Characterization of the Atmospheric State: Lower Boundary Condition

J. C. Doran, J. C. Barnard, J. M. Hubbe, J. C. Liljegren, W. J. Shaw and S. Zhong
Pacific Northwest National Laboratory
Richland, Washington

G. J. Collatz
NASA/Goddard Space Flight Center
Greenbelt, Maryland

D. R. Cook and R. L. Hart
Argonne National Laboratory
Argonne, Illinois

Introduction

It is convenient to consider two broad categories of climate-related modeling studies for which it is necessary to specify some kind of lower boundary conditions. The first of these categories is the use of general circulation or weather forecasting models, perhaps modified to carry out climate simulations. In these models, one normally has to specify something about the albedo of the surface to get the radiation balance right, the surface roughness to get the momentum exchange right, and the surface moisture availability to get the surface heat and water vapor fluxes right. Correctly specifying the surface moisture availability can be a major problem and may involve a sophisticated land surface parameterization scheme to take into account plant and soil characteristics. It is reasonable to expect that misrepresenting the water vapor flux by 10-20% on average over continental scales could lead to significant errors in simulated precipitation, temperatures, and circulation patterns.

The Atmospheric Radiation Measurement (ARM) Program is focused, however, on clouds and radiation; and it has chosen Cloud and Radiation Testbeds (CART) as the principal tool with which to carry out its work. In this context, what we need to be concerned about for the lower boundary conditions is somewhat different. What we want to know is how the incoming radiation is partitioned into various components by surface processes, and—more importantly—what is the resultant sensitivity of the cloud and radiation fields to that partitioning. These features then determine the accuracy to which we need to describe the lower boundary conditions.

It is convenient to divide this need into two categories as well: what is required by those concerned with instantaneous radiative fluxes (IRFs) and what is required by those more concerned with single column models (SCMs) or cloud ensemble models (CEMs). In the former category, there is relatively little need to deal explicitly with most surface processes because the effects of those processes can be measured directly (e.g., the water vapor profile over the Southern Great Plains [SGP] CART). One possible exception is the treatment of surface albedo in places such as the Arctic; other exceptions might be thought of, but, in general, the lower boundary conditions are unlikely to be a major concern for IRF needs in the near future.

Those concerned with SCMs and CEMs may not be so fortunate. Over the scales on which they work—hundreds of kilometers or more on a side—it is generally not possible to directly measure the effects of energy partitioning at the surface, yet that partitioning may affect the predictions of the various models. Thus, it is useful to consider in what ways surface conditions can affect quantities of interest for SCMs and CEMs, how sensitive the models are to such effects, how well we can now specify the relevant properties of the surface, and what we can expect in the near future.

In a column over the SGP CART, typical values of sensible and latent heat fluxes, averaged over 8 hours, are on the order of a few hundred W m^{-2}, although either or both may change by factors of two to three over more limited regions. Such fluxes can heat the boundary layer (BL) by several K during this time and moisten it by a few g kg^{-1}. While these are not insignificant amounts, if we can estimate these fluxes to an accuracy of about 20%, then the resultant errors would be on the order of 1 K and 0.3 g kg^{-1}. Those values are not particularly large compared with the uncertainties that can be introduced by current limitations on describing the lateral boundary conditions for SCMs and CEMs.

There are possible complications, however, that make the matter not quite so simple. The first complication is that the surface fluxes are not uniform over a site such as the SGP CART. The conventional wisdom, derived almost exclusively from mesoscale modeling studies, has been that variations in surface fluxes lead to variations in the thermal structure of the BL. These thermal inhomogeneities result in pressure gradients that produce secondary circulations, these circulations produce regions of convergence and divergence, and these processes redistribute heat and water vapor in the atmosphere (through what are known as mesoscale fluxes) in a manner that is not described by conventional descriptions of turbulent fluxes. Finally, this redistribution can lead to significant changes in BL profiles of temperature and water vapor.

While the SGP CART does not have the simple land use patterns normally specified in numerical studies of such effects, it does have striking contrasts in vegetation properties across the site, especially in the summer months after the winter wheat crop has been harvested. Using a land surface parameterization model and CART data to determine the required meteorological, vegetation and soil information, we can calculate the resultant distributions of sensible and latent heat fluxes across the CART. Under some conditions we find large flux contrasts, which suggests that there is the potential for producing secondary circulations that can significantly affect the structure of the BL. We have tried to demonstrate that significant secondary circulations are induced by these flux contrasts at the SGP CART or that mesoscale fluxes need to be considered for ARM modeling purposes, but so far we have had little success. With the exception of sea breeze effects, we do not believe anyone else has been able to show that thermally induced secondary circulations actually occur in nature to any important degree either, at least on scales important for the single column modelers or cloud ensemble modelers. This is not a particularly popular view among some investigators, but it is a view that we think is basically correct.

There is another possible complication, however, that may be more important. There is rather more evidence that cloud formation and properties are sensitive to the values of local surface heat and water vapor fluxes, at least on scales of 10-50 km. This sensitivity occurs because the BL structure can be modified locally, affecting the probability of cloud formation; the amount of water in the clouds; their geometry; and, possibly, the potential for deep convection. To study this, we have carried out a series of simulations with the Regional Atmospheric Modeling System (RAMS) mesoscale model, with explicit cloud microphysics and four nested grids; the innermost grid had a resolution of 2 km. We compared the simulated cloud liquid water content when the model was driven by spatially varying and by uniform surface fluxes. In one test, the mean cloud thicknesses differed by 30% in these two cases, and the mean integrated liquid water contents differed by a similar amount. If that kind of accuracy is acceptable for modeling fair weather cumulus clouds, then there is not a great deal to be gained by accounting for the spatial variations in the fluxes. If that kind of accuracy is not, or if one is also interested in the spatial distributions of cloud properties, then the spatial heterogeneities in the surface fluxes may need to be accounted for explicitly.

Cloud properties are affected not only by the distributions of surface fluxes but—if the fluxes are assumed to be spatially uniform—are also affected by the average values of those fluxes. To what accuracy, then, must we describe the partitioning of energy at the surface to obtain an acceptable result as far as cloud properties are concerned? To address this problem we have carried out a limited number of simulations in which the energy partitioning was changed so that the sensible and latent heat fluxes were increased or decreased relevant to some base state. We found relatively little effect when the sensible heat was increased by 20%, but more significant changes when the increase was 40%. Although our sample is obviously quite limited, we have made the working assumption that an accuracy of 20% in the flux partitioning is thus likely to be acceptable, but that 40% is not.

How well can we now specify the lower flux boundary conditions? There are a number of ways to estimate surface fluxes, and two of them are briefly considered here. The first is by direct flux measurements with ground stations, and the resultant accuracy then depends on factors such as the number of stations, their location, how representative of the CART those locations are, and so on. An alternative is to apply some sort of land parameterization scheme to calculate the fluxes, perhaps constraining the calculation with some collection of observations.

Let us begin with the measurements. Until recently, energy balance Bowen ratio (EBBR) stations have been the only regularly archived sources of surface heat and water vapor flux measurements at the SGP CART. The EBBRs are rather well distributed over the CART, and one might thus expect that if we simply average the flux values from those sites we would get a reasonably good mean value for the CART. Because of their geometry, however, the Bowen ratio stations have been restricted to pasture and areas of natural vegetation rather than cultivated fields. Because so much of the CART is planted in winter wheat and other crops, the use of EBBR data alone is likely to give a biased estimate of the fluxes over the area. In summer, for example, the harvested winter wheat areas can be expected to have high sensible heat fluxes and low latent heat fluxes compared with areas sampled by the EBBRs. Thus, the EBBR sensible heat values might be expected to be biased low compared with the true site-wide average.

We have also used a land surface parameterization model to calculate surface fluxes over the CART. The approach is to break the CART domain into small grid cells, determine the meteorological fields—temperature, wind speed, vapor pressure, precipitation—from ARM and other measurement networks, extract vegetation information from satellite data, specify soil types from one or more data bases, run the model for each small grid cell for whatever the time period of interest is, and then average the results over all the grid cells to extract the CART-averaged fluxes. In principle, this approach should avoid the bias introduced by simply averaging the EBBR data, but it will introduce its own set of uncertainties because of the structure of the model and a number of approximations and assumptions that were made to apply the model in this mode. Comparisons of the model results with observations show promising, but by no means perfect, agreement with observations.

Figure 1 shows comparisons from a 10-day period in July of 1995 of the sensible heat flux averages computed from the Bowen ratio stations and the site-wide average computed from the land surface model. In some cases (e.g., days 196-198) the results are very close; in other cases, the model maximum is as much as 100% higher than the data. We find corresponding problems with the latent heat fluxes, although the differences are not as large. The differences in the results of the two sets of sensible heat flux averages are consistent with the expected bias in the EBBR values described above.

Does this mean that we should use a land surface parameterization scheme to calculate fluxes and throw out the Bowen ratio data? Not at all, because models have their own set of problems that need to be worked out. However, it does mean that, at the moment, we should not have any real confidence that the flux estimates we are getting from the Bowen ratio data are good to the 20% figure that was suggested as a reasonable goal.

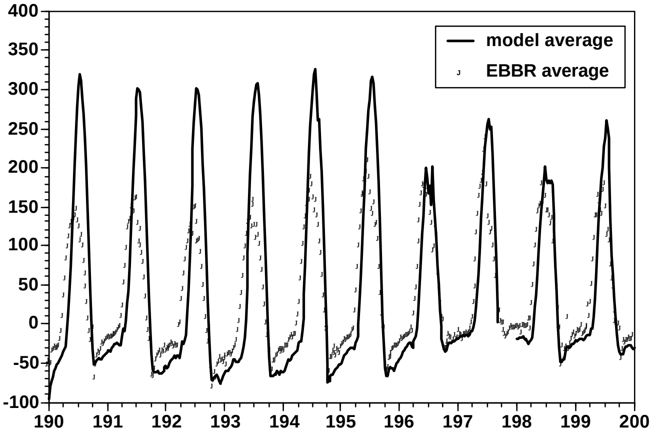

Figure 1. Comparison of CART sensible heat fluxes derived from averaging data for ten EBBRs and from averaging the results of a land surface parameterization model applied to the CART domain.

Where do we go from here? First, eddy correlation instruments are now collecting data from a variety of other locations—agricultural fields, in particular—that should make the averages from the flux stations more representative. Next, continued refinements in land surface parameterization schemes are being made, additional comparisons against observations are being carried out, and further improvements in performance may be expected. Other measurement and analysis approaches, such as those used to extract effective fluxes from measurements of BL structure, are also available; and these can provide additional cross-checks on values obtained from both models and flux data averages.

Site-wide surface flux averages with an accuracy of 20-25% are thus probably achievable in the next year or two, and those should suffice for many purposes of the ARM Program at the SGP CART. There are ongoing studies to determine whether additional refinements are necessary to adequately treat more unstable conditions that can trigger deep convection. These processes are typically dominated by synoptic forcing, and early indications suggest that the influence of surface fluxes is usually, but not necessarily always, small. Thus, some further exploration of this issue will also be necessary.