SCIAMACHY tropospheric NO$_2$ over the Alpine region and importance of pixel surface pressure for the column retrieval

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Abstract

This study evaluates NO$_2$ vertical tropospheric column densities (VTCs) retrieved from measurements of the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) above Switzerland and the Alpine region. A clear relationship between a spatially and temporally highly resolved Swiss NO$_x$ emission inventory and SCIAMACHY NO$_2$ columns under anticyclonic meteorological conditions supports the general ability of SCIAMACHY to detect sources of NO$_x$ pollution in Switzerland. Summertime NO$_x$ lifetime estimates derived from this relation agree reasonably with values from literature. A further evaluation of the SCIAMACHY data is based on the comparison with NO$_2$ VTCs retrieved from the Global Ozone Monitoring Experiment (GOME). The annual mean NO$_2$ VTCs calculated from both data sets clearly show the advantage of the improved SCIAMACHY pixel resolution for qualitatively estimating the NO$_x$ pollution distribution in a small country such as Switzerland. However, a more quantitative comparison of seasonally averaged NO$_2$ VTCs gives evidence for SCIAMACHY NO$_2$ VTCs being systematically underestimated over the Swiss Plateau during winter. A possible explanation for this problem (not reported in earlier literature) is the use of inaccurate satellite pixel surface pressures derived from coarsely resolved global models in the retrieval. The marked topography in the Alpine region can lead to deviations of several hundred meters between the assumed and the real mean surface height over a pixel. A sensitivity study based on selected clear sky SCIAMACHY NO$_2$ VTCs over the Swiss Plateau and two fixed a priori NO$_2$ profile shapes indicates that inaccurate pixel surface pressures have a considerable effect of up to 40% on the retrieved NO$_2$ columns. For retrievals in the UV-visible spectral range with a decreasing sensitivity towards the earth’s surface, this effect is of major importance when the NO$_2$ resides close to the ground, which occurs most pronounced during the winter season.
1 Introduction

Nitrogen dioxide is an important air pollutant. It can affect human health and plays a major role in the production of tropospheric ozone (Seinfeld and Pandis, 1998; Finlayson-Pitts and Pitts, 2000). The bulk of NO\textsubscript{x} is emitted by the high-temperature combustion of fossil fuel in the highly industrialised continental regions in the northern mid-latitudes. Important natural sources are biomass burning and the microbial production in soils of the non-polar continental surface. At higher altitudes in the troposphere NO\textsubscript{x} is directly injected into the troposphere by lightning and aircraft emissions (IPCC, 2001).

NO\textsubscript{x} is primarily emitted as NO which oxidises to NO\textsubscript{2} within a few minutes. The NO\textsubscript{2} concentration is affected by the partitioning of NO\textsubscript{x} into NO and NO\textsubscript{2} which depends on the abundance of ozone and reactive organic compounds as well as on solar light intensity and temperature, and which therefore changes with altitude and with time of day in the troposphere. NO\textsubscript{x} is removed from the troposphere mainly by conversion to nitric acid (HNO\textsubscript{3}). During daytime, HNO\textsubscript{3} is formed through the reaction of NO\textsubscript{2} with the OH radical. At night, a two step reaction mechanism forms nitrogen pentoxide (N\textsubscript{2}O\textsubscript{5}) which further reacts on surfaces and aerosol to HNO\textsubscript{3} (Dentener and Crutzen, 1993). HNO\textsubscript{3} is finally removed by dry and wet deposition (Kramm et al., 1995). The resulting NO\textsubscript{x} lifetime is highly variable with an annual average boundary layer lifetime of about one day (Warneck, 2000). However, due to the higher summertime abundance of OH, much shorter lifetimes of a few hours prevail during photochemically active summer days. In this study, we infer NO\textsubscript{x} lifetimes from the combination of SCIAMACHY NO\textsubscript{2} VTCs with a high-quality NO\textsubscript{x} emission inventory to check the reliability of SCIAMACHY data. Generally, NO\textsubscript{x} lifetimes are essential to determine emissions from space-borne data (e.g. Martin et al., 2003).

Although the NO\textsubscript{x} (≡ NO + NO\textsubscript{2}) concentration in Switzerland decreased during the last 15 years the Swiss NO\textsubscript{2} annual ambient air quality standard of 30 µgm\textsuperscript{-3} (≈16 ppb) is still exceeded in polluted areas (FOEN, 2005). Monitoring of nitrogen oxides there-
fore plays an important role for the assessment of reduction measures. Complementary to ground-based monitoring networks which provide detailed information of local near-surface air pollution, space-borne instruments such as the Global Ozone Monitoring Experiment (GOME) (Burrows et al., 1999) and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) (Bovensmann et al., 1999) provide area-wide data of NO$_2$ vertical tropospheric column densities (VTCs) with global coverage within a few days. The improved resolution of space-borne NO$_2$ VTCs (GOME pixel size: 320×40 km$^2$, SCIAMACHY: 60×30 km$^2$, Ozone Monitoring Instrument (OMI): 13×24 km$^2$) increasingly allows to detect NO$_2$ pollution features on a regional scale. However, these space-borne data and their complex retrieval are emerging techniques and validation is needed. Schaub et al. (2006) summarised different validation campaigns of GOME and SCIAMACHY NO$_2$ data and carried out a detailed comparison of GOME NO$_2$ VTCs retrieved by KNMI (Royal Dutch Meteorological Institute) and BIRA/IASB (Belgian Institute for Space Aeronomy) with NO$_2$ profiles derived from ground-based in situ measurements at different altitudes in the Alpine region.

In this paper we evaluate SCIAMACHY NO$_2$ VTCs over Switzerland and the Alpine region with regard to their use for air quality monitoring and modelling on a regional scale. For the first time, the focus is on the size of a small country such as Switzerland. The above mentioned GOME validation approach presented in Schaub et al. (2006) can not be adopted for SCIAMACHY here. In that approach in situ measurements from a number of widely separated stations located at different altitudes in Switzerland and Southern Germany have been used to estimate vertical NO$_2$ columns. The size of SCIAMACHY pixels, however, is too small to justify the combination of measurements that are spatially separated (the latter are only used for a qualitative comparison in this study). We therefore first perform a qualitative evaluation by relating SCIAMACHY NO$_2$ VTCs to a spatially and temporally highly resolved NO$_x$ emission inventory available for Switzerland, showing the general ability of SCIAMACHY data to detect the NO$_2$ pollution distribution on the scale of a small country. This comparison is then used to
infer seasonal mean daytime NO\textsubscript{x} lifetimes that are subsequently compared to values from literature.

Further, the SCIAMACHY NO\textsubscript{2} VTCs are evaluated by a comparison with GOME NO\textsubscript{2} columns over Switzerland and a qualitative comparison with the seasonal variation of NO\textsubscript{2} columns deduced from ground-based in situ measurements carried out at different altitudes. Evidence is found for SCIAMACHY NO\textsubscript{2} VTCs being systematically underestimated over the Swiss Plateau during the winter season. We will present a plausible reason contributing to this problem which is related to an inadequate representation of the surface topography in the NO\textsubscript{2} retrieval. This problem potentially affects any region on the globe with a marked topography and becomes increasingly important with improving pixel resolution when the retrieval is based on coarsely resolved input parameters, e.g. derived from global models.

2 Data

2.1 KNMI/BIRA GOME and SCIAMACHY tropospheric NO\textsubscript{2} observations

Nadir measurements from GOME on board ESA’s ERS-2 satellite and from SCIAMACHY on board ESA’s Envisat satellite are used in the present study. The GOME and SCIAMACHY observations are obtained at approximately 10:30 and 10:00 local time and individual pixels cover an area of 320×40 km\textsuperscript{2} and 60×30 km\textsuperscript{2}, respectively. The GOME and SCIAMACHY measurement principles are described in Burrows et al. (1999) and Bovensmann et al. (1999), respectively. The NO\textsubscript{2} VTCs studied in this work are the product of a collaboration between KNMI and BIRA/IASB. Both GOME and SCIAMACHY NO\textsubscript{2} data are publicly available on a day-by-day basis via ESA’s TEMIS project (Tropospheric Emission Monitoring Internet Service, www.temis.nl).

The first retrieval step is based on the Differential Optical Absorption Spectroscopy (DOAS) technique (Vandaele et al., 2005): a modelled spectrum is fitted to the measured reflectance spectrum in the spectral window from 426.3–451.3 nm. The modelled
spectrum accounts for spectral absorption features of NO$_2$, O$_3$, O$_2$-O$_2$ and H$_2$O. Scat-
ering by clouds, aerosols, air molecules and the surface is described by a low-order polynomial. This first retrieval step results in the slant column density (SCD) of NO$_2$, which can be interpreted as the column integral of absorbing NO$_2$ molecules along the effective photon path from the sun through the atmosphere to the spectrometer.

The second retrieval step separates the stratospheric contribution from the total SCD (Boersma et al., 2004). For KNMI retrievals this is achieved with a data-assimilation approach using the global TM4 chemistry transport model (CTM) (Dentener et al., 2003). The tropospheric SCD (SCD$_{trop}$) results from the subtraction of the stratospheric estimate from the total SCD.

In the third retrieval step, the SCD$_{trop}$ is converted into a VTC by applying the tropospheric air mass factor (AMF$_{trop}$). Following Palmer et al. (2001) and Boersma et al. (2004), the retrieved SCIAMACHY NO$_2$ VTC ($X_{SCIA}$) is calculated as

$$X_{SCIA} = \frac{N_{trop}}{M_{trop}(x_a, b)} = \frac{N_{trop} \cdot \sum_l x_{a,l}}{\sum_l m_l(b) \cdot x_{a,l}}$$

(1)

where $N_{trop}$ denotes the tropospheric slant column density, $M_{trop}$ the tropospheric air mass factor, $x_{a,l}$ the layer specific subcolumns from the a priori profile $x_a$, and $m_l$ the altitude-dependent scattering weights. The latter are calculated with the Doubling Adding KNMI (DAK) radiative transfer model (Stammes, 2001) and best estimates for forward model parameters $b$, describing surface albedo, cloud parameters (fraction, height) and pixel surface pressure. The a priori NO$_2$ profiles for every location and all times are obtained from the TM4 CTM. Cloud fraction and height are taken from the Fast Retrieval Scheme for Clouds from the Oxygen A band (FRESCO) algorithm (Koelemeijer et al., 2001). Since the TM4 model is driven by meteorological data of the European Centre for Medium-Range Weather Forecasts (ECMWF) the surface pressures in TM4 are taken from the ECMWF model on the 2°×3° resolution of the TM4 model. The surface pressure for an individual satellite pixel is linearly interpolated to the pixel location (hereafter ECMWF/TM4 surface pressure).
Errors of GOME tropospheric NO$_2$ retrievals have extensively been discussed in Boersma et al. (2004). Based on this work, errors for both GOME and SCIAMACHY NO$_2$ VTCs are estimated on a pixel-to-pixel basis and additionally provided in the TEMIS data sets. Error propagation studies have shown SCIAMACHY NO$_2$ VTC errors to be similar to GOME errors. However, these studies have not included the effect of surface pressure. The present work will show that, over a complex topography, this parameter can be expected to lead to larger errors for the higher resolved SCIAMACHY data.

2.2 Swiss NO$_x$ emissions

Swiss NO$_x$ emissions mount up to 33.2 kt N/year with traffic, industry, agriculture/forestry and residential activities contributing 58%, 24%, 12% and 6%, respectively, for the year 2000 (FOEN, 2005). The present study employs an hourly resolved NO$_x$ emission inventory for Switzerland available on a 3×3 km$^2$ grid. It combines the following basic data sets:

– Road traffic emissions of NO$_x$ for the reference year 2000 with a spatial resolution of 250 m were prepared by the consulting company INFRAS, Switzerland. An average diurnal variation is provided as well. Long-term trends of annual totals recently published in Keller and Zbinden (2004) were used to interpolate the emissions between 2000 and 2005.

– NO$_x$ emissions from residential activities, heating, industry, off-road traffic and agriculture/forestry for the reference year 2000 with a spatial resolution of 200 m and accounting for seasonal variations were prepared by the Meteotest company, Switzerland. Data sets for other years of interest were calculated on the basis of trends provided by the Swiss Federal Office for the Environment (FOEN, 1995).

Additional information on the emission inventory is summarised in Keller et al. (2005). Total emission inventories are usually based on a large number of input variables.
Each of these parameters – and, thus, also the resulting total emission inventory – are affected by uncertainties. Their assessment is a challenging task which needs further assumptions (e.g. Kühlwein and Friedrich, 2000). For the 3×3 km\(^2\) Swiss NO\(_x\) emission inventory an accuracy of ±15–20% is estimated in FOEN (1995). Kühlwein (2004) further pointed out increasing errors in emission inventories for increasing spatial resolutions. Thus, due to integration of the 3×3 km\(^2\) resolved emission data over the SCIAMACHY pixel size of 60×30 km\(^2\) in the present work, the above given error of 20% is considered as a reasonable upper limit, which will be assumed in this study.

3 Methods

3.1 Comparison of SCIAMACHY NO\(_2\) VTCs with a high resolution emission inventory and estimation of mean NO\(_x\) lifetimes

SCIAMACHY NO\(_2\) VTCs located entirely within the Swiss boundaries are related to the high resolution Swiss NO\(_x\) emission inventory presented in Sect. 2.2. NO\(_x\) emission rates between 9:00 and 10:00 (alternatively between 6:00 and 10:00) UTC are summed up over the individual pixel footprints.

First, the qualitative relation between NO\(_2\) VTCs and collocated NO\(_x\) emissions is discussed (Sect. 4.1.1). Then, neglecting any transport into or out of the column enclosed by the satellite pixel, seasonal NO\(_x\) lifetimes are estimated simply as the ratio between the observed column (in N-equivalents: g(N) km\(^{-2}\)) and the emission rate (in g(N) km\(^{-2}\) hr\(^{-1}\)). In order to account for inaccuracies in both the observed columns and the emission rates, the lifetime estimates are based on the calculation of a weighted orthogonal regression (York, 1966). SCIAMACHY NO\(_2\) VTC 1-sigma error estimates are taken from the TEMIS data file where error estimates are provided for each individual pixel (Boersma et al., 2004). For the NO\(_x\) emission rates added up over the individual SCIAMACHY pixels an error of 20% is assumed (Sect. 2.2).

SCIAMACHY NO\(_2\) VTCs are converted to NO\(_x\) VTCs by employing representative...
values for the seasonal mean NO$_2$/NO ratio. The latter depends on the abundance of ozone and reactive organic compounds as well as on solar light intensity and temperature. Thus, the ratio varies both spatially (horizontally and vertically) and seasonally. For the United States and based on 106 NO$_x$ monitoring data sets measured at different distances from the predominant emission sources, Chu and Meyer (1991) recommended a national default value for the NO$_2$/NO ratio of 3. NO$_x$ measurements operated since 1999 at a rural site at the edge of the Swiss Plateau (Rigi, 47° 04' N, 8° 28' E, 1030 m asl) using a standard chemiluminescence detector for the measurement of NO and a photolytic converter for the selective conversion of NO$_2$ to NO indicates a seasonal variation of monthly mean NO$_2$/NO ratios of between 1.6 (January) and 4.0 (August) for anticyclonic clear sky conditions and a time window between 10:00 and 12:00 UTC (Steinbacher, personal communication). Because the location of the measurement site on a mountain ridge roughly 500 m above the Swiss Plateau can lead to a decoupling from the near-ground Swiss Plateau air masses during winter and the NO$_2$/NO ratio is decreasing with height (e.g. Nakamura et al., 2003), we suppose that the wintertime ratio given above is rather low. Thus, for the present work, we assume seasonal mean NO$_2$/NO ratios of 3, 4, 3 and 2 for the spring (MAM), summer (JJA), fall (SON) and winter (DJF) season, respectively. Due to the bulk of NO$_x$ residing near the ground in polluted regions we further assume these NO$_2$/NO ratios to be representative for the whole tropospheric column.

The NO$_x$ emissions taking place at the location of the column are considered as the main flux of NO$_x$ into the column which, in an equilibrium state, is balanced by the chemical and physical (i.e. deposition) losses in the column. Neglecting transport and assuming first order losses only and steady state, we can write

$$\frac{dM}{dt} = E - k \cdot M = 0$$

(2)

and hence

$$M = \frac{1}{k} \cdot E = \tau \cdot E$$

(3)
with $M$ the amount of NO$_x$ in the column, $E$ the NO$_x$ emission rate (both converted to N-equivalents) and $\tau$ the lifetime. The basic assumption of steady state has also been made by Leue et al. (2001), Beirle et al. (2003) and Kunhikrishnan et al. (2004). It disregards the horizontal NO$_x$ transport into and out of the column. This transport, however, leads to a smearing effect that is depending on the distribution of the NO$_x$ emissions, the prevailing meteorology (e.g. wind speed and direction) and the chemical lifetime. For mapping isoprene emissions from space-borne data, Palmer et al. (2003) determined typical smearing length scales. For NO$_x$ lifetimes in the order of hours to one day, this length scale is $\sim$100 km (Martin et al., 2003). This might be problematic regarding the SCIAMACHY pixel size of 60×30 km$^2$. However, anticyclonic clear sky conditions (which are the present focus) are known to be associated with low wind speeds, i.e. rather stagnant air, and fast photochemistry, which reduces the importance of horizontal transport in the boundary layer.

Significant transport over larger distances (e.g. from highly polluted regions in adjacent countries to Switzerland as described in Schaub et al. (2005) for a frontal passage) is considered to be unimportant for the anticyclonic days investigated here.

3.2 Sensitivity of SCIAMACHY NO$_2$ VTCs to varying pixel surface pressure

Following Sect. 2.1 the mean pixel surface pressure is one of the parameters used in the column retrieval. For both GOME and SCIAMACHY pixels with centre coordinates within the region of interest ROI$_{CH}$ (Fig. 1) covering the whole Switzerland (6° E – 10.5° E, 45.75° N – 47.75° N) the deviations between the ECMWF/TM4 mean surface pressures used in the retrieval ($p_{surf}$) and the corresponding effective mean surface pressures ($p_{eff}$) are determined and compared to each other. $p_{eff}$ over the pixel extension is determined from the aLMo (Alpine Model, the MeteoSwiss numerical weather prediction model) topography which better represents the real topography as the aLMo resolution of 7×7 km$^2$ is much finer than the TM4 model grid (2°×3°, $\sim$220×240 km$^2$).

An estimate of the effect of inaccurate pixel surface pressure used in the retrieval is carried out for a subset of clear sky SCIAMACHY pixels. The AMFs$_{trop}$ and NO$_2$ VTCs
are first calculated for $p_{\text{surf}}$ as in the retrieval and then recalculated for the better surface pressure estimate $p_{\text{eff}}$. The criteria for the pixel subset are i) anticyclonic clear sky meteorological conditions (Alpine Weather Statistics; MeteoSwiss, 1985), ii) pixel cloud fraction $\leq 0.1$, and iii) a small standard deviation <65 m of the aLMo $7^\circ7$ km$^2$ grid cell heights enclosed within a SCIAMACHY pixel, the latter ensuring that the reprocessing is done for pixels over a flat region in the vicinity of the Alps rather than over the complex Alpine topography. The resulting SCIAMACHY pixels are located above the north-eastern Swiss Plateau (Fig. 2).

The sensitivity test is based on two characteristic (and fixed) CTM a priori NO$_2$ profile shapes (Fig. 3). In a first profile (A), the bulk of the NO$_2$ is residing near the ground. Such profile shapes are expected to occur over polluted regions and most pronounced during the winter months when vertical mixing is generally weak or non-existing. A second profile (B) shows a much lower NO$_2$ abundance near the ground and can be expected to represent either a remote profile or a summertime profile shape resulting from vertical mixing. As shown in Fig. 3 the use of a different surface pressure scales the profile vertically. The other retrieval (or forward model) parameters including surface albedo, cloud fraction and height, solar zenith angle and so on are kept constant.

4 Results and discussion

4.1 SCIAMACHY NO$_2$ VTCs and NO$_x$ emissions in Switzerland

4.1.1 Qualitative comparison

Figure 4a shows the comparison between SCIAMACHY NO$_2$ VTCs and the corresponding NO$_x$ emission rates for anticyclonic clear sky (pixel cloud fraction $\leq 0.1$) meteorological conditions together with a simple linear regression (n=243). Anticyclonic conditions are deduced from the Alpine Weather Statistics (MeteoSwiss, 1985). Although (i) the present comparison does not include any vertical profile information, (ii)
the smearing effect is not taken into account and (iii) different meteorological conditions can be expected to lead to different relations between the NO₂ VTCs and the corresponding emissions (due to different NO₂/NO ratios and different NOₓ lifetimes), the resulting correlation coefficient of R=0.72 indicates that the collocated emissions explain more than 50% of the variance in the NO₂ VTCs. Thus, SCIAMACHY seems to observe the sources of air pollution from space although its sensitivity is strongly decreasing towards the earth’s surface.

Figure 4b shows the correlation coefficient vs. the upper limit for the SCIAMACHY cloud fraction; i.e., SCIAMACHY pixels with cloud fractions lower than or equal to this limit have been taken into account. The comparison is carried out for all meteorological conditions as well as for anticyclonic conditions only. We suppose that the better correlations under anticyclonic conditions are due to low wind speeds and rather homogeneous air masses often prevailing during such conditions. Thus, the NO₂ columns are more directly related to the collocated NOₓ emissions. Note that the stable values of the correlation coefficients for higher upper cloud fraction limits in Fig. 4b are mainly due to the small number of cases that are additionally taken into account (denoted by the number of data points additionally shown in Fig. 4). The decreasing correlation coefficients with increasing cloud fraction limits can be understood from clouds screening the NO₂ below. In such situations, the retrieved column is strongly affected by the a priori assumption on the vertical NO₂ distribution (Schaub et al., 2006).

4.1.2 Near-ground NOₓ lifetime under anticyclonic clear sky conditions

For estimating seasonal NOₓ lifetimes we define clear sky conditions to prevail for SCIAMACHY pixels with a cloud fraction ≤ 0.2 (still yielding a correlation coefficient R > 0.5 in Fig. 4b). In this way the analysis can be based on a larger data set than available for a limit of 0.1. SCIAMACHY NO₂ VTCs are converted to NOₓ VTCs as described in Sect. 3.1.

Figure 5 shows for each season the relationship between individual SCIAMACHY NOₓ columns located entirely within the Swiss boundaries and the corresponding NOₓ
emission rates between 9:00 and 10:00 UTC. Additionally, the weighted orthogonal regression output is given. The relatively small intercepts suggest that under anticyclonic conditions the background NO\textsubscript{x} plays a rather marginal role and the SCIAMACHY observations are dominated by the local NO\textsubscript{x} emissions. From the slopes the corresponding column-average NO\textsubscript{x} lifetimes for the spring, summer, fall and winter season are calculated as $5.00 \pm 0.87$, $3.36 \pm 0.55$, $5.27 \pm 0.60$ and $11.21 \pm 2.13$ h, respectively. An additional estimate is calculated using a different time window between 6:00 and 10:00 UTC for summing up the NO\textsubscript{x} emission rates. The resulting NO\textsubscript{x} lifetimes are summarised in Table 1 and Fig. 6. The alternative time window used to derive the NO\textsubscript{x} emission rates (6:00–10:00 UTC instead of 9:00–10:00 UTC) has only a very small impact on the results even though NO\textsubscript{x} emission peaks due to morning traffic are included in this case.

Besides the NO\textsubscript{x} lifetimes estimated here, Fig. 6 denotes additional summertime lifetime estimates from literature:

- from measurements in power plant plumes: 5 h (Ryerson et al., 1998), 2.8 and 4.2 h (Nunnermacker et al., 2000) and 6.4 h (Sillman, 2000),
- from measurements in urban plumes: Boston: 5.5 h (Spicer, 1982), Nashville: 2.0 h (Nunnermacker et al., 2000), Zurich: 3.2 h (Dommen et al., 1999),
- from GOME NO\textsubscript{2} VTCs above Germany: 6.0 h (Beirle et al., 2003) and
- zonal mean in the boundary layer (0–2 km) from the GEOS-CHEM CTM: 3.0 h (Martin et al., 2003).

For spring, Martin et al. (2003) calculated a mid-latitude NO\textsubscript{x} lifetime from the GEOS-CHEM model of 8 h. For the winter season, Martin et al. (2003) and Beirle et al. (2003) reported on NO\textsubscript{x} lifetimes of 19 and 21 h, respectively.

Additional NO\textsubscript{x} lifetimes are estimated here for the main NO\textsubscript{x} loss mechanism which is the oxidation of NO\textsubscript{2} with OH to HNO\textsubscript{3}. These estimates are based on typical Swiss
Plateau values of pressure (960 hPa) and temperature and on OH concentrations taken from the BERLIOZ and the SLOPE96 campaigns as well as from long-term OH measurements carried out at Hohenpeissenberg. The BERLIOZ campaign took place at a distance of 50 km from Berlin; the SLOPE96 campaign focused on polluted air masses travelling from the city of Freiburg to the Schauinsland Mountain (south-western Germany); the Hohenpeissenberg station is located in Southern Germany at an altitude of 985 m asl. From a pollution point of view, all regions are similar to the Swiss Plateau and surroundings. For an assumed temperature of 298 K and based on OH concentrations taken from the BERLIOZ and the SLOPE96 campaigns with noontime values of \((4–8) \times 10^6 \text{ cm}^{-3}\) (Volz-Thomas et al., 2003; Mihelcic et al., 2003) and \((7–10) \times 10^6 \text{ cm}^{-3}\) (Volz-Thomas and Kolahgar, 2000), respectively, the resulting mean daytime NO\(_x\) lifetimes in summer are estimated to be 4.6 h and 3.0 h. Seasonally averaged 9:00–10:00 UTC OH concentrations determined from clear sky OH measurements at Hohenpeissenberg carried out between 1999 and 2005 (Rohrer and Berresheim, 2006; Berresheim, unpublished data, 2006) are used together with assumed temperatures for the summer, spring/fall and winter seasons of 298 K, 288 K and 278 K, respectively, to estimate NO\(_x\) lifetimes of 6.1, 3.9, 8.2 and 21.0 h for the MAM, JJA, SON and DJF seasons, respectively (Fig. 6).

The comparison of our NO\(_x\) lifetimes with estimates from literature shows that the summertime values obtained here are reasonable. Our estimate is near the lower end of the range of published values, but it is noteworthy that our values of 3.4 and 3.2 h (depending on the emission time window) perfectly agree with another study carried out in Switzerland by Dommen et al. (1999) yielding a lifetime of 3.2 h (Fig. 6). For spring and fall only few published values are available for comparison (Fig. 6). However, our result is still similar to these values for spring. For the fall season our estimate can only be compared to a lifetime value deduced from Hohenpeissenberg OH measurements and a conclusive statement can not be given. A stronger disagreement is found for winter where our mean NO\(_x\) lifetime values are nearly a factor of two smaller than the literature values shown in Fig. 6.
Our wintertime estimate could differ (i) due to the focus on a rather polluted region (in contrast to the zonal mean value given by Martin et al. (2003)), (ii) due to additional wintertime NO$_x$ loss mechanisms besides the oxidation to HNO$_3$ (which was the only loss considered by Martin et al. (2003) and for calculating the NO$_x$ lifetime from the Hohenpeissenberg OH data) or (iii) due to our approach focusing directly on the location of the NO$_x$ emissions (in contrast to Beirle et al. (2003) who estimated the NO$_x$ lifetime from GOME NO$_2$ VTCs downwind of emitting regions in Germany). However, based on the fact that the very similar wintertime NO$_x$ lifetime estimates given by Martin et al. (2003) and Beirle et al. (2003) and calculated from the Hohenpeissenberg OH measurements have been derived with independent methods, one could also argue that our wintertime NO$_x$ lifetime estimate (and, possibly, less pronounced also the spring and fall estimates) are too low. The disregard of the horizontal transport (smearing effect) could partly explain our lower values. However, due to the focus on anticyclonic clear sky conditions with enhanced photochemical activity and generally low wind speeds the importance of the smearing effect decreases and we suppose that other reasons could additionally play a role.

In our approach, a higher lifetime is associated with a steeper slope in Fig. 5, i.e. higher space-borne NO$_2$ VTCs over highly emitting regions. We therefore explore whether, most pronounced in winter, SCIAMACHY retrievals might underestimate the NO$_2$ VTCs over the polluted Swiss Plateau.

4.2 Comparing GOME and SCIAMACHY NO$_2$ VTCs over the Swiss Plateau

For a qualitative comparison of clear sky (pixel cloud fraction $\leq$0.1) GOME and SCIAMACHY NO$_2$ VTCs, the data are mapped onto a fine 0.125°×0.125° grid covering Switzerland and surroundings. For each cell a mean VTC is computed by averaging over all SCIAMACHY (2003–2005) (Fig. 7a) or GOME (1996–2003) (Fig. 7b) pixels covering the given cell. In contrast to the picture derived from the GOME columns, the higher resolved SCIAMACHY data clearly indicate individual population/industry centres such as the areas of Zurich and Basel as well as the Alpine chain and the Jura
Mountains.

For a more quantitative comparison seasonally averaged GOME and SCIAMACHY NO₂ VTCs are calculated from all clear sky pixels with centre coordinates located within the region ROIₜₚ (Fig. 1) covering the polluted regions of the Swiss Plateau (7° E – 9.5° E, 47° N – 47.75° N) only. Similar to Schaub et al. (2006), the ROIₜₚ excludes the complex Alpine terrain as far as possible. In Fig. 8a the resulting SCIAMACHY NO₂ VTCs are on average higher than the GOME columns in spring, summer and autumn. This can be understood because the extended GOME pixels always include less polluted regions outside of the Swiss Plateau. Surprisingly, the wintertime SCIAMACHY NO₂ VTC values are lower than the ones from GOME.

Figure 8b shows the same comparison with the seasonal mean columns normalised to the spring (MAM) season. Additionally, seasonally averaged NO₂ columns estimated from NO₂ data measured in situ between January 1997 and June 2003 at 15 ground-based sites at different altitudes in Switzerland and Southern Germany are shown. The elevated sites are assumed to detect NO₂ concentrations that are approximately representative for the appropriate height in the (free) troposphere over flat terrain. These measurements, together with boundary layer in situ measurements and an assumed mixing ratio of 0.02 ppb at 8 km, are used to construct NO₂ profiles. The latter are subsequently integrated to tropospheric NO₂ columns. Details on the data set and method of deriving vertical NO₂ profiles/columns can be found in Schaub et al. (2006). For the present study, the ground-based in situ data set is restricted to all clear sky days as indicated by the sunshine and high fog parameters from the Alpine Weather Statistics (MeteoSwiss, 1985) and the columns reach down to an assumed mean Swiss Plateau height of 450 m asl. The normalised seasonal variation of the ground-based data again indicates the highest NO₂ columns over the Swiss Plateau to occur during the winter season, which is better reflected by the GOME columns and expected due to the higher NOₓ lifetime in winter. Moreover, the seasonal variation of space-borne NO₂ VTCs over industrialised regions with a distinct wintertime maximum has also been described by Petritoli et al. (2004), Richter et al. (2005), van der A et al. (2006) and Uno et al. (2006).
Although in Fig. 8a SCIAMACHY and GOME have been sampled differently in space and time and, thus, a perfect agreement is not expected, it seems likely that SCIAMACHY values over the Swiss Plateau are underestimated in this season. A possible reason for this is discussed in the following section.

4.3 Inaccurate pixel surface pressure as a possible reason for too low wintertime SCIAMACHY NO₂ VTC retrievals over the Swiss Plateau

4.3.1 GOME and SCIAMACHY pixel surface pressures

Richter and Burrows (2002) and Boersma et al. (2004) discussed errors of GOME NO₂ VTC retrievals which in principle also apply to SCIAMACHY retrievals. They reported on the following retrieval parameters inducing inaccuracies in the AMF calculation, which is the major error source for tropospheric retrievals over polluted regions: the a priori NO₂ profile shape, the surface albedo, cloud characteristics (fraction and height) and aerosol concentration. Here, we propose an additional source for systematic errors of SCIAMACHY NO₂ VTCs over the Swiss Plateau: the mean surface pressure (or height) assumed for the retrieval of an individual pixel. This influence has not been investigated in the literature so far. Note that for large parts of the world, the mean surface pressures taken from global models are accurate enough. Over the Alpine topography, however, mean surface pressures taken from a coarsely resolved model could be problematic, particularly for higher resolved satellite pixels. Figure 9 illustrates the situation over the Alpine region: in a coarsely resolved model (e.g. global CTM used for the retrieval), the topography is averaged over extended grid elements, typically leading to an underestimation of the effective elevation of mountains and an overestimation of the effective ground height in the vicinity of the mountains. Due to the different horizontal extensions of GOME and SCIAMACHY pixels, it can be expected that the mean model heights calculated over the smaller SCIAMACHY pixels show a larger deviation from the averaged real surface heights than the mean model heights calculated over the extension of a GOME pixel.
For each GOME (1996–2003) and SCIAMACHY (2003–2005) pixel above ROI\textsubscript{CH} (Fig. 1) the original mean pixel surface pressure $p_{\text{surf}}$ derived from ECMWF/TM4 and $p_{\text{eff}}$ determined from the aLMo topography (Sect. 3.2) are converted to m asl based on pressure profiles derived from measurements at different altitudes in Switzerland. Figure 10 shows the resulting histogram distribution of $\Delta_{\text{surf}} = h_{\text{surf}} - h_{\text{eff}}$ for the GOME (Fig. 10a) and SCIAMACHY (Fig. 10b) pixels and Fig. 11 indicates the pixel centre locations and corresponding values of $\Delta_{\text{surf}}$. The following conclusions can be drawn:

– Due to the smoothed topography in ECMWF/TM4, the surface heights of the GOME and SCIAMACHY pixels are underestimated over the Alps and overestimated over the Swiss Plateau (Fig. 11).

– Lower minimum and higher maximum for $\Delta_{\text{surf}}$ are found for SCIAMACHY pixels (Figs. 10 and 11). This can be expected due to the smaller pixel size of SCIAMACHY compared to GOME (Fig. 9).

The above points confirm our expectation that certain parameters, such as the mean pixel surface pressure, can become increasingly inaccurate for better resolved satellite data if the spatial resolution of the forward model parameters is not improved accordingly. In the following section, the effect of an inaccurate pixel surface pressure on the resulting NO\textsubscript{2} VTC is investigated for selected SCIAMACHY columns.

4.3.2 Effect of inaccurate pixel surface pressure on SCIAMACHY retrievals

Figure 12 illustrates the situation over the Swiss Plateau where $h_{\text{surf}}>h_{\text{eff}}$ (for the Alps the situation is reversed with $h_{\text{surf}}<h_{\text{eff}}$). Following Eq. (1) (Sect. 2.1) and the formulation for the AMF\textsubscript{trop} given there, the following systematic errors due to inaccurate surface heights are expected:

– For positive $\Delta_{\text{surf}}$ ($h_{\text{surf}}>h_{\text{eff}}$; e.g. over the Swiss Plateau, Figs. 11 and 12) the near-ground NO\textsubscript{2} pollution is in reality located at a lower level than assumed in the
data retrieval. The retrieval therefore associates the high near-ground pollution with a too high sensitivity. This leads to an overestimated AMF\textsubscript{trop} and, thus, to an underestimated NO\textsubscript{2} VTC.

– For negative $\Delta_{\text{surf}}$ ($h_{\text{surf}}<h_{\text{eff}}$, e.g. over the Alps, Fig. 11) we expect a tendency towards overestimation of the NO\textsubscript{2} VTCs.

The effect of inaccurate pixel surface pressures is investigated following the method described in Sect. 3.2. Clear sky SCIAMACHY NO\textsubscript{2} VTCs are selected over the north-eastern Swiss Plateau with a smooth topography (Fig. 2). Table 2 presents an overview over the SCIAMACHY pixel parameters and the (re-)processed AMF$s_{\text{trop}}$. The comparison of the surface pressures $p_{\text{surf}}$ and $p_{\text{eff}}$ shows that in the region of the north-eastern Swiss Plateau the surface pressures differ by about 50 hPa, which corresponds to ~450 m.

The mean relative change in the AMF$s_{\text{trop}}$ due to the changing pixel surface pressure is $-27.2\pm1.3\%$ and $-11.7\pm1.8\%$ for the profile shapes A and B (Fig. 3), respectively. The mean relative change in the resulting NO\textsubscript{2} VTCs is $+37.5\pm2.4\%$ and $+13.3\pm2.4\%$, respectively. Obviously, the changes in the AMF$s_{\text{trop}}$ and the NO\textsubscript{2} VTCs due to changes in the pixel surface pressure are strongly dependent on the NO\textsubscript{2} profile shape. Given the distinctly different shapes A and B, the 13–38% NO\textsubscript{2} VTC error range is a reasonable first estimate of the effect of errors in the pixel surface pressure over a non-trivial topography.

The present sensitivity study is a first-order estimate of the effect of changing pixel surface pressure for a limited subset of SCIAMACHY pixels and based on assumed a priori profile shapes. Depending on the NO\textsubscript{x} emissions taking place at the pixel location, photochemical activity and prevailing meteorological conditions, real NO\textsubscript{2} profile shapes can differ from the shapes A and B used here. Nevertheless, we suggest that inaccurate pixel surface pressures used for the NO\textsubscript{2} retrieval over regions with a marked topography can have a considerable effect on the resulting columns. For retrievals in the UV-visible spectral range with a significant decrease of the sensitivity
towards the earth’s surface, this effect is of major importance when the NO$_2$ resides close to the ground. This situation is most pronounced in winter. Thus, the tendency for underestimated wintertime SCIAMACHY NO$_2$ VTCs over the Swiss Plateau described earlier could at least partly be explained by inaccuracies in the mean pixel surface pressure.

For GOME NO$_2$ VTCs over heavily polluted regions (NO$_2$ VTC$>1.0\times10^{15}$ molec cm$^{-2}$), Boersma et al. (2004) estimated mean AMF$_{trop}$ uncertainties of 15%, 2%, 15% and 9% due to inaccuracies in the cloud fraction, the cloud top height, the surface albedo and the a priori NO$_2$ profile shape, respectively. Even though GOME uncertainties can not directly be transferred to SCIAMACHY retrievals, the orders of magnitude let us assume that the effect of an inaccurate pixel surface pressure on the AMF$_{trop}$ of 12–27% is of equal importance as other types of errors for tropospheric retrievals over regions with a marked topography such as Switzerland.

5 Summary and conclusions

This study has evaluated SCIAMACHY NO$_2$ VTCs above Switzerland and the Alpine region. The clear relationship between a spatially and temporally highly resolved Swiss NO$_x$ emission inventory and SCIAMACHY NO$_2$ columns under anticyclonic meteorological conditions has demonstrated the ability of SCIAMACHY to detect the main NO$_x$ pollution features in Switzerland. The decreasing correlation between the two quantities when taking into account cloudy pixels indicates that SCIAMACHY is less likely to accurately detect sources of air pollution in cloudy situations. From the relation between the SCIAMACHY data and the NO$_x$ emission inventory, seasonal NO$_x$ lifetime estimates have been derived. Summertime NO$_x$ lifetimes have been found to be 3.2–3.4 h. These values agree well with lifetime estimates from literature. The plausibility of the NO$_x$ lifetimes estimated for winter is difficult to assess because of the lack of such data in literature. The values found from two studies and calculated here based on
OH concentration data are not necessarily representative for the study region. Nevertheless, an underestimation of the wintertime NO$_x$ lifetime based on the SCIAMACHY measurements can not be ruled out.

A comparison of SCIAMACHY and GOME NO$_2$ VTCs has shown the improvement of better resolved space-borne data with regard to monitoring the NO$_2$ pollution distribution on a regional scale. However, the quantitative comparison of seasonally averaged SCIAMACHY and GOME NO$_2$ VTCs provides evidence for SCIAMACHY NO$_2$ VTCs tending to systematically underestimate the tropospheric NO$_2$ columns over the Swiss Plateau during winter. This is further supported by the seasonal variation of NO$_2$ measured at ground-based in situ sites that is better reflected in the GOME columns.

A possible explanation for underestimated SCIAMACHY NO$_2$ VTCs over the Swiss Plateau is the use of inaccurate satellite pixel surface pressures derived from coarsely resolved global models in the retrieval. It has been found that the marked topography in the Alpine region can lead to deviations of several hundred meters between the assumed and the real mean surface height over a pixel, particularly pronounced for the smaller sized SCIAMACHY pixels. The resulting effect has been estimated based on selected clear sky SCIAMACHY NO$_2$ VTCs over the Swiss Plateau and two fixed a priori NO$_2$ profile shapes. An effect in the 10–40% range has been found for different profile shapes. Although real NO$_2$ profile shapes can differ from the fixed profiles used for the sensitivity study, the result suggests that inaccurate pixel surface pressures have a considerable effect on the NO$_2$ column retrieval.

In general, for the air pollution monitoring on a regional scale, higher resolved space-borne data are strongly required and very useful. SCIAMACHY NO$_2$ VTCs have shown to be sensitive to the near-ground NO$_2$ pollution in Switzerland. However, we further conclude from this study that in order to fully exploit the potential of such data, the retrieval should be done on a scale that better fits the satellite pixel size. This is of increasing importance with regard to the decreasing pixel sizes from 320×40 km$^2$ (GOME) to 60×30 km$^2$ (SCIAMACHY) to 13×24 km$^2$ (OMI).

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(FOEN). For providing information on ground-based NO\textsubscript{2} measurements in Switzerland we acknowledge the Swiss National Air Pollution Monitoring Network (NABEL) and M. Steinbacher. Furthermore we thank I. DeSmedt and M. Van Roozendael (BIRA/IASB) and H. Eskes and R. van der A (KNMI) for their work on making available the TEMIS GOME and SCIAMACHY NO\textsubscript{2} data set used in this study.

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Table 1. Seasonal NO$_x$ lifetime estimates based on a weighted orthogonal regression for two different time windows for averaging the emission rates over the SCIAMACHY pixels. The standard deviations are given by the standard deviations of the slopes of the regression lines.

<table>
<thead>
<tr>
<th>Emission rates (time window)</th>
<th>$\tau_{NO_x}$ (hrs) MAM ($\pm$ std. dev.)</th>
<th>$\tau_{NO_x}$ (hrs) JJA ($\pm$ std. dev.)</th>
<th>$\tau_{NO_x}$ (hrs) SON ($\pm$ std. dev.)</th>
<th>$\tau_{NO_x}$ (hrs) DJF ($\pm$ std. dev.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9–10 UTC</td>
<td>5.00 ($\pm$ 0.87)</td>
<td>3.36 ($\pm$ 0.55)</td>
<td>5.27 ($\pm$ 0.60)</td>
<td>11.21 ($\pm$ 2.13)</td>
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<tr>
<td>6–10 UTC</td>
<td>4.90 ($\pm$ 0.86)</td>
<td>3.22 ($\pm$ 0.53)</td>
<td>5.23 ($\pm$ 0.59)</td>
<td>11.53 ($\pm$ 2.19)</td>
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</table>
Table 2. Date, orbit/pixel number, cloud fraction, mean pixel specific ECMWF/TM4 surface pressure $p_{\text{surf}}$, mean pixel specific aLMo surface pressure $p_{\text{eff}}$, AMF$_{\text{trop}}$ based on $p_{\text{surf}}$ and AMF$_{\text{trop}}$ based on $p_{\text{eff}}$ for the selected SCIAMACHY pixels. Further denoted are the resulting relative changes in both the AMFs$_{\text{trop}}$ and the NO$_2$ VTCs.

<table>
<thead>
<tr>
<th>Date</th>
<th>Orbit, pixel number</th>
<th>Cloud fraction</th>
<th>$p_{\text{surf}}$ from ECMWF/TM4aLMo [hPa]</th>
<th>$p_{\text{eff}}$ from aLMo [hPa]</th>
<th>AMF$<em>{\text{trop}}$ calc. for $p</em>{\text{surf}}$</th>
<th>AMF$<em>{\text{trop}}$ calc. for $p</em>{\text{eff}}$</th>
<th>rel. change AMF$_{\text{trop}}$ [%]</th>
<th>rel. change NO$_2$ VTC [%]</th>
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<tr>
<td>10 Mar 04</td>
<td>7, 1117</td>
<td>0.024</td>
<td>912.22</td>
<td>964.22</td>
<td>1.023</td>
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<td>22 Jan 05</td>
<td>6, 574</td>
<td>0.011</td>
<td>903.92</td>
<td>956.62</td>
<td>1.315</td>
<td>0.941</td>
<td>–28.4</td>
<td>+ 39.7</td>
</tr>
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<td>22 Jan 05</td>
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<td>0.033</td>
<td>911.71</td>
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<td>1.359</td>
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<td>+ 38.4</td>
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<td>17 Nov 05</td>
<td>8, 731</td>
<td>0.008</td>
<td>899.13</td>
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<td>0.074</td>
<td>919.30</td>
<td>970.80</td>
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<td>912.22</td>
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<td>941.34</td>
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<td>1.004</td>
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<td>959.25</td>
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<td>03 Jul 05</td>
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<td>0.801</td>
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<td>+ 11.7</td>
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</table>
Fig. 1. Regions of interest used in this study covering the whole Switzerland (6° E–10.5° E, 45.75° N–47.75° N, ROI$_{CH}$) and the polluted Swiss Plateau (7° E–9.5° E, 47° N–47.75° N, ROI$_{SP}$). (Topographic map of Switzerland: © 2005 swisstopo).
Fig. 2. Topographic map of Switzerland (© 2005 swisstopo) with the location of the SCIAMACHY pixels used for the pixel surface pressure sensitivity calculation.
Fig. 3. CTM a priori NO$_2$ profiles A (poor vertical mixing/polluted) and B (strong vertical mixing/remote) given as layer-specific sub columns. The black profiles are associated with the ECMWF/TM4 surface pressure at the location of the SCIAMACHY pixel. The red profiles are reaching down to the effective surface pressure calculated from the aLMo model with a $7 \times 7$ km$^2$ resolution. For the examples shown here, surface pressures are taken from 10 March 2004 (profile A) and from 21 July 2001 (profile B).
Fig. 4. Comparison between SCIAMACHY NO₂ VTCs (from 2003–2005) and collocated NOₓ emission rates for pixels located entirely within the Swiss boundaries and anticyclonic clear sky meteorological conditions (pixel cloud fraction ≤ 0.1, n=243) (a). Correlation coefficients of the present comparison for different upper limits of cloud fraction (b).
Fig. 5. Clear sky (cloud fraction ≤ 0.2) SCIAMACHY NO$_x$ VTCs located entirely within the Swiss boundaries vs. NO$_x$ emission rates (both given in N-equivalents). NO$_2$ VTCs are converted to NO$_x$ VTCs using assumed values for the seasonal mean NO$_2$/NO ratios. The resulting NO$_x$ VTCs are compared to NO$_x$ emission rates enclosed within the individual pixels for the four seasons spring (a), summer (b), fall (c) and winter (d). The examples shown here are based on NO$_x$ emission rates taking place between 9:00 and 10:00 UTC. Additionally, the orthogonal regression calculation output (based on data errors as described in Sect. 3.1) is given (see also Table 1).
Fig. 6. Seasonal NO\textsubscript{x} lifetimes (and standard deviations) over the Swiss Plateau under anticyclonic clear sky conditions estimated in this study. Results from other studies are shown for comparison. These data have been deduced from campaigns in the U.S. (Spicer, 1982; Ryerson et al., 1998; Nunnermacker et al., 2000; Silliman, 2000) and in the Swiss Plateau (Dommen et al., 1999), from GOME NO\textsubscript{2} VTCs over Germany (Beirle et al., 2003) and from the GEOSCHEM model (Martin et al., 2003). Additionally, mean NO\textsubscript{x} lifetimes against oxidation to HNO\textsubscript{3} are calculated for (i) 960 hPa and 298 K with OH concentrations of (4–8)×10\textsuperscript{6} cm\textsuperscript{-3} measured during the BERLIOZ campaign (Volz-Thomas et al., 2003; Mihelcic et al., 2003) and of (7–10)×10\textsuperscript{6} cm\textsuperscript{-3} measured during the SLOPE96 campaign (Volz-Thomas and Kolahgar, 2000) as well as for (ii) seasonally averaged OH concentrations measured by Rohrer and Berresheim (2006) with 960 hPa and assumed temperatures for the summer, spring/fall and winter seasons of 298 K, 288 K and 278 K, respectively.
Fig. 7. Mean clear sky (satellite pixel cloud fraction ≤ 0.1) NO$_2$ tropospheric columns over the Central Alps and Switzerland deduced from GOME (1996–2003) (a) and SCIAMACHY (2003–2005) (b) retrievals. In contrast to the GOME picture, specific features such as the Alpine chain, the Jura Mountains, the Swiss Plateau and the areas of Greater Zurich and Basel clearly show up in the SCIAMACHY data.
Fig. 8. Seasonal mean and median NO$_2$ VTCs from GOME and SCIAMACHY over the ROI$_{SP}$ (Fig. 1) for clear sky conditions (cloud fraction $\leq 0.1$). For the four seasons MAM, JJA, SON and DJF, SCIAMACHY and GOME contributed with 76, 175, 129 and 86 and 52, 95, 33 and 7 NO$_2$ VTCs, respectively (a). Seasonal mean and median NO$_2$ columns from GOME, SCIAMACHY and derived from ground-based in situ NO$_2$ measurements normalised to the spring (MAM) season. The ground-based in situ columns were calculated following the method and data set described in Schaub et al. (2006) and for a Swiss Plateau ground height of 450 m asl. For the four seasons MAM, JJA, SON and DJF, 139, 165, 69 and 78 columns contribute to the seasonal values (b).
Fig. 9. A simplified illustration of the problem arising for highly resolved satellite pixels over a marked topography when retrieved with coarsely resolved input parameters. The red and blue lines denote the averaged real surface height at the location of individual SCIAMACHY and GOME pixels, respectively. Further, the real topography and the topography given in a coarsely resolved global model are indicated. Over the large GOME pixel extension, the mean height given by a coarsely resolved model better approximates the averaged real surface height than for the smaller SCIAMACHY pixels.
Fig. 10. Histogram distribution of the differences between pixel surface heights used in the retrieval and effective surface heights averaged over the pixels (Δsurf) for all GOME (1996–2003) (a) and SCIAMACHY (2003–2005) (b) pixels with centre coordinates above ROI_{CH} (Fig. 1).
Fig. 11. Differences between pixel surface heights used in the retrieval and effective surface heights averaged over the respective pixels ($\Delta$surf) for all GOME (1996–2003) (a) and SCIAMACHY (2003–2005) (b) pixels located over ROI$_{CH}$ (Fig. 1). The $\Delta$surf value for a pixel is indicated at its corresponding centre coordinate.
Fig. 12. Possible reason for too low SCIAMACHY NO$_2$ VTCs over the polluted Swiss Plateau: retrieval errors due to inaccurate pixel surface heights in regions with a marked topography.