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A comparison study of RAMS simulations 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 comparisons of Colorado State University's prognostic mesoscale Regional Atmospheric Modeling System (RAMS 4.3) results with observational data obtained from aircraft, wind profiler, lidar, tethered balloon and RASS during the Northeast Oxidant and Particle Study (NE-OPS) field program at Philadelphia, PA during a summer episode in 1999. Model simulations were performed for the 15–20 July 1999 period. The comparison of model-predicted temperatures with aircraft and tethered balloon data revealed that the mean relative error exhibited the same general trend in time for temperature noted by earlier investigators. The comparisons of model relative humidity with aircraft and tethered balloon indicate that the mean relative error varied from −13% to −21%. The mean relative error for water vapor mixing ratio with respect to lidar data exhibited a negative bias consistent with humidity bias corresponding to aircraft and tethered balloon. The largest root mean square (rms) errors obtained from 36 km resolution RAMS results and the regular upper air rawinsonde stations are associated with the relative humidity values. The smallest rms errors for any variable are all associated with the lower atmosphere while the largest rms errors are associated with the upper/mid-tropospheric region. The difficulty in correctly predicting upper level humidity is due to lack of consistency in the upper level moisture observations while the lower rms errors of relative humidity close to surface are due to increased availability of moisture data at surface. The results of the present study, by utilizing a variety of diverse observational platforms, broadly confirm the general traits of RAMS performance noted by earlier investigators.

Keywords: RAMS; Aircraft; Lidar; Profiler; RASS; Tethered balloon

1. Introduction

1.1. Rationale

Presently three-dimensional photochemical grid models are being increasingly used by regulatory agencies for the development of emission control strategies to improve air quality. One of the most critical inputs to the photochemical models, accurate meteorological information, is typically provided by prognostic regional/mesoscale models. Due to the critical role played by the meteorological inputs in the photochemical grid models, there is a need to perform extensive evaluations of mesoscale meteorological models with observations in order to understand their limitations and strengths

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(Pielke and Uliasz, 1998; Sistla et al., 2001). In the present work, comparisons of Colorado State University's Regional Atmospheric Modeling System (RAMS 4.3) results with Northeast Oxidant and Particle Study (NE-OPS) observations were undertaken during a major ozone episode which occurred during the summer of 1999 over Philadelphia.

1.2. Background

Both qualitative and quantitative assessments have been utilized to evaluate regional mesoscale meteorological models in air quality assessment practice (Lyons et al., 1995). Quantitative evaluations involve traditional statistical measures while qualitative evaluations utilize graphical comparisons of observed and simulated meteorological fields. However, it should be noted that, in meteorological studies, the observed and the simulated meteorological fields are not independent due to the use of four-dimensional data assimilation (FDDA). Also, while observations are primarily point measurements, the model predictions are gridded values of Reynolds average mean state variables.

Cox et al. (1998) compared four mesoscale models: RAMS, the Mesoscale Model 5 (MM5), the Navy Operational Regional Prediction System Version 6 (NORAPS6) and the Relocatable Window Model (RWM) and found that both RAMS and MM5 performed better than the other two models. The Texas Natural Resources Conservation Commission (TNRCC Report, 2001) performed RAMS and MM5 simulations over the Houston area for the 8–11 September 1993 ozone episode and found that RAMS simulated the sea breeze formation better than MM5. The 4 km RAMS simulation results indicated that the water vapor bias is slightly negative while the average absolute error of wind speed is about $1\ \mathrm{m\,s^{-1}}$ for the entire period. TNRCC investigators found that 4 km RAMS temperature mean relative error had maximum negative values between 12 and 14 UTC with crossover to the positive side occurring between 17 and 19 UTC, and a positive maximum bias occurring close to 00 to 02 UTC with another crossover to the negative side occurring between 04 and 05 UTC over the 8–11 September 1993 simulation period.

Buckley et al. (2001) undertook a statistical comparison of RAMS results with surface observations for the southeastern US spanning 2 years (April 1998 – March 2000). Their results indicated that for both surface temperature and surface wind speed there is a slight positive bias at all times, while the absolute mean bias for the surface wind direction is of the order of 30 – 40°. McQueen et al. (1997) evaluated RAMS against buoy data over the Chesapeake Bay area for 23 cases in 1994 and found that sensible heat fluxes and temperature were in good agreement with observations when the grid box size was limited to 5 km or less and the first model level had a thickness of 12 m. However, latent heat fluxes compared poorly with buoy observations especially under stable stratifications.

Fast (2002) utilized RAMS as one component of an air quality modeling study focusing on Philadelphia for the summer of 1999. The results indicated little model bias in the simulated model wind speed as compared to the wind profilers, but the simulated wind direction was more westerly by about 15°. The mixed layer temperature and specific humidity simulations were within 1–2 K and $1\text{–}2\ \mathrm{g\,kg^{-1}}$ of the corresponding observational values. Sistla et al. (2001) studied 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. Zhang et al. (2001) investigated the impact of different planetary boundary layer (PBL) 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 using the MM5V3 model for the period of 15–20 July 1999. The results of the above study revealed that there are substantial differences between the PBL structures and the PBL evolutions simulated by the above-mentioned different schemes, with the non-local mixing mechanism in the convective PBL closer to observations than the layer-to-layer eddy diffusion approach.

Doty (2001) performed RAMS3a simulations as part of the Southern Appalachian Mountain Initiative (SAMI) and found that the model generally underestimated moisture and overestimated wind speed while the temperature biases were within 1.5°C. Even though the present study has utilized FDDA, we did not incorporate the NE-OPS observations in FDDA, in order to use these observations for evaluating the mesoscale meteorological model. Even though RAMS has been evaluated in earlier studies using a variety of observational data (surface, sounding, profiler, etc.), the authors are not aware of a study where RAMS was evaluated using simultaneous measurements from such a wide ranging array of advanced platforms (aircraft, RASS, profiler, lidar and tethered balloon), as is attempted in the present study. A brief overview of the NE-OPS program along with observed synoptic features of the 15–19 July 1999 episode is described in Sections 1.3 and 1.4. The RAMS application is described in Section 2, and the results of this study are discussed in Sections 3 and 4.

1.3. NARSTO-NE-OPS overview

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 under a US Environmental Protection Agency (USEPA) initiative aiming to improve the current understanding of the underlying causes for occurrence of high ozone and fine particles concentrations in the northeastern United States. Various advanced meteorological aircraft, lidar, tethered balloon and radar wind profiler/RASS sounder and air chemistry (ground based particle/chemical samples) measurements were made at the Baxter Water Treatment Plant site, Philadelphia, PA (40.0764°N, 75.0119°W) during three field campaigns conducted in the summers of 1998, 1999 and 2001 (Philbrick et al., 2002). Also, DOE-G1 aircraft was flown over Philadelphia by the Brookaven National Laboratory during the NE-OPS campaign. Fig. 1a provides the location of Baxter, West Chester, Centerton, Rutgers, and Fort Meade instrumentation sites during the NE-OPS program along with the flight paths of University of Maryland aircraft.

1.4. Observed synoptic features of the 15–19 July 1999 episode

A high-pressure system found over land in the eastern US influenced the synoptic conditions over that region during the period 15–19 July 1999. The Appalachian lee trough, a typical pressure pattern for high ozone episodes and for the occurrence of low-level jets (LLJs) in the northeastern US persisted for 3 days, but was especially pronounced on 17–18 July 1999. Southwestern flow from the mid-Atlantic region to the northeastern US was caused by the presence of a lee trough along the Atlantic seaboard. The low-level westerly flow from the midwest to the northeast US was duly supported by the presence of large north–south pressure gradients above 37°N latitude. All the abovementioned patterns (conducive to a high ozone episode) persisted until a cold front passed through the eastern US on 19 July 1999 (Zhang et al., 2001).

2. Description of the RAMS 4.3 application

RAMS 4.3 (Walko and Tremback, 2001) utilizes an Arakawa C-grid on a rotated polar stereographic projection and employs a terrain following height coordinate system in the vertical direction. The model equations are compressible and non-hydrostatic. The RAMS application utilized a second-order advection scheme with a hybrid forward–backward-time split scheme for time differencing. RAMS 4.3 simulations were performed for the 15 July 1999; 12 UTC — 20 July 1999; 00 UTC period using three nested grids with horizontal grid resolutions of 36, 12 and 4 km, respectively. The outermost domain encompassed the entire eastern United States while the inner domain encompassed only the Philadelphia–New Jersey region (see Fig. 1b). Thirty-three layers in the vertical direction with vertical grid spacing ranging from 20 to 1000 m and a vertical grid stretch ratio of 1:2 were used in the simulations. The number of grid cells in the east–west and north–south directions are 74×68, 56×53 and 68×77 at the 36, 12 and 4 km grid resolutions, respectively. FDDA was employed using input fields blended from surface observations and global analysis fields. The global analysis fields were obtained from the National Center for Environmental Prediction (NCEP) reanalysis data at 2.5° horizontal resolution. The time interval for both the NCEP reanalysis fields and surface observations was 6 h. Model predictions for wind, temperature and water vapor were nudged towards these blended input fields with a nudging factor of $4.62962 \times 10^{-5}\ s^{-1}$ for all the grids and vertical layers. A scheme which employs prognostic turbulent kinetic energy approach (Mellor and Yamada, 1982) was utilized to parameterize the vertical diffusion. A convective parameterization scheme was activated for all the grids except for the 4 km grid. The radiation parameterization used the Chen and Cotton scheme (Chen and Cotton, 1983) and the bulk microphysics parameterization was activated. The study also utilized a soil/vegetation model. A two-way nesting approach was chosen for the simulations. The 36 km domain considered in this study encompasses about a thousand surface stations while the 12 and 4 km domains encompass 120 and 30 surface stations, respectively.

3. Results and discussion

3.1. Comparison of RAMS simulations with NE-OPS observations

In order to assess the performance of RAMS 4.3, various comparisons of model results from NE-OPS 1999 observations were undertaken. All heights noted in the following figures refer to height above mean sea level (MSL). Also all RAMS results (comparisons with NE-OPS observations) shown in this study correspond to the 4 km resolution RAMS simulations.

3.1.1. Comparison of RAMS simulations with aircraft data

The University of Maryland utilized C-172 and Aztec aircrafts in 52 spirals and 21 flybys during the NE-OPS

(a)

(b)

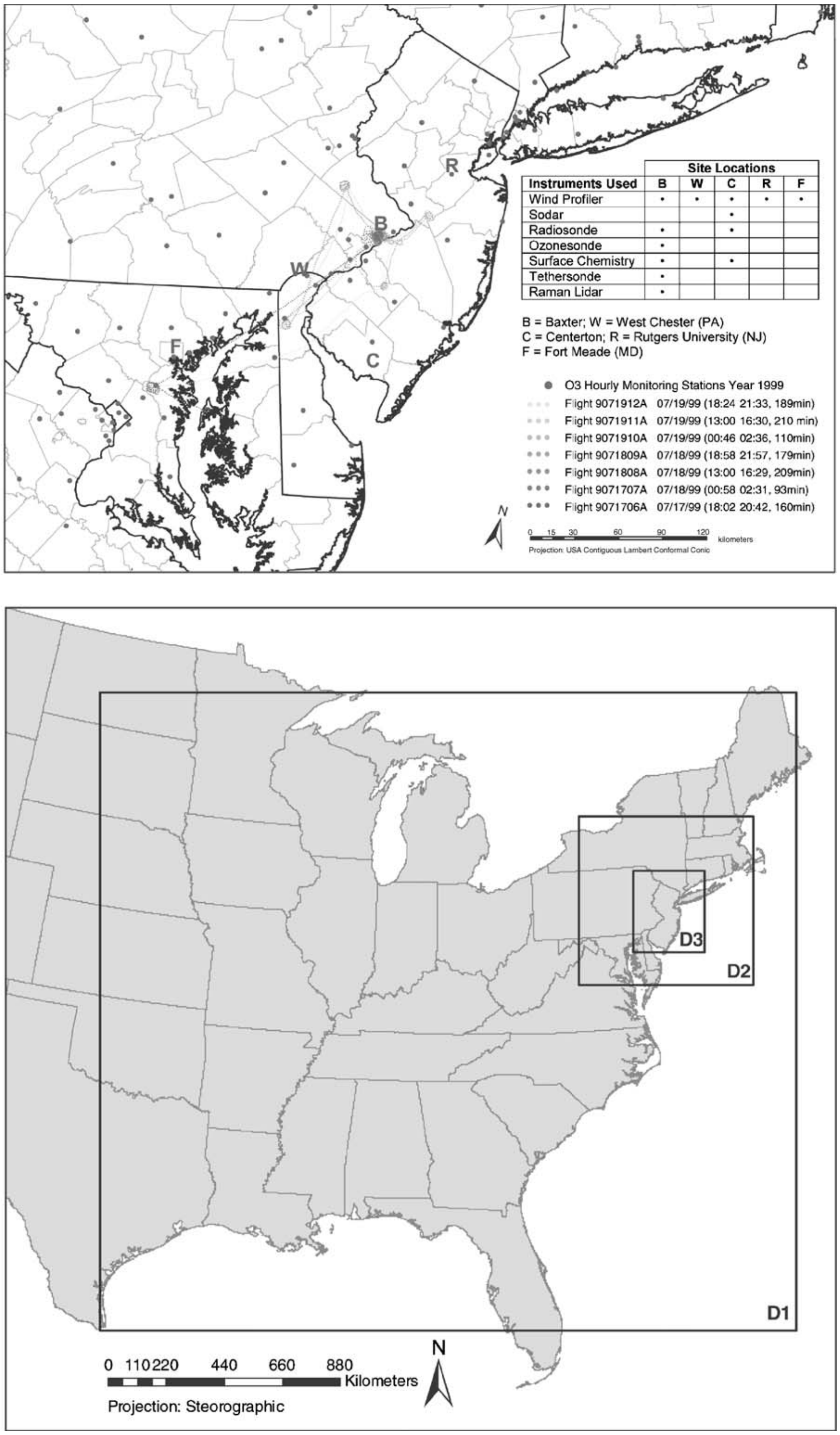

Fig. 1. (a) Location of Baxter, West Chester, Centerton, Rutgers, and Fort Meade instrumentation sites during the NE-OPS program along with the flight paths of University of Maryland aircraft; (b) the triply nested RAMS modeling domain with the 36 km (D1), 12 km (D2) and 4 km (D3) horizontal grid structure. The projection shown above is Steorographic projection, with the reference longitude and latitude being 84.35 $^\circ$ W and 37.34 $^\circ$ N.

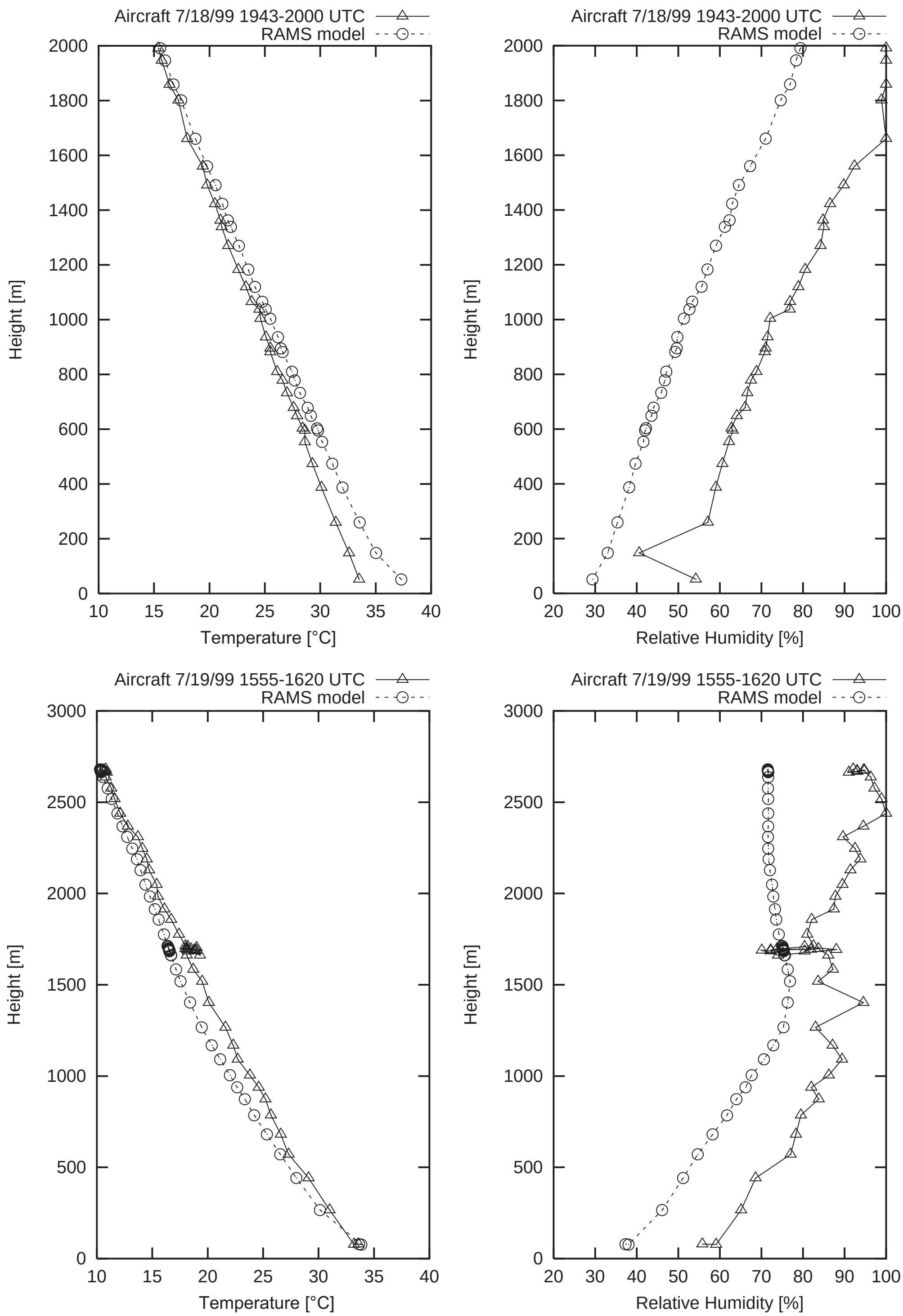

Fig. 2. Comparison of aircraft observations with RAMS 4 km model results over Philadelphia for temperature and relative humidity for 18 July 1999; 20 UTC (upper panels) and for 19 July 1999; 16 UTC (lower panels).

1999 program. The nominal ascent/descent rate of the aircraft during vertical survey spirals was 100 m min^{-1}. Since RAMS 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 was in one of its spiral paths, either ascending or descending, and coinciding with the model output time. Temperature and relative humidity model values at aircraft locations were obtained from the postprocessor of RAMS.

The comparison of aircraft observations with 4 km RAMS results are depicted in Fig. 2 (18 July 1999; 20 UTC and 19 July 1999; 16 UTC) for both temperature and relative humidity. The mean relative error, mean absolute error and the standard deviation of the difference (Buckley et al., 2001) were calculated over Philadelphia at different times using the observations in the vertical direction. The model temperatures at levels close to the surface have positive bias except for 19 July 1999; 16 UTC. This is consistent with results of Buckley et al. (2001). The temporal trend of the mean relative temperature error (TNRCC Report, 2001) is reflected in the model results of this study when they are compared with aircraft data, except for 19 July 1999; 02 UTC (not shown for brevity). For the latter, model results showed a very small negative bias (-0.4°C) while it should have a slight positive bias (TNRCC Report, 2001). The absolute mean error for temperature was within the desired forecast accuracy of 2°C (Cox et al., 1998). However, the mean relative error for relative humidity had negative values that ranged from -13% to -21%. Though earlier studies also showed results where humidity was underestimated (Doty, 2001; TNRCC Report, 2001), the magnitude of underestimation is slightly higher in this study. The mean absolute error and the standard deviation of the difference for aircraft varied from 0.46°C to 1.21°C for temperature, and up to 21.07% for relative humidity. The 4 km RAMS mean relative error for water vapor obtained by TNRCC varied from 0 to -2 g kg^{-1} with the average over all times being on the order of 1 g kg^{-1} or less (TNRCC Report, 2001). TNRCC investigators also found that the water vapor verification was improved when RAMS (with finest grid resolution of 1.33 km) was initialized with slightly more soil moisture. It appears from the above that accurate soil moisture initialization (by utilizing actual soil moisture fields) could improve the moisture verification.

3.1.2. Comparison of RAMS simulations with wind profiler data

Comparisons of the horizontal wind components obtained from the wind profiler with the 4 km resolution RAMS results are shown in Fig. 3 for 16 July 1999; 01 UTC and 17 July 1999; 04 UTC (top and bottom panels of Fig. 3). The LLJs, which play an important role in the transport of water vapor and pollutants, are clearly seen in the wind profiler observations in Fig. 3. The strongest LLJ during the period of 15–20 July 1999 occurred on 17 July 1999; 04 UTC over Philadelphia. The LLJs are typically westerly/southwesterly and are seen between heights of 600–1000 m. Zhang et al. (2001) investigated the nocturnal LLJs in the northeastern United States during 15–20 July 1999 by utilizing two different PBL parameterization schemes (Blackadar scheme and Gayno–Seaman scheme) in MM5. That study found that both PBL schemes produced LLJs that occurred at different times and were weaker than the NE-OPS profiler observation. It then restricted the FDDA to regions above the PBL and also allowed the convective energy computation to all PBL regimes. These modifications produced LLJs with improvements in timing as well as in the strength of the jet. However, it was found that both PBL schemes still failed to reproduce the sharp vertical gradients near the jet core. This was attributed to the fact that the vertical resolution of the model 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 RAMS is 125 m around 500 m. While Zhang et al. (2001) utilized twice-a-day observations and global analysis data at 00 and 12 UTC for FDDA, the present study utilized four times-a-day global analysis data and surface observations at 00, 06, 18 and 24 UTC for FDDA. The above possibly produced better simulation of the sharp gradients near the LLJ core. Also, unlike in Zhang et al. (2001), in the present study FDDA was utilized to nudge horizontal wind components, temperature and moisture over the entire atmosphere including the PBL. Though the model underestimated the LLJ on 17 July 1999; 04 UTC (mean relative error of the zonal (u) and meridional (v) velocity components being -2.47 and -2.50 m s^{-1}), the mean relative error for the other LLJs on other days are positive. The mean absolute error and the standard deviation of difference varied from 1.03 to 3.33 m s^{-1} for u and 0.64 to 2.86 m s^{-1} for v component of velocity. Considering the desired forecast accuracy of 2.5 m s^{-1} for wind speeds greater than 10 m s^{-1} and accuracy of 1.0 m s^{-1} otherwise (Cox et al., 1998), the results of this study by and large satisfy the above requirement.

3.1.3. Comparison of RAMS simulations with RASS and lidar data

Comparisons of virtual temperature obtained from RASS with 4 km RAMS results are shown in the top panels of Fig. 4 for 19 July 1999; 00 and 17 UTC. The temporal trend in the mean relative error for the virtual temperature is similar to the temporal trend in the mean relative error for temperature, with values varying from 1.62°C to -3.2°C. In a recent study, Angevine et al. (1998) compared the wind profiler and

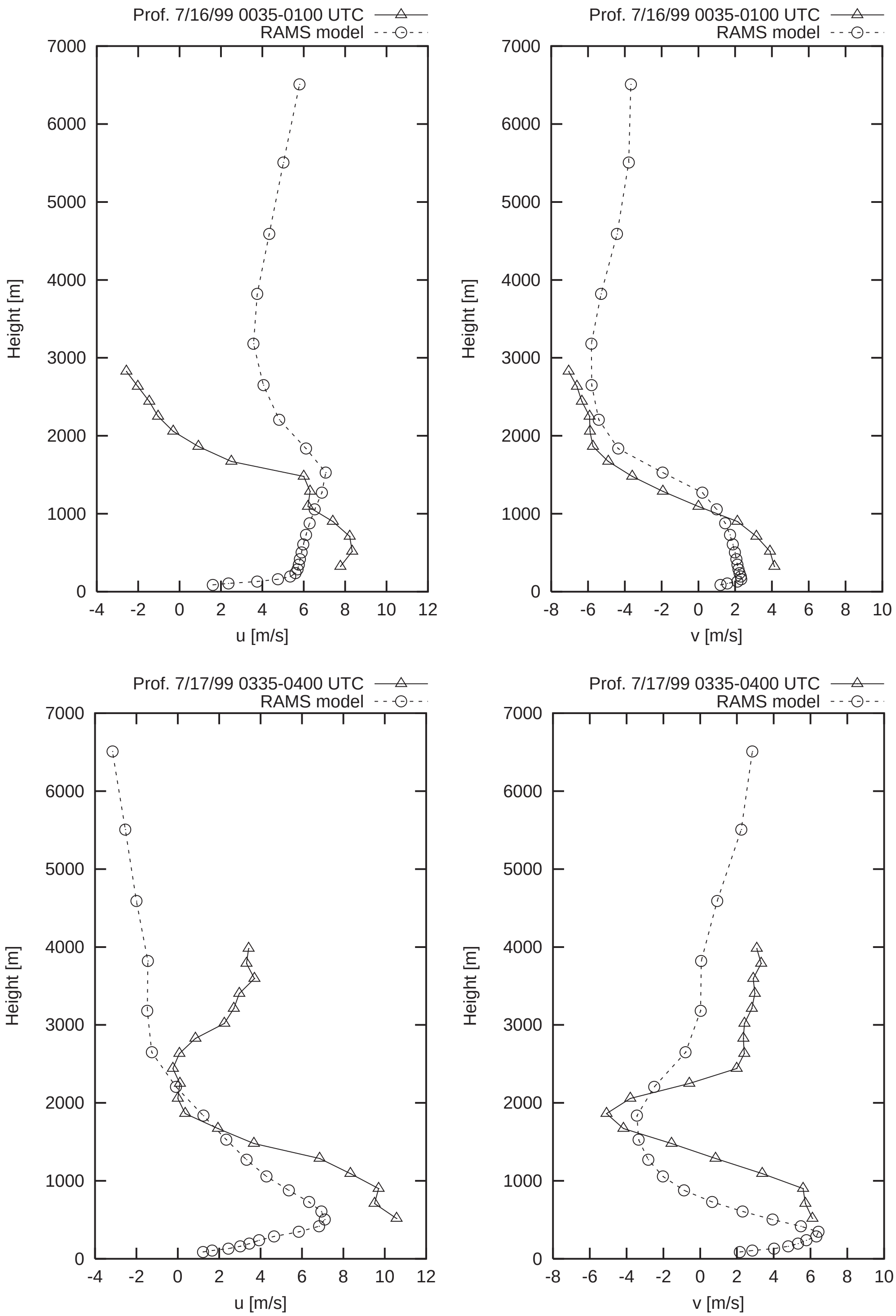

Fig. 3. Comparison of wind profiler observations with RAMS 4 km model results over Philadelphia for the zonal and meridional velocity components for 16 July 1999; 01 UTC (upper panels) and for 17 July 1999; 04 UTC (lower panels).

RASS measurements with measurements from a 450 m tower, and found that the virtual temperature as measured by RASS was only accurate to about 0.5°C. Zhang et al. (2001) found differences of $1-2°C$ in the virtual temperature profile between the aircraft, tethered balloon and RASS measurements during the NE-OPS campaign for 17 July 1999; 20 UTC. The mean absolute error and standard deviation of difference for virtual temperature varied from 1.24°C to 1.63°C and 0.37°C to 1.78°C. Comparisons of the temperature and water vapor mixing ratio values obtained from the Pennsylvania State University lidar with RAMS results are shown for 17 July 1999; 04 UTC (lower panel of Fig. 4). In the lidar figures the median value of every five observations are depicted for convenience. While the mean relative error for water vapor mixing ratio varied between −0.88 and −1.25 g kg^{-1} up to 7 km altitude, the same statistic within the lowest 3 km was up to −2.5 g kg^{-1}. However, the mean relative error of temperature with respect to lidar data varied from 8.89°C to 13.39°C. The above large overestimations of temperature are possibly due to errors in the temperature lidar data at the stated times. The mean absolute error for temperature varied up to 14.66°C while the standard deviation of difference varied up to 5.94°C. Both of the above statistics for the water vapor mixing ratio varied between 0.85 and 1.83 g kg^{-1}.

3.1.4. Comparison of RAMS simulations with tethered balloon data

Comparisons of RAMS 4 km resolution predicted profiles of meteorological variables with the tethered balloon data are shown in Fig. 5 for 16 July 1999; 06 UTC: for convenience, the median value of every five tethered balloon observations is shown. The mean relative error for relative humidity has negative values varying from −13% to −20% except for 15 July 1999; 14 UTC where it had a positive bias of 5% (figure for 15 July 1999; 14 UTC comparison data is not shown for brevity). Since the model integrations started from 15 July 1999; 12 UTC, the possibility of the model being spun up in a matter of 2 h is somewhat unlikely, which explains the positive bias in relative humidity. Also, the underestimation of the water vapor mixing ratio with respect to lidar data up to heights of 3 km is consistent with the underestimation of the relative humidity with respect to aircraft and tethered balloon data. The temporal trend of the mean relative error for temperature is similar to that calculated by TNRCC investigators with the mean absolute error varying from 0.15°C to 3.2°C (TNRCC Report, 2001). Considering the very large positive bias in temperature from lidar data, and the absence of similar large biases in temperature from aircraft and tethered balloon data, it appears likely that the temperature data obtained from lidar have errors. A southwesterly jet-like feature is seen in Fig. 5 (16 July 1999; 06 UTC). Wind speeds corresponding to the jet-like features are well simulated by RAMS as seen in Fig. 5. The mean absolute error and the standard deviation of difference for wind speeds varied from 0.46 to 3.43 m s^{-1} while the same statistics for the wind direction varied between 6° to 58°. However, by and large the absolute bias in wind direction is restricted to 30°, which is within the desired forecast criteria (Cox et al., 1998). The mean absolute error and standard deviation of difference for temperature varied from 0.15°C to 3.21°C while for the relative humidity the above variation is up to 20.19%.

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

The model meteorological variables (obtained from domain D1) were extracted at the station locations and then interpolated through log pressure to the standard meteorological levels of 1000, 850, 700, 500, 400, 300, 250, 200 and 150 hPa, and the root mean square errors of the horizontal wind components, temperature and relative humidity were calculated. Table 1 lists the root mean square (rms) errors of the 36 km RAMS results with rawinsonde observations summed over all the rawinsonde stations and over all the standard meteorological pressure levels from 1000 to 150 hPa for 15–20 July 1999. The maximum rms errors are associated with the relative humidity values (expressed as fraction) while the smallest errors are associated with temperature values. The rms errors associated with the horizontal wind components are somewhat moderate. Representative levels for the lower troposphere (850 hPa) , mid-troposphere (500 hPa) and upper troposphere (200 hPa) were identified and the recomputed rms errors, summed only over all the rawinsonde stations, were calculated at these three levels. It is seen that the smallest rms errors are all associated with the lower troposphere while the largest rms errors are associated with the upper/mid-tropospheric region (not shown for brevity). The vertical structure of RAMS is such that the region from the surface to the lower troposphere is defined by 16 layers in the vertical direction while the region from the lower to mid-troposphere and the region from the mid-troposphere to the upper troposphere are defined by 7 and 10 layers in the vertical direction, respectively. The above lack of resolution of the upper and the middle tropospheric vertical structure could contribute to the large rms errors over the middle and upper troposphere. Cox et al. (1998) found that all models in their study (including RAMS) had difficulty in accurately predicting upper air dew point depression with the highest forecast accuracy being only 29%. Cox et al. (1998) attributed the above to difficulty in accurately initializing dew point depression due to lack of consistency in upper level moisture observations. Also, all models generally

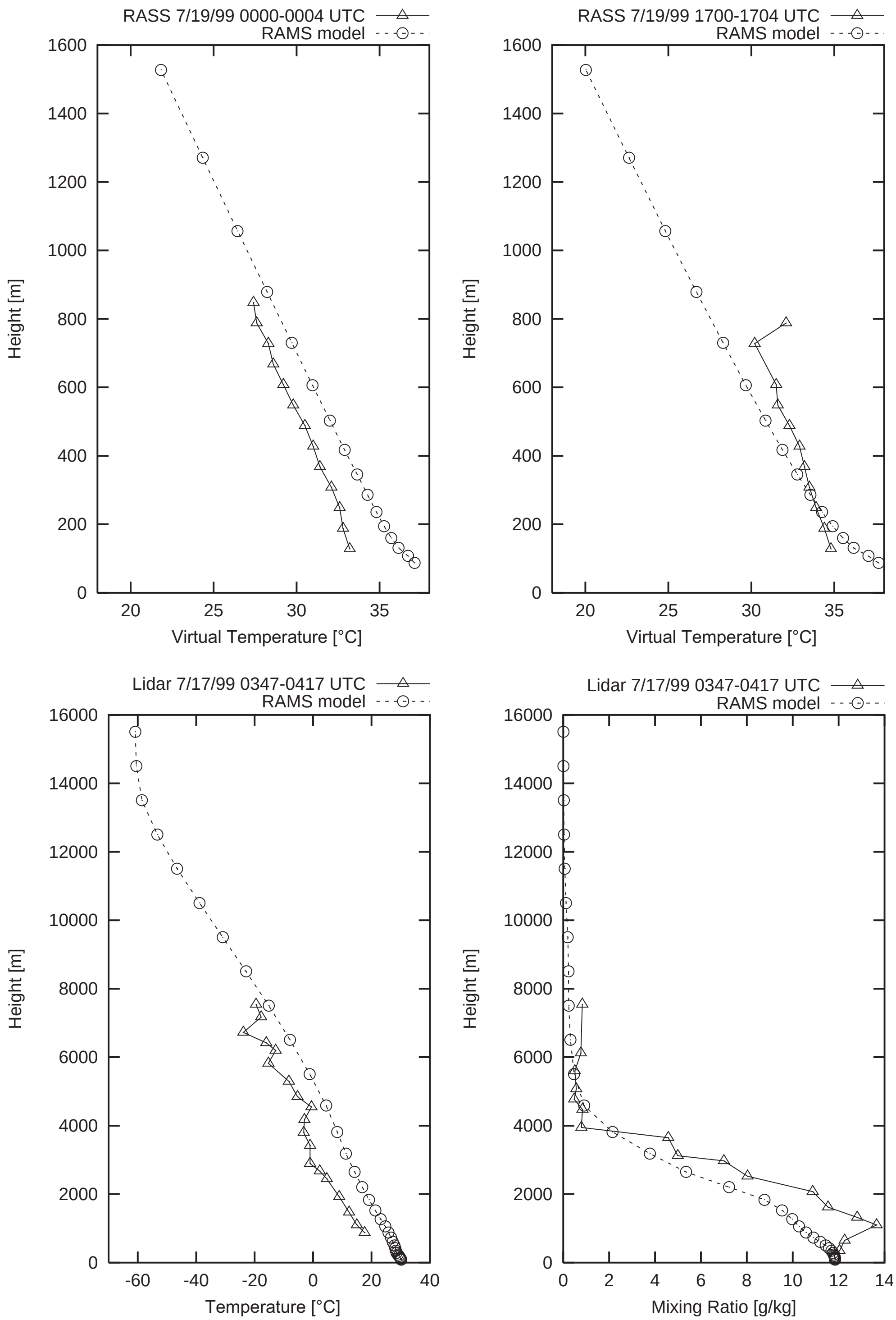

Fig. 4. Comparison of RASS observations with RAMS 4 km model results over Philadelphia for virtual temperature for 19 July 1999; 00 and 17 UTC (upper panels) and comparison of lidar observations with RAMS 4 km model results over Philadelphia for temperature and mixing ratio for 17 July 1999; 04 UTC (lower panels).

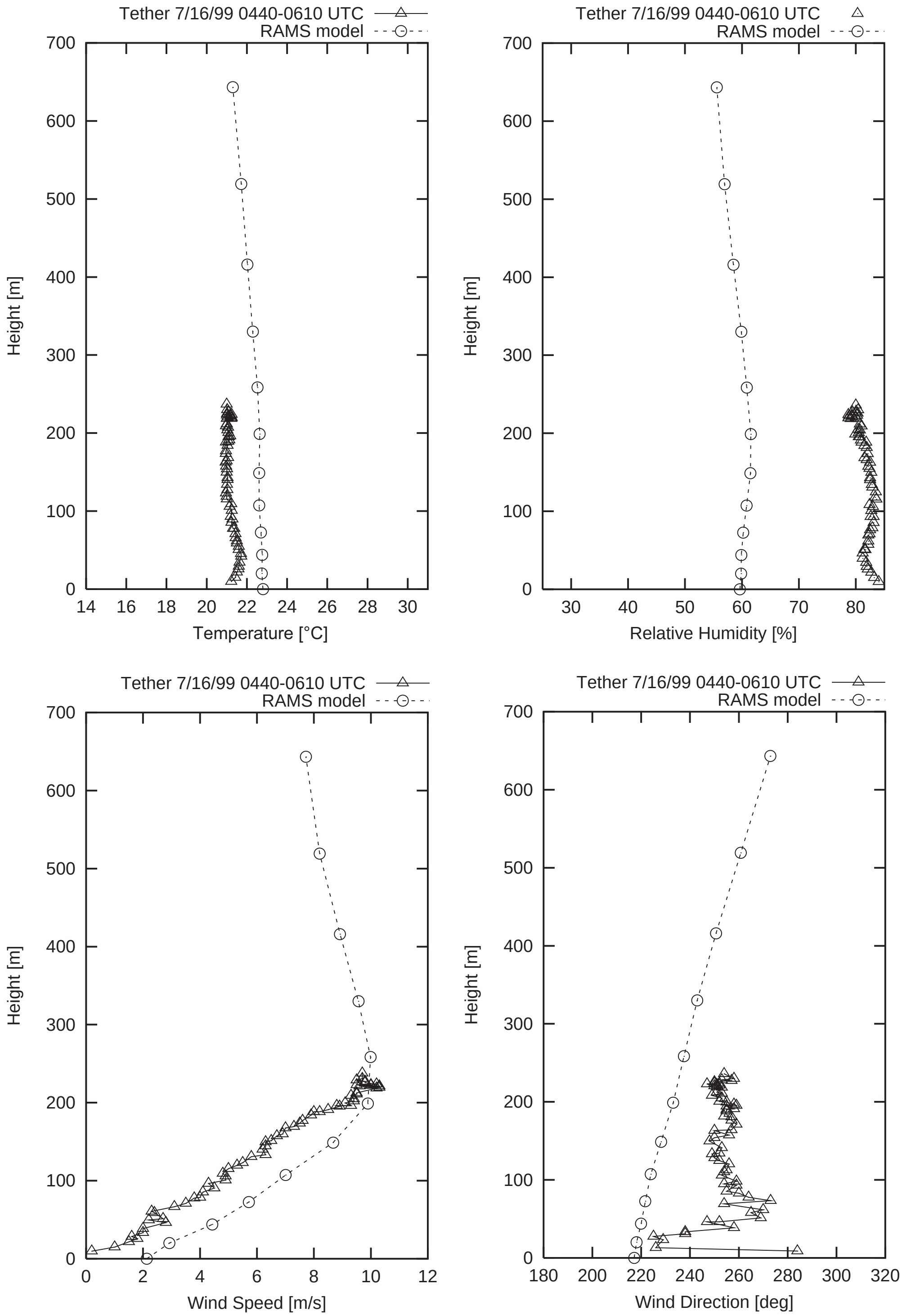

Fig. 5. Comparison of tethered balloon observations with RAMS 4 km model results over Philadelphia for 16 July 1999; 06 UTC for temperature and relative humidity (upper panels) and for wind speed and wind direction (lower panels).

Table 1
Root mean square errors of 36 km resolution and 33 layers in the vertical direction RAMS results with rawinsonde observations summed over all the rawinsonde stations and over all the standard pressure levels from 1000 to 150 hPa for 15–20 July 1999.

Date and time	u(m/s)	v(m/s)	T(°C)	RH
15/07/99, 12 UTC	2.76	3.58	1.25	0.55
16/07/99, 00 UTC	3.86	3.65	1.25	0.51
16/07/99, 12 UTC	4.20	4.26	1.82	0.55
17/07/99, 00 UTC	4.17	3.77	2.11	0.55
17/07/99, 12 UTC	3.99	3.51	2.20	0.53
18/07/99, 00 UTC	3.16	3.90	1.78	0.46
18/07/99, 12 UTC	3.45	3.44	1.65	0.45
19/07/99, 00 UTC	3.14	4.26	1.43	0.42
19/07/99, 12 UTC	3.88	3.80	1.38	0.44
20/07/99, 00 UTC	4.26	4.09	1.36	0.41

predict humidity fields much better on the surface since more data exist (Cox et al., 1998).

4. Summary

This study presents comparisons of the prognostic RAMS 4.3 results with aircraft, wind profiler, tethered balloon, lidar and RASS data collected during the NE-OPS field program over Philadelphia, PA during a summer episode in 1999. The comparisons of model-predicted temperatures with aircraft and tethered balloon data reveal that the model exhibits the general temporal trend in the mean relative errors for temperature that have been noted in earlier studies. The model, however severely overestimates temperature when compared with lidar data. Comparisons of model-predicted relative humidity with aircraft and tethered balloon indicate that the mean relative error varied from −13% to −21%. The mean relative error for water vapor mixing ratio with respect to lidar data revealed a negative bias of $-1.25\ \mathrm{g\,kg^{-1}}$ for heights up to 7 km, and a negative bias of $-2.5\ \mathrm{g\,kg^{-1}}$ for heights up to 3 km. This indicates that the underestimation of water vapor mixing ratio up to 3 km with respect to lidar data is consistent with the underestimation of the relative humidity with respect to aircraft and tethered balloon data. Some earlier studies have found that RAMS underestimates the humidity fields and the present results conform to the above trait. An earlier investigation had found improvement in the humidity prediction when RAMS was initialized with more soil moisture; so accurate soil moisture initialization could lead to improved prediction of the moisture fields. The largest rms errors obtained from 36 km resolution RAMS results and the regular upper air rawinsonde stations are associated with the relative humidity values. The smallest rms errors for any variable are all associated with the lower atmosphere while the largest rms errors are associated with the upper/mid-tropospheric region. The difficulty in correctly predicting upper level humidity is due to the lack of consistency in upper level moisture observations while the lower rms error of relative humidity close to surface is due to availability of moisture data at the surface. In conclusion, the results of the present study, based on data from a wide variety of diverse observation platforms, broadly corroborate the general traits of RAMS performance as noted by past studies.

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