# Evaluation of the NCEP Mesoscale Eta Model Convective Boundary Layer for Air Quality Applications

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## ABSTRACT

Atmospheric models are a basic tool for understanding the processes that produce poor air quality, for predicting air quality problems, and for evaluating proposed solutions. At the base of many air quality models is a mesoscale meteorological model. The National Centers for Environmental Prediction (NCEP) is now using a model with spatial resolution better than that used for many previous air quality studies. Mixing depth and wind and temperature profiles in the convective boundary layer are the key parameters that must be predicted correctly by a meteorological model for air quality applications. This paper describes an evaluation of the Eta Model predictions of these parameters based on comparisons to measurements made by boundary layer wind profilers at sites in Illinois and Tennessee. The results indicate that the Eta Model is quite usable as a meteorological driver for air quality modeling under reasonably simple terrain and weather conditions. The model estimates of mixing depth, boundary layer winds, and temperature profiles are reasonably accurate. This performance stems from a combination of recent Eta Model advancements in PBL and surface layer physics, land surface physics, 4D data assimilation, and vertical and horizontal resolution.

## 1. Introduction

Air quality models of various levels of complexity are commonly used in research to understand air quality problems, to forecast poor air quality episodes, and to choose among mitigation strategies. Many of these models rely on meteorological fields produced by a mesoscale meteorological model. The quality of the meteorological model output is critical to the success of the air quality modeling effort. However, the evaluation of mesoscale meteorological models is usually focused on significant weather events (precipitation, fronts, cyclones, snowstorms, warm season severe weather). The conditions commonly leading to air quality episodes—light winds, high pressure, abundant sunshine—are completely different than those leading to severe weather. Furthermore, the meteorological parameters most critical to air quality modeling are not necessarily as critical to weather forecasting. The most critical parameters for air quality applications are the mixing depth and the wind and temperature profiles in the daytime convective boundary layer. Meteorological models have generally not been evaluated on their ability to forecast these parameters accurately. Validation of the diurnal variation of model surface heat and moisture fluxes and model planetary boundary layer (PBL) structure, such as mixing depth and vertical profiles of wind, temperature, and humidity, is a desired addition to the typical suite of validation parameters for mesoscale weather prediction models.

Since June 1993, the National Centers for Environmental Prediction (NCEP) have operationally executed a mesoscale meteorological model known as the Eta Model because of its vertical coordinate (Mesinger and Black 1992; Black 1994). Since its initial introduction into NCEP operations in the early 1990s at 80-km, 17-layer resolution, the Eta Model resolution was increased to (a) 48 km, 38 layers on 12 October 1995; (b) 32 km, 45 layers on 9 February 1998; and (c) 22 km, 50 layers on 26 September 2000. For the summer evaluation periods of 1997, 1998, and 1999 considered in this study, the aforementioned operational model resolutions that were in effect were (a), (b), and (b), respectively. With respect to the PBL, the newer vertical resolutions that succeeded the original 17-layer resolution are particularly noteworthy. For example, over the Illinois and Tennessee sites of the present study, the 45-layer (38-layer) version includes about 13 (10) layers in the lowest 1.5 km of the atmosphere. In addition to the increasing ver-

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tical resolution, during the early 1990s NCEP developed and implemented several upgrades to Eta Model PBL physics (Mesinger 1993a,b; Janjić 1994; Janjić 1996a,b; Rogers et al. 1996; Chen et al. 1997).

In the mid- and late 1990s, to realize the full potential of the upgraded Eta Model PBL physics and resolution, NCEP embraced an ongoing effort in partnership with external investigators to improve the Eta Model land surface treatment of the surface energy and water budgets, especially the sensible, latent, and ground heat fluxes. This is accomplished through development, evaluation, and periodic upgrades of a comprehensive land surface model or LSM (now called the NOAH LSM) for the Eta Model (Chen et al. 1996; 1997; Mitchell et al. 2000a,b). In addition to these NCEP studies, further assessments of Eta land surface fluxes were carried out by several external investigators (Betts et al. 1997; Yucel et al. 1998; Marshall et al. 1999; Berbery et al. 1999; Hinkelman et al. 1999).

Of these, only the study by Betts et al. examined Eta Model behavior in the PBL above the surface, using profile data from radiosondes launched roughly every 90 min during intensive observing periods of the First International Satellite Land Surface Climatology Project Field Experiment of 1987 (FIFE-1987). The Betts study identified and solved weaknesses in the Eta Model LSM treatment of 1) bare soil evaporation and 2) seasonal cycle of vegetation greenness, but the study was limited to just three Eta Model 48-h forecast reruns for three individual summer cases in 1987.

Our study here assesses the convective PBL behavior of the Eta Model at high temporal resolution over a large sample of operational forecasts, specifically, daily model forecasts over a 3-month period in summer 1997, a 1.5-month period in summer of 1998, and a 2-month period in summer of 1999. The summer 1997 period follows the 18 February 1997 implementation of several Eta LSM physics improvements, including those cited above from the Betts study. The summer 1998 period follows the aforementioned 9 February 1998 implementation of the higher resolution (32 km/45 layers). This latter implementation also included further LSM upgrades from two to four soil layers and an improvement in the soil moisture initialization (discussed and illustrated in Marshall et al. 1999). Hence by assessing summer 1998 as well as summer 1997 at the same site (IL), we can assess whether any notable changes in PBL behavior are realized from the intervening model changes. By assessing two different sites between 1998 (IL) and 1999 (TN) during a period of no forecast model changes, we can assess whether the summer convective PBL behavior in the model is similar between two separate sites in the same climatological region—both characterized by relatively flat terrain, significant green vegetation in summer, and similar warm season precipitation climatology.

The 1997 and 1998 measurements shown here were taken at the Flatland Atmospheric Observatory (FAO), located at the University of Illinois Bondville Road Field Site southwest of Champaign–Urbana, Illinois. The terrain is extraordinarily flat, varying less than 5 m over several kilometers of horizontal distance. Corn (maize) and soybeans are grown in roughly equal proportions in the area. In 1999, measurements were made at the Cornelia Fort Airpark in Nashville, Tennessee, as part of a Southern Oxidant Study intensive campaign. The Cornelia Fort site (CFA) is in the bottomlands of the Cumberland River and is influenced by downtown Nashville under southerly flow.

The 915-MHz lower-tropospheric or boundary layer wind profiler was developed at the National Oceanic and Atmospheric Administration (NOAA) Aeronomy Lab (Carter et al. 1995; Ecklund et al. 1988). These transportable systems have been deployed at a large number of meteorology and atmospheric chemistry experiments, as well as in long-term studies. A review of some research results from these profilers was presented by Rogers et al. (1993). The wind profiler is a sensitive Doppler radar. Unlike the more familiar weather radars, the profiler is designed to respond to fluctuations of the refractive index in the clear air, although it is also sensitive to particles such as hydrometeors and insects.

The profiler used in these comparisons was permanently installed (from 1991 through 1998) at the FAO. The vertical resolution was 60 m with a minimum height of 150 m above ground level (AGL). The antenna was a nine-panel (3 m × 3 m) phased array. Six beam positions, four oblique beams in two coplanar pairs and two vertical beams of orthogonal polarizations, were used. The dwell time on each beam was approximately 25 s. The maximum height of the 60-m resolution measurements varied from 1.5 to 3 km depending on atmospheric conditions, especially humidity, but was always sufficient to cover the daytime convective boundary layer. Angevine et al. (1998b) discuss the height coverage in detail.

Mixing-depth measurements are made from the profiler reflectivity data by a well-established technique (Angevine et al. 1994c; Grimsdell and Angevine 1998), and have an uncertainty of approximately 100 m (Cohn and Angevine 2000) in the absence of clouds; large cloud fractions make the determination much more difficult, but such cases are excluded from these comparisons.

Profiler wind measurements, when averaged over at least 30 min, have accuracy and precision better than 1 m $s^{-1}$ (Angevine and MacPherson 1995; Angevine et al. 1998a). The intermittent contamination algorithm (''bird algorithm''; Merritt 1995) was used; this algorithm is quite helpful in removing intermittent contamination from a variety of objects, particularly birds.

The profiler was also equipped as a Radio Acoustic Sounding System (RASS; Angevine et al. 1994b) to measure virtual temperature profiles. When utilizing RASS, an acoustic signal is emitted by four loudspeakers and focusing dishes arranged around the perimeter of the profiler antenna. The profiler measures the speed of sound, and the virtual temperature is derived there-

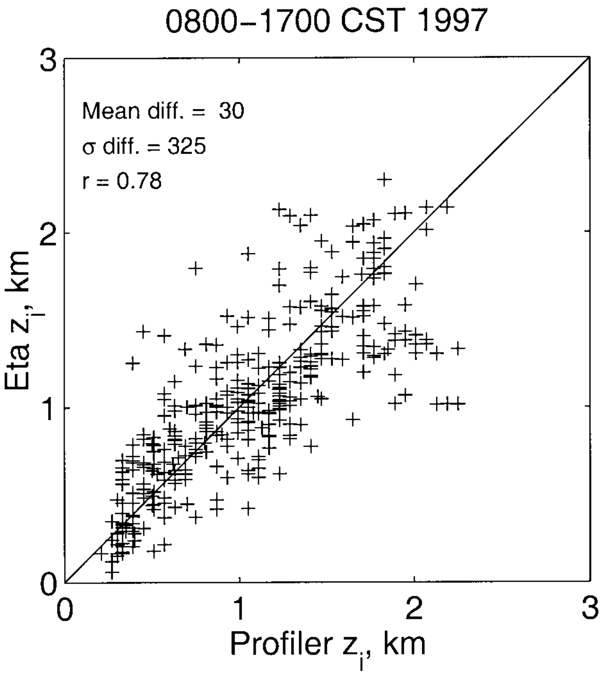

FIG. 1. Scatterplot comparing mixing depth from the Flatland profiler and Eta Model for 360 h in 1997. See text for details of time period and data selection.

from. The profiler was operated in RASS mode for 3 min every half hour and the rest of the time ran in the normal wind mode described above. Data are available approximately 50% of the time up to 800 m AGL (Angevine et al. 1998b). The height coverage of RASS at 915 MHz is limited by acoustic attenuation, in addition to the effects of horizontal wind that blows the acoustic energy out of the radar beam. Although the accuracy of RASS is better than 1 K, it is affected by range-dependent biases that are not fully understood (Görsdorf and Lehmann 2000; Peters and Angevine 1996). The precision of RASS virtual temperature measurements is approximately 0.5 K (standard deviation) when compared to radiosondes, which of course contribute some of that uncertainty (Angevine and Ecklund 1994).

## 2. Results

Measurements and model output were compared for 10 June–10 August 1997, 14 July–2 September 1998, and 1 June–31 July 1999. The Model Output Location Time Series (MOLTS) form of the Eta output (http://www.emc.ncep.noaa.gov/mmb/gcip.html) was used. This MOLTS archive, provided by NCEP to the National Center for Atmospheric Research (NCAR) for distribution, includes hourly time series of Eta Model output at every Eta Model atmospheric level, as well as at the land surface and soil subsurface, for over 1100 locations of interest to the research and operational community. For the 1997 and 1998 comparisons, the 1200 UTC model forecast for the Bondville field site (FAO) was used. The actual coordinates of the field site are 40.05°N, 88.38°W; the actual model grid location is 40.28°N, 88.20°W, about 30 km northeast. Comparisons were made for hours between 1400 and 2300 UTC [0800 and 1700 central standard time (CST)] so the model forecast lead time varied from two to 11 hours. For 1999, the Cornelia Fort profiler was at 36.20°N, 86.70°W, and the MOLTS location was at 36.44°N, 86.54°W, approximately 34 km northeast of the profiler site.

The Eta Model boundary layer scheme does not predict mixing depth explicitly. We examined many different techniques for diagnosing the mixing depth from the model output. The best method for the 1997 data was to compute the bulk Richardson number $R_{1b}$ and consider the mixing depth to be the first layer above ground that had $R_{1b} > 0.25$. A threshold on virtual potential temperature ($\theta_v > \theta_{vs} + 0.2$, where $\theta_{vs}$ is the surface virtual potential temperature) worked nearly as well. The next best method used a threshold on the turbulence kinetic energy (TKE). Searching for a relative humidity peak, a peak in the negative gradient of $\theta_v$, or a peak in the negative gradient of TKE gave much greater scatter in the comparison.

The top of a convective boundary layer is present as a distinctive signature in a time–height plot of profiler reflectivity. Generally, a strong peak of reflectivity is seen at the boundary layer top, although the strength of this peak depends on a variety of factors. The reflectivity peak is the result of strong gradients of temperature and especially humidity (White et al. 1991). Boundary layer heights were found by a hybrid objective–subjective method. First, an algorithm (Angevine et al. 1994c) found the hourly median height of reflectivity peaks. Then these automatic estimates were examined and revised, and the quality of the estimate determined subjectively.

The profiler winds shown are 1-h averages. Before profiler data can be used, they must be subjected to quality control (“cleaning”) to remove contamination from aircraft, radio frequency interference, birds, precipitation, and other sources. The first step in data quality control is to choose appropriate days that are reasonably free of persistent rain and that have reasonably well-formed convective boundary layers. Then, the statistical filtering technique described by Angevine et al. (1994a) was applied to the data. In brief, this technique discards data where any of the three moments (signal-to-noise ratio, velocity, and spectral width) fall outside two or three standard deviations (depending on the moment) of each 1-h time series. There is also a floor of signal-to-noise ratio below which all data are discarded. This technique discards obvious outliers while preserving turbulence information. Hours with more than 12 outliers (out of approximately 24) were discarded entirely.

The RASS temperature measurements were processed by a similar technique, except that all measurements for the entire day were processed as a block. The RASS

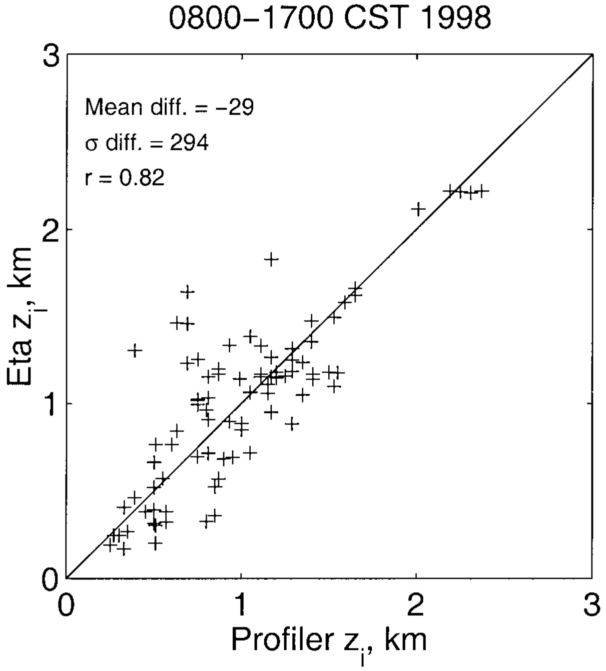

FIG. 2. Same as in Fig. 1 but for 90 h in 1998.

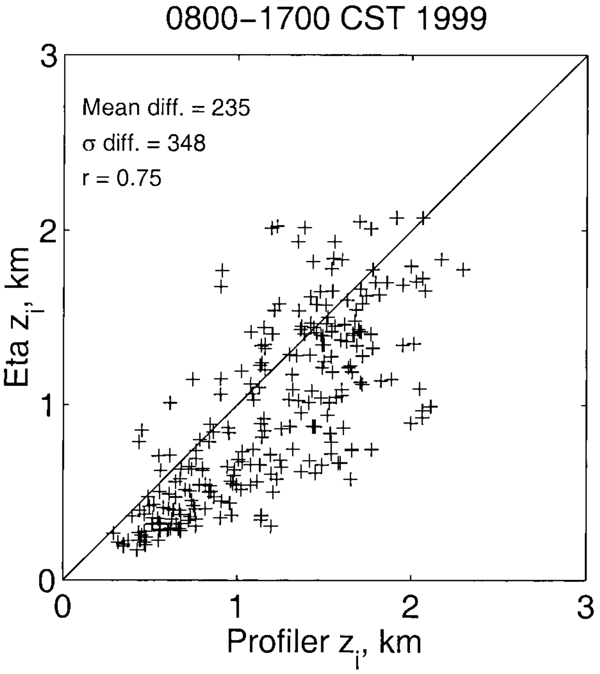

FIG. 3. Same as in Fig. 1 but for 255 h at Cornelia Fort Airpark (CFA) in Nashville, TN, in 1999.

data were corrected for vertical velocity (Angevine et al. 1994b), but no other corrections were applied.

As a result of these quality controls and of occasional Eta Model forecast cycles missing from the archive, not all hours of all days within the period are included in the comparisons. The number of hours of each day varies with time of day, about half as many hours having well-defined mixing depths in the late afternoon as in the morning. The late-afternoon behavior of the mixing depth is not well understood, so the comparisons shown here only include data up to 1700 CST. The number of hours in the wind speed and virtual temperature comparisons at each height are shown in the respective figures.

Figures 1, 2, and 3 are scatterplots comparing mixing depths from the model and the profiler. The mean difference (profiler minus model), standard deviation of the difference, and correlation coefficient are also shown. There are 360 h of data from 51 days in the 1997 comparison (Fig. 1); 90 h from 12 days in 1998 (Fig. 2) due to two extended outages in the profiler data; and 255 h from 59 days in 1999 (Fig. 3). The scatter, as measured either by the correlation coefficient or the standard deviation of the difference, is about the same in all three years. The upper panels of Figs. 4, 5, and 6 show scatterplots for morning and afternoon separately. In 1997 and 1999, the comparisons are much worse in the afternoon hours. Profiler mixing-depth measurements are less precise in the presence of clouds, which are more prevalent in the afternoon. The physical processes controlling the mixing depth are also different in the morning and afternoon. In the morning, the surface energy balance and the nocturnal inversion control the mixing height. In the afternoon, the portion of the temperature profile near the final mixing depth is the most important factor, and it is in turn controlled by advection. The reasonable correlation in the 1998 afternoon data is probably fortuitous. The lower panels of Figs. 4, 5, and 6 show the mean diurnal behavior of the mixing depth. There is virtually zero model bias at all hours in the mixing depth in 1997 and 1998. In 1999 the mixing depth is underestimated substantially and systematically by the Eta Model throughout the day. The model underestimate in 1999 is largely due to an urban heat-island effect at the CFA site, as indicated by comparisons with other profilers outside the urban area (not shown). The model grid point used is well outside the urban area and we would not expect it to capture urban effects.

As noted above, the comparisons were worse in the afternoon when cumulus cloud cover is known to be more prevalent. Afternoon ''fair weather'' cumulus is a subgrid-scale process in mesoscale models. In the Eta Model, the treatment of subgrid shallow convection (Janjić 1994) addresses only the vertical transport of heat and moisture in the vicinity of the PBL top. There is no associated estimate or inference of shallow cumulus cloud fraction and, hence, no interaction of such with the Eta Model radiation scheme. In these datasets, there is no correlation between cloud fraction predicted by the model and that measured by the ceilometer (not shown). The study by Hinkelman et al. (1999) includes a daily assessment of Eta cloud predictions using a 35-GHz cloud radar over a 6-month period during January

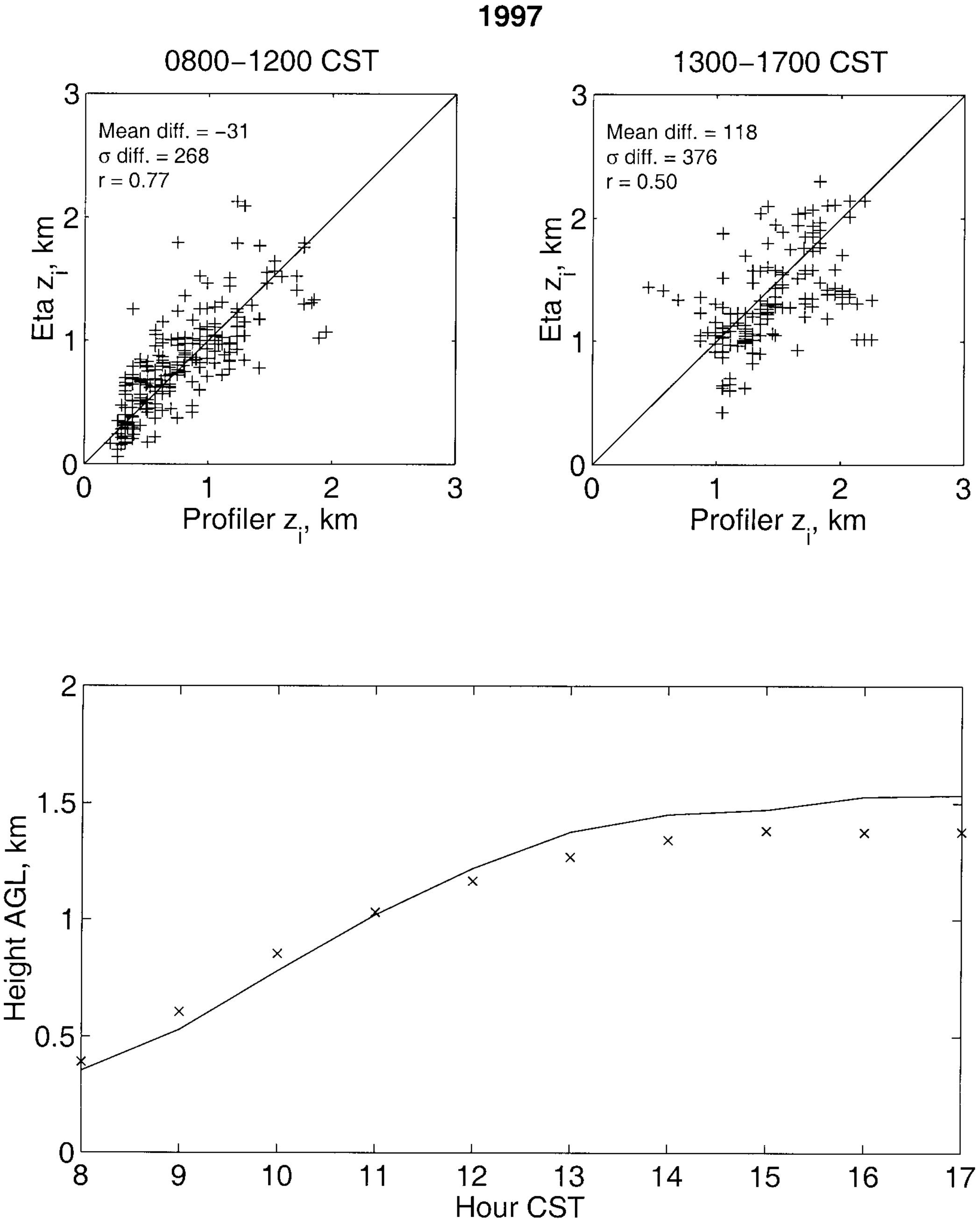

FIG. 4. (a) Mixing-depth comparison for morning hours of 1997 at Flatland. (b) Afternoon hours. (c) Composite hourly average mixing depth from the profiler (solid) and Eta Model (×).

through June 1997 at a site in north-central Oklahoma. In the spring months of April, May, and June, as convection becomes more dominant, the Eta Model showed a clear tendency to underpredict low- and midlevel cloud frequency and amount. This, in turn, contributes to an Eta Model positive bias in both surface solar insolation and surface sensible heat flux in summer. These latter biases are confirmed in several Eta Model validation studies (Betts et al. 1997; Hinkelman et al. 1999; Berbery et al. 1999). At their northeast Kansas study site in summer, Betts et al. inferred that the Eta Model produces reasonable daytime PBL depths despite the positive surface sensible heat flux bias owing to the model's corresponsing underestimation of entrainment at the top of the PBL. We plan to focus on comparisons of model versus profiler-inferred PBL-top entrainment in a future study.

The wind comparisons as a function of height are shown in Figs. 7, 8, and 9. The model underestimates the wind speed slightly below 200 m AGL in 1997,

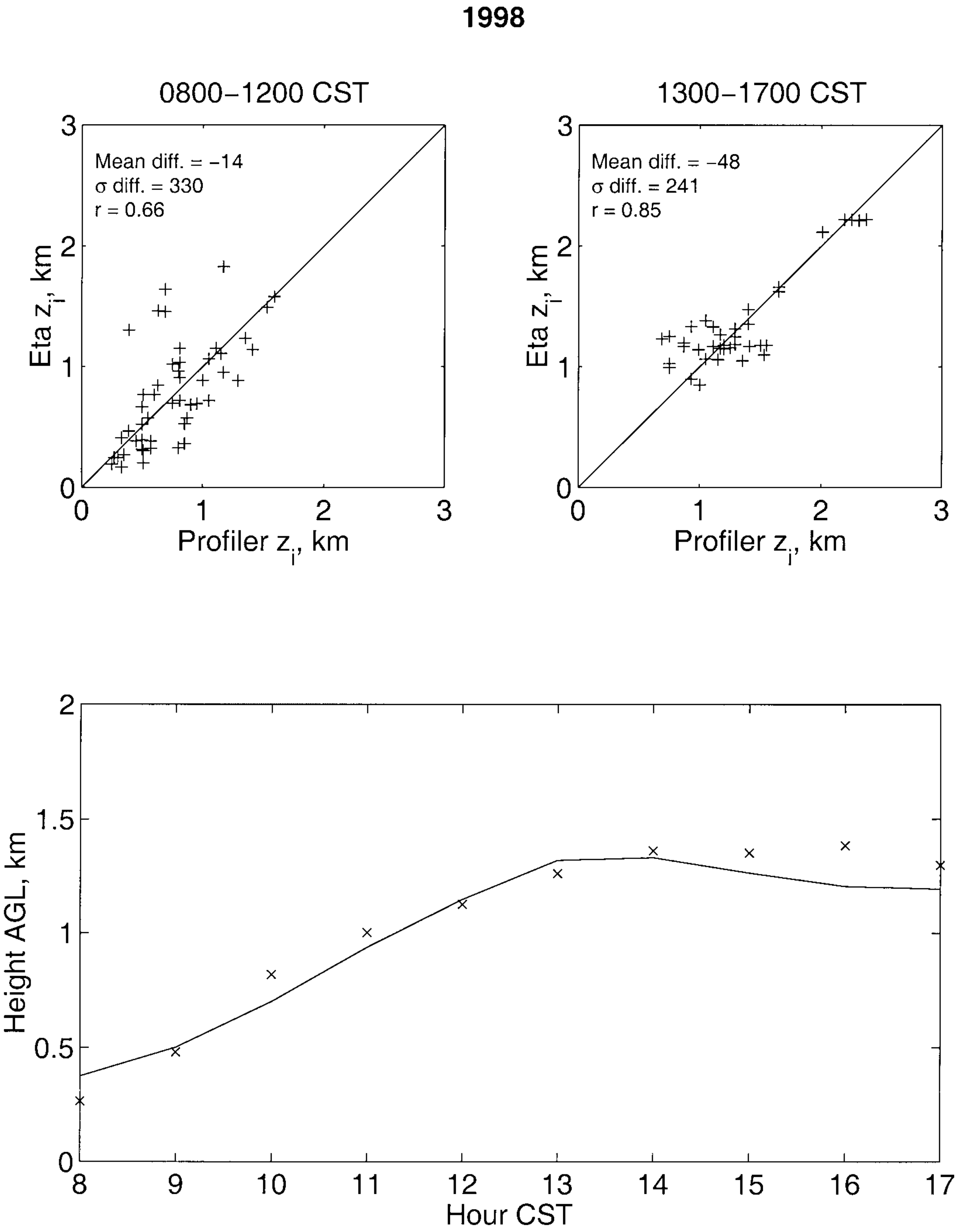

FIG. 5. Same as in Fig. 4 but for 1998.

overestimates it slightly below 400 m in 1998, and overestimates it substantially in 1999. The vector difference, which is of most direct application to air quality because it directly estimates the error in the transport of a parcel, is somewhat less in 1998 than in the other two years, probably mostly due to the lack of larger wind speeds in that dataset. Scatterplots of vector difference versus profiler speed for 1999 show a few large vector differences at small speeds (points along the upper *y* axis), the most serious kind of error. In general, though, smaller wind speeds lead to smaller vector differences as expected. The standard deviation of the difference is slightly less and correlations are slightly higher in 1998, likely as a result of the improved vertical resolution of the model. Again, the greater differences and larger standard deviations in 1999 are probably due to urban effects not captured by the model. As a whole, we can summarize the wind

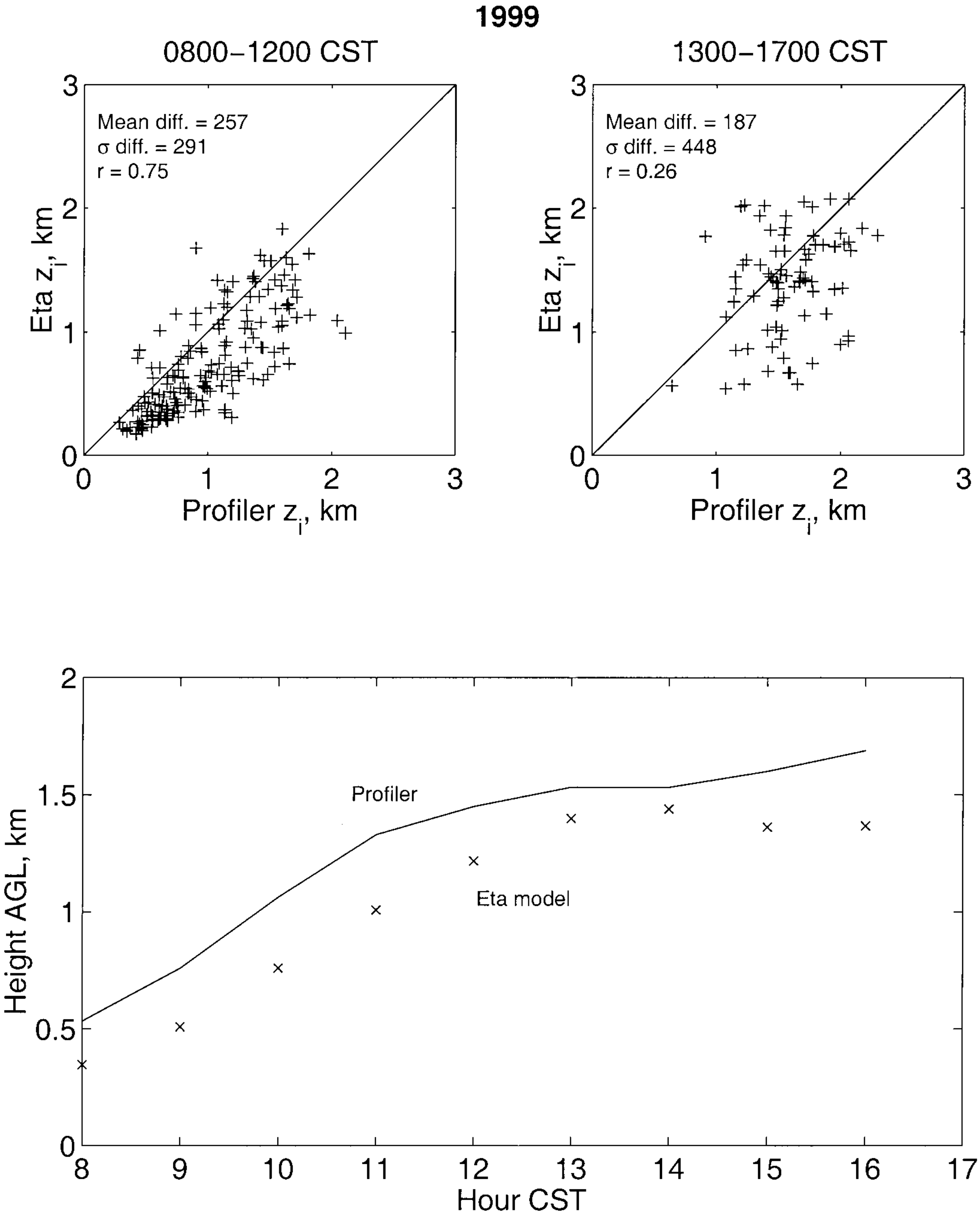

FIG. 6. Same as in Fig. 4 but for CFA 1999.

comparisons by saying that an average air parcel will diverge approximately 3 m $s^{-1}$ in the model with respect to the measurements.

Comparisons of virtual temperature are shown in Figs. 10, 11, and 12. The mean error profile has the characteristic shape almost universally observed in RASS comparisons to radiosondes (Görsdorf and Lehmann 2000; Angevine and Ecklund 1994; Riddle et al. 1996), the RASS tending to be cooler at the lowest levels and warmer above. Such comparisons have shown mean differences in the middle levels of less than 1 K, so it is likely that the model was slightly cooler in 1997, slightly warmer in 1998, and somewhat cooler in 1999. Actual warmer temperatures over the urban area likely contributed somewhat to the larger warm bias seen in the 1999 data. The standard deviation of the difference is much less below 500 m in 1998 than in 1997, though the correlation is slightly smaller, and is larger in 1999.

Another factor that can contribute to the site to site and year to year variability observed in Figs. 10–12 in low-level model temperature bias and standard deviation is similar variability in the bias of the model's soil moisture

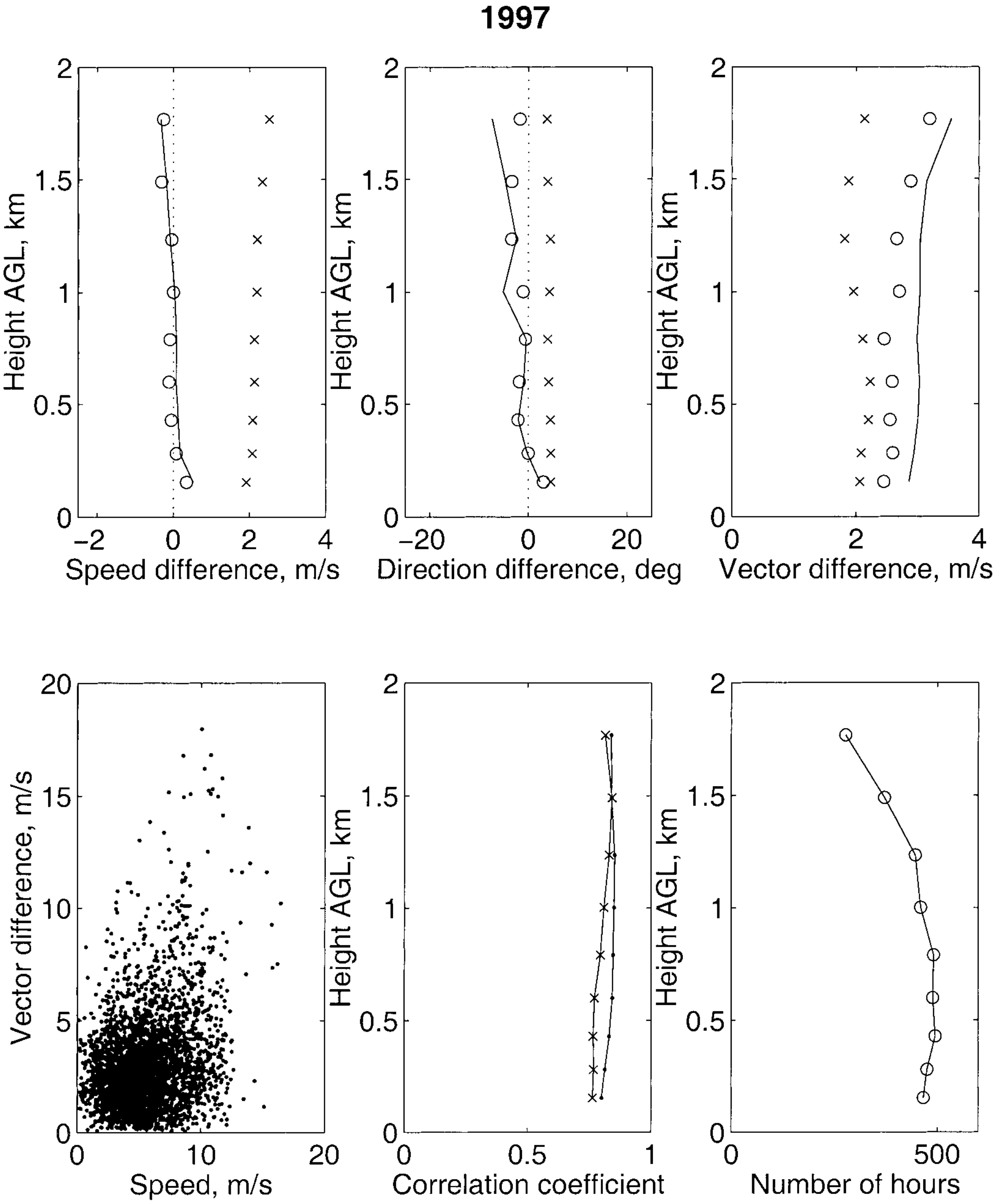

FIG. 7. Wind comparison for Flatland 1997. (a) Wind speed difference (all differences are profiler–Eta). Line is mean, circles are median, and ×'s are standard deviation/10. (b) Wind direction difference, same notation. (c) Vector difference, same notation. (d) Vector difference vs profiler wind speed. (e) Correlation coefficient of *u* and *v* components. (f) Number of hours included in comparison at each height.

and green vegetation cover/canopy resistance and, hence, variability in the model's surface Bowen ratio and skin temperature. The Eta Model soil moisture is a continuously evolving land state variable in the land surface physics of the Eta Model during the continuous self-cycling Eta Data Assimilation System (EDAS). This EDAS soil moisture is a product of the Eta Model's precipitation, surface latent heat flux, and surface infiltration/runoff in the EDAS, as described and demonstrated in Marshall et al. (1999) and Mitchell et al. (2000a). Hence, as the location, magnitude, and sign of the Eta Model's precipitation bias shift from month to month, so too do those of the Eta Model soil moisture and skin temperature (Mitchell et al. 2000a). Concerted efforts are under way at NCEP to minimize Eta Model soil moisture bias via assimilation of observed precipitation and other land data assimilation initiatives (Mitchell et al. 2000a,b). In the appendix that follows, several NCEP and National Environmental Satellite Data, and Information Service (NESDIS) Internet sites are provided to allow Eta Model users to routinely assess Eta

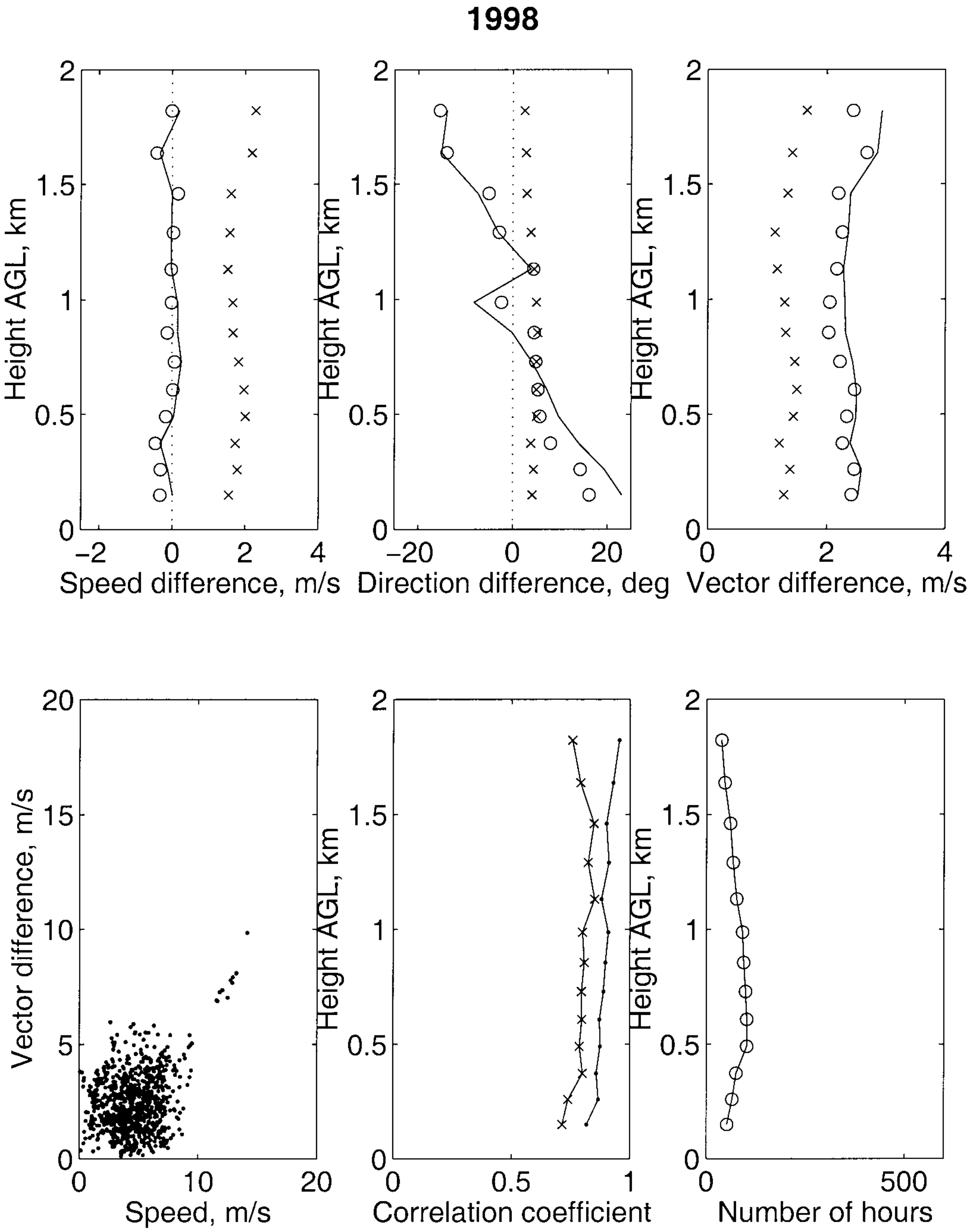

FIG. 8. Same as in Fig. 7 but for Flatland 1998.

Model 2-m air temperature, surface skin temperature, precipitation bias, and soil moisture patterns, by region of the continental United States and month of year.

## 3. Conclusions

This study indicates that the Eta Model is quite usable as a meteorological driver for air quality modeling on relatively cloud-free days in the summer Midwest, characterized by 1) relatively flat terrain, 2) significant green vegetation cover, and 3) reasonably abundant rainfall. The estimates of mixing depth, boundary layer winds, and temperature profiles are reasonably accurate. This reasonable performance stems from the cited combination of recent Eta Model advancements in PBL and surface-layer physics, land surface physics, 4D data assimilation, and vertical and horizontal resolution, though further improvements are needed in modeling cloud fraction, cloud–radiation interaction, PBL-top entrainment, and soil moisture initialization.

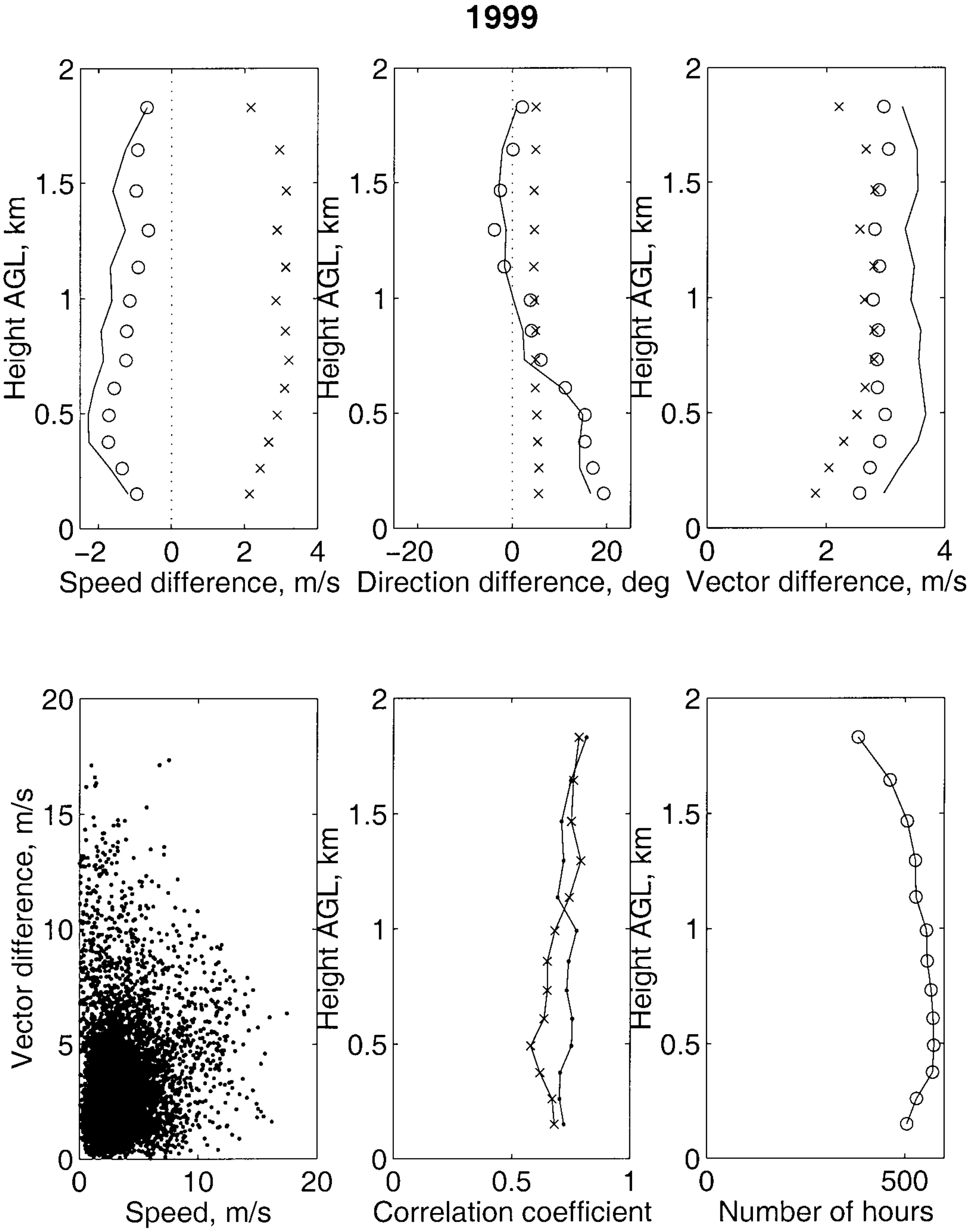

FIG. 9. Same as in Fig. 7 but for CFA 1999.

The Eta Model undergoes continuous improvement, so the results shown here are representative only of the time periods tested. It is somewhat difficult to compare the three periods (summers of 1997, 1998, and 1999) directly since there are so many fewer hours available for the comparison in 1998 and the profiler was in a different location in 1999. Nonetheless, there are indications that the 1998 version of the model produces more accurate mixing depths and boundary layer winds than the 1997 version.

The mixing depths agree well in the mean for the simpler Flatland cases (1997 and 1998), but show considerable scatter in the individual hourly values. Though the model internally computes a mixing depth in its PBL physics, this mixing depth is not output by the model and hence is not archived. Hence, the results here are partly dependent on the method used to diagnose mixing depth from other model output. (Future model changes should add explicit output and archive of the model-computed mixing depth.) In this paper, we used a bulk

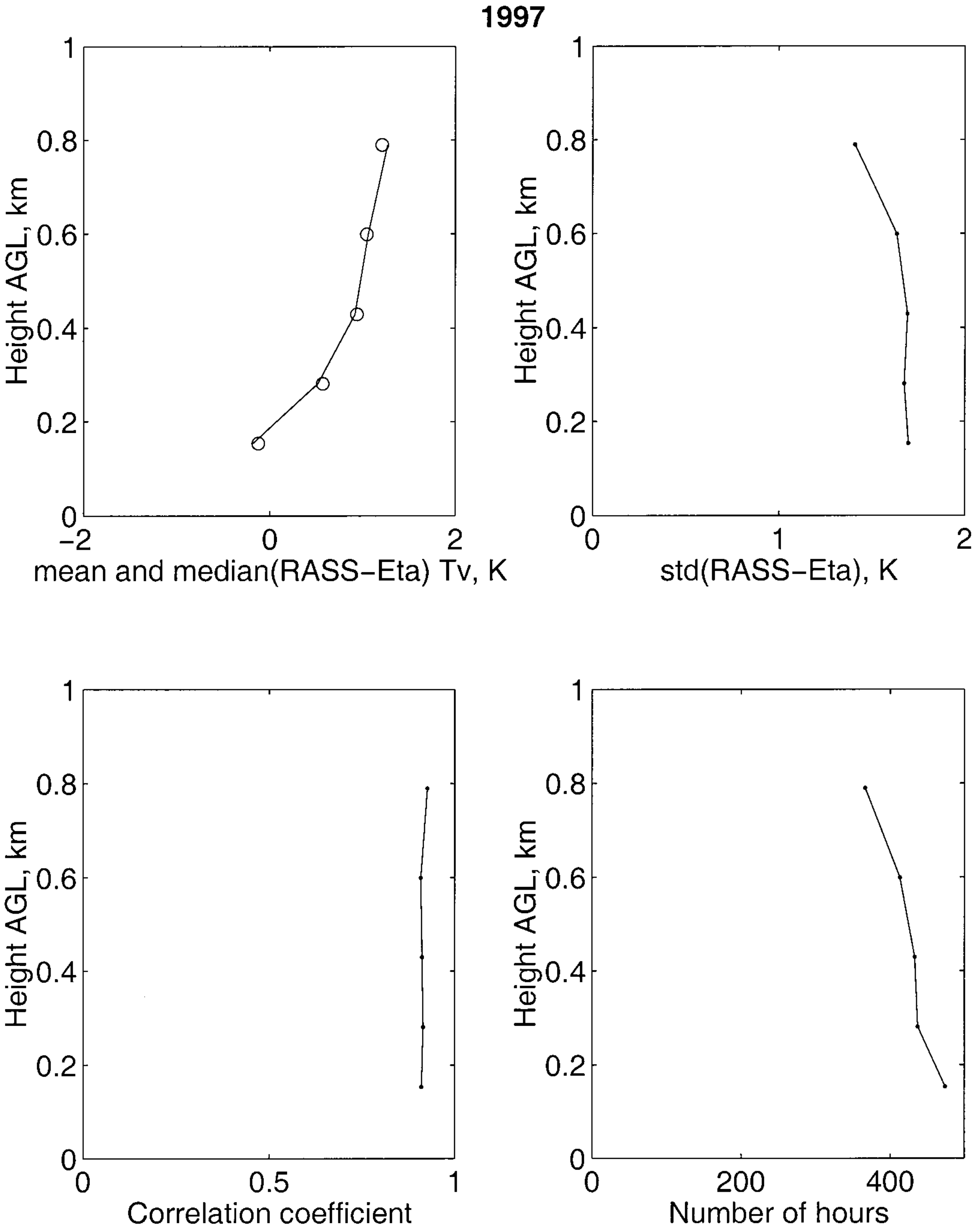

FIG. 10. Virtual temperature comparison for Flatland 1997. (a) Difference profile. (b) Standard deviation of difference/10. (c) Correlation coefficient. (d) Number of hours included in comparison at each height.

Richardson number method that was originally tuned for the 1997 data. A threshold on turbulent kinetic energy produced slightly better results for 1998 (not shown). It is interesting that the humidity profiles are not usable for diagnosing mixing depth in either year. Clouds may be a source of some of the scatter in the mixing depth comparisons. There is no correlation between clouds predicted by the model and measured by a ceilometer. Cases with large cloud fractions are excluded from the comparison by the requirement that the boundary layer be reasonably well defined in order to measure it with the profiler, so the relevant case is shallow or fair-weather cumulus clouds. The 1999 comparisons are complicated because of the urban area and less homogeneous terrain.

Virtual temperature comparisons show the characteristic height-dependent instrumental bias observed with RASS. The difference in the bias at 400–800 m AGL

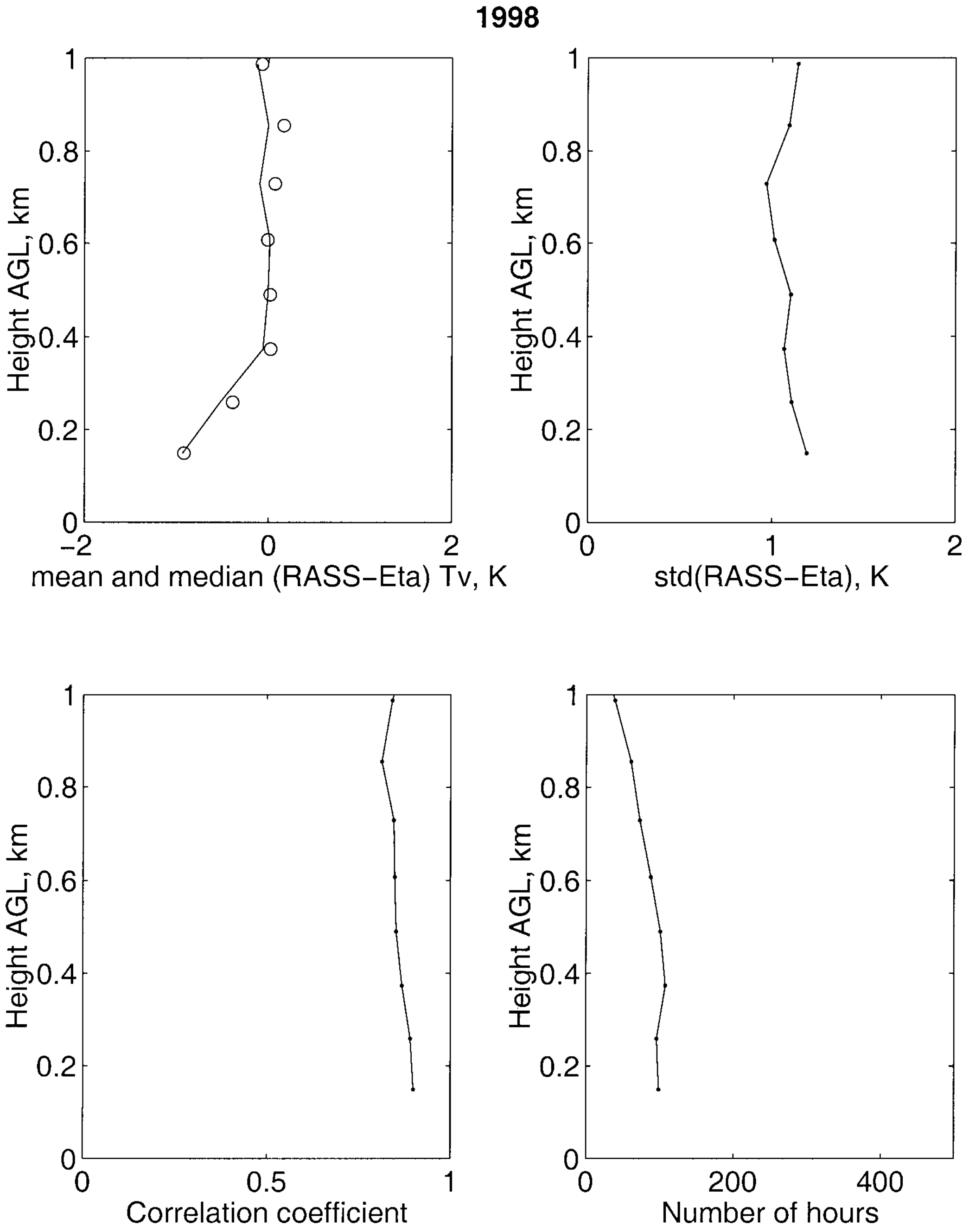

FIG. 11. Same as in Fig. 10 but for Flatland 1998.

may indicate that the model is slightly warmer in 1998 than in 1997, and somewhat cooler in 1999.

It remains to be shown by additional study whether the reasonable performance demonstrated here extends to the nighttime stable boundary layer, the cool season, more cloudy conditions, or arid or mountainous regions. The model PBL performance over complex terrain is likely not as good. Profiler measurements are not available on a routine basis to provide widespread assessments over a variety of regions, climate zones, and seasons. As an alternative, NCEP provides routine monthly assessments by region of several quantities linked to diurnal PBL behavior. First, regional verifications against surface stations are provided of the monthly mean Eta Model diurnal cycle of 1) 2-m air temperature and relative humidity, and 2) 10-m wind speed. Second, in collaboration with NESDIS, NCEP provides monthly assessments by region of Eta Model land surface skin temperature and solar insolation versus that of Geostationary Operational Environment Satellite (GOES)

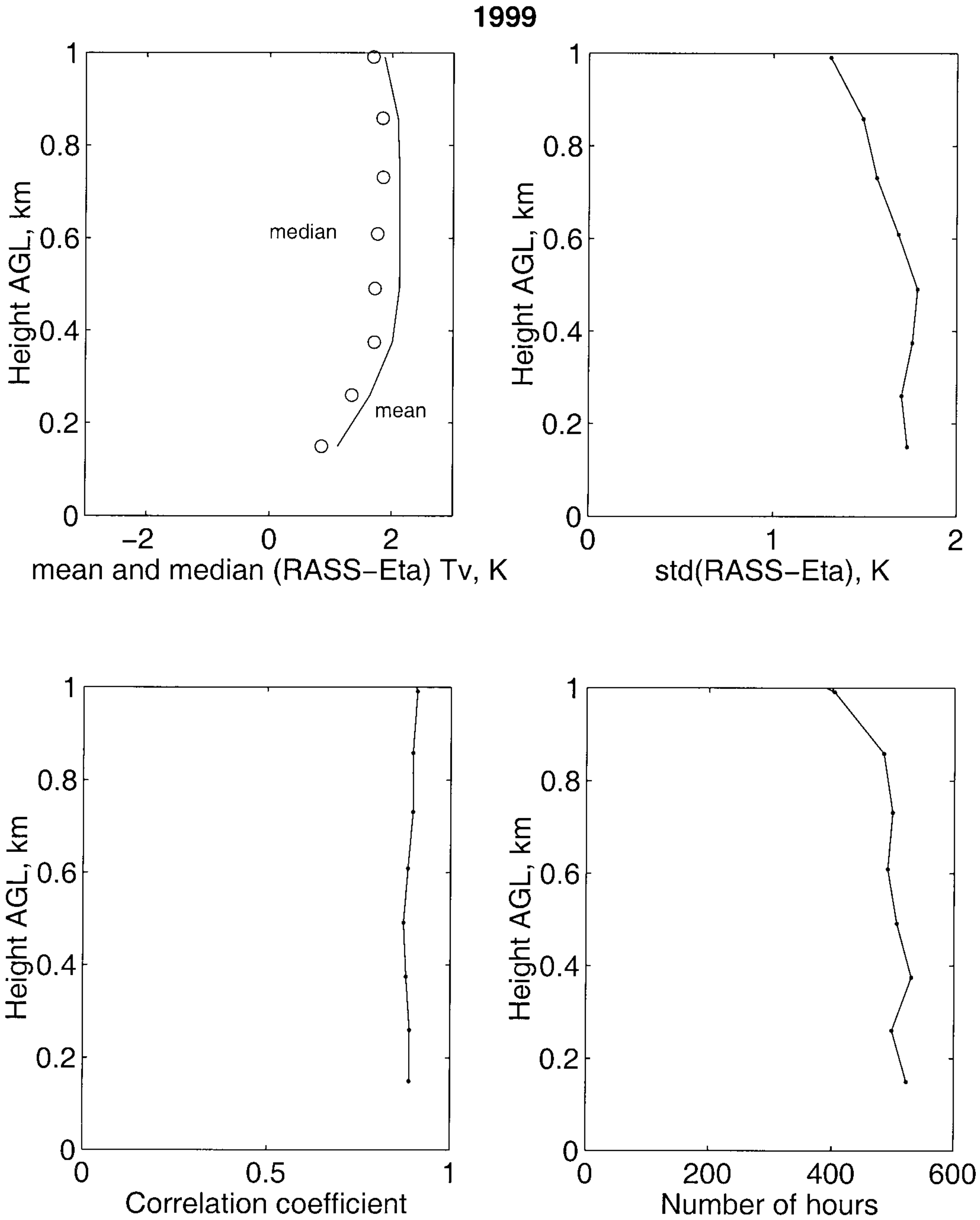

FIG. 12. Same as in Fig. 10 but for CFA 1999.

based satellite retrievals for three times daily (1500, 1800, 2100, UTC). Third, for each day over the past year, at four to six selected upper-air stations across the continental United States (CONUS), NCEP provides 0000 UTC plots of Eta 24-h forecast versus radiosonde-observed vertical soundings of temperature, dewpoint, and wind vectors. Last, CONUS maps of observed and modeled monthly total precipitation (and their difference), monthly land surface water budget components, and end-of-month model soil moisture are provided. At the time of this writing, the Internet sites for these four types of assessments are given in the appendix. Model users are encouraged to inspect these sites on a monthly basis throughout the year to develop a sense of model performance in their region throughout the annual cycle.

Validation of the diurnal variation of model surface heat and moisture fluxes and model PBL structure, such as mixing depth and vertical profiles of wind, temperature, and humidity, is a desired addition to the typical suite of validation parameters for mesoscale weather-prediction models. While the increasing availability of real-time surface-flux observing sites has enhanced routine model validation of surface fluxes, routine model validation of PBL structure still relies foremost on traditional twice-per-day operational radiosonde observations, which lack the temporal frequency to validate the PBL diurnal cycle and the peak daytime mixing depth. Hence the validation of model PBL diurnal behavior at high temporal frequency with profiling systems is an important addition to model validation.

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## APPENDIX

## Internet sites for Eta Model Validation

1) Regional monthly verification against surface stations of Eta Model 0–48-h monthly mean diurnal cycle of 2-m air temperature and humidty and 10-m wind speed: http://www.emc.ncep.noaa.gov/mmb/research/nearsfc/nearsfc.verf.html
2) Regional monthly verification against GOES-based satellite retrievals of Eta Model forecast land surface skin temperature and solar insolation at three times daily (1500, 1800, 2100 UTC): http://orbit-net.nesdis.noaa.gov/goes/gcip/html/scatter.html
3) Daily verification over past year at four to six CONUS upper-air stations of the Eta Model 24-h forecast versus radiosonde-observed vertical profiles of temperature, dewpoint, and wind vector: http://www.emc.ncep.noaa.gov/mmb/gcp/board/board.html
4) CONUS maps of monthly verification of observed versus Eta Model monthly total precipitation, with companion maps of Eta Model surface water budget components, and Eta Model end-of-month soil moisture: http://www.emc.ncep.noaa.gov/mmb/gcp/h2o/index.html

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