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A multimethodological approach to study the spatial distribution of air pollution in an Alpine valley during wintertime

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Abstract. In order to investigate the spatial distribution of air pollutants in the Inn valley (Tyrol, Austria) during wintertime, a joint field campaign of the three research projects ALPNAP (Monitoring and Minimisation of Traffic-Induced Noise and Air Pollution Along Major Alpine Transport Routes), INNAP (Boundary Layer Structure in the Inn Valley during high Air Pollution) and INNOX (NO_x-structure in the Inn Valley during High Air Pollution) was carried out in January/February 2006. In addition to continuous ground based measurements, vertical profiles of various air pollutants and meteorological parameters were obtained on six selected days. For in-situ investigations, a tethered balloon was used to analyse the lowest atmospheric layers, 0–500 m above the valley bottom (a.v.b.), and a research aircraft sampled at 150–2200 m a.v.b. An aircraft equipped with an aerosol backscatter lidar performed nadir measurements at 3000 m a.v.b. Combined results from a typical day show a strongly polluted layer up to about 125 m a.v.b. in the morning. Around midday concentrations on the valley floor decrease indicating some vertical air exchange despite thermally stable conditions. Strong vertical and horizontal gradients with enhanced pollution levels along the sunny side of the valley up to 1300 m a.v.b. were observed in the afternoon. This vertical mixing due to thermally or dynamically driven slope winds reduces the concentration of air pollutants at the bottom of the valley and causes the formation of elevated pollution layers.

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1 Introduction

Growing mobility is associated with increasing emissions from fossil fuel burning. Many of the emitted compounds have detrimental effects on human health. The European Commission estimates the environmental costs (air pollution, noise and global warming) of overall traffic in the European Union to be 1.1% of the gross domestic product. The growth of goods transport (2.8%) is slightly faster than the economic growth (2.3% per year, between 1995 and 2004). Due to the increasing demand of door-to-door and just-in-time service, a disproportional large share of this growth is carried on roads (European Commission, 2006).

Being part of the Brenner route, one of the main transport routes between northern and southern Europe, the Inn- and the Wipp-valley face particularly high HDV (Heavy-Duty-Vehicle) traffic density. The traffic volume in the eastern Inn valley has doubled from 1980 to 2000 (Verkehrsclub Österreich, 2004) and it is predicted to increase further by about 40% until 2012 (Thudium, 2003). Technical progress in emission reduction does not compensate for the effect of the ongoing increase of traffic density. Air quality legislation threshold values were exceeded at 6 out of 13 NO_2, and at 7 out of 12 PM_{10} measurement stations in Tyrol in the year 2005 (Weber et al., 2005). Therefore, strategies to improve air quality have been implemented. The Tyrolean government introduced a HDV ban during nights and a speed limit for light duty vehicles (LDV) of 100 km/h during the winter season (November–April) for the Inn valley motorway (A12). This is supposed to reduce emissions of NO_x and PM_{10} by approximately 10% (Thudium, 2005; Oettl et al., 2006).

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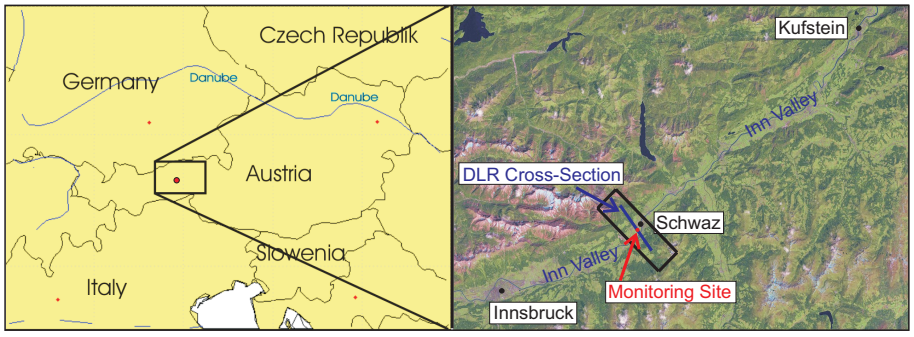

Fig. 1. Map of the measurement location in the Inn valley, Tyrol, Austria. Ground-based measurements were located near the town Schwaz at 540 m m.s.l. The blue line indicates the flight leg of the DLR Cessna. The flight path of the MetAir Dimona was within the black box in the right panel.

However, not only emission levels, also meteorological conditions, that control dilution and dispersion of pollutants, have a large impact on air quality, especially over complex terrain. Beside channeling the traffic into some main routes, the mountainous landscape of the Alps also forces the air flow along the valley, even though tributaries significantly influence the main valley wind system (Zaengl, 2004). In contrast to flat terrain, air pollutants can only be removed vertically and along the valley axis. Moreover the mountains reduce wind speed and favour inversion layers that restrict vertical dilution (Dreiseitl and Stöhr, 1991). A thermally driven wind system, that occurs in the Inn valley on 30% of all days (Vergeiner and Dreiseitl, 1987), can lead to a recirculation of polluted air (Grießer, 2003). Specific mountain effects cause morning NO_x concentrations to be up to nine times higher in the Inn valley than over flat terrain with the same emission source strength (Wotawa et al., 2000).

Previous investigations in the Inn valley were mostly based on point measurements and dispersion models (e.g. Thudium, 2005; Oettl et al., 2006; Schnitzhofer et al., 2008). In order to proof the spatial representativeness of point measurements and to validate and improve existing models there is a need of airborne in situ measurements. During the MEMOSA-project the summertime distribution of various air pollutants was studied across the Alps on 7 flight days between 1990 and 1992 (Schlager and Graf, 1993). In the VOTALP-project that took place in the Mesoclina-valley (Switzerland) in summer 1996, airborne in situ measurements were performed to investigate advection of polluted air from the Po valley via the valley wind regime. Using a simple box model it was found, that the whole valley air volume was exchanged 3–6 times through slope and valley wind systems during fair weather conditions in summer (Carnuth and Trickl, 2000; Furger et al., 2000; Henne et al., 2004). Through these thermally driven wind systems air pollutants can even be injected into the free troposphere (Prévôt et al., 2000b; Henne et al., 2004). The same process was proposed to reduce pollutant levels in the Inn valley during summer months (Schnitzhofer et al., 2008).

In winter the vertical air exchange is minimized due to a stably stratified valley atmosphere. However, results from a wintertime field study in two Alpine valleys in France in the year 2003 indicate some vertical transport of polluted air via slope winds (Chazette et al., 2004), which is consistent with observed minima in daytime concentration in the wintertime Inn valley (e.g. Schnitzhofer et al., 2008). In addition, a positive correlation of snow cover and valley depth to inversion strength and duration was found (Chazette et al., 2004).

The aim of the three research projects INNOX (NO_x-structure in the Inn Valley during High Air Pollution), INNAP (Boundary layer structure in the Inn valley during high air pollution) and ALPNAP (Monitoring and Minimisation of Traffic-Induced Noise and Air Pollution Along Major Alpine Transport Routes; Heimann et al., 2007) was to study the wintertime boundary layer of the Inn valley during events of high air pollution. In this paper we present an overview of the obtained dataset and give a detailed three-dimensional picture of the distribution of air pollutants on 1 February 2006, which represents a typical fair, cold winter day.

2 Experimental

2.1 Location and ground based measurements

The field campaign took place in the Inn valley near the town of Schwaz, Tyrol, Austria, in January and February 2006 (Fig. 1). The monitoring station for ground-based measurements was located between Schwaz and Vomp (11.69° E, 47.34° N), at 540 m above mean sea level (m.s.l.), about 750 m southeast of the A12 motorway. On average 52 000 vehicles per day (15% heavy duty vehicles) were counted on the motorway at Vomp in 2006 (Satzinger et al., 2007). At this location the valley runs from southwest to northeast, with a width of about 1.5 km on the floor. The mountains on

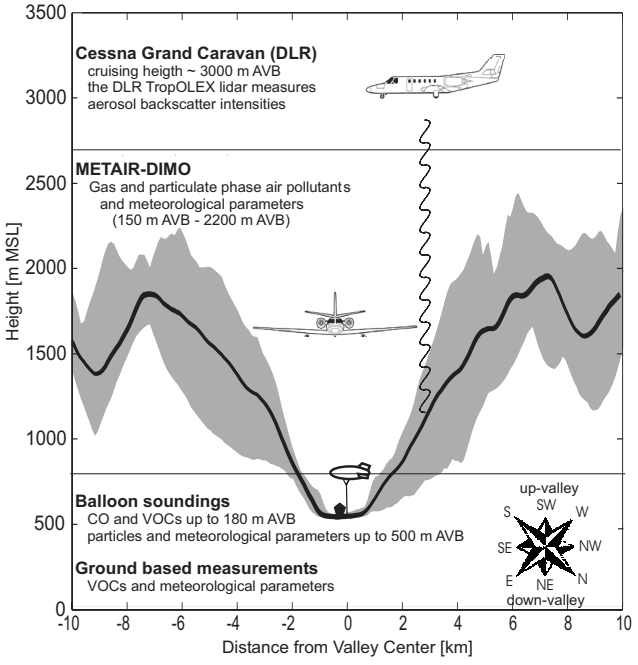

Fig. 2. Experimental setup from the joint field campaign of the research projects ALPNAP, INNAP and INNOX. The black line represents the terrain height of the average valley slopes in the 6×20 km box plotted in Fig. 1; the shaded area represents the widest and narrowest part. The view is headed in the valley upward direction i.e. south west.

either side of the valley reach over 2500 m m.s.l., with a mean crest height of 2000 m m.s.l. and a lowest mountain pass of 1900 m m.s.l., within the investigation area.

Volatile organic compounds (VOCs) were measured with a Proton-Transfer-Reaction Mass-Spectrometer (PTR-MS) that has been described in detail previously (Hansel et al., 1995; Lindinger et al., 1998a,b). In addition, a meteorological station measuring radiation and temperature, pressure, wind (direction and speed), and humidity on different heights, up to 10 m a.v.b., was in operation. While meteorological data were gathered from October 2005 until March 2006, the PTR-MS was in use from 10 January until 14 February. On six intensive measurement days the three-dimensional distribution of various air pollutants was characterised (experimental setup see Fig. 2).

2.2 Balloon measurements

A tethered balloon (24 m^3) filled with helium, suitable to lift 7 kg of measurement equipment, was in use for soundings up to 500 m a.v.b. (compare Jensen et al., 2002). A sonde was fixed on the balloon measuring temperature, humidity, wind (direction and speed), and pressure. The orientation of the streamlined balloon was used to derive the wind direction. Every 10 s these parameters were measured and transmitted to the ground station. A GRIMM particle counter was in use to measure size selected particle number concentrations (15 size bins). Next to the meteorological sonde the inlet of a 200 m long 1/4″ thin wall teflon line was mounted, which supplied air to the ground based analysing instruments (AL 5001 CO analyser, PTR-MS). Measurements of the gaseous species were limited to about 180 m a.v.b., while balloon ascents without the teflon tube were conducted up to 500 m a.v.b. The measurement sequence was adjusted to the 10 s time resolution of the meteorological data. Within 10 s one mean value of CO, and 10 different masses were measured with the CO analyser, and the PTR-MS, respectively. The inlet residence time was typically 23 s at 7 standard liter per minute pumping speed.

Table 1. Data gained from MetAir-Dimo measurements.

Resolution	Parameter
10 Hz	time, aircraft position, pressure, wind speed and wind direction, temperature, humidity, CO_2, CO, particle number concentration $>0.3\,\mu$m
1 Hz	terrain height, shortwave radiation, temperature, humidity, O_3, NO, NO_2, particle number concentration $>0.5\,\mu$m
1 min	particle number in 15 size bins from 0.3 μm to 20 μm
10 min	42 identified C_4 to C_{10} hydrocarbons

2.3 Aircraft measurements

Two research aircraft were deployed to investigate the spatial variability of air pollution in the Inn valley with in-situ and remote sensing techniques.

The Dimona research aircraft (Diamond Aircraft Dimona TTC-ECO, call sign HB-2335) from MetAir AG (Switzerland) conducted measurements from about 150 m a.v.b. (minimum safety flight altitude) up to 2200 m a.v.b. The list of obtained data is given in Table 1. The temporal resolution for the measured parameters range from 0.1 s to 10 min, with the lowest temporal resolution available for the gas chromatographic (GC) data. With a typical speed of 150 km h^{-1} the Dimona covers a distance of about 25 km within 10 min. Therefore, the GC-data have to be interpreted as average values over a larger area. Nevertheless the flight pattern of the Dimona – it stayed at a constant altitude for each GC cycle – enabled to obtain vertical profiles of more than 30 VOCs. A detailed description of the whole system is given by Neininger et al. (2001).

The second aircraft from the Deutsches Zentrum für Luft- und Raumfahrt (DLR) performed downward looking aerosol backscatter lidar measurements. The TropOLEX lidar, operating in the nadir pointing mode, was installed onboard a Cessna Grand Caravan measuring backscatter intensities at

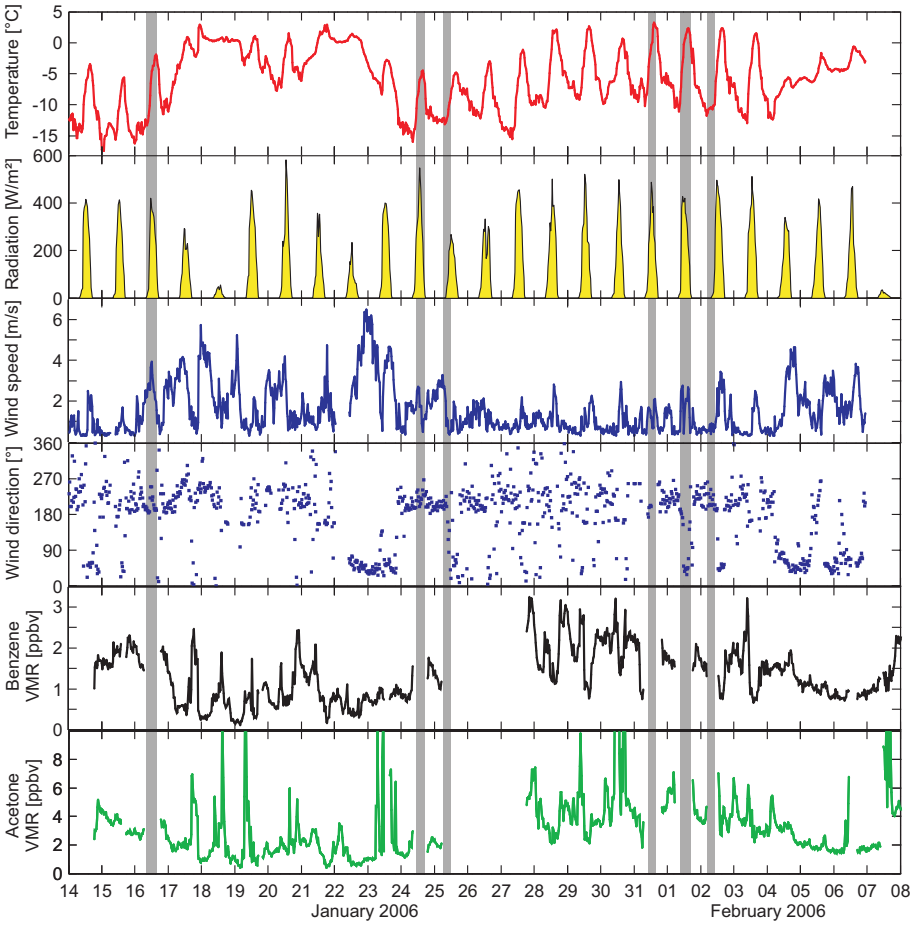

Fig. 3. Overview graph of temperature, shortwave incident radiation, wind speed and wind direction, benzene and acetone VMRs for the whole period of PTR-MS measurements near Schwaz from 14 January until 8 February 2006 (half hourly values). Grey bars indicate days when balloon soundings and aircraft measurements were performed.

wavelengths of 1064 nm and 532 nm. Details about the measurement principle can be found in Meister et al. (2003). A regular flight pattern consisted of several along and across-valley transects at a constant altitude of about 3000 m a.v.b. The horizontal and vertical resolution was 45 m and 15 m, respectively.

3 Results and discussion

3.1 Time series of ground based measurements

The winter 2005/2006 was cold in the Inn valley with a January mean temperature in Jenbach (about 10 km downvalley from the measurement site) 4.4°C below the average (1993–2002). The Inn valley bottom was snow covered from mid November with roughly 30 cm snow in Schwaz during the field campaign in January/February 2006.

Figure 3 shows temperature, shortwave incoming radiation, wind speed and wind direction, and the volume mixing ratios (VMRs) of benzene and acetone for the whole period of ground based VOC-measurements. Grey bars indicate days when balloon soundings and aircraft measurements were performed. The variations in the VOC signal are rather difficult to interpret. In some cases a diurnal pattern anti-correlated with temperature and radiation, in other situations synoptical weather systems strongly influenced pollution levels in the Inn valley, when for example a cold front passage disturbed the stable stratification of the valley atmosphere.

VOC measurements started on 14 January, right at the end of a longer period influenced by a high pressure system above southern Scandinavia, a low pressure system above Italy and therefore an easterly flow over Austria that advected cold air from eastern Europe. During this synoptic situation pollutants accumulated in the valley due to strong inversion layers that trapped pollutants close to the valley floor. The solar radiation modified the inversion layers, but was not strong enough to break them up. Benzene and acetone VMRs (see Fig. 3) were high throughout the day until 17 January. Then

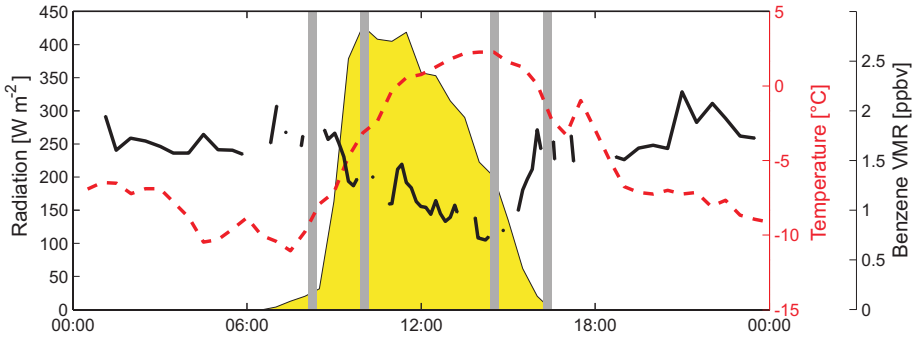

Fig. 4. Diurnal variation of ground level benzene VMR (black solid line), shortwave-incoming radiation (yellow area) and 2 m air temperature (red dashed line) on 1 February 2006. The grey bars indicate times when vertical profiles, plotted in Fig. 5, were measured.

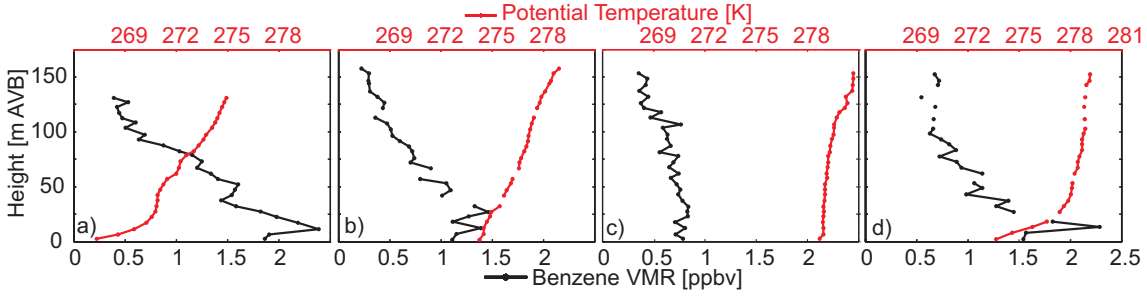

Fig. 5. Vertical profiles of benzene VMR (black) and potential temperature (red) on 1 February 2006. Data points represent average values over 5 height m. Profiles match with times indicated by gray bars in Fig. 4 – **(a)**: 07:56–08:19 UTC; **(b)**: 09:50–10:07 UTC; **(c)**: 14:23–14:51 UTC; **(d)**: 16:10–16:22 UTC.

one week of variable conditions followed with some snowfall most intensively on 18 and 22 January. The VOC signal was highly variable, with short times of high values, due to surface temperature inversions. However, the overall VOC signal was lower because of less stable atmospheric conditions and higher wind speeds compared to the beginning of the measurement period. From 23–25 January arctic air from Northeast Europe was advected to Austria. On these days with a rather undisturbed daily temperature cycle VOC levels started to rise again. On 25 and 26 January a cut-off low moved from Finland across Switzerland to the Pyrenees and brought overcast conditions but no precipitation. From 27 January to 4 February again a high pressure system influenced the weather in Tyrol with undisturbed incoming radiation. Unfortunately, there was an instrument failure from 25–27 January, however, levels on 29 January were high again and showed diurnal variations anticorrelating with temperature and shortwave radiation until 4 February. The mean values for benzene and acetone averaged over the whole measurements period were 1.25 ppbv and 3.1 ppbv, respectively. This exceeds values measured in Zürich in winter 2005/06 (Gaeggeler et al., 2008) by a factor of 1.8 and 2.5.

3.2 Case study: 1 February 2006

On 1 February 2006 the synoptic situation in the Alpine region was characterized by a high pressure system with weak winds. The solar insolation was only disturbed by some thin cirrus clouds and the associated daytime heating reduced the thermal stability in the lowest 500 m, where a weak upvalley flow developed during the day (see Fig. 3 and compare Harnisch et al., 2008). Similar situations were frequently observed during our measurement period (compare Fig. 3).

Measurements were conducted with both aircraft in the morning as well as in the afternoon. In addition 10 vertical profiles of VOC VMRs and 4 of particle number concentration were obtained by balloon measurements.

3.2.1 Diurnal cycle

Figure 4 shows the diurnal variation of shortwave-incoming radiation, temperature and the benzene VMR near ground on 1 February 2006. Grey bars indicate times when vertical profiles of benzene VMR and potential temperature were measured (Fig. 5). A clear diurnal pattern in benzene levels was observed with a ∼2 ppbv nighttime maximum and a ∼0.75 ppbv daytime minimum. This does not coincide with

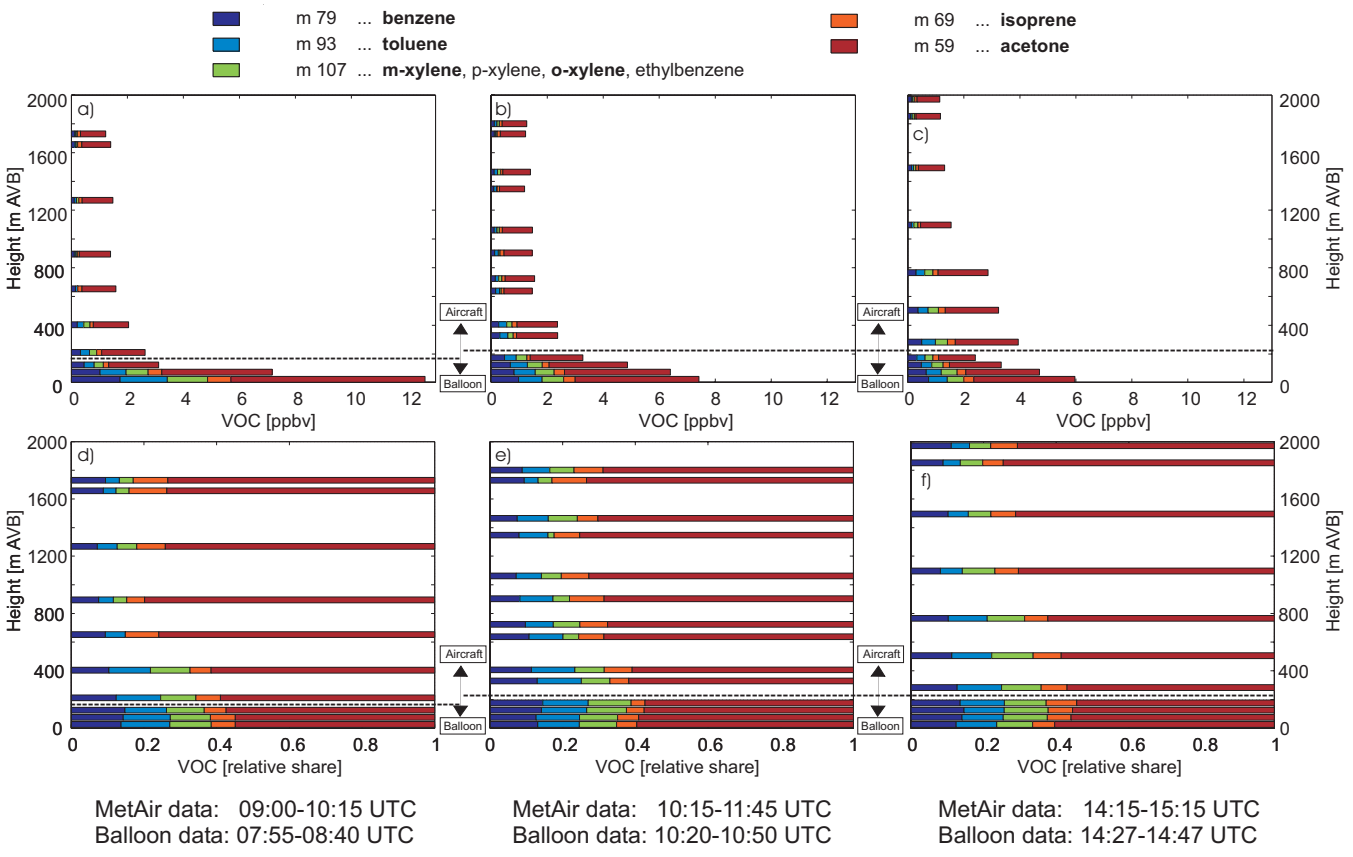

Fig. 6. Vertical profiles of VOCs measured with a PTR-MS system (balloon soundings) and an onboard GC (MetAir-Dimo). PTR-MS signals on nominal masses (m59, m69, m79, m93, m107) are calibrated with the designated main compound (bold) but also correspond to other GC-identified substances with the same mass **(a–c)**. In **(d–f)** the relative share of these compounds is shown. PTR-MS data are averaged over 50 m altitude, while GC data were sampled over 9 min, during which the aircraft tried to stay at the same height level.

traffic emission source strength. It indicates that meteorological parameters were mainly responsible for the diurnal variation of pollution levels by determining dispersion and dilution conditions. During night a surface inversion develops due to the radiation deficit of the surface. Near ground emitted pollutants are trapped in the stable surface boundary layer. The vertical profile at 08:00 UTC, before the sun has reached the valley floor, shows how the stable stratification prevents a vertical air exchange and how pollutants accumulate in a shallow layer (Fig. 5a). At 100 m a.v.b. benzene levels have already decreased by a factor of four compared to surface values. Two hours later at 10:00 UTC the low level temperature inversion is much less intense and the benzene VMR has decreased. However, there is still a significant benzene gradient within the lowermost 100 m a.v.b. (Fig. 5b). The benzene level near ground reaches its minimum at 15:00 UTC, when the daily temperature maximum occurs. At this time, the valley atmosphere is well mixed up to 100 m a.v.b. and benzene is homogenously distributed within this layer (Fig. 5c). Benzene levels on the ground increase again when the radiation balance at the surface becomes negative. A low-level temperature inversion reduces the dilution volume and pollutant levels increase immediately (Fig. 5d). The observed diurnal variation is similar to previous observations at this location and in other Alpine valleys throughout the year (Schnitzhofer et al., 2008; Prévôt et al., 2000a). Beside this diurnal pattern governed by thermal stratification, a short and sharp increase in benzene VMR was observed at 11:00 UTC (see Fig. 4). This was caused by a short-term reversal of the valley wind system and advection of more polluted air from the lower Inn valley (compare wind data in Fig. 3).

3.2.2 Vertical profiles of VOCs

Figure 6 displays the vertical profiles of a series of selected VOCs as measured by PTR-MS (0–200 m a.v.b., ballon) and GC (150–2200 m a.v.b., aircraft). All GC measured compounds that can not be separated with a PTR-MS (the xylene isomers and ethylbenzene have the same nominal mass) were summed up. PTR-MS data were vertically averaged over 50 m for this plot.

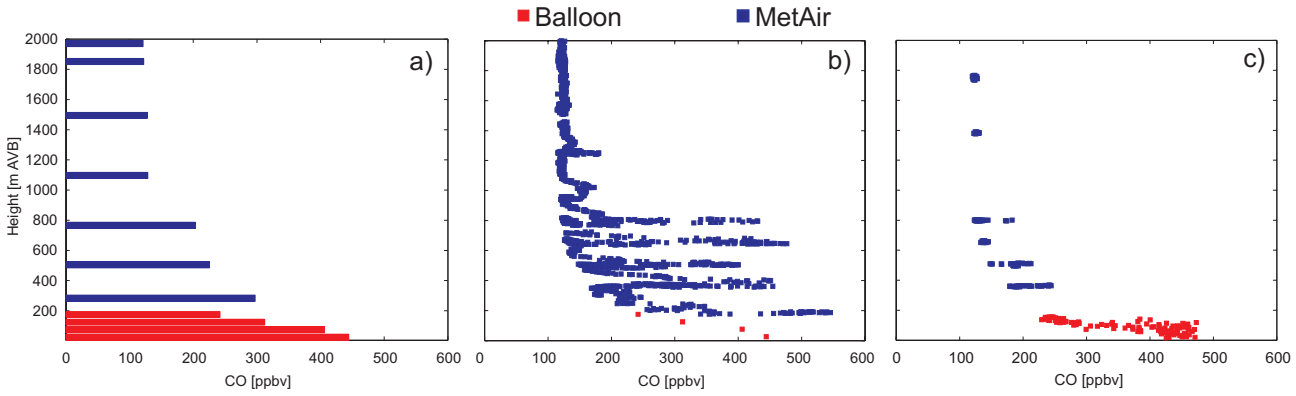

Fig. 7. Vertical profiles of CO obtained from balloon and aircraft measurements. **(a)** shows balloon data (red) averaged over 50 height m and aircraft data averaged over 10 min (blue). **(b)** shows balloon data averaged over 50 height m and 1 Hz CO data. In **(c)** the balloon data are averaged over 10 s and from the 1 Hz aircraft data only those in vicinity (600 m north-south; 6.5 km east-west) of the balloon location are plotted.

In the morning (between 07:55 and 10:15 UTC) the VOC concentration near the ground was about 5 times higher compared to levels above 200 m a.v.b. (Fig. 6a). In Fig. 6d the corresponding relative fraction of the selected compounds is plotted. Aircraft and balloon data are in excellent agreement, both in absolute and relative values. The relative portion of acetone increased with height, due to its compared to the other compounds, longer atmospheric lifetime and therefore higher tropospheric background concentration. The stable valley atmosphere trapped freshly emitted pollutants near the ground and separated them from the chemically aged air aloft.

Around midday (between 10:15 and 11:45 UTC) pollutants were redistributed in the lowest air layers due to the break-up of the surface inversion. There was still a vertical gradient but levels near ground had decreased while levels from 100 up to 500 m a.v.b. had increased. Again, the agreement between the two measurement systems was very reasonable (Fig. 6b and e).

In the afternoon (between 14:15 and 15:15 UTC) a further decrease of VOC VMRs near the ground, and an increase from 200 m up to 1000 m a.v.b. was observed. Compared to the morning values the VMR of some compounds have increased by a factor of two. This is similar to the diurnal variation of VOCs in higher air layers observed in the Swiss Alps during summertime (Prévôt et al., 2000b), where increased VOC values could be found up to 4000 m m.s.l. during undisturbed clear weather conditions. While the relative share of the measured VOCs was similar for balloon and aircraft measurements (Fig. 6f), discrepancies occurred in absolute values, with lower concentrations for the balloon soundings than for the aircraft measurements (Fig. 6c). This difference can be explained by the different spatial footprint areas of the measurements. The balloon soundings provided one vertical profile in the middle of the valley, while the aircraft data represent an average over the whole valley width at one particular altitude. Whereas during morning hours pollutants were more homogeneously distributed, in the afternoon differences between the sunny and the shaded side of the valley occurred. This becomes evident in the high time resolution CO measurements (Fig. 7b and Sect. 3.2.4). When averaging the CO data over 10 min (corresponding to one GC cycle), the profile looks similar to the VOC profile, with lower values for the balloon data than for the aircraft measurements (compare Figs. 7a and 6c between 200–300 m a.v.b.). However, if only CO data in the vicinity to the balloon (600 m north-south and 6.5 km east-west distance) location were used a homogenous profile was found (Fig. 7c).

3.2.3 Vertical particle measurements

In contrast to the balloon and aircraft VOC measurements, for the particle measurements the same instrument, a GRIMM counter, was used on both platforms. Due to lower concentrations aloft a longer time integration was used for the aircraft measurements (1 min compared to 10 s of the balloon). For comparison, the aircraft GRIMM data were selected $\pm$500 m cross valley distance from the balloon (i.e. all data between 500 m northwest and 500 m southeast from the balloon). For the temperature measurement this distance was reduced to $\pm$100 m, due to its 1 Hz resolution. In Fig. 8 the particle mass concentrations from 0.3–1 μm (calculated from the sum of the 5 smallest available GRIMM size bins assuming a density of 2800 kg m^{-3} for the particles; PM1) are plotted together with the potential temperature.

Morning data (see Fig. 8a–b) show stable conditions throughout the whole valley. Beside the surface inversion, further inversion layers appeared at 150 and at 300 m a.v.b. These temperature inversions restricted the vertical air exchange and caused strong gradients in the particle mass

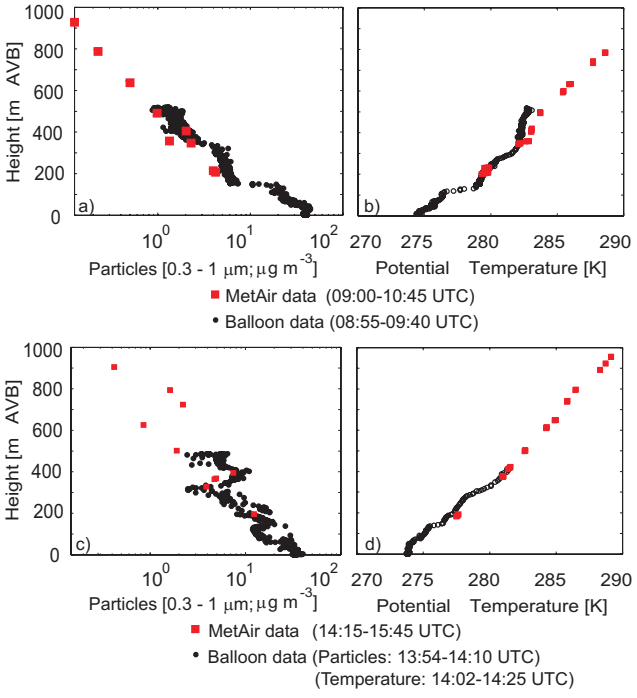

Fig. 8. Comparison of Balloon and MetAir-Dimo particle (GRIMM) and temperature measurements in the morning **(a–b)** and in the afternoon **(c–d)** on 1 February 2006. Particle mass concentrations from 0.3–1 μm (a, c); and potential temperature (c–d) are shown.

concentration. The more polluted air underneath was separated from the cleaner air aloft. Aircraft data are in good agreement with balloon measurements but do not resolve the detailed vertical structure, due to the chosen flight pattern and the lower temporal resolution. The bigger size bins (not plotted here) show the same distribution but were close to or below the detection limit.

In the afternoon the situation was even more complex (see Fig. 8c–d). The potential temperature profile shows the break up of the surface inversion and a mixed layer in the lowermost 80 m a.v.b., which was topped by an inversion layer. In that height a strong decrease in the particle mass concentration occurred. Below the inversion at 150 m a.v.b., which weakened since the morning, an increase in the particle mass concentration was observed. A second and third local maximum in the particle mass concentration occurred at 400 and 750 m a.v.b. This is discussed further in Sect. 3.2.5. Again balloon and aircraft data match very well and the high spatial resolution of the balloon measurements is essential to resolve the detailed structure.

3.2.4 Valley cross section

An even more detailed picture of the spatial distribution of air pollutants in the valley atmosphere was obtained from 1 Hz aircraft in situ measurements. In Fig. 9a–c the 1 Hz CO data from the MetAir-Dimo are plotted together with data from the balloon soundings in the morning, around midday, and in the afternoon of 1 February 2006. Figure 9d–f show the NO_2 distribution, Fig. 9g–i the O_3 distribution. NO_2 and O_3 were not measured on the balloon. In the morning (Fig. 9a) there was a strong gradient due to the low level temperature inversion close to the ground with levels about 4 times lower at 150 m a.v.b. than on the valley floor (for details compare benzene data; Fig. 5a). Already early in the day, the aircraft measurements show horizontal differences below 500 m a.v.b., with CO and NO_2 VMRs being twice as high along the sunny slope of the valley compared to the shaded one. Aloft levels represent the background concentration and no gradients were observed. Around midday (Fig. 9b and e) pollutants near ground were redistributed as described in Sect. 3.2.2. Again, highest CO levels occurred near the sunny slopes. In the afternoon (Fig. 9c and f) the picture gets even more asymmetric. Extended levels of CO and NO_2 were found up to 1300 m a.v.b. and values at 800 m a.v.b. near the sunny slope were comparable with those near the ground. Background levels at the shaded side of the valley were found down to 500 m a.v.b. At 1000 m a.v.b. the CO VMRs were almost four times higher than on the shaded side of the valley. An opposite distribution was found in the O_3 concentration (Fig. 9g–i). Wherever NO_2 was high O_3 was low because of NO titration. The asymmetric distribution was most likely caused by a vertical transport of pollutants via upslope winds. However, this circulation was not directly detected by aircraft wind measurements. This suggests the presence of a very thin upslope wind layer in which pollutants were lifted and from where they were then advected towards the middle of the valley. This horizontal transport underneath strong inversions explains the layer structure discussed in Sect. 3.2.3. The development of the slope wind layer at the sunny side of the valley was favored by snowfree treetops along the sun exposed slope.

3.2.5 In situ particle measurements vs. lidar data

A very detailed picture of the spatial distribution of particles was obtained from the DLR lidar measurements, which give backscatter intensity at 1064 nm. In Fig. 10 lidar measurements are compared with MetAir-Dimo and balloon in situ measurements of particles larger than 0.3 μm in the afternoon of 1 February 2006. The aerosol distribution was strongly asymmetric and small scale structured. In the lowest 200 m a.v.b. a minimum of backscatter intensity was observed in the middle of the valley, with slightly higher values along the shaded slopes up to about 300 m a.v.b. and elevated values along the sunny slope up to 1300 m a.v.b. Here, the aerosol concentration for particles larger than 0.3 μm is almost 150 particles per cm^3. In addition to the polluted slope layer 3 aerosol layers spread out horizontally from the sun-exposed slope towards the valley center. Layers 1 and

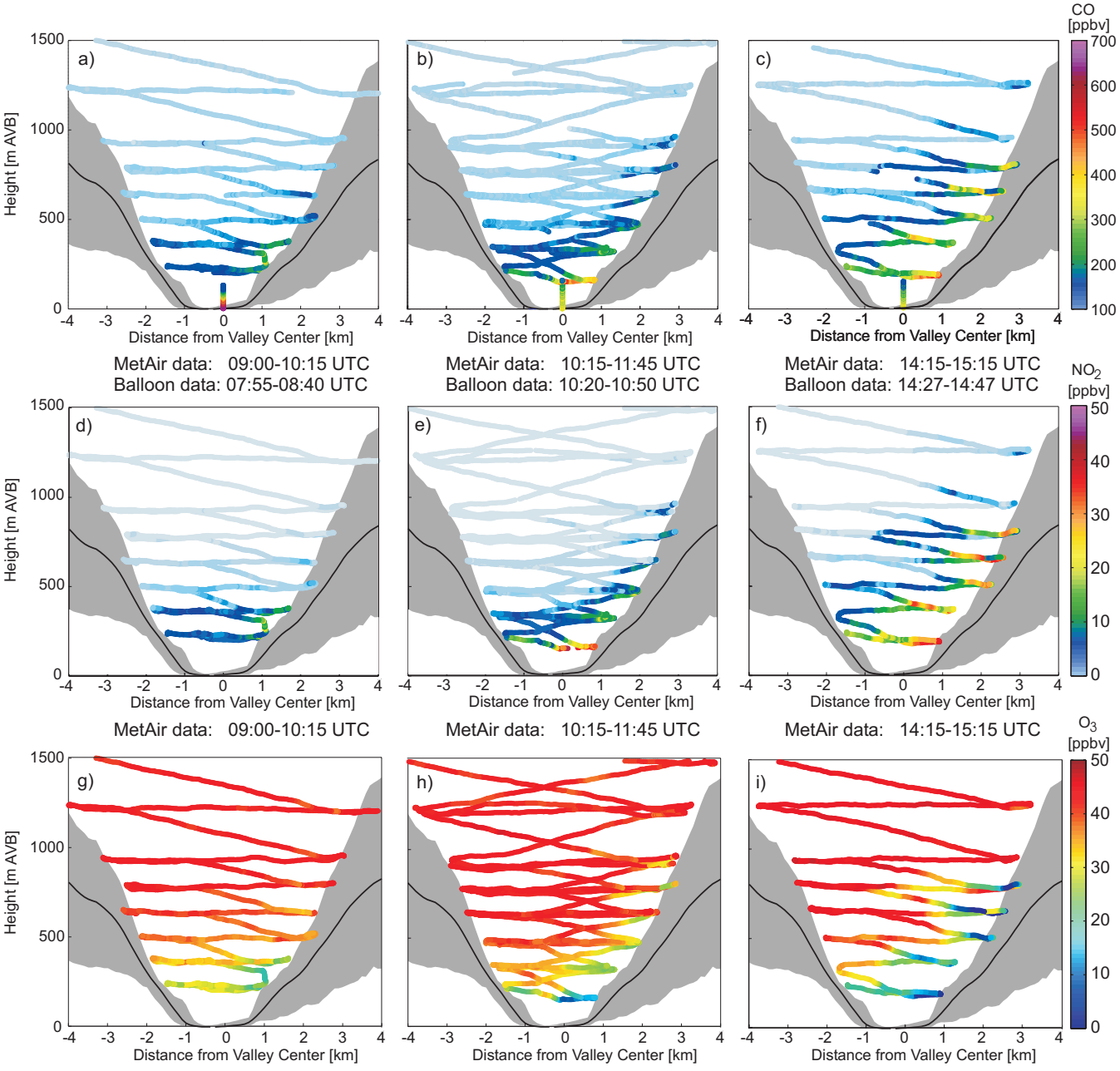

Fig. 9. Vertical transect of CO VMR across the Inn Valley near the town Schwaz in the morning **(a)**, around midday **(b)** and in the afternoon **(c)** on 1 February 2006. **(d–f)** show the NO_2, and **(g–i)** the O_3 distribution for these times. The black line represents the terrain height of the average valley slopes in the 6×20 km box plotted in Fig. 1; the shaded area represents the widest and narrowest part. The view is headed in the valley upward direction i.e. south west.

2 at 400 and 750 m a.v.b., respectively were also detected in particle profile measurements (compare Sect. 3.2.3). Again, a horizontal transport at the height of the inversion layers as proposed by Vergeiner and Dreiseitl (1987) was observed (compare also Fig. 8). The asymmetric distribution in the afternoon was also observed on other days (Gohm et al., 2009). The export of air pollutants from the valley into the free troposphere could not be quantified with this experimental setup but is expected to be small on 1 February 2006, since the vertical transport did not significantly overshoot the main crest and a reverse of the slope wind circulation after sunset partly transported the polluted air back to the valley bottom (Harnisch et al., 2008). However, a significant export of air pollutants might occur during situations with even more active

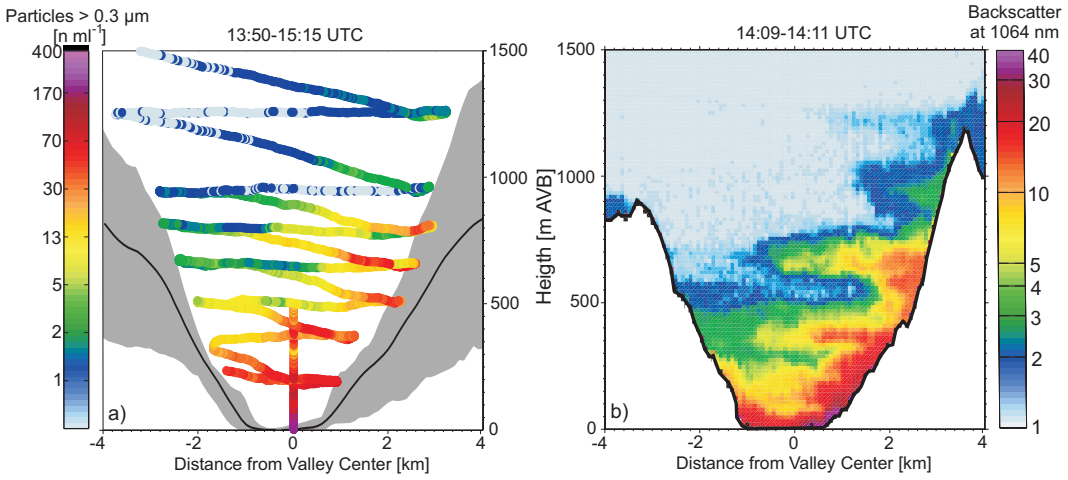

Fig. 10. Vertical transect of MetAir-Dimo and balloon in situ particle measurement **(a)** and DLR remote sensing lidar measurements **(b)** in the afternoon of 1 February 2006. Backscatter intensities at 1064 nm (arbitrary units) and particles larger than 0.3 μm (n ml^{-1}) were measured by TropOLEX-lidar and aircraft-MetOne-laser/balloon GRIMM, respectively. The black line in the left panel represents the terrain height of the average valley slopes in the 6×20 km box plotted in Fig. 1; the shaded area represents the widest and narrowest part. The view is headed in the valley upward direction i.e. south west. In the right panel the black line represents the terrain hight across the DLR transect (see Fig. 1)

slope winds and stronger winds above crest height (Gohm et al., 2009, compare 24 January 2006), via a process described by Henne et al. (2004).

4 Conclusions

The three dimensional distribution of air pollutants was studied in the eastern Inn valley near the town of Schwaz during wintertime 2006. Airborne in situ and remote sensing measurements were conducted in addition to ground based measurements.

Ground based VOC data obtained by a PTR-MS instrument between 14 January and 10 February 2006 showed highest values whenever a prolonged period of fair winter weather led to a stably stratified valley atmosphere with multiple strong inversion layers below which pollutants were trapped and accumulated over days. Under these conditions a diurnal pattern was observed with a daytime minimum due to incident radiation that partly eroded the surface inversion.

Data from tethered balloon soundings gave insight into the diurnal variability of the lowest 180 m a.v.b. A strong surface inversion was responsible for a shallow, strongly polluted layer in the morning. During the day this inversion broke up and pollutants were homogenously distributed within the lowest 100 m a.v.b., with decreased levels near the ground and increased levels further aloft. After sunset air pollutant concentrations started to increase again in the lowermost air layers as the surface inversion developed again.

Aircraft measurements extended the vertical profile from about 150 m a.v.b. up to crest height. Aircraft and balloon data taken in the small overlap of CO and VOC measurements and the broader one for particle and meteorological data were in good agreement. Due to the high temporal resolution of some aircraft measurements not only vertical but also horizontal differences were observed. While in the morning minor horizontal gradients occurred, the distribution got asymmetric in the afternoon, with higher concentration along the sun-exposed slopes up to 1300 m a.v.b. Upward transport was found to take place in a shallow slope wind layer. This flow was observed to split at the height of strong inversion layers and to partially advect the polluted air towards the middle of the valley. This mixing process became most obvious in the lidar data, which provided the best spatial coverage but did not give absolute particle number concentration. Three layers with high backscatter intensities reaching from the sunny slope to the middle of the valley were identified on 1 February 2006. This multiple stratification that was also observed during balloon particle profiling, seems to occur frequently during fair winter weather as it was also observed on other measurement days (e.g. 24 January 2006).

The experiment provided a dataset that covers the entire valley atmosphere in a cross transect. Although data with low temporal resolution provided valuable information on the vertical distribution, fast measurements were essential to understand the complex transport mechanisms in an Alpine valley. Balloon soundings of the lowest part of the atmosphere resolved the strong gradients and the high variability of air pollutants.

The obtained data confirm the great impact of meteorological conditions on air quality in the Inn valley. Strong inversion layers, low wind speeds and recirculation of polluted air via thermally driven winds lead to prolonged periods of high air pollutant levels. Despite the stable stratification of the valley atmosphere, a vertical transport of air pollutants via slope winds reduces their concentration at the bottom of the valley, causes the formation of elevated pollution layers and even exports pollutants from the valley during specific situations in wintertime.

In further work this dataset has been used for the validation of mesoscale transport and particle dispersion models (Lehner and Gohm, 2009) and detailed studies of the mechanism of air pollution transport (Gohm et al., 2009). A comparison between in situ particle and lidar measurements can be found in Harnisch et al. (2008).

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