The effect of surface heterogeneity on fluxes in the stable boundary layer

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1 Introduction

Natural land surfaces are inherently heterogeneous with surface properties that vary over a wide range of spatial scales. These heterogeneities come in the form of changes in surface temperature, surface soil moisture, and aerodynamic surface roughness. The role that these heterogeneities play in land-atmosphere coupling and atmospheric boundary layer (ABL) dynamics is well recognized and has received considerable attention from researchers (Mahrt, 1987, Roy and Avissar, 2000, Bou-Zeid *et al.*, 2007, Stoll and Porté-Agel, 2009, Huang and Margulis, 2010). Most studies of the heterogeneous ABL have focused on the daytime convective boundary layer (CBL). In the CBL, strong positive buoyancy forces dominate mixing with the result that small-scale heterogeneities are usually considered to have minimal effect on average surface fluxes (Roy and Avissar, 2000). In contrast, the impact of heterogeneity on the stable boundary layer (SBL) has received considerably less attention (Fernando and Weil, 2010).

In weather, hydrologic, and climate models, the impact of surface heterogeneity on average surface fluxes must be parameterized as a function of the land surface cover and the average momentum, temperature, and moisture at the first model level. The form of these parameterizations can have a strong impact on model results (Viterbo *et al.*, 1999, King *et al.*, 2001, 2007). Several researchers have developed model formulations specifically designed to represent heterogeneity in these large-scale models. Most of the developed models were either specifically designed for neutral or convective conditions or not well validated for SBLs (Avissar and Pielke, 1989, Claussen, 1991, Blyth, 1995, Bou-Zeid *et al.*, 2007). In the SBL, the combination of weak turbulent mixing, intermittent turbulence, and weak surface fluxes with the nonlinear relationship between ABL turbulence and local fluxes makes direct parameterization of SBL fluxes based on processes highly problematic (Fernando and Weil, 2010).

The limited amount of work done to develop heterogeneous SBL parameterizations has been based on numerical studies. Stoll and Porté-Agel (2009) and Miller and Stoll (2012) used the large-eddy simulation (LES) technique to examine heterogeneous surface temperature and aerodynamic roughness distributions, respectively, in the SBL. In an off-line model study based on their LES data, Stoll and Porté-Agel (2009) found that standard models based on bulk Monin-Obukhov similarity theory (Brutsaert, 1998) or tile approaches (Avissar and Pielke, 1989) were not able to capture the LES average surface fluxes. Using their LES results, they formulated a new model using local similarity theory (Nieuwstadt, 1984) that improved the representation of average surface fluxes. Miller and Stoll (2012) carried out a similar study over heterogeneous aerodynamic roughness distributions. They found that for continuously turbulent SBL conditions, bulk similarity models that use an effective aerodynamic roughness length calculated based blending height theory give reasonable results for average surface fluxes.

Here, LES is used to extend the results of Stoll and Porté-Agel (2009) and Miller and Stoll (2012) to the case of combined aerodynamic roughness and surface temperature heterogeneity. This paper is organized as follows. First, a brief description of the numerical code and test case setup is given. Next, simulation results over combined aerodynamic surface roughness and surface temperature transitions are presented. Finally, a summary of the key results of this study is given.

2 Numerical Simulations

2.1 Case Description

The numerical code used in this study is outlined in Stoll and Porté-Agel (2006a) and Stoll and Porté-Agel (2008). Briefly, it solves the filtered Navier-Stokes equations and the filtered heat equation using a combination of spectral and finite difference methods. Following Beare *et al.* (2006), the aerodynamic surface roughness for momentum and heat are assumed to be equal. Lateral boundary conditions are periodic and the top boundary conditions are zero stress and zero flux for momentum and heat, respectively, with a Rayleigh dampening zone in the top 100 m of the domain. The lower boundary condition uses a local application of Monin-Obukhov similarity theory to calculate momentum and heat fluxes at every surface grid point (Stoll and Porté-Agel, 2006b). Subgrid scale fluxes of momentum and heat are calculated using the scale-dependent Lagrangian dynamic model developed by Stoll and Porté-Agel (2006a).

To examine the impact of combined aerodynamic surface roughness and surface temperature heterogeneity, a series of idealized simulations were performed. Following Stoll and Porté-Agel (2009), the Global Energy and Water Cycle Experiment (GEWEX) ABL Study (GABLS) first LES intercomparison test case (Beare *et al.*, 2006) was used as a base case for the heterogeneous simulations. Besides the addition of surface heterogeneity, the only notable deviation from the GABLS I LES case was an expanded horizontal domain (800 m instead of 400 m). Here a total of four different simulations are presented including, the homogeneous base case (presented in detail in Stoll and Porté-Agel, 2008), a heterogeneous temperature distribution with homogeneous aerodynamic roughness (presented in detail in Stoll and Porté-Agel, 2009), a hot-rough-to-cold-smooth (HRCS) combined transition, and a cold-rough-to-hot-smooth (CRHS) combined transition. In all of the simulations, the patches consist of spanwise homogeneous abrupt streamwise transitions with patch length scales of 400 m. Because of the periodic boundary conditions, the patches repeat indefinitely in the steamwise direction. For the simulations over heterogeneous surface temperature distributions, the surface temperature over individual patches was cooled differentially following Stoll and Porté-Agel (2009) for eight physical hours until it reached a difference of 6 K for the case with a homogeneous aerodynamic surface roughness and the two combined temperature and aerodynamic surface roughness simulations. In the combined heterogeneous aerodynamic surface roughness and surface temperature cases, the roughness transition has a jump in aerodynamic surface roughness $z_{o,1}z_{o,2}^{-1} = 10$ where $z_{o,1} = 0.1$ m is the upstream roughness and $z_{o,2}$ is the downstream roughness. Each simulation was run for a total of 12 physical hours with statistics averaged over the last one hour. Table 1 gives mean boundary layer statistics averaged over the last one physical hour of each simulation and over the horizontal directions including the the boundary layer height δ calculated following Kosovic and Curry (2000), the average surface friction velocity u_*, the average surface temperature scale $\theta_* = -q_s u_*^{-1}$ where q_s is the average surface flux, the Obukhov length $L = -u_*^3\theta_0\left(\kappa g q_s\right)^{-1}$ where θ_0 is a reference potential temperature scale, $\kappa = 0.4$ is the von Karman constant, and g is gravity, and Δ is the grid spacing.

Table 1: Mean boundary layer characteristics for the different surface types characterized by the type of surface conditions: homogeneous (Hom), heterogeneous surface temperature with a 6 K temperature difference (Hetθ6), combined heterogeneous temperature and aerodynamic surface roughness HRCS, and combined heterogeneous temperature and aerodynamic surface roughness CRHS.

case	δ (m)	u_* (m/s)	θ_* (K)	L (m)	Δ (m)
Hom	185	0.254	0.0435	100	3.3
Hetθ6	208	0.264	0.0353	133	3.3
HRCS	225	0.260	0.0316	144	3.3
CRHS	164	0.236	0.0435	86	3.3

2.2 Results

2.2.1 Mean boundary layer profiles

Weather and climate models must parameterize the surface fluxes of heat and momentum based on the average temperature and velocity values at their lowest computational levels. In this section, the mean profile of temperature and wind speed are examined to explore how the combined surface temperature and aerodynamic roughness heterogeneity affects them. The one-dimensional profiles are created by averaging the LES velocity and temperature fields over horizontal planes and in time over the last one hour (hours 11-12) of each simulation. Turbulent fluctuations need to calculate turbulence scaling parameters are defined as fluctuations from the spatially plane averaged values.

Figure 1 shows the mean wind speed profiles from each of the simulations. All of the simulations exhibit an elevated wind maximum at the boundary layer top. This agrees with the results of Stoll and Porté-Agel (2009). In their simulations over heterogeneous surface temperature distributions, all of the simulations, regardless of temperature contrast or patch size, developed a nocturnal jet. The formation of a nocturnal jet also agrees with Neiuwstadt's (1984) theory for the stead-state homogeneous SBL and the LES results of Beare *et al.* (2006). The vertical location of the nocturnal jet is different for each simulation but its strength (maximum wind speed in the jet) remains nearly constant. The differences in vertical location are closely linked to the differences in boundary layer height between the simulations. Stoll and Porté-Agel (2009) observed the same behavior. In their study, simulations with different temperature contrast had different boundary layer and nocturnal jet heights. The addition of aerodynamic surface roughness heterogeneity in combination with the surface temperature heterogeneity, has the affect of enhancing the surface heat flux contrast between the patches. The flux contrast enhancement is biased towards the rougher surface so that the HRCS simulation has a larger boundary layer height than the Hetθ6 simulation and the CRHS has a smaller boundary layer height.

The potential temperature profiles shown in figure 2 have a similar dependence on surface heterogeneity. The inversion height differences between the simulations closely follow the boundary layer and nocturnal jet height trends. The HRCS simulation shows an increased potential temperature within the boundary layer compared to the Hetθ6 simulation and the CRHS simulation has a strong decrease. This pattern agrees with the changes in surface heat flux and Obukhov length with the CRHS case exhibiting stronger cooling and a more stratified boundary layer and the HRCS case having weaker cooling and a less stable boundary layer.

To further examine how combined surface temperature and aerodynamic surface roughness transitions affect the SBL, the non-dimensional shear Φ_M and non-dimensional temperature gradient Φ_H are plotted for the lowest 40 m of the boundary layer in figures 3 and 4 as functions of the stability parameter z/L.

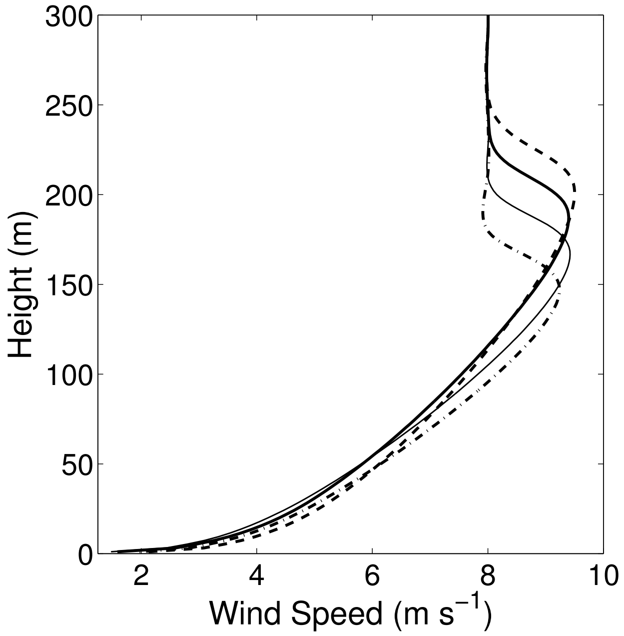

Figure 1: Mean wind speed profile averaged over the last one hour of the simulation for homogeneous and heterogeneous SBL simulations. The thin solid line is the homogeneous case (Hom), the thick solid line is the heterogeneous temperature case (Hetθ6), the dashed line is combined heterogeneity case HRCS and the dot-dashed line is combined heterogeneity case CRHS. See Table 1 for simulation abbreviations.

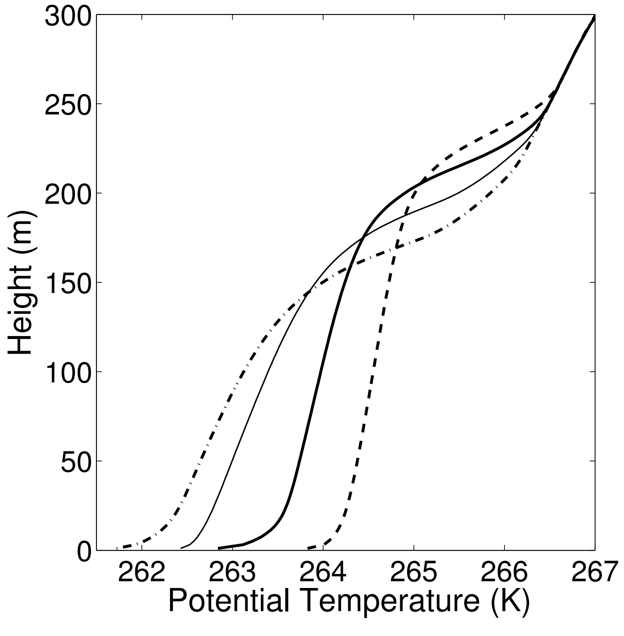

Figure 2: Mean potential temperature averaged over the last one hour of the simulation for homogeneous and heterogeneous SBL simulations. The thin solid line is the homogeneous case (Hom), the thick solid line is the heterogeneous temperature case (Hetθ6), the dashed line is combined heterogeneity case HRCS and the dot-dashed line is combined heterogeneity case CRHS. See Table 1 for simulation abbreviations.

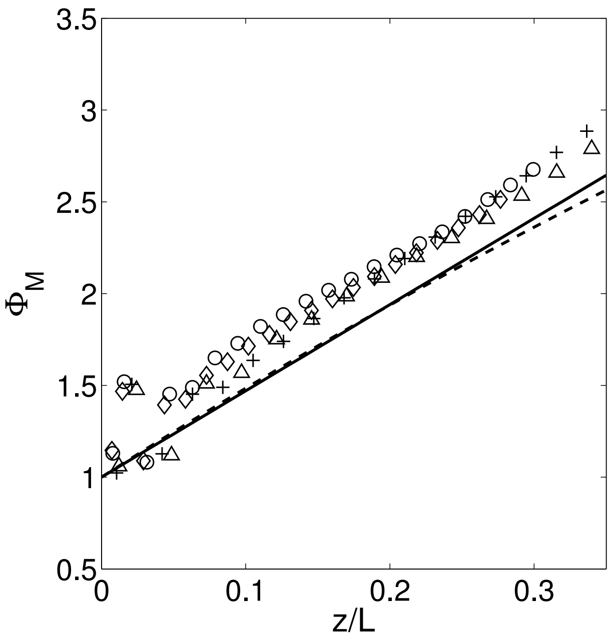

Figure 3: Non-dimensional velocity gradient as a function of z/L in the lowest 40 m of the domain. Graph symbols are as follows: pluses Hom, circles Hetθ6, triangles CRHS and diamonds HRCS. The solid line and dashed lines correspond to the formulations proposed by Businger et al. (1971) and Beljaars and Holtslag (1991), respectively.

Φ_M is defined as

$$\Phi_M = \frac{\kappa z}{u_*}\sqrt{\left(\frac{\partial \langle u \rangle}{\partial z}\right)^2 + \left(\frac{\partial \langle v \rangle}{\partial z}\right)^2} \tag{1}$$

and Φ_H is defined as

$$\Phi_H = \frac{\kappa z}{\theta_*}\frac{\partial \langle \theta \rangle}{\partial z}. \tag{2}$$

In equations 1 and 2, κ =0.4 is the von Karman constant and $\langle u \rangle$, $\langle v \rangle$ are the mean velocity components in the streamwise and spanwise directions, respectively, $\langle \theta \rangle$ is the average potential temperature and the angle brackets $\langle\ \rangle$ indicate a horizontal plane averaged value. Many weather and climate models directly use the integrals of Φ_M and Φ_H as their boundary conditions (Beljaars and Holtslag, 1991, Mahrt, 1996).

The non-dimensional temperature gradient has a much more distinct dependence on the surface heterogeneity than the non-dimensional shear does. This same effect was seen over homogeneous aerodynamic surface roughness with heterogeneous surface temperature distributions by Stoll and Porté-Agel (2009). For all patch sizes and temperature contrasts that they tested, Φ_M closely matched established similarity theory profiles. The addition of an aerodynamic roughness jump of one order of magnitude does not alter this conclusion. In contrast, Φ_H shows a strong dependence on surface heterogeneity with all three heterogeneous cases deviating from established similarity relationships. These deviations bring into question the use of basic average similarity theory in the heterogeneous SBL.

2.2.2 Testing heterogeneous surface flux models

Many different parameterizations have been developed to model average fluxes over heterogeneous surfaces. These include bulk parameterizations based on equations 1 and 2 (Mahrt, 1996, Brutsaert, 1998,

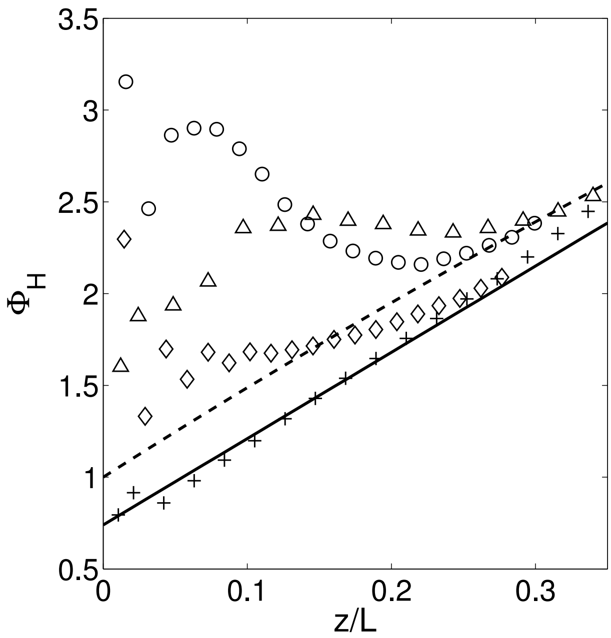

Figure 4: Non-dimensional potential temperature gradient as a function of z/L in the lowest 40 m of the domain. Graph symbols are as follows: pluses Hom, circles Hetθ6, triangles CRHS and diamonds HRCS. The solid line and dashed lines correspond to the formulations proposed by Businger et al. (1971) and Beljaars and Holtslag (1991), respectively.

e.g.,), tile models that apply Monin-Obukhov similarity theory locally over patches with different land surface characteristics at either the first model level (Avissar and Pielke, 1989) or at the blending height (Arola, 1999), and recently, the model developed by Stoll and Porté-Agel (2009) specifically for the heterogeneous SBL (see Stoll and Porté-Agel, 2009, for a detailed description of each method). In this section the tile model and the model of Stoll and Porté-Agel (2009) are tested using the LES velocity and temperature fields. This is accomplished by comparing the predicted surface heat fluxes from the model calculated using the plane and time averaged velocity and temperature fields (plotted in figures 2 and 1) at different hypothetical weather and climate model levels Z_m and comparing it to the calculated average surface heat flux from the LES model runs given in table 1. Previous work (Stoll and Porté-Agel, 2009) has demonstrated that flux aggregation models do a better job at predicting surface shear stress values than surface heat flux values, and therefore, only heat flux model predictions are examined here.

Figure 5 shows predicted surface heat flux values using the tile model (Avissar and Pielke, 1989) for the three heterogeneous surface cases. For all three, the tile model predicts the wrong sign of the surface heat flux at all model levels. This agrees with the results of Stoll and Porté-Agel (2009) who found similar behavior over heterogeneous surface temperature transitions (note the Hetθ6 case is identical to the high resolution simulation presented in Stoll and Porté-Agel, 2009). The combined aerodynamic surface roughness and temperature transition cases show better agreement with the LES data (less negative) but the new model still fails to predict the correct sign of the surface flux. Inspection of the flux predictions over each patch (not shown) used by the tile model to calculate the average heat flux, indicates that the tile model under predicts the negative heat flux over the colder patch in both the HRCS and CRHS cases. This under prediction is worse when the colder patch is also the smoother patch. Stoll and Porté-Agel (2009) observed a similar failure of the tile model to properly predict negative heat fluxes over cold patches. In general, the tile model does an adequate job of predicting the flux over the hot patches for all of the simulations.

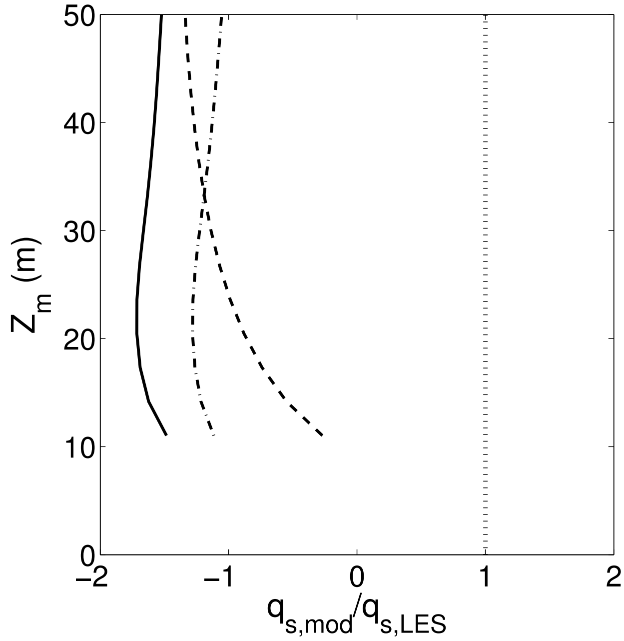

Figure 5: Surface heat flux $q_{s,mod}$ calculated using the tile model (Avissar and Pielke, 1989) at different model heights Z_m divided by the LES predicted heat flux $q_{s,LES}$. The lines represent the Hetθ6 case (solid line), the HRCS case (dot-dashed line) and the CRHS case (dashed line). The dotted line indicates a perfect correlation between the modeled and LES surface heat flux predictions.

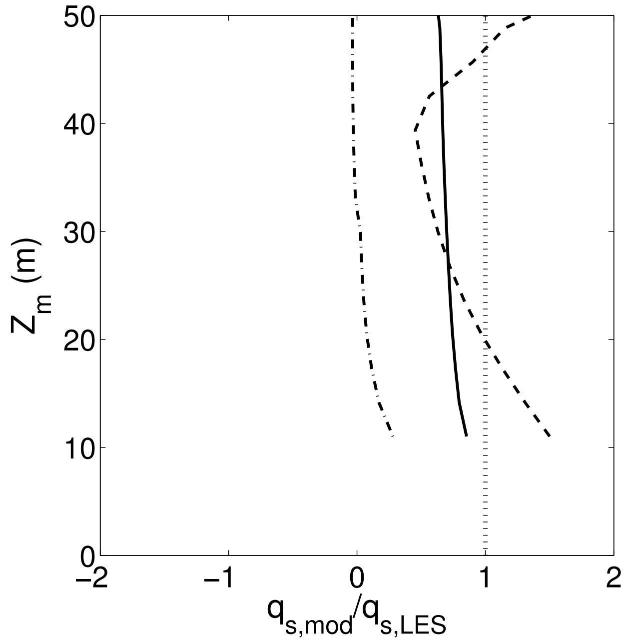

Figure 6: Surface heat flux $q_{s,mod}$ calculated using the model developed by Stoll and Porté-Agel (2009) at different model heights Z_m divided by the LES predicted heat flux $q_{s,LES}$. The lines represent the Hetθ6 case (solid line), the HRCS case (dot-dashed line) and the CRHS case (dashed line). The dotted line indicates a perfect correlation between the modeled and LES surface heat flux predictions.

Stoll and Porté-Agel (2009) developed a new model aimed at correcting the under prediction of the tile model over colder patches. They observed that advection of warmer air over the colder surface results in enhanced negative fluxes over the cold patches and a strong deviation from a constant flux layer. To correct this, they used Neiuwstadt's local scaling hypothesis (Nieuwstadt, 1984) to derive new stability corrections that account for the presence of surface heterogeneity. They found that this new model greatly improved average surface heat flux predictions. Figure 6 shows this new model for each of the heterogeneous test cases. The Hetθ6 case shown in the figure is one of the cases used by Stoll and Porté-Agel (2009) in developing the model. The new model clearly improves the surface heat flux predictions compared to the tile model for the combined temperature and aerodynamic roughness cases. Although it improves predictions and calculates the correct sign at the lowest model levels for both cases, it still fails to adequately match the LES results, especially for the HRCS case. Inspection of individual patch predictions (not shown) indicates that the new model suffers from a similar deficiency to the original tile model. It under predicts fluxes from the colder patch when the colder patch is also the smoother of the two patches.

3 Summary

Natural land surfaces are inherently heterogeneous. Representing this heterogeneity is a challenge in weather and climate models which must parameterize it based on grid-averaged values of atmospheric variables (e.g., velocity and temperature) at their first computational nodes. This study focuses on the ability of published land surface flux models to represent the heterogeneous SBL over combined aerodynamic surface roughness and surface temperature transitions. LES was used for this purpose.

The simulation were based on the GABLS I LES intercomparison case (Beare *et al.*, 2006). They consisted of abrupt streamwise transitions in surface temperature and aerodynamic surface roughness. Two combined cases were simulated, one with a hot-rough surface and a cold-smooth surface and another with a cold-rough surface and a smooth-hot surface. The surface heterogeneity had important impacts on mean boundary layer statistics and resulted in the simulation mean profiles deviating significantly from Monin-Obukhov similarity theory.

Two existing surface flux parameterizations were studied, the tile model (Avissar and Pielke, 1989) and a new model specifically designed for the heterogeneous SBL (Stoll and Porté-Agel, 2009). Both models had difficulty representing all of the heterogeneous SBL configurations studied here. This was attributed to insufficient negative heat flux over the colder patches, especially when the colder patch was also the smoother patch. While the new model improves predictions relative to the original tile model, it appears to have a limitation on the degree of local stability it can represent. This is possibly linked to a break down in some of its assumptions (e.g., linear heat flux with height over the cold patch). Future work is needed to develop models for the heterogeneous SBL that are more robust to a wide range of conditions. In addition, the results presented here do not include feedback between the surface boundary conditions and atmospheric predictions that is present in actual weather and climate models. To fully understand the implications of the model errors presented here, coupled simulations (e.g., with one-dimensional column models) are needed.

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