Response to Anonymous Referee #1

General Comment. The manuscript presents three case studies of the exchange of polluted air masses between an Alpine valley and the foreland (Po basin). The case studies are based on multi-site, multi-instrument field data complemented by numerical modelling. They cover three different seasons. The case studies nicely illustrate the complex transport phenomena that occur during the episodes which each last several days. Qualitative agreement is quite good, however, quantitative disagreement between model and observations leads to various hypotheses for the reasons, which require further study and improvements. The paper is carefully written, well-structured and nicely illustrated. Its content is very relevant in the context of the complex dynamical and chemical (transport) processes in and near mountainous terrain. I strongly encourage publication in ACP, pending the few minor corrections below.

We thank the reviewer for taking the time to revise our manuscript and for his/her pertinent comments. Our reply to these is given hereafter (the text in italics represents a citation of the revised manuscript and the figure references follow the updated numbering).

Referee's comment 1. The authors extensively use lidar backscatter (scattering ratio) for tracking the aerosol load of the valley atmosphere (Figs. 4a, 5, 10a, 11, 13a). This parameter is well correlated with relative humidity, which is strongly temperature dependent, but less so with absolute humidity SH (Fig. S8b). SH is a better indicator of air mass transport (and particulates) than RH, i.e. I would expect to see more variation in SH when Po basin air arrives to replace the valley air mass. This is visible for example in the afternoon on 28 May. Could you discuss the constancy of SH with the arrival of the Po valley air mass and its implications for the humidity profile in more detail?

Author's response 1. We thank the reviewer for this comment, which gave us the opportunity to study in more depth the measured and the model simulated SH fields, their difference and the relation of this difference to model inaccuracies in reproducing the wind fields. In fact, this further analysis showed that the model-based evolution of SH is strictly linked to the simulated wind regimes (as expected) and further revealed some inaccuracies of the model.

In fact, we found *differences between the simulated and measured daily cycle of specific humidity* (e.g., Fig. S15 for case study 1 as an example). *In particular, the measured SH usually increases during the first advection day as a result of the transport from source areas with more stagnating conditions, but stays rather constant for the rest of the episode. Conversely, COSMO yields larger dynamics, with SH maxima in the late afternoon and subsequent decrease.* This is likely due to the fact, that *COSMO overestimates the nighttime drainage winds (katabatic winds), as noticeable from Fig.S13* (the figure refers again to case study 1). *This might trigger enhanced cleansing of the lower atmospheric layers during the night as simulated by FARM, but undetected by the ALC.*

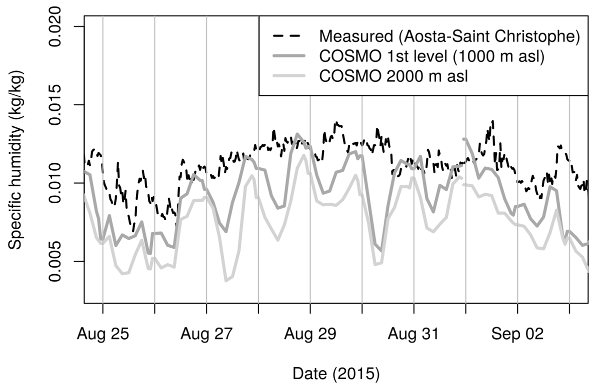

Figure S15: Comparison among specific humidity measured at Aosta–Saint Christophe and simulated by COSMO at two different altitudes (surface and 2000 m a.s.l.).

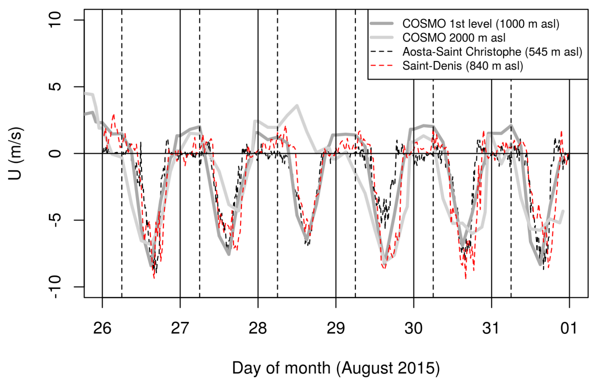

Figure S13: Zonal component of wind velocity during episode 1 (August 2015) from COSMO (1000 and 2000 m a.s.l.) and two surface stations (Aosta–Saint Christophe and Saint-Denis). Positive *U* represent wind from the west, negative *U* wind from the east.

Following the reviewer's suggestions, and our related analysis, Sections 4.1.2 and 4.4 were updated accordingly, as well as the conclusions.

As a final remark, please note that the sharp increase of SH in the afternoon of 28 May is due to rainfalls, as visible from the corresponding ALC panels and also mentioned in the text (former line 12, page 30).

RC2. Another aspect is the vertical extent of the scattering ratio in the late afternoons of case study 1 and 3. The wind field indicates strong winds in the lower few hundred meters above valley floor (up to ca. 1200 m), while higher up winds are rather weak or calm (at 2000 m). Yet the polluted air mass almost instantaneously reaches from 1000 to 2000 m upon arrival. With a wind shear from 10 m/s to 1 m/s over 1000 m can we expect quasi-simultaneous arrival of polluted air on all altitudes? Is this

front-like structure real or is it an effect of radiative cooling which increases RH and particle growth throughout the valley atmosphere? Or – alternatively – is this an artifact of the combination of real backscatter measurements with the modeled wind field?

AR2. We think that the impression of a “front-like” structure mentioned by the reviewer is partly due to the temporal extent of former Figs. 4 and 13, and the resulting “squeezing” of the daily ALC profiles. In fact, if we consider only one day at a time, e.g. 25 May 2017 (case 3, former Fig. 3 in the discussion paper, also reported here below), or 27 August 2015 (case 1, Fig. A here below), we observe a different, and more accurate picture of the phenomenon. These figures, also representative of a general behaviour noticeable during the advection events, show a more gradual growth of the layer characterised by large SR values. In particular, two distinct regions can be identified: a first one, where an initial increase of SR is visible (region 1, light-blue/green colour), and a second one, where the backscatter is rapidly enhanced (region 2, yellow colour). Based on the discussion in Sects. 4.4 and S7, we ascribe these regions to two different physical processes. Region 1 defines the spatio-temporal domain where advection of dry aerosol during the afternoon occurs. Real transport of aerosol is indeed confirmed at the surface, e.g., by an increase of the number of particles detected by the OPC during event days and an increase of mass concentration from the PM monitors, which operate in dry conditions and are thus not influenced by hygroscopic processes. This region (e.g., quantitatively defined by the SR=3 envelope) can be effectively fitted by a smooth curve as a function of time, as done using a sigmoid function in the companion paper (Diémoz et al., 2019, to be submitted to ACP). Conversely, region 2 refers to the domain where hygroscopic growth takes place during the evening/night, as soon as the sun sets and RH increases. Further investigations and parametrisations of this last phase would require the measurement of profiles of different meteorological variables as well as knowledge of the aerosol properties along the vertical, and will be the topic of future studies.

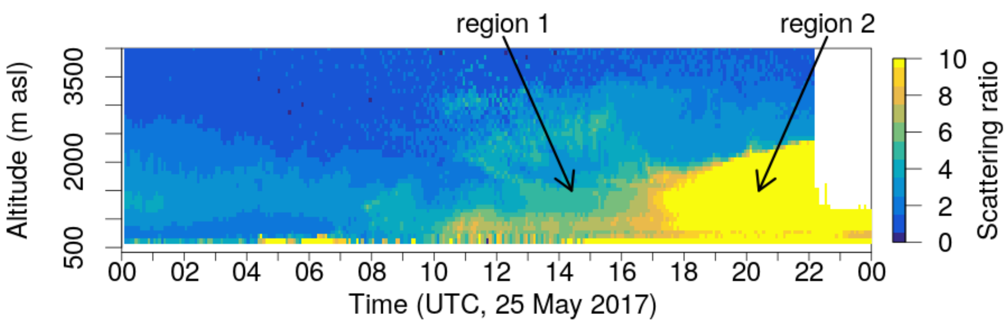

Figure 3 (discussion paper): ALC profile on 25 May 2017.

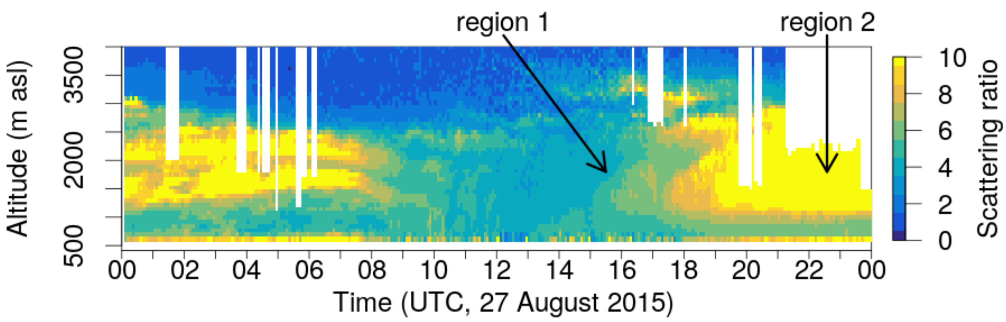

Figure A: ALC profile on 27 August 2015.

A second factor mentioned in the reviewer's comment is the wind profile. We think that some artifacts in the modelled wind fields by COSMO are triggered by *the smoothed valley orography used in the NWP model compared to the real one. This is displayed in Fig. S14, showing the difference of the Digital Elevation Model (DEM) used within COSMO and a more realistic DEM (10 m resolution): both valleys and mountain crests are clearly smoothed out by COSMO, with absolute differences well* > 500 *m (and up to 1000 m)* (Sect. 4.4 of the revised text). *This difference could [...] explain why the altitude of the entrainment zone (i.e., the boundary between the free atmosphere and the boundary layer where the thermally-driven circulation develops) is underestimated by COSMO compared to the height of the aerosol layer detected by the ALC.*

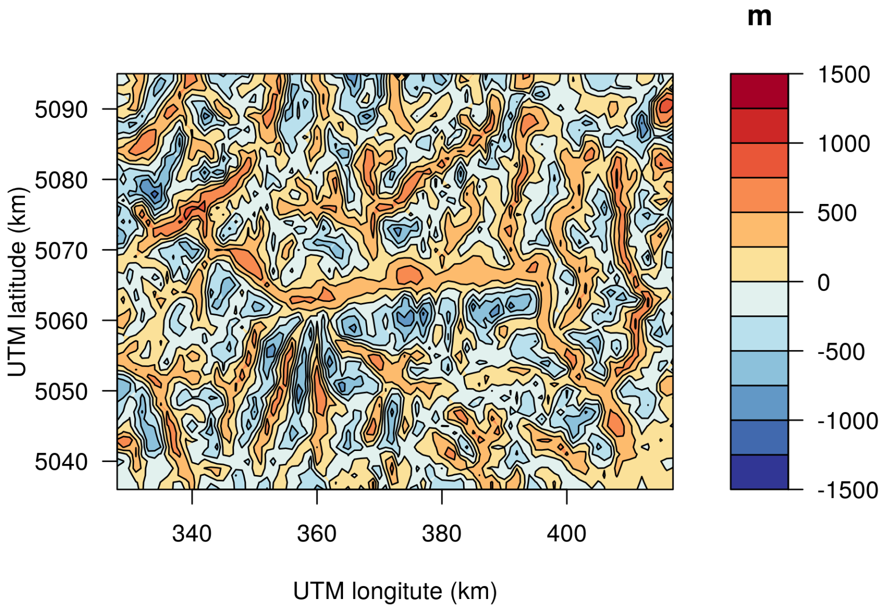

Figure S14: Difference between the (smoothed) Digital Elevation Model (DEM) used by COSMO-I2 (2.8 km resolution) and a higher-resolution DEM ("real topography", 10 m resolution).

RC3. The back-trajectories are good indicators of the regional origin of the polluted air. The graphical representation of all heights up to 4000 m hides, however, the details of the low-level (< 1500 m) transport route of the air masses within the valley. I suggest to show additional afternoon graphs only for these low levels.

AR3. We thank the reviewer for pointing this out. Following this and the other reviewer's comments, the back-trajectories figures were modified in this way: we plotted in separate panels trajectories ending at altitudes < 2000 and > 2500 m a.s.l. over Aosta–Saint Christophe. Also, following a remark from referee #4 (RC7) to further simplify the figures, we only show back-trajectories for specific times corresponding to the most significant variations of circulation patterns. Finally, according to referee #3 (RC15), for each time selected we added a bottom panel with the trajectory altitude along their journey. An example of the new plots now included in the paper is provided in Fig. 5.

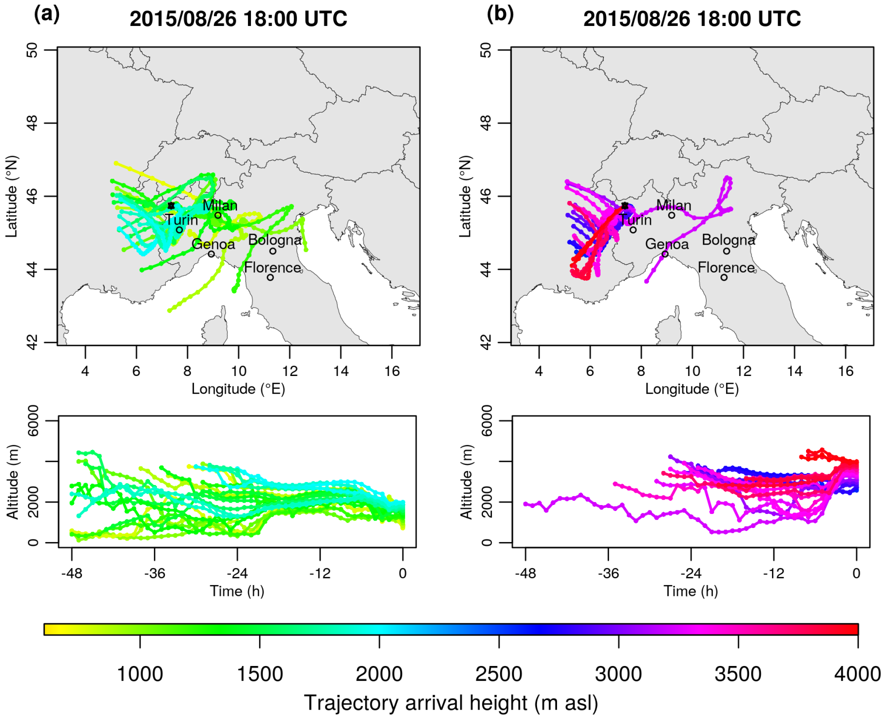

Figure 5: 48-hours back-trajectories ending at Aosta–Saint Christophe on 26 August 2015 at 18 UTC at altitudes lower than 2000 m a.s.l. (a) and higher than 2500 m a.s.l. (b). The trajectories are cut at the border of the COSMO model. The colour scale represents the back-trajectory arrival height. Corresponding altitudes of the backtrajectories vs time are reported in the bottom panels. The dots along each trajectory mark a 1-hour step and the black star indicates the trajectory arrival point (Aosta–Saint Christophe).

RC4. The COSMO-I2 model with 2.8 km grid resolution might still be too coarse for a detailed 3-d simulation of the valley atmosphere with its various mixing processes. With the valley width of 4 km at Aosta, two grid points fit into the valley cross-section at the floor. This may be insufficient for resolving the complex 3-d flow field of an Alpine valley, and may be another explanation of a part of the discrepancy between model and observations.

AR4. The reviewer raised a highly topical issue. We are aware of this problem and decided to integrate Sect. 4.4 with the following text:

As a final remark, we also mention that the 2.8 km grid resolution of the COSMO-I2 model might still be insufficient for resolving the complex 3-D flow field of an Alpine valley and is too coarse to reproduce the mountain atmosphere with its various mixing processes. Follow-up studies using next generation NWP models with increased resolution (1 km or lower) would be of great interest. On the other hand it should also be noticed that decreasing the grid spacing below the scale for which turbulence parametrisations have been developed, i.e. modelling the "grey zone" (or "terra incognita", e.g., Wyngaard, 2004), does not necessary lead to better performances. In this context, comparison of high-resolution simulations with our vertically-resolved dataset could represent a challenging future benchmark for this relevant topic of ongoing research.

RC5. P13L7 omit “the” – should read “covering central and southern Europe”

AR5. Done.

RC6. P22L4 Valley-mountain (and sea-land) breezes are ... (shift the bracket)

AR6. Done.

RC7. P27L20 hundreds

AR7. Done.

RC8. Fig. 7, caption I could not find the link to the video

AR8. We added the following link to the caption: `https://doi.org/10.5446/38391`.

RC9. Supplement: P11L15 replace “grow” with “growth”

AR9. Done.

RC10. Fig. S10 mention the PM10 units for all graphs, not only for a) and b). This can be done in the caption.

AR10. Done.

References

Diémoz, H., Gobbi, G. P., Magri, T., Pession, G., Pittavino, S., Tombolato, I. K. F., Campanelli, M., and Barnaba, F.: Transport of Po Valley aerosol pollution to the northwestern Alps. Part 2: long-term impact on air quality, submitted to Atmos. Chem. Phys., 2019.

Wyngaard, J. C.: Toward Numerical Modeling in the “Terra Incognita”, J. Atmos. Sci., 61, 1816–1826, doi:

10.1175/1520-0469(2004)061<1816:TNMITT>2.0.CO;2, 2004.