P3.3 BOUNDARY LAYER STRUCTURE IN THE INN VALLEY DURING HIGH AIR POLLUTION (INNAP)

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1. INTRODUCTION

Over the last decades air pollution in the Alpine region has become an intensely debated subject at political and public levels. Clear evidence exists that heavy traffic along the major Alpine transport routes, such as the Brenner route through the Inn Valley (Austria) and over the Brenner Pass, has strongly contributed to the air pollution problem in Alpine valleys (e.g., Beauchamp et al., 2004). The increase of immission of several pollutants, such as nitrogen oxide (NO_x) and particulate matter (aerosols) are related to an increase of traffic-induced emission. A traffic scenario for the eastern Inn Valley predicts an increase of the total traffic volume per year of more than 35% between the years 2002 and 2012 (Thudium, 2003).

In addition to studies on traffic-flow and emission scenarios, there is a demand for improving the understanding of atmospheric processes which control transport and redistribution of air pollutants over complex terrain. This observational study discusses some of these processes, specifically transport and redistribution by valley and slope winds as well as local dilution through convective and shear-induced turbulent mixing. Subject of our investigation is the wintertime boundary layer of the lower Inn Valley (Austria) during episodes of high air pollution (see Fig. 1). For this purpose, airborne lidar observations have been collected in the winter 2006 within the framework of the research project INNAP**.

2. DESCRIPTION OF DATASETS

2.1 *Airborne lidar observations*

The study is based on the analysis of aerosol backscatter intensities collected with the DLR TropOLEX lidar (Meister et al., 2003) which was operated on board of the DLR Cessna C-208B Grand Caravan aircraft in a nadir-pointing mode. The targets of the lidar observations were small dust particles (particulate matter). Such aerosols are typically emitted by anthropogenic sources, e.g., heavy traffic as well as industrial and domestic burning. The measured backscatter intensities are proportional to the number and size of aerosols in each resolved volume. Morning as well as afternoon flights were conducted on four selected days between January and February 2006. Repeated vertical cross-sections of backscatter intensity, aligned parallel and perpendicular to the valley axis, reveal the temporal evolution and the spatial structure of aerosols within the valley atmosphere. Such lidar observations have been successfully used in other studies for investigating flows over complex terrain (e.g., Gohm and Mayr, 2004; Gohm and Mayr, 2005).

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**Boundary layer structure in the Inn Valley during high air pollution.

2.2 *Radiosoundings*

During the aircraft missions of INNAP, additional radiosondes were launched from the Airport of Innsbruck, which is located close to the target area (see Fig. 1(a)). We will use this dataset in order to discuss the thermodynamic structure and the wind system of the valley atmosphere.

3. CASE STUDIES

In the following analysis we will focus on the afternoon situation of two selected winter days. These two cases were characterized by two different type of aerosol distributions, which were determined by different atmospheric conditions rather than different emission characteristics. In both cases the valley wind system was disturbed by the synoptic scale flow. Figure 2 provides a visual impression of the target area. On both days the valley floor was snow-covered while the treetops of the timbered slopes were mostly snow-free.

3.1 *16 January 2006*

The synoptic scale situation over the Alps on 16 January 2006, depicted by the ECMWF analysis (not shown), was determined by the passage of a weak cut-off low which moved from Italy over Austria to the Czech Republic between 15 and 17 January. In the target area (Fig. 1b), this low pressure system caused neither precipitation nor clouds. However, the system was responsible for a low-level temperature and pressure difference between the southern and northern Alpine forelands. The Italian Po Valley (south of the Alps) was filled with cooler air compared with the Bavarian Alpine foreland (north of the Alps). This mesoscale air mass difference, combined with the fact that on 12 UTC 16 January the synoptic scale pressure low at 700 hPa was located already north of the Alps, was responsible for southerly flow through mountain gaps such as the Brenner Pass. This type of compensation flow, is known as shallow south foehn (e.g., Gohm et al., 2004) and is usually restricted to heights below the Alpine crest level. This situation led to southerly (down-valley) flow in the Wipp Valley, between Brenner Pass and Innsbruck, and to westerly (down-valley) flow in the Inn Valley, between Innsbruck and Schwaz (see Fig. 1a).

Figure 3a depicts the vertical flow structure in the Inn Valley at Innsbruck, located approximately 30 km west of the target area (Fig. 1). The valley atmosphere below 1000 m above mean sea level (MSL) is characterized by down-valley winds and high thermal stability (strong vertical gradient of potential temperature). The valley atmosphere above 1000 m MSL is affected by shallow foehn through the Brenner gap and, therefore, has neutral stability (well mixed), low humidities and southerly winds. Above crest level ($\geq$ 2200 m MSL) winds turn to synoptic-scale westerly directions.

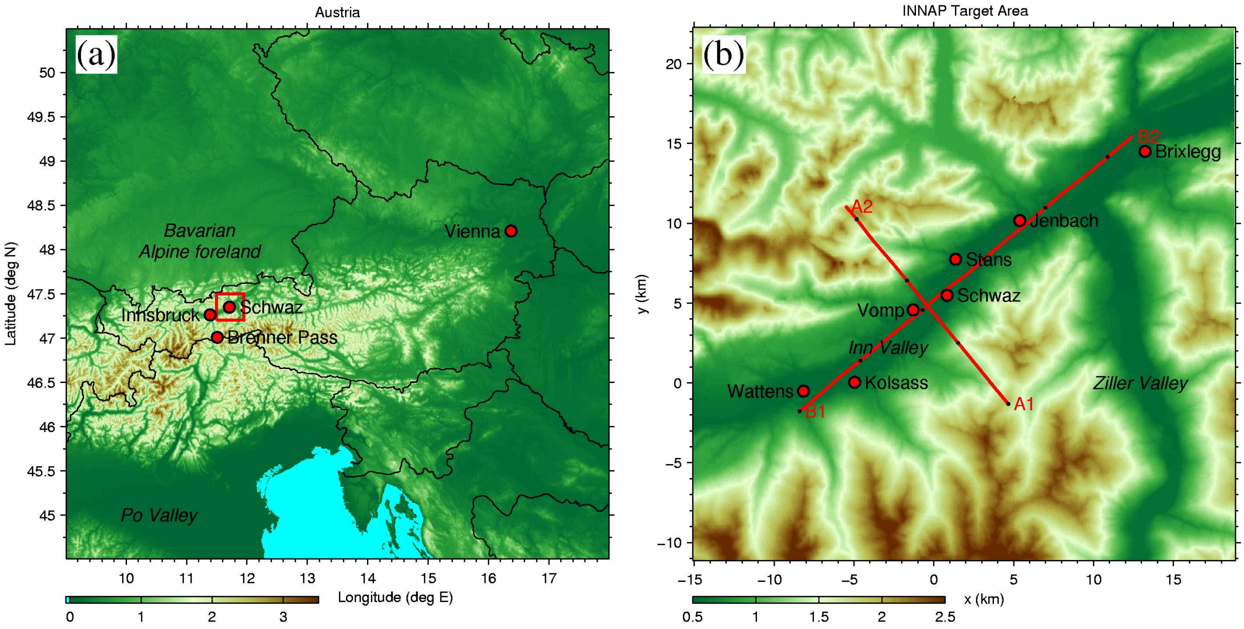

FIG. 1: Topography of the target area: (a) overview (Austria) and (b) close-up (the Inn Valley near the town of Schwaz). The red box in (a) marks the domain of (b). Red solid lines in (b) show two selected flight legs across (A1A2) and along (B1B2) the Inn Valley, respectively. Black dots in (b) correspond to major tick marks on the abscissa of Fig. 4 and are drawn at a horizontal spacing of 5 km.

The measured aerosol distribution in the Inn Valley is shown in Fig. 4a-b based on two vertical cross-sections. The orientation of these two transects is shown in Fig. 1b. Essentially, the vertical aerosol structure correlates with the temperature and wind structure of the previously discussed sounding: In Fig. 4a highest backscatter intensities (and therefore highest aerosol concentrations) are observed in a shallow 100–200-m thick surface layer. The temperature inversion within the lowest 500 m above ground level (AGL) keeps the polluted surface layer very thin and prevents strong mixing. Above the surface layer, but still within the inversion, backscatter intensities are more than a factor of two lower. The neutral stratified foehn layer above the inversion is characterized by low aerosol concentrations with backscatter intensities being about a factor of ten lower in the foehn layer than near the surface. In fact, the foehn layer is decoupled from the polluted surface layer by the inversion layer. Mechanical turbulence (weak stability and wind shear; see Fig. 3a) is presumably the reason for the well mixed aerosol distribution in the foehn layer. However, near the southward-facing sun-exposed terrain slope, backscatter intensities are higher than over the valley center. This feature is most likely related to upslope winds which are driven either thermally due to surface-layer heating above the snow-free trees (see Fig. 2) or dynamically by the shallow foehn. A combination of both effects is conceivable. A secondary circulation, as observed in other studies for curved valleys (e.g., Weigel and Rotach, 2004), may also play a role.

The aerosol structure is not homogeneous in the along-valley direction, either (Fig. 4b). The top of the near-surface aerosol layer is slanted leading to a polluted layer being about 200 m deeper in the eastern part of this transect (e.g., near the town Jenbach) than in the western part (e.g., near the town Kolsass). Since the air mass was slightly colder in the lower Inn Valley (not

FIG. 2: The lower Inn Valley: Photo taken at 0918 UTC 16 January 2006 on the DLR Cessna Grand Caravan at approximately 3600 m MSL. The view is northeastward from Vomp towards Jenbach (see Fig. 1b).

shown) it appears that the shallow down-valley flow observed in the western part was lifted above the cooler air mass causing the observed asymmetry. It is noteworthy that profile measurements of pollutants near Schwaz with a tethered balloon (not shown) indicated a rapid increase in the depth of the polluted layer soon after sunset (R. Schnitzhofer, personal communication). This change in the vertical structure at a specific location is most likely related to the wind reversal (from down-valley to up-valley winds!) which occurred at the same time. Thus, in this specific case the up-valley flow was most likely responsible for advecting more polluted air from the lower Inn Valley after sunset. However, from this result it cannot be deduced that the lower Inn Valley is generally more polluted than the upper Inn Valley.

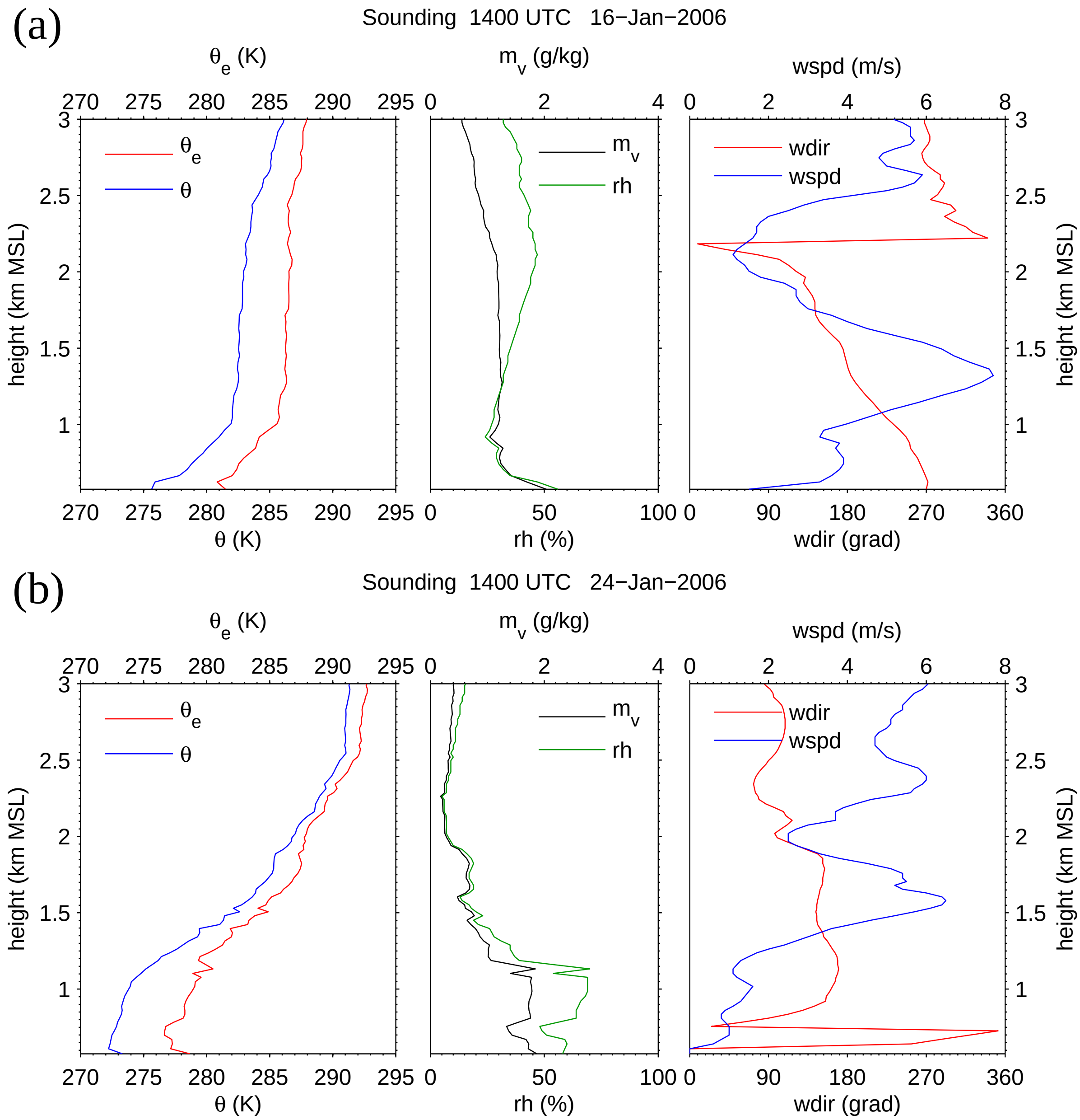

FIG. 3: Radiosounding at Innsbruck Airport at (a) 14 UTC 16 January 2006 and (b) 14 UTC 24 January 2006: Vertical profiles of (left) potential temperature (K; blue) and equivalent potential temperature (K; red), (middle) relative humidity (%; green) and water vapor mixing ratio (g kg^{-1}; black), and (right) horizontal wind speed (m s^{-1}; blue) and wind direction (degrees; red).

3.2 *24 January 2006*

On 24 January 2006 the Alpine region was under the influence of northeasterly flow on the backside of a pressure trough. During the previous days this system advected cold Arctic air to central Europe. The ECMWF analysis at 12 UTC (not shown) indicates that the cold-air outbreak had reached the Mediterranean. In the Inn Valley cold air advection by up-valley winds ceased in the early morning hours and at the time of our airborne measurements down-valley flow prevailed near the surface.

The vertical sounding in Fig. 3b shows that the Inn Valley atmosphere is characterized by a weakly stable and relatively humid layer below ∼1000 m MSL which is topped by a pronounced temperature inversion. Above the inversion the air is very dry. Compared with the previously discussed case the center of this inversion is located significantly (about 500 m) higher. Winds blow down-valley within a shallow surface layer and from south between this surface layer and the crest level. Similar to the previously discussed case this southerly flow component is most likely caused by air mass differences, i.e. slightly cooler air in the Po Valley than over the Bavarian Alpine foreland. However, southerly winds are much weaker on 24 than on 16 January (cf. Figs. 3a and 3b). Nevertheless, this air mass difference may be strong enough to explain the fact that no thermally driven up-valley flow could develop on this sunny day[1].

[1] At this place it is noteworthy that a valley wind regime with periods of up-valley winds in the afternoon can even develop in wintertime. Such a situation was observed in the Inn Valley, e.g., on 15 January 2006.

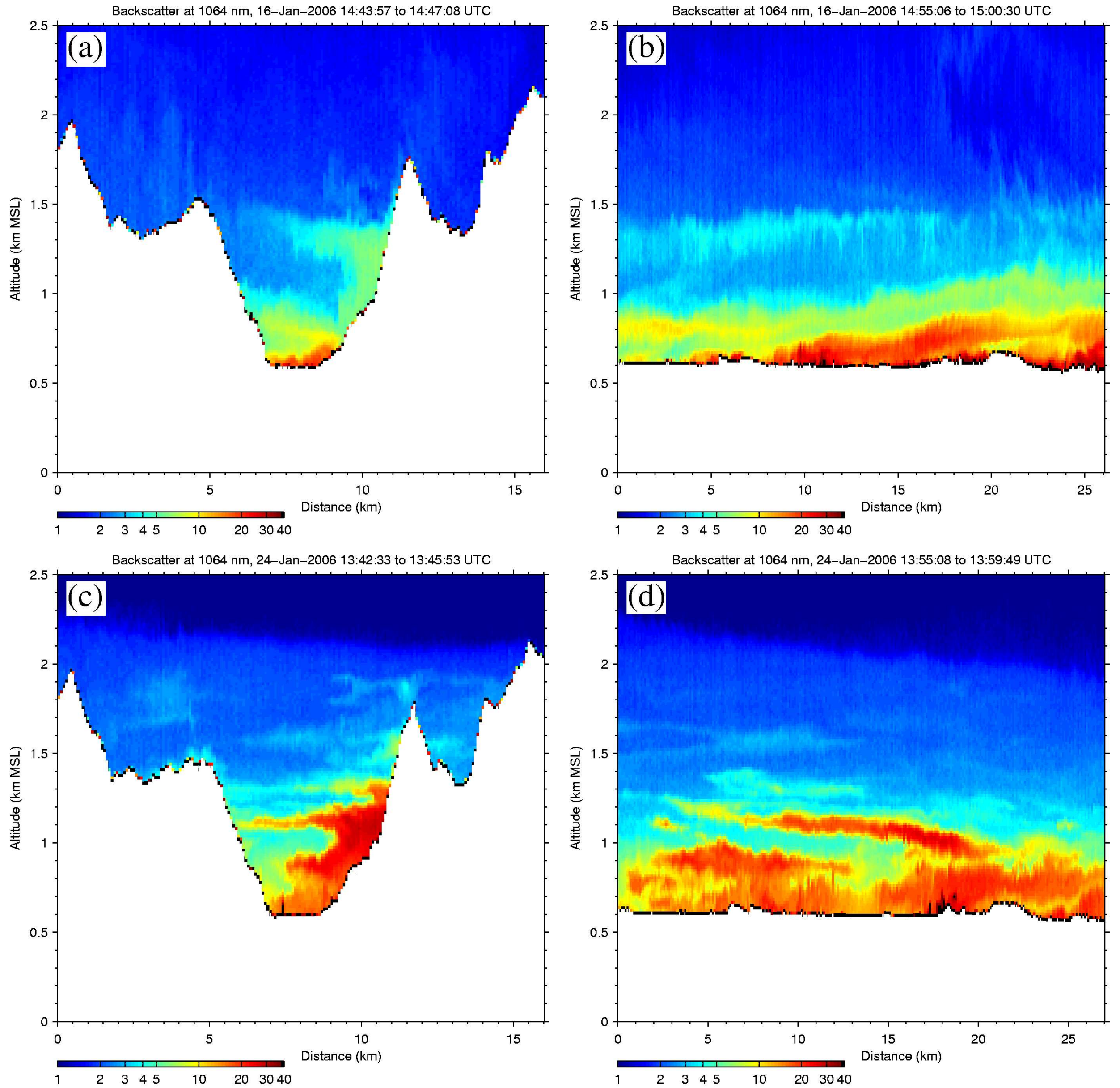

FIG. 4: Observed range-corrected backscatter intensity (arbitrary units, logarithmic color scale) at 1064 nm for (a)–(b) 15 UTC 16 January 2006 and (c)–(d) 14 UTC 24 January 2006: Vertical transects (a) and (c) along leg A1A2 from southeast to northwest and (b) and (d) along leg B1B2 from southwest to northeast (see Fig. 1b). Orography is white.

The prominent feature in the vertical lidar transect across the Inn Valley (Fig. 4c) is the asymmetric structure of aerosol concentration with respect to the valley center. The sun-exposed slopes on the northern side are much more polluted than the southern slopes. It is very likely that thermally driven up-slope winds are responsible for the transport of pollutants from the valley floor to higher levels. When these up-slope winds reach the inversion layer at approximately 1300 m MSL (cf. Fig. 3b) they are deflected horizontally, i.e. aerosols are transported from the northern slopes across the valley southward. Such an impact of an inversion layer on slope winds, in which rising air parcels are forced to leave the slope layer below the inversion, was discussed by Vergeiner and Dreiseitl (1987). In our case a circulation pattern establishes with up-slope winds above the northern slopes whereas on the southern side slopes winds are negligible or even reversed. This process forms two secondary elevated aerosol layers at approximately 1100 and 1200 m MSL which can be also identified in the along-valley transect (Fig. 4d). From a single vertical sounding the origin of theses layers could be hardly identified.

Compared with the previous case, the depth of the primary aerosol layer near the surface does not show a strong along-valley asymmetry with a slanted layer top (cf. Figs. 4b and 4d). Yet, aerosol concentrations within this layer are not homogeneous. Close to the surface backscatter intensities vary up to a factor of four.

4. DISCUSSION AND CONCLUSIONS

Slope and valley winds, either thermally or dynamically driven, are capable of redistributing pollutants which are emitted, e.g., by combustion processes near the valley floor even in very thermally stable wintertime conditions. Thus, populated areas located along the valley slopes at altitudes even significantly (i.e. several hundred meters) above the emission sources may also be affected by air pollution through horizontal and vertical transport by local wind systems.

Our lidar observations show strong spatial inhomogeneities in the aerosol distribution even in wintertime when weak thermal forcing is usually assumed. Strong horizontal gradients of pollutants were observed in across- and along-valley directions. Therefore, care should be taken when point-measurements from surface stations and profile-measurements from vertical soundings are used to deduce the exposure of air pollution for a larger domain without knowing the real horizontal distribution of pollutants.

Acknowledgments

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