OPERATIONAL MONITORING OF SO_2 EMISSIONS USING THE GOME-2 SATELLITE INSTRUMENT

Meike Rix[(1) (2)], Pieter Valks[(1)], Jos Van Geffen[(3)], Cordelia Maerker[(1)], Katrin Seidenberger[(1)], Thilo Erbertseder[(1)], Michel Van Roozendael[(3)], Nan Hao[(1)], Diego Loyola[(1)]

[(1)]German Aerospace Center, Münchner Str. 20, 82234 Wessling, Germany
[(2)]Technical University of Munich, Arcisstr. 21, 80333 München, Germany
[(3)]Belgian Institute for Space Aeronomy, Ringlaan-3-Avenue Circulaire, 1180 Brussels, Belgium

Abstract

Satellite-based remote sensing measurements of atmospheric sulphur dioxide (SO_2) provide valuable information on anthropogenic pollution and volcanic activity. Sensors like GOME-2 on MetOp-A make it possible to monitor SO_2 emissions on a global scale and daily basis. SO_2 total column amounts are retrieved in near-real time using the UV range of backscattered sunlight making it possible to detect and track volcanic eruption plumes. Trajectory matching is applied to relate detected SO_2 to particular volcanoes and to estimate eruption parameters such as the height of the volcanic plume. Taking this information as input, dispersion modelling is used to forecast the motion of the volcanic plume. The high sensitivity of the GOME-2 instrument to SO_2 allows measuring anthropogenic SO_2 in the boundary layer and volcanic SO_2 from non-eruptive degassing. This can provide critical information for early warning of volcanic hazards as changes in the SO_2 emissions can indicate increased volcanic activity.

INTRODUCTION

Atmospheric sulphur dioxide is produced mainly by volcanic eruptions and anthropogenic activities like power plants, metal smelting, refineries and burning of fossil fuels. Due to its generally low background level it is an excellent marker for pollution events and volcanic activity. Its lifetime varies from approximately 1-2 days in the troposphere to several weeks in the stratosphere. In the troposphere it is transformed into sulfuric acid and is responsible for acid rain. If SO_2 is brought into the stratosphere by volcanic eruptions, it can remain there for several weeks and travel over long distances (e.g. Kasatochi eruption, Aug. 2008), as sulfuric aerosols it can also have a cooling effect on the atmosphere (Pinatubo eruption, 1991) [McCormik et al., 1995].

Volcanic eruptions pose a major danger to people living in the vicinity of volcanoes. With the fast growing population more and more people live close to active volcanoes. Besides being a direct danger to the local population, volcanic eruptions have also proven to be a major hazard to aviation. The difficulty to correctly predict the time and location of volcanic eruption events, especially in remotely located areas, has caused many disasters. Volcanic eruptions and passive degassing of volcanoes are the most important natural source of SO_2. During an eruption, SO_2 is the third most abundant gas found in volcanic plumes after H_2O and CO_2. Changes in SO_2 flux can be a precursor for the onset of volcanic activity.

Satellite-based instruments operating in the ultraviolet (UV) spectral region have played an important role in monitoring and quantifying SO_2 emissions. The Total Ozone Mapping Spectrometer (TOMS) was the first satellite instrument to detect volcanic SO_2 released during the El Chichon eruption in 1982 [Krueger, 1983]. The detection sensitivity for SO_2 was limited to large SO_2 amounts due to the discrete wavelengths that were designed for ozone measurements. The detection limit for SO_2 greatly improved for the Global Ozone Monitoring Experiment (GOME) launched 1995 onboard the ERS-2 satellite and the Scanning Imaging Spectrometer for Atmospheric Cartography (SCIAMACHY) launched in 2002 onboard the ENVISAT satellite. However, these instruments have a fairly poor

spatial coverage. They need several days for the acquisition of a contiguous global map and may therefore miss smaller short-lived volcanic events. The newest UV satellite sensors OMI (Ozone Monitoring Instrument) on EOS-Aura since 2004 and GOME-2 on MetOp-A [Callies et al., 2000] since 2006 make it possible to monitor volcanic activity and anthropogenic SO_2 pollution on a global scale and daily basis. Both sensors have also proven their ability to detect passive degassing of volcanoes [Carn et al., 2008], which is particularly valuable for early warning servicesMaximum length for a final paper for inclusion in conference or workshop proceedings will be 8 pages for a regular presentation, 10 pages for a "Keynote" or "Special" presentation, maximum file size is 8MB – please respect font sizes and layout specifics given below.

RETRIEVAL OF SULFUR DIOXIDE

Total SO_2 columns are retrieved from measurements of the GOME-2 instrument on MetOp-A. GOME-2 is a nadir-scanning UV-VIS spectrometer with a spectral coverage of 240 – 790 nm and a spectral (FWHM) resolution between 0.26 nm and 0.51 nm. It measures the back-scattered radiation from the earth-atmosphere system. In addition, a direct sun spectrum is recorded once a day. The nominal size of the field of view is 80 km x 40 km. With the normal operation mode near global coverage is achieved at the equator in one day. The operational GOME-2 total column SO_2 product is produced by the German Aerospace Center (DLR) in the framework of EUMETSAT's Satellite Application Facility on Ozone and Atmospheric Chemistry Monitoring (O3M-SAF), the PROMOTE and the Exupéry projects.

SO_2 columns are retrieved from GOME-2 UV backscatter measurements of sunlight in a two-step procedure [Valks and Loyola, 2008]. In a first step, slant column densities (SC) of SO_2 are determined using the well established Differential Optical Absorption Spectroscopy (DOAS) method [Platt, 1994] in the wavelength region between 315 – 326 nm. Input parameters for the DOAS fit include the absorption cross-section of SO_2, for which the temperature is adjusted depending on the assumed height of the volcanic SO_2 plume, and the absorption cross-sections of interfering gases, ozone and NO_2. A further correction is made in the DOAS fit to account for the ring effect (rotational Raman scattering).
In the 315 – 326 nm wavelength range used for the retrieval a strong interference of the SO_2 and ozone absorption signals can be observed, especially at high solar zenith angles. Therefore, an interference correction needs to be applied to the SO_2 slant column values [Valks and Loyola, 2008].

In a second step, the corrected slant column densities of SO_2 are converted to geometry-independent vertical column (VC) amounts through division by an appropriate air mass factor (AMF) as VC = SC/AMF.
For SO_2, the AMF is strongly dependent on measurement geometry, surface albedo, clouds, aerosols, and most importantly, the shape of the vertical SO_2 profile in the atmosphere. For the AMF calculations, an a priori volcanic SO_2 profile is assumed with a predefined central plume height. As the correct plume height is rarely available at the time of measurement, the SO_2 column is computed for three different assumed volcanic plume heights: 2.5 km, 6 km and 15 km above ground level. The lowest height represents passive degassing of low volcanoes, the second height effusive volcanic eruptions or passive degassing of high volcanoes and the third height explosive eruptions. The AMFs are calculated with the radiative transfer model LIDORT [Spurr et al., 2001].

TRAJECTORY MATCHING AND DISPERSION MODELLING

In order to attribute increased SO_2 values observed by the GOME-2 satellite instrument to a particular emission source and to determine plume height, emission time and duration a trajectory matching technique is applied. Calculating coherent ensembles of trajectories allows determination of the origin of the SO_2 plume and the effective emission height. The estimation of the plume height is particularly important for the correct quantitative determination of the SO_2 loading from the GOME-2 observation. For this purpose an ensemble of ~ 1000 trajectories, evenly distributed between 0 and 20 km, is

started at the location of the GOME-2 pixel containing the maximum SO_2 amount. Trajectory density maps are calculated using ECMWF reanalysis data to determine the most probable origin of the detected SO_2 by matching a list of volcano locations. After determination of the SO_2 source the ensemble is filtered for those trajectories that directly hit the associated volcano to determine the emission height, time and duration. For this analysis the 3D kinematic trajectory model FLEXTRA [Stohl et al., 1999] is used.

As trajectory models neglect processes like convection and turbulence and therefore deliver only qualitative information, further analysis of the satellite observations is carried out using the Lagrangian particle dispersion model FLEXPART [Stohl et al., 2005]. The calculations, as the trajectory analysis, are based on ECMWF data and provide a three dimensional forecast for the SO_2 transport. The dispersion of particles is calculated according to the atmospheric motion and random movements represent the effects of turbulence. Removal of SO_2 from the plume has been neglected for first comparisons. However, FLEXPART takes deposition processes into account. Input parameters such as time and duration of the eruption as well as emission height are taken from the trajectory modeling results [Maerker et al., 2008].

VALIDATION

An initial validation of the GOME-2 total SO_2 columns with ground-based observations and other satellite measurements has been carried out [Van Geffen et al., 2008]. SO_2 columns for an explosive volcanic eruption reaching stratospheric heights (Kasatochi) and for an effusive eruption (Kilauea) were compared with results from SCIAMACHY, OMI and ground based Brewer spectrometer measurements. Further a comparison of SO_2 measurements using a MaxDOAS instrument in Beijing with GOME-2 observations in that region has been carried out. Comparisons for the stratospheric SO_2 plume from the Kasatochi eruption show that the three satellite instruments capture the structure of the SO_2 cloud very well: the locations of the peak SO_2 values and the dimensions of the SO_2 cloud match nicely (Fig. 2). Differences in the observed total SO_2 columns can mostly be explained by differences in the retrieval methods for the two instruments. The Brewer spectrometer measurements in Uccle and Manchester that captured the enhanced SO_2 concentrations related to the overpass of the Kasatochi SO_2 cloud match very well with the GOME-2 SO_2 measurements. The comparisons for the low-level SO_2 plume from the Kilauea eruptions on Hawaii show a good agreement between the total SO_2 columns from GOME-2 and SCIAMACHY [Van Geffen et al., 2008]. The results of the MaxDOAS instrument match nicely with the SO_2 amounts observed by GOME-2. Both instruments show enhanced SO_2 values during the winter months (Fig. 1).

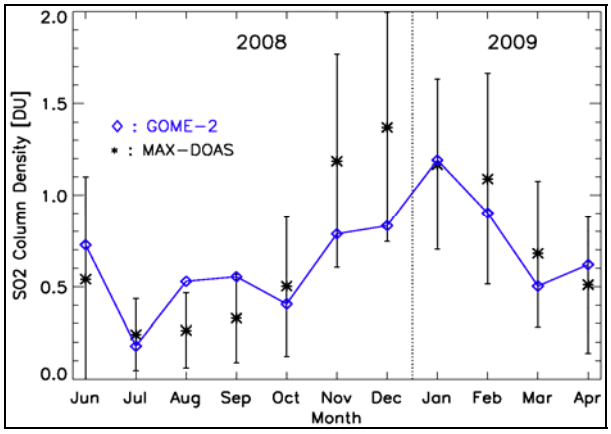

Figure 1: **Comparison of GOME-2 observations with MaxDOAS measurements in Beijing, China (39.9°N, 116.4°E)**

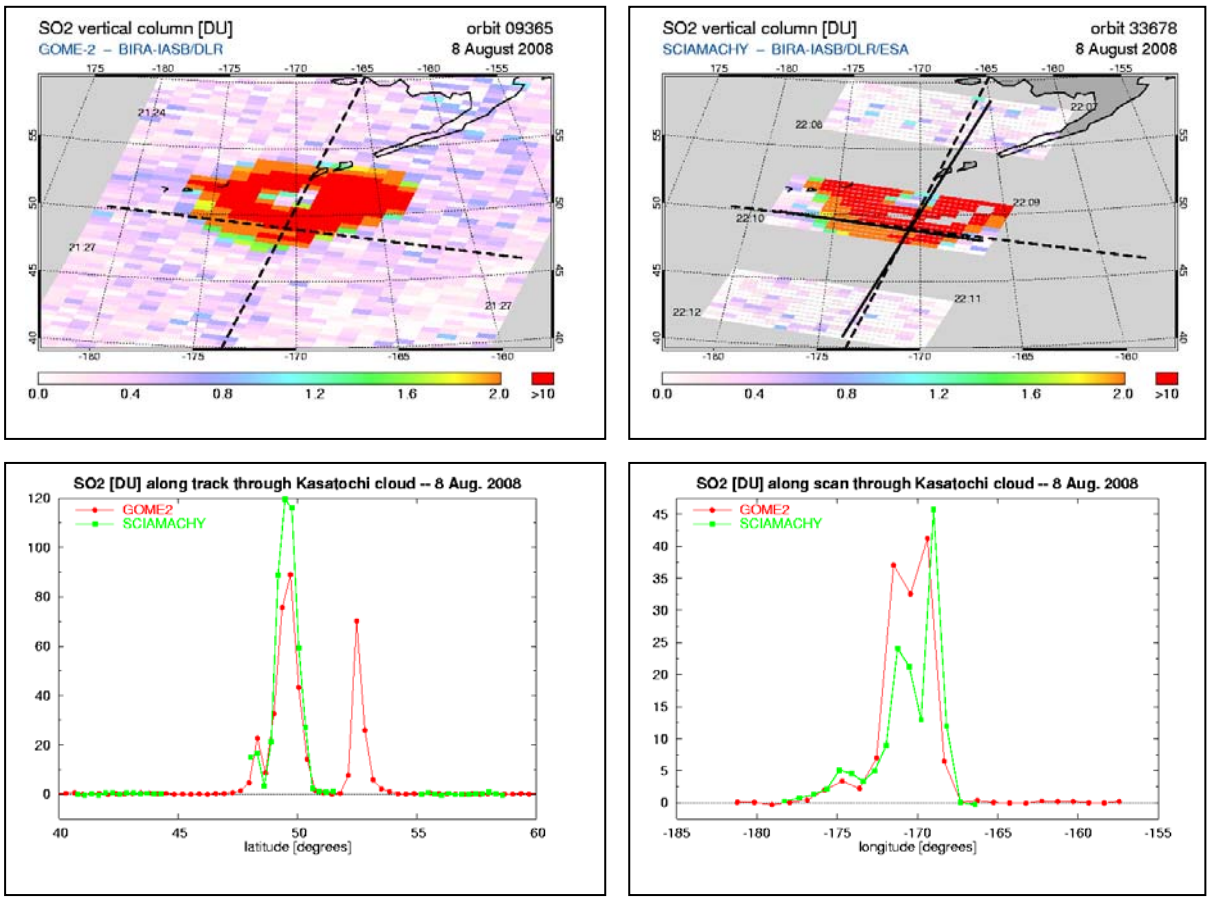

Figure 2: **Along-track and along-scan lines in the GOME-2 (dashed) and SCIAMACHY (solid) orbit used for a direct pixel-to-pixel comparison of data on 8 August 2008 (top) and comparison of the total SO_2 column (bottom). Differences in the observed total SO_2 columns can mostly be explained by differences in the retrieval methods for the two instruments. An interesting feature can be observed in the measurements, the erupted SO_2 was distributed into a circular pattern by atmospheric winds. The lack of SO_2 in the center is clearly visible in the along track observations.**

KASATOCHI ERUPTION

On the afternoon of 7 August an explosive eruption occurred at the Kasatochi volcano located in Alaska's Aleutian Island chain. Kasatochi had not been active in over 100 years. Three major eruptions emitted large amounts of volcanic ash and gas into the atmosphere. After the eruption, the plume drifted to the southeast where it formed a distinct loop due to atmospheric winds. The SO_2 plume was first detected during the GOME-2 overpass on 8 August. GOME-2 measured maximum SO_2 column amounts of > 150 DU the first day after the eruption. An estimation from the GOME-2 data of the total erupted mass of SO_2 during the Kasatochi eruption yields about 1.5 Tg of SO_2 (With a GOME-2 pixel size of 40 km x 80 km 1 DU corresponds to a total mass of approximately 91.5 tons of SO_2.). The SO_2 that was emitted during the eruption of the Kasatochi volcano was transported towards the east on the following two days and was later dispersed into spiralling patterns. One week after the eruption the SO_2 cloud reached Europe on 14 August (Fig. 3, top), where it could be detected by ground-based instruments. The SO_2 cloud could be traced for several weeks as it was distributed all over the northern hemisphere. Using trajectory analysis Kasatochi was confirmed as the most probable source of the detected SO_2 and the emission height was estimated to 10 - 15 km (Fig. 4). Taking these results as input for the dispersion modelling, a comparison of the model results and the GOME-2 measurements for 14 August shows good agreement (Fig. 3). Differences can be observed near the Rocky Mountains, they are due to a second eruption emitting SO_2 that has not been taken into account in the modeling.

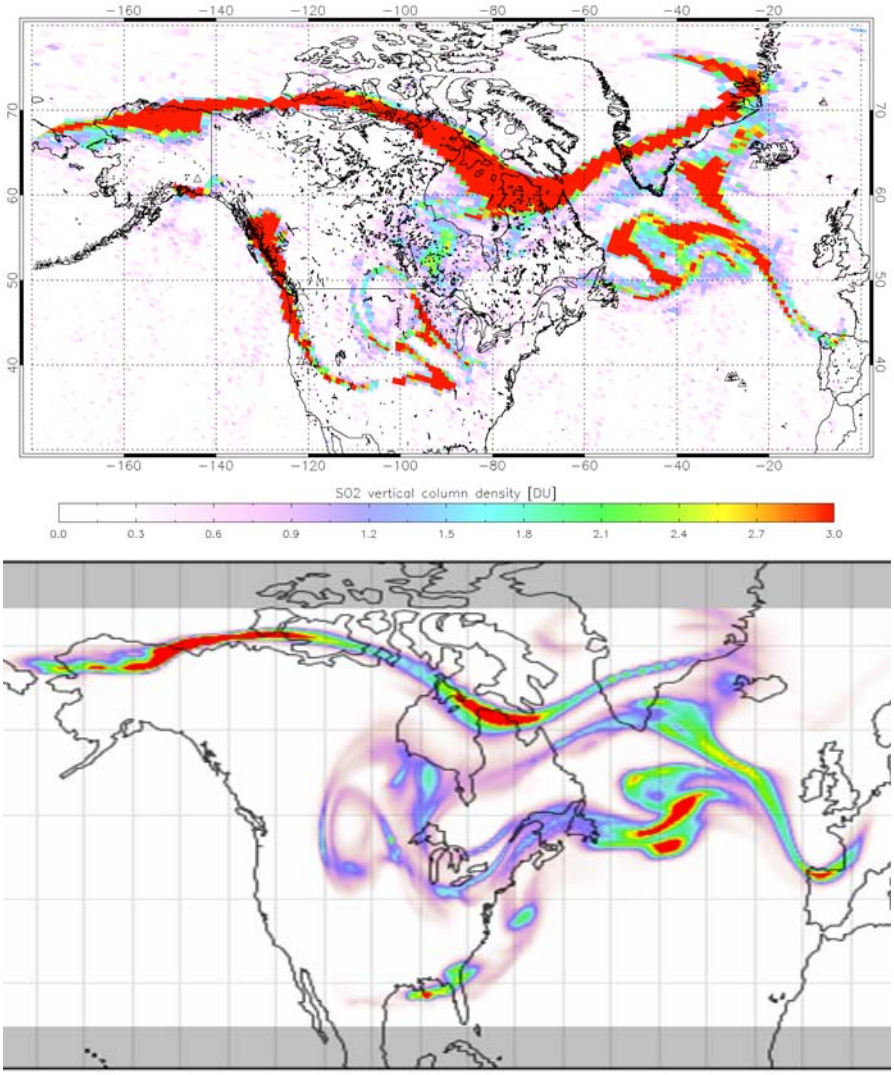

Figure 3: **GOME-2 measurement of the SO_2 cloud from the Kasatochi eruption on 14 August (top) and SO_2 cloud from the Kasatochi eruption on the same day modeled with FLEXPART (bottom)**

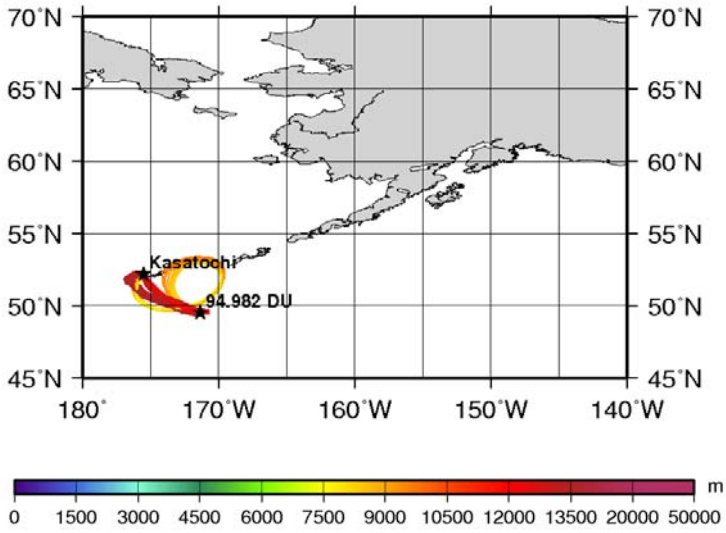

Figure 4: **FLEXTRA analysis for plume height determination for the Kasatochi eruption on 7 August 2008. The trajectories show, that the volcanic eruption plume reached altitudes of more than 10 km.**

VOLCANIC DEGASSING AND AIR POLLUTION

With the high sensitivity GOME-2 provides, small SO_2 amounts can be detected which is important for monitoring volcanic degassing and anthropogenic pollution with typical values of less than 3 DU. Volcanic degassing can be observed with the GOME-2 instrument for several volcanic regions, e.g. Papua New Guinea/Vanuatu, Ecuador or Mexico. Daily maps of the GOME-2 SO_2 data are provided for all volcanic regions worldwide (http://wdc.dlr.de/sensors/gome2). GOME-2's high sensitivity to SO_2 also at low altitudes makes it possible to regularly monitor air pollution in the boundary layer and to determine changes and trends. By averaging over longer time periods the observed SO_2 emissions can be related to their sources. Anthropogenic SO_2 pollution can be observed for example in China, Russia and South Africa.

An example for the ability of the GOME-2 instrument to monitor changes in the degassing behavior of volcanoes is provided in Fig. 6. It shows the averaged GOME-2 SO_2 column densities for 2007 – 2008 in the volcanic region of Papua New Guinea/Vanuatu and the daily emission estimates. The three main degassing volcanoes in this area are clearly visible in the image (top), from north to south they are Rabaul (1) (688 m), Bagana (2) (1750 m) and Ambrym (3) (1334 m). Given the low summit elevations of the considered volcanoes we assumed a plume height of 2.5 km for the analysis. The daily amounts of emitted SO_2 from these volcanoes are highly variable, they vary between no detectable SO_2 emissions and > 8000 tons/day. During the 2-year time period of the three volcanoes Ambrym produced the highest amount of SO_2 emitting approximately 0.75 Tg. The volcano was showing higher activity especially towards the end of 2008 with daily emissions reaching values of up to 9000 tons/day. Rabaul volcano emitted approximately 0.63 Tg of sulfur dioxide. Rabaul can be considered the most active volcano in this region as the emission of the SO_2 gas is often accompanied by emission of ash plumes and explosions [Smithonian Institution, 2008]. Emissions from Bagana during the 2-year period are lower than from the other volcanoes ranging around 0.49 Tg SO_2. This volcano shows the least frequent activity with long time periods with little or no SO_2 emissions. All three volcanoes are known to have erupted in historical times, with two recent major explosive eruptions at Rabaul in 1994 and 2006. These two eruptions led to evacuation of Rabaul town, damaged land and property and interfered with aviation. The 1994 eruption was also accompanied by lahars and pyroclastic flows and caused fatalities. Therefore it would be of great value to link the SO_2 emissions to the volcanic activity at these volcanoes, and use them as an additional precursor for the onset of future eruptions to reduce the threat to the local population.

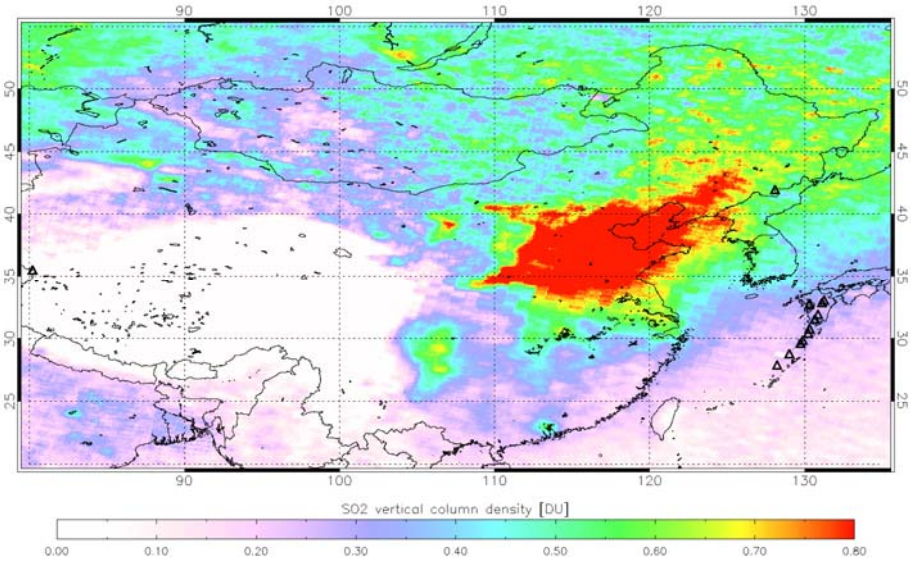

***Figure 5*: Anthropogenic SO_2 pollution over China, observed with GOME-2, 2007 - 2008**

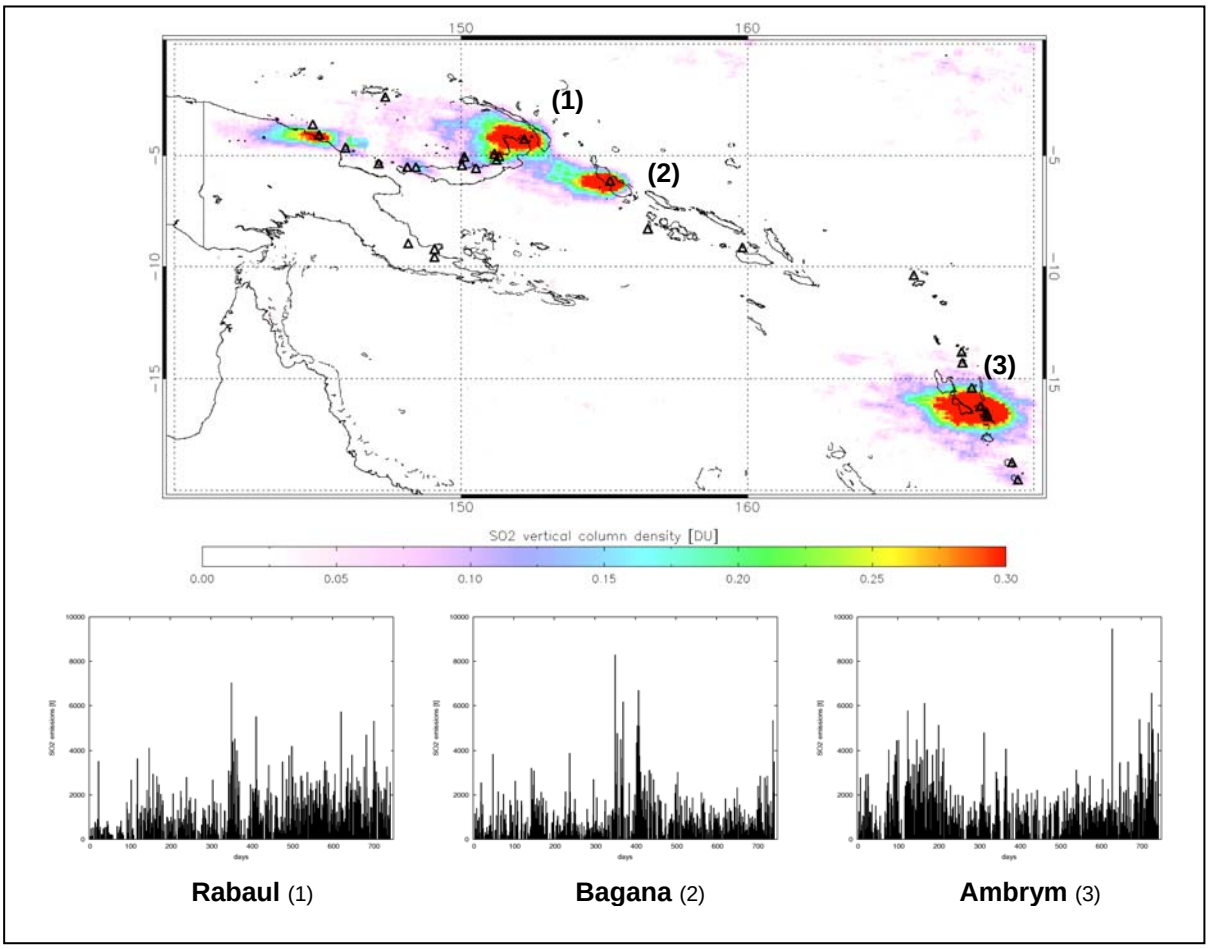

Figure 6: **Averaged SO_2 emissions (top) and daily SO_2 emissions estimated (bottom) from GOME-2 measurements from passively degassing volcanoes in the volcanic region Papua New Guinea/ Vanuatu from 2007 – 2008**

CONCLUDING REMARKS

Sulfur dioxide monitoring from satellite instruments is a valuable tool in monitoring air quality and volcanic activity. The GOME-2 instrument provides the opportunity for monitoring long-range transport of volcanic clouds, detection of small eruptions, investigation of pre-eruptive degassing and monitoring anthropogenic pollution on a global scale and daily basis.

SO_2 from GOME-2 observations is retrieved using the Differential Optical Absorption Spectroscopy in near-real time, which is important for early warning services. For enhanced SO_2 values trajectory matching is applied to locate the emission source and in case of volcanic eruptions estimate the emission height. Dispersion modelling can then be used to forecast the transport of the SO_2 plume.

Satellite based SO_2 measurements are especially of great value for reducing volcanic hazards. The ability to detect and track volcanic eruption plumes together with the estimation of the plume height is important for aviation hazard mitigation. Whereas the monitoring of pre-eruptive degassing plays a crucial role in early warning of volcanic unrest as increased gas fluxes are often an indicator for increased volcanic activity.

Current research activities focus on improving the detection of small SO_2 amounts, typically observed for volcanic degassing situations and anthropogenic pollution. As the standard DOAS is restricted to optically thin conditions a direct fitting algorithm for SO_2 is being set up for GOME-2 data, that can use shorter wavelength regions to achieve a higher sensitivity for low SO_2 amounts.

ACKNOWLEDGEMENTS

The research described in this paper has been performed within Exupéry, developed within the German GEOTECHNOLOGIEN Program, the ESA/DUE project GlobVolcano and the Aviation Control Support service of the GMES Service Element for Atmospheric Monitoring (PROMOTE). The GOME-2 level-1 data were provided by EUMETSAT.

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