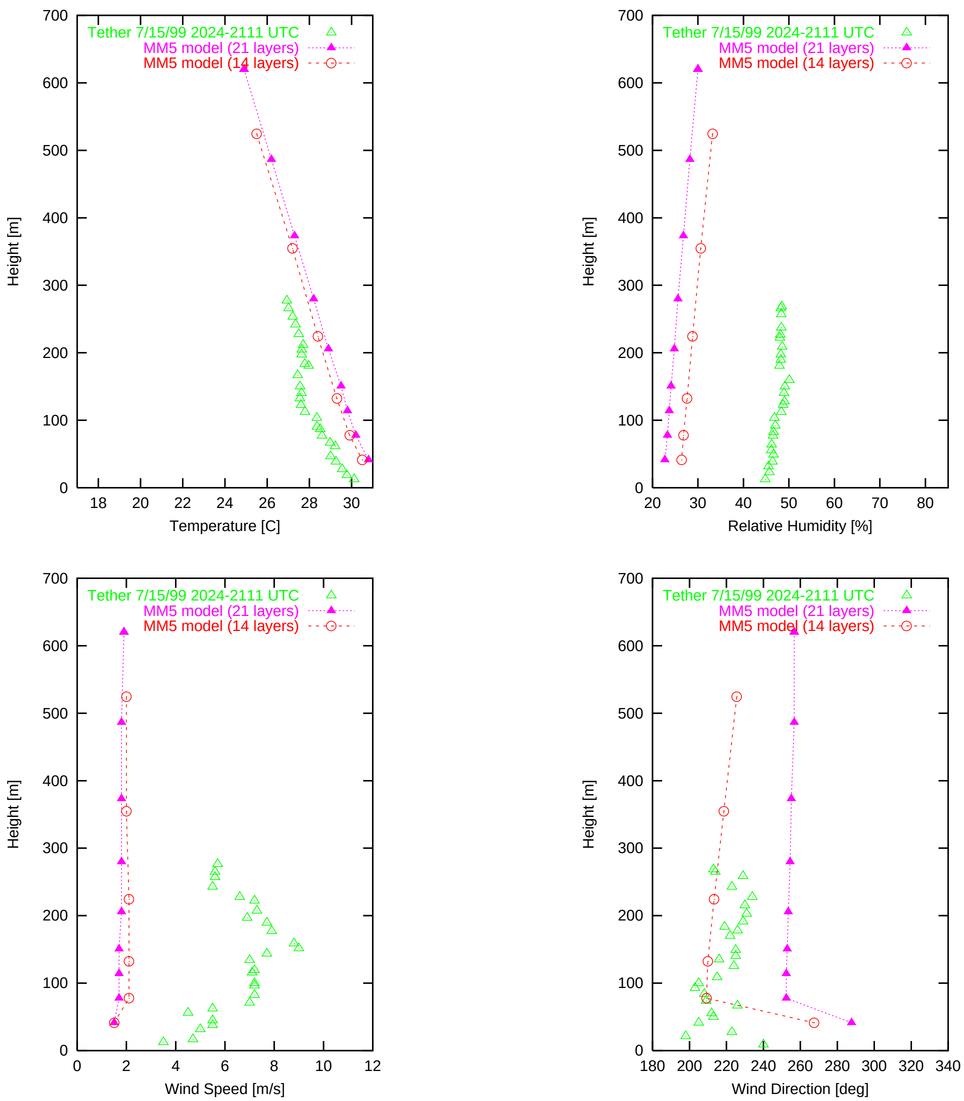

Figure 12. Comparison of tethered balloon observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for July 15, 1999; 21 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels)

Table III provides the root mean square (rms) error of the 36 km MM5 model results (both the 14 & 21 layers in the vertical direction) with rawinsonde observations summed over all the rawinsonde stations and over all the standard meteorological pressure levels from 1000 hPa to 250 hPa for July 15-19, 1999. The maximum root mean square errors are associated with the relative humidity values while the smallest errors are associated with temper-

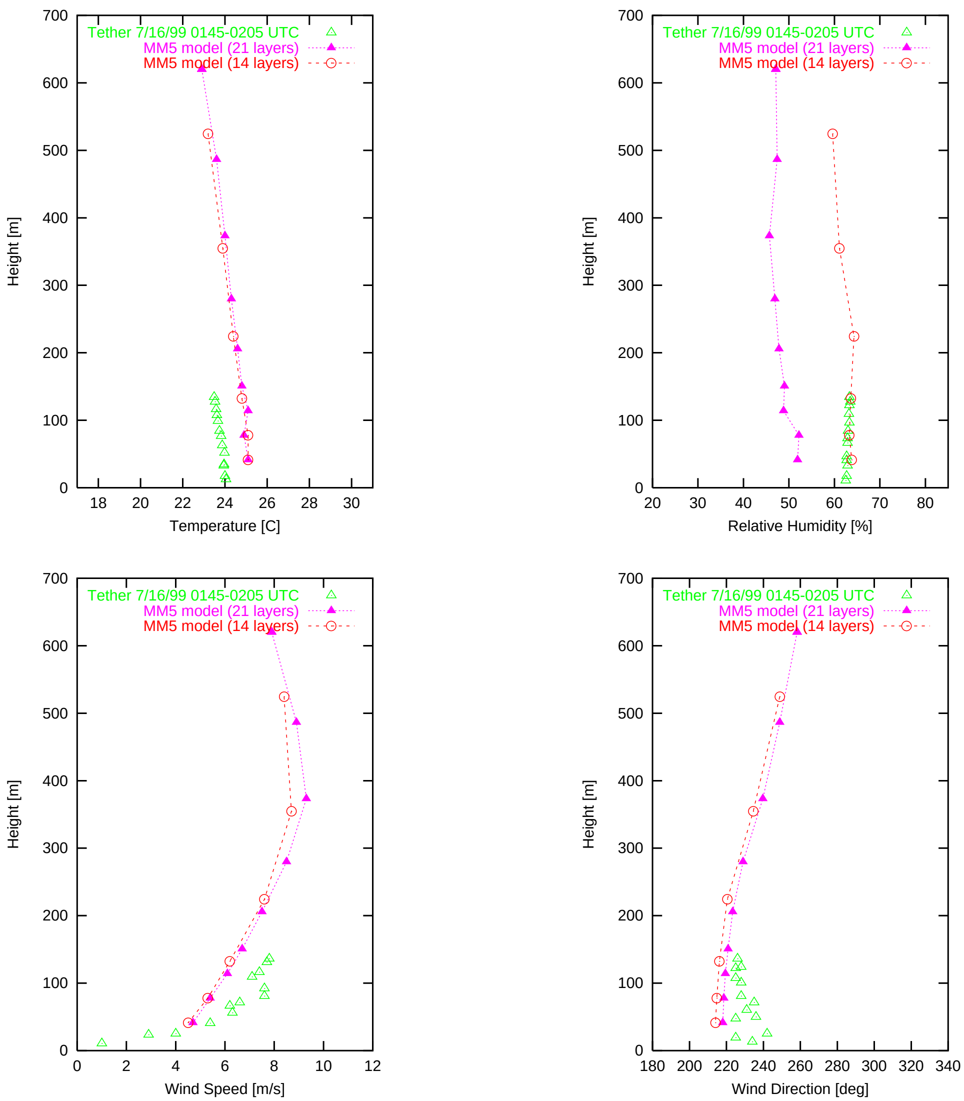

Figure 13. Comparison of tethered balloon observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for July 16, 1999; 02 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels)

ature values. The rms errors associated with the horizontal wind components are also quite small. It is pertinent to note that the rms error applied to relative humidity values is expressed as a fraction and not as a percentage and hence is pretty high. In order to investigate the rms errors at each individual standard meteorological pressure level we recomputed equation (2) without summing over the vertical pressure levels and dividing by k_z. A representative level for

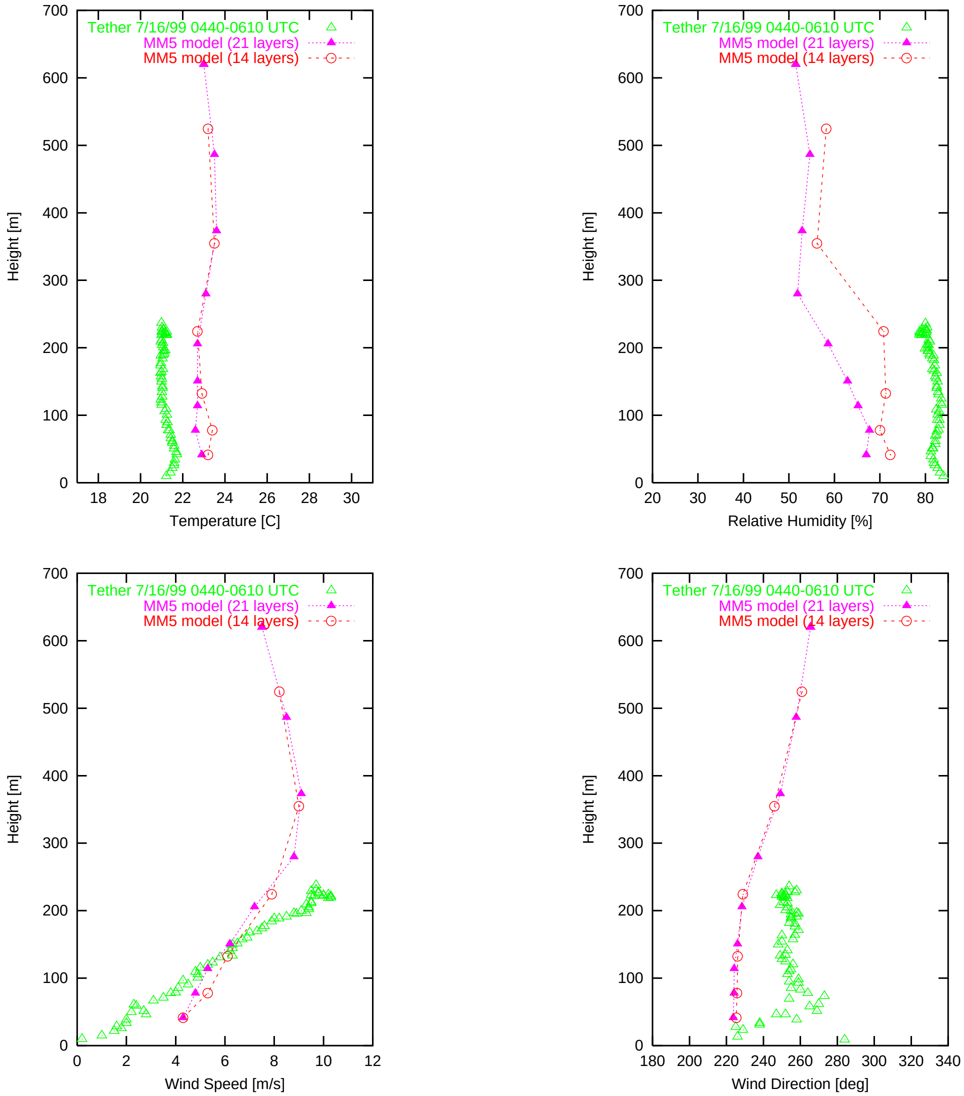

Figure 14. Comparison of tethered balloon observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for July 16, 1999; 06 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels)

the lower troposphere (850 hPa) , mid-troposphere (500 hPa) and upper troposphere (250 hpA) were identified and the recomputed rms errors summed over all the rawinsonde stations only is depicted in Tables IV and V. It is apparent that the largest rms error are all associated with the upper troposphere while the smallest rms errors are associated with the lower troposphere with the mid-tropospheric rms errors assuming intermediate values. Eight (of 14

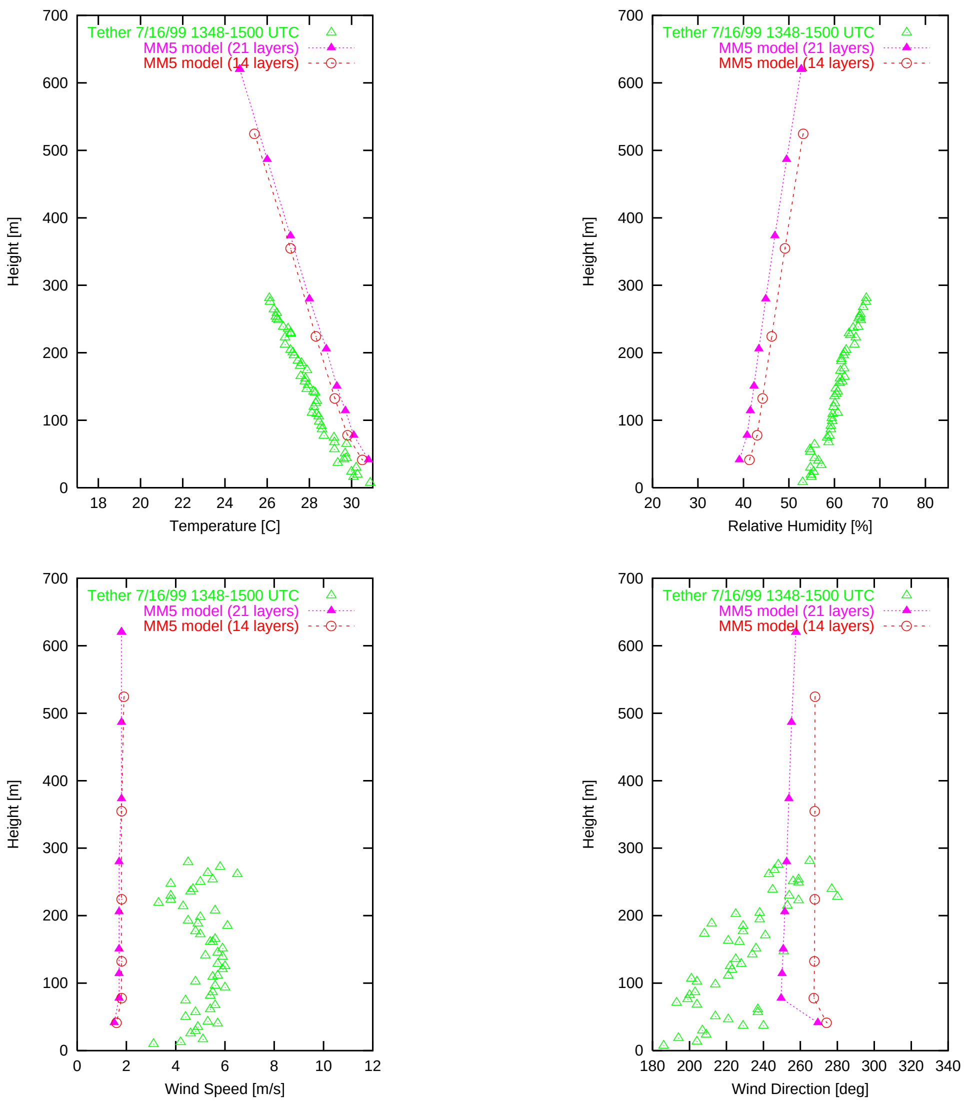

Figure 15. Comparison of tethered balloon observations with MM5 4 km model results (both 21 layers and 14 layers) over Philadelphia for July 16, 1999; 15 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels)

vertical σ levels) and thirteen (of 21 vertical σ levels) constitute the region from the surface to 850 hPa. The region from lower to mid-troposphere is made up of 4 and 3 levels (in the 21 layers and 14 layers in the vertical direction) while the region from middle to upper troposphere is made of 4 and 3 levels (in the 21 layers and 14 layers in the vertical direction). This indicates that the vertical structure is quite adequate in the region encompass-

Table III. Root Mean square errors of 36 km MM5 model results with rawinsonde observations summed over all the rawinsonde stations and over all the standard pressure levels from 1000 hPa to 250 hPa.

Date & Time	Layers in vertical direction	u m/s	v m/s	T K	RH
07/15/99	14	2.09149	3.05840	1.72382	0.595811
12 UTC	21	1.48548	1.91543	0.82510	0.608512
07/16/99	14	2.58296	2.58909	1.68319	0.605914
00 UTC	21	2.16336	2.18143	0.99066	0.612860
07/16/99	14	2.86362	2.31664	1.57972	0.599858
12 UTC	21	2.38441	2.24555	0.995761	0.610729
07/17/99	14	2.30851	2.30094	1.41953	0.602262
00 UTC	21	1.96166	1.95530	0.916552	0.607604
07/17/99	14	2.51445	2.42998	1.42804	0.566747
12 UTC	21	2.02128	2.05373	0.886457	0.572698
07/18/99	14	2.43788	2.87969	1.37848	0.514097
00 UTC	21	1.98071	2.41225	0.825205	0.527200
07/18/99	14	2.12063	2.73169	1.49555	0.477266
12 UTC	21	1.60634	2.27392	0.98829	0.502378
07/19/99	14	2.40804	3.32446	1.36175	0.506450
00 UTC	21	1.99076	2.71894	0.87440	0.531410
07/19/99	14	2.46461	3.04963	1.36995	0.493660
12 UTC	21	1.77272	2.62247	0.91668	0.518302

ing the lower troposphere while the same cannot be said about the middle and upper troposphere. The above lack of resolution of the upper and the middle tropospheric vertical structure could contribute to the large rms errors observed in Tables IV & V.

4. Conclusions

This study presented a comparative evaluation of the prognostic MM5 meteorological mesoscale model predictions with data from the North East Oxidant and Particle Study (NE-OPS) research program over Philadelphia, PA during a summer episode in 1999. Also, this study focused on a comparative evaluation of MM5 applications with different number of layers in the vertical direction (21 and 14) and compared the performance of the alternate simulations with NE-OPS observations. The results indicate that the 14 layer simulation is able to capture by and large the atmospheric mesoscale structure

Table IV. Root Mean square errors of 36 km MM5 model results with rawinsonde observations summed over all the rawinsonde stations at 850, 500 and 250 hPa for July 15-17, 1999.

Date & Time	Layers in vertical direction	Pressure hPa	u m/s	v m/s	T K	RH
07/15/99	14	850	1.35012	1.47547	0.53739	0.32052
12 UTC		500	1.66383	1.79642	0.89681	0.66705
		250	3.05946	5.11148	3.66277	0.79197
07/15/99	21	850	0.88707	1.02529	0.25261	0.33181
12 UTC		500	0.94490	1.10998	0.52254	0.67432
		250	2.07280	3.03142	1.87481	0.82261
07/16/99	14	850	1.78555	1.35336	0.46993	0.26163
00 UTC		500	1.95592	2.31380	0.67152	0.69708
		250	4.05191	4.32392	3.53581	0.77458
07/16/99	21	850	1.77280	1.30281	0.41137	0.29725
00 UTC		500	1.43958	1.76662	0.55967	0.71176
		250	2.87451	2.78742	2.05573	0.78889
07/16/99	14	850	2.04537	1.61763	0.50703	0.26241
12 UTC		500	2.04494	1.97189	0.68252	0.69677
		250	4.71236	2.95428	3.15528	0.74520
07/16/99	21	850	1.97779	1.78412	0.44860	0.28750
12 UTC		500	1.53596	1.60638	0.48257	0.71939
		250	3.62092	2.62815	1.77340	0.75359
07/17/99	14	850	1.45747	1.41498	0.53972	0.29470
00 UTC		500	1.84637	2.14269	0.85696	0.71981
		250	3.53992	3.36958	2.82619	0.75166
07/17/99	21	850	1.26226	1.27449	0.45892	0.32181
00 UTC		500	1.44207	1.63197	0.65362	0.72856
		250	2.61824	2.66699	1.69586	0.74521
07/17/99	14	850	1.24535	1.07234	0.44326	0.27937
12 UTC		500	2.12001	1.75922	0.73655	0.65204
		250	4.29264	4.21764	2.81934	0.72391
07/17/99	21	850	1.17883	1.04399	0.38648	0.29175
12 UTC		500	1.69521	1.47940	0.55616	0.66434
		250	3.11533	3.16585	1.52894	0.73327

Table V. Root Mean square errors of 36 km MM5 model results with rawinsonde observations summed over all the rawinsonde stations at 850, 500 and 250 hPa for July 18-19, 1999.

Date & Time	Layers in vertical direction	Pressure hPa	u m/s	v m/s	T K	RH
07/18/99	14	850	1.27089	1.58769	0.50923	0.23656
00 UTC		500	1.47384	2.10863	0.75346	0.57499
		250	4.67909	5.44452	2.80172	0.73416
07/18/99	21	850	1.37286	1.41492	0.56238	0.24727
00 UTC		500	1.12685	1.69249	0.54705	0.60183
		250	3.16797	4.40405	1.54208	0.74864
07/18/99	14	850	1.32170	1.43879	0.45561	0.27417
12 UTC		500	1.69209	2.11538	0.77539	0.50391
		250	3.73808	4.79116	2.92439	0.65448
07/18/99	21	850	1.22728	1.39672	0.40461	0.29336
12 UTC		500	1.38206	1.98761	0.57605	0.52820
		250	2.37169	3.51914	1.67955	0.71407
07/19/99	14	850	1.74896	1.42285	0.48508	0.31270
00 UTC		500	1.48688	2.39937	0.79508	0.51721
		250	3.81688	5.86148	2.71151	0.70300
07/19/99	21	850	1.24150	1.31555	0.46878	0.33287
00 UTC		500	1.31886	2.04829	0.58214	0.52700
		250	2.96501	4.52733	1.59429	0.75270
07/19/99	14	850	1.21315	1.11880	0.40400	0.34894
12 UTC		500	1.95891	2.61562	0.67639	0.47360
		250	4.75787	4.97902	2.78087	0.68587
07/19/99	21	850	1.15233	1.09677	0.37368	0.33591
12 UTC		500	1.40136	2.39237	0.51196	0.48084
		250	2.97546	4.04605	1.56825	0.72630

as well as the 21 layer simulation. The results of the comparison of the aircraft temperature data indicate that the temperature values are more or less robustly simulated by both MM5 simulations. However, the temperature predictions by the simulation with 21 layers in the vertical direction is slightly more closer to the aircraft observation as compared with the simulation with 14 layers in the vertical direction. The results of the comparison with aircraft relative humidity values indicate that both MM5 applications appear to underestimate the relative humidity values especially in the lower atmosphere. The virtual temperature profiles predicted by both MM5 applications compare favorably with RASS data. Both the MM5 applications successfully simulate the low level jets seen over Philadelphia during the period July 16-19, 1999.

In fact, both the MM5 applications reasonably reproduce the sharp gradients in the horizontal wind components seen near the jet core. The mixing ratio profiles obtained from the lidar instrument compares reasonably well with both the MM5 simulation results except for some underestimation by the model with 21 layers in the lower atmosphere. While both MM5 simulations compare reasonably well with the lidar temperature data for some instances, the models seem to overpredict the temperature for other occasions. The model predicted temperature profiles are in reasonable agreement with the tethered balloon observations while the relative humidity and wind speed are somewhat underestimated. The comparison of tethered balloon observations indicate that there appears to be perceptible differences between the two MM5 applications with 21 and 14 layers in the vertical direction with the former predicting the meteorological variables better in some instances and vice versa. The jet like features seen in the tethered balloon wind speed observation are reasonably well simulated by both the MM5 applications. The largest root mean square (rms) errors obtained from 36 km MM5 model results and the regular upper air rawinsonde stations are associated with the relative humidity values for both 21 and 14 layers in the vertical direction. The rms errors of temperature and the horizontal wind components are quite small for both the 21 and 14 layers in the vertical direction. The largest rms errors for any variable are all associated with the upper atmosphere while the smallest rms errors are associated with the lower troposphere.

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