8. A STATISTICAL-DYNAMICAL APPROACH TO PARAMETERIZE SUBGRID-SCALE LAND-SURFACE HETEROGENEITY IN CLIMATE MODELS

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Abstract. Land surface interacts strongly with the atmosphere at all scales. This has a considerable impact on the hydrologic cycle and the climate. Therefore, in order to produce realistic simulations with climate models, their land-surface processes must be parameterized accurately. Because continental surfaces are usually extremely heterogeneous over the resolvable scales considered in these models, surface parameterizations based on the 'big leaf–big stoma' approach (that assume grid-scale homogeneity) fail to represent the land-atmosphere interactions that occur at much smaller scales.

A parameterization based on a statistical-dynamical approach is suggested here. With this approach, each surface grid element of the numerical model is divided into homogeneous land patches (i.e., patches with similar internal heterogeneity). Assuming that horizontal fluxes between the different patches within a grid element are small as compared to the vertical fluxes, patches of the same type located at different places in the grid can be regrouped into one subgrid surface class. Then, for each one of the subgrid surface classes, probability density functions (pdf) are used to characterize the variability of the different parameters of the soil-plant-atmosphere system. These pdf are combined with the equations of the model that describe the dynamic and the energy and mass conservations in the atmosphere.

The potential application of this statistical-dynamical parameterization is illustrated by simulating (i) the development of an agricultural area in an arid region and (ii) the process of deforestation in a tropical region. Both cases emphasize the importance of land-atmosphere interactions on regional hydrologic processes and climate.

1. Introduction

It has become increasingly apparent in recent years that the distribution of sensible heat flux at the Earth's surface is a critical factor in producing and modifying regional (mesoscale) atmospheric circulations often associated with terrain inhomogeneities such as land-sea boundaries, urban-rural areas, bare soil-vegetated areas, and mountain-valley structures (e.g., McNider and Pielke, 1981; Garrett, 1982; Zhang and Anthes, 1982; Ookouchi et al., 1984; Sellers et al., 1986; Wilson et al., 1987; Mahfouf et al., 1987; Segal et al., 1988; Avissar and Pielke, 1989). Shukla and Mintz (1982) have demonstrated that water availability at the Earth's surface has a crucial impact on the Bowen ratio (i.e., the ratio between sensible and latent heat flux) and, as a result, on the global climate simulated with General Circulation Models (GCMs). Therefore, the parameterization of the Earth's surface in climate models is a major concern for climate modelers.

Several parameterizations of the land surface have been suggested for application in climate models. As recently discussed and reviewed by Avissar and Verstraete (1990), these parameterizations have improved from the prescription of surface potential temperature as a periodic heating function (e.g., Pielke, 1974; Neumann and Mahrer, 1971; Mahrer and Pielke, 1976) to more realistic formulations based...
on the solution of energy budget equations applied to the soil surface (e.g., Pielke and Mahrer, 1975) and, when present, vegetation layers (e.g., McCumber, 1980; Yamada, 1982; Sellers et al., 1986; Dickinson et al., 1986; Avissar and Mahrer, 1988a).

For instance, McCumber (1980) introduced a refined parameterization of the soil layer (based on the solution of governing equations for soil water and heat diffusion) and a bulk layer of vegetation following a scheme suggested by Deardorff (1978). Yamada (1982) suggested a multilayer higher-order vegetation canopy representation and Sellers et al. (1986) proposed a two-layer vegetation module to account for two different types of vegetation (e.g., trees and shrubs) which may be found in a single grid element of their GCM. These parameterizations all are based on the concept of ‘big leaf–big stoma’ which implies that land is homogeneously covered by a single big leaf within a grid element of the numerical climate model. This big leaf usually has a single stoma which is sensitive, in the most sophisticated parameterizations, to the environmental conditions known to have an effect on the mechanism of the stomata (i.e., solar radiation, temperature, humidity, carbon dioxide, and soil water potential in the root zone). This stoma controls the plant transpiration and, as a result, the Bowen ratio and the surface heat fluxes.

With the ‘big leaf–big stoma’ approach, the density of the vegetation is characterized by a ground cover parameter, $\sigma_f$, which is the fractional area over which the foliage prevents shortwave radiation from reaching the ground. Thus, $\sigma_f$ varies between zero (bare ground) and one (full canopy cover). The surface energy fluxes (sensible and latent) are calculated from two energy budget equations, one for the vegetation layer and one for the soil surface (which is partly bare and partly covered by vegetation). Usually, no storage of heat is allowed in the canopy layer and, therefore, the net radiative energy absorbed by the plant canopy is released back in the atmosphere as sensible and latent heat. The contribution of the vegetation and the bare soil to the global energy fluxes from each grid element of the model are linearly extrapolated using $\sigma_f$. Such a ‘big leaf–big stoma’ parameterization has been proposed and is thoroughly described by Avissar and Mahrer (1988a). Its formulation, including a few modifications implemented by Avissar and Pielke (1989), is summarized in the Appendix.

In regional climate models, however, one horizontal grid cell typically represents a domain of 10–100 km$^2$. In GCMs, the represented region can be as large as 10$^6$ km$^2$. On these scales large heterogeneities of soil type and soil wetness, of vegetation type and vegetation density, of topography, of urbanization, etc., are frequently observed. They result in large heterogeneities of the Bowen ratio*. For instance, Wetzel and Chang (1988) estimated that for numerical weather prediction models with a grid spacing of 100 km or greater, the expected subgrid-scale

* The Bowen ratio is extremely sensitive to the availability of water at the land surface. Its value ranges from infinity in very dry regions to approximately zero over wet areas. It may even be negative over moist areas under particular atmospheric conditions (oasis effect), e.g., the advection of dry air over unstressed vegetation.