Mixing in the SBL over Temperature-Heterogeneous Surfaces: LES Findings and Some Parameterisation Ideas

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Representation of stably-stratified boundary-layer turbulence in numerical models of atmospheric circulation is one of the key unresolved issues that slows down progress in climate modelling, numerical weather prediction, and related applications. Turbulence in a stably stratified boundary layer (SBL) is weak and often intermittent in space and time. It responds to various effects, for example, internal gravity waves, cold air meandering, and horizontal heterogeneity of the underlying surface. Current SBL models do not include these important effects in a physically meaningful way. In the present study, the effect of horizontal temperature heterogeneity of the underlying surface on the turbulence structure and mixing efficiency in the SBL is analyzed using large-eddy simulation (LES).

Using the NCAR MMM LES code (Moeng 1984, Moeng and Wyngaard 1988, Sullivan et al. 1994, 1996, Sullivan and Patton 2008, 2011), one SBL flow with a homogeneous surface temperature, referred to as case HOM, and one flow with a heterogeneous surface temperature, referred to as case HET, are generated. The momentum and temperature fluxes at the surface are computed with the Monin-Obukhov surface-layer flux-profile relationships applied locally, i.e. point-by-point in the LES. The time varying surface temperature is determined by a specified surface cooling rate. In the homogeneous case, a constant cooling rate of –0.375 K/hr is applied over the first 8 hours of the simulations. In the heterogeneous case, the cooling rate is constant in the spanwise direction and varies sinusoidally in the streamwise direction – the horizontal-mean surface temperature is the same as in the homogeneous case. Eight hours of cooling leads to a surface temperature difference of 6 K between the warm and the cold stripes. Following this initial period, both simulations are continued, using a constant cooling rate of –0.375 K/hr. The set-up of our simulations is broadly similar to that of Stoll and Porte-Agel (2009) differing in the magnitude of the surface cooling rate and the shape of the surface-temperature heterogeneity patterns (a series of spanwise homogeneous surface temperature patches that alternate between two temperature values in the simulations of Stoll and Porte-Agel versus a sinusoidal variation of the surface temperature in our simulations). In order to obtain approximations to ensemble-mean quantities, the LES data are averaged over horizontal planes and the resulting profiles are then averaged over several thousand time steps. The number of samples varies between the different cases but the sampling time covers the last 1.75 hours of simulations.

The LES data are used to compute various statistical moments of the fluctuating fields (mean wind and mean potential temperature, second-order and third-order turbulence moments, pressure-velocity and pressure-scalar covariances), to estimate terms in the second-moment budgets, and to assess the relative importance of various terms in maintaining the budgets. It should be noted that the LES-based second-moment budgets are often estimated on the basis of resolved-scale fields only (cf. Mironov et al. 2000, Mironov 2001). However, the sub-grid scale (SGS) contributions may be substantial, particularly in the SBL, and should be retained in order to close the second-moment budgets to a good order. In the present study, the budgets of the turbulence kinetic energy (TKE), of the temperature variance, and of the vertical temperature flux are computed with due regard for the SGS contributions to the various budget terms.

A comparative analysis of the turbulence structure of SBLs with temperature-homogeneous and temperature-heterogeneous surfaces is performed. The SBL over a temperature-heterogeneous surface is more turbulent than over a temperature-homogeneous surface. Comparing cases HOM and HET, in the latter the SBL is deeper, has larger velocity variances and hence larger TKE, and is better mixed with respect to mean potential temperature. The latter result confirms a pervious finding of Stoll and Porte-Agel (2009). Perhaps the most striking difference between HOM and HET is in the temperature variance and its budget. Due to the surface heterogeneity, the third-order moment, i.e. the vertical flux of temperature variance, is non-zero at the surface. Hence, the turbulent transport term (divergence of the above third-order moment) not only redistributes the temperature variance in the vertical, but is a net gain. The temperature variance in HET is larger near the surface than in HOM. This increase in the temperature variance explains the reduced magnitude of the downward temperature (heat) flux in the heterogeneous SBL. The temperature variance enters the budget of the temperature flux as a buoyancy production term. Since that term is positive, it partially compensates the mean-gradient production term that generates the downward (i.e. negative) temperature flux. An increase of the temperature variance in a heterogeneous SBL results in a reduced magnitude of the temperature flux and hence of the buoyancy flux. Then, less TKE is spent working against gravity, leading to more vigorous mixing. The results outlined above are presented in Mironov and Sullivan (2010).

Motivated by the LES finding, possible ways to incorporate the effect of sub-grid scale surface temperature heterogeneity into SBL turbulence models (parameterization schemes) are considered. A tile approach, where several parts with different surface temperatures and different soil temperature profiles are considered within a host model grid box, offers considerable scope for alleviating problems associated with the treatment of SBL turbulence. The implementation of such a tile approach into numerical weather prediction models COSMO and ICON of the German Weather Service is underway (E. Machulskaya 2011, personal communication).

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