P1.21 LARGE-EDDY SIMULATION OF DOWNSLOPE FLOWS

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1. INTRODUCTION

Drainage winds or slope flows are common features in regions of complex terrain. During the daytime, solar heating causes upslope flow as warm air rises toward higher terrain. At night, cooling causes flows in the opposite direction when more dense air along the upper regions of slopes accelerates downhill. The focus of this study is the behavior of these downslope flows, which are also referred to as katabatic or drainage winds.

Observations show that katabatic flows are characterized by a low level jet of cold air having a rapid decrease in velocity near the surface with a more gradual decrease above the flow (Figure 1). Temperature in the slope flow increases rapidly from the surface to about the center of the jet before slowly approaching the background conditions in the overlying air. This structure is maintained by a balance between the buoyancy, which acts to accelerate the flow downhill, surface drag, which decreases the flow speed, and transport processes, which move momentum away from the jet, increasing the slope flow depth. A key component in the these transport processes is the turbulence momentum transport, which is generated by the strong shear in the slope flow jet.

Because slope flows are typically very shallow, their dynamics are not well represented in mesoscale models. Consequently, a more thorough understanding of the dynamical processes that govern slope flows is needed if we are to improve local forecasts in regions of complex terrain. For example, accurate simulation of slope flows could have enormous effects on the prediction of minimum surface temperature.

Here, we utilize a large-eddy simulation (LES) model (Skyllingstad 2002) to examine the detailed turbulence structure of a simple slope flow.

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LES models directly simulate motions associated with turbulent eddies. Therefore, fluxes associated with turbulence can be calculated from the velocity and scalar transport, without relying on parameterizations. Comparisons are presented between the LES model and a mesoscale circulation model using equivalent slope parameters. The mesoscale model is the Advanced Regional Prediction System (ARPS) described in Xue et al. (1995). The goal of these comparisons is to see if typical boundary layer parameterizations can duplicate important features of slope flows.

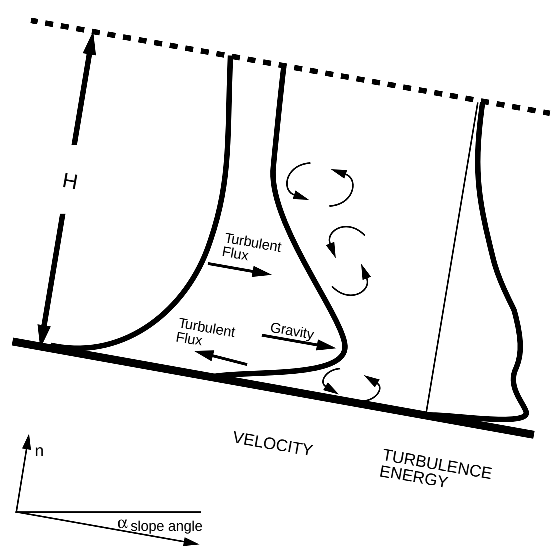

Figure 1. Schematic showing vertical profiles of temperature, velocity, and turbulence energy in a typical slope flow with slope angle a. Turbulence is most energetic above and below the slope flow core because of increased shear.

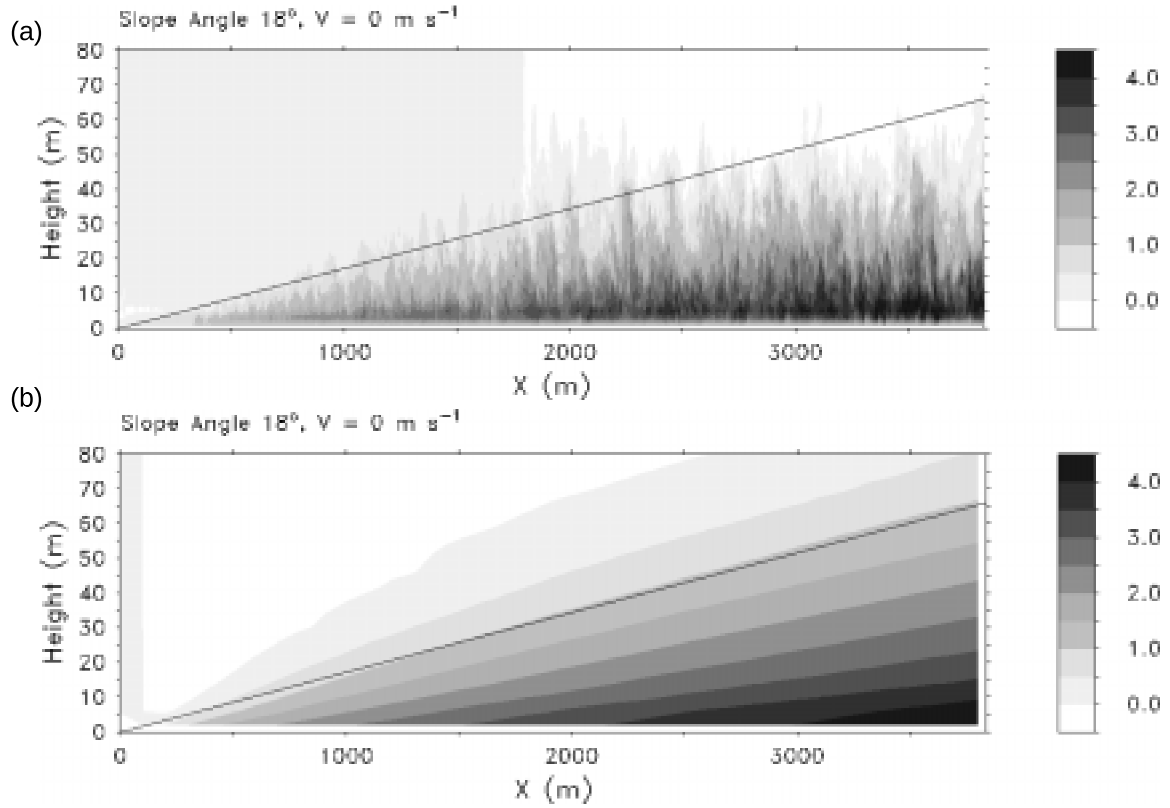

Figure 2. Cross section plot of the downslope velocity (m s^{-1}) for (a) LES model and (b) ARPS mesoscale model. Solid line represents the slope flow depth predicted by the Manins and Sawford (1979) model.

Slope flows are modeled in the LES by applying a rotated equation of motion,

$$\frac{\partial u_i}{\partial t} = -u_j \frac{\partial u_i}{\partial x_j} - \frac{\partial}{\partial x_j}\langle u''_i u''_j \rangle - \frac{\partial \tilde{P}}{\partial x_i} - g_i \frac{\rho'}{\rho_\circ}$$

where u_i are the components of velocity, double primes denote the subgrid scale fluxes, $\tilde{P}$ is a modified pressure, $g_i = (\sin\alpha, 0, \cos\alpha)g$ is gravity, g, rotated by the slope angle, α, ρ' is perturbation density, and ρ_o is the average density. Horizontal boundaries in the LES model are periodic in the along slope direction, open on the downslope boundary and closed on the upslope boundary. Mass flux at the model top is set equal to the total mass flux out the downslope boundary by setting the model top vertical velocity to the area weighted outflow speed.

Slope flow angles of 18^o and 1.6^o are considered. For the LES model, the domain encompasses a channel extending 3840 m from the closed top of the slope to the open boundary on the opposite boundary. Domain depth is 100 m with a width of 256 m and a grid resolution of 2 m.

For the ARPS simulation, a 22 km channel is simulated with a triangular mountain centered at the middle of the domain. The model is run in an approximate two-dimension mode with 220 grid points in the cross slope direction and 6 grid points in the along slope direction. Resolution is set to 100 m in the horizontal direction, with an expanding vertical grid starting at 5 m at the surface and increasing to 50 m at 500 m height. ARPS uses a terrain-following vertical grid, so the effective vertical spacing varies depending on the height of the underlying terrain. Ridge width in the mesoscale domain is set to 12 km, yielding a 6 km uniform slope and a 5 km flat run out on each side of the ridge. Horizontal boundaries are open in the cross slope direction, and periodic in the along slope direction. Both models are started from rest with a constant potential temperature of 300 K and a surface cooling rate of 30 W m^{-2}.

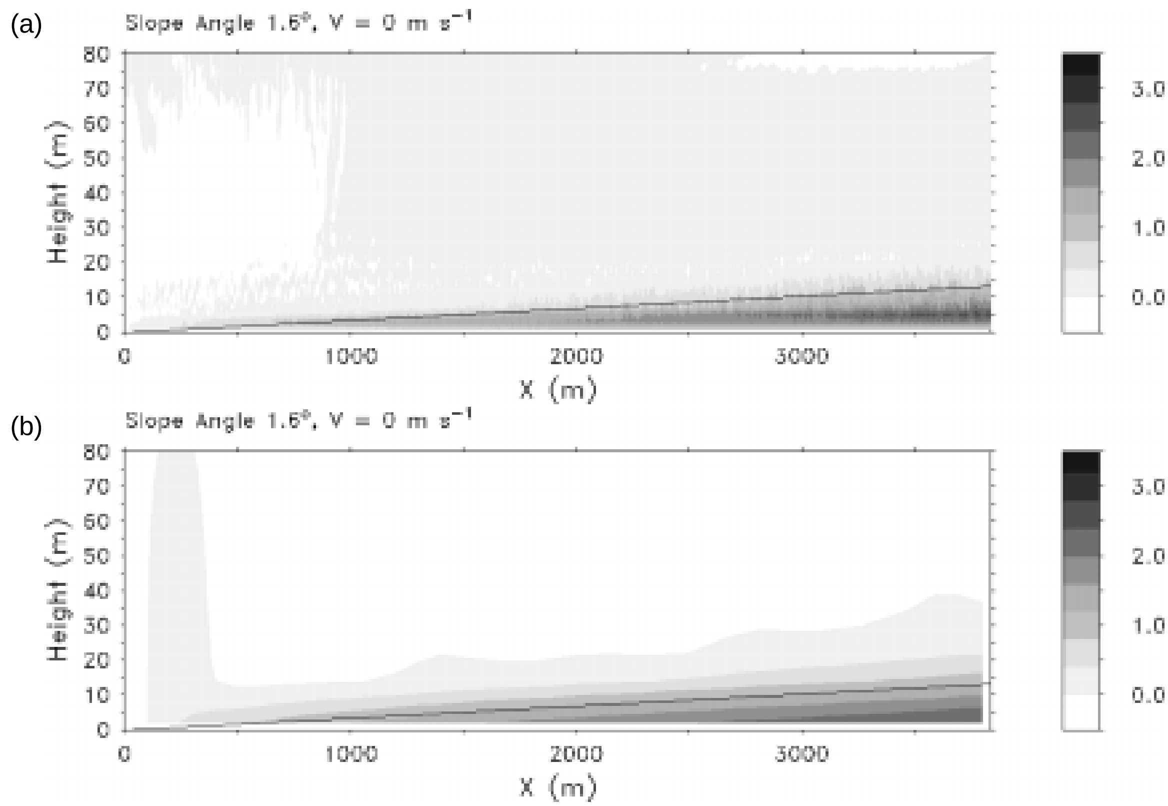

Figure 3. Same as Figure 2, but for slope angle of 1.6^{o}.

2. RESULTS

Simulation results for the 18^{o} slope after 1.5 hours are shown in Figure 2 for the LES and ARPS models. Results from the ARPS model are interpolated from the original terrain-following grid to a uniform 2 m grid for comparison with the LES output. By this time, both models have developed slope flows that are roughly in equilibrium. Probably the most notable difference between the LES and mesoscale simulations is the much more variable velocity in the LES case versus the smooth mesoscale output. Velocity variations in the LES represent turbulent eddies that actively transport momentum and potential temperature in the slope flow. Similar fluxes in the mesoscale model are parameterized via eddy exchange coefficients that are calculated using the Mellor and Yamada (1982) level 1.5 turbulence closure. Overall the range of velocities and depth of the slope flow are similar in the two simulations. Exceptions are the low level jet structure produced in the LES, which does not appear in the mesoscale simulation because of poor vertical resolution, and flattening of the slope depth near the outflow boundary in the LES, which may be a result of improper boundary conditions.

Comparison of the 1.6^{o} slope from both cases (Figure 3) shows better agreement. In this case, the low level jet is not as well defined in the LES compared with the 18^{o} slope, but is still stronger than the mesoscale case. Comparison of horizontally average profiles of downslope velocity from both simulations (not shown) show how the two models differ in the vertical slope flow structure. The LES has a clearly defined jet, whereas the mesoscale model shows a velocity maximum at the lowest grid point.

Plots of the turbulent kinetic energy (TKE) from the two models (Figure 4) for the 18^{o} slope case help explain the different behavior between the two models. For ARPS, TKE is nearly a factor of 2 larger than the LES value. Stronger subgrid turbulence in ARPS forces a deeper slope flow and weaker stratification, which in turn promotes production of more TKE. This is shown more clearly by plotting the potential temperature from the two simulations (Figure 5). Stronger mixing in the

ARPS case yields a higher surface temperature in comparison with the LES simulation. Consequently, the vertical gradient of potential temperature is weaker in ARPS

3. SUMMARY

Comparisons between LES and mesoscale model results for two slope flow angles show good agreement between general flow characteristics such as flow depth and vertical gradients. Significant differences are noted in finer details, for example, the mesoscale model is unable to resolve the low level jet produced by the LES model. Other differences are noted in vertical profiles. Analysis of the average TKE from the two models shows significant differences, with the ARPS model having TKE values a factor of 2 greater than the LES results. Higher values of TKE in the mesoscale model may be a result of a feedback between increased turbulence mixing and reduced vertical temperature gradients. As TKE increases, potential temperature is mixed more rapidly, causing a reduction in the buoyancy destruction term. Consequently, TKE is able to increase more readily in response to strong shear produced by the slope flow. Higher TKE values may be in response to the terrain-following coordinates, which require modifications to the TKE budget equation buoyancy term.

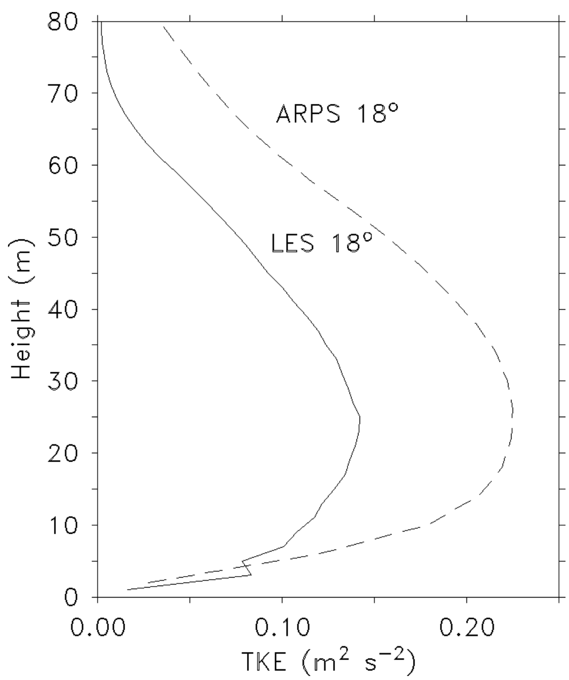

Figure 4. TKE averaged between 2,220 and 3,420 m downslope from the ridge top in the LES and ARPS models.

Future research will examine the individual terms in the mesoscale and LES TKE budget simulations to see if modifications can be made to improve boundary layer prediction in regions of complex terrain.

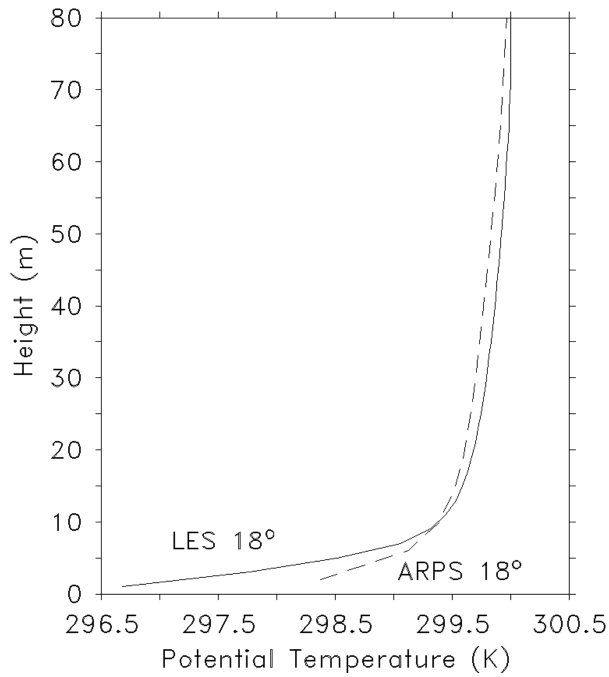

Figure 5. Same Figure 4, but for potential temperature.

4. REFERENCES

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