Weaver and Avissar (2001; hereafter WA01) investigated the response of the atmosphere to landscape heterogeneity to assess the importance of mesoscale fluxes of sensible and latent heat arising from differences in land use in the southern Great Plains. To do so they used the RAMS mesoscale model (Pielke et al. 1992) and a surface flux dataset (Doran et al. 1998) derived from observations and the Simple Biosphere Model (Sellers et al. 1996). They selected 6 days for analysis based on the criterion that the study region located at the Department of Energy’s Atmospheric Radiation Measurement Program’s Cloud and Radiation Testbed (CART) was not obscured by clouds with obvious nonlocal origins. WA01 noted that mesoscale fluxes of latent heat on those 6 days were large, especially near and above the top of the boundary layer. They argued that regions of strong vertical motion that they associated with mesoscale fluxes were closely correlated with regions of precipitation on 1 of the 6 days they studied and with cloudy regions on 2 other days. From these findings, WA01 concluded that landscape heterogeneity arising from human influences can “significantly affect local weather and climate.” They further concluded that the inability to predict mesoscale fluxes is a serious failing of general circulation models (GCMs) used to predict climate change and that further studies in parameterizing such fluxes for use in GCMs is therefore necessary. In these comments we offer a somewhat different interpretation and perspective on the findings of WA01.

**APPROACH.** Before beginning our discussion we would like to make some preliminary comments. First, we compliment WA01 for their efforts in this area. We have urged an approach such as theirs for some time, and we have carried out some related studies in our own earlier work (Doran and Zhong 2000; Zhong and Doran 1997, 1998). We believe that careful modeling exercises such as those described by WA01 are quite valuable and capable of providing useful information. Second, we acknowledge that under some circumstances vertical motions triggered by subgrid-scale land use differences may contribute to the development of clouds and convective precipitation; in fact, we have identified a possible example in an earlier paper that did not explicitly focus on this issue (Doran and Zhong 2000). We suggest, however, that the significance of mesoscale fluxes for climate studies may be overstated in the WA01 paper and that the methods of analysis used by WA01 may contribute to this problem.

In our remarks below we use findings derived from the results of RAMS model simulations we had previously carried out over the past several years. Those simulations were used to investigate the effects of heterogeneous land use patterns in the CART, and the spatially varying sensible and latent heat flux values used by us as lower boundary conditions were the same ones we provided to WA01 for their study. Most of our RAMS simulations were originally done using a horizontal grid spacing of 6.25 km for the innermost nested grid. There had been some concern expressed, however, that such a resolution is too coarse to resolve mesoscale circulations adequately, so we had also repeated a number of our simulations using a finer grid with a 2.08-km grid spacing (e.g., Doran and Zhong 2000). We did this for some but not all of the days WA01 chose for their analysis. Our grid spacing was nearly the same as that used by WA01 (2.0 km), and the fine-resolution domains used by WA01 and us were also similar. We compared some of our results with those of WA01 and found generally common features. For example, the vertical velocity patterns...
shown in WA01’s Fig. 4a for 6 July are easily recognized in our own results (not shown), and the magnitudes of the vertical velocities in the figure and the maximum vertical velocity for that day quoted in their Table 1 are comparable to those we obtained. Thus, we are confident that differences of interpretation between WA01 and us do not arise from any systematic or other important differences in results of our simulations and theirs.

**DISCUSSION.** Why, then, do we suggest another perspective may be in order? We have three reasons for this suggestion. First, we believe that the effects of mesoscale fluxes arising from land use differences within a GCM grid cell may indeed be important for precipitation and cloud formation locally and at certain times, but they are unlikely to have a demonstrably significant impact on climate as simulated by GCMs. Second, we suggest that an analysis of the importance of landscape heterogeneity in terms of profiles of mesoscale fluxes of latent heat may not be a particularly informative approach and can even be misleading. Finally, we feel that until a much more compelling demonstration of the effects of mesoscale fluxes on the quantities predicted by GCMs is produced, WA01’s call for further efforts in parameterizing the effects of such is premature.

We begin with a discussion of precipitation. WA01 show that areas of precipitation that developed on 13 July 1995 occurred near regions in which the simulated vertical velocities were large, on the order of 1 m s\(^{-1}\) at an altitude of approximately 1100 m AGL. Although they make a persuasive case that mesoscale fluxes helped to trigger this precipitation, the conclusion that this effect is therefore an important factor for climate may not be justified. Figure 1 shows a plot of the domain-averaged precipitation totals over the study area, which is approximately the size of a typical GCM grid cell, for a 55-day period during the summer of 1995; the totals are derived from the Next Generation Weather Radar (NEXRAD) stage III data obtained from the Arkansas–Red River Forecast Center and the temporal resolution for these data is 3 h. The arrow in the figure identifies the period 1500–1800 LST on 13 July that WA01 described. The contribution from this time period to the overall precipitation totals is nearly negligible and it is not at all apparent that the failure of a GCM to produce this precipitation event would be a serious indictment of the model’s performance. The large amounts of precipitation found on many of the days during the summer were associated with much larger-scale processes, which are unlikely or at least very difficult to show to be linked to mesoscale fluxes induced by landscape heterogeneity within a GCM grid cell.

A similar comment may be made about cloud fraction. WA01 note that no clouds were observed in the satellite images on 3 of their 6 case study days, all of which had conditions that were considered favorable for development of strong land use–induced mesoscale circulations. On the 3 days when clouds were observed and were linked to the simulated areas of updrafts in the domain, the extent of the observed clouds was rather limited so that the effect on the fractional cloud cover for the domain was quite small. Again, it is questionable whether the failure of a GCM to explicitly simulate such a small fractional cloud cover on a few days should be construed as an important feature in a climate simulation. We have previously argued (Zhong and Doran 1997) that the inability of GCMs to resolve subgrid-scale variations in the ambient meteorology is likely to be at least as important, and probably more important, than the inability to represent the effects of subgrid-scale land use differences, and we find little in the recent results of WA01 to indicate otherwise.

We next turn to the issue of mesoscale fluxes. In their Fig. 5, WA01 show a large domain-averaged mesoscale flux of latent heat at 1600 LST on 13 July 1995 between approximately 1500 and 3000 m AGL. Based on these results and similar results from the other days they analyzed, they conclude that it is necessary for GCMs to parameterize such fluxes. We have two difficulties with this conclusion. First, the case they have chosen to show (13 July) has the largest mesoscale latent heat flux of the 6 days they studied. One other day (7 July) has a similar magnitude flux, but on 2 days (6 and 12 July) the magnitude is roughly two-thirds as great, and on 2 other days (12 and 21 July) the magnitude is only about one-third as large. Second, just as the effects of subgrid-scale land use differences on clouds and precipitation were small
Fig. 2. Simulated vertical profiles of potential temperature and water vapor mixing ratio averaged over the CART domain for variable (solid) and uniform (dashed) flux cases at 1600 LST, 6 Jul 1995.

(even for the 13 July case), so too are the effects on boundary layer structure small when averaged over a domain the size of a GCM cell. For example, in Fig. 2 we compare vertical profiles of potential temperature and mixing ratio at 1600 LST on 6 July averaged over the CART and determined from simulations using spatially variable and spatially uniform (corresponding to the domain-averaged value) surface flux distributions. This day was an “intermediate” case whose maximum mesoscale latent heat flux was near the median value of the cases WA01 considered. There are some differences in the profiles simulated with the varying and uniform fluxes but they are rather small. Whether these differences are important as far as climate simulations are concerned is, at this time, a matter of opinion, but in our judgment they are not.

This brings us to our last point, the lack of a convincing demonstration that the performance of climate models is significantly and adversely affected by their failure to include the effects of mesoscale circulations. WA01 note that mesoscale flux processes “produce substantially more total LH transport . . . in the upper PBL, with correspondingly significant implications for production of clouds and precipitation.” If mesoscale flux effects are truly significant from a climate standpoint, then that should be evident in some measurable way. WA01 further note, however, that the circulations induced by heterogeneous land use “take on different orientations and peak locations in response to differences in large-scale meteorology.” If circulations are not anchored to specific landuse features, it will be difficult in practice to assess the extent to which climate models are affected by the failure to include the effects of mesoscale fluxes or to judge how much their performance would be improved if mesoscale fluxes were parameterized in some fashion. One possible indication might be a large and persistent underestimate in cloud cover and precipitation simulated by GCMs over or near regions of heterogeneous land cover, contrasting with clearly better performance in regions where the land cover is more homogeneous. WA01 found, however, that even in their RAMS simulations they were unable to produce realistic cloud cover and precipitation. Given this difficulty and the range of performance found in current-day climate models, it is unclear how a meaningful test of the sensitivity of such models with regard to mesoscale fluxes can be carried out.

In summary, we believe the phenomenon of mesoscale fluxes is indeed an interesting one and we agree with WA01 that there can be circumstances in which they affect local convergence and divergence patterns, vertical velocity fields, cloud formation, and precipitation. We suggest, however, that among the problems affecting climate models, the failure to include the effects of mesoscale fluxes has not been shown to be one of the more significant ones. Until such effects can be shown conclusively to be important for climate simulations, it is not apparent what can and should be parameterized. Perhaps some small (and difficult to verify) incremental improvements in climate models would result if the effects of mesoscale fluxes were somehow to be included, but we do not believe that the analysis presented by WA01 justifies a major effort in the development of such parameterizations at this time.

REFERENCES


We greatly appreciate that Doran and Zhong have taken the time to comment on our paper (Weaver and Avissar 2001, hereafter WA01). Before replying, we would like to point out that their own efforts in this area have been significant; in fact, our recent methods owe a great deal to their insistence that numerical studies of mesoscale circulations should, whenever possible, be constrained with realistic land surfaces and meteorological background conditions. In addition, we are indebted to them for providing their valuable Atmospheric Radiation Measurement (ARM) program’s Cloud and Radiation Test bed (CART) surface flux dataset to us.

As to their comment, Doran and Zhong make clear that they do not question the existence or (occasional) local importance of mesoscale circulations forced by a heterogeneous land surface, and their associated clouds, precipitation, and vertical transport properties. Rather, they question our further assertion that these mesoscale phenomena, in aggregate, can reasonably be expected to influence weather and climate on larger spatial and longer temporal scales. The corollary to this assertion is that a failure to account for these subgrid-scale effects is a deficiency of present-day climate models that should be corrected as soon as possible. It is our interpretation of our results, rather than the results themselves, which is criticized. Here we briefly clarify our own interpretations in the context of the concerns Doran and Zhong raise.

Doran and Zhong make several important points. These may be summarized as follows: (i) mesoscale circulations and vertical mesoscale fluxes arising from landscape heterogeneity are unlikely to influence climate at the general circulation model (GCM) grid-element scale or larger; (ii) mesoscale fluxes are not the best indicator of the importance of landscape heterogeneity effects; and (iii) given the presumed weakness of the case for the influence of mesoscale circulations and fluxes on climate, the improvement of GCM parameterizations should be focused in other areas.

In making their first point, Doran and Zhong show a time series of observed Arkansas-Red Basin River Forecast Center (ABRFC) ARM/CART-averaged precipitation during summer 1995 (their Fig. 1). They show that total, domain-averaged precipitation on 13 July, a day for which our results show a signature of precipitation generated by mesoscale circulations, was negligible relative to other, wetter days, when much more of the domain was covered by larger-scale precipitation systems. We suggest that this analysis, while valid, is perhaps overly simplified. We put forward two main arguments here. First, since Doran and Zhong are averaging over the entire ARM/CART domain, the totals they show reflect the combination of precipitation intensity and the proportion of the overall domain covered by precipitating clouds. If we focus on a smaller scale within their averaging area, for example closer to the scale of the individual shallow convective complexes present on 13 July, the intensity of the precipitation is not negligible in its particular local corner of the domain. Figure 1 shows ABRFC hourly precipitation, for the entire month of July 1995, at a single grid cell within the small area that experienced landscape-generated mesoscale precipitation on 13 July. It is true we have purposely chosen a location that received some of the largest amounts of rainfall form this mesoscale system; nonetheless, at this location, the landscape-heterogeneity-related event was one of the most significant rainfall events of the entire month. In addition, the rainfall here will have affected local soil moisture, and such changes to the “memory” of the land-atmosphere system have the potential to influence this particular region for a
time period much longer than the timescale of the individual mesoscale precipitation event itself. Given this analysis, a valid question is then, over how many local regions globally are these mesoscale effects occurring, and how often? Depending on the answer, the net impact might be important. To address this question, we should consider not only mesoscale circulations due to land use or vegetation gradients, but also those that form in coastal areas (seas and lakes), at ice breaks, in regions of strong mesoscale topographic variation, etc. In addition, in other climatological regimes (e.g., the Tropics), atmospheric effects arising from landscape heterogeneity may have a larger influence on regional hydrometeorology than in the dry, midlatitude region considered here. For example, evidence suggests that mesoscale circulations that produce a great deal of shallow convective clouds have a larger impact on boundary layer thermodynamics, through the influence of the water phase change on buoyancy, than those that produce little or no clouds (Pielke et al. 1998).

Second, and perhaps more importantly, we must consider the possible indirect effects of mesoscale circulations on larger-scale precipitation, that is, their impact on the atmospheric thermodynamic and dynamic state and on the coupling between the land surface and the atmosphere. Can we assert a priori that landscape heterogeneity, via mesoscale circulations, is not indirectly influencing the magnitude of the many larger rainfall peaks shown in Doran and Zhong’s Fig. 1? Recall that in WA01, we have only focused on those case study days that are most favorable for unambiguously observing the signal of landscape-generated mesoscale circulations; that is, clear, dry days without any obviously nonlocal, large-scale systems to confuse the issue. Thus, by experimental design, these days are going to be small contributors to total precipitation during a given month or season; the most we can hope for is that the land surface heterogeneity will force some rather local, probably isolated clouds and precipitation (in spite of the overall unfavorable conditions for moist convection) that we can attempt to match up with satellite imagery and surface observations, as in WA01. As Doran and Zhong point out, a time period with considerable precipitation will likely be messy, characterized by a mixture of precipitation scales from the synoptic on down, making the clear identification of the effects of mesoscale circulations difficult or impossible. This does not mean, however, that their impact will necessarily be negligible.

In providing justification for this view, we address Doran and Zhong’s second point; namely, that vertical mesoscale fluxes of sensible heat and moisture are not especially good indicators of the significance of mesoscale circulations at larger scales. While we feel that the concept of mesoscale fluxes is a useful one, this point is well taken. As they correctly state, the key is not the fluxes, but their impact on the vertical profiles of the various thermodynamic variables. In their Fig. 2, they show the influence for the 6 July case of mesoscale circulations on the $\theta$ and $q$ fields. While some differences between their model simulations with and without surface heterogeneity are evident, particularly in $q$, they appear relatively small and perhaps unimportant. We offer a different comparison to suggest, however, that mesoscale circulations can have a significant impact on lower atmospheric stability. Here we show (Fig. 2a) vertical profiles of $\theta$ at 1700 LT, averaged over our 250 km x 250 km Regional Atmosphere Modeling System (RAMS) experiment domain (covering most of the ARM/CART) for our simulations of the 6 July case with and without surface heterogeneity (i.e., essentially the same comparison Doran and Zhong make for $\theta$ and $q$ in their Fig. 2). In our opinion, the impact on the vertical distribution of $\theta$ is significant; the effect of the landscape-generated mesoscale circulations on this horizontal scale is to reduce the conditional instability with respect to moist convection of the lowest 2 km of the atmosphere. This is highlighted in Fig. 2b, which shows the $\theta$ difference between the two 6 July simulations. The net difference in $\theta$ in the layer between 1000- and 2000-m altitude is on the order of 5 K. We have also included in Fig. 2b the same result for the 13 July case, showing that, even though (as Doran and Zhong point out) the mesoscale latent heat flux was stronger on the 13th compared to the 6th, the impact of these fluxes on the maximum $\theta$ difference was actually greater on the 6th, thus highlighting some of the nonlinear aspects of the problem.

The above analysis seems to indicate that the mesoscale circulations could inhibit the later development of large-scale convection by stabilizing the lower troposphere, itself a potentially important effect. This would be consistent with the conclusions from more general work (e.g., Betts et al. 1996; Pal and Eltahir 2001) suggesting that boundary layer deepening and consequent entrainment of drier above-boundary layer air, both characteristics of the mesoscale updraft regions that we simulated, should reduce the moist static energy per unit mass of the boundary layer, thus decreasing the likelihood of convection. There are still complicating factors, however. For example, while the net effect of the mesoscale circulations is to stabilize
the atmosphere at the scale of the ARM/CART, at smaller scales there are pockets of both greater and lesser stability, compared to simulations without surface heterogeneity. In addition, due to their ability to transport water vapor horizontally, the mesoscale circulations produce significant net moistening of the lower atmospheric column in the regions of strongest mesoscale upward motion (WA01). How the likelihood of large-scale convection might depend on different horizontal scales of instability and patterns of moisture distribution is not yet well understood.

We must also account for dynamical effects: mesoscale circulations produce areas of enhanced upward motion that might be able to trigger larger-scale convection. As with the thermodynamical impacts, we do not have a good understanding of what scales of dynamical convective triggering are most important. Conceivably, these thermodynamical and dynamical influences could compete under some circumstances and reinforce each other under others; for example, a tendency toward large-scale stabilization of the column could be overcome by the triggering due to increased local upward motion. Clearly, more study is needed. Doran and Zhong have recently taken steps in this direction by attempting to assess the impact of landscape heterogeneity over the ARM/CART on the stability of the prestorm environment (Doran and Zhong 2000). They concluded that the impact was not significant, though they point out that the stability indices that they used (CAPE, lifted index, and modified K index) were imperfect predictors of the observed convective precipitation, that they did not consider any effects of dynamical triggering, and that studying a greater number of cases might yield additional information.

Over timescales longer than diurnal, the cumulative impact of mesoscale circulations generated by landscape heterogeneity may alter the atmosphere sufficiently to influence regional hydrometeorology at large scales (e.g., subcontinental). Under conditions favorable for the repeated, daily generation of mesoscale circulation (e.g., periods of persistent clear skies), progressive changes in atmospheric stability, due to effects such as illustrated in Fig. 2, could be produced, thus possibly influencing the location and intensity of precipitation when the next synoptic-scale disturbance entered the domain. Dalu et al. (2000) have shown that, even disregarding water vapor transport, persistent mesoscale flow should have an impact on atmospheric stability that is significant compared to boundary layer turbulence and diabatic heating. Since soil wetness is a major control on the partitioning of surface fluxes into sensible and latent heat, these impacts on precipitation might also systematically alter the surface heterogeneity that is the driving force for the landscape-generated mesoscale circulations, thus resulting in positive or negative feedbacks. In addition, if the frequency and coverage of cumulus cloud production is altered by changes in mesoscale landscape heterogeneity, these surface effects can then "scale up" through the corresponding changes in the production of cirrus anvils, thereby influencing much greater horizontal domains. Over long timescales, all these effects may alter the strength of coupling between the surface and the atmosphere, persistence of soil moisture, precipitation recycling, and other important contributing factors to a given pattern of regional hydrometeorology.

These ideas are consistent with a philosophy that considers the land surface as another evolving, integrated component of the climate system rather than simply a static boundary condition (Pielke 2001). This viewpoint explicitly recognizes the nonlinear feedbacks between the surface and the atmosphere, thus implying that the details of how the two components are coupled, regardless of scale, might be important to the system’s long-term evolution. This nonlinearity makes it difficult to say definitively whether smaller-scale processes are less important than larger-scale ones. Doran and Zhong suggest that much of what we propose as the potential impact of mesoscale circulations at climate scales is still speculation. We understand their point of view, but given all the knowledge gained over the past decade on this issue, we feel that rather than “speculating,” we have enough evidence to “assume” an important impact. Because the climate
system is nonlinear, we are not in favor of discounting processes and scales because their importance, or lack thereof, has yet to be demonstrated to everyone's satisfaction: GCMs now include representations of many phenomena that, at their inception, were considered extraneous. We all have interests in different aspects of climate, and since a good climate simulation requires that we include all relevant components, we feel the greatest progress will come with study on diverse fronts. Based on our interpretation of the evidence for the hypothesis that mesoscale landscape heterogeneity effects are important for climate, we feel the burden should rest more strongly on the side of falsification than on the side of proof.

We welcome the dialogue initiated by Doran and Zhong as an important part of the development of our ideas, and hopefully the ideas of others.

REFERENCES


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Containing expanded versions of the invited papers presented at the International Symposium on the Life Cycles of Extratropical Cyclones, held in Bergen, Norway, 27 June–1 July 1994, this monograph will be of interest to historians of meteorology, researchers, and forecasters. The symposium coincided with the 75th anniversary of the introduction of Jack Bjerknes’s frontal-cyclone model presented in his seminal article, “On the Structure of Moving Cyclones.” The monograph’s content ranges from a historical overview of extratropical cyclone research and forecasting from the early eighteenth century into the mid-twentieth century, to a presentations and reviews of contemporary research on the theory, observations, analysis, diagnosis, and prediction of extratropical cyclones. The material is appropriate for teaching courses in advanced undergraduate and graduate meteorology.

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