Response to Referees – Impact of black carbon on daytime valley and slope winds in idealised simulations

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We thank the referees for their constructive comments on our submitted manuscript. We have copied the comments of the referees here in black and include our response to each individual comment in blue. The Supplementary Figures labeled as A1-A4 in the original submitted manuscript are now labeled as S1-S4 and placed in the Supplementary material of the revised manuscript. Figures referred in the response are labeled as R1–R8 and are placed in the end of this document. Figures 2 and 3 are modified in the revised manuscript and the new versions are shown here as Figures R5 and R8, respectively.

Referee report 1

Dear Authors,

This study examines the effect of Black Carbon (BC) on daytime valley and slope winds using high-resolution idealised WRF-Chem simulations. The research is highly relevant not only to the mountain meteorology community but also contributes the air-quality by addressing this important gap in the literature from the side of process understanding. The manuscript presents innovative ideas, and the results offer valuable insights that could benefit the literature. I believe the manuscript is well designed, with an appropriate literature survey, a well-structured methodology and sound results. The manuscript has strong potential for publication in ACP. However, I believe the manuscript still have open questions to be discussed.

1. I wonder if the selected grid spacing is enough to properly resolve the valley flow system (more precisely the slope flows), especially given the fact that this work aims for process understanding. As the authors probably know, many works have addressed this topic in the literature in the last few years (see, for instance, Wurps et al., 2020), and a common agreement in the community is that an appropriate horizontal grid resolution to resolve convective flows in complex terrain would range between 20 m and 100 m. Considering

the recent improvements in computing power and recent publications addressing similar questions (see Basic et al., 2025) using high-resolution simulations, I think the work would benefit from the introduction of an inner domain using a grid spacing below 100 m.

We have performed a sensitivity test by running the CTRL simulation with horizontal grid spacing of 100 meters and time step of 1 second. Due to computational limits, the domain was narrowed to half-width by keeping the valley dimensions and shape the same. Now, instead of having the parallel valley between -20 km$< x < -10$ km and 10 km$< x < 20$ km, the periodic x-boundaries are located at $x = \pm 10$ km. Essentially the domain topography is the same as in the original simulations due to the periodic boundaries in x-direction and the same along-valley length of the domain.

Figure R1 shows cross-sections of the along-valley wind, cross-valley wind and potential temperature in the two simulations in the afternoon between 14:00-15:00. The general structures of the daytime fields are very similar between the simulations. The valley-averaged variables presented in the original manuscript are shown in Figure R2 for the sensitivity test. The v-component of the wind (panel a), u-component of the wind in the nearest 300 meters to the slope surface (panel b), and the potential temperature contrast between the valley volume and the air above the plain (panel c) are in very good agreement between the simulations. The finding is similar to what has been found by Wagner et al. (2015) in their idealised valley simulations. They also did a sensitivity test comparing simulations with horizontal grid spacings of 200 meters and 100 meters and found the general flow structure in the idealised valleys very similar between the two simulations. To resolve the details of the up-slope flow, the horizontal grid spacing should be in the order of 10-20 meters, similar to the simulations in Basic et al 2025. Unfortunately, this high resolution with the current domain configuration is not feasible given our limited computational resources.

We have added an appendix section (Appendix A in the revised manuscript) to describe the sensitivity test which is referred to briefly in the section 2.1 Model setup. The shown figures here in the response are added in the Supplementary material and referred in the Appendix A.

2. I don't understand why the authors used a south–north orientation for the valley. The consequence is having asymmetrical incoming radiation in the simulation, which to me only adds unnecessary complexity to the problem. The fact that the slope flows develop unevenly in the domain is not really discussed in the manuscript and does not contribute in any way to the main question. Indeed, the authors include only the east slope in the analysis (when showing cross-sections). Wouldn't it be easy to avoid this issue by rotating the valley 90 degrees?

   We agree the diurnal asymmetry in the cross-valley direction adds an unnecessary complexity in the valley flow. However, due to averaging over the whole domain width in the cross-valley direction and with the periodic x boundaries, the asymmetries are averaged out in most of the analysis that consider the whole valley volume. The asymmetry of the cross-valley circulation is discussed in Sections 3.2-3.3.

The model setup is also motivated by the authors previous work on Himalayan valleys, which are south-north oriented. However, we acknowledge that this motivation is not conveyed in the manuscript as it is not central to this specific study. Furthermore, given the computational cost of these simulations, we do not think it is worthwhile to re-run all of these simulations for an east-west valley as we do not expected the overall conclusions to change. For further development of the idealised setup for future studies, the symmetric radiation exposure by having a east-west oriented valley at the equator could be considered. For clarity, the full-width cross-sections (originally shown in the Supplementary) are now shown in the manuscript instead of only the zoomed in capture of the east slope.

3. Section 3.1, line 233: In this portion of the text, you discuss the accumulation of BC near the surface during the spin-up (in a way, the initial condition for BC). I wonder if you can really explain the accumulation near the surface as you do. It is true that the combination of the stable near-surface atmosphere and the downslope flows can lead to accumulation near the surface (inside the valley), but the down-valley flow helps to "clean" the valley during the night. I guess a proof of this can be seen in the fact that, after the spin-up, concentrations both inside and outside the valley are mostly equal. The question is, then, how much of the surface accumulation is due to the BC transported by the slope flows? or whether such surface accumulation is simply the result of the strong inversion near the surface preventing any mixing.

   We agree that mentioning the down-valley winds in this sentence did not really explain the development of the BC field during the night of the spin-up. We removed this part from the sentence "and from the valley into the plain at low levels (not shown)". The revised manuscript now reads as:
   "During the night of the spin-up, BC has accumulated more in the near-surface layer than at higher altitudes (Fig. 2g). This is a result of the nocturnal winds in the valley flowing down the slopes and the surface-based inversion that develop during the night (Fig. 2b), as the similar vertical distribution of BC is found above the plain as well (Fig. 2g). Through the course of the day, the vertical gradient of BC weakens (Fig. 2h-j) as the convective mixing and vertical transport by the valley and slope wind circulation takes place (Section 3.2)."
   The Figure 2 of the revised manuscript is shown here as Figure R5.

   My second point here is: how can you explain that during the first six hours of daylight (and I assume turbulent mixing, at least in SGS) there is hardly any change in the concentration inside the valley?

   The vertical profiles of BC in Figure 2 (in the manuscript) are averaged above $x = 0$. Indeed the profile of BC concentration above the valley center does not seem to drastically change. However, the distribution of BC in the cross-valley direction changes, seen in the cross-sections at 06:00-07:00 (Figure R6) and at 12:00-13:00 (Figure R7). The highest concentrations are found in the morning near the valley centre ($|x| < 1$ km) below $z < 1$

km. By mid-day BC has dispersed within the convective boundary layer and transported above the ridges by the up-slope winds ($x = \pm 10$ km). It is clear that the BC mass is transported from the plain into the valley and lifted by the up-slope winds out of the valley volume. We have not computed the BC mass exchange between the valley volume and its surroundings.

4. Section 3.4, Here, you mentioned less along-valley momentum is transported out of the valley volume in AER simulation. However, I do not see that difference. Indeed, there are differences in the momentum in the along valley direction, but I'm not sure how significant would be the difference when computing the total transported momentum.

   In the afternoon 12:00-16:00 the net along-valley momentum tendency is larger in the simulation with black carbon (Figure 5c, black dashed line). Momentum budget terms that contribute to the difference in the net momentum tendencies between the simulations are ADV (larger in AER than CTRL), and PGF and SGS (larger in CTRL than AER). The largest difference from the individual terms appears to come from the ADV term in the cross-valley direction (Fig 5f, red dotted line) which in the end causes the larger along-valley momentum in the case AER despite the weaker PGF.

5. Coming back to the grid resolution, I think the need to decrease the grid spacing becomes appreciable in the momentum and heat budgets, where you show that the SGS seems to be very important, when compared with the other terms, specially in the heat budget. I think the manuscript would be way more robust if you solve the small turbulent eddies (adding to the resolved turbulent term), which at the end drive the mixing during the daytime in the boundary layer.

   Figures R3 and R4 show the along-valley momentum budget and heat budget analysis of the sensitivity test, respectively. The sensitivity test was described in response to comment 1. When comparing the original CTRL simulation (top row) to the sensitivity run (middle row), the difference in the resolved transport in ADV and TRB terms and in the sub-grid-scale SGS term are negligible. Resolving the smaller eddies to reduce the SGS term would indeed require much higher resolution, probably in the order of 10 - 20 meters, which is unfortunately not feasible given our limited computational resources. The sensitivity test shows that the horizontal grid spacing of 200 meters does resolve more or less the same features as the grid spacing of 100 meters. Due to computational limits, the sensitivity test is not carried over for the AER simulation in which the online-coupled chemistry module increases the computation time around four times longer than in the CTRL simulation. Figures R3 and R4 shown here in the response are added in the supplementary material of the manuscript and referred to in the Appendix A describing the sensitivity test.

Minor comments:

- Line 188: I guess that the parallel valley is located at x>10 km and x<30 km, isn't?

  This typo is fixed in the manuscript – the parallel valley is located at $|x| > 10$ km as the domain center is defined as $x = 0$.

- Line 366: Are you sure that you meant along-valley momentum there? I think you are referring to cross-valley in the text.

  The budget analysis considers only momentum in along-valley direction. The transport of along-valley momentum in cross-valley direction is discussed in the manuscript.

- I've found a few typos in the text, but I'm sure that would be corrected once the manuscript achieves its final form. We have carefully proof read the manuscript again and also corrected a number of typos that the other reviewer identified so hopefully this is mainly resolved now.

Referee report 2

Report on the paper
Impact of black carbon on daytime valley and slope winds in idealised simulations
by J. Mikkola et al.

Summary:
The objective of this paper is to address the impact of aerosol on wind circulation in an alpine valley. A simplified configuration is considered: the aerosol consists in black carbon (BC) which influences the local winds through absorption of incoming solar radiation, the valley is an idealized one with no wind and a uniform stratification at the initial time. However the vertical profile of aerosol concentration is realistic, as are the dimensions of the valley. The main result is that the short-wave absorption of BC in the upper part of the boundary layer reduces ground heating and therefore up-slope wind speeds, thereby leading to a stronger up-valley wind than in the case with no BC despite the plain-valley temperature difference is lower.

General comments:
This is a very good paper: the analysis is carefully conducted, convincing results are obtained, on a little explored topic, and the write-up is remarkably clear. I therefore recommend the publication of this paper provided the specific comments indicated below are taken into account in a revised version.

Specific comments:

- p. 2, l. 19-20: "*Under fair-weather and weak large-scale weather forcing, the daytime valley circulation is efficient in transporting pollutants vertically into the free troposphere*": this general statement is not correct. During wintertime anticyclonic event at mid-latitude for instance, a very shallow convective layer (of depth a few tens of meters only) develops around noon, with therefore no impact on the free troposphere. So the meteorological situations for which this sentence is valid should be specified (or those for which it is not valid should be indicated).

Thank you for pointing this out. We have revised the sentence as follows: "Under favorable conditions, such as fair-weather, weak large-scale forcing, and weakly stable or unstable stratification, the daytime valley circulation is efficient in transporting pollutants into the free troposphere and reducing pollutant concentrations in the near-surface layers (Serafin et al., 2018)."

- l. 46: *the heating due to absorption further stabilises the top of the BL*: please clarify (heating cannot stabilize).

  The sentence is revised as: "If absorbing aerosols are located near the BL top or right above it, the absorption of incoming solar radiation leads to warming and further increases the stability of the top of the BL while reducing the shortwave radiation reaching the lower levels hence weakening the surface heating (Chen et al. (2022), Ma et al. (2020))."

- l. 127: can you justify the choice of the resolution of 200 m?

  We performed a sensitivity test by running the CTRL simulation with horizontal grid spacing of 100 meters (200 meters in the original) and time step of 1 second (2 seconds in the original). Detailed description of the comparison to the original CTRL simulation is found in the response to Referee #1 under their comments 1 and 5. To summarise, the decrease in grid spacing to half of the original did not cause a notable change in the valley-volume-averaged variables (Figure R2) or in the general flow structure (Figure R1). The along-valley momentum and heat budget analysis show that the resolved ADV and TRB terms and the unresolved SGS term have negligible changes (Figures R3 and R4). Similar result was found by Wagner et al. (2015) who compared also idealised valley simulations with horizontal grid spacing of 200 and 100 meters. To resolve the eddies in the up-slope winds, the grid spacing should probably be decreased down to the scale of 10 - 20 meters, which is unfortunately not possible to carry out due to limitation in our computational resources. We have added a new appendix section (Appendix A in the revised manuscript) describing this model sensitivity test and the Figures R1–R4 are added in the Supplementary materials.

- l. 130: what do you mean by *symmetric*?

  Symmetric lateral boundary refers to so-called solid-wall lateral boundary condition which is described in WRFv4 model description (see Chapter 6 in Skamarock et al. 2019). The wind component normal to the boundary is zero at the boundary and symmetric away from the boundary. In our case, the "north" and "south" boundaries in y-direction are symmetric, hence the wind component in y-direction, v, follows the relation

$$v(y_b - y) = -v(y_b + y)$$

, where y_b is the location of the symmetry boundary. The symmetry boundaries are located at $y = \pm 100$ km in our simulation domain. Other variables follow the relation

$$\psi(y_b - y) = \psi(y_b + y).$$

In practice this means no mass, momentum or heat is transported through the y-boundaries. We have added a reference to the Chapter 6 in Skamarock et al. (2019)) in this part of the text.

- l. 168: Figure A1c (initial BC profile) should be placed in the main text. This is indeed an essential component of the study.

  The initial profile of potential temperature and BC have been added to the Figure 2, shown here as Figure R5, and the text is adjusted to reflect these changes.

- l. 193: how is the Reynolds decomposition for the advective term performed (namely, how is the mean term ADV defined)?

  The resolved horizontal fluxes are taken directly from the WRF advection routines. The vertical flux is computed with recalculated vertical velocity based on the geopotential equation. The resolved flux is decomposed in the density-weighted average (ADV) and perturbation component (TRB) based on the total resolved flux, which is the sum of these two. Detailed explanation is found in the model description article Göbel et al. (2022) (sections 2.5 and 3) which we refer to in the text. The sub-grid-scale diffusion is taken directly from the WRF diffusion routines.

- l. 268: *and develop in a deeper layer*: the fact that the layer is deeper in AER than in CTRL is not clear from the figures.

  We agree the difference is not clearly visible in the cross-section. The end of this sentence was removed and it read now as: ”However, the up-valley winds are stronger in the up-valley jet (0 km $< y <$25 km) in case AER at the shown time 14:00-15:00 and they extend slightly further into the valley.”

- l. 280: I do understand that shortwave absorption above the valley will result in reduced surface heating and increased stability in the valley. But I do not understand how the absorption within the valley could also contribute to these two effects.

  Absorption of shortwave radiation within the valley similarly reduce the radiation reaching the surface hence decrease the surface heating. However, we agree the warming due to absorption within the valley does not necessarily increase the stability as there is more BC near the valley bottom than above the valley centre. We have revised this sentence as: ”In case AER, the reduction in surface heating stems from the absorption of shortwave radiation by BC within and above the valley. In addition, the heating due to shortwave absorption above the valley increases the stability.”

- Figure 3a: what do the very perturbed black closed lines at the left part of the figure, between 0 and 2 km, correspond to? Is there a way to suppress them?

This appears to be the result of the value of the contour line (304 K) being right around the potential temperature of that part of the domain. Similar structure of contours appears in different parts of either CTRL or AER if the contour interval is kept at 1.0 K but the temperatures shifted some decimals higher from the integer kelvin values. Averaging in x direction would remove these contours from that part of the domain, but, the spatial averaging inside the valley leads to difficult interpretation of the cross-section. We suggest to keep the figure as it is regarding the potential temperature contours.

- l. 287: *can be seen as a drop* : this is very difficult to see. I suggest BC concentration to be represented separately from the temperature tendency due to short-wave, both for Figure 3e and Figure 3f (even though these figures will be strongly correlated according to the text). So Figure 3 would consist in 8 frames. This would also avoid displaying the very noisy curves for BC concentration in Figure 3e.

  The BC and potential temperature tendency from the SW radiation scheme are now separated in their own panels, as suggested, shown here as Figure R8.

- l. 314: *(not shown)*. It would be useful actually to display in the supplementary material the mass flux associated with the up-valley component for case AER and CTRL, versus timef.

  Figure R9 shows the integrated massflux in the valley volume. Panel (a) shows the integrated positive massflux in y-direction (i.e. up-valley directed). Panel (b) shows the integrated horizontal massflux in x-direction associated with the up-slope winds. This means the grid boxes with non-positive (non-negative) u-component of the wind are ignored for east slope (west slope). The Figure is added in the Supplementary material.

- l. 415-417: the end of the sentence, from likely, is not clear and should be rephrased (the first part of the sentence refers to case CTRL and the second part to case AER with no clear connection between the two parts of the sentence).

  The sentence was split in two: "Throughout the day, the export of heat by the cross-valley component of ADV is stronger in case CTRL than in case AER. This is likely caused by the reduced surface heating and increased stability due to the shortwave absorption by BC leading to weaker up-slope winds in case AER (Sections 3.2-3.3)"

Technical corrections (the text taken from the article is written in italics and the suggested corrections are shown in quotation marks " ...")
We thank the referee for their generous efforts to improve the text flow and the level of details to fix typos in the manuscript. Those comments that are not separately replied but are marked with a check mark (✓), are addressed in the manuscript as suggested with possible small changes.

- l. 4: *consist* → "consists" ✓
- l. 11: *associated with up-valley winds* → "by these winds"

The sentence refers to exchange of momentum associated with the up-valley winds (i.e. up-valley directed momentum). To avoid this misunderstanding, we slightly revised the sentence: ”Momentum budget analysis for the valley volume shows that weaker up-slope winds reduce the export of momentum associated with the up-valley winds out of the valley atmosphere, allowing stronger up-valley winds to form despite the weaker forcing.”

- l. 42: to the temperature inversion at the BL top → ”to the temperature inversion top of the BL”✓
- l. 50: *suppresses* → ”reduces”✓
- l. 56: *dissipation* → ”dispersion”✓
- l. 72: *in to* → ”into”✓
- l. 75: *consider* → ”reach”✓
- l. 82: add ”therefore” before *up-valley winds*✓
- l. 100-106: the sentences ”*The factors (...) at the valley surface*” are ill-placed. I would move them after the sentence ending in line 85 (namely after ... *than the up-slope wind*).✓
- l. 140 shortwave → ”Shortwave” ✓
- l. 146: suppress *local* since no valley location is referred to. Also suppress *Henceforth, all times are local time.*

  The reference to timezone or local time is required by the journal even for an idealised setup with no actual location. Therefore the reference to local time is stated here.

- Figure 1a: the representation is strange: why are there three levels of grey?

  The topography is colored on grey-scale based on the surface height. We did try other representations of the 3D-topography with no better outcomes than the original.

- l. 198-199: The sentence *The momentum budget ... WRF-Chem* should be moved after the sentence ending with *(Göbel et al, 2022).*

  Few sentences reordered in the paragraph to improve the text clarity.

- l. 206: defined the generic terms $F_{\theta,i}$ and $F_{v,i}$ after the sentence ending with: *is the potential temperature.*✓
- l. 261: *and up-valley winds* → ”namely up-valley winds”✓
- l. 267: $x<25$ *km* → ”y<25 km”✓
- l. 322-323: add ”the” before *air* (l. 322) and before *ridge* (l. 323). ✓
- l. 337: add ”the” before *four terms* and ”(see Eq. (1))” after are plotted.✓

- l. 375-376: I would write "down-valley" in place of *negative along-valley* and "up-valley" in place of *positive along-valley.*✓

- l. 377, end of line: *up-valley* → "up-slope" (if I am correct).

  This sentence refers to the exported up-valley momentum seen as up-valley winds above the ridges, hence the original text is correct.

- l. 382-384: I would rephrase this paragraph as follows (changes are underlined): "Figure 6 shows the temporal evolution of the heat budget for the valley volume (see Eq. (2)). The heat budget involves a resolved mean advective term (ADV), a resolved turbulent term (TRB), a sub-grid scale diffusion term (SGS) which involves the surface sensible heat flux, and the heating tendencies due to shortwave (RSW) and longwave radiation (RLW)."✓

- l. 397: suppress *which includes the surface sensible heat flux in this analysis.*✓

- l. 407: *the the* → "the"✓

- l. 426: I would add "indeed" after leads✓

- l. 429-431 could be rephrased as follows: " (...) 13:00 and 19:00 the case AER has stronger up-valley winds than the CTRL case, although the potential temperature difference between the valley atmosphere and the air above the plain is weaker. Based on the classic valley wind theory, the weaker potential temperature difference and associated weaker pressure-gradient force should result in weaker up-valley winds, which is not the case."✓

Finally, the very careful write-up leads to repetitions at several instances. Here is how this could be improved:

- l. 144-146: *The simulation with the coupled aerosol-meteorology feedback is referred as AER and the reference simulation without the aerosol-meteorology feedback is referred as CTRL.* → "These simulations are referred to as AER and CTRL, respectively." ✓

- l. 159-162: *During the 24-h spin-up run, BC is already transported by developing winds and partly removed by dry deposition at the surface. During the spin-up run 3 % of the initialised total BC mass is deposited at the surface and during the simulation AER an additional 1.5 % (not shown). Neither BC nor any other compound are emitted or produced by secondary processes during the simulation.* → "During the 24-h spin-up run, BC is transported by developing winds and 3% are removed by dry deposition at the surface. During the subsequent 24 hours of simulation AER, an additional 1.5 % is removed by deposition at the surface."

  Revised as suggested keeping the "... 3% of the initialised total BC mass.." and the third sentence "Neither BC nor any other compound are emitted or produced by secondary processes during the simulation." from the original text. We think it is important to emphasise there is no online emissions or production of BC or any other aerosol compounds.

- l. 165-166: *To exclude the changes in the BC aerosol population due to ageing during the simulation, in this study we include only aged hydrophilic BC.* → "As already said in the Introduction, we only include aged hydrophilic BC." ✓

- l. 168-169: *During the course of the spin-up run the BC does not affect the thermodynamic and kinematic fields but its distribution is shaped by the winds and temperature field.* → to be suppressed (already said). ✓

- l. 175-176: *For reference, some observations of BC from urban regions with mountain influence are given here as an example to put our simulation setup in context. Putero et al. (2018) ...* → "For reference, Putero et al. (2018) ..." ✓

- l. 191: the first sentence on l. 191 repeats the first sentence of section 2.1.1 while containing new information. Please modify the text to avoid this redundancy.

  These two sentences are revised to avoid the repetition.

- l. 196: *are summed and referred to as* → "are referred to as" (the word summed is confusing).

  Revised as: "The sum of the x and z-components is referred to as the cross-valley component."

- l. 199-201: *For a detailed description on how WRFlux retrieves the budget terms and which other components 200 are available but not used in this study, please refer to the published model description Göbel et al. (2022) and the WRFlux Github-repository (Göbel, 2022)* → suppress this sentence (repetition). ✓

- l. 202: remove *Using the tendency budget terms from WRFlux* (this is already said). So start the sentence with: "The along-valley ..." ✓

- l. 209-210: remove *the left-hand-side of the equation is the mass-weighted tendency of v or θ and the right-hand-side is the sum of the mass-weighted budget terms $F_{v,i}$ or $F_{\theta,i}$, respectively.* (already said) ✓

References

Göbel, M., Serafin, S., and Rotach, M. W. (2022): Numerically consistent budgets of potential temperature, momentum, and moisture in Cartesian coordinates: application to the WRF model, *Geosci. Model Dev.*, 15, 669–681, `https://doi.org/10.5194/gmd-15-669-2022`

Skamarock, C., Klemp, B., Dudhia, J., Gill, O., Liu, Z., Berner, J., Wang, W., Powers, G., Duda, G., Barker, D. M., and Huang, X. (2019): A Description of the Advanced Research WRF Model Version 4. `https://www2.mmm.ucar.edu/wrf/users/docs/technote/v4_technote.pdf`

Wagner, J.S., Gohm, A. and Rotach, M.W. (2015): The impact of valley geometry on daytime thermally driven flows and vertical transport processes. *Q.J.R. Meteorol. Soc.*, 141: 1780-1794. `https://doi.org/10.1002/qj.2481`

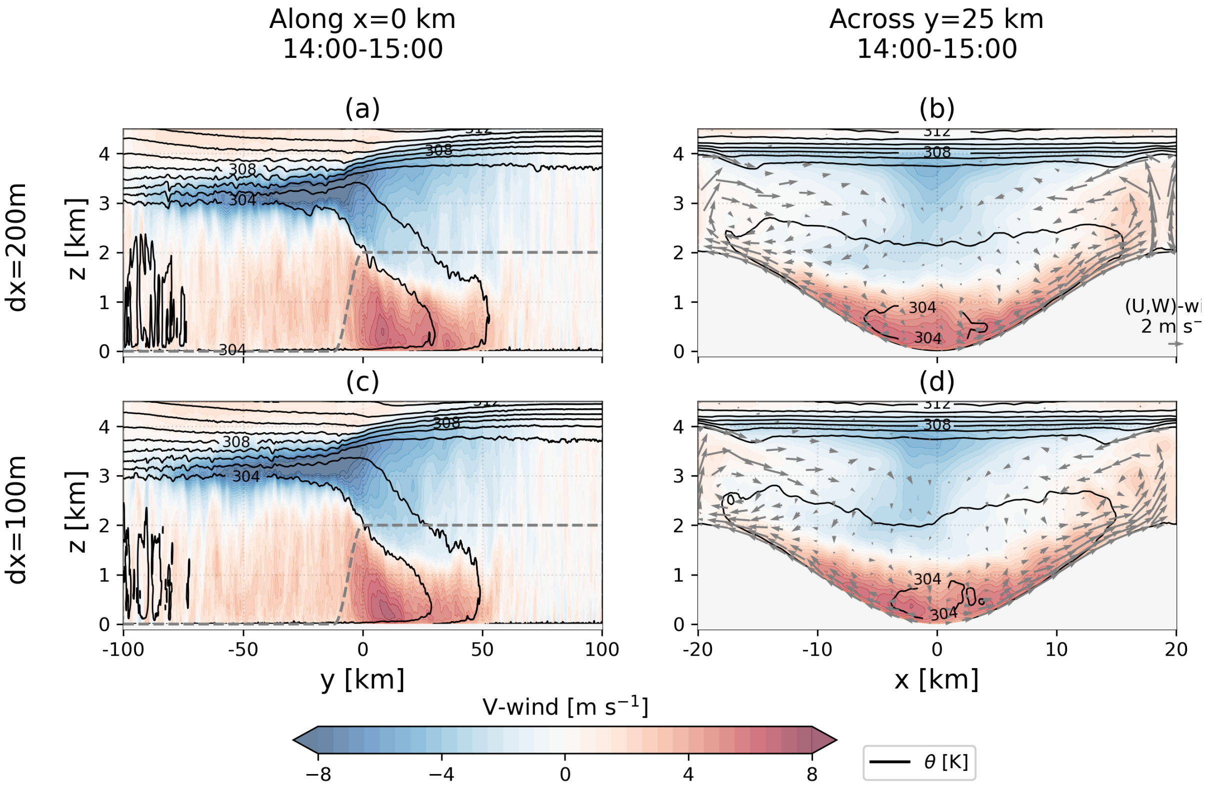


Figure R1: Cross-sections **(a,c)** along the valley centre line and **(b,d)** across the valley at $y = 25$ km averaged between 14:00 and 15:00. Panels **(a-b)** are from the original case `CTRL` and panels **(c-d)** are from the sensitivity simulation with higher resolution. The cross-sections show the along-valley wind speed (shaded) and potential temperature (black solid lines). Positive along-valley wind speed refers to up-valley hence right-ward wind in **(a,c)**. Grey dashed line in **(a,c,e)** show the ridge height at $x = \pm 10$ km.

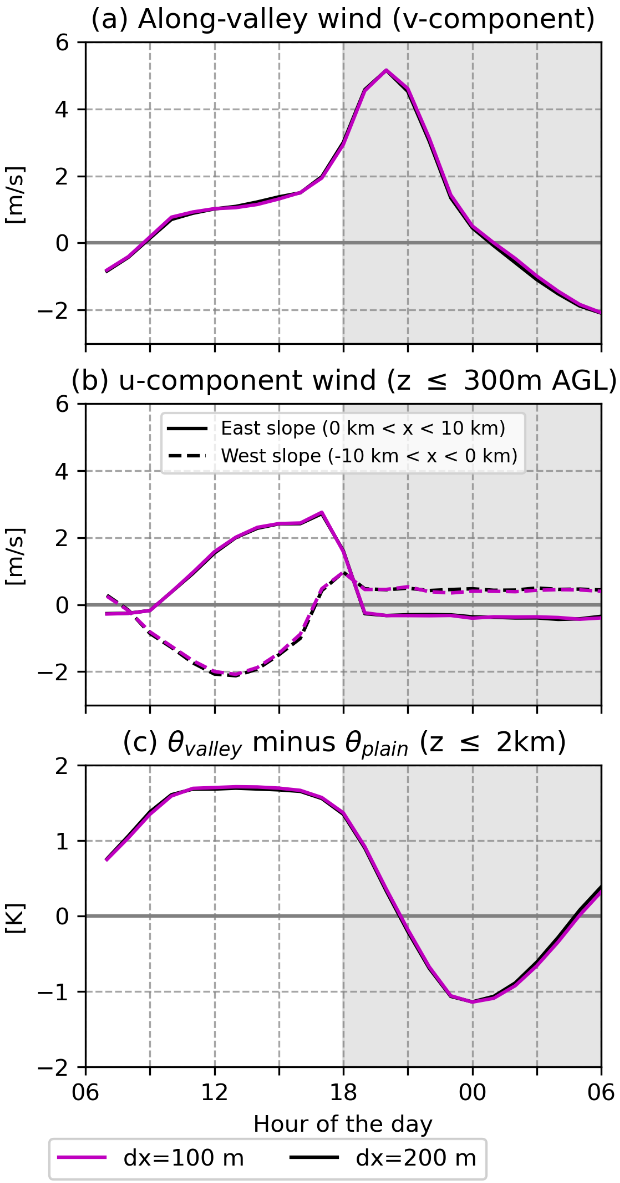


Figure R2: Sensitivity test of theCTRLsimulation with horizontal grid spacing of 200 meters (original case `CTRL`, shown on black lines) and 100 meters (purple lines). Mass-weighted average of the **(a)** v-component of the wind in the valley volume **(b)** u-component of the wind in the nearest 300 m layer from the surface in the valley. **(c)** Mass-weighted potential temperature difference between the valley volume ($y > 0$ km) and the lowest 2 km above the plain ($y < 0$ km).

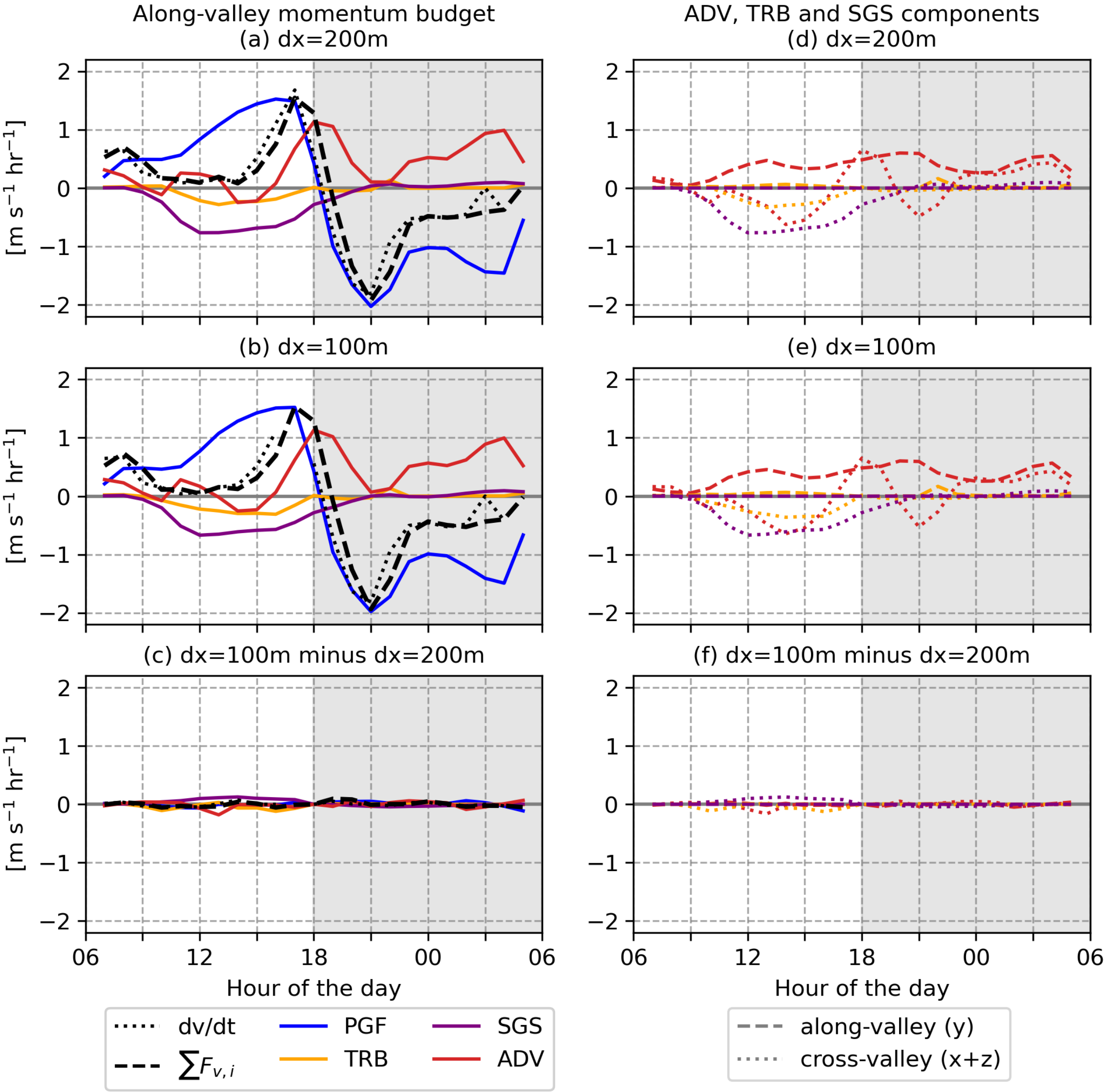


Figure R3: Along-valley momentum budget for the valley volume in **(a)** original `CTRL` and **(b)** sensitivity run with horizontal grid spacing of 100 meters and **(c)** difference between the two cases. Left-hand-side of the Equation 3 in the manuscript for along-valley momentum is shown on black dotted line and the sum of the terms on the right-hand-side as black dashed line, respectively. **(d-f)** Same as (a-c) but for the tendency due to mean advection, resolved turbulence and sub-grid-scale diffusion decomposed into along and cross-valley components. The cross-valley component includes the vertical one.

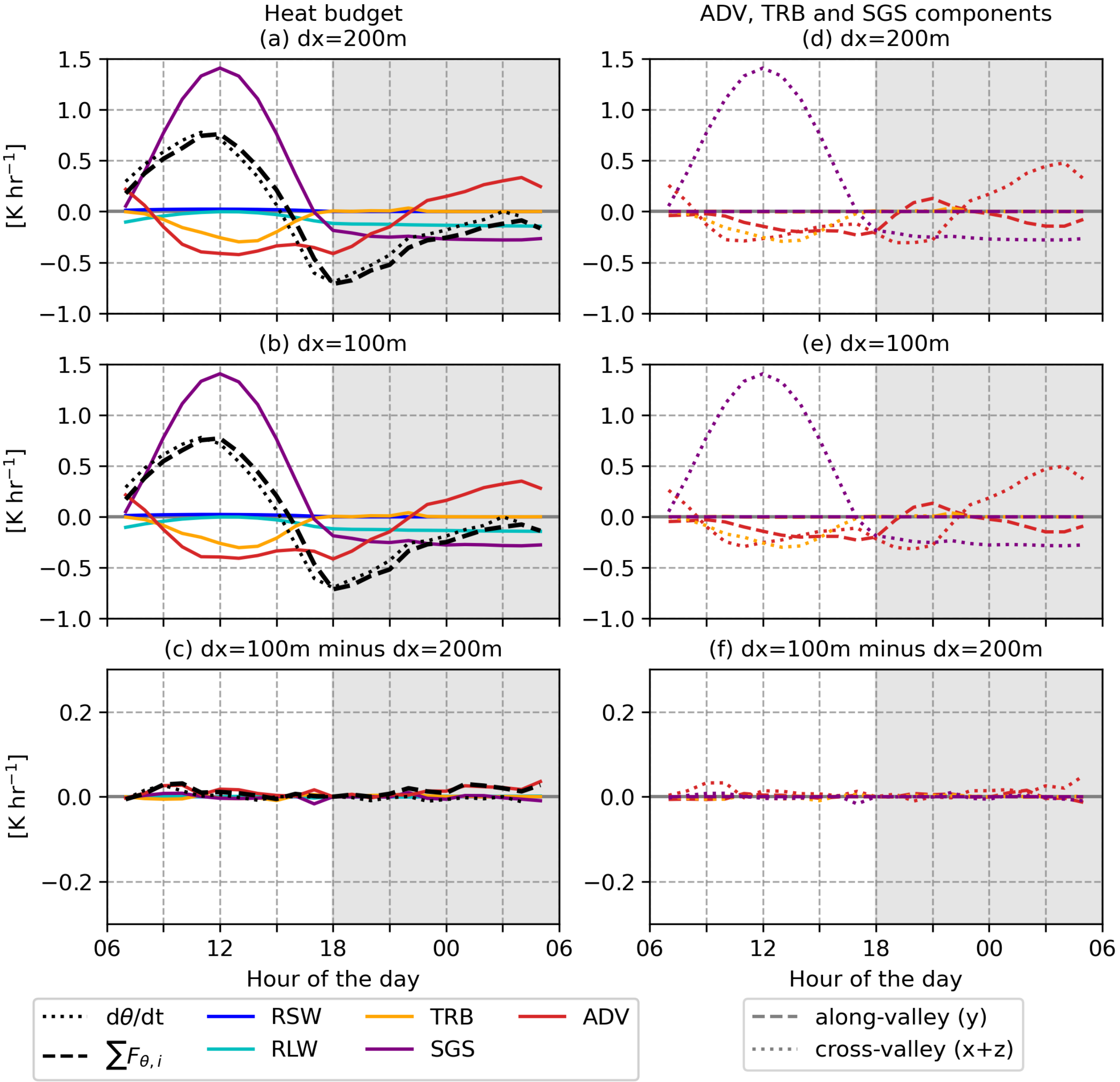


Figure R4: Heat budget for the valley volume in **(a)** original `CTRL` and **(b)** sensitivity run with horizontal grid spacing of 100 meters and **(c)** difference between the two cases. Left-hand-side of the Equation 3 in the manuscript for heat is shown on black dotted line and the sum of the terms on the right-hand-side on black dashed line, respectively. **(d-f)** Same as (a-c) but for the tendency due to mean advection, resolved turbulence and sub-grid-scale diffusion decomposed into along and cross-valley components. The cross-valley component includes the vertical one.

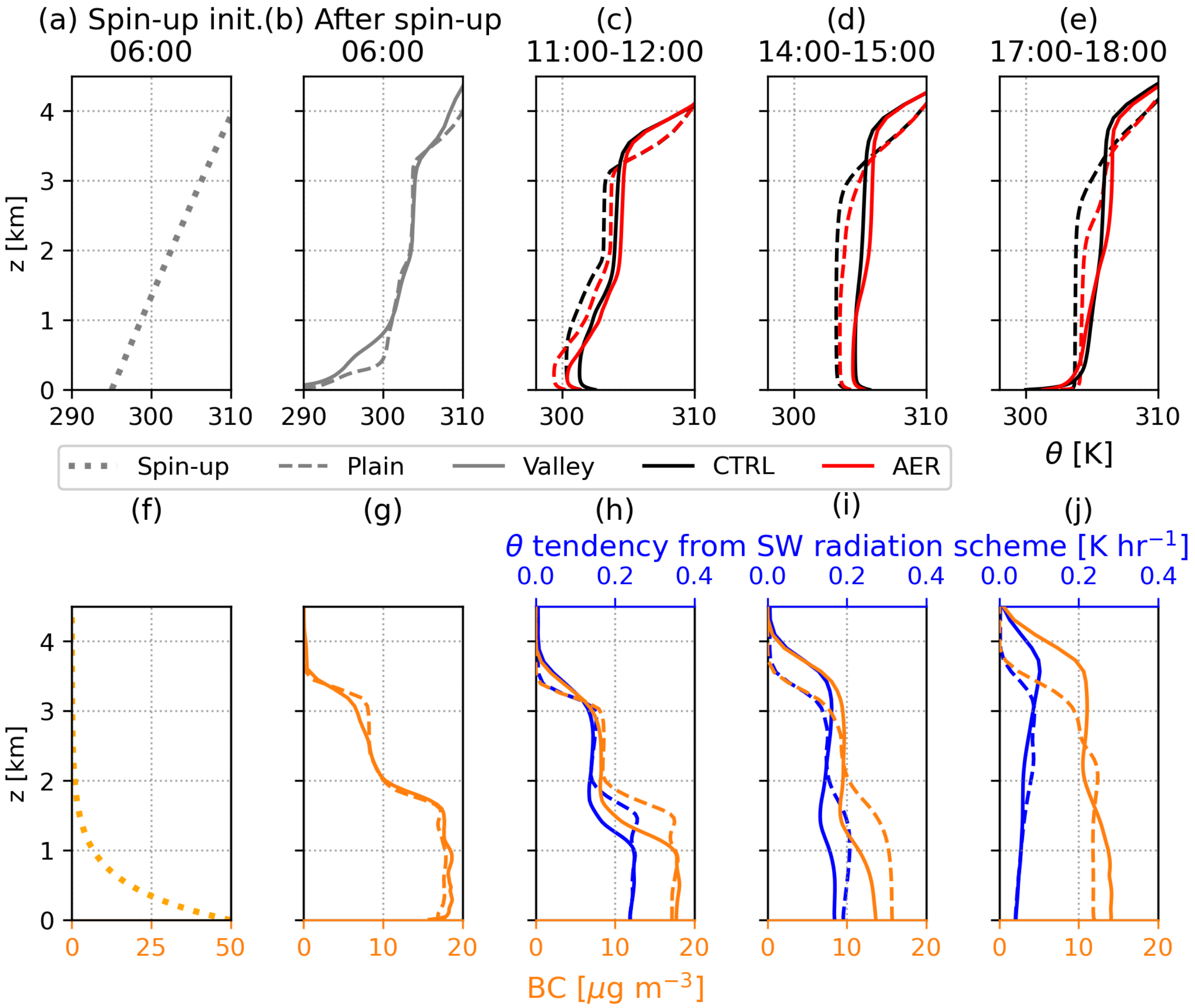


Figure R5: Figure 2 in the revised manuscript. Top row: Vertical profile of potential temperature in both cases `AER` and `CTRL` Bottom row: Vertical profile of black carbon and potential temperature tendency from shortwave radiation scheme in case `AER`. **(a,f)** Horizontally uniform initial conditions of the spin-up run. **(b,g)** Initial condition of the cases `AER` and `CTRL` after the 24-hour spin-up. Hourly averages between **(c,h)** 11:00-12:00 **(d,i)** 14:00-15:00 and **(e,j)** 17:00-18:00. Solid lines show the vertical profile averaged over the valley centre line ($y > 0$ km, $x = 0$ km) and dashed lines above the plain ($y < 0$ km, $x = 0$ km). Note the different temperature and black carbon concentration scales between the panels and that both cases `AER` and `CTRL` have the same spin-up and initial state shown in **(a-b)**.

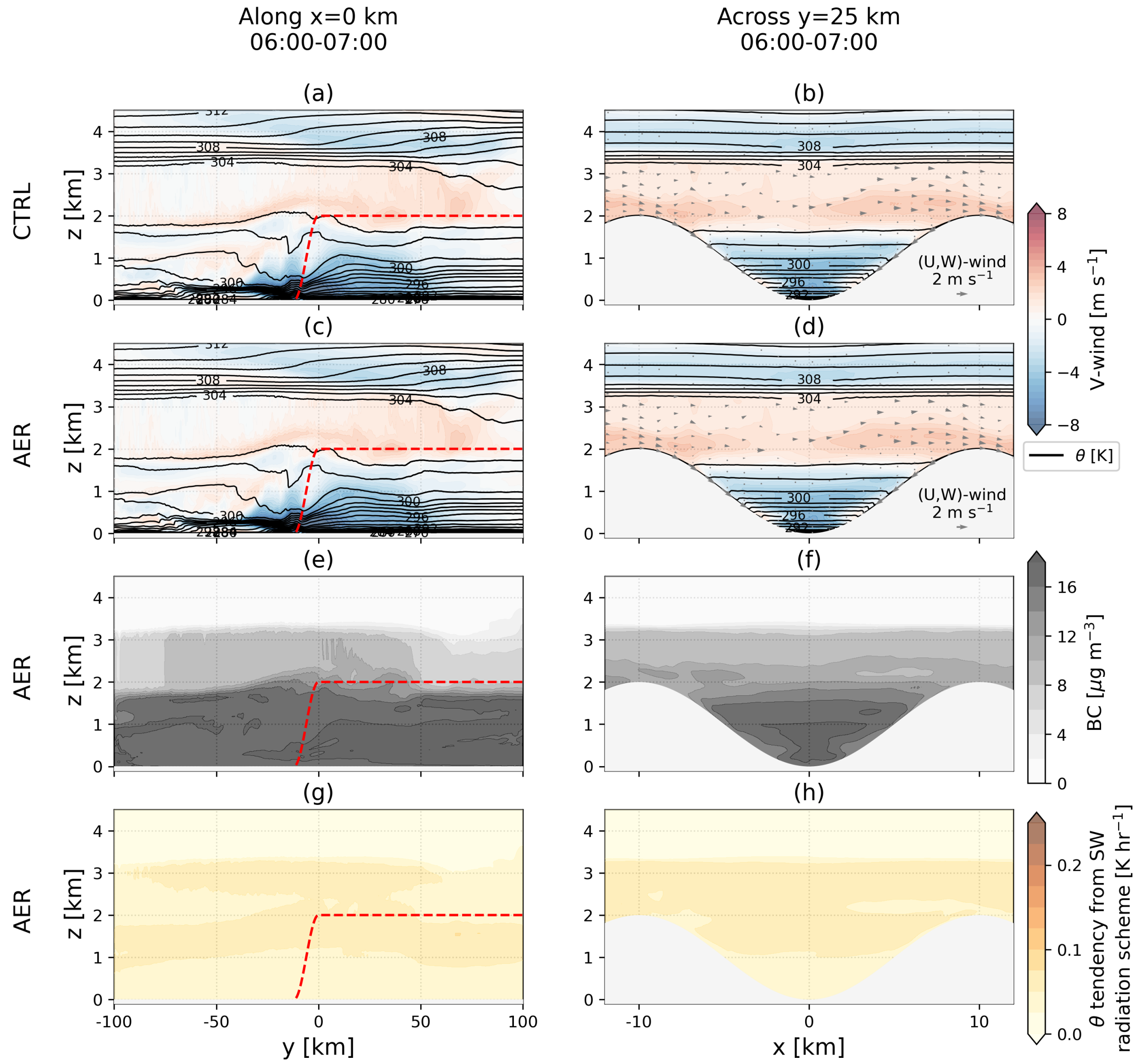


Figure R6: Cross-sections **(a,c)** along the valley centre line and **(b,d)** across the valley at $y = 25$ km averaged between 06:00 and 07:00. Panels **(a-b)** are from the original case `CTRL` and panels **(c-d)** are from the sensitivity simulation with higher resolution. The cross-sections show the along-valley wind speed (shaded) and potential temperature (black solid lines). Positive along-valley wind speed refers to up-valley hence right-ward wind in **(a,c)**. Grey dashed line in **(a,c,e)** show the ridge height at $x = \pm 10$ km. **(e-f)** Black carbon concentration **(g-h)** Potential temperature tendency from shortwave radiation scheme. Red dashed line in **(a,c,e,g)** show the ridge height at $x = \pm 10$ km.

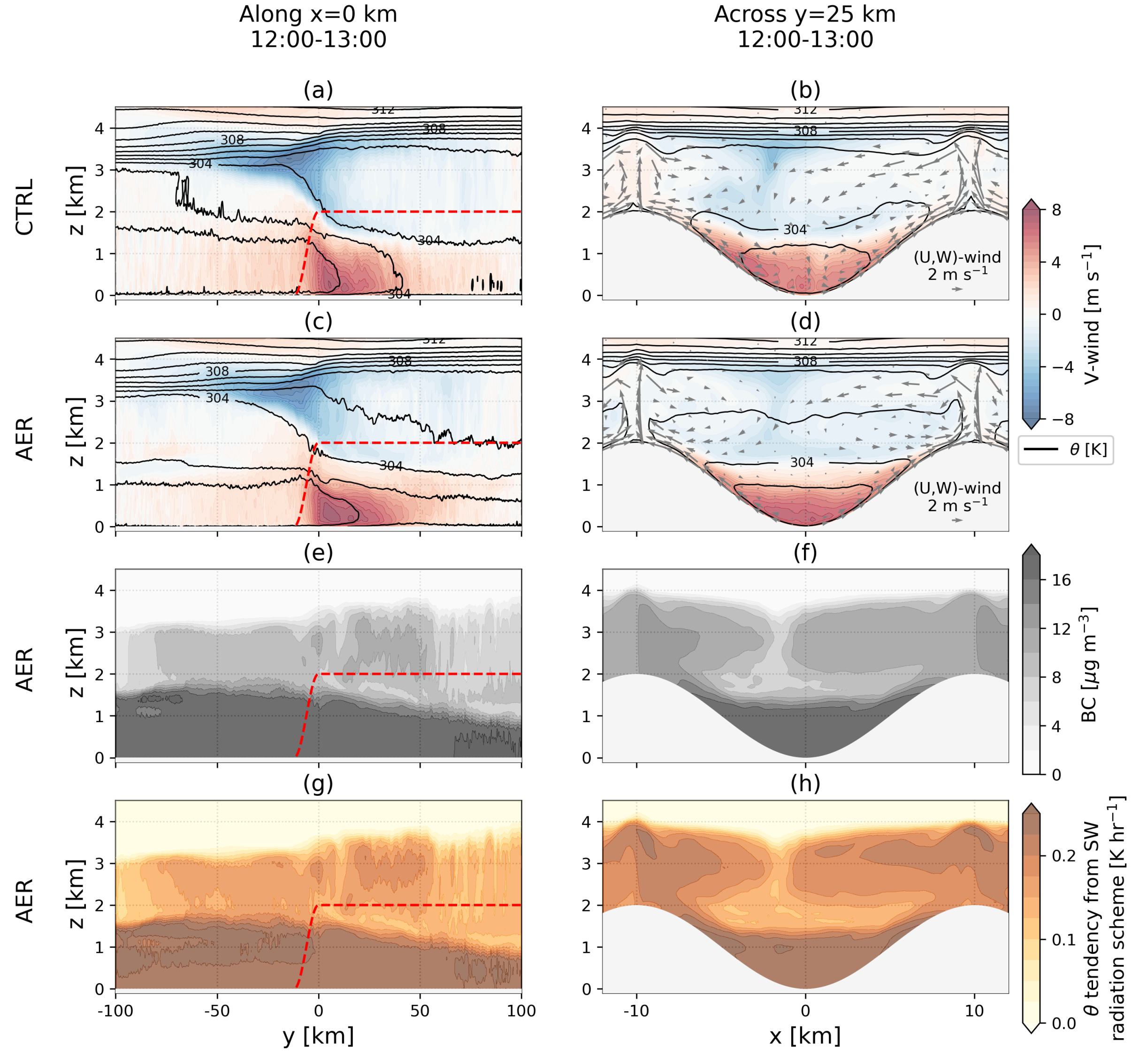


Figure R7: Same as Figure R6 but averaged between 12:00 and 13:00.

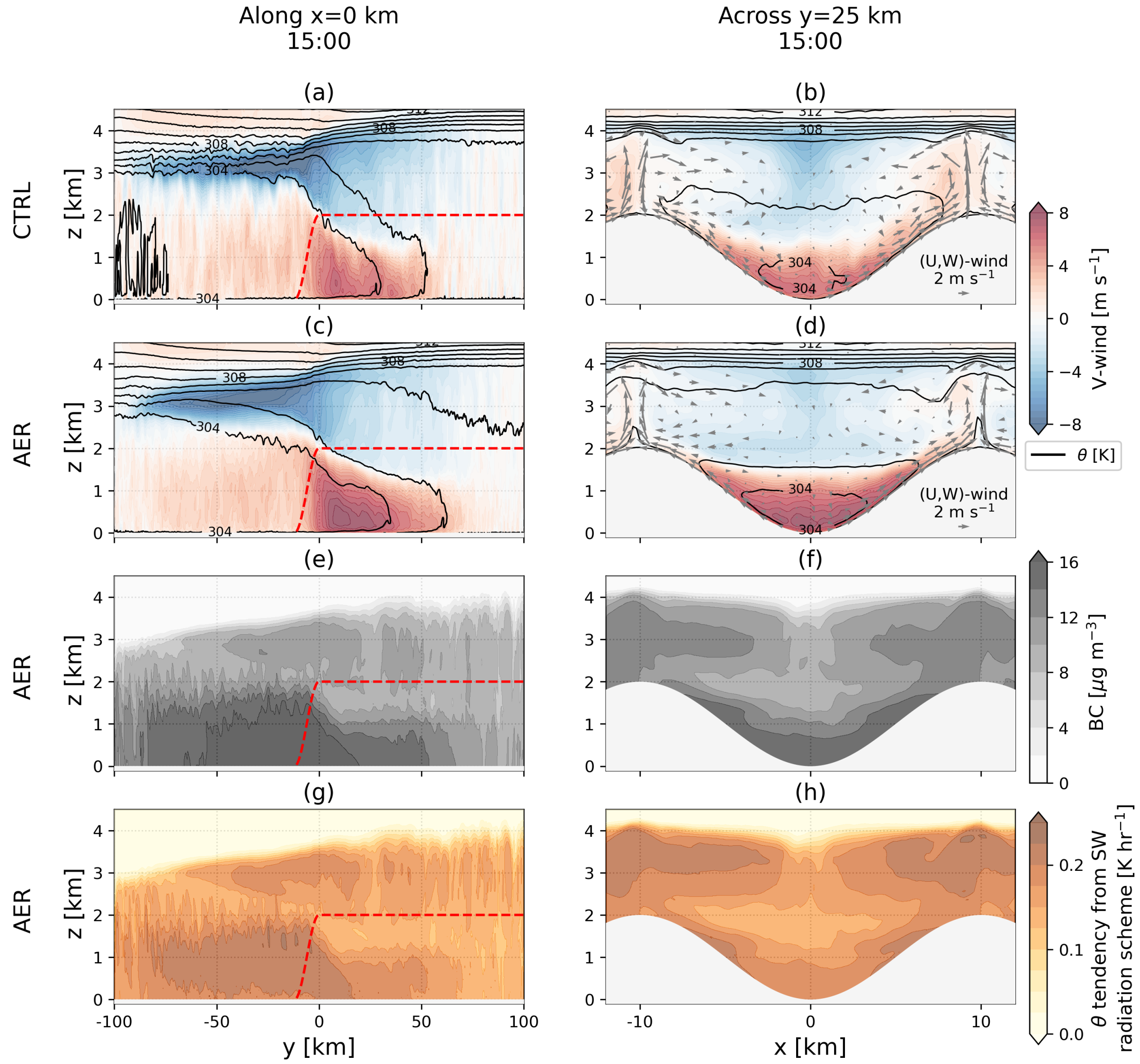
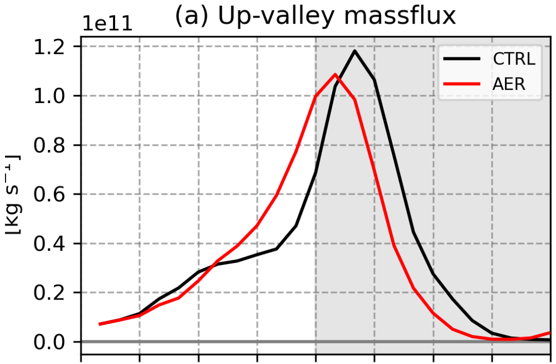


Figure R8: Same as Figure R6 but averaged between 14:00 and 15:00. This Figure appears in the revised manuscript as Figure 3.



(a) Up-valley massflux

(b) Up-slope massflux (z ≤ 300m AGL)

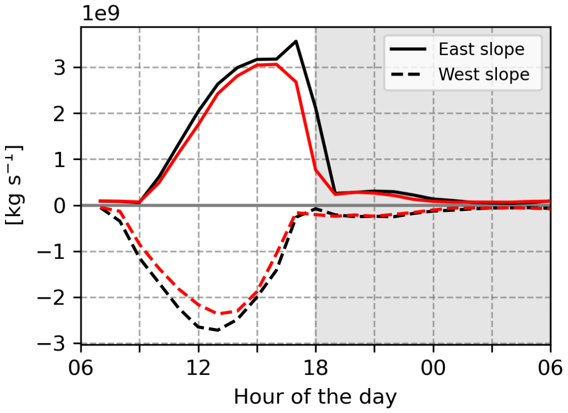


Figure R9: Integrated horizontal massflux in **(a)** up-valley direction meaning the grid boxes with non-positive v-component of the wind ignored **(b)** up-slope direction meaning the grid boxes with non-positive (non-negative) u-component of the wind ignored for east slope (west slope). Positive (negative) values refer to up-slope massflux on the east slope (west slope).