HIGHWAY EMISSION STUDY WITH A DOAS IN THE INN VALLEY NEAR INNSBRUCK

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ABSTRACT

To study the development of high air pollution episodes in a valley with transit traffic, urban areas and industry a highway emission study was performed in the Inn valley near Innsbruck, Austria. A DOAS with emitter/receiver unit and three retroreflectors was used for this study. One retroreflector was installed at a telephone emitter mast on the other side of the highway (120 m path length) so that the path was about 10 m above highway level. Another retroreflector was set up for a path parallel to the highway and the third retroreflector was used to operate a path perpendicular and away from the highway. The path across the highway was directly above the air quality station Vomp, which is situated only three meters away from the motorway. A first measurement campaign was performed between October 2005 and February 2006.

The concentrations of NO and NO_2 above the highway are clearly dominated by the traffic volume. Higher concentration values were found during week days than during the weekend and in the morning and evening hours respectively. The concentrations above the highway are compared to those measured at the other DOAS paths and at two other locations, i.e. nearby the highway as well as in a distance of about 1 km. This data are investigated regarding the temporal variations of highway emissions (10 times higher during peak hours in the morning and afternoon compared to night hours) and dispersion conditions During synoptically undisturbed winter periods the persistent inversion conditions lead to relatively high air pollutant concentrations from late afternoon until mid-morning. In the afternoon the stable layer is potentially broken up. In this context the influences of the quasi-regular mountain wind system (valley and slope winds) are studied.

Keywords: *Nitrogen oxides, air quality, meteorology, highway emissions.*

1. INTRODUCTION

The dispersion of emissions in a deep valley is strongly reduced due to frequent inversions, low wind speeds compared to flat terrain and a limited mixing volume. Advection of fresh air mainly takes place due to winds parallel to the valley axis (Vergeiner and Dreiseitl, 1987). Winds across the valley axis will only enter the valley and bring fresh air masses down to the valley floor if the thermal stratification of the air within the valley is not too stable. Stable stratification is most likely to occur in clear nights and over a snow cover. In cold winters this can lead to a system of several inversions, one above the next, within a few hundreds meters of height above ground (Emeis et al., 2007). The height of the near-surface layer is essential for the vertical dispersion of air pollutants because it determines and limits the speed and the range of vertical dispersion. This so-called mixing-layer height (MLH) depends heavily on the synoptic weather situation. Due to these specific meteorological phenomena in deep valleys the air pollution can be high. A general description of mountain-specific meteorological features and air quality issues together with a large citation list of relevant literature can be found in Chapters 3 and 4 of Heimann et al. (2007).

Several emission reduction measures were implemented during the last 20 years but due to increasing amounts of heavy duty vehicles and passenger cars the overall air quality in Alpine regions is even worse. The EU air quality thresholds (European Air Quality Framework Directive 96/62/EC and its daughter directives 1999/30/EC and 2000/69/EC) for e.g. PM_{10} and/or NO_2 are too often exceeded. Additionally an ongoing deeper understanding of the health impact of such air pollutants requests new emission standards and the ambient concentration thresholds for air pollutants are continuously redefined. In this light the currently established threshold values for NO_2 as of 2010 seem to be too high because there are new research results about the influence of high NO_2 concentrations upon the mortality rate (Samoli et al., 2006). But also the increasing NO_2/NO ratio in traffic emissions is a reason for high NO_2 concentration levels. The increasing amount of NO_2 is attributed to a growing number of diesel cars, an increased efficiency of diesel engines and new particulate filters (Carslaw, 2005).

A campaign in the lower Inn-valley was designed to determine cross-valley air pollution and meteorological information as well as vertical profiles to determine flow regimes (valley, slope winds), MLH, stability in the boundary layer and emission sources at specific locations. This campaign covered the major part of the winter season 2005/2006. The most important goal for the field campaign was to study the spatial variation and distribution of air pollution induced by inner Alpine traffic within a cross-section along the northern and southern slopes. Consequently the dependence of the observed air pollution patterns on meteorological parameters like wind, stability and MLH as well as on emissions of air pollutants was investigated. Further, the field data are used for the set-up and validation of numerical simulations of air quality.

Mainly the latter objective requires spatially representative measurement data. In areas with low gradients and outside of narrow valleys point measurements may be sufficient. In highly complex terrain path-averaged (or even volume-averaged measurement by scanning with remote sensing techniques) can be advisable. Averaging techniques must be applied to measurement results that will be used as input for models or for comparison with model results. This is necessary if the spatial resolution of the models does not match the spatial representativeness of the measurements.

Consequently, a path-averaging measurement method, a DOAS, was applied. The interpretation of the DOAS measurement results will be presented within this paper. The general set-up of the field measurements is described in section 2. The data from the measurement campaign and interpretation results are presented in section 3. The section 4 is discussion of processes and gives conclusions.

2. METHODOLOGY

The field campaign in the Inn valley was performed between November 2005 and February 2006 and was based on existing monitoring networks. The target area was centred on Schwaz / Vomp (47°20’ N / 11° 41 E / 540 m a.s.l.), where exceedances of nitrogen dioxide (NO_2) and PM_{10} thresholds during winter are frequently observed by the continuously recording monitoring network.

During the campaign a dense network of meteorological and air pollution monitoring sites was operated. In the following sections only those instruments are described, whose results are discussed in this article and which were run permanently throughout the winter.

A routine monitoring network of the regional authority (Land Tyrol, abbreviated LT) exists in the area. Here we use data from the monitoring station Vomp Raststätte in only three meters distance to the A12 motorway. Additional air pollution instrumentation was operated included an open-path DOAS (Differential Optical Absorption Spectroscopy, a long-path air pollution information in different directions). The DOAS used at site 1 contains an analysator (AR 500) an emitter/receiver unit (ER 130) and points to three retroreflectors from OPSIS GmbH. One retroreflector was installed at a telephone emitter mast on the other side of the motorway (120 m path length) so that the path was about 10 m above motorway level (Tr1) and perpendicular across the motorway. This path across the motorway was directly above the air pollution monitoring station Vomp Raststätte. Another retroreflector was set up for a path more or less parallel to the motorway (Tr2) and the third retroreflector was used to operate a path perpendicular to and away from the motorway (Tr3). See Figure 1 for a sketch of the three beams.

Figure 1: Location of DOAS and the LT station vicinity of the motorway

The measurement campaign was started by an intercomparison of the DOAS with in situ measurement devices for NO and NO_2 from 20 until 27 October 2005 at a site in about 2 km distance to the motorway as main source with consequently relatively low concentration levels. At the end of the campaign another comparison was performed at a monitoring site of LT in Innsbruck from 06 until 16 February.

In this valley section the motorway is aligned along the valley axis so that the dominant valley winds are blowing more or less along the motorway. A further discussion of meteorological measurements including the MLH investigations is given in Schäfer et al. (2008).

3. MEASUREMENT RESULTS

The outlined intensive measurements in the lower Inn valley give a detailed picture of the situation due to highway emissions during a winter season. At first the averaged conditions will be described. In the next section the results of the investigation of high air pollution episodes are presented. The characteristics of diurnal variations conclude the findings.

3.1. Average conditions

3.1.1. Weather

From the meteorological and air pollution point of view it is essential to figure out how “typical” the winter 2005 / 2006 was. Therefore background measurements were taken from permanent weather stations of the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) and from air quality stations from the Land Tyrol.

In Table 1 the monthly mean values of the 10 year period 1993 – 2002 are compared to the measurements from the Jenbach station in the lower Inn valley. It reveals two important anomalies: First the unusually low temperatures in January 2006 with the continuation of a persistent (three weeks) high pressure regime with only short intermittent disturbances. This led to unusually cold weather in January, namely in the target area 4.4°C below the average from 1993 – 2002 (-1.0°C). Second, a persistent blanket of snow in the target area Inn valley started at mid November and lasted until the end of the measurement campaign. A cold surface prior to the first snow fall in November is a precondition for this, but also the lack of warm intermittent (foehn) periods afterwards and sufficient snow supply - see the December 2005 precipitation - are important.

Table 1: Comparison of 10 year (1993 – 2002) long term mean values to the winter 2005 / 2006 at the station Jenbach of the Land Tyrol in the lower Inn valley (source: Jahrbücher of ZAMG, www.zamg.ac.at)

Parameter	**November**	**December**	**January**
Mean temperature 2005 / 2006 (°C)	2.9	-1.9	-5.4
10 yr mean temperature (°C)	4.0	-0.2	-1.0
Days with snow deck 2005 / 2006	12	31	31
10 yr mean days with snow deck	5.8	16.7	17.1
Precipitation 2005 / 2006 (mm)	35	120	59
10 yr mean precipitation (mm)	94	62	60

3.1.2. Air pollution and exceedances of threshold values

Table 2 compares the concentration characteristics of the winter period 2005 / 2006 to the mean state of the period 2000 – 2004 (for PM_{10}: 2001 – 2004) at the permanent LT station Vomp Raststätte. The NO_2 concentrations in November (+18.2 %) and December (+21.2 %) are higher than the five year mean NO_2. This enhancement can be caused by higher NO_2 emissions because a shift towards a higher share of NO_2 to NO took place – the NO concentrations during the winter 2005 / 2006 differ by -6.1 % in November and -12.4 % in December to the five year mean. PM_{10} is a bit but not significantly higher than during the period 2001 – 2004. These numbers are in qualitative agreement with the weather conditions, with early snow cover but no particularly outstanding persistent weather pattern. So from the air pollution point of view November and December 2005 can be seen as typical months.

The threshold exceedances at the valley floor are basically related to a stable layering of the valley atmosphere during nearly all the time. The stable layering of the valley atmosphere was interrupted during time periods of some days in November and December due to air mass exchanges. In January 2006 on the other hand the dominant high pressure regime periods led to particularly high pollution burden. While all thresholds have been exceeded more often than in previous years, the frequent exceedances of the half hourly mean NO_2 threshold (HMW) has not been observed in previous winters.

Table 2: Relevant air pollution parameters including the number of threshold exceedances for the period 2000 to 2004 (PM10 2001 to 2005) to winter values 2005/06 at the permanent LT station Vomp Raststätte. The thresholds are: NO2 half hourly mean (HMW) 200 µg/m3 (from 2010 on), 18 exceedances per year; PM10 daily mean 50 µg/m3, 18 exceedances per year

Parameter	**Nov.**	**Dec.**	**Jan.**
Mean NO_2, 2005/06 [µg/m^3]	70.8	87.9	126.0
5 yr mean NO_2 [µg/m^3]	59.9	72.5	83.8
Number of threshold exceedances NO_2 HMW, 2005/06	3	0	126
5 yr mean number of threshold exceedances NO_2 HMW	0	0.6	1
Mean PM_{10}, 2005/06 [µg/m^3]	35	43	66
4 yr mean PM_{10} [µg/m^3]	33.3	39.7	42.9
Number of threshold exceedances PM_{10} daily mean, 2005/06	2	10	23
4 yr mean number of threshold exceedances PM_{10} daily mean	4	9.3	10.8

3.1.3. Spatial representativeness of measurements

The application of in situ (point) measurements or path-averaged measurements (e.g. DOAS) depends on the expected local concentration gradients and the purpose of the measurements. In areas with low gradients or flat terrain point measurements may be sufficient. In highly complex terrain a denser measurement network or path-averaged (or even volume-averaged measurement by scanning with remote sensing techniques) is advisable. Averaging techniques must be applied to measurement results that will be used as input for models or for comparison with model results. This is necessary if the spatial resolution of the models does not match the spatial representativeness of the measurements.

In Figure 2 the results of path-averaged NO and NO_2 concentration measurements along the DOAS path perpendicular away from the motorway (Tr3) are plotted against the DOAS path measurements across the motorway (Tr1). The results show a slight decrease of NO_2 concentrations from the path across the motorway in comparison to the path away from the motorway (correlation coefficient R^2 about 80 % and a gradient of about 0.85) but a dominant decrease of NO (correlation coefficient R^2 about 50 % and a gradient of about 0.6). Generally, the concentrations are clearly dominated by the traffic volume and therefore are the highest at the motorway. The decrease of concentrations with distance to motorway is attributed to diffusion mainly. However, NO_2 is not only emitted but rapidly formed from NO too so that the decrease with distance from the source is much less than for NO.

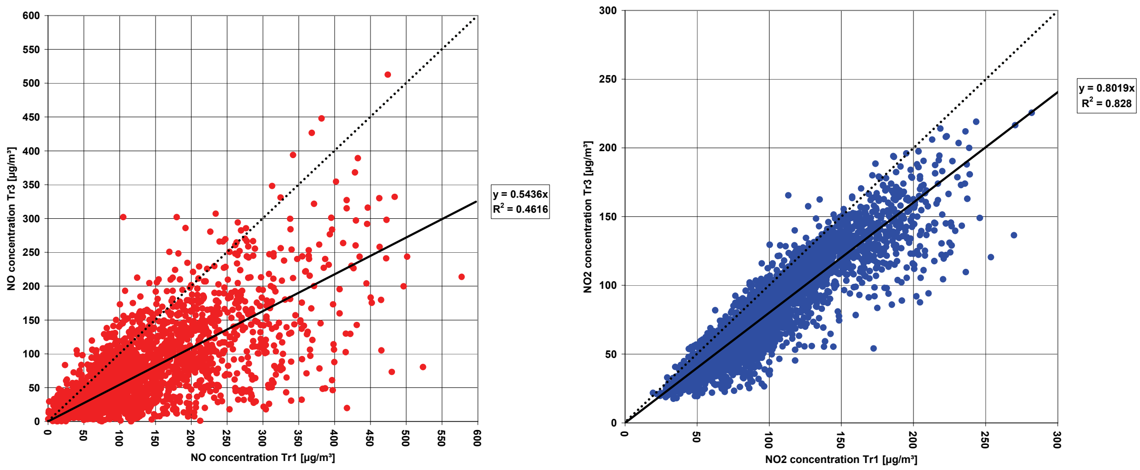

Figure 2: NO (above) and NO_2 (below) concentration measurements as half-hourly mean values during the whole campaign at the at the DOAS path perpendicular to and away from the motorway (Tr3) and at the DOAS path perpendicular across the motorway (Tr1) with a 1 : 1 line (dotted) and a linear regression curve together with the correlation coefficient R^2

The DOAS measurements reveal a mean NO_2/NO concentration ratio of about 1/3 as calculated on the data basis of Figure 2. This resembles typical near-emission conditions, while the NO_2/NO_x ratio with 1/4 is rather high and above the ratios usually assumed in air pollution simulations. Moreover, this is also a little bit higher than values of 17 % reported for London roadside traffic in 2003 (Carslaw, 2005). Carslaw (2005) found the NO_2/NO_x ratio in 1997 as 5 – 6 %. The measured NO_2/NO_x ratio in this work may be caused by the high amount of heavy duty vehicles at this transit-route as well as the very high amount of about 75 % diesel vehicles within the passenger car fleet in Austria, but also some chemical transformation in the field close to the emission source may already have taken place.

There is some evidence that diesel engine emissions have shifted towards more NO_2 (Carslaw 2005). The tendency that the overall NO_2/NO_x emission ratio has increased over the last few years is also seen in the NO_2/NO_x concentration ratio at the LT station Vomp Raststätte in three meters distance to the motorway A12 between 1997 and 2006 with an overall higher ratio since 2002 (Schäfer et al., 2008). Notably this site is located right beneath the DOAS path Tr1. The mean value during the campaign is 0.2 which is a little bit lower than that of the DOAS data. Again this may be attributed to the different distances to the road traffic (10 m minimum for DOAS as compared to 3 m for LT).

3.2. Episodes

The atmospheric conditions during the campaign were characterised by a stable layering of the valley atmosphere during nearly all the time. The stable layering was interrupted during the time periods 29 – 30 November 2005, 03 – 07 December 2005 and 12 – 14 December 2005 connected to foehn events (29 November) or air mass exchange due to frontal passages (03 and 05 December cold front from west, 01 December warm air from the south). January was dominated by a persitent high pressure regime that caused two high pollution episodes.

Besides the overall emission of pollutants the dispersion conditions are certainly crucial for the resultant air quality (see e.g. Schäfer et al., 2005; Schäfer et al., 2006; Wiegner et al., 2006)). In anticyclonic weak wind conditions as analysed here, the vertical extent of the polluted layer, the mixing layer, is the most important parameter. Very low MLH around 100 m are observed during the two high pressure periods with weak winds from 06 until 15 January 2006 and from 24 until 4 Feb 2006, shortly intermitted on 26/27 January 2006 (Schäfer et al., 2008)

The latter demonstrated that under such weather conditions air pollutants can accumulate in the valley air. The two high pressure situations with weak winds both times led to increases in the mean CO concentration from 400 to 1200 µg/m^3 (factor 3) and in the mean PM_{10} concentration from 20 to 70 µg/m^3 (factor 3.5). For PM_{10} the two periods show 21 exceedances of the limit value of 50 µg/m^3, this is more than half the number of presently permitted exceedances per year, and it is three times the number of exceedances per year permitted from 2010 on.

The detailed situation in the small-scale region around the motorway A12 is more complex. Here the MLH is not the dominating influence upon the air pollutant concentrations. This can be concluded from Figure 3 showing the temporal variations of NO concentrations from the three DOAS paths (Tr1, Tr2 and Tr3, figure 1)) together with wind speed. Similar analysis is shown in Figure 4 regarding NO_2 concentrations. These days are selected as one of the most polluted ones during sunny and stable weather conditions with no larger-scale winds. Only the daily valley winds with wind speeds less than 1 m/s occurred.

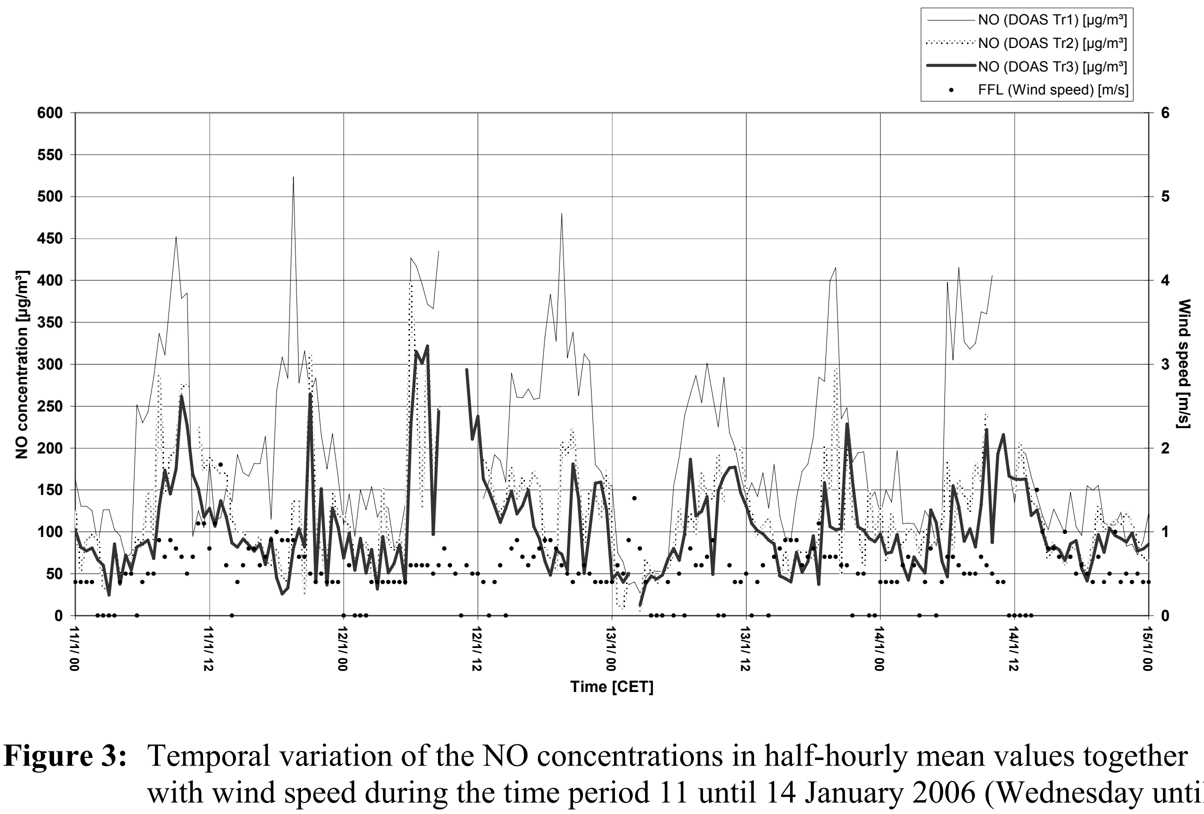

Figure 3: Temporal variation of the NO concentrations in half-hourly mean values together with wind speed during the time period 11 until 14 January 2006 (Wednesday until Saturday) from the DOAS path perpendicular across the motorway (Tr1), the DOAS path parallel at the motorway (Tr2) and the DOAS path perpendicular to and away from the motorway (Tr3)

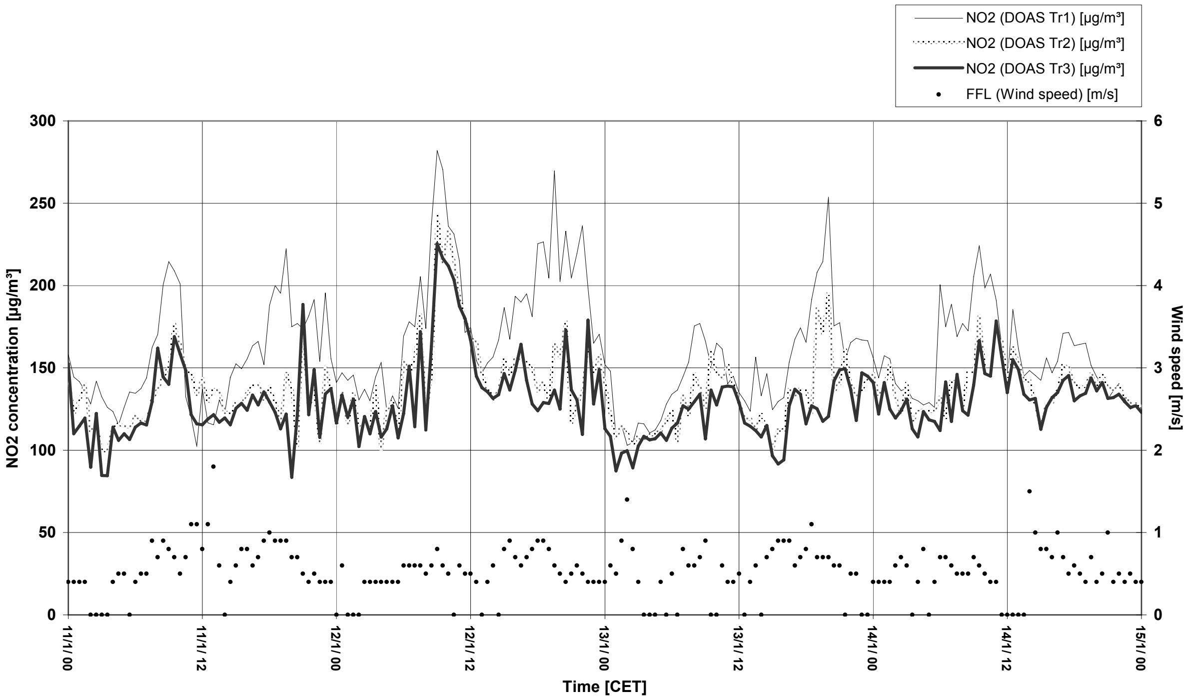

Figure 4: Temporal variation of the NO_2 concentrations in half-hourly mean values together with wind speed during the time period 11 until 14 January 2006 (Wednesday until Saturday) from the DOAS path perpendicular across the motorway (Tr1), the DOAS path parallel at the motorway (Tr2) and the DOAS path perpendicular to and away from the motorway (Tr3)

The concentration data show a clear and repeatable diurnal variation. Peak concentrations are observable during the morning and afternoon hours due to peaks in the motorway traffic. The similar daily marches are obvious when comparing the vehicle counts at the motorway near the position of the DOAS measurement during the time period 11 until 14 January 2006. The NO and NO_2 concentrations across the motorway are larger in comparison to the concentrations nearby the motorway. The minimum of the concentrations during the early afternoon hours is caused by the lower traffic volume as well as by the relatively good mixing of the 100 to 200 m deep surface layer due to solar heating. A clear weekly trend is apparent.

In general, the daily differences in air pollution at a given location are due to temporal variations of the relevant emission sources (e.g. motorway emissions are 10 times higher during peak hours in the morning and afternoon compared to night hours) and meteorological conditions (stability, valley and slope winds). Further, the position of the location (distance to the relevant sources as well as height difference) is clearly important.

There was no significant correlation of the air pollutants NO_x, PM_{10} and CO with temperature, wind speed, wind direction and precipitation during the whole winter period (Wittig et al., 2007).

4. DISCUSSIONS AND CONCLUSIONS

NO_2 threshold hourly values of 200 µg/m^3 were exceeded near the motorway during some hours of each day within the time periods 09 – 22 January and 25 January – 02 February 2006. Analysis demonstrates not only the dominating influence of traffic emissions (for nitrogen oxides in general and for PM_{10} in the vicinity of the motorway) but also the role the weather conditions to the overall air quality situation within the valley. Inside of valleys complicated layered structures may evolve. The determination of up to five lifted inversions is made for the first time and presented together with wind fields from SODAR measurements in Emeis et al. (2007). The impact of these phenomena on air quality needs further investigations and consideration of further locations along the valley.

Close to the motorway the air pollutant concentrations are in general highest. But there are also periods without such a spatial gradient of concentration i.e. the concentrations nearby the motorway are higher than across the motorway. This may be caused by secondary thermal circulations like slope winds inducing winds across the motorway. More detailed analysis of the inherent effects on air quality is in process in which context a dedicated measurement campaing has been performed during winter 2007 – 2008.

However, even the considerable effort within the measurement campaigns addressed in this study can only hardly give a comprehensive three-dimensional picture. Using the available data for input and validation of air pollution modelling might foster progress with that respect.

Further information about the project work can be obtained from Heimann et al. (2007) and from the ALPNAP web site http://www.alpnap.org/.

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