SO_2 column and plume height retrieval from direct fitting of GOME-2 backscattered radiance measurements

Theory

Introduction

The use of satellite measurements for SO_2 monitoring has become an important aspect in the support of aviation control. Satellite measurements are sometimes the only information available on SO_2 concentrations from volcanic eruption events and enhanced SO_2 may indicate the presence of ash. Satellite instruments also provide information on SO_2 pollution sources. SO_2 columns have been derived from several UV nadir sensors (GOME, SCIAMACHY, GOME-2) with traditional DOAS methods. However, both SO_2 and O_3 strongly absorb in the UV range of 310-320 nm (Figure 1); this limits the accuracy of the DOAS technique, which is valid for optically thin media only. **We therefore present an enhanced technique for the simultaneous retrieval of total vertical columns of O_3 and SO_2 from satellite measurements**. The method involves direct fitting of simulated Earthshine radiances to the measured radiance spectrum. **In the process, the use of parameterized vertical SO_2 profiles allows for the derivation of the peak height of the SO_2 plume, along with the total column amounts.**

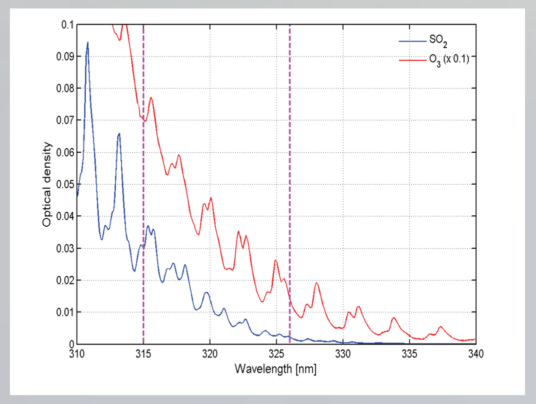

Figure 1 *UV absorption spectrum of O_3 and SO_2. Note the scaling of the ozone spectrum. The dashed lines indicate the retrieval fitting window mostly used when retrieving SO_2 from GOME or SCIAMACHY data.*

Background physics

The way different layers of the atmosphere contribute to the top-of atmosphere radiance spectrum I_{TOA}, can be visualized by means of the vertical profile of the local air mass factor and its gradient (Figure 2). This indicates a difference between the I_{TOA} Jacobians with respect to total gas column and gas height, as explained in Yang *et al*. [2010, [5]]. Put into words: **Changing the SO_2 concentration in an atmospheric layer has a different effect on I_{TOA} than changing the altitude of this layer.** This phenomenon allows for the derivation of both total column and height information of an SO_2 plume.

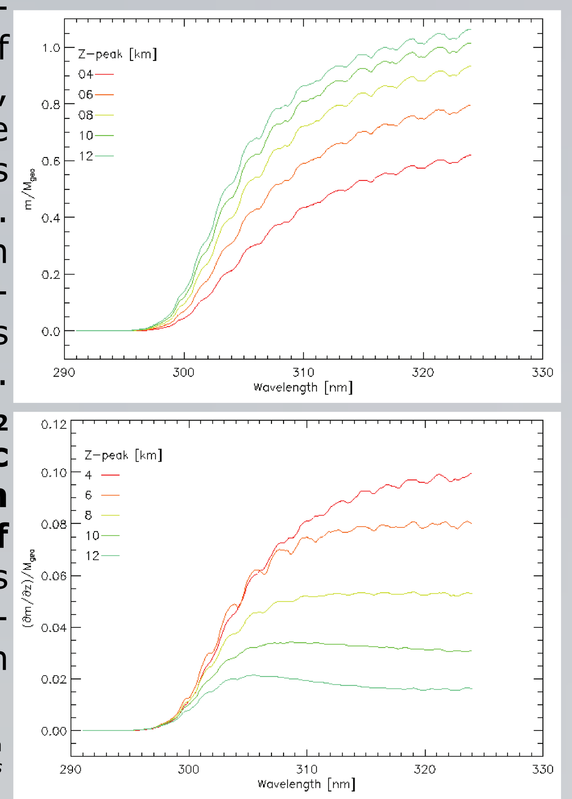

Figure 2 *Wavelength dependency of SO_2 layer air mass factor* m *and its derivative ∂m/∂z, normalized to the geometrical air mass factor* M_{geo}*. Colours represent different plume heights.*

Method

We derive SO_2 total vertical column density and effective SO_2 plume height by means of the direct fitting retrieval algorithm GODFIT [1]. This iterative scheme performs forward radiance and Jacobian calculations with the LIDORT radiative transfer model [2] and contains an optimal estimation inversion scheme. **In the model atmosphere, volcanic SO_2 plumes are parameterized on a fine layering grid** (see Figure 3).

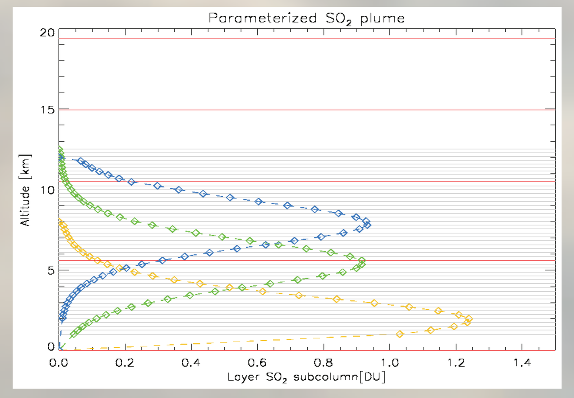

Figure 3 *Examples of SO_2 plume parameterization, for peak heights of 2, 5.5, and 8 km. Red lines show the basic layering grid; for the SO_2 plumes, these layers are repartitioned (gray lines), such that the vertical air columns are preserved. Each plume is defined by a top*

Examples

Below we show results from retrievals of SO_2 vertical column density (VCD) and effective plume height. For the retrievals from GOME-2 observations a second order surface albedo closure polynomial was used as well as a Ring-spectrum scale factor. Clouds were treated as Lambertian reflectors and with use of the independent pixel approximation. Aerosols were not included. For the plume height element of the state vector, *a priori* information has to be applied.

Kasatochi, 9 August 2008

The high SO_2 concentrations emitted in the 2008 eruption from this Aleutian volcano could be observed for many days.
Simultaneous retrieval results of SO_2 total column and plume height for this eruption are depicted in Figure 4. Excellent agreement was found with the VCD and height derivations from Nowlan et al. [2011 [2]]. For the comparison with their work we adopted an *a priori* plume height uncertainty of 2 km. In general, little or no altitude information will be available before the volcano is observed by GOME-2. We therefore usually adopt an *a priori* uncertainty of σ=5km.

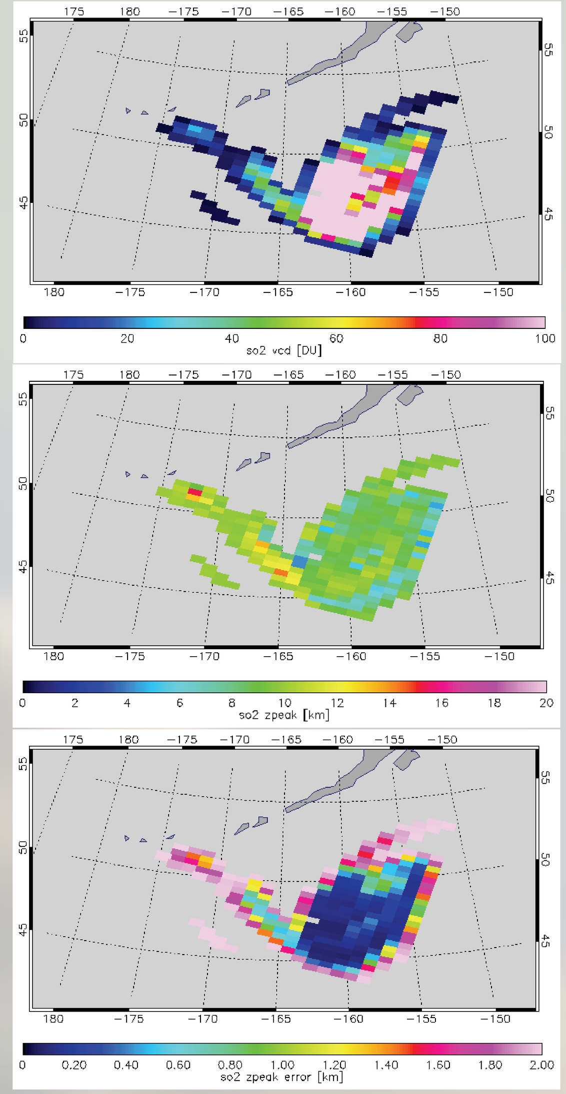

Figure 4 *SO_2 vertical column density (top) and plume height information for emissions from the Kasatochi volcano on 9 August 2008. For this well studied object an* a priori *uncertainty of 2 km was adopted.*

Nabro, 15 June 2011

With a violent offset on the late night of 12 June this eruption provided the highest levels of SO_2 ever detected from space. Within days the gases had spread over the Middle East and well into Asia were the could be followed for several weeks.
Figure 5 shows SO_2 VCD and plume height results for 15 June 2011. From the figure we can tell that **derived plume height values are most reliable close to the source (where concentrations are high) or for plumes at higher altitudes, which are easier to detect.**

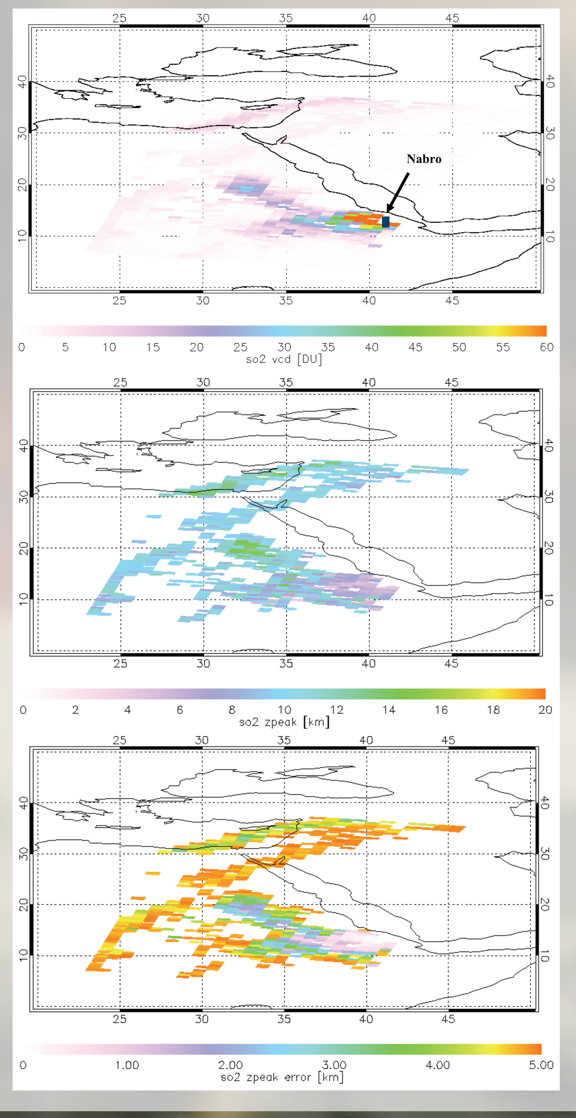

Figure 5 *SO_2 vertical column density (top) and plume height from observations of the Nabro eruption on 15 June 2011. The adopted a priori height uncertainty is σ=5 km.*

Validation

Validation of the derived SO_2 plume height results is not straightforward, since for most eruptions no independent measurements (from airplanes, from ground or otherwise) exist. For the verification of our results we therefore relay on trajectory models and the spaceborne lidar instrument CALIOP on the CALIPSO platform. The application of both methods is illustrated below.

Merapi, 5 November 2010

The devastating Merapi eruption emitted large volumes of gas and ash as high as the lower stratosphere. Our GOME-2 plume height retrievals indicate that the large gas concentrations reached an altitude of around 14 km, with some values as high as 18 km (Figure 6). Nearby CALIOP measurements on 5 November show ash layers around 15 and 17 kilometres. Even though SO_2 and ash do not necessarily reside at the same altitude, the CALIOP results are in good agreement with our derived plume height values.

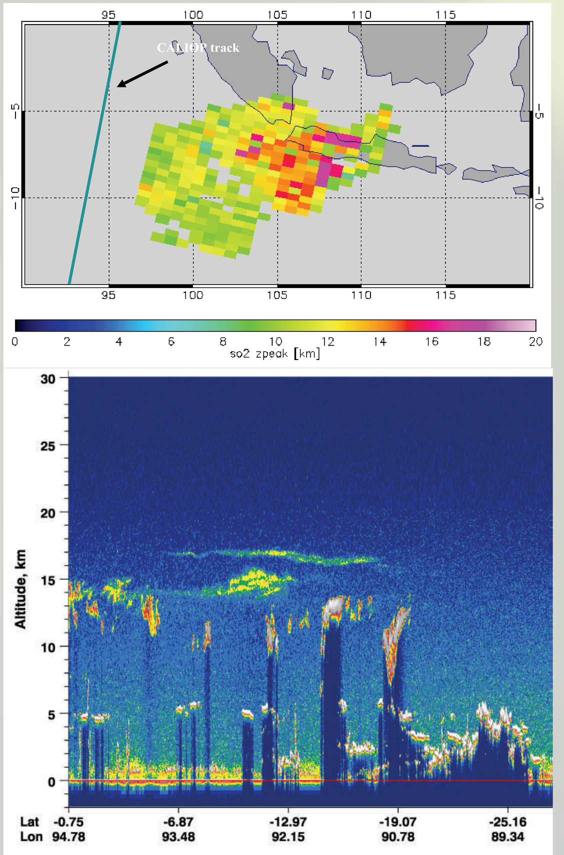

Figure 6 *GOME-2 SO_2 plume height (top) and CALIOP backscatter measurements. The lower GOME-2 plume height values of about 10 km at the outside of the SO_2 cloud are less reliable, as SO_2 concentrations are low and the results is mainly determined my the* a priori *value of 10 km.*

FLEXPART

Figure 7 (top panel) shows a 24 hour forward prediction with the FLEXPART trajectory model (Stohl *et al.*, 2005 [4]) for the Nabro SO_2 distribution of Figure 5. Only GOME-2 pixels with an SO_2 VCD larger than 10 DU where used as input for the model.
The lower panels of Figure 7 show the GOME-2 plume height retrieval result for the morning of 16 June. Although the Nabro eruption proves difficult, with extended regions of low SO_2 concentrations, FLEXPART confirms that our GOME-2 height retrievals are accurate for pixels with sufficiently large SO_2 concentrations (small retrieval model errors on the height result.)

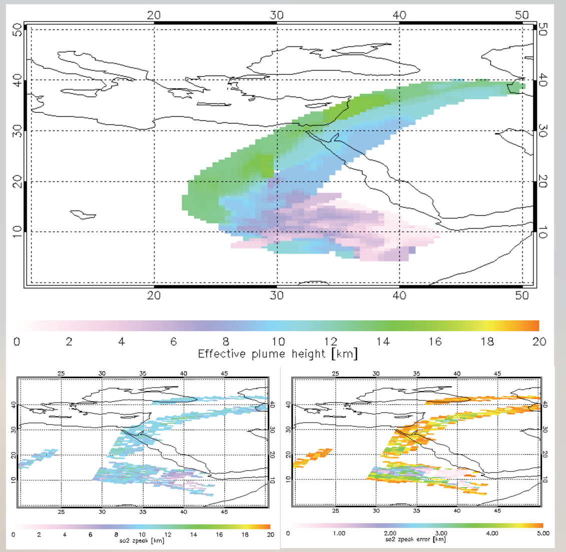

Figure 7 *FLEXPART SO_2 effective height (top) and GOME-2 retrieved plume height with error for Nabro at 16 June 2011, around 07 hrs UT. Input to the FLEXPART run are pixels from Figure 5 with SO_2 VCD > 10 DU.*
Note that the northernmost branch of the SO_2 distribution is not represented in the FLEXPART results, as it originates from SO_2 concentrations lower than 10 DU.

References

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