Response to Interactive comment on "Stably stratified canopy flow in complex terrain" by X. Xu et al.

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Reviewer #1

General Comments: The manuscript reported numerical studies of stably stratified canopy flow with complex terrain using Reynolds averaged Navier-Stokes (RANS) equations and RNG k-ε turbulent model. Thermal stratification in canopy flow is a long-standing problem for numerical modeling using available computational fluid dynamics (CFD) techniques. The major challenge is the intermittent turbulence associated with canopy flow under thermal stratification conditions. Advanced tools such as large eddy simulations (LES) cannot accurately capture the intermittent turbulence feature. On the other hand, direct numerical simulation (DNS) needs prohibitive computational resource makes it un-realistic to handle this problem. So the studies conducted in this work represent the latest effort in this area, in particular, the quantification and budget analysis of turbulent kinetic energy (TKE) under stably stratified canopy flow in complex terrain. Overall, the paper is a very good study and this reviewer recommends for publication with ACP after minor revision.

Authors:

We are grateful for reviewer's positive comments!

Reviewer #1

Special Comments: Page 28488 L22-25: the authors mentioned the computational domain size and grid used. On Page 28489 L4 provided the surface roughness height to be 0.01m. Did the authors conduct mesh independence studies to make sure the mesh sizes chosen in the simulation were fine enough so that the numerical results obtained were not sensitive to the mesh size? Please clarify this issue. Also please clarify what mesh size used close to the ground of the terrain and mesh size used in the area far away from the ground.

Authors:

We have tested the sensitivity of mesh grids in this numerical modeling. The vertical resolution of canopy structure (Leaf area density profile) in this numerical simulation is at a 1m resolution. We tested the mesh sensitivity of mesh grids at a finer resolution (0.2-1m) than canopy structure resolution. The results have low dependency on grid spacing lower than 0.6m at ground surface. The mesh size from the ground to the top of canopy is

0.5m and stretched from 0.5m at the top of canopy to about 1.5m at the top boundary of the domain. The grid spacing is described in L25-26, page 28488 and L1-3, page 28489.

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Page 28486 L1-5: This manuscript mentioned super-stable layers near leaves. The authors provided reference of Yi et al. (2005). Are there any research reports to show the turbulent flow field in this region? It is a tough task and might be out of the scope of this paper, just curiosity. A friendly reminder here is that the paper should emphasize that the flow is fully turbulent, even in the region of the super-stable layer. Even though RANS can still handle super-stable layer, the reason is that no matter RANS or large-eddy simulation (LES), turbulent intermittence is a significant challenge for accurate numerical simulations which might finally rely on experimental measurement.

Authors:

The supper stable layer has been demonstrated by a few more eddy-flux measurements (van Gorsel et al., 2011; Alekseychik et al., 2013) since Yi et al. (2005) reported it. However, to our knowledge, there is no research on the details of full turbulence development in the super-stable layer. As the reviewer pointed out, studying turbulent intermittence around the supper stable layer would be interesting. We will keep this in mind and address this point in our future study.

References:

van Gorsel, E., Harman, I. N., Finnigan, J. J., Leuning, R.: Decoupling of air flow above and in plant canopies and gravity waves affect micrometeorological estimates of net scalar exchange. Agric. For. Meteor. 151, 927-933, 2011.

Alekseychik, I. Mammarella, P., Launiainen, S., Rannik, Ü., Vesala, T.: Evolution of the nocturnal decoupled layer in a pine forest canopy. Agric. For. Meteor. 174-175, 15-27, 2013.

Reviewer #1

Page 28496 L10-15 about discrete Richardson number for stability of canopy flow, is there any way to output your RANS results of turbulent intensity, which might be directly used to check the consistence with the predicted Richardson numbers shown in Fig. 4? Answer to this question is optional (the paper extensively discussed the Ri and temperatures (Fig 3 and Fig 4)).

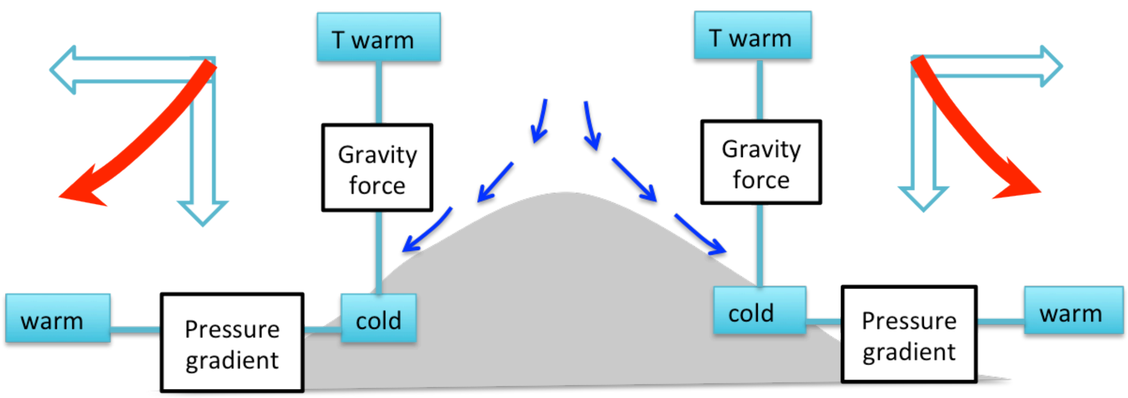
Authors:

We appreciate reviewer's suggestion. Unfortunately, we did not have the calculated turbulent intensity.

Reviewer #1

Page 28497 L25-30 about wind flow structures, there are two major factors to form the scenario, "converges towards the hill," the terrain and the cooling rate. Which factor is the dominant term? If cooling rate removed, will still generate this phenomenon? Please explain.

Authors:
The sinking flow above hill is initialized by the buoyancy force. However, if there is no slope, the descending wind would be very weak and there will be no convergence above the summit of hills. The temperature gradient in vertical and cooling on the slope surface and canopy layer leads to gravity force in vertical. In addition, the cooling on slope surface leads to positive pressure gradient in horizontal from the slope surface. The symmetric terrain makes the convergence symmetric. A schematic figure below shows the net force along the slope resulted from gravity force in vertical and pressure gradient in horizontal.
The forces that control the flows can be described as: hydrodynamic pressure gradient $F_{hd} = d\Delta p/dx \approx U^2 H/L^2$ and buoyancy force (or hydrostatic pressure gradient) $F_{hs} = g(\Delta\theta/\theta_0)\ sin\alpha \approx g(\Delta\theta/\theta_0\ )H/L$, *where* α *is the slope angle,* $\Delta\theta$ *is the potential temperature difference between the ambient air and the colder slope flow,* θ_0 *is the ambient potential temperature (Belcher et al., 2008).* Froude number Fr=U/NL=$\sqrt{F_{hd}/F_{hs}}$, where $N = (g/\theta\ _0)d\theta/dz$, L is the hill length scale. When Fr <<1, the hydrostatic pressure gradient is large enough to initialize drainage flow.



Reviewer #1
Page 28501 L12-24 about turbulent kinetic energy budget analysis in Figures 9-10, is there any way to validate the each term, e.g. any available experimental data about these? Which of these terms can be determined through experimental measurement? In such a way, it might be helpful to validate CFD results in the future (based RANS methodology).

Authors:
Meyers and Baldocchi (1991) have analyzed TKE budget in a deciduous forest under near neutral to slightly unstable condition. They simplified the calculation of vertical profile and ignore the buoyancy production. However, Leclerc et al. (1990) showed the importance of buoyancy production in both stable and unstable condition by observation in a deciduous forest. Direct measurements of turbulent pressure fluctuations in plant canopies are extremely difficult. Surface pressure

fluctuations are used to approximate the anemometers level pressure fluctuation to infer the role of pressure fluctuations in canopy turbulence (Maitani and Seo, 1985; Shaw et al. 1990; Shaw and Zhang, 1992). However, the calculation with surface pressure fluctuation fails to separate pressure diffusion and return-to-isotropy components of pressure-velocity interactions (Dwyer et al., 1997).The canopy flows are coupling results of topography and vegetation. The TKE fields are sensitive to the terrain's aspect ratio (Katurji et al., 2011), which are also shown in our numerical results.

References:

Meyers, T.P., Baldocchi, D. D.: The budgets of turbulent kinetic energy and Reynolds stress within and above deciduous forest. Agric. For. Meteor. 53, 207-222, 1991.

Meyers, T. P. and Paw U, K. T.: 1986, Testing of a Higher-Order Closure Model for Flow Within and Above Plant Canopies, Boundary-Layer Meteorol. 37, 297–311, 1986.

Leclerc, M. Y., Beissner, K. C., Shaw, R. H., den Hartog, G., Neumann, H. H.: The influence of atmospheric stability on the budgets of the reynolds stress and turbulent kinetic energy within and above a deciduous forest. J. Appl. Meteor. 29, 916–933, 1990.

Katurji, M., Zhong, S., Zawar-Reza, P.: Long-range transport terrain-induced turbulence from high-resolution numerical simulations. Atmos. Chem. Phys., 11, 11793–11805, 2011.

Wilson, N. R. and Shaw, R. H.: A Higher Order Closure Model for Canopy Flow, J. Appl. Meteorol. 16, 1197–1205, 1977.

Dwyer, M. J., Patton, E. G., and Shaw, R. H.: Turbulent kinetic energy budgets from a large-eddy simulation of airflow above and within a forest canopy, Bound.-Lay. Meteorol., 84, 23–43, 1997.

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Other comments: Overall this study brings lots of transition phenomena due to thermal stratification and the complex terrain interaction each other. For instance, the wind shear changes from the case H/L=0.6 to H/L=1.0 are very interesting (Fig. 6 and Fig. 7 of the paper), look forward to seeing experimental measurement for this variation. It is a very good work.

Authors:

To validate the numerical results, the necessary intensive measurements of wind and temperature fields below and above the top of canopy under different atmospheric stability are required.