Evaluating Mesoscale Model Predictions and Parameterizations Against SGP ARM Data on a Seasonal Timescale

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Introduction

A major objective of the Atmospheric Radiation Measurement (ARM) Program is to test and improve parameterizations for cloud and radiative processes. A common strategy adopted for this purpose within the ARM science team is to utilize single-column models (SCMs) driven by appropriate boundary conditions derived from observations, so as to isolate the parameterizations themselves. In practice, accurate boundary conditions are very difficult to retrieve from observations, therefore limiting the SCM approach to relatively short intensive operational periods (IOPs), while leaving the overwhelming bulk of the ARM observations virtually untouched. An alternative approach is developed hereafter, which makes use of the continuous data stream provided by ARM. It consists of directly evaluating the predictions and parameterizations of the National Center for Atmospheric Research (NCAR)/Penn State Mesoscale Model (MM5) at the location where observed data are available. The analysis is performed for a long series of daily runs, on a seasonal timescale, i.e., a time period long enough to be relevant to the climate goals of ARM.

This study aims first at evaluating the accuracy of the simulated energy budget and cloud field, how they relate to each other, and also at investigating the major reasons for the differences between observations and the model. Basics questions addressed by this study are: how well is the surface radiative budget simulated, are the model errors explained by weaknesses in the parameterization of cloud optical properties, or by a lack of aerosols in radiative calculations, and how important are the errors related to differences in the cloud cover (e.g., no cloud versus cloud)?

In the present approach, the boundary conditions, including surface and large-scale forcings, are not prescribed, as it is done for SCM runs, but calculated by the model. As a result, within this “less controlled” framework, differences between the model and observations can sometimes be related to inaccurate surface and/or large-scale forcings. However, because the subgrid (parameterized) processes and the resolved motions are tightly coupled, this type of error also helps identify weaknesses of parameterizations. Furthermore, this analysis provides some guidance on the relevance of using outputs from mesoscale models to generate large-scale boundary conditions for SCMs (e.g., large-scale advection of ice anvils, Petch and Dudhia 1998).

Data and Method

In the study, we take advantage of an ensemble of MM5 real-time forecast runs that were performed by Jim Bresch for the Storm and Mesoscale Ensemble Experiment, spring 1998 (SAMEX '98). The resolution was 30 km for the outer domain, which covered the 48 contiguous states of United States, and 10 km for the inner two-way nested domain, which included, in particular, the Southern Great Plains (SGP) site (Figure 1).

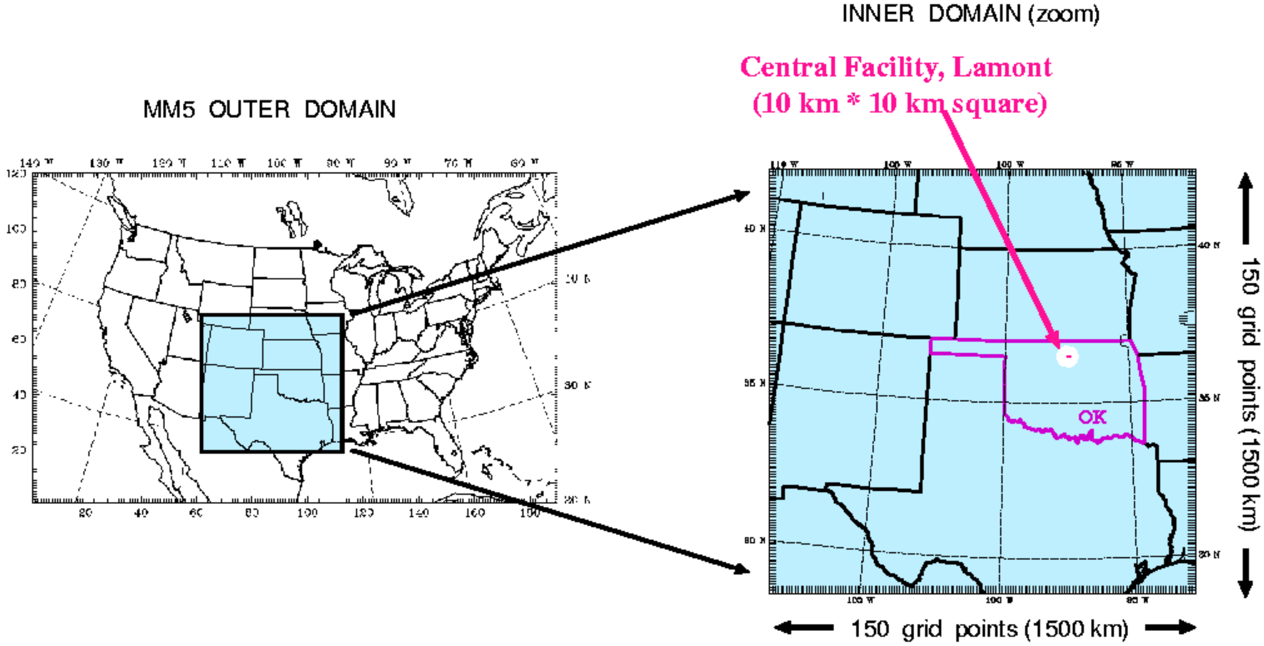

Figure 1. Domain simulated with MM5. The grid point corresponding to the central facility site is indicated by a red square (surrounded by a white disk).

The simulated period extends from April 15, to June 23, 1998. Each day, a 27-hr run was performed, except for a few missing days. Initial and boundary conditions were generated from the National Centers for Environmental Prediction's "early-ETA" analysis, MM5 initial conditions, and available surface and upper air data. The runs were non-hydrostatic, with full-physics. Parameterizations included, in particular, the radiation scheme of Dudhia (1989), the National Centers for Environmental Prediction's (NCEP's) medium range forecast (MRF) boundary scheme, an explicit moisture scheme (with simple ice physics), and the cumulus parameterization of Grell (1993).

The model time series is created from the last 24 hr of each run. The evaluation is performed for a single vertical column of the model corresponding to the location of the ARM SGP central facility in Oklahoma. In Figure 1, the red square surrounded by a white disk indicates the (small) size of the horizontal area covered by the simulated column. This obviously stresses the challenge encountered by the model for this "strict" evaluation. For instance, it may happen that a mature cloud passing across the central facility was initially correctly initiated in the model (right timing and location). However, a small error in the propagation speed or direction, or a rapid dissipation of the cloud as it passed through a simulated area dryer than observed has resulted in a cloud that never reached the central facility. In that case, the model will be in error.

Various sources of data are available at the ARM site. A large ensemble of independent measurements characterizing the surface budget and cloud field is used hereafter; it includes in particular the Surface Meteorological Observation System (SMOS), Energy Balance Bowen Ratio (EBBR), Baseline Surface Radiation Network (BSRN), the Millimeter-wavelength Cloud Radar (MMCR), Microwave Water Radiometer (MWR), and the Balloon-Borne Sounding System (BBSS). Observed data are usually sampled on a much finer timescale (~ a few sec.) than needed for this type of analysis (~30 min. or more), so that the main processing applied to observed data consists in systematically averaging over a proper timescale.

Evaluation of Surface Parameters

The examination of surface parameters gives a first synthetic insight on the accuracy of the simulated surface energy budget, but also on the relevance of the simulated cloud field, through its large signature on radiative fluxes.

Time series of precipitation (Figure 2) indicates that the model captures most of the rainy events, especially the stronger. In terms of intensity, the agreement for each individual event also appears reasonable, given the framework of this evaluation. This also gives confidence in the realism of the water fluxes that are provided to the soil model implemented in MM5 (Chen and Dudhia 1999). The 7-day mean simulated rainfall rate is however larger than observed, mainly because of a systematic overestimation of the rainfall rate during strong convective events. The reasonable simulation of surface rainfall suggests a good timing of those clouds which are precipitating but does not guarantee the accurate simulation of the whole variety of clouds that play a role in the SGP radiative budget at Lamont. This is further investigated with the help of surface radiative fluxes.

The largest day-to-day fluctuations of the downward shortwave (SW) radiative flux are related to variations of the cloud coverage (Figure 3, upper panel). Many of them are associated with the rainy events. These fluctuations are also well captured by the model (Figure 3, lower panel). A close day-to-day examination shows that the model also captures the occurrence of several cloudy but non-rainy periods. Indeed, the 70-day mean simulated SW downward flux departs from the measured flux by less than 15 Wm^{-2}. Moreover, a typical problem with pyranometers used to measure this flux is a tendency to underestimate the actual flux by several Wm^{-2} (D. Slater, personal communication). The underestimation likely reaches 5 Wm^{-2} to 10 Wm^{-2} for the present time period. Therefore, it seems that the model only slightly overestimates the SW downward flux at the surface, by 5 Wm^{-2} to 10 Wm^{-2}. On a daily timescale however, the error is usually much larger. When the timing of rainy events is not well reproduced, the simulated day-mean SW downward flux can depart from observed by more than 100 Wm^{-2} (for example day 21, Figure 4). On a longer timescale also, a few other important factors have been identified, that induce a systematic overestimation of the SW flux at the surface. This is particularly clear for days 43 to 50 (Figure 4). For this period, the simulated column is almost

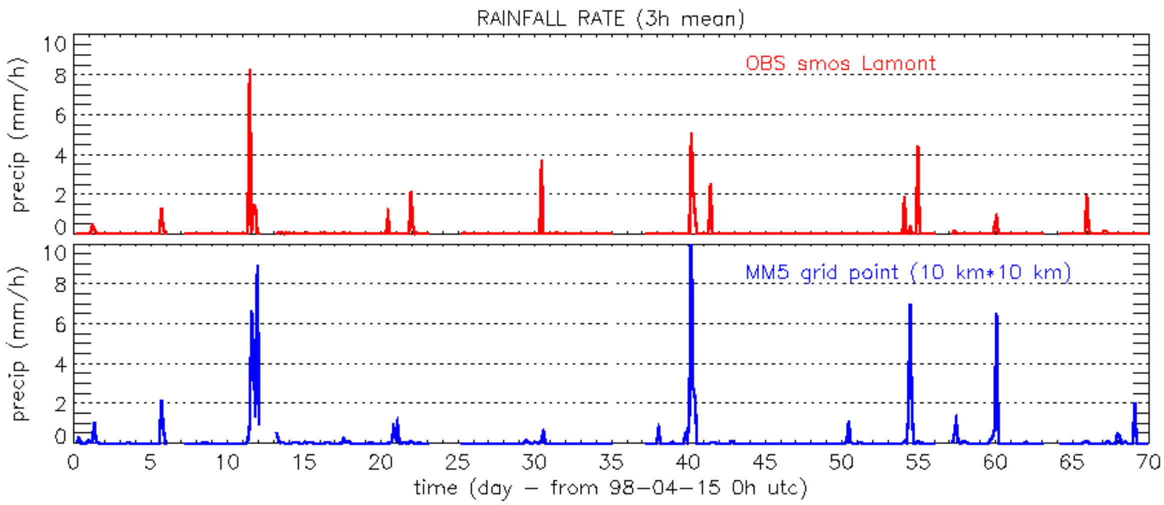

Figure 2. Time series of rainfall rate as observed (upper panel, red line) and simulated (lower panel, blue line) at the central facility.

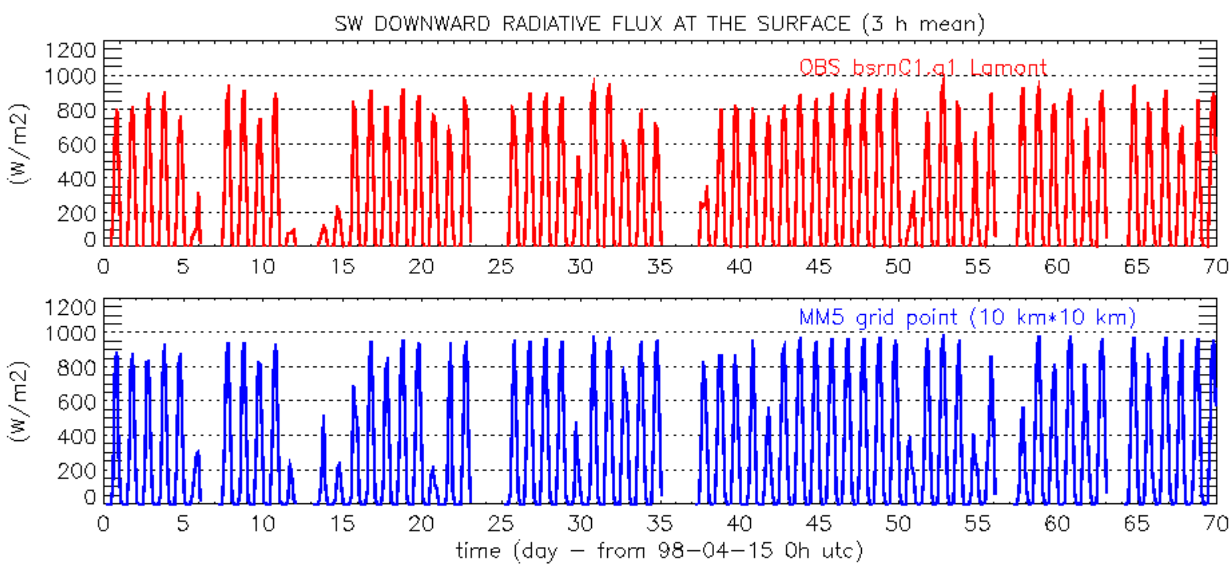

Figure 3. Same as Figure 2, except for the SW downward flux at the surface (upper panel measured, lower panel simulated).

completely clear, whereas the MMCR data indicate the frequent presence of thin high cirrus (from May 27, to May 31, 1998, in particular). Among the various causes leading to the underestimation of cirrus in the model, the "framework" might play a role too. In effect, the simulated time series consists in an ensemble of daily runs. Each day, the cloud cover is totally removed, when the model is re-initialized. Therefore, it seems difficult to keep track of thin long-lived cirrus from one day to the other. The utilization of the model in a four-dimensional data assimilation (FDDA) mode (Parsons and Dudhia 1997) may contribute to improve the simulation of thin cirrus. Also, when both the model and the

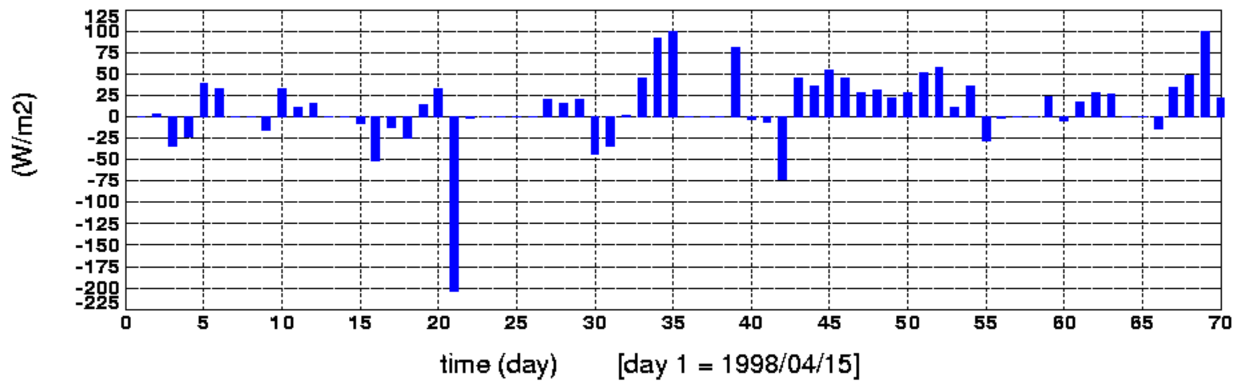

Figure 4. The daily (24-h) mean difference between simulated and measured SW downward flux at the surface.

MMCR indicate clear-sky conditions, the simulated SW downward flux can still be larger by a few tens of Wm^{-2} than observed (e.g., day 49: June 2, 1998). In fact, under clear-sky conditions, the observed SW downward flux shows much more day-to-day variations than simulated. This suggests that the lack of aerosols in the model is likely to play a role in the model overestimation of the SW downward flux at the surface. Finally, a first evaluation of simulated low level clouds also reveals an overall underestimation of this type of clouds, as compared to radar MMCR data. Further analysis is needed for this type of cloud.

Time series of simulated and observed longwave (LW) downward fluxes at the surface is shown in Figure 5. The general trend over the season is well captured, beginning with values around 300 Wm^{-2} in April, and then gradually increasing up to more than 400 Wm^{-2} in late June. Sudden increases associated with the occurrence of clouds are also fairly well reproduced (e.g., days 14 and 54). The simulated flux agrees quite well with observations during the first 20 days. After that period, however, it is generally overestimated by values of the order of several tens of Wm^{-2}. A careful examination shows that this bias is not associated with clouds. In fact, under cloudy conditions, model and observations usually agree, for example, for the days 50, 55, and 60. At the same time, the bias is too large to be explained by errors in the simulated thermodynamical fields. A better understanding of this problem is achieved with the help of off-line tests. Fourteen fully clear-sky days are extracted from the whole time series, and MM5 thermodynamical profiles are used as input for three different radiation schemes, namely MM5, Community Climate Model Version 3 (CCM3) radiation schemes, and Rapid Radiative Transfert Model (RRTM). Both the CCM3 radiation scheme (Kiehl et al. 1998) and RRTM (Mlawer et al. 1997) lead to a substantial improvement compared to the standard radiation scheme, with a systematic reduction of the downward longwave radiative flux at the surface. This decrease is explained by differences in the treatment of water vapor radiative properties in the LW interval. This is illustrated in Figure 6, which shows that the difference between the fluxes computed with CCM3 and MM5 radiative schemes increases almost linearly with the precipitable water amount. The slope is of the order of 2 W kg^{-1}. This explains why, in Figure 5, the agreement with observations is quite good during the first relatively dry 20 days, but worse latter on, as the total precipitable water increases significantly.

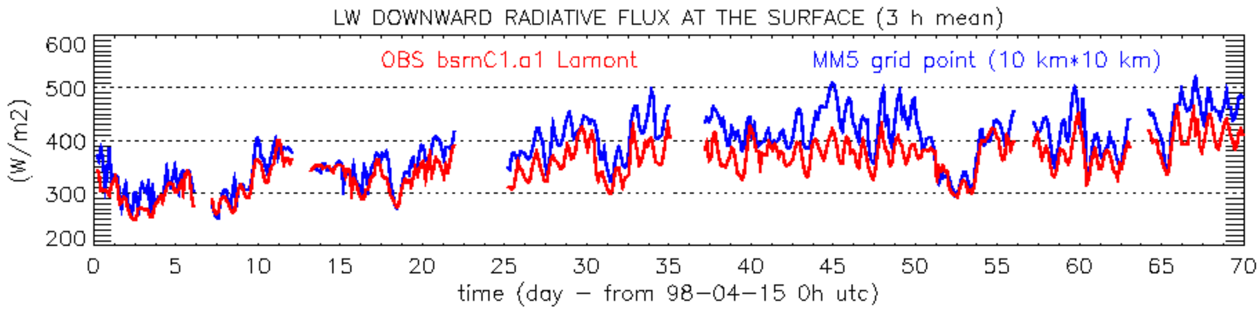

Figure 5. Same as Figure 2, except for the longwave downward flux at the surface.

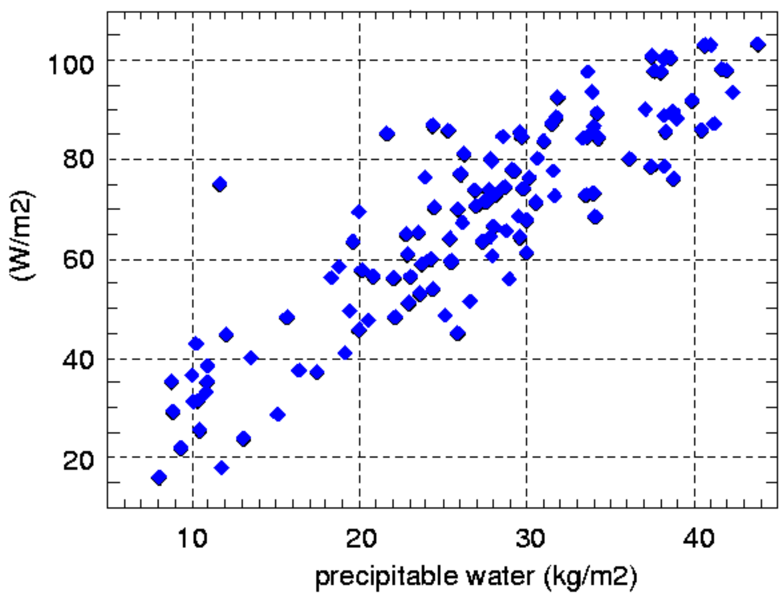

Figure 6. Scatter plot of the differences between clear-sky LW flux at the surface as simulated with MM5 and CCM3 radiation as a function of precipitable water off-line test with 14 clear-sky days (~110 profiles).

Improvement of MM5 with RRTM LW Radiation Scheme

The existing radiation scheme (Dudhia 1989) was designed first to interact with clouds. At the same time, it was important to keep a scheme efficient in terms of computational cost. However, it is likely that a more sophisticated parameterization of radiation becomes necessary for specific types of study, in particular when the surface energy budget is involved.

Previous off-line radiation tests show that either CCM3 or RRTM LW parameterizations improve the simulation of the downward LW flux at the surface. Here, the impact of implementing an alternative radiation in the model is analyzed with a few on-line tests. Results from two additional runs are presented for May 29, and compared to the standard run. This day, very moist and clear, corresponds to a particularly critical case. A first run is performed with CCM2 radiation (Hack et al. 1993, NCAR Technical Note 382)—noted CCM2 RAD—and a second one with RRTM LW radiation scheme (+ standard SW radiation).

Figure 7a clearly shows the large improvement that is achieved in this fully coupled run. It consists of a homogeneous shift of more than 50 Wm^{-2}. Now, model and observations agree within less than 20 Wm^{-2}. The spikes in the observed flux (e.g., at 12 h and 17 h) are related to the presence of clouds. At the same time, there was no cloud in the model, so that this feature is not reproduced. It is also worth noticing that the two radiative schemes—RRTM and CCM2 RAD—lead to surface fluxes values that differ by up to 20 Wm^{-2}.

An interesting consequence of the improvement of radiative fluxes occurs at the surface (Figure 7b). In the standard runs, surface air frequently does not cool enough at night. For this particular case, temperature was especially too high at the end of the night by more than 4 K. This is not any more the case, and the slope of the nighttime cooling is now very close to observed, with RRTM and CCM2 RAD. Both schemes also act to reduce the overestimation of sensible heat flux that was found in the standard run under clear-sky conditions, thus resulting in an improved surface energy budget.

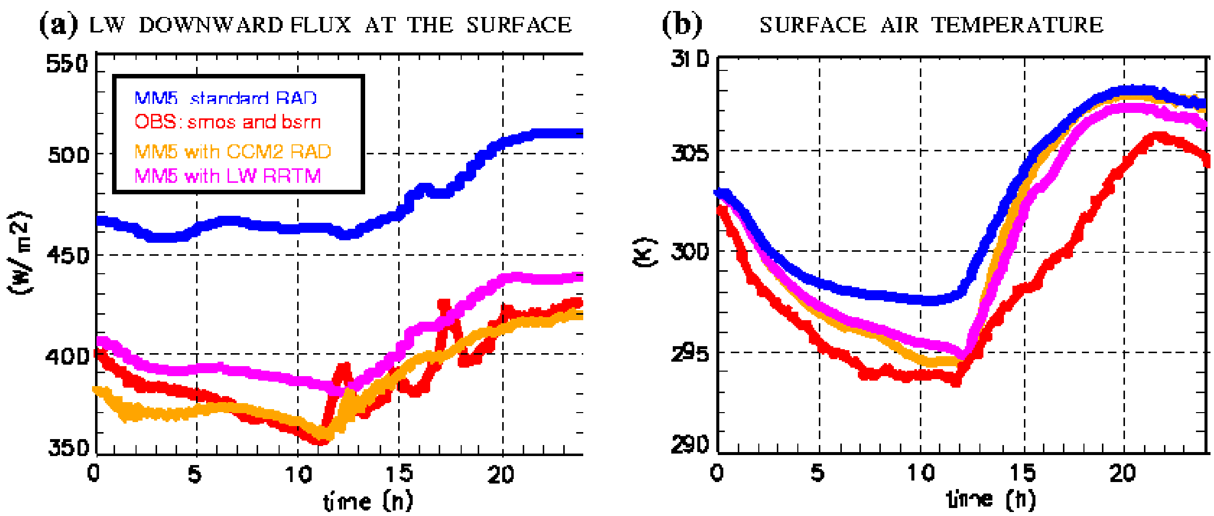

Figure 7. The comparison of surface parameters simulated by MM5 with various radiative schemes and observations, for runs of the day May 29, 1998 (day 44).

Mean atmospheric cooling rates, Qrad, are presented in Figure 8. Above 800 mb, values of Qrad are relatively close to each other for the three radiation schemes. Major differences occur below: the downward LW flux at the surface is larger in standard runs together with a stronger cooling rate at low levels. For this particular case, the difference is quite significant, and is probably balanced by vertical fluxes, propagating the bias to the surface. Such a difference should also impact the representation of boundary layer clouds in the model.

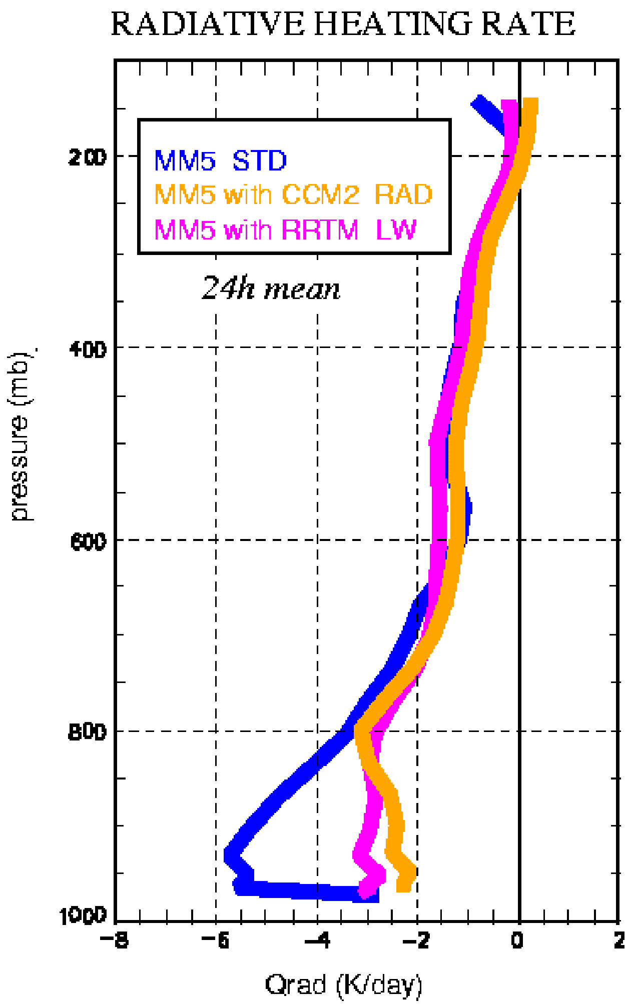

Figure 8. 24-hr mean radiative heating rate for MM5 simulations of the day May 29, 1998.

Evaluation of Thermodynamical Profiles

Simulated thermodynamical fields are evaluated with sounding data. The 101 soundings available at 0 hr Universal Time Coordinates (UTC) and 12 hr UTC are used and compared with model instantaneous fields at the same time, after interpolation on the model vertical grid. ("0 hr UTC" in the model corresponds to simulated profiles after 24 hr of simulation, not at the beginning of the simulation. The initial fields usually agree much better with observations.) The seasonal trend and smaller scale variations are fairly well reproduced by the model, as illustrated in Figure 9 for the vertically integrated temperature. Indeed, most of the time, the integrated temperature remains within 1 K from observed. The largest departure is related to a precipitating event that was not reproduced by the model (day 20).

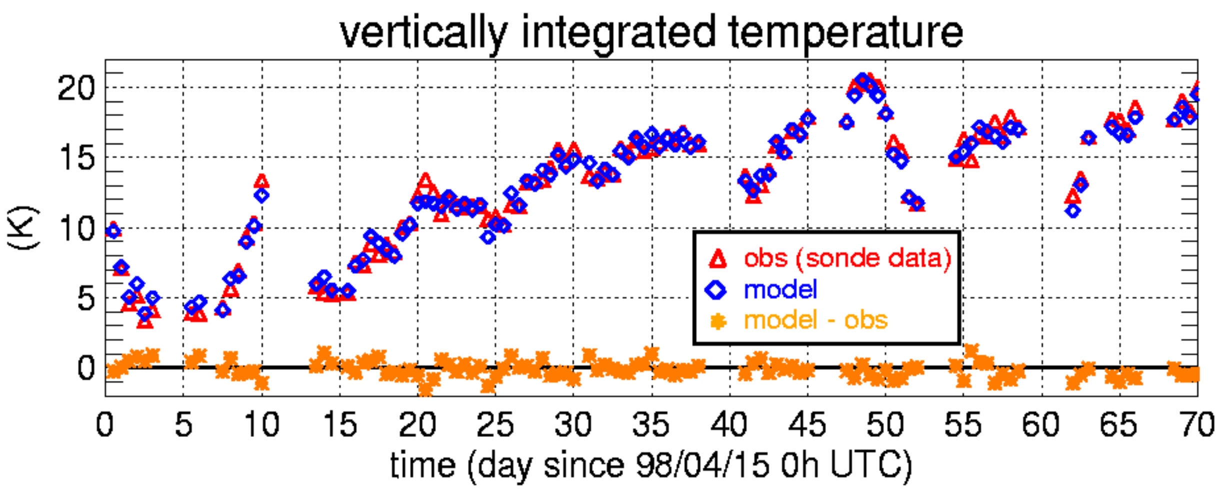

Figure 9. Vertically integrated temperature (observed initial value + 10 K), derived from sounding data (red triangles), simulated (blue diamonds), and the difference model minus observations (orange stars).

Errors tend to compensate each other during the first 35 days. This is not the case, however, for the second half of the time series, characterized by a cold bias on average. This feature suggests that the LW parameterization plays a role in this result, and that the cold bias should be much reduced with a more sophisticated LW radiation scheme.

On average, simulated temperature departs from observations by less than 1 K at any level (Figure 10a). The vertical structure of the difference between model and observations is coherent with the previous analysis, with a cold bias below 600 hPa, except for the lowest level of the model, warmer by 0.4 K.

Mean simulated moisture profile is within 1-g kg^{-1} from measured (Figure 10b). On average, the model is moister than observed, with a maximum bias around 800 hPa. This comparison somehow overestimates the moisture bias. In effect, measurements at this site (with Vaisala sondes) do show a moist bias that is maximum in spring-summer (S. Richardson and B. Lesht, personal communication). The bias usually increases in height and intensity from the end of the night (12 hr UTC) to the end of the afternoon (0 hr UTC), and is coupled to a similar time-height variation of the cold bias maximum. It is unlikely that errors in surface moisture fluxes (larger than measured by 10 Wm^{-2} to 20 Wm^{-2}) explain the magnitude of the upper boundary layer bias. Indeed, the coupled T-qv bias suggests that it is related to the previously noted underestimation of shallow cloud in the model.

Finally, despite some discrepancies, time series of temperature (and moisture to a lesser extent) shows a satisfying agreement with measurements. Moreover, it is likely that the implementation of RRTM LW radiation scheme will help improving these fields. The model thermodynamical state always stays close to real atmosphere, which also contributes to the reasonable simulation of the cloud cover previously noted. Although this result is not extremely surprising (the model is re-initialized every day), it gives some confidence that this type of fine scale model, as a complement to "purely observed data sets," represents an interesting tool for evaluating and improving parameterizations that are used in large-scale models.

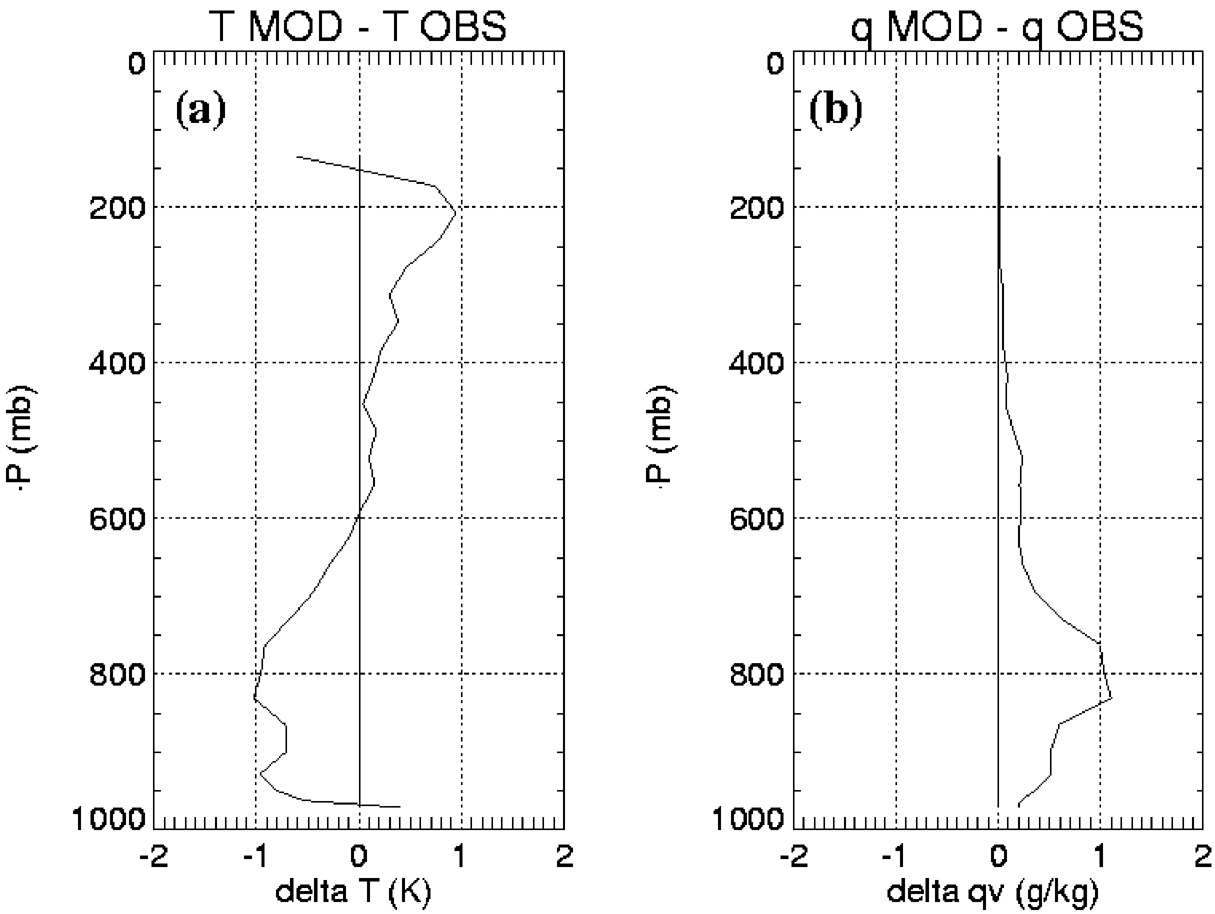

Figure 10. The difference between simulated and observed profiles of (a) temperature and (b) mixing ration (average over 101 profiles).

Summary

This study has presented an evaluation of the surface energy budget and cloud field simulated by the mesoscale model MM5 at the SGP central facility site in Lamont. The analysis is performed on a seasonal timescale, with the help of the continuous flow of data provided by ARM, for the period April 15, 1998, to June 23, 1998. Model outputs were generated from time series of daily runs performed over North America with a 10-km grid mesh at the Lamont site. The analysis shows that the model captures fairly well most of the precipitating events. The cloud cover also compares favorably with radar data, although low level clouds and thin cirrus is frequently underestimated. The average SW downward flux is within 5 Wm^{-2} to 10 Wm^{-2} from observed. The underestimation of cirrus and the absence of aerosol radiative effects in the simulation partly explain the model overestimation of the SW downward flux. An overestimation of the downward LW flux at the surface was also found under clear-sky condition, for moist atmospheric condition. This problem disappears with the implementation in MM5 of the LW radiative scheme RRTM.

Finally, simulated thermodynamical profiles agree within 1K and 1g kg^{-1} with sounding data on average over the whole period.

The present study first shows that this type of approach is indeed suitable for a mesoscale model. The availability of data stream over long timescales proved to be very valuable. For instance, weaknesses of the LW radiation scheme were season related (through the precipitable water seasonal cycle). The level of accuracy of the cloud cover also suggests that this type of fine scale simulation is an appropriate testbed for testing and improving cloud microphysical and radiative parameterizations. Finally, it would be interesting to investigate the relevance of large-scale forcings derived from the model compared to those diagnosed from observations.

Acknowledgments

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