

# OPERATIONAL MONITORING OF SO<sub>2</sub> EMISSIONS USING THE GOME-2 SATELLITE INSTRUMENT

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## ABSTRACT

Satellite-based remote sensing measurements of atmospheric sulphur dioxide (SO<sub>2</sub>) provide valuable information on anthropogenic pollution and volcanic activity. Sensors like GOME-2 on MetOp-A make it possible to monitor SO<sub>2</sub> emissions on a global scale and daily basis. SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> allows measuring anthropogenic SO<sub>2</sub> in the boundary layer and volcanic SO<sub>2</sub> from non-eruptive degassing. This can provide critical information for early warning of volcanic hazards as changes in the SO<sub>2</sub> emissions can indicate increased volcanic activity.

## 1. 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<sub>2</sub> 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) [1].

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<sub>2</sub>. During an eruption, SO<sub>2</sub> is the third most abundant gas found in volcanic plumes after H<sub>2</sub>O and CO<sub>2</sub>. Changes in SO<sub>2</sub> 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<sub>2</sub> emissions. The Total Ozone Mapping Spectrometer (TOMS) was the first satellite instrument to detect volcanic SO<sub>2</sub> released during the El Chichon eruption in 1982 [2]. The detection sensitivity for SO<sub>2</sub> was limited to large SO<sub>2</sub> amounts due to the discrete wavelengths that were designed for ozone measurements. The detection limit for SO<sub>2</sub> 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 [3] since 2006 make it possible to monitor volcanic activity and anthropogenic SO<sub>2</sub> pollution on a global scale and daily basis. Both sensors have also proven their ability to detect passive degassing of volcanoes [4], which is particularly valuable for early warning services.

## 2. RETRIEVAL OF SULFUR DIOXIDE

Total SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> columns are retrieved from GOME-2 UV backscatter measurements of sunlight in a two-step procedure [5]. In a first step, slant column densities (SC) of SO<sub>2</sub> are determined using the well established Differential Optical Absorption Spectroscopy (DOAS) method [6] in the wavelength region between 315 – 326 nm. Input parameters for the DOAS fit include the absorption cross-section of SO<sub>2</sub>, for which the temperature is adjusted depending on the assumed height of the volcanic SO<sub>2</sub> plume, and the absorption cross-sections of interfering gases, ozone and NO<sub>2</sub>. 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<sub>2</sub> and ozone absorption signals can be observed, especially at high solar zenith angles. Therefore, an interference correction needs to be applied to the SO<sub>2</sub> slant column values [5].

In a second step, the corrected slant column densities of SO<sub>2</sub> are converted to geometry-independent vertical column (VC) amounts through division by an appropriate air mass factor (AMF) as  $VC = SC/AMF$ .

For SO<sub>2</sub>, the AMF is strongly dependent on measurement geometry, surface albedo, clouds, aerosols, and most importantly, the shape of the vertical SO<sub>2</sub> profile in the atmosphere. For the AMF calculations, an a priori volcanic SO<sub>2</sub> profile is assumed with a predefined central plume height. As the correct plume height is rarely available at the time of measurement, the SO<sub>2</sub> 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 [7].

### 3. TRAJECTORY MATCHING AND DISPERSION MODELLING

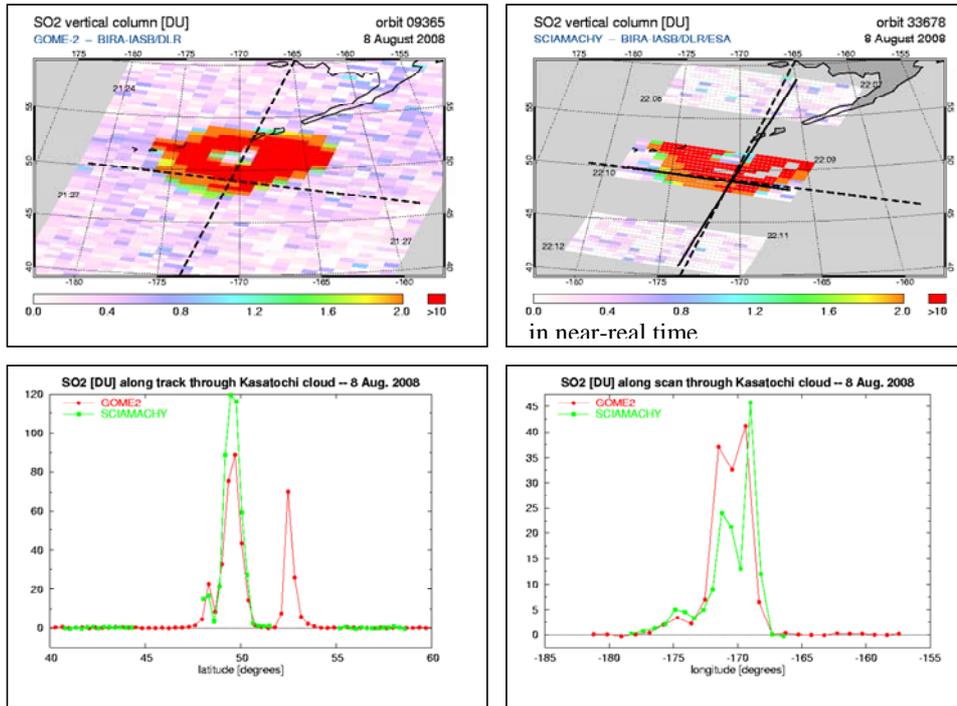
In order to attribute increased SO<sub>2</sub> values observed by the GOME-2 satellite instrument to a particular emission source and to determine plume height,

emission time and duration a trajectory matching technique is applied. Calculating coherent ensembles of trajectories allows determination of the origin of the SO<sub>2</sub> plume and the effective emission height. The estimation of the plume height is particularly important for the correct quantitative determination of the SO<sub>2</sub> 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<sub>2</sub> amount. Trajectory density maps are calculated using ECMWF reanalysis data to determine the most probable origin of the detected SO<sub>2</sub> by matching a list of volcano locations. After determination of the SO<sub>2</sub> 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 [8] 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 [9]. The calculations, as the trajectory analysis, are based on ECMWF data and provide a three dimensional forecast for the SO<sub>2</sub> transport. The dispersion of particles is calculated according to the atmospheric motion and random movements represent the effects of turbulence. Removal of SO<sub>2</sub> 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 [10].

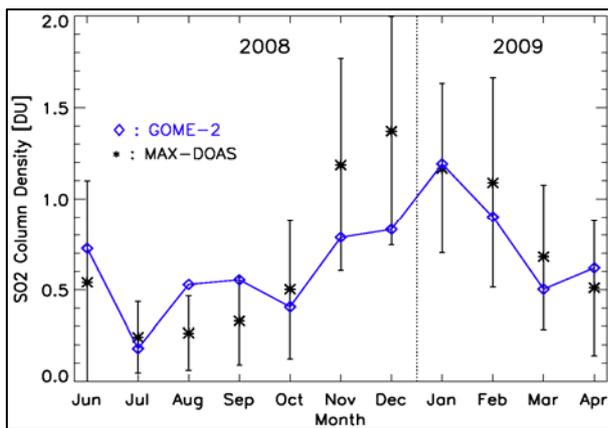
### 4. VALIDATION

An initial validation of the GOME-2 total SO<sub>2</sub> columns with ground-based observations and other satellite measurements has been carried out [11]. SO<sub>2</sub> 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<sub>2</sub> measurements using a MaxDOAS instrument in Beijing with GOME-2 observations in that region has been carried out. Comparisons for the stratospheric SO<sub>2</sub> plume from the Kasatochi eruption show that the three satellite instruments capture the structure of the SO<sub>2</sub> cloud very well: the locations of the peak SO<sub>2</sub> values and the dimensions of the SO<sub>2</sub> cloud match nicely (Fig. 1). Differences in the observed total SO<sub>2</sub> 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<sub>2</sub> concentrations related to the overpass of the Kasatochi SO<sub>2</sub> cloud match very



**Figure 1:** 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<sub>2</sub> column (bottom). Differences in the observed total SO<sub>2</sub> 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<sub>2</sub> was distributed into a circular pattern by atmospheric winds. The lack of SO<sub>2</sub> in the center is clearly visible in the along track observations.

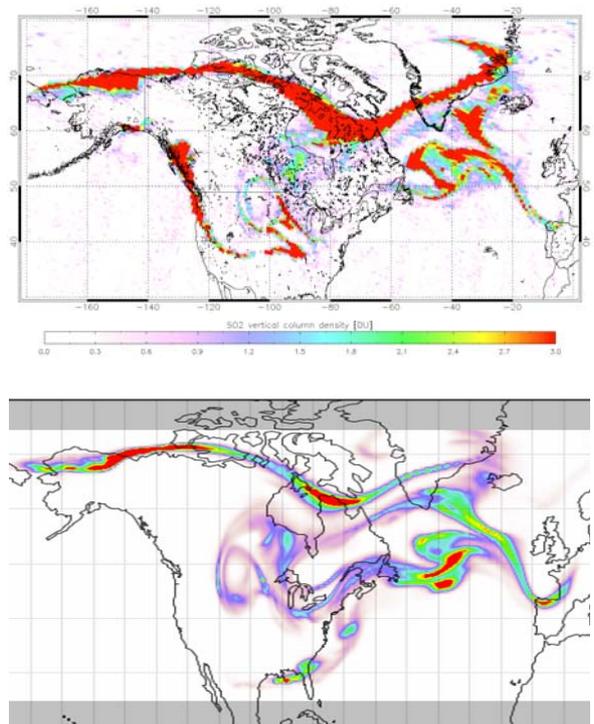
well with the GOME-2 SO<sub>2</sub> measurements. The comparisons for the low-level SO<sub>2</sub> plume from the Kilauea eruptions on Hawaii show a good agreement between the total SO<sub>2</sub> columns from GOME-2 and SCIAMACHY [11]. The results of the MaxDOAS instrument match nicely with the SO<sub>2</sub> amounts observed by GOME-2. Both instruments show enhanced SO<sub>2</sub> values during the winter months (Fig. 2).



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

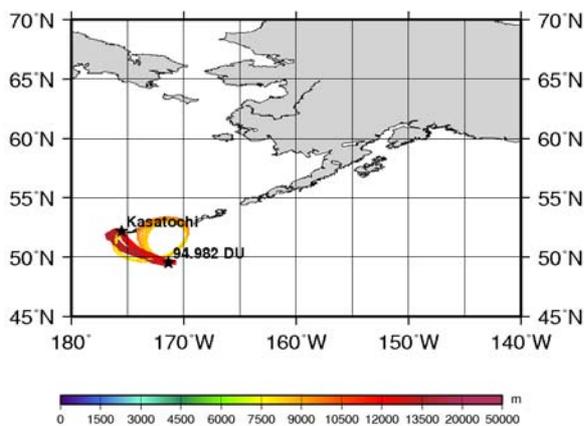
### 5. KASATOCHI ERUPTION

On the afternoon of 7 August an explosive eruption occurred at the Kasatochi volcano located in Alaska's



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

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<sub>2</sub> plume was first detected during the GOME-2 overpass on 8 August. GOME-2 measured maximum SO<sub>2</sub> 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<sub>2</sub> during the Kasatochi eruption yields about 1.5 Tg of SO<sub>2</sub> (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<sub>2</sub>). The SO<sub>2</sub> 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<sub>2</sub> cloud reached Europe on 14 August (Fig. 3, top), where it could be detected by ground-based instruments. The SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> that has not been taken into account in the modelling.

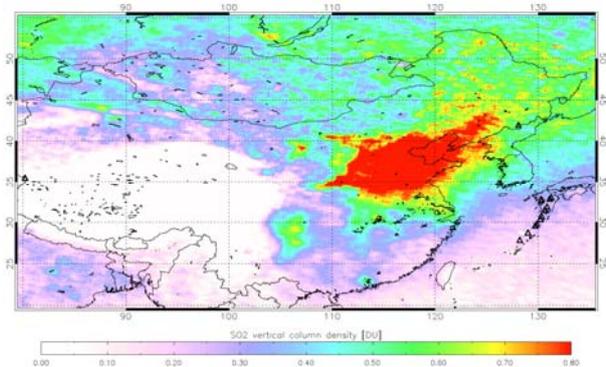


**Figure 4:** FLEXTRA analysis for plume height determination for the Kasatochi eruption on 7 August 2008. The trajectories show, that the volcanic eruption plume reached altitudes of more than 10 km.

## 6. VOLCANIC DEGASSING AND AIR POLLUTION

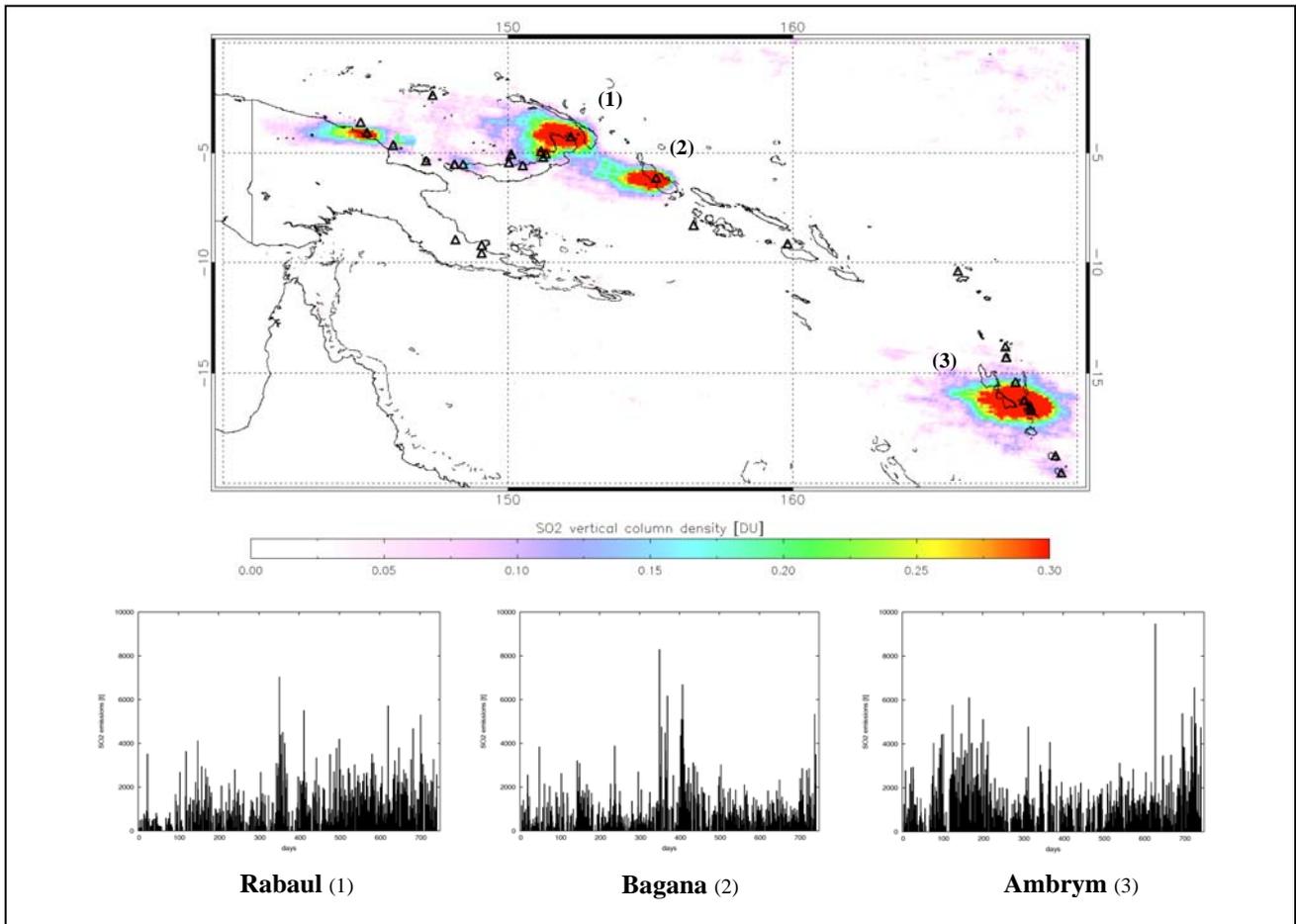
With the high sensitivity GOME-2 provides, small SO<sub>2</sub> amounts can be detected which is important for monitoring volcanic degassing and anthropogenic

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<sub>2</sub> data are provided for all volcanic regions worldwide (<http://wdc.dlr.de/sensors/gome2>). GOME-2's high sensitivity to SO<sub>2</sub> 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<sub>2</sub> emissions can be related to their sources. Anthropogenic SO<sub>2</sub> pollution can be observed for example in China, Russia and South Africa.



**Figure 5:** Anthropogenic SO<sub>2</sub> pollution over China, observed with GOME-2, 2007 - 2008

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<sub>2</sub> 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<sub>2</sub> from these volcanoes are highly variable, they vary between no detectable SO<sub>2</sub> emissions and > 8000 tons/day. During the 2-year time period of the three volcanoes Ambrym produced the highest amount of SO<sub>2</sub> 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<sub>2</sub> gas is often accompanied by emission of ash plumes and explosions [12]. Emissions from Bagana during the 2-year period are lower than from the other volcanoes ranging around 0.49 Tg SO<sub>2</sub>. This volcano shows the least frequent activity with long time periods with little or no SO<sub>2</sub> emissions.



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

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<sub>2</sub> 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.

## 7. 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> plume.

Satellite based SO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> is being set up for GOME-2 data, that can use shorter wavelength regions to achieve a higher sensitivity for low SO<sub>2</sub> amounts.

## ACKNOWLEDGEMENTS

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