

Response to anonymous Referee #2

We would like to thank the reviewer for taking the time to make detailed and helpful comments. The comments have been carefully addressed and our replies are summarized below.

General comments

(a) The figures need resolution improvement.

Thanks for the comments. We have improved the resolutions of all figures in the revised version.

(b) The authors used many acronyms to refer to the different simulations. In my opinion, this can confuse the reader in a first moment and it makes the reading slower. On the other hand, I understand the necessity to use it. My suggestion is to explain the logic behind the character choice and try to simplify the acronyms, i.e. shorter acronyms. Furthermore, avoid using non-alphanumeric symbols like underscore.

Thanks for the good suggestion. We have given the logical description of the characters in the title of Table 1, as: “Parameters for the 3D simulations over the homogeneous surface (HOM) and heterogeneous surface with surface heat flux anomalies (A) under different conditions: with one (1L) or two (2L) lake patches, with initial wind and geostrophic wind (W), without geostrophic wind (NG), with the constant surface heat flux (C)”. We also have changed the test names using the constant surface heat flux of A1L_C, A2L_C, A1LW_C, and A2LW_C into A1LC, A2LC, A1LWC, and A2LWC in the text.

Specific comments

(1) Page 7, lines 135-140 - The authors employed ERA-Interim data, with 1x1 degree resolution, to describe the flow synoptic features. Why did they chose this specific data set instead of another one with better time and spatial resolution as ERA5? A short explanation about this choice would be appreciated.

Thanks for your suggestions. Sorry, we described the resolution of the reanalysis data not clearly in the paper. We used the ERA-Interim Reanalysis Data with a $0.25^\circ \times 0.25^\circ$ resolution for the zonal and vertical winds in Fig. 3, and $1^\circ \times 1^\circ$ resolution for temperatures and geopotential heights. We paid more attention to the synoptic wind field and the circulations induced by the surface heat flux anomaly. We have replotted Fig. 3 using ERA-Interim reanalysis data with a $0.25^\circ \times 0.25^\circ$ resolution for all variables. We have changed in the text: “...using the ERA-Interim Reanalysis Data with a $1^\circ \times 1^\circ$ resolution...” to “...using the ERA-Interim Reanalysis Data with a $0.25^\circ \times 0.25^\circ$ resolution...”

(2) Page 7, line 151 - The authors used 200-m of spatial resolution on their simulations. Is it an appropriate resolution for LES regarding the turbulence gray zone? In some papers on literature, this order of resolution size is called Very Large Eddy Simulations (VLES). Maybe the authors could clarify it better on the text. Furthermore, how about time resolution (time step) for these simulations? Please include a brief comment about it on the text.

Thanks for your comments. A large horizontal domain ($135 \text{ km} \times 30 \text{ km}$) 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 confirm 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 convective 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 paper). Clouds developed from a cloud base approximately 1000 m at about 12:30 (Fig. R1).

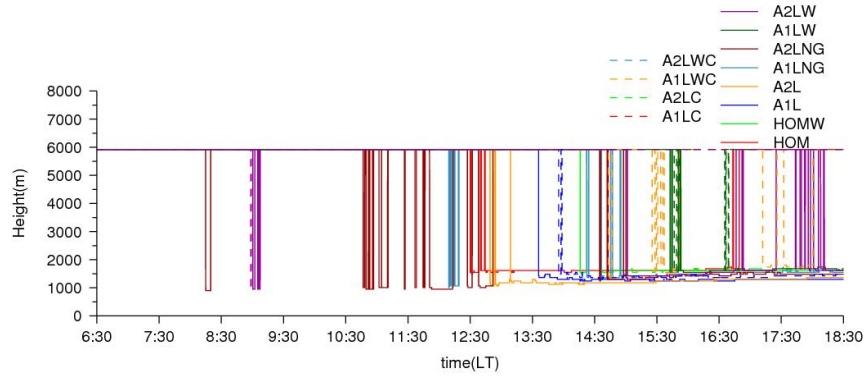


Fig. R1 The heights of cloud base for different runs.

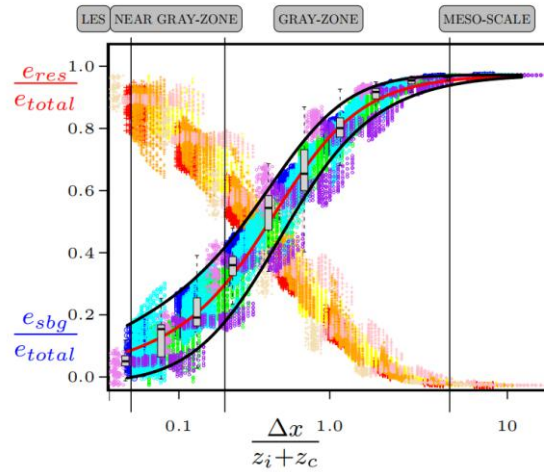


Fig. R2 The partition of the LES, near gray-zone, gray-zone and mesoscale (Shown in Fig. 4 from Honnert et al. (2020))

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 (Fig. R2). According to Honnert et al (2020), the CBL gray zone is roughly at $200 \text{ m} < \Delta x < 2 \text{ km}$ when LES converging simulations is achieved at $\Delta x \sim 20 \text{ m}$ with taking $z_i = 1000 \text{ m}$. 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.

Some LES studies have used horizontal grid spacing of larger than 200 m to investigate 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 desert.

We have clarified the resolution choice: “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 kilometeric 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.

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.

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.

(3) Page 7, line 152 – The authors did a vertical grid spacing description at that point. I suggest a more precise description including:

(i) how many vertical levels were used on simulations setup;

(ii) how they were stretched;

Thanks for your suggestions. Seventy-four (74) levels were set up in the vertical direction. We have revised the statement as: “There were 74 levels in the vertical direction, with a vertically stretched grid having a minimum spacing of 1.1 m in the surface layer and a maximum of 64.8 m above 2000 m.”

(4) Page 8, lines 158-161 - The authors indicated the initial conditions for the simulations. Could they mention figure 2 here? A simple indication as: “These conditions will be detailed on figure 2” would be enough

Thanks for your reminding. We have added the description as your suggestion: “These conditions will be detailed on Fig. 2.”

(5) Page 11, figure 2: The initial conditions obtained from upper air sounding present a non-smooth shape with a pronounced vertical variation (mainly for the wind components), which is expected for high-resolution measurement. My question is: were they used exactly as it was showed on figure 2 as initial condition or were they smoothed to accomplish it? If so, please, show the initial condition smoothed profile on figure 2 as well.

Thanks for your comments. Sorry about the inaccurate description of the initial profiles. The initial profiles shown on Figs. 2g and 2h are the radiosonde initial profiles, which were interpolated to the model grid as the LEM initial profiles. We have revised the caption of Fig. 2 and added the model initial profiles in Fig. 2 as well.

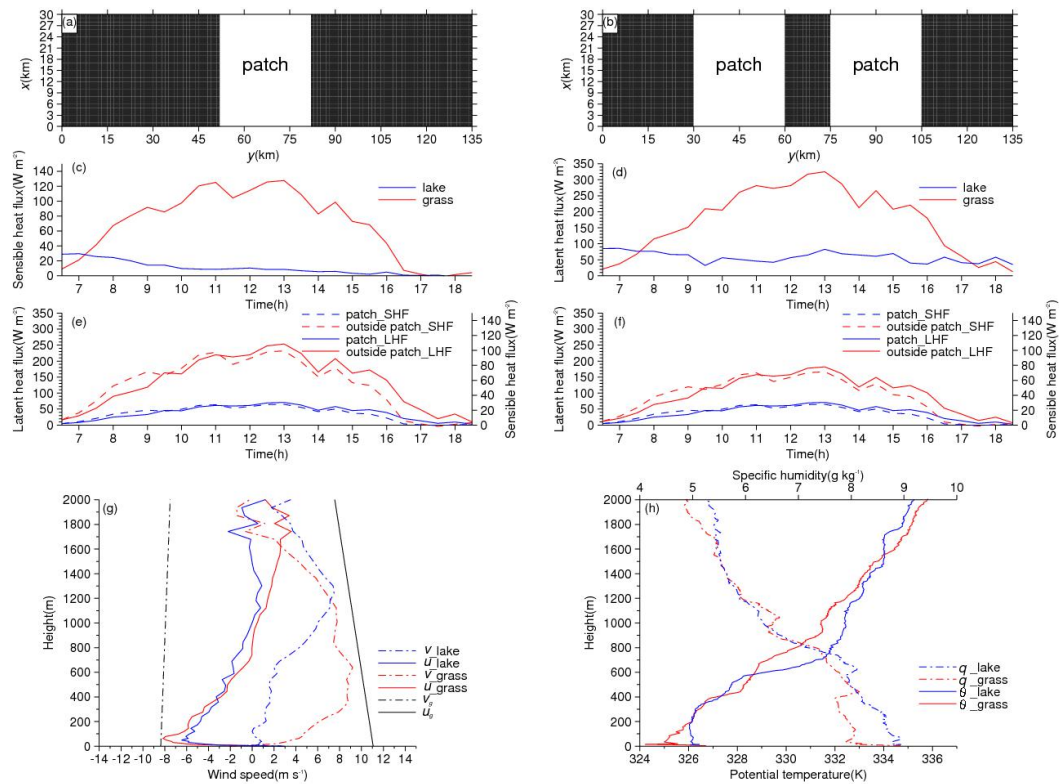


Fig. 2. Sketch of the heterogeneous surface (a and b), (c and d) surface sensible heat flux and latent heat flux over the grassland (red line) and the lake (blue line) from observation. The SHF and the LHF for runs with (e) one and (f) two lake patches and a constant heat flux. Figs. 2g and 2h show the initial profiles of the winds (solid lines for u , dash lines for v), potential temperature (solid lines), and special humidity (dash lines) over the lake patches (blue lines) and patches outside (red lines) in LEM. The input geostrophic winds are also shown (black lines)

(6) Page 14, figure 3 - About this figure, I have the following concern/suggestions:

(i) It is not clear to me why the authors mixed different vertical levels to compare temperature and other variables at different times. Could you explain it better? For me, it makes more sense to compare same levels at different times.

(ii) The lines for geopotential height are not clear on these plots as well as its labels (values). Could you improve that?

(iii) Each wind vector seems to be plotted at 0.25 degree. Is it an interpolation for the ERA Interim 1x1 degree resolution data? If so, please remark it. Again, if the resolution for the synoptic wind field is an important feature, it seems to me that another reanalysis dataset would be more interesting for this work.

We appreciate your suggestions. We wanted to confirm the occurrence of the lake breeze at different levels and different time before. But it makes more sense to compare the variables at the same level and different time as you commented. We have replotted figure 3 shown below. In order to show clearly, the geopotential height lines and its labels are presented in black.

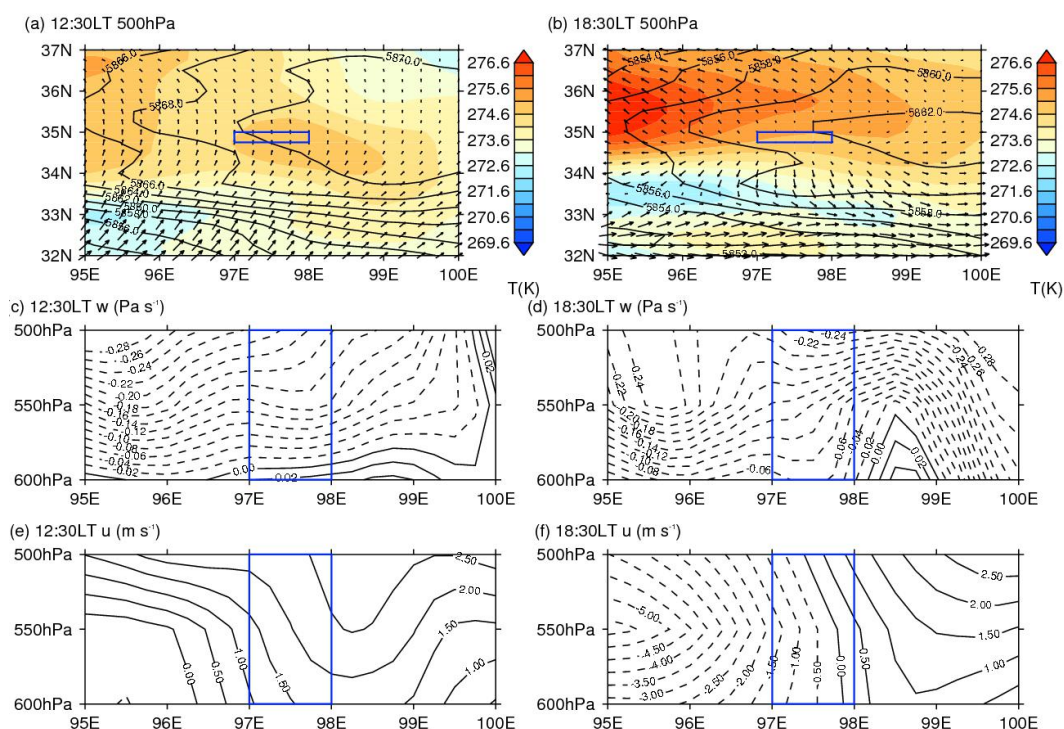


Fig. 3. Synoptic background on July 29, 2012. Blue boxes represent the two lakes area. (a) and (b) show the wind field (vector arrow), temperature field (color-filled contour), and geopotential height field (black lines) at 500 hPa (~5500 m) at 12:30 LT (Fig. 3a) and at 18:30 LT (Fig. 3b). The vertical wind (w , Figs. 3c and 3d) and the zonal wind (u , Figs. 3e and 3f) below 500 hPa are also shown

It seems that the comment (1) and comment (6) (iii) are related. As the answer for comment (1), we used the ERA-Interim Reanalysis Data with a $0.25^\circ \times 0.25^\circ$ resolution for the zonal and vertical winds in Fig. 3, and $1^\circ \times 1^\circ$ resolution for temperatures and geopotential heights. We paid more attention to the synoptic wind field and the circulations induced by the surface heat flux anomaly. We have replotted Fig. 3 using ERA-Interim reanalysis data with a $0.25^\circ \times 0.25^\circ$ resolution for all variables. We revised the statement as: “...using the ERA-Interim reanalysis data with

a $0.25^\circ \times 0.25^\circ$ resolution for the two lakes area...The southerly wind controlled the entire region at 500 hPa at 12:30 LT (Fig. 3a) then it became divergent flow at 18:30 LT (Fig. 3b).”

(7) Page 21, figure 7 – About this figure I have the following concern/suggestions:

(i) What day time are these profiles related to? It was not clear on the text.

The profiles of the buoyancy production/destruction and the shear production term, and wind velocity shown in Fig. 7 are the results at 15:30 LT. According to your comments, we have added the time as: “..... which is from the contributions of the resolved (RES) and subgrid (SGS) eddies at 15:30 LT (Figs. 7a, 7b, and 7c)”

(ii) I suggest using the designation “Buoyancy production/destruction” instead “Buoyancy flux” to refer to the turbulent kinetic energy (TKE) budget equation term to avoid any misinterpretation. Furthermore, “Buoyancy flux” is not precise to describe it on a physical sense.

Thanks for your suggestion. We have changed the “buoyancy flux” to “buoyancy production/destruction” for the title and the caption in figure 7.

(iii) The buoyancy production/destruction profiles showed a similar behavior for wind/no wind simulations in a homogeneous surface. However, for heterogeneous surface simulations, it is clear that resolved heat flux reaches a lower maximum and decreases differently from pure-convection (no wind) simulation. Could you briefly explain it on the text?

Thanks for your suggestion. 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 patches (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 thermal internal boundary layer (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.

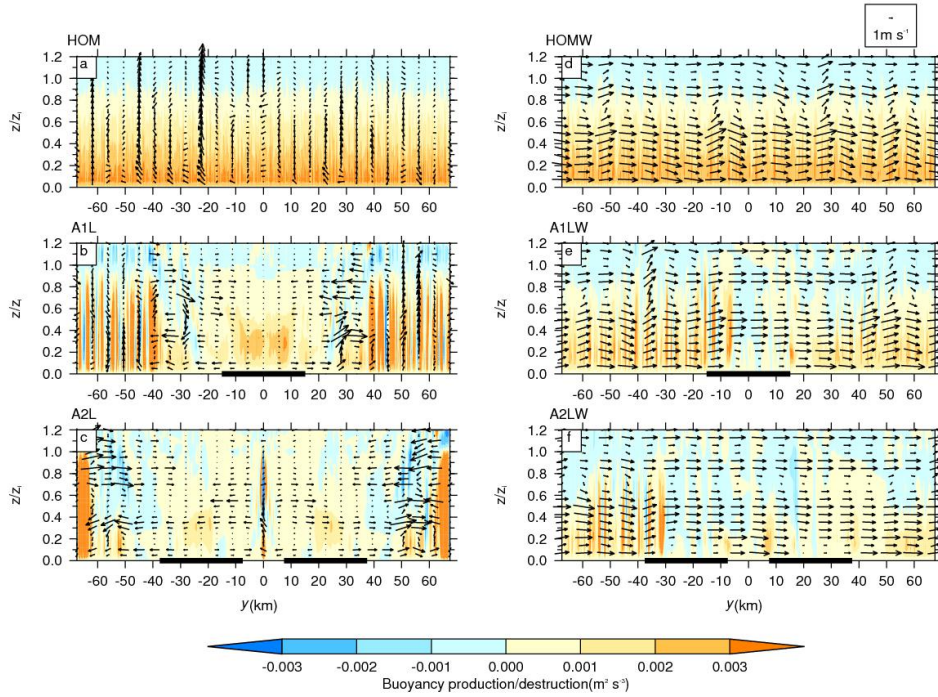


Fig. S4. The y - z cross sections of the buoyancy production/destruction (contour) with superimposed wind vectors composed of v and w wind over (a, d) homogeneous and (b, e, c, f) heterogeneous surfaces with (d, e, f) and without (a, b, c) background flow. Black lines on the x -axis represent the lake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

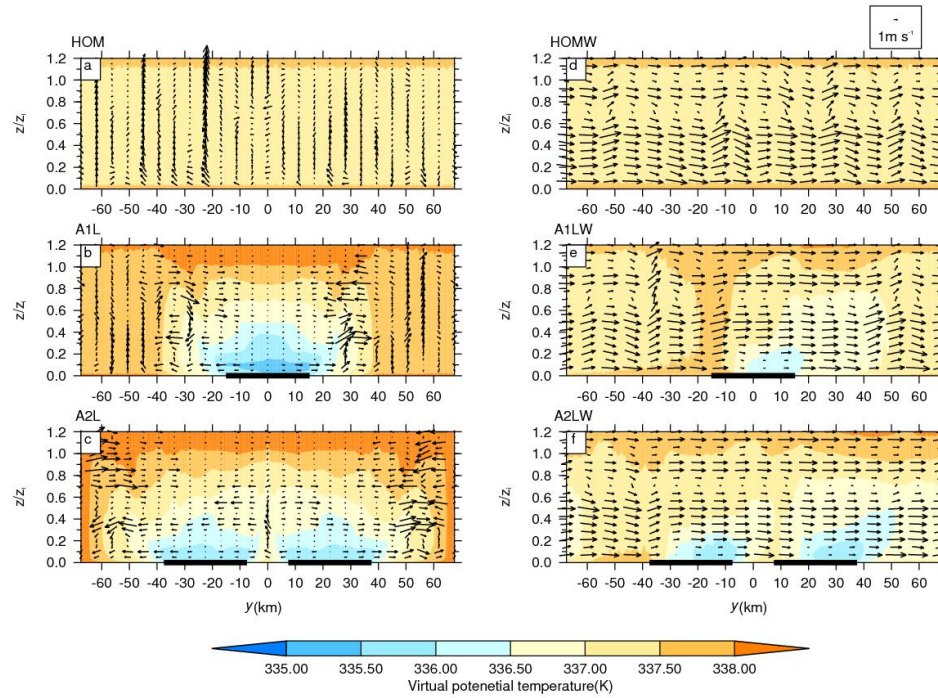


Fig. S5. The y - z cross sections of the virtual potential temperature (contour) with superimposed wind vectors composed of v and w wind over (a, d) homogeneous and (b, e, c, f) heterogeneous

surfaces with (d, e, f) and without (a, b, c) background flow. Black lines on the x-axis represent the lake patches

(iv) I suggest a new figure, like figure 6, to describe the effect of buoyancy TKE budget term. It could be included on the main paper or on the supplementary documentation. It would clarify the interaction of lake patches with atmospheric flow and how it impacts the TKE balance.

Thanks for your suggestions. We have added a figure (Fig. S3) in the supplementary documentation, which shows the y-z section of the buoyancy production for runs with and without background wind over homogeneous and heterogeneous surfaces. We have added analyses about the interaction of lake patches with atmospheric flow as: “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, especially in the downstream of the patch (Fig. S4 in the supplement), which is 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 thermal internal boundary layer (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.”

(v) Is the wind shear the source of SGS shear production peak at $z/z_i = 0.6$ or is there an unusual feature on the momentum flux profile? Again, a plot with the momentum

flux profile (resolved and SGS) could be presented on the supplementary documentation to clarify it.

Thanks for your suggestion. Corresponding to the Fig.7b, we have plotted a figure of the momentum flux profiles as Fig. S3 added in the supplement. It confirms that the wind shear causes the peak of the SGS shear production at $z/z_i = 0.6$. Because the larger momentum above $0.6 z_i$ is transported downward, which leads to the increase of the wind speed and wind shear below. We have added comments as: “In addition, wind shear is the source of the SGS shear production peak at $z/z_i = 0.6$ due to the larger momentum flux above $0.6 z_i$ (see Fig. S3) increasing the wind speed and wind shear below.”

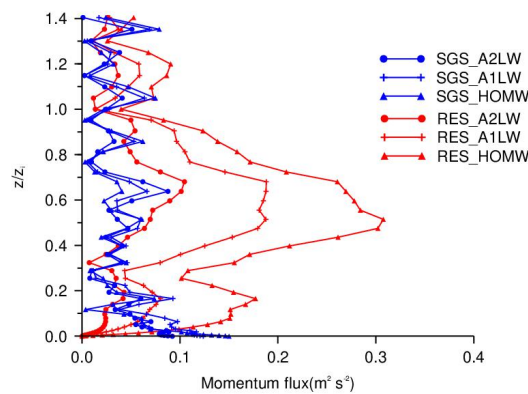


Fig. S3. Vertical profiles of the momentum flux for runs HOMW, A1LW, and A2LW with background flows. The resolved and subgrid results are presented as red and blue lines, respectively

(vi) The wind profiles presented an interesting feature on heterogeneous surface simulations. In the homogeneous case, the wind profile seems to be log-linear close to surface and showed a clear mixed layer above it. For the lake simulations, the wind profiles exhibit a feature similar to a stable boundary layer, with a maximum local wind. It is an interesting feature that could be better discussed on the text. I suggest plotting the potential temperature profile associated to these wind profiles to better understand the PBL vertical structure at this time. One could say that an internal boundary layer process would be occurring here. Furthermore, I suggest plotting a

log-linear law and the geostrophic wind components with wind profiles to better visualize and discuss these wind profiles.

We appreciate your detailed comments. We have replotted the Fig. 7d with including log-linear wind profiles and virtual potential temperature profiles associated with these wind profiles. 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. A constant geostrophic wind profile is used in this study. Considering the geostrophic wind components have been shown in the Fig. 2g, they are not plotted 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.”

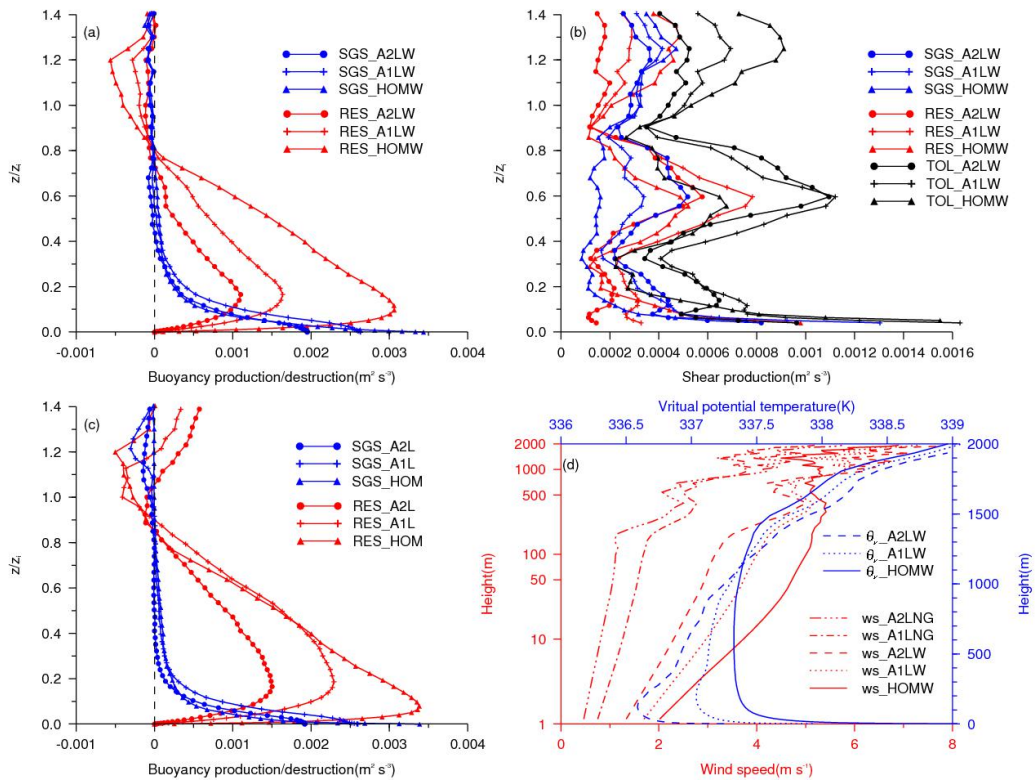


Fig. 7. Vertical profiles of (a) the buoyancy production and (b) the shear production term for runs HOMW, A1LW, and A2LW with background flows, and (c) the profiles of the buoyancy flux for runs HOM, A1L, and A2L without background flows. (d) The simulated horizontal wind (red lines) versus logarithm of height for runs HOMW, A1LW, A2LW, A1LNG and A2LNG, and the virtual potential temperature profiles (blue line) 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

(vii) Regarding the possible internal boundary layer formation, an extra plot for potential temperature, similar to figure 6, could be made.

Thanks for your suggestion. The vertical distribution of the potential temperature is plotted as Fig. S5 in the supplement. Please find the detailed replay in the comment 7 (vi).

(8) Page 22, line 408 – I wonder if the weaker updrafts could explain the buoyancy TKE

budget term features highlighted previously. What do the authors think about that? If these two characteristics are related, please detail it on the text.

Thanks for your reminding. The weaker updrafts for wind simulations also correspond to the weaker buoyancy production term in the analysis of Fig.7. We also added the statement like: “...which is confirmed by the weaker buoyancy production/destruction for the heterogeneous simulations in the Figs. 7a and 7c.”

(9) Page 23, figure 8 – I think it would be interesting to add an extra plot here with the homogeneous cases. It helps to evaluate the lake patch impact on the local circulation.

Thanks for your suggestion. We have added the instantaneous y-z cross sections of the vertical velocity and wind vectors above the homogeneous surfaces for runs without (Fig. 8g) and with (Fig. 8h) background wind. We also added the statement, like: “Comparing with the spatial distribution of the vertical velocity over the homogeneous surface (Figs. 8g and 8h), the lake patch/patches alters both the boundary-layer convection intensity and the local circulation.”

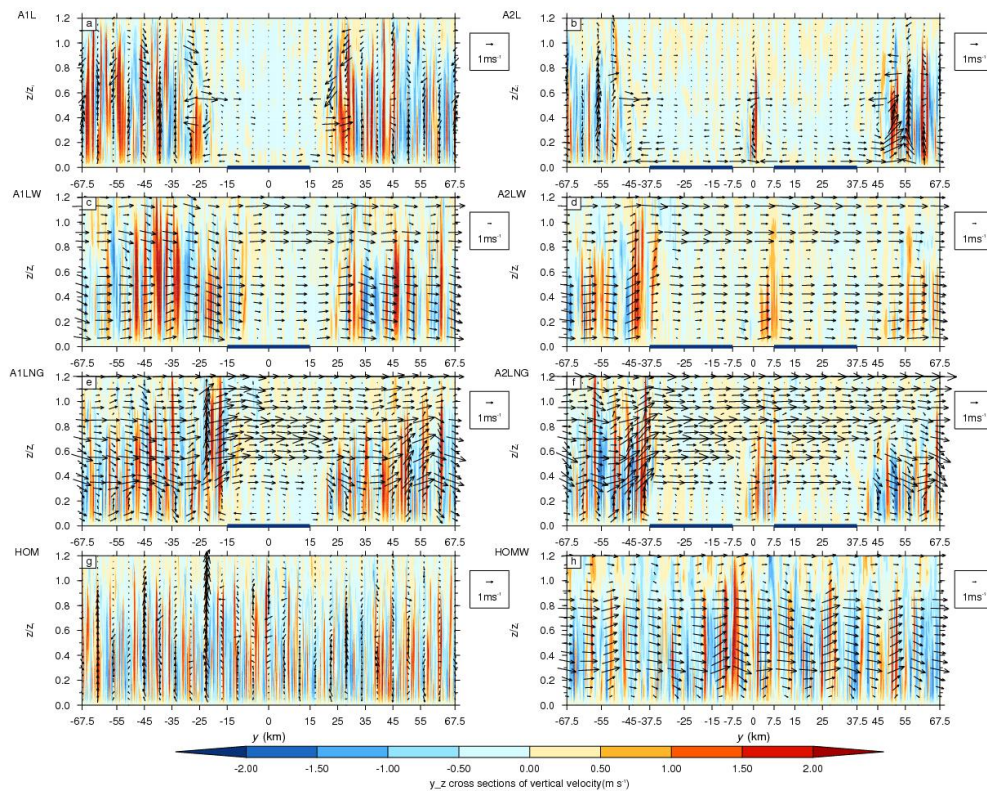


Fig. 8. Instantaneous y - z cross sections of the vertical velocity (m s^{-1}) and wind vectors above the heterogeneous surfaces for runs (a and b) without and (c and d) with background wind, and (e and f) with the geostrophic wind removed, as well as the results over homogeneous surfaces for runs with (h) and without (g) background flow. The blue lines on the x -axis represent the lake patches

(10) Page 432, figure 10 – What time is it on the simulation? Is it on the same time of wind profiles from figure 7? I am asking it because the negative heat flux on the wind-simulations, above the lake patch, could be decreasing the turbulent viscosity and increasing the wind speed consequently. What do the authors think about that? It is important to note that the minimum flux value (negative) is in a magnitude so strong as it is close the surface. Furthermore, it happens around the same height of local maximum wind. I suggest plotting the potential temperature associated to these heat fluxes to better understand it.

Thanks for your comments. Yes, it is at the same time of wind profiles from Fig. 7. We have added the time in the caption of Fig. 10. The wind profiles in Fig. 7d are the domain-averaged. We have plotted mean profiles of the potential temperature and

wind speed above the lake patch shown in the following Fig. R3. It shows that the wind speed over the patch increases significantly for the wind simulations, and the height of the largest wind speed corresponds to height of the minimum heat flux over the lake patch/patches (at about $0.3 z_i$ in Fig. 10d). The downward transport of the heat flux inhibits the turbulence mixing over the lake patch, and increases the wind speed consequently. This probably contributes to the local maximum wind speed. We have added the following text: “Notice that the minimum heat flux (at about $0.3 z_i$) is in the magnitude so strong as it is close to the surface ($0.1 z_i$). It probably contributes the local maximum wind speed.”

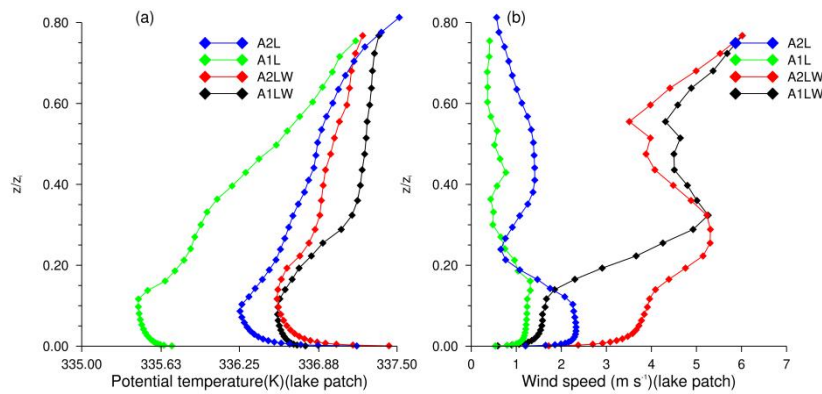


Fig. R3 The profile of the simulated potential temperature (left) and wind speed (right) over lake patch with (red and black lines) and without (blue and green lines) background wind at the same time of Fig. 10 and Fig. 7

(11) Page 26, figure 11 – This figure shows a clear transition between the land-lake PBL. I would like to see the wind speed of homogeneous simulation to compare it with the heterogeneous ones, as well as a comparison for potential temperature and heat flux. It could be interesting to understand a possible internal boundary layer formation.

Thanks for your suggestion. 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.”

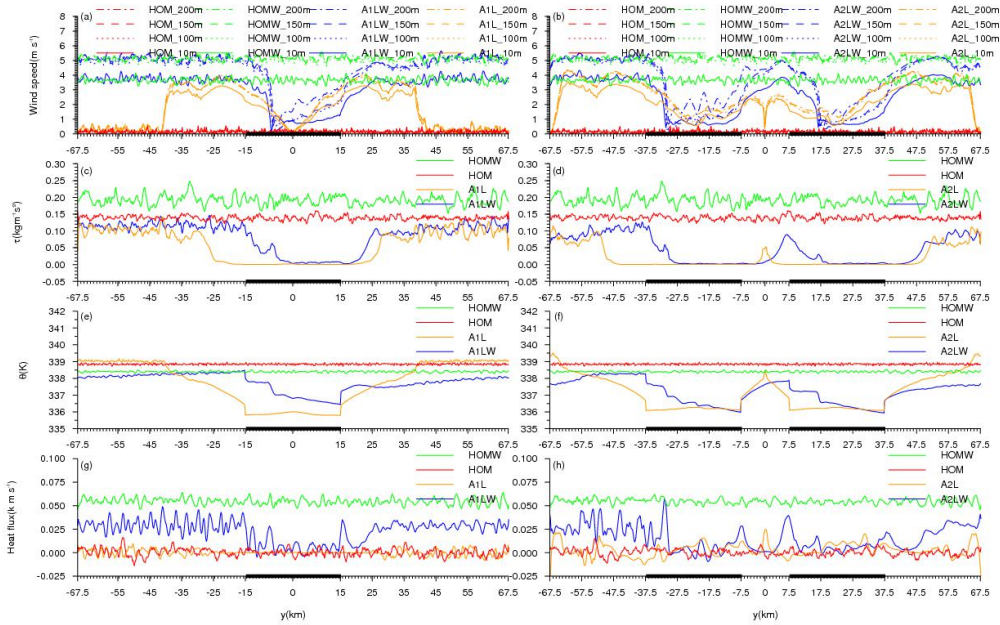


Fig. 11. Variations in the (a and b) wind speed, (c and d) Reynolds stress, (e and f) potential temperature and (g and h) heat flux in the horizontal direction below 200 m for the cases with (blue and green lines) and without (yellow and red lines) background flows over homogeneous (red and green lines)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