Evaluating NCEP Eta Model–Derived Data against Observations

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ABSTRACT

Data derived at the National Centers for Environmental Prediction via four-dimensional data assimilation using the Eta Model were evaluated against surface observations from two observational arrays, one located in the semihumid, continental climate of Oklahoma and Kansas and the second in the semiarid climate of southern Arizona. Comparison was made for the period of the Global Energy Water-cycle Experiment Continental-scale International Project's ''GIST'' dataset in 1994 and their ''ESOP-95'' dataset in 1995, and for the months of March and May in 1996. Coding errors in the Eta Model's postprocessor used to diagnose near-surface temperature and humidity are shown to have compromised the GIST and ESOP-95 near-surface data. A procedure was devised to correct the GIST and ESOP-95 near-surface fields by mimicking the corrected code used in the Eta Model since January 1996. Comparison with observations revealed that modeled surface solar radiation is significantly overestimated except in clear-sky conditions. This discrepancy in cloudy-sky solar radiation was altered little by the substantial January 1996 revisions to Eta Model physics, but the revisions are shown to have greatly improved the model's ability to capture daily and seasonal variations in near-surface air temperature, specific humidity, and wind speed. The poorly modeled surface radiation complicates evaluation of modeled surface energy fluxes, but comparison with observations suggests that the modeled daytime Bowen ratio may be systematically high. This study clearly demonstrates the strong sensitivity of model-calculated, near-surface variables to the physics used to describe surface interactions in the data assimilation model. To mitigate against this and to aid intercomparisons between other data, it is recommended that model-derived data always include sufficient information to allow potential users to recalculate the extrapolation to the surface using a user-defined model of surface–atmosphere exchanges.

1. Introduction

In an effort to support the Global Energy Water-Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) research community, the National Centers for Environmental Prediction (NCEP) operational Eta Model and its companion data assimilation system are being used to produce an archive of near-surface meteorological variables, surface heat fluxes, subsurface variables, and synthetic soundings across the Mississippi River basin. It is obviously important that these model-derived data are evaluated against real observations wherever possible. There are several successful examples of such comparisons for continental-scale atmospheric hydrological budgets. Berbery et al. (1996), for example, derived estimates of the atmospheric hydrological cycle from the Eta Model analysis and forecast products for the Mississippi river basins, and the Eta Model analyses compare well with observational estimates. Comparisons of radiosonde observations and Eta Model analyses during the GIST-1994 period also showed good agreement between modeled and observed humidity transport (Yarosh et al. 1996). Prior studies have attempted to evaluate the Eta Model performance in near-surface variable forecasts (e.g., Betts et al. 1997). The present study focuses on the longer-term evaluation of Eta Model near-surface variables in comparison with two multisite observational networks to investigate not only the diurnal cycle of Eta Model forecasts in near-surface variables, but also its longer-term evolution in early spring and late summer. Feedback from these diagnostic studies has already been used in conjunction with NCEP's own Eta Model evaluation program to improve the Eta Model physical parameterizations. One of the observational arrays used in the present study is located in the semiarid climate of southern Arizona, while the second array is located in the

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more humid continental climate of Oklahoma and Kansas.

The primary goal of the research reported here was to investigate the Eta Model's past performance in documenting critically important near-surface weather data products over land and thus to define where model improvement may be required. It is envisaged that such evaluation will also be helpful to users of GCIP data archives and, with this in mind, particular attention was given to the period of 12 July–31 August 1994, this being the period of the GCIP Initial System Test (GIST), and to the period of 1 May–31 July 1995, this being the GCIP 1995 enhanced special observing period (ESOP-95). In response to feedback on performance from this and other evaluations of model performance, substantial revisions were made to the Eta Model in January 1996. For this reason, we also report the results of a comparison for March and May 1996 in order to provide an evaluation of the effect of these changes.

The modifications to the Eta Model in January 1996 included corrections for errors in the computer code used to diagnose near-surface variables from those predicted at the lowest model level. This was not an error in the Eta forecast model equations and did not affect operational predictions. However, the error is now known to have contaminated some of the surface variables released in GCIP's GIST and ESOP-95 datasets. Therefore, it was necessary to create a procedure to recalculate these variables correctly from the available data in order to make a worthwhile comparison between the model-calculated near-surface data and field observations prior to 1996 in this study. A procedure was devised that, as far as possible, mimicked the extrapolation calculation currently used in the Eta Model (see section 2 and the appendix). The recalculated fields it provided for 1994 and 1995, together with the (already correctly extrapolated) near-surface fields for 1996, are those for which evaluation is made against observational data.

2. Data sources

a. Retrospective surface extrapolation of Eta Model fields

The procedure used to recalculate the near-surface fields of temperature, humidity, and wind speed is described in the appendix. In overview, it seeks to simulate the interpolation procedure used in the Eta Model since January 1996 using the data available in the GIST and ESOP-95 datasets. By applying an iterative technique, values of surface-layer fluxes, stability factors, and exchange coefficients are calculated that are appropriate to the surface-layer scheme currently used in the Eta Model, but which are also consistent with the values of temperature, humidity, and wind speed calculated for the lowest model level and surface in the two datasets. Most of the required variables are either directly available in these datasets or can be reliably calculated from the data that are available (see the appendix). However, the value of aerodynamic roughness length z_0 is not available; therefore, it was necessary to assume a fixed, universal value of 0.125 m for this parameter.

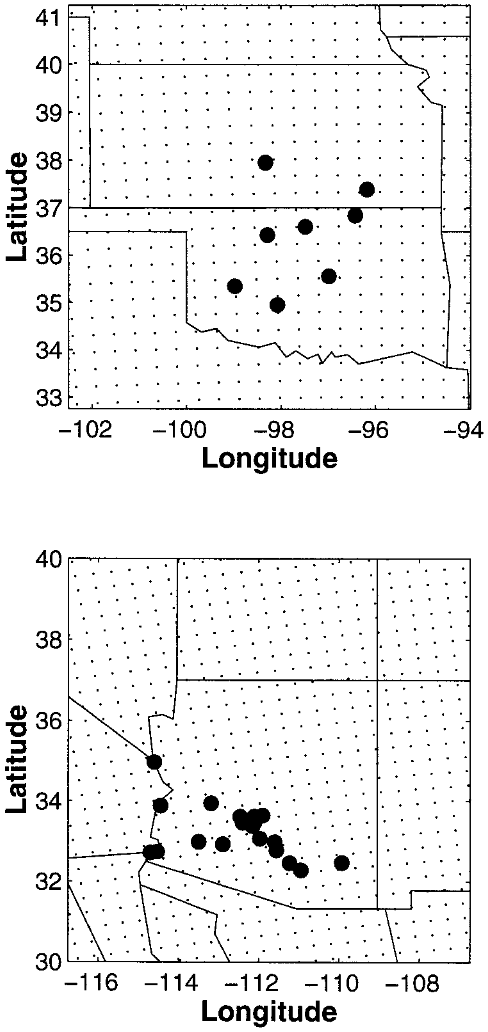

FIG. 1. The locations for which comparisons between Eta Model–derived data and observations were made in this study (a) in Oklahoma and Kansas and (b) in southern Arizona. In each case, the locations of the center of the grid boxes used in the Eta Model are shown as dots, while the location of the sites at which observations were made are shown as large, filled circles.

b. Observational arrays

Two contrasting study areas were selected for the purposes of comparison with Eta Model data. Figure 1 shows the location of these two study areas, which are (a) in Oklahoma and Kansas and (b) in southern Arizona. In these figures, the locations of the center of the grid squares used in the Eta Model are superimposed as dots, while the locations of the individual measurement sites used in this study are indicated by the large,

TABLE 1. Location and elevation of the observation sites in the southern Great Plains (CART) area used in this study.

Site identity	Location	Elevation (m)
E4	37.953°N, 98.329°W	513
E7	37.383°N, 96.180°W	283
E12	36.841°N, 96.427°W	331
E13	36.605°N, 97.485°W	318
E15	36.431°N, 98.284°W	418
E20	35.564°N, 96.988°W	309
E22	35.354°N, 98.977°W	465
E26	34.957°N, 98.076°W	400

filled circles. Site-average values of variables were used in this analysis to minimize the effect on the comparison of local, site-specific influences in the observational data. Linear average values of the observations were compared with linear average values of the model-calculated data for the grid point closest to each measurement site.

1) OKLAHOMA/KANSAS

The study site in Oklahoma and Kansas is a relatively humid, continental site with large seasonal variations in temperature and specific humidity, often with widespread and variable cloud cover and with substantial convective rainfall in summer, when it gives rise to spatial variability in the surface soil moisture and surface flux exchanges. Measurements are taken from the Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) observational network, which was established by the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement (ARM) program. The network consists of clusters of in situ and remote-sensing instruments in an array that spreads across a relatively homogeneous region covered in grassland, cropped areas and some wooded regions between 33° and 38.5°N and 95.5° and 99.5°W (U.S. Department of Energy 1990).

The data used in this study were measured using an energy balance–Bowen ratio (EBBR) system. This is a ground-based system that uses in situ sensors to estimate the vertical fluxes of sensible and latent heat. The observed variables are 30-min averages of the energy fluxes of sensible and latent heat, air temperature, relative humidity, net radiation, near-surface soil moisture, near-surface soil heat flux, near-surface soil temperature, barometric pressure, and wind speed, all measured using proprietary sensors. The EBBR system uses a unique automatic exchange mechanism that helps to reduce errors from instrument offset by exchanging pairs of temperature and humidity sensors. The present analysis uses data from eight individual locations in north-central Oklahoma, the coordinates and elevation of which are given in Table 1. The reader is referred to Peppler et al. (1996) for a recent review of the range and status of observations at the CART site.

TABLE 2. Location and elevation of the observation sites in the southern Arizona (AZMET) area used in this study.

Station name	Location	Elevation (m)
Tucson	32.280°N, 110.946°W	713
Yuma Valley	42.782°N, 142.300°W	32
Coolidge	32.980°N, 111.605°W	422
Maricopa	33.069°N, 111.972°W	361
Aguila	33.947°N, 113.189°W	655
Parker	33.883°N, 114.448°W	94
Bonita	32.464°N, 109.929°W	1346
Waddell	33.618°N, 112.460°W	407
Litchfield	33.467°N, 112.398°W	309
P. Greenway	33.621°N, 112.108°W	401
Marana	33.461°N, 111.233°W	601
Yuma N. Gila	32.552°N, 114.529°W	44
P. Encanto	33.479°N, 112.096°W	375
Eloy	32.774°N, 111.557°W	461
Dateland	32.986°N, 113.497°W	163
Scottsdale	33.643°N, 111.900°W	469
Paloma	32.927°N, 112.896°W	219
Mohave	34.967°N, 114.606°W	146
Laveen	33.376°N, 112.150°W	315

2) SOUTHERN ARIZONA

The study site in southern Arizona comprises the region between 31.5° and 36°N and 108° and 115°W. The semiarid environment that typifies this southern Arizona site is due both to its location relative to the equator and the orographic drying effect of mountain ranges in the western United States. The region is characterized by rugged mountain ranges separated by flat valley floors. The limited annual rainfall of less than 400 mm occurs mainly as convective thunderstorms in a summer monsoon season and as frontal storms during the winter. Daily temperature changes can be high (about 20°C).

Observations are taken from the Arizona Meteorological Network (AZMET) system, a network of automatic stations installed in 1986 for agricultural and horticultural purposes. As a result, the measurement stations are often installed adjacent to regions of irrigated agriculture, and the data may in part be influenced by this fact. This study focused on 19 individual stations that are concentrated near the center of the southern Arizona study area. Information on the location and elevation of these sites is provided in Table 2. The available basic data fields used in this study are air temperature and relative humidity, solar radiation, wind speed, precipitation, and soil temperatures at 5 cm and at 10 cm, all measured using commercial sensors. AZMET stations do not measure the Bowen ratio. More detailed information on the AZMET observational network is available on the World Wide Web at http://ag.arizona.edu/azmet/.

3. Results

a. *Comparison of uncorrected and corrected surface extrapolation*

The contamination of the surface fields provided in the GIST and ESOP-95 data sites is illustrated in Fig.

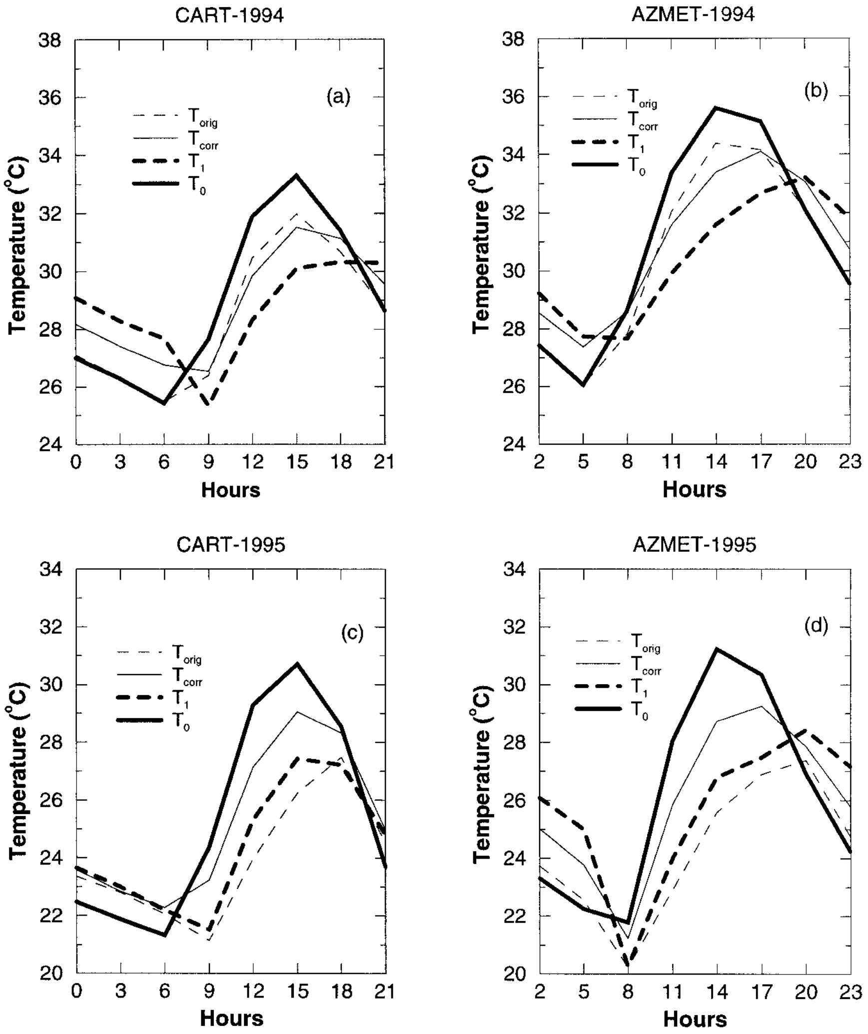

FIG. 2. The mean daily cycle of modeled surface temperature T_0 and air temperature at the lowest model level T_1, together with the near-surface air temperature calculated using the original, faulty interpolation code used in the Eta Model prior to January 1996, T_{orig}, and the correction code described in the appendix, T_{corr}; (a) and (b) are averages over the GIST period in 1994, and (c) and (d) are averages over the ESOP-95 periods in each case for the CART and AZMET sites, respectively.

2 for the case of near-surface atmospheric temperature. This figure shows the diurnal pattern of modeled surface temperature and air temperature at the lowest model level, together with the estimated near-surface air temperature given by the original (faulty) interpolation procedure and the temperature given by the retrospective correction procedure described in the appendix. Figures 2a,b show the average daily temperature cycles for the entire GIST periods at the CART and AZMET sites, respectively, while Figs. 2c,d give the average equivalent daily cycles for the entire ESOP-95 period.

The effect of the coding errors in the original interpolation procedure on the calculated near-surface air temperature is different between 1994 and 1995 but is consistent between sites in each year. The air temperature at the lowest model level is expected to be higher than the surface temperature at night, when there is radiative cooling of the ground, and lower than surface temperature during the day, when there is normally surface heating. On the average, the near-surface air temperature should be intermediate to these two temperatures. However, at both the CART and AZMET sites, the near-surface air temperature originally provided by the Eta Model only satisfies this last condition during the day for the GIST period (Figs. 2a,b). At night during this period, the original near-surface air temperature is unrealistically close to surface temperature. The behavior is even more dubious during ESOP-95 (Figs. 2c,d). The near-surface air temperature in the ESOP-95 data is then often outside realistic bounds and is clearly erroneous (and low) throughout the day at both sites. On the other hand, the behavior of the near-surface air temperature given by applying the correction procedure described in the appendix is shown in these diagrams to be plausible at all times of day, at both sites and for both the GIST and the ESOP-95 periods. As should be expected, the correction procedure applied to the 1996 data reproduces the (by then correctly interpolated) values given by the Eta Model to within numeric roundoff (not shown).

b. *Evaluation of model-derived data relative to observations*

The model-derived data recalculated using the correction procedure were compared with observed data from the CART and AZMET sites in the GIST and ESOP-95 periods. Exploratory comparisons were also made with observations for March and May 1996 in order to test the effect of the revisions to the model code made in January 1996. At the CART site, the available observations included net radiation and latent and sensible heat flux, but at the AZMET site the only directly observed energy flux is incoming solar radiation. It was considered preferable to make a comparison between measured and modeled specific humidity rather than relative humidity at both sites and it was therefore necessary to calculate the specific humidity from the available measurements of air temperature and relative humidity.

1) SITE ELEVATION AND SURFACE PRESSURE

There are differences between the actual elevation at which the observations used in this study are made and those assumed in the Eta Model. On the average, the Eta Model grid is 310.6 m higher than observations in the case of the AZMET site and 45.8 m higher than observations in the case of the CART site. It is possible that this difference reflects a more general phenomenon. The surface elevation used in the Eta Model might well tend to be higher than the true surface elevation because the procedure used to define the surface in the ‘‘step mountain’’ topography used in the model (Mesinger 1996) is deliberately biased toward selecting higher elevations within each grid square. This bias is likely to be greater for areas with significant subgrid orography (i.e., greater in Arizona than in Oklahoma and Kansas). On the other hand, in the case of the AZMET sites, the fact that these are lowland agricultural sites may in part contribute to this difference. This elevation difference might contribute to bias between modeled-derived data and observational data, especially in the case of air temperature and especially (in this study) in southern Arizona. However, in regions where surface observations are plentiful, the assimilation of temperature data via EDAS will likely tend to moderate such bias.

A comparison between observed and modeled surface pressure at the CART site for the GIST and ESOP-95 periods and March–May 1996 is illustrated in Fig. 3. Although the model grid is (45.8 m) higher than observation sites in this study area, the modeled surface pressure is about 0.2 kPa higher than observed values (rather than lower). There may also be a phase lead in the mean diurnal cycle of modeled surface pressure that is superimposed on the average offset. At this writing, the origin of these discrepancies remains uncertain.

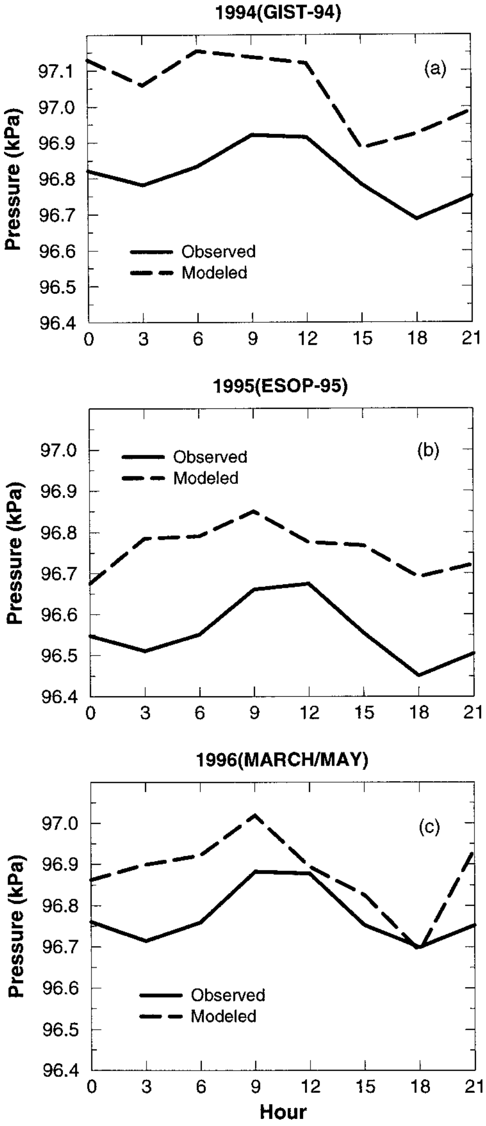

FIG. 3. The mean daily cycle of modeled and observed surface pressure for the CART site averaged over (a) the GIST period in 1994, (b) the ESOP-95 period in 1996, and (c) the months of March and May in 1996.

2) SURFACE ENERGY FLUXES

Figure 4 shows a comparison between the model-derived and observed daily average cycle of net radiation for the CART site (Figs. 4a,c,e) and between the

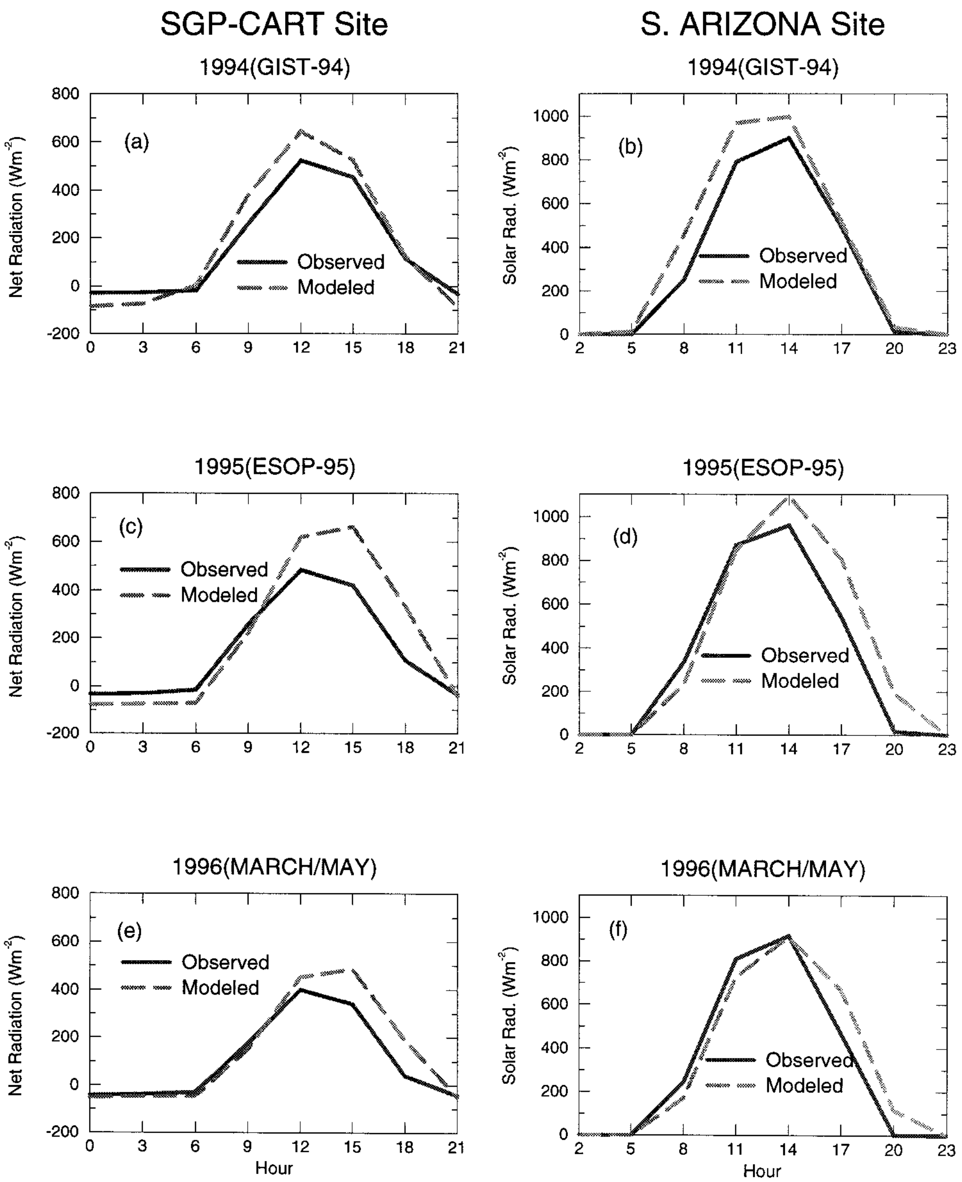

FIG. 4. The mean daily cycle of modeled and observed surface net radiation for the CART site [(a), (c), and (e)], and the mean daily cycle of modeled and observed incoming surface solar radiation for the AZMET site [(b), (d), and (f)]. The data in (a) and (b) were averaged over the GIST period in 1994, those in (c) and (d) over the ESOP-95 period in 1996, and those in (e) and (f) over the months of March and May in 1996.

model-derived and observed mean diurnal cycle of incoming solar radiation for the AZMET site (Figs. 4b,d,f). Figures 4a,b show averages for the GIST period; Figs. 4c,d give averages for the ESOP-95 period; and Figs. 4e,f show averages for the months of March and May in 1996.

Certain features are very clear and consistent in these figures. It is apparent that the radiation physics used in the Eta Model consistently give rise to substantial (10%–15%) overestimates of surface solar radiation at both study sites. This feature was altered little by the model revision in January 1996 at the CART site. There may be some improvement in 1996 in the case of the AZMET site, but in practice the results shown in Fig. 4f might well be deceptive because in this case, the comparison is made at a time of year when cloud cover is very low at the AZMET site, and this could account for any improvement. In the case of the CART site, the outward nighttime net radiation was also substantially overestimated prior to the 1996 model revisions, but this model weakness was greatly aided by those revisions. It is likely that the improvement between the modeled and measured net radiation (in effect, longwave radiation) at night is the result of changing from a slab

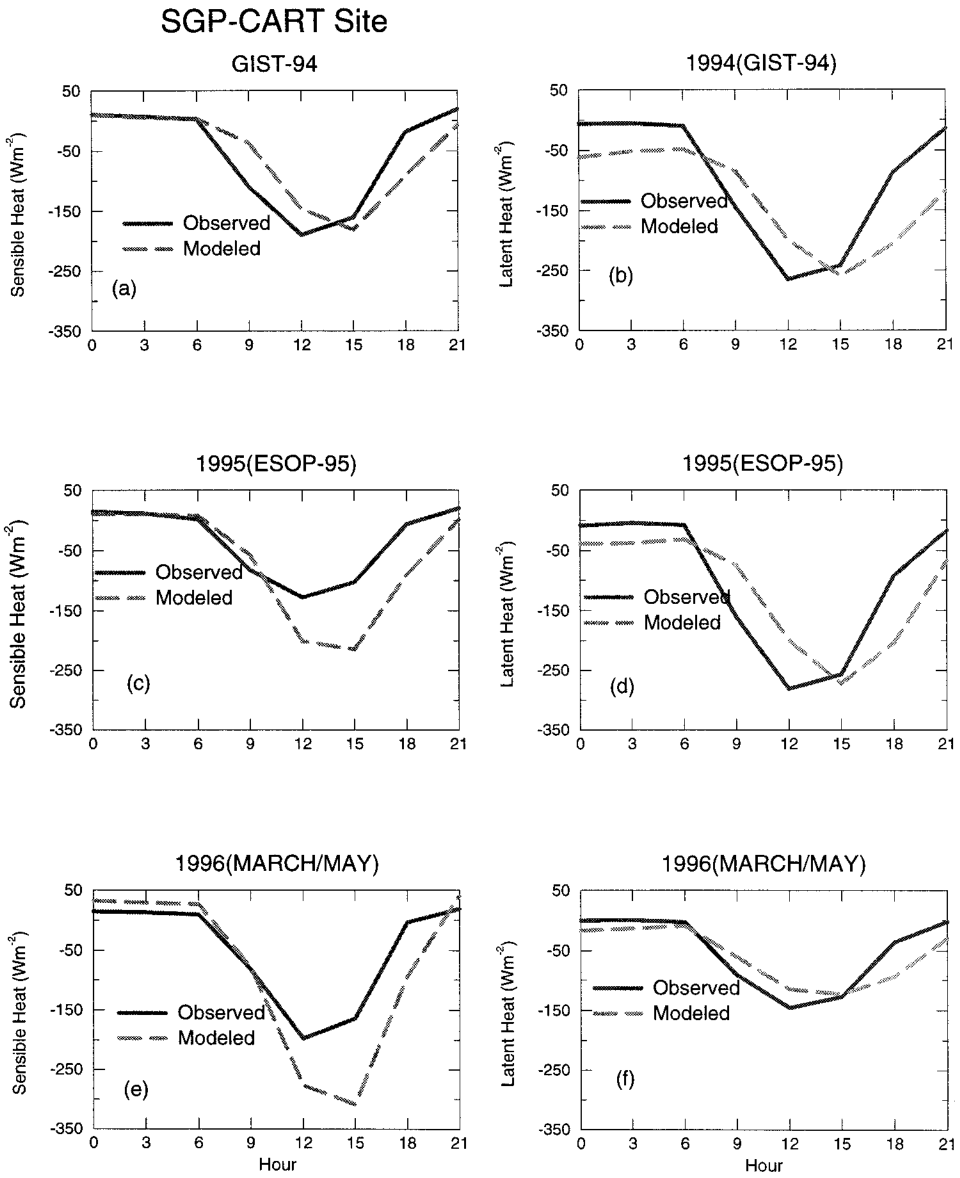

FIG. 5. The mean daily cycle of modeled and observed surface sensible heat flux for the CART site [(a), (c), and (e)], and the mean daily cycle of modeled and observed surface latent heat flux for the CART site [(b), (d), and (f)]. The data in (a) and (b) were averaged over the GIST period in 1994, those in (c) and (d) over the ESOP-95 period in 1996, and those in (e) and (f) over the months of March and May in 1996.

model (with excessive thermal inertia) to a two-layer soil model in 1996.

As pointed out by Betts et al. (1997), other numerical weather prediction models also appear to have a bias toward high incoming solar radiation, presumably because the model atmosphere is too transparent, lacking representation of aerosols and haze. The Eta Model shortwave radiation code was reexamined in light of its comparison with data, and two errors were found. First, the model was not representing the significant absorption of shortwave radiation in the atmosphere; second, the earth's orbit was being treated as circular rather than elliptical. These weaknesses account for about half of the high bias, and they were corrected in the operational Eta Model in February 1997. In addition, aerosols also significantly absorb and scatter the shortwave radiation and, as an interim measure, the total energy entering the atmosphere was reduced by 3% to simulate the effect of aerosols. Aerosols will be accounted for explicitly in the next update of the Eta Model's radiation scheme.

The above-described errors in modeled radiant energy exchange complicate interpretation of observed differences between modeled and observed latent and sensible heat fluxes. Measurements of these fluxes were available for the CART site, and a comparison is made for the mean diurnal cycle of sensible heat flux in Figs. 5a,c,e

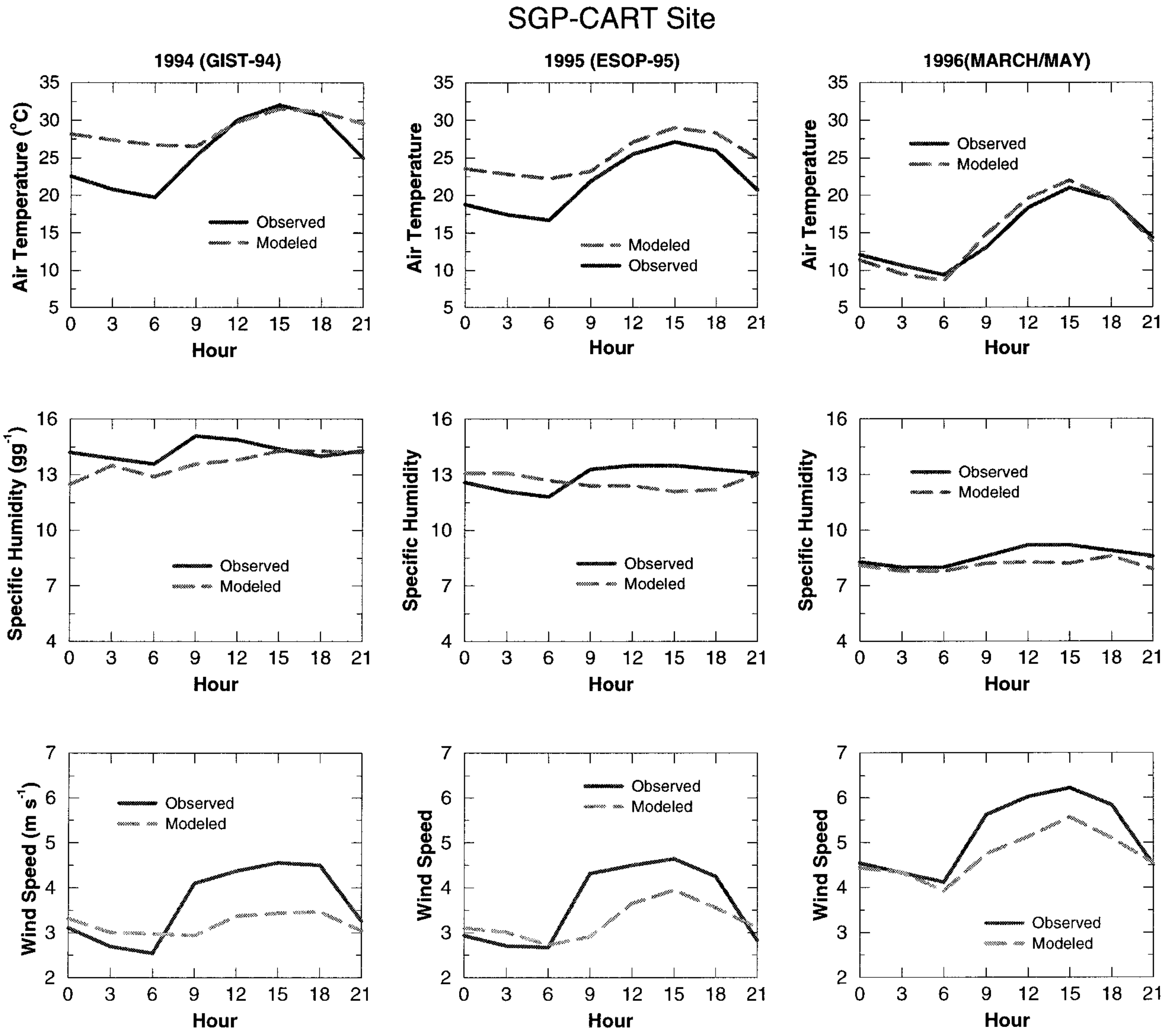

FIG. 6. The mean daily cycle of modeled and observed air temperature (upper row of diagrams), specific humidity (middle row of diagrams), and wind speed (lower row of diagrams) for the CART site. The left-hand column of diagrams was averaged over the GIST period in 1994, the center column over the ESOP-95 period in 1995, and the column on the right over the months of March and May in 1996.

and for the mean diurnal cycle of latent heat flux in Figs. 5b,d,f. In each case, these comparisons are for the GIST and ESOP-95 periods and for March–May 1996, respectively.

Figure 5 clearly shows that the recently reported (Chen et al. 1997) phase lag of about 2 h in the diurnal cycle of both the latent heat and sensible heat fluxes is present during the GIST and ESOP-95 periods, but that this was largely removed by the January 1996 model improvements. The previously poor simulation of nighttime latent heat flux also was somewhat improved by these model revisions, presumably due to the improved simulation of nighttime net radiation already demonstrated in Fig. 4f. The overall magnitude of the daytime latent heat fluxes is broadly correct in all three years, but there is a significant (~50 W m^{-2}) outward modeled latent heat at night prior to 1996, which is unrealistic. The excess modeled surface net radiation during the day is seen largely to be used by the Eta Model to overestimate the daytime sensible heat flux.

3) NEAR-SURFACE WEATHER VARIABLES

Figures 6 and 7 show comparisons of modeled and observed air temperature, specific humidity, and wind speed for the CART site and the AZMET sites, respectively. In each case, comparison is made for the GIST period, the ESOP-95 period, and for March–May 1996.

The most striking feature in these figures is the improvement in the Eta Model's ability to capture the mag-

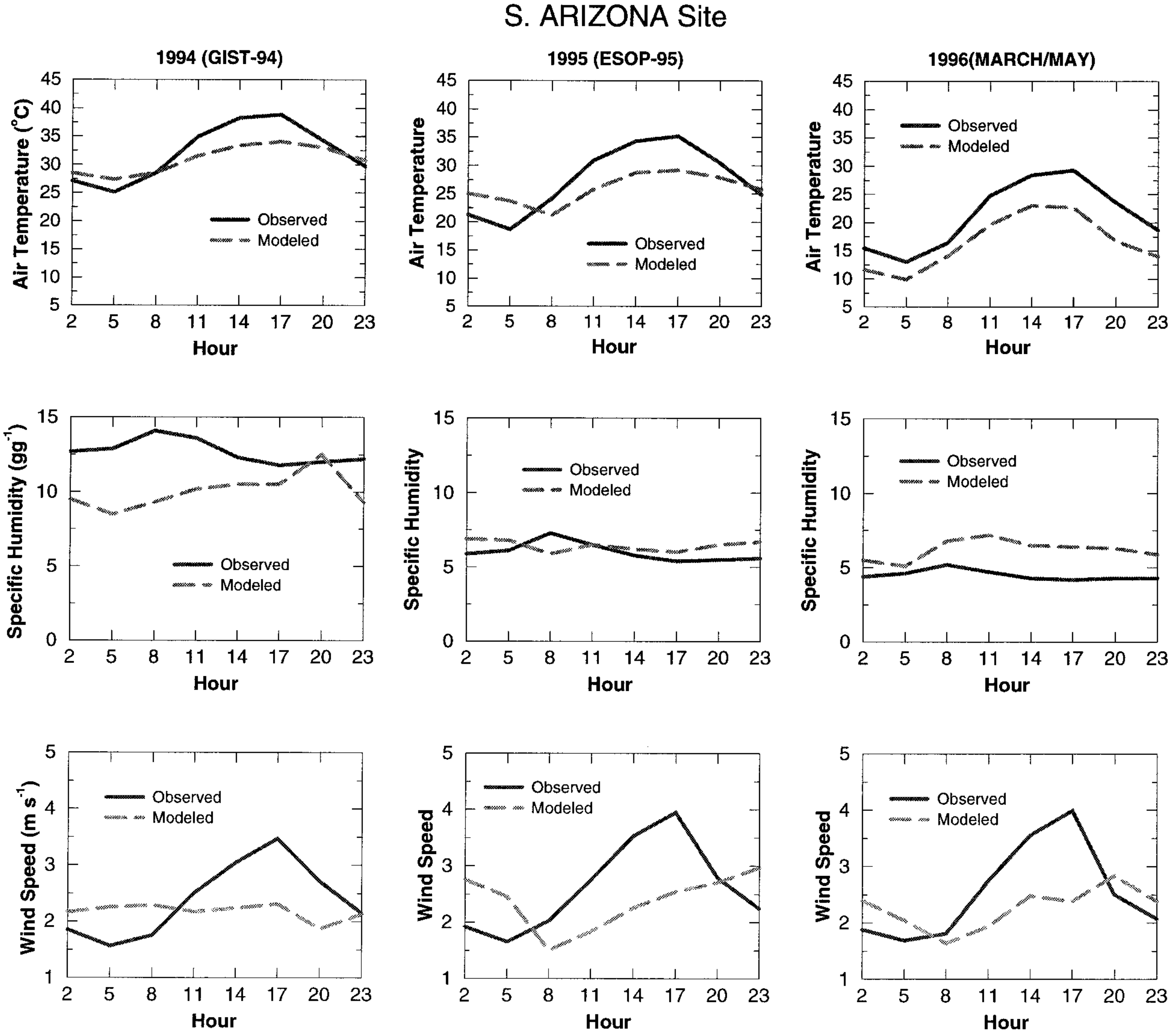

FIG. 7. The mean daily cycle of modeled and observed air temperature (upper row of diagrams), specific humidity (middle row of diagrams), and wind speed (lower row of diagrams) for the AZMET site. The left-hand column of diagrams was averaged over the GIST period in 1994, the center column over the ESOP-95 period in 1995, and the column on the right over the months of March and May in 1996.

nitude of the diurnal cycle in near-surface air temperature at both study sites after the January 1996 model revisions—although there is clear evidence of a systematic negative bias in the mean value (of around 5°C) in the case of the AZMET site in the 1996 data. This bias may in part be related to the discrepancy between the elevation assumed in the model and the actual elevation at which observations are made. Wind speed is poorly captured by the Eta Model, and there is little evidence of improvement following the January 1996 revisions. The observed diurnal cycle in specific humidity and that given by the model are small at both the CART and AZMET sites. However, in the case of the AZMET site, there is a systematic difference between the observed and modeled specific humidity, with the modeled values lower in 1994 but higher in 1996. This change may well be related to the change in the surface models over this period. However, it is important to remember that the AZMET measurements of near-surface humidity may themselves be biased by the fact that the observational sites tend to be located close to regions of irrigated agriculture. Consequently, the difference between observations and the model could be influenced by the timing of periods of irrigation relative to the times used for this comparison.

An intercomparison between individual 3-h near-surface weather variables over the entire averaging period in each year is shown in Figs. 8 and 9. These two diagrams include not only the scatter associated with daily variations but also the greater scatter associated with

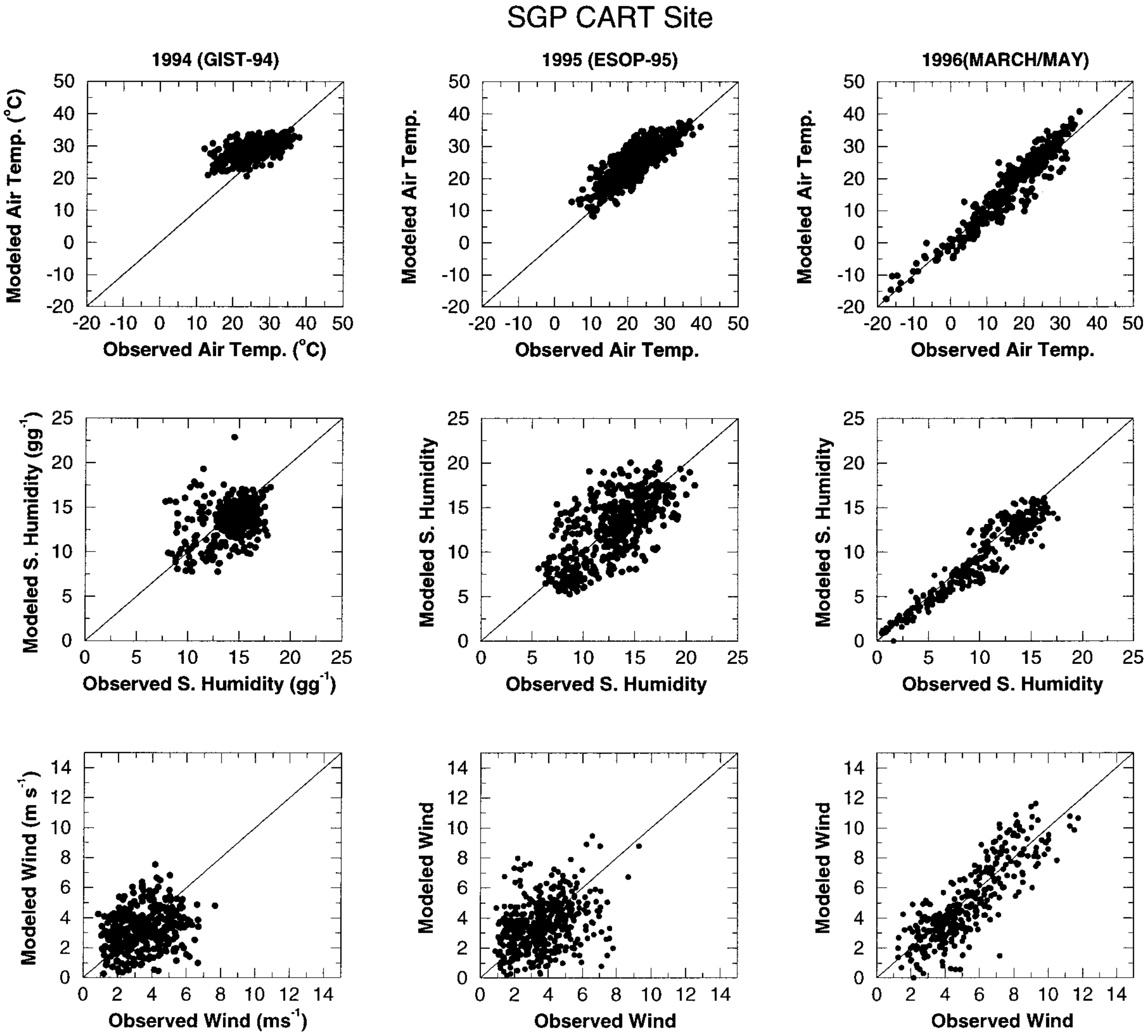

FIG. 8. Intercomparison between 3-h values of modeled and observed air temperature (upper row of diagrams), specific humidity (middle row of diagrams), and wind speed (lower row of diagrams) for the CART site. The left-hand column of diagrams is data for the GIST period in 1994, the center column for ESOP-95 period in 1995, and the column on the right for the months of March and May in 1996.

day-to-day variations and gradual trends throughout the period for which comparison is made. There is strong evidence in these figures that the January 1996 Eta Model revisions gave a worthwhile improvement in the model's ability to capture these longer-term variations in near-surface weather variables. However, this benefit is less apparent at the AZMET site because of the small range of specific humidity and wind speed sampled in that 1996 data. The bias in the mean temperature at the AZMET site is again revealed in Fig. 9.

4. Summary, conclusions, and recommendations

In the course of making the changes to the Eta Model in January 1996, coding errors that had previously been in that portion of the model used to interpolate meteorological variables between the lowest model level and the surface were corrected. As part of this study, a correction procedure was devised that could be applied retrospectively to the GIST and ESOP-95 datasets to recalculate estimates of near-surface weather variables from reliable observations within those datasets. For consistency, the correction procedure closely followed the revised interpolation procedure now used in the Eta Model. Applying this correction procedure greatly improved the plausibility of the interpolated values (see section 3). Recognizing that this correction procedure may well have value to other researchers, we have included a detailed description of it as an appendix to this paper. Evaluation of model-calculated near-surface air temperature, humidity, and wind speed against observations in 1994 and 1995 was made using the inter-

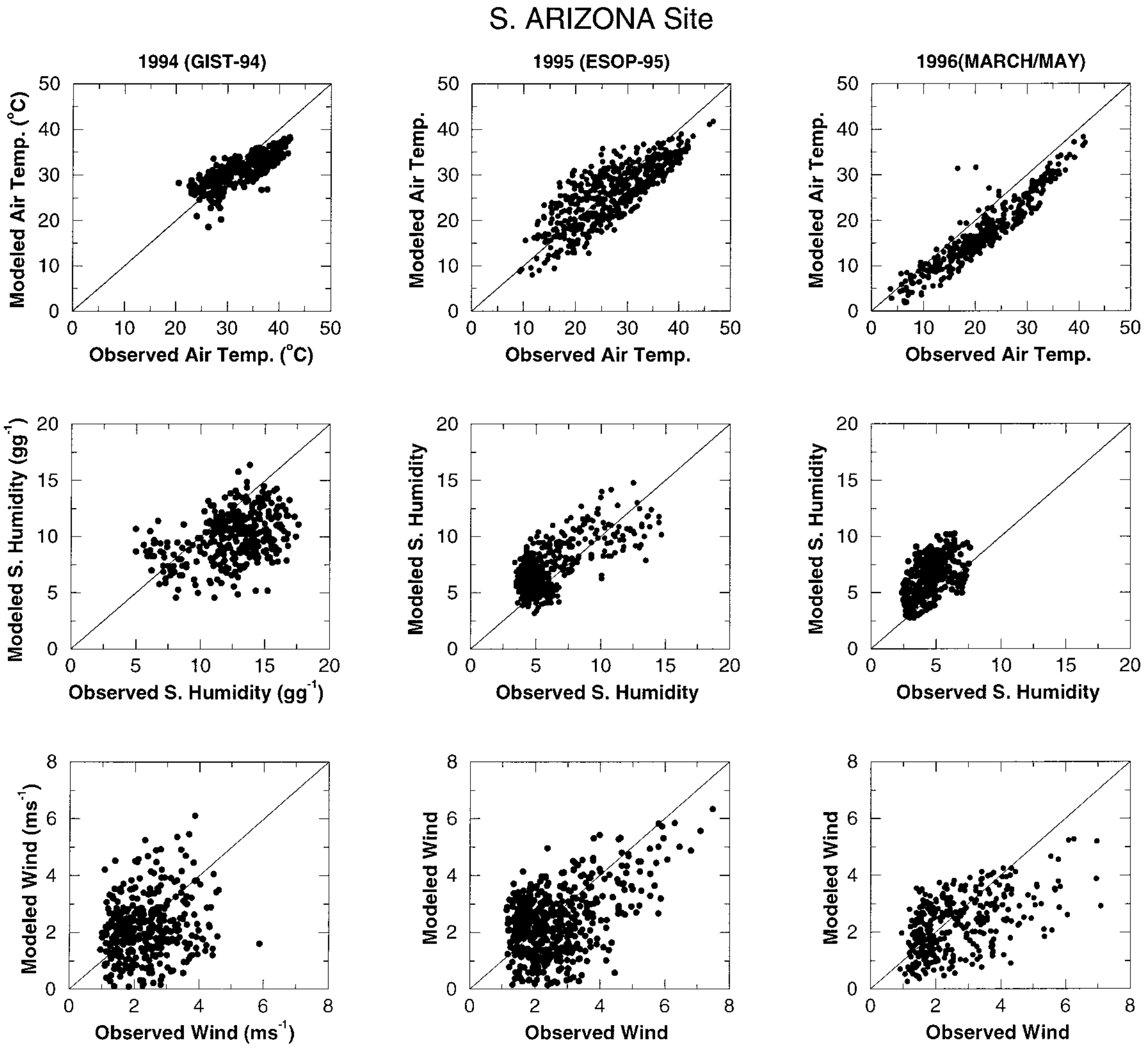

FIG. 9. Intercomparison between 3-h values of modeled and observed air temperature (upper row of diagrams), specific humidity (middle row of diagrams), and wind speed (lower row of diagrams) for the AZMET site. The left-hand column of diagrams is data for the GIST period in 1994, the center column for ESOP-95 period in 1995, and the column on the right for the months of March and May in 1996.

polated values derived using this new correction code, rather than original faulty values in the GIST and ESOP-95 datasets.

The most important discrepancy between Eta Model–derived surface fields and observations is in surface radiation, especially solar radiation. The results of this study provide clear evidence that the Eta Model gives estimates of solar radiation at the ground which are significantly greater than measured values, especially in cloudy midday and afternoon conditions. These discrepancies were not removed by changes in the Eta Model made in January 1996, and they are large, being typically 10%–15%. The January 1996 model upgrade did, however, remove a 2-h phase slip in the modeled sensible and latent heat fluxes. The overall magnitude of the modeled daytime latent heat fluxes seems to be correct but, because the modeled net radiation is incorrect, this in fact implies that the modeled Bowen ratio is biased high.

There is evidence that the near-surface air temperature given by the 1994 and 1995 versions of the Eta Model (with corrected interpolation) is greater than nighttime observations by about 3°–5°C at both comparison sites. This difference is presumably the result of the overestimation of the nighttime longwave radiation loss, itself due to the large thermal inertia of the original ''slab'' model (Betts et al. 1997). The Eta Model also underestimated the magnitude of the diurnal cycle in air temperature relative to observations in 1995 and 1996, albeit by differing amounts at the two study sites. This particular weakness was much improved by the January 1996 model revisions, but a significant negative bias of about 5°C in the mean value of air temperature remained at the AZMET site. This may in part be related to the fact that the model assumes a ground-level elevation that is high relative to observations by more than 300 m in this study area.

The realistic representation of surface evaporation is a key issue in comparisons between modeled and observed near-surface variables. The latent heat flux has, of course, a direct influence on the Bowen ratio, and it also indirectly affects near-surface weather variables, but it is itself affected by many factors other than precipitation and surface radiation fluxes. Betts et al. (1997) showed that the partition of total evaporation between bare-soil evaporation and canopy evapotranspiration is very sensitive to the green vegetation fraction (which has a specified seasonal cycle at each grid point in the Eta Model). They demonstrated that replacing the 1° × 1° green vegetation fraction from the ISLSCP 1987 dataset by the (roughly 10% higher and arguably more realistic) 0.15° × 0.15° 5-yr average green vegetation fraction data from Gutman and Ignatov (1997) significantly increased calculated evaporation and moderated the day-to-day changes, because canopy evapotranspiration becomes relatively more important. Betts et al. (1997) also found that using a simple linear method (Mahfouf and Noilhan 1991) to describe direct evaporation from bare-soil rather than the so-called threshold method (Pan and Mahrt 1987) gave a more moderate and realistic relationship between soil evaporation and surface soil moisture. These two model revisions were incorporated into the operational Eta Model in February 1997, and the modification to bare-soil evaporation is certain to have an effect on surface evaporation in arid and semiarid areas such as in Arizona, where the green vegetation fraction is small.

Soil moisture initialization is also an issue when assessing Eta Model performance in predicting surface heat fluxes and near-surface weather variables. This problem has not yet been fully resolved at any global forecast center. In the 1994–95 version of the Eta Model (Janjic 1990, 1994), soil moisture in the simple bucket model was initialized to the climatological annual mean. However, the 1996 Eta Model with the improved soil–vegetation–hydrology land surface scheme (Chen et al. 1991) was initialized to the soil moisture given by the NCEP Global Data Analysis System (GDAS) (Kanamitsu et al. 1991). Although the GDAS uses a similar soil–vegetation–hydrology scheme, there are differences in the physical parameterizations used in the Eta Model and the NCEP global forecast model. In addition, there are differences in topography and model resolution between the Eta Model and GDAS, and the latter has a known soil moisture bias due to biases in forecast precipitation and solar radiation. (It has been noticed that the GDAS soil moisture field has a substantial positive bias in the southeastern United States during the warm season, for instance, and currently high values of soil moisture given by GDAS soil moisture are arbitrarily reduced during the Eta Model initiation.) Some of the above-reported biases in Eta Model surface energy partition and near-surface weather variables may well be directly related to poor soil moisture initiation and, as a short-term improvement, a fully continuous data assimilation for North America is being developed (Rogers et al. 1995). This will use the Eta Model and so remove the current differences in physical parameterizations. The longer-term plan is to develop the Land Data Assimilation System (LDAS) (Mitchell 1994) in which the Eta's soil–vegetation–hydrology model will be driven in an offline, one-dimensional mode by observed hourly precipitation (Baldwin and Mitchell 1996) and hourly satellite-derived net radiation. It is anticipated that the use of observed surface forcing in LDAS will significantly improve the long-term evolution of calculated soil moisture and improve initiation for the Eta Model.

In general, the diurnal variation in near-surface air pressure and wind speed is poorly captured by the Eta Model–derived data, and there is little evidence of a significant improvement in this respect following the January 1996 model revisions. On the other hand, there is strong evidence that longer-term variations in air temperature, specific humidity, and wind speed were substantially improved by these same model revisions.

The results of this study demonstrated a need to investigate and improve the Eta Model's description of solar radiation transfer through the atmosphere with the aim of reducing the calculated surface values in cloudy conditions and to investigate the extent to which the ground-level elevation assumed in the model can bias the comparison with actual near-surface observations. At this writing, some of the reported discrepancies are currently being explored, but some, such as the high bias in solar incoming radiation, the representation of clouds, and the formulation of evaporation, have in fact already been reexamined and improved in a new version of the operational Eta Model, which was implemented in February 1997. In a recent long-term test (to be described elsewhere), the Eta Model predictions were verified against the observed 2-m temperature and specific humidity over the entire United States. They were found to greatly reduce the high bias in temperature and low bias in humidity throughout a 48-h forecast period by reducing the solar radiation and the increasing evaporation.

While the above comparisons suggest that the GCIP Eta Model data products may well be useful and that they are progressively acquiring greater reliability, some caution is required in advocating their use as a substitute for local observations. As shown in this study, possible discrepancies between the elevation used in the model and that of a local site (on average 310.6 m in the case of the AZMET site) may seriously compromise the credibility of model-generated data. Subgrid variations in topography, soil moisture (e.g., by irrigation), and local cloud cover (and hence surface radiation) within an individual 40 km × 40 km model grid further complicate the relationship between modeled and local values, especially at short timescales. (Note: for the purpose of comparisons, this paper uses area-average and time-average data to diminish the influence of subgrid-scale variability.) Most important, the Eta Model only predicts values at the lowest level modeled in the atmosphere, with near-surface weather variables and surface heat fluxes then diagnosed from these predicted variables. In this way, their value is dependent on the method used to make diagnoses.

An important general recommendation from this research therefore relates to GEWEX's philosophy of distributing model-generated data fields and to the growing belief that such fields can satisfy some of the data needs that will not otherwise be fulfilled by the Earth Observing System. On the basis of this study, it is apparent that model-derived, near-surface data fields are very sensitive to model errors, not just possible errors from computer coding faults but, more fundamentally, errors associated with poorly represented processes such as radiation and surface exchanges. Providing continuity in such model-derived surface fields other than by successive reanalyses is therefore problematic. Given this fact, it is important that model-calculated fields include all the data and metadata required to calculate the near-surface fields and not just the surface fields themselves. This would provide the opportunity for potential users to provide their own surface interpolation using improved radiation estimates (perhaps from satellites) and improved representation of surface exchanges and in this way minimize the model dependence of the data.

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APPENDIX

Corrections to Surface Layer Extrapolation

a. Eta Model surface-layer exchange scheme

In the Eta Model, the flow of humidity and sensible heat between the lowest model layer and the surface are described by bulk exchange equations with the exchange coefficient for the two fluxes, $C_{H,E}$, assumed the same for the two fluxes. Hence, the (kinematic) fluxes of humidity E_k $(=E/\rho)$ and sensible heat H_k $(=H/\rho c_p)$ are described by the equations

$$H_k = C_{H,E}(\theta_s - \theta_1) \tag{A1}$$

$$E_k = C_{H,E}(q_s - q_1), \tag{A2}$$

where q_1 and θ_1 are the humidity and potential temperature at the lowest model level, respectively; q_s and θ_s are the humidity and potential temperature at the surface, respectively. The exchange coefficients $C_{H,E}$ and that for the momentum flux C_M are given by (Brutsaert 1982; Garratt 1992)

$$C_{H,E} = \frac{ku_*}{F_{H,E}} \tag{A3}$$

$$C_M = \frac{ku_*}{F_M}, \tag{A4}$$

with

$$F_{H,E} = \left[\ln\left(\frac{z_1 - z_0}{z_{ot}}\right) - \Psi_h\left(\frac{z_1}{L}\right) + \Psi_h\left(\frac{z_{ot}}{L}\right)\right] \tag{A5}$$

$$F_M = \left[\ln\left(\frac{z_1 - z_0}{z_{om}}\right) - \Psi_m\left(\frac{z_1}{L}\right) + \Psi_m\left(\frac{z_{om}}{L}\right)\right], \tag{A6}$$

where z_{om} and z_{ot} are the roughness lengths for momentum and heat, respectively; z_1 is the height of the first model layer; Ψ_m and Ψ_h are stability functions for momentum and sensible heat, respectively; k $(=0.4)$ is the von Kármán constant; and u_* is the friction velocity. In these expressions, z_{om} is equal to z_o, where z_o is the aerodynamic roughness length of the underlying surface, while z_{ot} is found from z_o by applying the "Zilitinkevich fix," that is,

$$z_{ot} = z_0 \exp[-C_Z(u_* z_0)^{1/2}], \tag{A7}$$

where C_Z $(=0.1)$ is an empirical constant, the value of which was estimated by Chen et al. (1996b) from field data. The friction velocity is derived assuming Beljaars' (1995) correction from

$$u_* = \{C_M[(U_1)^2 + W_*^2]^{1/2}\}^{1/2}, \tag{A8}$$

with

$$W_*^2 = 1.44\left[\left(\frac{g}{270}\right) Z_{pl} C_{H,E}(\theta_1 - \theta_s)\right]^{2/3}, \tag{A9}$$

where Z_{pl} is the thickness of the planetary boundary layer, which is set equal to 1000 m.

Prior to January 1996, the stability functions for momentum and sensible heat used in the Eta Model, Ψ_m and Ψ_h, were calculated from $\zeta = z/L$, where L is the Monin–Obukov length, following the relationship derived by Lobocki (1993) for the Mellor–Yamada level 2 model, thus:

$$\Psi_m = \begin{cases} -0.96\ \ln(1 - 4.5\xi), & -5 < \xi < 0 \\ \left(\dfrac{\xi}{R_{FC}}\right) - 2.076\left(1 - \dfrac{1}{\xi + 1}\right), & 0 < \xi < 1 \end{cases}$$

$$\Psi_h = \begin{cases} -0.96\ \ln(1 - 4.5\xi), & -5 < \xi < 0 \\ \left(\dfrac{\xi R_{IC}}{R_{FC}^2 \Phi_T(0)}\right) - 2.076 & \\ \quad \times [1 - \exp(-1.2\xi)], & 0 < \xi < 1, \end{cases} \tag{A10}$$

where R_{IC} (=0.183) is a critical gradient Richardson number, R_{FC} (=0.191) is a critical flux Richardson number, and $\phi_T(0)$ (=0.8) is the dimensionless gradient for neutral values.

After January 1996, the Lobocki functions were replaced by the Paulson functions following Sun and Mahrt (1995), thus:

$$\Psi_m = \begin{cases} 2\ \ln\left(\dfrac{1 + x}{2}\right) + \ln\left(\dfrac{1 + x^2}{2}\right) & \\ \quad - 2\ \arctan(x) + \dfrac{\pi}{2}, & -5 < \xi < 0 \\ -5\xi, & 0 < \xi < 1 \end{cases}$$

$$\Psi_m = \begin{cases} 2\ \ln\left(\dfrac{1 + x^2}{2}\right), & -5 < \xi < 0 \\ -5\xi, & 0 < \xi < 1 \end{cases} \tag{A11}$$

with $x = (1 - 16\xi)^{0.25}$.

b. Retrospective correction procedure

The retrospective correction for the earlier faulty extrapolation code sets seeks to duplicate the computer code used in the Eta Model after January 1996. In particular, it included the ''Beljaars'' correction to friction velocity and the ''Zilitinkevich fix'' for roughness length (Zilitinkevich 1995), together with the Paulson (1970) version of the stability factors.

Much of the input data required (specifically the temperature, humidity, and pressure at the lowest model level and the surface temperature and pressure) are available in these datasets. However, some of the variables required to make the extrapolation are not directly available. Missing variables include the potential temperature at the surface and lowest model level, the wind speed at the lowest model level, and the atmospheric humidity immediately adjacent to the underlying surface, the friction velocity, and the Monin–Obukov length, together with certain key parameters such as the height of the lowest model level and the roughness length. When recalculating the extrapolation from the first model level to the surface, it was necessary to estimate these missing variables from those available in the datasets or, if this was not possible, to prescribe them.

Assuming the hydrostatic equation and a uniform lapse rate, the height of the lowest model level was estimated from the temperature and pressure at the surface (T_s and p_s) and those at the lowest model level (T_1 and p_1), which were available in the data using the equation

$$z_1 = \left[\frac{(T_s - T_1)\ \ln(p_1/p_s)}{(g/R_a)\ \ln(T_1/T_s)}\right], \tag{A12}$$

where R_a (=R_d + 0.608q_1) is the gas constant for moist air, with the gas constant for dry air R_d (=287.04 J K^{-1} kg^{-1}) and q_1 the humidity at the lowest model level.

The missing value of z_0 was (arbitrarily) set to 0.125 m, this being a plausible value for land surfaces, while U_1, the wind speed at the lowest model level, was calculated from

$$U_1 = (u_1^2 + v_1^2)^{1/2}, \tag{A13}$$

where u_1 and v_1 are the zonal and the meridional wind vectors, respectively, at the lowest model level, which are available in the data archive.

The potential temperatures at the surface and lowest model levels can be calculated from

$$\theta_1 = T_1\left(\frac{1000}{p_1}\right)^{R_d(1+0.608_{q_1})/c_p} \tag{A14}$$

$$\theta_s = T_s\left(\frac{1000}{p_s}\right)^{R_d(1+0.608_{q_s})/c_p}. \tag{A15}$$

However, because the potential temperature has some (albeit small) dependency on the missing value of surface humidity, Eq. (A15) had to be successively recalculated inside the iterative loop described below.

To make the retrospective interpolation of weather variables, it was necessary to compute a self-consistent set of exchange coefficients, Monin–Obukov length, stability corrections, friction velocity, and sensible heat flux using the equations used to describe exchanges between the surface and the lowest model level in the Eta Model since January 1996 [i.e., Eqs. (A1)–(A9) and Eq. (A11)]. To be useful for extrapolation, these values must also be consistent with the values of temperature, humidity, and wind speed at the lowest model level and the surface temperature, which are available in the GIST and ESOP-95 datasets.

Starting from the initial assumed values $C_{\mathrm{M}} = C_{H,E} = 0.01$ and an initial estimate of θ_s (calculated with q_s set to q_1), a consistent set of initial values of W_*, u_*, z_{0t} was calculated using Eqs. (A9), (A8), and (A7), respectively, together with an estimate of Monin–Obukov length using the value of H_k derived from Eq. (A1). The correction code then performed 10 iterations of a computational sequence that involved making successive recalculations of the stability-related functions (Ψ_m and Ψ_h and F_M and $F_{H,E}$), the momentum exchange factors (W_*, u_*, z_{0t}), the surface potential temperature and humidity (θ_s and q_s), the exchange coefficients (C_M, $C_{H,E}$), and Monin–Obukov length. ''Damping'' of the changes in the Monin–Obukov length was used between iterations to ensure an orderly progression toward the self-consistent, asymptotic set of preferred values for this set of variables.

The final step in the interpolation procedure was to calculate values of exchange coefficients relevant to the measurement heights for near-surface air temperature, humidity, and wind speed, respectively, using the postiteration values of u_* and the appropriate heights in Eq. (A3)–(A6), together with the value of the Monin–Obukov length calculated over the appropriate height range. The required values of near-surface air temperature, humidity, and wind speed were then calculated from these exchange coefficients and the postiteration values of sensible heat, humidity fluxes, and friction velocity. (Note: the values of latent heat, sensible heat, and friction velocity calculated during this correction procedure are not necessarily identical to those originally calculated in the GIST and ESOP-95 datasets because of the different stability factors used. However, in practice the differences were found to be small.)

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