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Impact of surface-heterogeneity on atmosphere and land-surface interactions

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ABSTRACT

Land-surface heterogeneity occurs on many scales, but its inclusion remains an unsolved problem in land-surface and atmospheric boundary-layer schemes for weather and climate models. We investigate the propagation of land-surface heterogeneity in a convective boundary layer using an atmosphere and land-surface coupled large-eddy model. Simulations are made for land surfaces of different heterogeneity scales and a uniform land surface. A multi-scale analysis is carried out and it is found that while domain-and-time averaged fluxes and state variables are not sensitive to land-surface heterogeneity, atmospheric patterns are. Close to the surface, atmospheric patterns are dominated by land-surface forced patterns; away from the surface, "eigen" patterns dominate and forced patterns reemerge for large averaging times. While small-scale land-surface features are more rapidly destroyed by turbulence, large-scale features can persist over hundreds of meters.

1. Introduction

Biases in surface-flux estimates due to surface heterogeneity have long been recognized (e.g., Avissar and Pielke, 1989). How land-surface heterogeneity can be represented in land-surface and atmospheric boundary layer (ABL) parameterization schemes for weather and climate models remains an unsolved problem. Two categories of approaches have been taken for treatment of land-surface heterogeneity, namely, the mosaic approach (Avissar and Pielke, 1989; Koster and Suarez, 1992) and the effective-parameter approach (Wood and Mason, 1991; Mahrt et al., 1992). The mosaic approach only accounts for the aggregation effect, but not the dynamic effect, although recent improvements have been made (Schomburg et al., 2010, 2012). The effective-parameter approach considers the dynamic effect, but effective parameters are difficult to estimate because land-surface heterogeneity occurs on a range of scales and the effective parameters depend both on heterogeneity scales and strengths and on the capacity of the atmosphere to diffuse the land-surface signals. It is attempted in both approaches to reduce the heterogeneous problem to a homogeneous problem, without addressing the question how land-surface heterogeneity propagates in the atmosphere.

Large-eddy simulation (LES) models have been developed to study ABL flows and ABL-land surface interactions (Stevens and Lenschow, 2001). Earlier LES models were not coupled with land-surface schemes, and the simulations were mostly done with fixed surface forcing and no feedbacks. We refer to such simulations as forced LES, in contrast to (atmosphere and land-surface) coupled LES. With forced LES, one studies the effect of surface patterns on the ABL (e.g., Hechtel et al., 1990; Avissar and Schmidt, 1998; Albertson and Parlange, 1999; Raasch and Harbusch, 2001; Letzel and Raasch, 2003; Kang and Davis, 2008; Huang et al., 2008; Huang and Margulis, 2009; Maronga and Raasch, 2012). Raasch and Harbusch (2001) found that the impact on ABL of surface heterogeneity of scale of the ABL depth mainly depends on the amplitude of the fluxes imposed, but not on the heterogeneity configuration. Avissar and Schmidt (1998) found that a background wind can considerably reduce the impact of surface heterogeneity. Hechtel et al. (1990) found no significant impact of surface heterogeneity (scales of 450–900 m) on ABL dynamics and concluded that the use of homogeneous surface is sufficient to simulate the development of convective ABLs. Huang and Margulis (2009) found that energy flux profiles are not sensitive to land-surface heterogeneity scales. Maronga and Raasch (2012) carried out LES driven with observed surface fluxes and found that the mean vertical scalar transport

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over a heterogeneous and a homogeneous surface hardly differs if the same area-mean surface flux is specified.

Coupled LESs has also been done for heterogeneous surfaces (e.g., Patton et al., 2005; Courault et al., 2007; Huang et al., 2008; Huang and Margulis, 2010; Brunsell et al., 2011). But the basic conclusions reached from the coupled LESs are similar to those from the forced LESs. Patton et al. (2005) reported that hourly-averaged vertical fluxes are hardly affected by surface-heterogeneity scales, although the relative contributions of eddies to the fluxes are. Applying wavelet analysis to a land surface, Brunsell et al. (2011) obtained four different surface-heterogeneity scales and studied their impact using coupled LES. They reported that land-surface heterogeneity scales have little impact on ABL dynamics.

However, the land-surface schemes used in the above-mentioned LESs are the same as designed for weather and climate models, in which the soil layers are configured to represent the exchanges between atmosphere and land surface on diurnal and longer time scales. Liu and Shao (2013) pointed out that such a soil-layer configuration is too slow to represent the atmosphere and land-surface feedbacks on large-eddy scales, i.e., the coupled LESs published so far are in essence forced LESs. It is thus not surprising that the forced and coupled LESs have reached the same conclusions. Shao et al. (2013) constructed LES-ALM (Large-Eddy Simulation Atmosphere and Land Surface Model, see Section 2.1) with a fine soil-layer configuration and several other improvements to the land-surface scheme, and evaluated the model with measurements. The thin soil-layer configuration employed in LES-ALM enabled the land surface to respond to atmospheric large eddies.

The above review suggests that the earlier LES results in relation to the impact of land surface heterogeneity on ABL dynamics must be reexamined. To bridge the gap between LES findings and parameterization applications is the main motivation of our work. In this paper, we are particularly interested in the propagation of surface heterogeneity of different scales in the ABL. To this end, we consider four different land-surface configurations. The first three are based on a real land-surface; they have the same land-use fractions but differ in the heterogeneity scales. The last configuration is a uniform surface of pasture. Simulations with LES-ALM are carried out for the four cases and the results are analyzed to estimate the impact of surface heterogeneity scales on the ABL dynamics. In Section 2, we describe the model and configurations. In Section 3, we analyze the simulation results and report our findings on the effects of surface heterogeneity on fluxes and state variables and the propagation and persistency of land-surface patterns in the atmosphere. In Section 4, we present our conclusions and an outlook.

2. Methodology

2.1. Model description

The LES-ALM used in this study (Shao et al., 2013) is the Weather Research and Forecast (WRF) large-eddy flow model (Skamarock et al., 2008) and its land-surface scheme is the Noah Land Surface Model (LSM) (Chen and Dudhia, 2001). Several modifications are made to the Noah scheme for large-eddy simulation of atmosphere and land-surface processes. First, the canopy is vertically resolved explicitly with a multi-layer vegetation model. Second, a fine soil-layer configuration is used to allow for realistic feedbacks between large eddies and the land surface (Liu and Shao, 2013; Shao et al., 2013). Third, the bulk exchange coefficients are estimated based on the LES sub-gird turbulence, not based on the Monin-Obukhov similarity theory (MOST) (Monin and Obukhov, 1954). This is necessary for three main reasons: (1) on the spatial and temporal scales, the flow resolved by the LES grid is no longer stationary and homogeneous and the basis of applying MOST is unjustified; (2) MOST similarity functions are empirical, based on measurements averaged typically over 15–30 min, and do not apply to large-eddy scale turbulence; and (3) exchange coefficients based on MOST are often inconsistent with those derived from LES sub-grid turbulence schemes, causing inconsistency in model boundary condition and closure. In LES-ALM, the bulk exchange coefficients are computed from the LES sub-grid closure and extrapolated to the land surface, thereby avoiding the use of the MOST similarity functions.

2.2. Land surface and surface heterogeneity

Based on land-use pattern SP1 (Fig. 1a) of the Selhausen-Merken field-experiment site of the German Collaborative Research Center 32 (TR32) project (Vereecken et al., 2010), two synthetic land-use patterns (SP2 and SP3) are designed with the same land-use fractions. In SP2 (Fig. 1b), through low-pass filtering, the small-scale features of SP1 are removed while the large-scale pattern of SP1 is retained. SP3 (Fig. 1c) represents a random pattern that has no dominant scale. In our dataset, five land-use types are considered, each corresponding to a set of vegetation parameters, including leaf-area index, vegetation height, vegetation cover, surface albedo etc., as summarized in Table 1.

The probability density function (PDF) of the land-use types for all three land-surface configurations is identical. An integral quantity for characterizing the PDF is the information entropy, defined as

$$S = -k_b \sum_i P_i \ln P_i \quad (1)$$

with k_b being a normalization coefficient and P_i the probability of the state i. According to Equation (1), SP1, SP2 and SP3 have the same amount of information but differ in patterns. To place in context the different impacts of SP1, SP2 and SP3 arising from pattern, with respect to those arising from a systematic change in land-surface properties, a land surface of uniform pasture, SP4, is also considered (pasture is chosen, because it covers a large fraction of the land-surface in the study area as seen in Fig. 1). In contrast to SP1, SP2 and SP3, SP4 has a different content of land-surface information relevant to atmosphere and land-surface interactions.

We use cluster analysis to estimate the heterogeneity scale. To do this, a land-surface property, α, is divided into J bins of width $\Delta\alpha$ and bin j includes all properties in the interval $\alpha_j \pm \Delta\alpha/2$. For a spatially gridded land surface, adjacent cells with α in the same bin belong to the same cluster. This operation results in N clusters, and the scale for cluster n is defined as

$$l_n = \frac{4A_n}{C_n} \quad (2)$$

where A_n is the area and C the circumference of cluster n. Following Lynn et al. (1995) and Avissar (1995), we define the scale of heterogeneity as a weighted average of l_n

$$L = \left(\sum_n^N f_n l_n^m \right)^{1/m} \quad (3)$$

where f_n is the fractional area of cluster n and m is an empirical parameter. As in Lynn et al. (1995), $m = 2$ is used here, which implies L is the fractional-area weighted root mean square of l_n. Alternatively, L can be defined as the most likely value of l_n. Both definitions lead to the heterogeneity scales of $L_1 = 360$ m (~6Δx,