Evaluation of Surface Fluxes from MM5 Using Observations

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ABSTRACT

Direct observations of surface fluxes of momentum, sensible, and latent heat from towers and aircraft are compared to output from the NCAR–Penn State Mesoscale Model MM5. The model flux parameterization is seen to work well if appropriate values of the roughness length z_0 and moisture availability parameter M are specified. Although the surface fluxes are quite sensitive to these parameters, as found by earlier investigators, it is not obvious how to select a value for M a priori. An initial estimate of M should take into account the rainfall and cloudiness history and probably other factors. Because temperature and humidity near the surface are quite sensitive to the fluxes, it is suggested that the difference between observed and calculated air temperatures could be used iteratively to guide the choice of M.

1. Introduction

Research on global climate change processes relies heavily on large-scale climate models. Since these models typically have a grid size on the order of 100 km, they must use subgrid parameterizations for processes such as convective transport and radiative transfer. Another physical process that needs to be included is the turbulent transfer of heat, momentum, and water vapor between the earth's surface and the atmosphere. The transfer of water is especially important (Starr and Melfi 1991). Furthermore, mechanisms of turbulent transport may be applied to the transport of other scalar quantities such as carbon dioxide.

Mesoscale models can be used as a framework to test parameterizations of turbulent fluxes because they can be compared to detailed and localized observations. The Pennsylvania State University and the National Center for Atmospheric Research (NCAR) jointly developed a mesoscale model that has been used to study a variety of mesoscale phenomena. The present version, MM5 (Grell et al. 1994), is a three-dimensional nonhydrostatic primitive equation solver with cloud physics and has been used with a horizontal resolution down to less than 5 km. When high resolution of the planetary boundary layer is desired, as in this study, a Blackadar scheme is used that parameterizes the fluxes of momentum and sensible and latent heat at the earth's surface. As part of an ongoing effort to characterize and to improve the performance of this model, this paper will present a comparison of surface fluxes from several model runs with in situ measurements.

Tests of boundary layer parameterizations using one-dimensional models have shown them to be quite sensitive to the characterization of the surface. Carroll (1993) found a maximum sensitivity of the fluxes of momentum and sensible heat to soil thermal diffusivity and the surface albedo. Segal et al. (1989) evaluated the sensitivity of sensible heat flux to the surface temperature of wet soil during the winter in midlatitudes (which is the case for this study). Even earlier, Carlson and Boland (1978) determined that their parameterization, which is used in MM5 for the latent heat flux, was most sensitive to the thermal inertia of the soil during the night and to their surface moisture availability parameter during the day.

Carlson and Boland (1978) also compared their model to several sets of observations; however, the fluxes in these datasets were derived from profile measurements. The present study uses direct flux measurements made using the eddy-correlation technique. Betts et al. (1993) made comparisons to an area average of eddy correlation and Bowen ratio flux observations to a grid point in a climate model with 100-km resolution. Since the present study uses grid resolutions of 5 and 6 km, it was possible to compare parameterized fluxes to measurements more directly.

Although certain aspects of MM5 have been greatly improved over earlier versions, the flux parameterization is based on two studies—Deardorff (1978) and Carlson and Boland (1978)—done 17 years ago. The present study will investigate whether it is necessary to

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TABLE 1. Characteristics of STORM-FEST flight legs used for this study. Local time (CST) is UTC minus 6 h.

Day	Start time (UTC)	Altitude (m AGL)	Orientation (°/relative wind)	Length (km)
52	2040	97	227°/upwind	56
58	1856	103	229°/cross	62
58	2036	88	229°/cross	60
61	1830	93	134°/cross	43
61	2006	84	132°/cross	43
70	1954	87	233°/cross	56
70	2119	90	237°/cross	29

change this aspect of MM5 by comparing model results to direct flux observations.

2. Data description

Data from two experiments will be shown in this study. The first was the Winter Icing Storms Program (WISP) experiment centered in northeastern Colorado during February and March 1991. Measurements were included in this experiment to support model and instrument development for the Atmospheric Radiation Measurement (ARM) program. The second was the STORM-Fronts Experiment Systems Test (STORM-FEST) experiment centered in eastern Kansas during the same months in 1992. In both experiments, the NCAR Atmosphere–Surface Turbulent Exchange Research (ASTER) facility (Businger et al. 1990) was deployed with several three-component sonic anemometers with collocated fast-response temperature and humidity sensors to measure directly the fluxes of momentum and sensible and latent heat using the eddy-correlation technique. ASTER also includes sensors to measure wind, temperature, and humidity profiles, radiation, and soil thermal characteristics. During WISP/ARM, a radar wind profiler and RASS system were available to provide wind and temperature observations above the lowest model level. During STORM-FEST, profilers also were available, however, data from the NCAR King Air research aircraft were used since the King Air also measured fluxes and sampled over distances more compatible with the model grid spacing.

Both ASTER sites were selected to be similar to the surrounding terrain. At the WISP/ARM site, the surface was senescent grassland, and at the STORM-FEST site the surface was an unplanted agricultural field that was mostly bare soil. The measurements were made at a height of 10 m and should be representative of the terrain between 0.5 and 100 km upwind depending on stability (Horst and Weil 1994). Nevertheless, patchiness of the ground cover in the region (characterized by roughness length, albedo, and surface moisture) could cause systematic differences between the tower measurements and a true area average represented by the model.

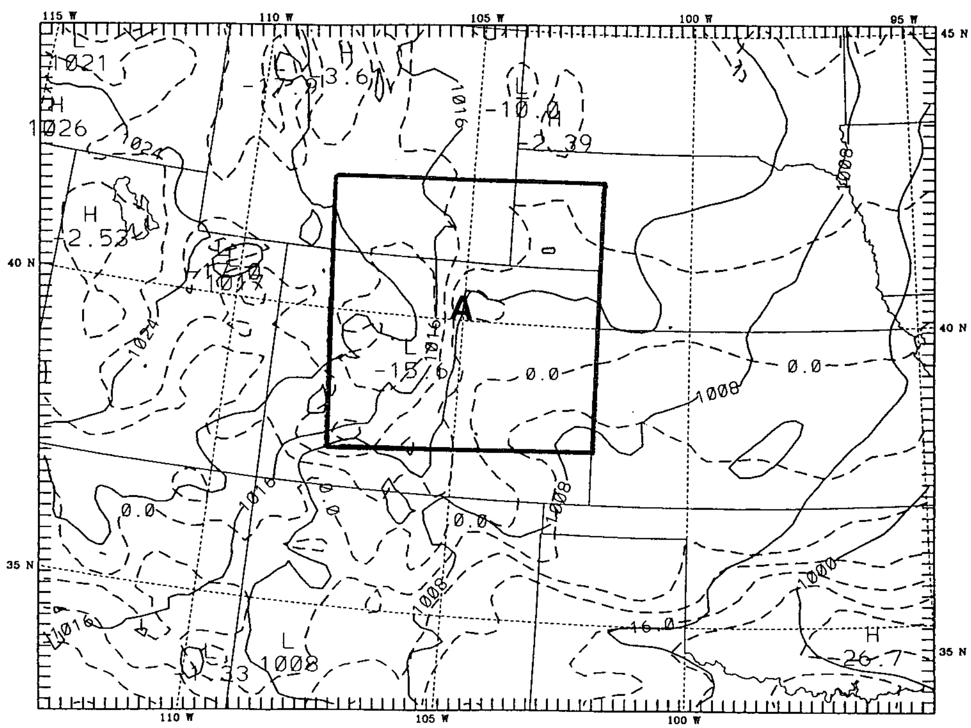

FIG. 1. Surface pressure (solid lines) and temperature (dashed lines) contours from the MM5 run with 20-km resolution 12 h into the WISP/ARM case. The box indicates the domain of the 5-km MM5 run.

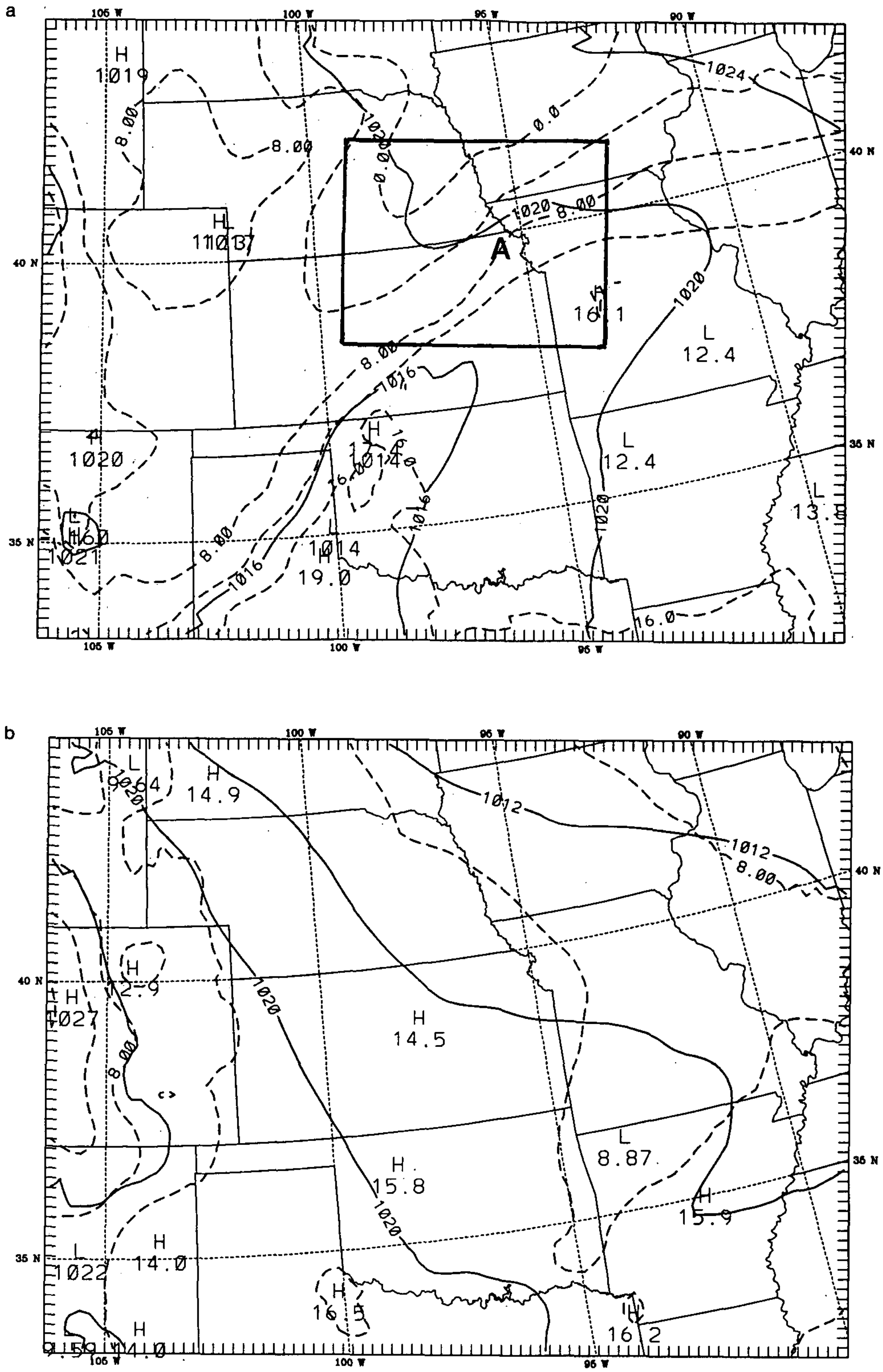

FIG. 2. Like Fig. 1 for the STORM-FEST cases. The box in (a) indicates the domain of the 6-km run of MM5. Runs are shown from (a) day 52, (b) day 58, (c) day 61, and (d) day 70.

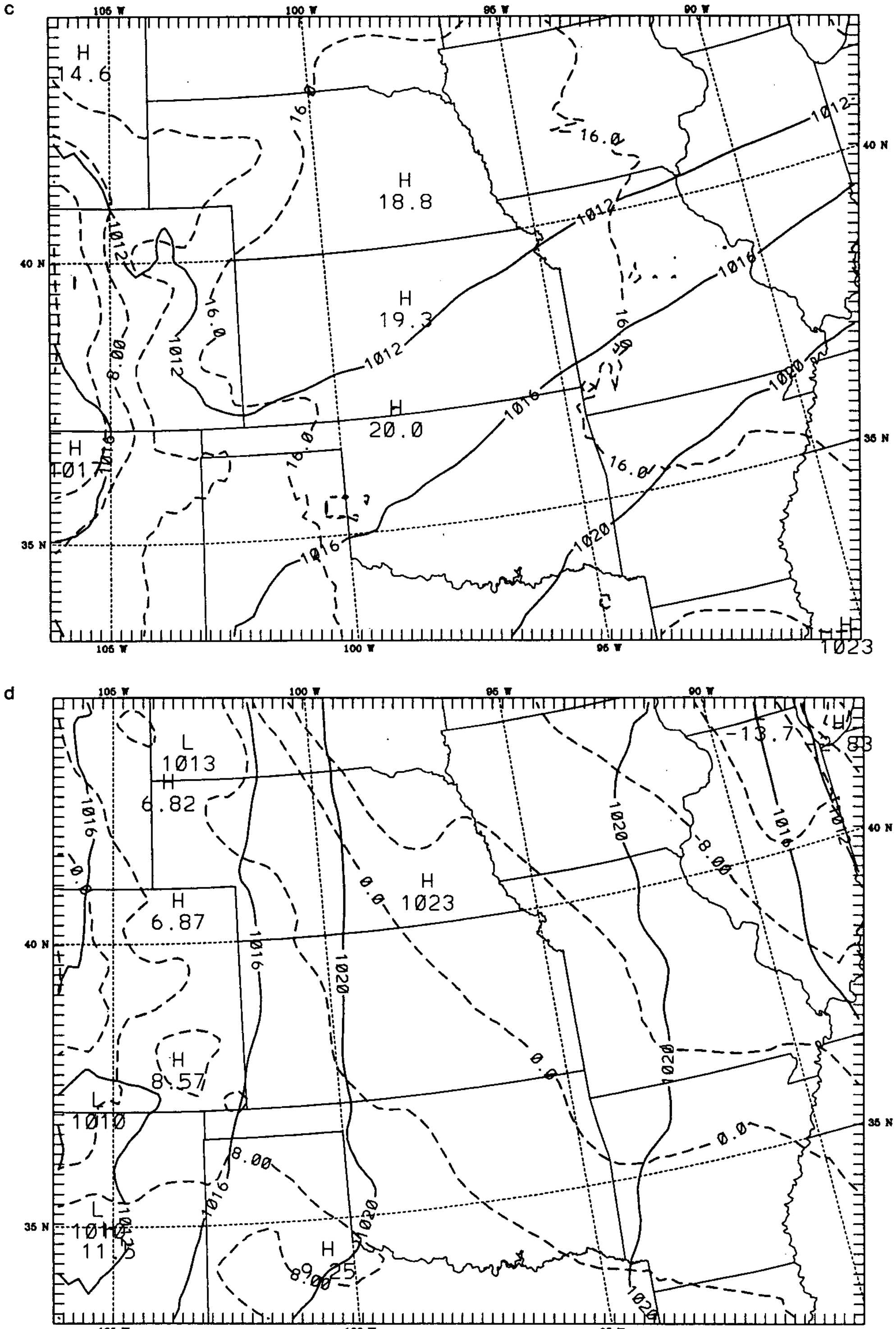

FIG. 2. (*Continued*)

The site used for WISP/ARM had somewhat complex terrain, so it was necessary to check its homogeneity. This was done by comparing fluxes measured at 4 and 10 m. On average, values of both u_* and θ_* from the two levels were within 4%, so the site could be considered homogeneous at least up to 1-km scales.

TABLE 2. MM5 run characteristics.

Program	Start time (UTC), day	Resolution (km)	Levels	Surface type	z_0 (cm)	Moisture availability (%)
WISP/ARM	0000, 65	5	23	Range/grass	10	30
STORM-FEST	1200, 52	6	27	Agricultural	5	60
	1200, 58					
	1200, 61					
	1200, 70					

During STORM-FEST, data from the NCAR King Air research aircraft were used to investigate the question of representativity. The King Air made eddy-correlation flux measurements along legs (see Table 1) that crossed over the ASTER site during this program. These measurements, made about 100 m above the ground, would be expected to differ somewhat from the ASTER measurements due to the larger flux footprint and also to be somewhat smaller in magnitude since momentum and energy fluxes generally decrease with height from their surface values.

Five cases were chosen for study, one from WISP/ARM and four from STORM-FEST.

1) 6 March 1991 (WISP/ARM), Julian day 65. A weak cold front moved south through eastern Colorado between 0000 and 1200 UTC, causing the conditions to change from mild to cold (Fig. 1).

2) 21 February 1992 (STORM-FEST), Julian day 52. A warm front aligned northeast–southwest moved north through Kansas during the first 12 h, then became stationary, with initially cold temperatures that changed to mild (Fig. 2a).

3) 27 February 1992 (STORM-FEST), Julian day 58. Weak west to northwest surface flow existed. There was little thermal advection during the day and conditions were mild (Fig. 2b).

4) 1 March 1992 (STORM-FEST), Julian day 61. Conditions were similar to day 58 with a weak southwest to south surface flow (Fig. 2c).

5) 10 March 1992 (STORM-FEST), Julian day 70. The surface flow was north to northwest behind a cold front, which turned to the south as another system approached from the west. At the beginning of this day some snow from the cold front was on the ground but had mostly disappeared by the end of the period. Temperatures were initially cold and became milder (Fig. 2d).

3. Model description

The model used for this study is the National Center for Atmospheric Research–Pennsylvania State University Mesoscale Model (NCAR–PSU MM5) recently developed to include a nonhydrostatic option, multiple nesting, and four-dimensional data assimilation (Grell et al. 1994; Dudhia 1993). The model was run on a 60-km grid with subdomains of 20- and 6.67-km grid size for the STORM-FEST cases. These subdomains each have two-way interaction with their parent domain, whereby information from the coarser mesh is fed into the finer mesh through the boundaries, and information from the fine-mesh interior is fed back to the coarser mesh at every time step. The WISP/ARM case was run with one-way nesting, whereby hourly information from a 20-km grid run was fed into a 5-km run via its lateral boundaries and initial conditions.

The model physics included the Grell cumulus parameterization (Grell 1993) scheme on the coarser two meshes, explicit microphysics with ice and an atmospheric radiation scheme (Dudhia 1989) on all meshes, a high-resolution Blackadar-type planetary boundary layer (Zhang and Anthes 1982) that will be described in more detail below, a surface energy budget, and an upper nonreflecting boundary condition modified from Klemp and Durran (1983).

The model surface properties such as albedo, roughness length, moisture availability, and heat capacity are specified according to one of 13 land-use categories and a summer–winter season.

The model runs are summarized in Table 2. To initialize the model on the 60-km grid for the STORM-FEST cases, the model fields were taken from the Mesoscale Analysis and Prediction System (MAPS) analysis provided by the National Oceanic and Atmospheric Administration Forecast Systems Laboratory, which has the same horizontal grid size as the MM5 domain. However, the boundary conditions after this initialization were taken from a 180-km MM5 run initialized 12 h earlier from the National Meteorological Center's Medium Range Forecast (MRF) data. These boundary conditions were also used for real-time operational forecasts using MM4 during STORM-FEST. The 20- and 6.67-km domains were initialized at the beginning of the simulation by interpolation from the 60-km domain using the same terrain. For these four cases, the model was initialized at 1200 UTC 21 February, 27 February, 1 March, and 10 March 1992 and run for 36 h. However, excess clouds were created by the model since it did not include a term for ice sedimentation. [This term has since been added following Heymsfield and Donner (1990).] These clouds in turn significantly reduced the radiation available for surface heating, so the flux comparison was poor on the second day. For this reason, only the first 24 hours of these model runs were used.

For the WISP/ARM case, a 36-h, 40-km simulation was initialized with a Nested Grid Model (NGM) analysis at 1200 UTC 5 March 1991, enhanced by standard upper-air observations, and run with four-dimensional data assimilation. The 24-h, 20-km simulation took boundary and initial conditions from the 40-km simulation after 12 h, and a 24-h, 5-km simulation was similarly one-way nested inside the 20-km domain, starting at 0000 UTC 6 March. The terrain for the 5-km simulation was of higher resolution than that of the 20-km domain.

The STORM-FEST cases were run with MM5, version 0 (Grell et al. 1994; Dudhia 1993). During WISP/ARM, a nonhydrostatic version of MM4 was run. Since this model was a precursor to MM5, both will be referred to as MM5.

a. Flux parameterization

The Blackadar parameterization in MM5 uses flux-profile relationships applied to values at a single height. These relationships are semiempirical since they are based on the budget equations of turbulent kinetic energy, temperature variance, and humidity variance but use coefficients that have been determined experimentally (e.g., Businger et al. 1971). The surface characteristics needed in these relationships are defined in MM5 based on land-use categories.

The momentum flux parameterization solves for the friction velocity $u_* \equiv (-\overline{u'w'})^{1/2}$, where u' and w' are fluctuations of the along-wind and vertical wind components from the average components, U and W, measured at a height z above the earth's surface. This is calculated from

$$u_* = \frac{kU}{\ln(z/z_o) - \psi_m}, \tag{1}$$

where k is the von Kármán constant (MM5 uses $k = 0.4$) and z_o is a length, specified by land-use category, that characterizes the surface roughness. The value of u_* is kept above 0.1 m s^{-1} over land surfaces. The stability correction ψ_m is given as a function of the stability parameter $\zeta \equiv z/L$, where L is the Obukhov length defined as $\theta u_*^3/kg\overline{w'\theta'}$, g is gravitational acceleration, and θ' represents fluctuations of temperature from the mean θ. For unstable conditions, ψ_m is given by (Zhang and Anthes 1982)

$$\psi_m = -1.86\zeta - 1.07\zeta^2 - 0.249\zeta^3, \tag{2}$$

when $|h/L| > 1.5$, and $\psi_m = 0$ when $|h/L| \leq 1.5$, where h is the boundary layer height. Zhang and Anthes had an additional offset of 0.0954 in (2), which has been left out of MM5 to avoid a discontinuity at $\zeta = 0$. Equation (2) is intended to approximate the equation found by Paulson (1970):

$$\psi_m = 2\ln\left(\frac{1+x}{2}\right) + \ln\left(\frac{1+x^2}{2}\right) - 2\tan^{-1}(x) + \frac{\pi}{2}, \tag{3}$$

where $x \equiv (1 - \gamma\zeta)^{1/4}$. Zhang and Anthes apparently used a value for γ of 16—the value used by Dyer and Hicks (1970) to fit their data. For stable conditions, $\psi_m = -5\zeta$, in general agreement with Webb (1970) and Businger et al. (1971).

The stability is determined using the bulk Richardson number $\mathrm{Ri}_B \equiv gz(\theta - \theta_o)/\theta U^2$, with θ_o being the temperature near the surface (at $z = z_o$). For $\mathrm{Ri}_B > 0.2$, Ri_B is set equal to 0.2. The value for ζ is then computed as $\mathrm{Ri}_B \ln(z/z_o)$ in unstable conditions and $\mathrm{Ri}_B \ln(z/z_o)(1.1 - 5\,\mathrm{Ri}_B)^{-1}$ in stable conditions. This description avoids the need to iterate in the solution of the fluxes since for each time step (20 s) the fluxes can be calculated directly from the mean temperatures.

The parameterization for sensible heat flux is similar to that for momentum flux. The characteristic temperature, $\theta_* \equiv -\overline{w'\theta'}/u_*$, is calculated by

$$\theta_* = \frac{k(\theta - \theta_o)}{\Pr[\ln(z/z_o) - \psi_h]}, \tag{4}$$

where ψ_h again is determined in unstable conditions by a third-order polynomial fit (without the offset) to

$$\psi_h = 2\ln\left[\frac{1 + (1 - \gamma\zeta)^{1/2}}{2}\right] \tag{5}$$

and is set to ϕ_m in stable conditions. The turbulent Prandtl number Pr is set to 1 in MM5, as suggested by Webb (1970).

The parameterization for latent heat flux is somewhat different than for the other fluxes. MM5 uses the parameterization developed by Carlson and Boland (1978) for $q_* \equiv -\overline{w'q'}/u_*$, where q' represents fluctuations of humidity from the mean Q:

$$q_* = \frac{Mk[Q - Q_s(\theta_o)]}{\ln(ku_*z/K_a + z/z_l) - \psi_h}. \tag{6}$$

MM5 uses a value for the top of the molecular sublayer, z_l, of 0.01 m over land. Equation (6) uses the humidity of air saturated at the surface temperature θ_o and a moisture availability parameter M, again defined by land-use category, which can be interpreted as a "wetted area fraction" (see section 3b). Equation (6) is used instead of the flux-profile relation analogous to (4)

$$q_* = \frac{k(Q - Q_o)}{\Pr[\ln(z/z_o) - \psi_h]} \tag{7}$$

to "permit slow diffusion when [turbulent transfer] equals zero" (Zhang and Anthes 1982). Since molecular diffusion is an added resistance to the transfer of water vapor from the surface, the flux into the atmosphere is lower than without diffusion. A model run in which (7) was used in MM5 required unrealistically low values of M to obtain reasonable fluxes. Another interpretation of (6) is that the roughness length for moisture is lower since K_a/ku_* has a maximum value of 0.06 cm (using the value of the background molecular diffusivity K_a of 2.4×10^{-5} m^2 s^{-1}), whereas the value for z_o is 5–10 cm.

The surface temperature θ_o is calculated as the temperature of the top of a slab of soil maintained at constant temperature at the bottom. The change in the temperature of this slab is determined by the energy balance between net radiation, the transfer of heat with the underlying substrate, and the sensible and latent heat fluxes. Therefore, errors in the sensible and latent heat fluxes will show up as an error in θ_o.

Equations (1), (4), and (6) are derived empirically from surface-layer data. The surface layer is generally taken to extend to $0.1h$. With the top of the lowest model level at 73 m, this parameterization is valid for $h > 730$ m, which may have been the case during the day but was not during the night. However, the fluxes at night were small, so significant differences between the model output and measurements during these periods were not observed.

b. *Moisture availability*

As mentioned earlier, Carlson and Boland (1978) found that this latent heat flux parameterization is quite sensitive to M during the day. Furthermore, they "found it advisable to set $M = 1.0$ when [the latent heat flux] was less than zero." Nevertheless, MM5 simply uses a value for M that is independent of the sign of the moisture flux. It may be useful at this point to discuss an interpretation of M using a simple model for evaporation over bare soil. If it is assumed that water is evaporated only from the surface of the soil (ignoring evaporation of water in air pockets into the soil and the subsequent transfer of this relatively humid air to the surface), then evaporation will depend only on the fraction of the surface that has exposed water molecules. If a water molecule is exposed, it may be assumed to have the temperature θ_o, and thus the humidity just above it would be $Q_s(\theta_o)$. Where water is not present, the humidity above the surface would have approximately the ambient value Q. In this case, $Q_o = (1 - f)Q + fQ_s(\theta_o)$, where f is the "wetted-area fraction." However, from inspection of the numerators of (6) and (7), it is apparent that $f \equiv M$; thus, M is approximately the wetted-area fraction when vegetation is not present.

c. *Parameterization implementation*

For the WISP/ARM model runs, fluxes calculated from the model variables were output every 3 h. For WISP/ARM, the grid point including the ASTER site had a land-use category of marsh, apparently due to some nearby water. To get a more realistic value, model values from an adjacent grid point that had the category of range/grassland were used. During STORM-FEST, fluxes were output every hour and interpolated from the four surrounding grid points (all with agricultural land use) to the ASTER location. Averages of the ASTER values were computed over 30-min periods starting at the beginning of the comparison time.

The MM5 parameterization was tested external to the model by applying it to the ASTER measurements of mean quantities. This approach allowed changes to the parameterization to be studied without having to rerun MM5. The external parameterization also was applied to MM5 mean values, and this verified that it produced fluxes in agreement with those output from MM5 itself.

4. Results

Before beginning a detailed comparison of the model to the observations, it is necessary to check the consistency of the observations themselves.

a. *Observations*

During WISP/ARM, a sodar was used to make wind speed and direction observations at a height of 56 m. The wind speeds were mostly greater than the ASTER 10-m measurements, as expected. The MM5 wind speeds at 36 m generally fell between these two observations, also as expected.

Also during WISP/ARM, RASS temperature measurements at a height of 500 m were available to check the model temperature profile. Unfortunately, the sodar data indicate that the boundary layer grew only to about 250 m during the day used for this study, so the RASS data recorded only the temperature of the overlying air.

Values measured by the King Air during STORM-FEST were compared whenever available. All mean variables were close to the ASTER measurements, with winds somewhat higher as expected; however, the fluxes often were different. Table 3 shows that except for day 52, all of the u_* values from the King Air were larger than those measured at the ASTER tower. This probably is due to an increased effective roughness length observed by the aircraft, which measured over a larger spatial domain that contained large roughness elements such as trees and hills. This effect has been observed by Arya (1981) and later by Beljaars and Holtslag (1991) and Mahrt and Ek (1993). Note that the u_* values from MM5, which were processed using $z_o = 5$ cm, agree reasonably well with the King Air measurements, indicating that this value for z_o should

TABLE 3. Fluxes measured by ASTER and the King Air (KA) and calculated by MM5 (using the default values for M) during periods of the King Air flights. A second value is shown for the MM5 cases that were rerun using better values for M (day 61, M = 0.1 and day 70, M = 1.0).

	u_* (cm s^{-1})			$-\rho C_p u_* \theta_*$ (W m^{-2})			$-\rho L u_* q_*$ (W m^{-2})		
Day	ASTER	KA	MM5	ASTER	KA	MM5	ASTER	KA	MM5
52	19	11	34	70	62	32	119	64	53
58	30	50	60	143	156	182	128	116	225
	19	49	56	92	119	95	120	113	205
61	51	70	71/79	113	86	95/231	76	128	346/117
	51	72	67/73	123	119	66/192	93	136	337/116
70	51	66	64/63	200	196	303/263	230	153	132/178

be used to obtain fluxes from the area-average data rather than the local value of 0.5 cm observed at the ASTER site. (One MM5 case with z_o set to 0.5 cm was run, and, as expected, the average wind speed became unreasonably large due to the decreased drag of the surface.)

The sensible heat fluxes generally agree between ASTER and King Air measurements. This is consistent with the results of Beljaars and Holtslag (1991), who found that heat transfer is a function only of the surface type and scales with one roughness length at all heights in the surface layer. However, the MM5 heat fluxes often are quite different. This result must be due to an error in either the sensible or latent heat flux parameterization.

The latent heat fluxes do not agree nearly as well as the sensible heat fluxes between the ASTER and King Air measurements. This may be due to flight tracks passing over land with different moisture characteristics. Note that the day 61 tracks were at a different orientation than other days and that this was the only day when the King Air latent heat fluxes were larger than ASTER. There also was some snow on the ground under the King Air flight tracks that may have been responsible for the King Air latent heat fluxes being lower than those from ASTER. The MM5 latent heat fluxes are much higher than either of the observations on days 58 and 61 and are lower on days 52 and 70. This result will be explored in the next section.

b. MM5 evaluation

Figures 3–5 give a comparison of the mean variables and fluxes from ASTER, MM5, and the King Air for the day 61 case. Figure 3a shows that the wind speeds at 36 m from MM5 again are slightly higher than the

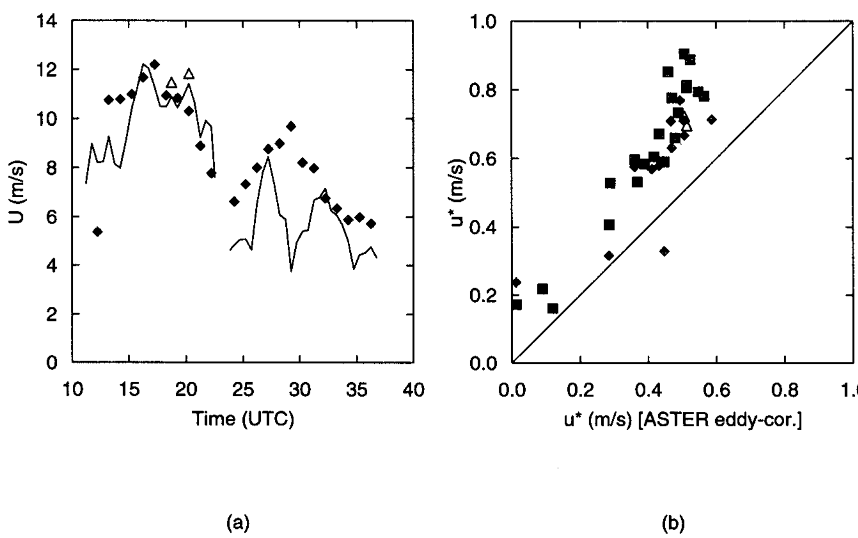

FIG. 3. (a) Time series of U measured by ASTER at 10 m (solid line) and the King Air at about 100 m (triangles) and calculated by MM5 (diamonds) for STORM-FEST day 61. Also shown (b) is a comparison of u_* calculated from Eq. (1) using ASTER measurements (squares), calculated by MM5 (diamonds), and measured by the King Air (triangles) versus flux measurements made by ASTER.

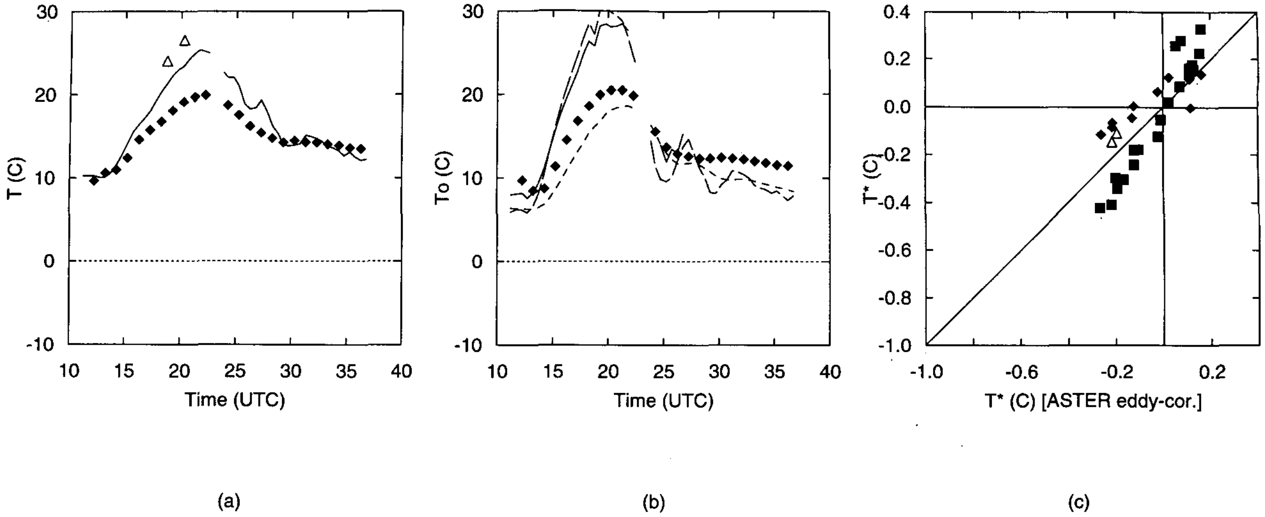

FIG. 4. (a) Time series of T (computed as potential temperature) measured by ASTER at 10 m (solid line) and the King Air at about 100 m (triangles) and calculated by MM5 (diamonds) (a) for STORM-FEST day 61. (b) The time series of θ_o extrapolated from ASTER potential temperature profiles to z_o (solid line), calculated by MM5 (diamonds), and measurements from ASTER of the radiative surface temperature (long dashes) and soil temperature at 1-cm depth (short dashes). (c) The comparison of θ_* calculated from Eq. (4) using ASTER T and extrapolated θ_o measurements (squares), calculated by MM5 (diamonds), and measured by the King Air (triangles) versus flux measurements made by ASTER.

ASTER observations at 10 m and are slightly lower than the King Air measurements at 100 m, as expected. However, Fig. 3b shows that the u_* values using the parameterization are higher than the values observed by ASTER. The parameterized u_* values do agree with the King Air flux measurements, indicating that the difference is due to the larger effective roughness length discussed above.

Figure 4a shows that although the King Air and ASTER air temperature measurements are in reasonable agreement, the MM5 temperatures are up to 6°C low. Also, the MM5 θ_o values, shown in Fig. 4b, are much lower during the day and higher during the night than the ASTER measurements of either radiative surface temperature or the extrapolated air temperature to z_o. These values for θ_o are only slightly larger than the soil temperature measured at a depth of 1 cm, which might be expected when the surface latent heat flux is large. Since the air–surface temperature difference, $\theta - \theta_o$, from MM5 is smaller than the measurements, the MM5 sensible heat fluxes are much smaller than the measured ASTER fluxes (Fig. 4c), a result that will be explored in the following paragraphs. However, as expected, the MM5 parameterization applied to the ASTER measurements of θ and θ_o yielded higher fluxes because of the higher air–surface temperature difference. Using a smaller roughness length for heat transfer, as suggested by several investigators (e.g., Beljaars and Holtslag 1991), does not change the sensible heat flux significantly since both the extrapolated value for θ_o and the denominator in (4) change.

Figure 5a shows that the MM5 values for humidity become much larger than either the ASTER or King Air measurements soon after initialization. The cause for this is readily apparent in Fig. 5b, which shows that the parameterization using $M = 0.6$ generates water vapor fluxes that are much too large even when ASTER Q and θ_o measurements are used in the parameterization. Obviously, the high water vapor fluxes injected too much water vapor into the atmosphere. Furthermore, the large latent heat fluxes made less of the surface energy available for sensible heat, which caused MM5 to predict low air and surface temperatures.

MM5 was rerun with $M = 0.1$ for the agricultural land-use category to verify the above analysis. Figure 6 shows that the momentum fluxes are essentially unchanged (since only the stability correction would be different). However, the air and surface temperatures seen in Fig. 7 are much closer to the ASTER observations and cause the θ_* values to agree almost perfectly. Figure 8 shows that both the mean humidity and the latent heat fluxes from MM5 are closer to both the King Air and ASTER observations. Table 3 also shows that the latent heat fluxes from this model run agree with the King Air better than the run with $M = 0.6$, although the sensible heat fluxes are somewhat worse. This discrepancy apparently is due to a narrow cloud band that passed over the ASTER site but was not formed in the model.

Table 4 summarizes the results from all seven 24-h runs of MM5 that were used for this study. As mentioned above, 1 day during WISP/ARM was modeled along with 4 days during STORM-FEST. In addition, the STORM-FEST day 61 case was rerun using the parameters calculated from the ASTER data. Run 61M

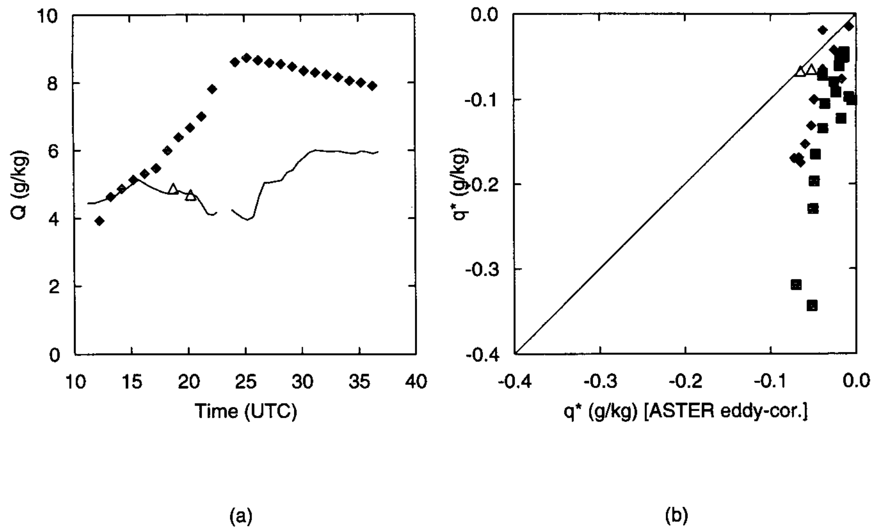

FIG. 5. (a) Time series of Q measured by ASTER at 10 m (solid line) and the King Air at about 100 m (triangles) and calculated by MM5 (diamonds) for STORM-FEST day 61. Also shown (b) is a comparison of q_* calculated from Eq. (6) using ASTER Q and extrapolated T_g measurements (squares), calculated by MM5 (diamonds), and measured by the King Air (triangles) versus flux measurements made by ASTER.

is the case mentioned above, with M set to 0.1; for run 61MZ, z_o also was set to 0.5 cm instead of 5 cm.

Several features are immediately seen in this table. First, the MM5 wind speeds were high for one-half of the STORM-FEST cases and agreed well with the observed speeds for the other cases. With the good wind speed comparison during WISP/ARM, u_* from MM5 using z_o = 10 cm agreed reasonably well with the observed fluxes. This value again is larger than the local value of 3 cm at the ASTER site and is probably due to variations in terrain that become significant roughness elements for the areal-averaged model. As observed above, the STORM-FEST u_* values from MM5 are mostly higher than the ASTER observations but are probably close to representative since they agree with the King Air measurements.

For the other four cases studied, the MM5 moisture prediction ranges from too low through too high, depending on the local precipitation and evaporation history. Both Q and q_* from MM5 were high for STORM-FEST day 58—similar to day 61. Both of these days followed several days of clear skies, which dried out

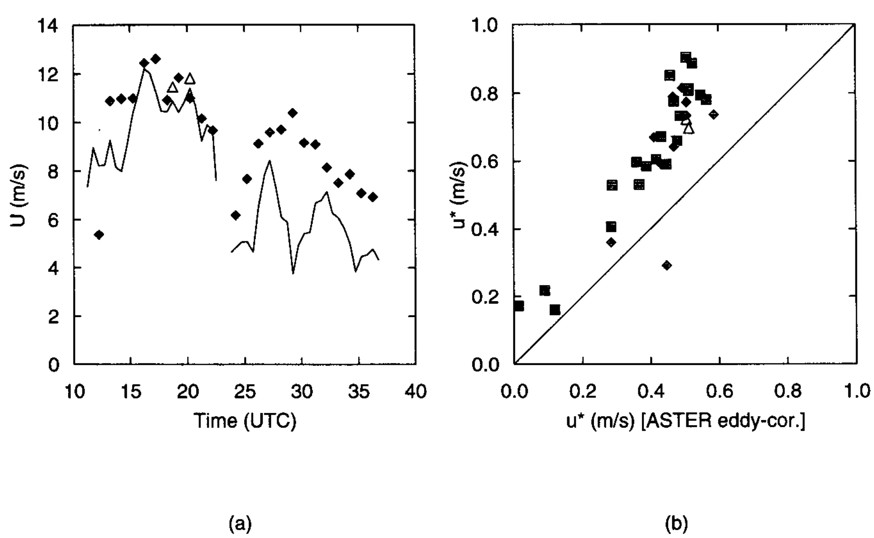

FIG. 6. Like Fig. 3 but with M = 0.1 in the q_* parameterization.

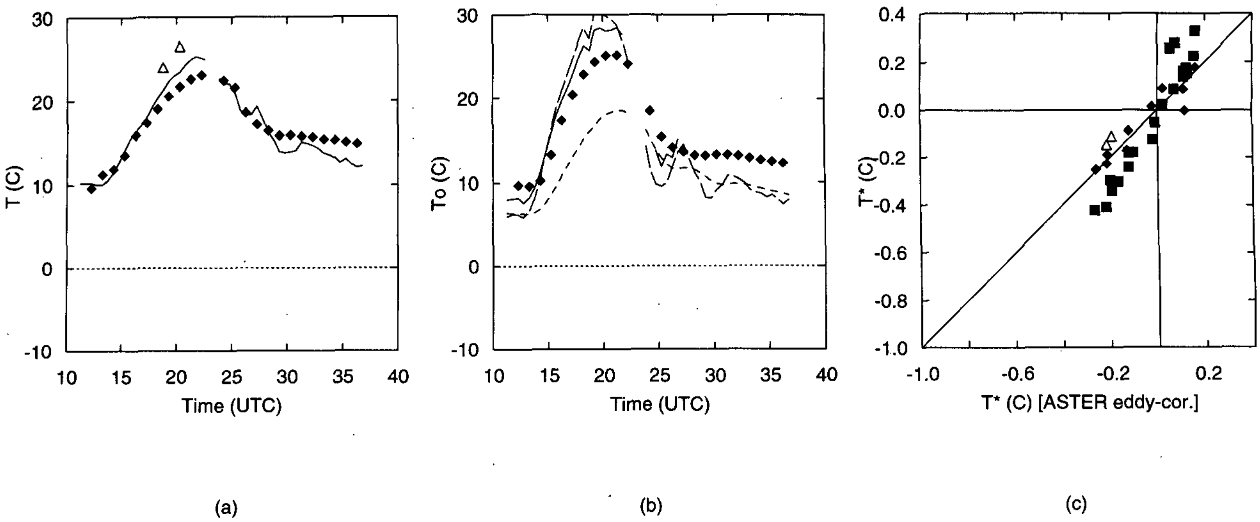

FIG. 7. Like Fig. 4 but with $M = 0.1$ in the q_* parameterization.

the surface from the previous rainfall (Fig. 9). Indeed, the value of 24% for the soil moisture content in the top 3 cm on day 61 was the lowest measured at the ASTER site during STORM-FEST. Thus, moisture truly was not "available." As seen before, setting $M = 0.1$ in the model makes both Q and q_* agree well on day 61. By applying the parameterization to the ASTER observations, it was found that setting $M = 0.2$ would work for day 58.

In contrast, Q and q_* from MM5 were too low for STORM-FEST days 52 and 70, since both days had high soil moisture values. There was precipitation the day before day 70, and cloud cover slowed the evaporation of rain that fell 3 days before day 52. For these cases, it was necessary to increase M to 1.0 in the parameterization to get better agreement with the observations. Setting $M = 0.3$ (the value for range/grassland currently in the MM5 land-use classification table) worked reasonably well for the WISP/ARM case.

The sensible heat fluxes agree better for the STORM-FEST cases other than the day 61 case since day 61 had the largest error in the predicted latent heat flux. Day 58 had θ_* values lower by 30%, which was caused by inaccurate predictions of both the mean air and surface temperatures due to the high MM5 moisture flux. Days 52 and 70 had good agreement of the temperatures and the sensible heat flux. The WISP/ARM case had low MM5 θ_* values, which were caused by values of θ_o that were lower by 2°–4°C. It is not clear why θ_o was so low—possibly the cloud cover was

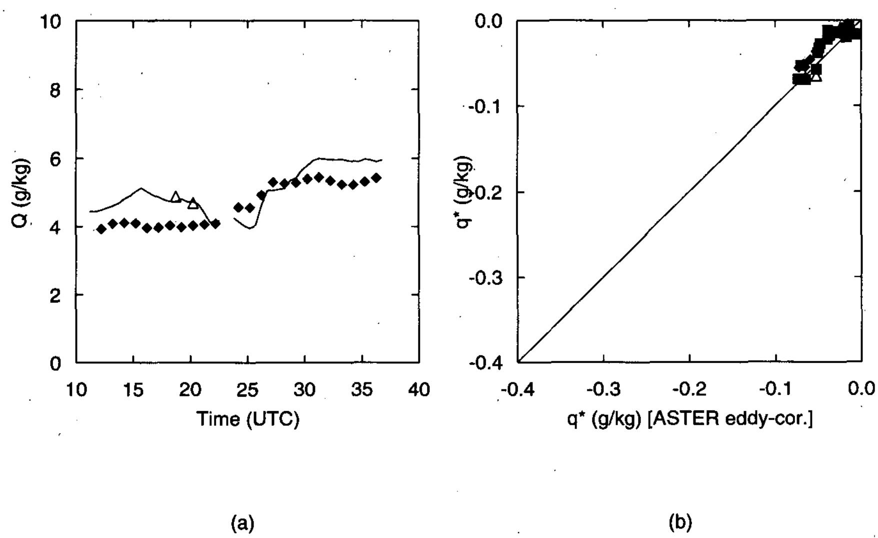

FIG. 8. Like Fig. 5 but with $M = 0.1$ in the q_* parameterization.

TABLE 4. Results from comparison of means and fluxes for this study. For mean quantities the dimensional root-mean-square (rms) difference between MM5 and observed values is given. This rms value is given as "+" when MM5 is consistently higher, "−" when MM5 is lower, and unsigned if both cases occur. Flux quantities are categorized by the slope from a regression with measured fluxes, where a slope of 1.0 is perfect agreement and numbers less than one indicate an underestimate by the parameterization. When two values are given for the slope, the first is from the parameterization using observed mean values, and the second using MM5 values. Both the value for M used by default in MM5 and the value that would be needed to obtain the best agreement in the q_* comparison are shown. Also shown are measured values for soil moisture in percent and the number of days since precipitation was observed.

	WISP/ARM	STORM-FEST					
	65	52	58	61	61M	61MZ	70
U	+2.9	+2.0	+2.0	2.0	+2.4	+3.4	1.7
u_*	1.0/0.6	1.3	1.4	1.7	1.4/1.3	1.1/1.3	1.4
θ	1.8	+2.2	2.3	−2.6	1.5	1.6	1.2
θ_0	−3.4	1.3	8.9	5.2	2.4	3.9	1.4
θ_*	0.9/0.5	0.8/0.8	1.4/0.7	1.7/0.5	1.4/0.9	1.5/0.9	1.3/1.1
$\bar{q}$	0.7	0.3	1.1	+2.5	−0.6	0.5	0.2
q_*	0.7/0.5	0.1	2.0/0.9	5.0/2.5	0.8	1.0	0.4
M_{default}	0.3	0.6	0.6	0.6	—	—	0.6
M_{best}	0.4	1.0	0.2	0.1	—	—	1.0
Moist	NA	31	26	24	—	—	30
Precip	1	3	3	6	—	—	1

underpredicted, allowing too much cooling during the night at the beginning of the run.

As noted earlier, the θ_* values calculated from the observed air–ground temperature differences are mostly higher than those using model data. In part, this is caused by uncertainty extrapolating the ASTER temperature profiles measured at heights between 1 and 10 m down to z_o, especially for unstable conditions. Ap-

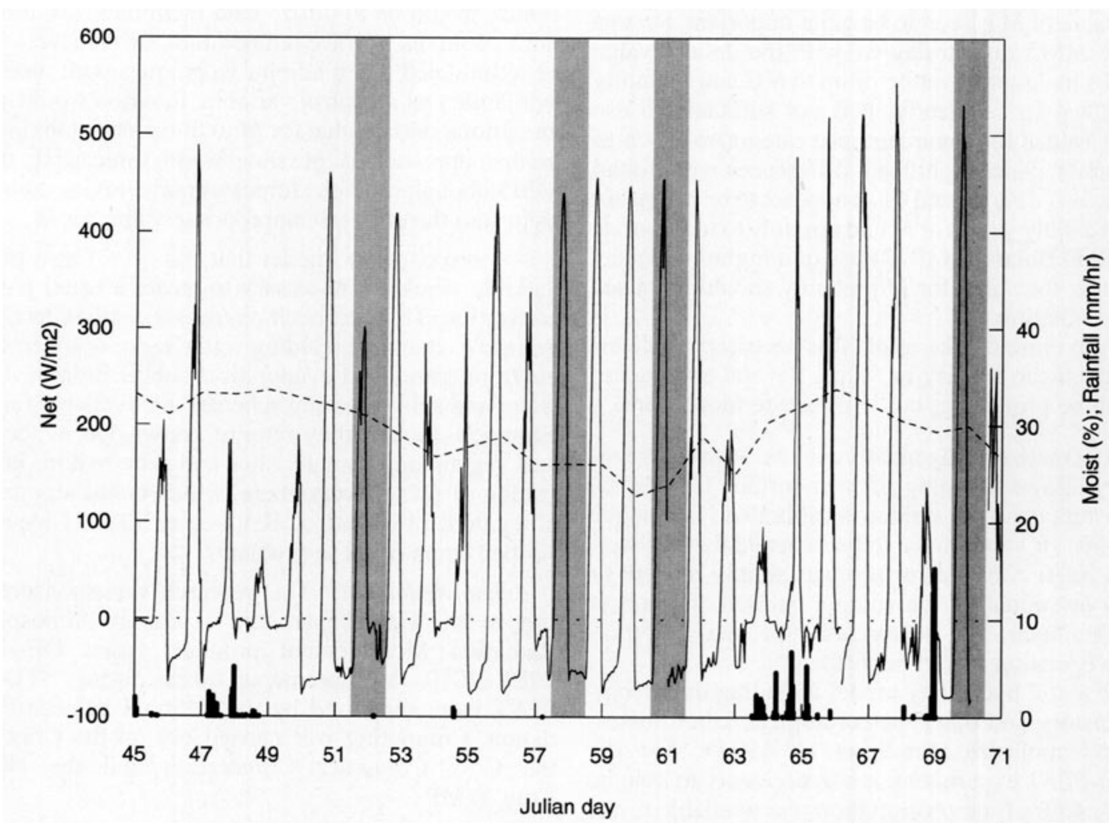

FIG. 9. Time series of net radiation (solid line), soil moisture (dashed line), and rainfall (thick bars) during STORM-FEST. Some of the "rainfall" values are wind-blown snow detected by the optical rain gauge. The four cases used in this study are highlighted in gray.

plying the parameterization to the ASTER observations using the flux-profile relations given by Businger et al. (1971) gave better agreement between the parameterized and observed fluxes than using (3) and (5), primarily because of the smaller value for k.

5. Discussion

It is seen that the flux parameterizations used in the MM5 model work reasonably well. However, appropriate values for the constants used by these parameterizations—specifically z_o and M—must be used. It was necessary to use a near-surface air temperature at a height of z_o, rather than radiometric surface temperature or the lowest measured air temperature, to get good agreement between modeled and observed values of θ_o and the heat fluxes. It also may be better to use a ''roughness'' length for temperature that is smaller than that for momentum.

It was shown that the MM5 values for z_o were consistent with the effective roughness for the grid square, which was larger than the roughness found from local measurements (e.g., Wood and Mason 1991). These values appeared to be reasonable for the two sites studied (Colorado grassland and Kansas agricultural land); however, other land-use categories or even these categories in different regions or seasons were not studied.

The value of M is seen to be quite important. Results from the MM5 run on day 61 with the default value had errors in air temperature of up to 6°C and humidity of up to 8 g kg^{-1}. Clearly, it is not sufficient to use biannual values for some land-use categories (such as agricultural). Since significant differences were found in M between days 58 and 61, it appears to be necessary to assign a daily value for M and possibly to incorporate Carlson and Boland's (1978) use of a nighttime value. In addition, the value for M probably should be raised after precipitation.

Given the importance of M, it is necessary to determine a means to specify its value. Several approaches appear to be promising, but will require more work.

- Use remote sensing measurements. Microwave radiometry allows mapping of near-surface (0–2 mm) soil moisture once the surface is calibrated (Schmugge et al. 1986). It would have to be assumed that the wetted-area fraction of the surface was simply related, or possibly just equal to, the volume fraction of water in such a thin layer. The interpretation of data with transpiring vegetation would be difficult.
- Use a soil hydrology model including the precipitation history and other meteorological data to determine soil moisture (Smith et al. 1994). For the STORM-FEST experiment, it was necessary to assume that only 40% of the precipitation was available to the soil (i.e., 60% surface runoff) to balance the accumulated soil moisture minus evaporation. Although the ASTER site was at a local maximum in the topography, it was not obvious how the value of 40% would be specified. [Note that this value is in reasonable agreement with the climatological mean of 60% for the entire Mississippi Basin drainage during February shown by Roads et al. (1994).] A further complication is how to relate soil moisture to M, which requires knowledge of the shape of the soil moisture profile and soil properties. Unfortunately, the correlation found for the STORM-FEST data between M and soil moisture was quite weak, with an order-of-magnitude change in M associated with only a 7% change in soil moisture. For simple soils, the moisture profile can be modeled (Hillel 1977); however, the existence of vegetation will complicate the profile.
- When observations are available, the most computationally efficient method for determining the surface moisture flux may be simply to run MM5 iteratively. This approach could be made more efficient by running only from sunrise to noon and comparing observed and predicted near-surface air temperatures. It should be possible to get reasonable agreement within two such iterations since M probably can be guessed to within 0.4 and an accuracy of 0.1 appeared to be sufficient for this study. Furthermore, the horizontal variation of moisture availability could be determined from differences between the observed and predicted near-surface temperatures. A continuous version of this procedure would be to utilize data assimilation. Observations of fluxes, surface temperature, or moisture could be assimilated using adjoint techniques with moisture availability as a control variable. Iteration would yield an optimal initial value for M to fit the data. Obviously, neither approach is possible when forecasting using MM5, though previous forecasts may provide some insight into the currently appropriate value for M.

A more complex model that has $Q(z_o)$ as a model variable would be necessary to create a better parameterization. This approach requires a detailed model of surface exchange, including water vapor transfer to the air from plants and evaporation/sublimation of liquid water and snow. Several schemes are available for this approach, though they require knowledge of the soil and vegetation characteristics and they require initialization of $Q(z_o)$ everywhere, which is not reported as a standard observation. Betts et al. (1993) have described some of these problems.

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