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Large-eddy simulation of turbulent flow past a rough-to-smooth surface transition: the effect of surface boundary conditions

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Understanding the effects of surface roughness transitions on the spatial distribution of surface shear stress and velocity is key to improving predictions of turbulent transport in the atmospheric boundary layer (ABL). One of the main issues that affect large-eddy simulation (LES) performance is the treatment of the surface boundary condition. Due to the high Reynolds number of ABL flows, the lowest grid point is necessarily far away from the viscous sub-layer, and typically in the so called surface layer (logarithmic layer in homogeneous neutrally-stratified boundary layers). The most common boundary condition formulations for LES of ABL flows calculate the fluctuating (filtered) surface shear stress from the resolved (filtered) horizontal velocity at the lowest grid point using Monin-Obukhov similarity (MOS) theory (the log-law under neutral conditions).

In large-eddy simulation over heterogeneous surfaces, where much of the surface heterogeneity is explicitly resolved, the surface boundary condition still requires the calculation of the local (spatially filtered) surface shear stress as a function of the filtered fluctuating velocity at the lowest computational grid points. It has been shown that the direct application of the log-law for prediction of surface shear stress downwind of transitions can lead to large errors because the similarity theory is strictly valid only when applied over homogeneous surfaces and considering averages quantities.

In addition, according to the previous studies, downwind of a rough-to-smooth transition, the log law underestimates the average surface shear stress especially at the initial part after the roughness transition and that underestimation shows a great dependence with the height at which the model is applied (i.e. the height of the lowest grid point). This is due to the fact that a large fraction of the internal boundary layer (IBL, i.e. the layer of flow that is affected by the downwind surface) velocity field is transitioning and, therefore, is not fully adjusted to the downwind surface. Indeed the velocity is in equilibrium with the surface, and thus follows the log-law, only in the lowest part of the IBL, commonly referred to as the equilibrium sub-layer. That equilibrium sub-layer is relatively shallow and, even though it grows with distance from the transition, it takes some distance to reach the height of the lowest grid point in LES.

In this study, LES with a scale dependent dynamic SGS model is used to simulate turbulent flows past a rough-to-smooth surface transition. Two types of boundary conditions are tested: (i) standard formulations based on local application of MOS, and (ii) a new model, based on a modification of a recently proposed model of Chamorro and Porte-Agel (2010). The new model assumes that the wind velocity downwind of a rough-to-smooth transition can be estimated as a weighted average of two logarithmic profiles: the first log law, which is recovered above the internal boundary layer, corresponds to upwind velocity profile; the second log law is adjusted to the downwind aerodynamics roughness. Within that layer, the local log law model can predict the surface shear stress well. The performance of the new model is tested with wind-tunnel measurements. The proposed model shows improved predictions of surface shear stress distribution at different positions downwind of the transition. Also, the prediction of this model shows very small dependence on the height (i.e. grid size) at which the model applied.

Keywords: Atmospheric boundary layer; Large-eddy simulation; Roughness transition; Surface shear stress model