Effects of land-surface heterogeneity upon surface fluxes and turbulent conditions

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Summary

In this paper, we examine the effects of land-surface heterogeneity on the calculation of surface-energy and momentum fluxes in a meso-scale atmospheric model. A series of numerical experiments has been carried out with a combination of different resolutions for the atmosphere and the land surface, which allows an examination of the aggregation and dynamic effects associated with land-surface heterogeneity. The numerical results show that for a given atmospheric model resolution, increased land-surface resolution leads to better estimates of surface-energy and momentum fluxes, and for a given land-surface resolution, increased atmospheric model resolution also improves the estimates of these fluxes. This latter result contradicts the prevailing view that subgrid variation in atmospheric data plays only a minor role in estimating the fluxes. It is also shown that subgrid and land-surface heterogeneity leads to increased turbulent fluctuations. The responsible mechanisms of this effect are both the subgrid variation of surface-energy fluxes and their impact upon the development of convective cells. It is suggested that subgrid atmospheric motions induced by surface heterogeneity may be an important factor which needs to be considered in subgrid closure schemes for atmospheric models.

1. Introduction

Atmospheric processes are closely related to energy, mass and momentum fluxes over the land surface. These fluxes are influenced both by atmospheric conditions and land-surface properties. The land surface is always more or less heterogeneous and for a given resolution of the atmospheric model, its heterogeneity can never be represented with sufficiently fine resolution. The consequences are inaccuracies arising from the aggregation effect (e.g., Giorgi and Avissar, 1997) and the dynamical effect (e.g., Avissar and Schmidt, 1998).

The aggregation effect occurs because of the nonlinear nature of the land-surface processes. The surface fluxes on the grid scale are not simply related to the mean atmospheric variables over the grid and the “average” land-surface parameters. Therefore, the surface fluxes on the grid scale can be substantially incorrect if the heterogeneity of the land surface is inadequately represented. Wetzel and Chang (1987) have shown that the nonlinear dependency of evapotranspiration on soil moisture results in profoundly different relationships between them on regional and local scales. The dynamic effect occurs because land-surface heterogeneity generates subgrid motions that are not resolved by the numerical grid. In general, subgrid closure schemes parameterize the subgrid fluxes through the gradient of grid variables. However, this approach does not account for land-surface heterogeneity and is unlikely to represent the subgrid fluxes well.

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Many recent studies are concerned with the impact of subgrid land-surface heterogeneity on the estimation of surface fluxes in global circulation and/or weather-prediction models [but see Mölders et al. (1996) for a study with a meso-scale model]. Various approaches have been proposed for the purpose, most of which have the objective to account for the aggregation effect for a given resolution of the atmospheric model. In some studies, effective (grid-averaged) parameters are introduced for each grid cell (e.g., Mahrt et al., 1992). The use of effective parameters can be justified in conditions of moderate heterogeneity (Giorgi and Avissar, 1997). An alternative is the mosaic approach (Aivissar and Pielke, 1989) in which all the areas (within a grid cell) having the same properties are combined into a tile and these tiles exchange fluxes with the atmosphere independent of the other tiles. A more correct but computationally more expensive method is the explicit method in which a surface type (a combination of soil, vegetation, etc.) is assigned to a subgrid.

In considering the aggregation effect, the atmospheric forcing is usually assumed to be uniform over a grid cell. It is not conclusive whether this assumption is adequate. Mahrt and Sun (1995) used data of three field experiments and concluded that assuming spatially constant atmospheric forcing but varying surface properties provided a close approximation of the area composite fluxes. Other studies seem to have reached different conclusions. Mölders et al. (1996) found a reduction in surface evaporation when the area-weighted near surface atmospheric forcing was used. Ghan et al. (1997) found that subgrid-scale variations in precipitation have a large impact on regional evaporation. While neglecting spatial variations in precipitation increased summertime evaporation by 15%, neglecting the spatial heterogeneity of vegetation and soil increased it only by 4% and 2%, respectively.

Studies on the dynamic effects of surface heterogeneity can be found in Mahfouf et al. (1987), and Seth and Giorgi (1996) among many others. Land-surface discontinuity over large areas may trigger meso-scale circulations which affect background velocity field, thermal stratification and humidity profile. Land-surface heterogeneity in general enhances shallow convective precipitation due to two mechanisms which are affected by the spatial distribution of water availability for evapotranspiration, namely turbulence and meso-scale circulations. Lynn et al. (1998) used a two-dimensional cloud-resolving model to study the generation of deep moist convection over heterogeneous landscapes by prescribing different arrangements of dry and wet patches. They showed that rainfall occurred most intensely along sea-breeze-like fronts which formed at patch boundaries.

A key question which has not been well examined is how subgrid atmospheric motion interacts with subgrid land-surface heterogeneity and how this interaction might influence the atmospheric motions on the grid scale. It seems that the understanding of this problem is critical to a better treatment of subgrid land-surface heterogeneity in atmospheric models.

In this study, we examine both the aggregation and the dynamic effect, using a meso-scale atmospheric model [FOOT3D: Flow Over Orographically Structured Terrain (3-Dimensional), Brücher et al., 1998] coupled with a land-surface model based on the force-restore method (Jacobsen and Heise, 1982; Noilhan and Planton, 1989). In particular, we examine how and how strong the increased resolution of the land-surface properties influence the surface energy fluxes determined in the model, and the inter-relationship between subgrid motions and subgrid surface heterogeneity. For these purposes, we carried out a series of numerical tests with three different atmospheric resolutions, three land-surface resolutions and several combinations. The results of these tests are useful for the development of a new treatment of subgrid land-surface heterogeneity, and for providing an answer for how much land-surface information is necessary for a given atmospheric resolution.

2. Model description

2.1 The flow model

FOOT3D is developed at the Institute for Meteorology and Geophysics, University of Cologne. Designed for a variety of applications in a range from the mesoscale γ down to microscale α over complex terrains (Brücher, 1997), FOOT3D is a non-hydrostatic limited-area model using