RC2: 'Comment on acp-2021-325', Anonymous Referee #2, 11 Aug 2021

Response to anonymous Referee #3

We would like to thank the reviewer for taking the time to make detailed and useful comments. Details of the changes made are now given in the supplement in reply to your comments made one by one.

Specific comments

(1). The authors use the quasi-three-dimensional large eddy simulations (LES) in this study. The horizontal model domian of 135 km x 30 km with the mesh grid of 200 m. My question is why did not the author use the higher LES resolutions in this study? I wonder if the resolution of 200 m is appropriate for a LES study? In addition, what is the timestep in the simulations?

Thanks for your comments. A large horizontal domain (135 km×30 km) is used to include possible mesoscale circulation due to the surface heat flux anomaly in this study. Considering the high computational cost, we employed a grid spacing of 200 m for the LES simulations. However, previous studies about the turbulence gray zone confirms the spatial resolution of 200 m in our study is appropriate.

Honnert et al. (2011) defined a dimensionless mesh size $\Delta x/(z_i+z_c)$ to quantify the resolved and subgrid parts of the turbulence at different scales of any free convetice boundary layer, where z_i and z_c are the ABL height and the depth of the shallow cloud layer, respectively. Honnert et al. (2011) found that the resolved and subgrid TKE are equal for $\Delta x/(z_i+z_c)$ = 0.2. In our study, the CBL height reaches to about 700 m at 09:30 and up to 1900 m at 18:30 (Fig. 4 in the main text). Clouds developed from a cloud base approximately 1000 m at about 12:30 (Fig. R1 is shown following).

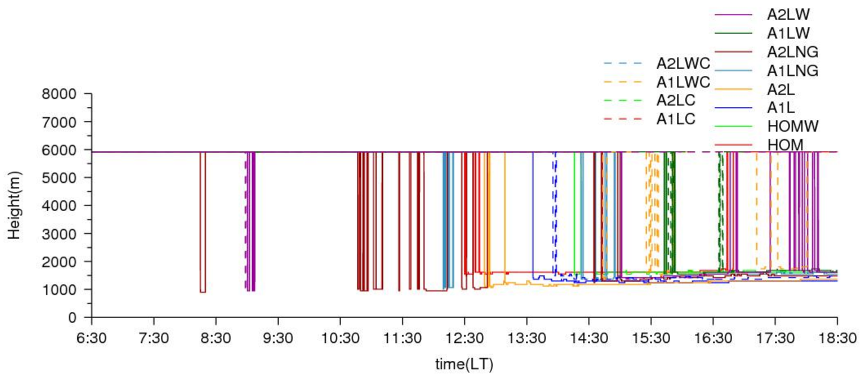

Fig. R1 The heights of cloud base for the different runs.

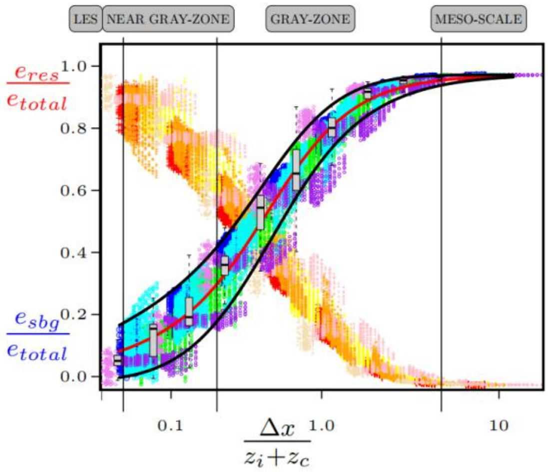

Fig. R2 The partition of the LES, near gray-zone, gray-zone and mesoscale (Shown in Fig. 4 from Honnert et al. (2020))

The calculated dimensionless mesh size is about 0.12 at 12:30, and about 0.08 at 15:30, which indicates the resolved TKE is larger than the subgrid part, especially for the time of 15:30 (as Fig. R2). Accoroding to Honnert et al (2020), the CBL gray zone is roughly at 200 m < Δx < 2 km when LES converging simulations is achieved at Δx ~ 20 m with taking z_i = 1000 m. It illustrates that the horizontal resolution of 200 m in our simulation lies in the near gray zone during the early CBL development (12:30)， but is an appropriate resolution for the time of 15:30.

There are LES studies with the horizontal grid spacing equaling to or larger than 200 m investigating the CBL turbulence over the heterogeneous surface (Huang et al. 2010; Rai et al. 2016; Xu et al. 2018). For example, Huang et al. (2010) used the Met Office Large Eddy Model with grid spacings of 200 m to simulate the effects of surface heat flux anomalies on the formation of deep boundary layer over the Sahara dessert.

We have clarified the resolution choice, as: "According to Honnert et al. (2011) and Honnert et al. (2020), the horizontal resolution of 200 m is reasonable in this LEM study."

The time step of 0.01s is applied for all simulations in this paper.According to your suggestion, a brief comment is added: "The time step is 0.01s for all simulations."

Honnert, R., Masson, V., & Couvreux, F. (2011). A diagnostic for evaluating the representation of turbulence in atmospheric models at the kilometric scale. J. Atmos. Sci., 68 , 3112-3131.

Honnert R , Efstathiou G A , Beare R J, et al. The Atmospheric Boundary Layer and the "Gray Zone" of Turbulence: A Critical Review[J]. Journal of Geophysical Research: Atmospheres, 2020, 125.

Xu H, Wang M , Wang Y, et al. Performance of WRF Large Eddy Simulations in Modeling the Convective Boundary Layer over the Taklimakan Desert, China[J]. Journal of Meteorological Research, 2018.

Huang Q, Marsham J H , Parker D J, et al. Simulations of the effects of surface heat flux anomalies on stratification, convective growth, and vertical transport within the Saharan boundary layer[J]. Journal of Geophysical Research Atmospheres, 2010, 115.

Rai R K , Berg L K , Kosovi B, et al. Comparison of Measured and Numerically Simulated Turbulence Statistics in a Convective Boundary Layer Over Complex Terrain[J]. Boundary-Layer Meteorology, 2016, 163(1):1-21.

(2). The thermal internal boundary layer (TIBL) would form when cold air passes over the warm surface. It has been reported that a large scale convective TIBL could form due to the surface heterogeneity. If there exists a TIBL when the air flows from the cold lake patch to the warm grass land in your study? How does the TIBL affect the turbulence interaction over the heterogeneous surfaces in your simulations?

Thanks for your comment. The TIBL forms when the air blowing from the cold lake to the warm grassland in our study. According to the other reviewer's comment, we have plotted the vertical TKE distribution for the runs with wind in Fig. 6d, 6e, 6f. We have added the statement about how the TIBL affect the turbulence interaction over the heterogeneous surfaces: "The similar TKE distribution occurs when the background wind exists over the homogeneous surface (Figs. 6a and 6d). It should be noted that there is larger TKE over the patch/patches (below 0.2 z_i) as the similar pattern of TKE in Papangelis et al. (2021), from which the TIBL can be recognized (Figs. 6e and 6f). The background wind tends to reduce the TKE outside patch/patches while enhance it over the patch/patches. Moreover, the background wind inhibits the development of the patch-induced circulation because the divergent wind derived from the heterogeneous surface can not be viewed at 15:30."

Papangelis G, Tombrou M, J Kalogiros. The Saharan convective boundary layer structure over large scale surface heterogeneity: A large eddy simulation study[J]. Atmospheric Research, 2020, 248:105250.

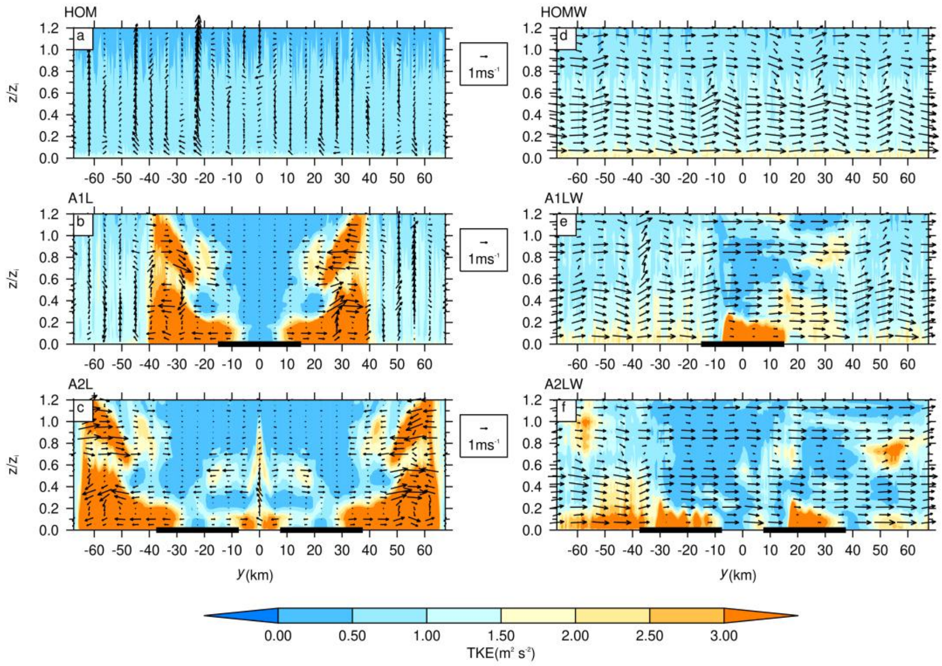

Fig. 6. The y-z cross sections of the TKE (contour) with superimposed wind vectors composed of *v* and *w* wind over (a, d) homogeneously heated and (b, e and c, f) heterogeneously heated surfaces with (d, e, f) and without (a, b, c) background flow. The black lines on the x-axis represent the lake patches.

In order to further illustrate the effects of the TIBL on turbulence, we have added more comments about the RES buoyancy production/destruction reaching a lower maximum for wind simulations in the text as following: "The buoyancy production/destruction in the TKE budget equation is $B = \frac{g}{\theta_v}\overline{w'\theta_v'}$. The RES buoyancy production/destruction profiles show that the lower maximum occurs for the wind simulations over the heterogeneous surfaces. It is because the larger positive buoyancy production/destruction decreases outside the patch (Fig. S4 in the supplement) due to the significantly weakened updrafts of the patch-induced circulations by the background wind. Comparing with no wind simulations (Fig. S4b, S4c), the buoyancy production/destruction over the patch/patches decreases for wind simulations. It is probably caused by the relatively warm air in a TIBL formed over the patch/patches (Fig. S5b, S5c) due to the abrupt change in surface heat flux (Mahrt, 2000) with air flowing from the warm patch to the cold patch. Similar with the results of Zhou et al. (2018) and Liu et al. (2020), the cold center of the TIBL (Fig. S5e, S5f) moves to the downwind of the lake patches. ”

Liu, R., Sogachev, A., Yang, X., Liu, S., Xu, T., Zhang, J. 2020. Investigating microclimate effects in an oasis-desert interaction zone. Agricultural and Forest Meteorology, 290, 107992.

L. Mahrt, 2000. Surface Heterogeneity and Vertical Structure of the Boundary Layer. , 96(1-2), 33–62. doi:10.1023/a:1002482332477

Zhou, Y., Li. D., Liu, H. and Li, X.: Diurnal variations of the flux imbalance over homogeneous and heterogeneous landscapes. Boundary-Layer Meteorology, 168:417–442. https://doi.org/10.1007/s10546-018-0358-2, 2018.

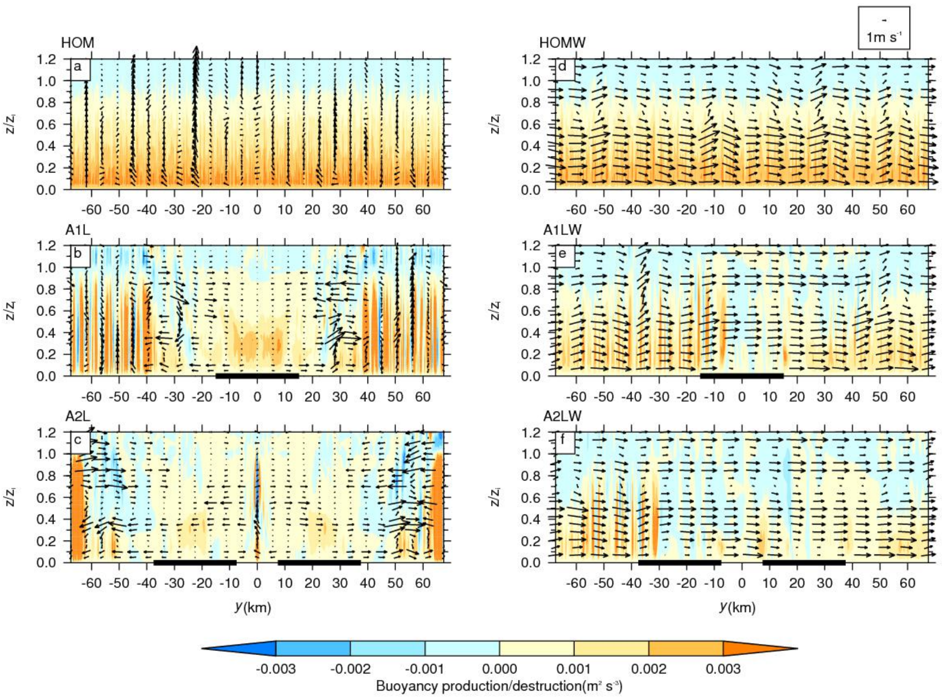

Fig. S4. The y-z cross sections of the buoyancy production/destruction (contour) with superimposed wind vectors composed of *v* and *w* wind over (a, d) homogeneous and (b, e, c, f) heterogeneous surfaces with (d, e, f) and without (a, b, c) background flow. Black lines on the x-axis represent the lake patches

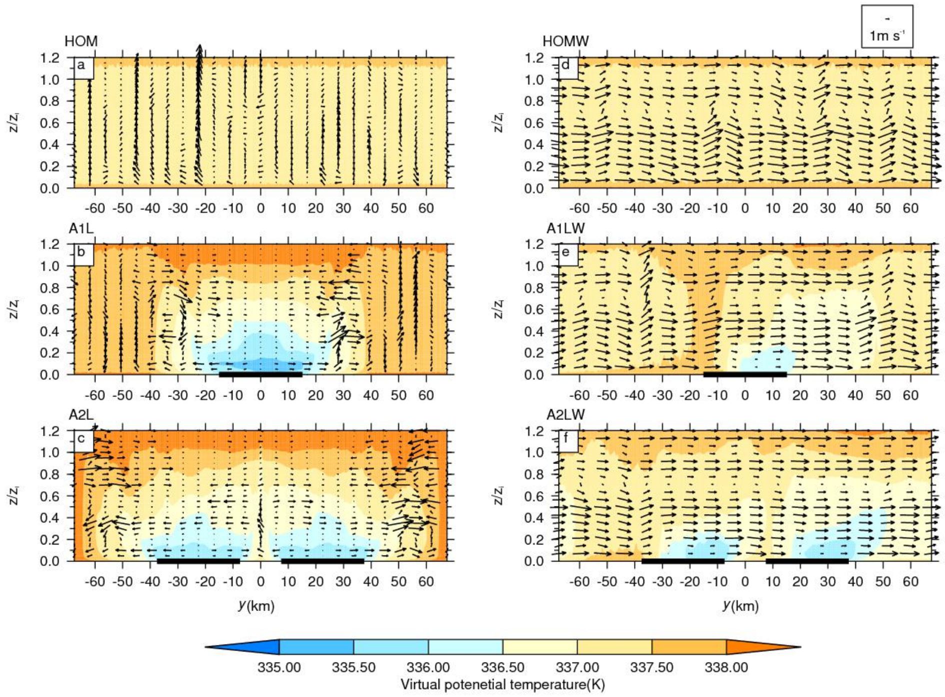

Fig. S5. The y-z cross sections of the virtual potential temperature (contour) with superimposed wind vectors composed of *v* and *w* wind over (a, d) homogeneous and (b, e, c, f) heterogeneous surfaces with (d, e, f) and without (a, b, c) background flow. Black lines on the x-axis represent the lake patches

In order to illustrate the effects of the geostrophic wind on the TIBL, wind profiles from runs with no geostrophic wind (runs A1LNG and A2LNG) have been added in the Fig. 7d. The following text is added: "Fig. 7d showed the wind profiles (red lines) for runs with background wind (HOMW, A1LW, A2LW) and without geostrophic wind (A1LNG, A2LNG), and the virtual potential temperature profiles (blue lines). It shows that patch-induced circulations reduce the modeled mean wind speed below the height of about 800 m, for the largest wind speed exists in the homogeneous case (red solid line). The wind profile is log-linear below the height of 20 m and shows a clear mixed layer above it for the homogeneous run, which correspond to a mixed layer shown by the virtual potential temperature profile (blue solid line). For the one/two-lake simulations, the wind profiles (red dotted and dashed lines) exhibit a feature of a stable boundary layer (blue dotted and dashed lines) with a maximum local wind at about 400 m. It should be noted that the stable stratification of wind profiles between 200 m and 1000 m are probably caused by the process of the TIBL. It is confirmed by the similar wind profile features from the runs without geostrophic wind over the heterogeneous surface."

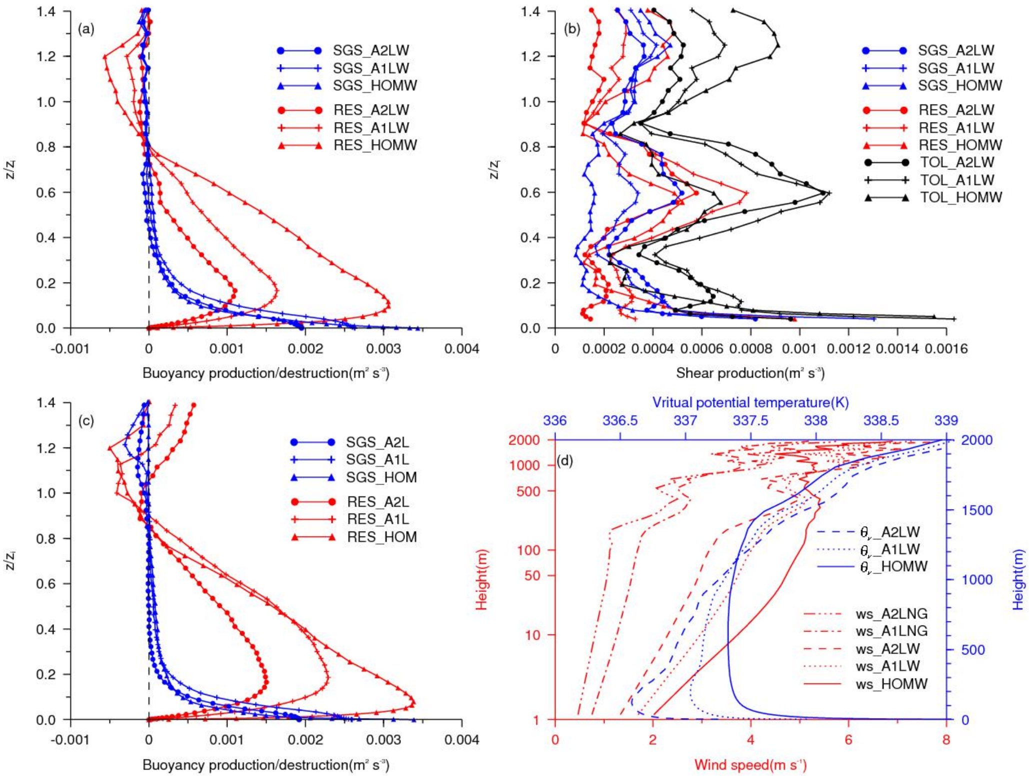

Fig. 7. Vertical profiles of (a) the buoyancy production and (b) the shear production term for runs HOMW, A1LW, and A2LW with background flows, and (c) the profiles of the buoyancy flux for runs HOM, A1L, and A2L without background flows. (d) The simulated horizontal wind (red lines) versus logarithm of height for runs HOMW, A1LW, A2LW, A1LNG and A2LNG, and the potential temperature profiles (blue lines) at this time. The resolved and subgrid results are presented as red and blue lines in (a), (b) and (c), respectively. The black lines in (b) are the total (resolved and subgrid scale) shear production term.

We have added the wind speed near the surface from the homogeneous simulations, and the potential temperature and sensible heat flux in Fig. 11. We have added the following statement about the TIBL, as: "Moreover, the potential temperature (Figs. 11e, 11f) and the sensible heat flux (Figs. 11g, 11h) increase abruptly from the lake patch to the grass patch (e.g. from y=15 km to y=25 km in Fig. 11e), which indicates the formation of the TIBL.”

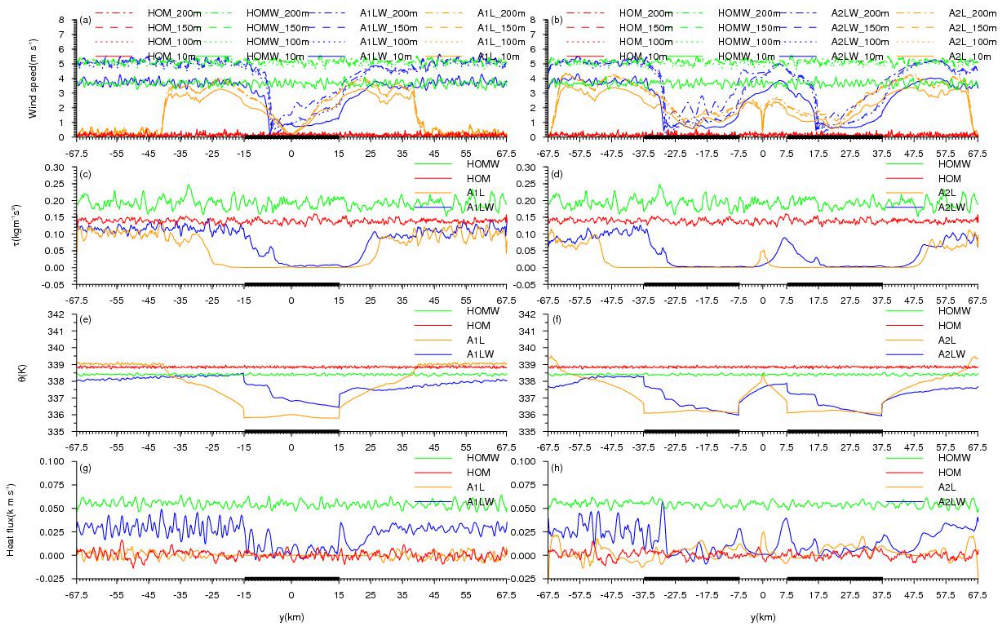

Fig. 11. Variations in the (a and b)wind speed, (c and d) Reynolds stress, (e and f) potential temperature and (g and h) heat flux in the horizontal direction below 200 m for the cases with (blue and green lines) and without (yellow and red lines) background flows over homogeneous (red and green lines) and heterogeneous (blue and yellow lines) surfaces. Black lines on the x-axis represent the lakes.

Detailed comments

1) p8, line 164-165, here ‘various ambient wind’ refers to the initial wind or the geostrophic wind?

The “various ambient wind” refers to initial wind and geostrophic wind. We have changed the “ambient wind” to the “background wind”.

2) p11, Fig 2d, Is the unit (km) of the height in Fig. 2d correct?

Thanks for your reminding. We have corrected the unit of “km” to “m” in the Fig. 2g.

3) p13, line239-240, sentence does not read well. You use three times ‘induced’, reword it.

We have rewritten this sentence: “...the turbulent fluxes were divided into two parts: circulation induced part and background turbulence induced part...”

4) p13, line 251, 254, please unified ‘fig’ and ‘Fig’, and check all through the paper

We have used the unified “Fig” in the paper.

5) p15, line 290, ‘with at a 3 h interval’ should be ‘‘with a 3 h interval’’

We have changed the sentence as: “...using the radiosondes with a 3 h (hour) interval during the simulation...”

6) p17, line 325-327, Sentence does not read well, reword it.

Thanks for your suggestion. We have rewritten this sentence, as: “...The region of negative heat flux above that altitude is often called the entrainment layer, which is thicker in the cases with background wind.”

7) p28, line 502, ‘confirms’ should be ‘confirm’

We have changed “confirms” to “confirm”.

8) p30, fig. 13, I suggest plotting the joint distribution for cases of HOM, A1L and A2L in a panel instead of two.

Thanks for your suggestion. We have plotted the joint distribution for cases of HOM, A1L and A2L in a panel instead of two.

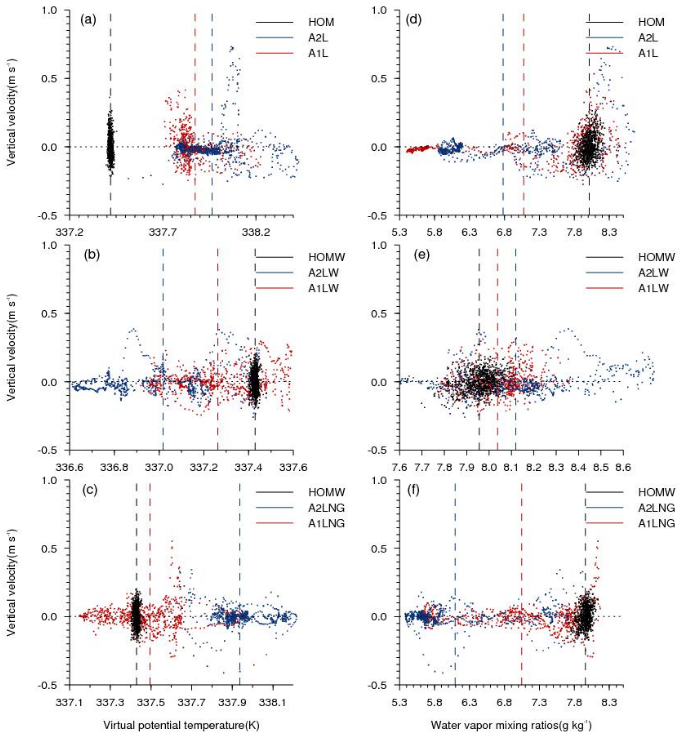

Fig. 13. The joint vertical velocities, virtual potential temperatures (a, b, c) and water vapor mixing ratios (d, e, f) at the top of the CBL for the homogeneous runs (black dot) and heterogeneous runs (red for one-lake and blue for two-lakes). The black dotted lines represent the mean vertical velocity. The black, red and blue dashed lines show the mean virtual potential temperatures and water vapor mixing ratios for the homogeneous, one-lake and two lakes runs, respectively.

9) I suggest the authors polishing the English proficience of this ms again.

We have polished the English in the text according to your comment.