Monitoring of volcanic SO_2 emissions using the GOME-2 satellite instrument

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Abstract— **Atmospheric sulfur dioxide is an important indicator of volcanic activity. Space based atmospheric sensors like GOME-2 on MetOp and OMI on EOS-Aura make it possible to detect the emissions of volcanic SO_2 and monitor volcanic activity and eruptions on a global scale. With GOME-2, it is possible to detect and track volcanic eruption plumes and SO_2 from passive degassing in near-real time (NRT). This is particularly important for early warning services, as increases in SO_2 fluxes are an indicator for new episodes of volcanic unrest. The SO_2 daily measurements from space are used for several early warning services related volcanic risk (Exupéry, GlobVolcano) and for aviation warning purposes (GSE-PROMOTE).**

Keywords- sulfur dioxide, GOME-2, volcanic degassing

I. INTRODUCTION

Atmospheric sulfur dioxide (SO_2) is produced mainly by volcanic activity and anthropogenic activities like power plants, refineries, metal smelting and burning of fossil fuels. 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).

Volcanic eruptions and passive degassing of volcanoes are the most important natural source of SO_2 [1] and atmospheric SO_2 is an important indicator of volcanic activity. Volcanic eruptions pose a major threat the local population, the infrastructure in the vicinity of the volcano and to aviation. As regular ground based monitoring is only carried out for a limited number of volcanoes, satellite instruments can provide additional valuable information especially for remotely located volcanoes. Space based atmospheric sensors like GOME-2 on MetOp and OMI on EOS-Aura make it possible to monitor volcanic activity and eruptions on a global scale and daily basis. With these new sensors it is possible to detect and tract volcanic eruptions plumes in near-real time (NRT) which is important for early warning services. Both sensors have also proven their ability to detect passive degassing of volcanoes [2], which is particularly valuable for early warning services as increases in SO_2 fluxes are an important indicator for new episodes of volcanic unrest.

In this context the NRT volcanic SO_2 data retrieved GOME-2 will be used in two early warning services for volcanic unrest, Exupéry, a mobile volcano fast response system, developed within the German Geotechnology Program [3] and the ESA/DUE project GlobVolcano. A further service that makes use of the GOME-2 SO_2 data is the Aviation Control Support service of the GMES Service Element for Atmospheric Monitoring (PROMOTE).

II. RETRIEVAL OF VOLCANIC SO_2

Total SO_2 columns are measured with the GOME-2 instrument on the MetOp satellite which was launched in October 2006. GOME-2 is a UV-VIS spectrometer with a spectral coverage of 240 – 270 nm and a resolution of 0.5 nm. The size of the field of view can be varied from 5 km x 40 km to 80 km x 40 km, with a normal operation mode global coverage is achieved in 1 ½ days. MetOp has an equator crossing time of 9:30 a.m. local time.

The SO_2 slant columns (SC) from volcanic activity are retrieved from UV backscatter measurements using the well established Differential Optical Absorption Spectroscopy (DOAS) method [4]. For the DOAS fit the wavelength region between 315 – 326 nm is used to determine the slant column density of SO_2. Input parameters for the DOAS include the absorption cross-section of SO_2, for which the temperature is adjusted depending on the assumed height of the SO_2 plume, and the absorption cross-sections of interfering gases, ozone and NO_2 [5]. A further correction is made in the DOAS fit to account for the ring effect (rotational Raman scattering).

In the wavelength range 315-326 nm used for the retrieval, there is a strong interference of the SO_2 and ozone absorption signals especially for high solar zenith angles. Therefore an offset correction needs to be applied to the SO_2 slant column values. The correction accounts for an equatorial offset that is calculated on a daily basis. The effects of the ozone interference and the solar zenith angle are corrected on the basis of one year of ozone and SO_2 data.

The corrected slant column densities of SO_2 are then converted to geometry-independent vertical column (VC) amounts through division by an appropriate air mass factor (AMF):

$$VC = SC/AMF \tag{1}$$

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For SO_2 this AMF is strongly dependent on surface albedo, clouds, aerosols, and most importantly, the shape of the vertical profile of SO_2 in the atmosphere. For the AMF calculations an a priori volcanic SO_2 profile is assumed with a predefined central plume height and a Gaussian SO_2 distribution. As the correct plume height is rarely available at the time of measurement, the SO_2 column is computed for three different assumed SO_2 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 [6], taking into account the measurement geometry, the surface albedo and the presence of clouds.

To attribute the detected SO_2 plume to a particular volcano the trajectory matching technique is applied using the FLEXTRA model [7]. Calculating ensembles of trajectories allows determination of the origin of the SO_2 plume and the effective emission height [8]. The estimation of the plume height is particularly important for the correct quantitative determination of the SO_2 loading.

III. Case Studies

In this section we present selected results for a volcanic eruption and for volcanic degassing detected with the GOME-2 instrument. As an example of an explosive volcanic eruption that emitted large amounts of SO_2 into the atmosphere, the eruption of Kasatochi volcano in August 2008 was selected. The degassing of volcanoes is shown for three volcanoes in the volcanic region of Papua New Guinea/ Vanuatu. In both cases estimates of the total emitted SO_2 amounts were calculated.

A. Volcanic Eruption: Kasatochi, August 2008

On the afternoon of August 7th an explosive eruption occurred at Kasatochi volcano located in Alaska's Aleutian Island chain. Kasatochi volcano had not been active in over 100 years. Three major eruptions emitted large amounts of volcanic ash and gas into the atmosphere that rose to an altitude of at least 10 km. After the eruption, the plume drifted southeastward from the volcano over the Pacific Ocean where it formed a distinct loop due to atmospheric winds. The SO_2 plume was first detected during the GOME-2 overpass on August 8th (Fig. 1, top left). GOME-2 measured maximum SO_2 column amounts of > 150 DU the first day after the eruption. (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.) A first estimate from the GOME-2 data of the total erupted mass of SO_2 during the Kasatochi eruption yields about 1.2 x 10^6 tons of SO_2. All measurements with a vertical column density above a threshold value of 0.8 DU were considered for the estimation of the total emitted SO_2 mass, which might lead to exclusion of SO_2 containing pixels to the edge of the volcanic cloud. The SO_2 that was emitted during the eruption of Kasatochi volcano was then transported towards the east on the following two days by atmospheric winds and was later dispersed into spiraling patterns. One week after the eruption the SO_2 cloud reached Spain on the 14th of August (Fig. 1, bottom). The SO_2 cloud could still be traced for several weeks as it was distributed all over the northern hemisphere.

The eruption of Kasatochi volcano poses a good example on how satellite measurements can provide valuable information on the activity of remotely located volcanoes. In the region of the Aleutian Island chain the density of volcanoes is very high but most of these volcanoes are not regularly monitored. The Kasatochi eruption however brought large amounts of ash and SO_2 into altitudes that are important for aviation, where they are a major danger to aircrafts.

B. Passively degassing volcanoes: Papua New Guinea/ Vanuatu

Daily maps of the GOME-2 SO_2 data are provided for all volcanic regions worldwide. Furthermore average SO_2 maps for optional time periods can be calculated. In Fig. 2 monthly averaged maps for the geographical region of Papua New Guinea/ Vanuatu are shown as an example for the ability of the GOME-2 instrument to monitor changes in the degassing behavior of volcanoes. The time period discussed is from January 2008 to August 2008.

The three main degassing volcanoes in this area are clearly visible in the March 2008 picture (Fig.2, second row, left), from north to south they are Rabaul (688 m), Bagana (1750 m) and Ambrym (1334 m). Given the low summit elevations of the considered volcanoes we assumed a plume height of 2.5 km for the analysis. For the estimation of the total emitted SO_2 amount for each volcano during the period shown in the plots, all measurements with vertical SO_2 columns above 0.6 DU were taken into account (The low threshold value was selected because typical observed SO_2 values for degassing situations are often below 1 DU).

Of these three volcanoes Rabaul shows the most frequent SO_2 emission and also often the highest SO_2 vertical column amounts, which are above 0.8 DU for most of the observed time period. However the monthly averaged amounts of emitted SO_2 from this volcano are highly variable. During the displayed time period Rabaul volcano emitted approximately 2.5 x 10^5 tons 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 [9]. For Bagana a higher variability in the SO_2 emissions can be observed. In February and March 2008 average SO_2 burdens of more than 0.8 DU were observed in the vicinity of the volcano (Fig. 2, top, right/ second row, left) followed by a time period where no detectable amount of SO_2 was emitted, April 2008 (Fig. 2, second row, right). Bagana shows the highest observed monthly emissions of all three volcanoes with a total amount of ~ 59000 tons of SO_2 emitted in February 2008. During the eight months discussed here, the total emitted SO_2 was approximately 1.7 x 10^5 tons. Ambrym also shows continuous SO_2 emissions over the selected time period but the emitted amounts can vary considerably for the different month. The total emitted mass is similar to that of Bagana with ~ 1.9 x 10^5 tons of SO_2.

This case illustrates that the ability of GOME-2 to detect SO_2 degassing patterns provides valuable information for early warning of volcanic risk.

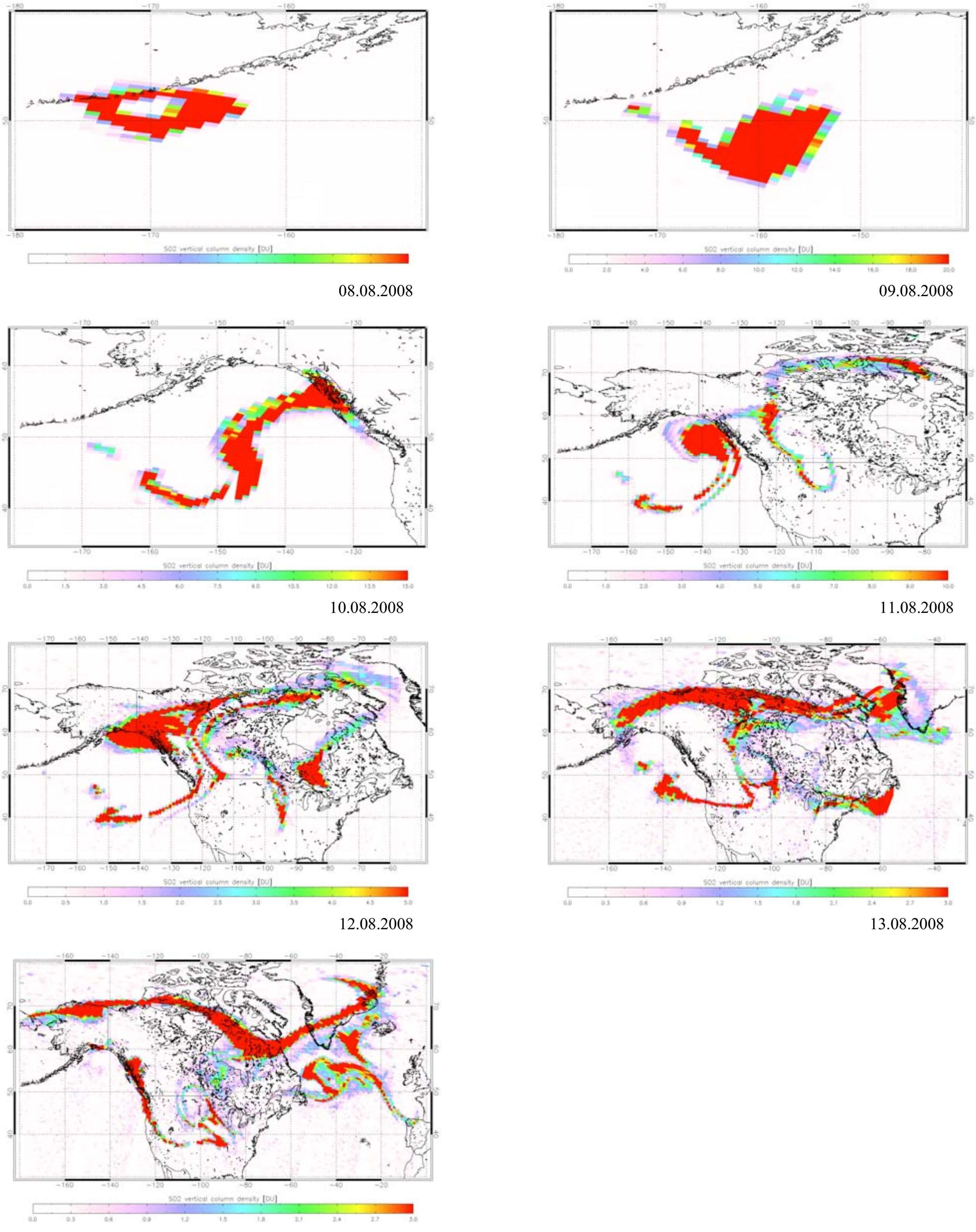

Fig. 1: Volcanic SO_2 plume as detected by the GOME-2 instrument from the Kasatochi eruption starting 08. August 2008. The SO_2 cloud was transported over North-America and reached Europe on the 14. August 2008

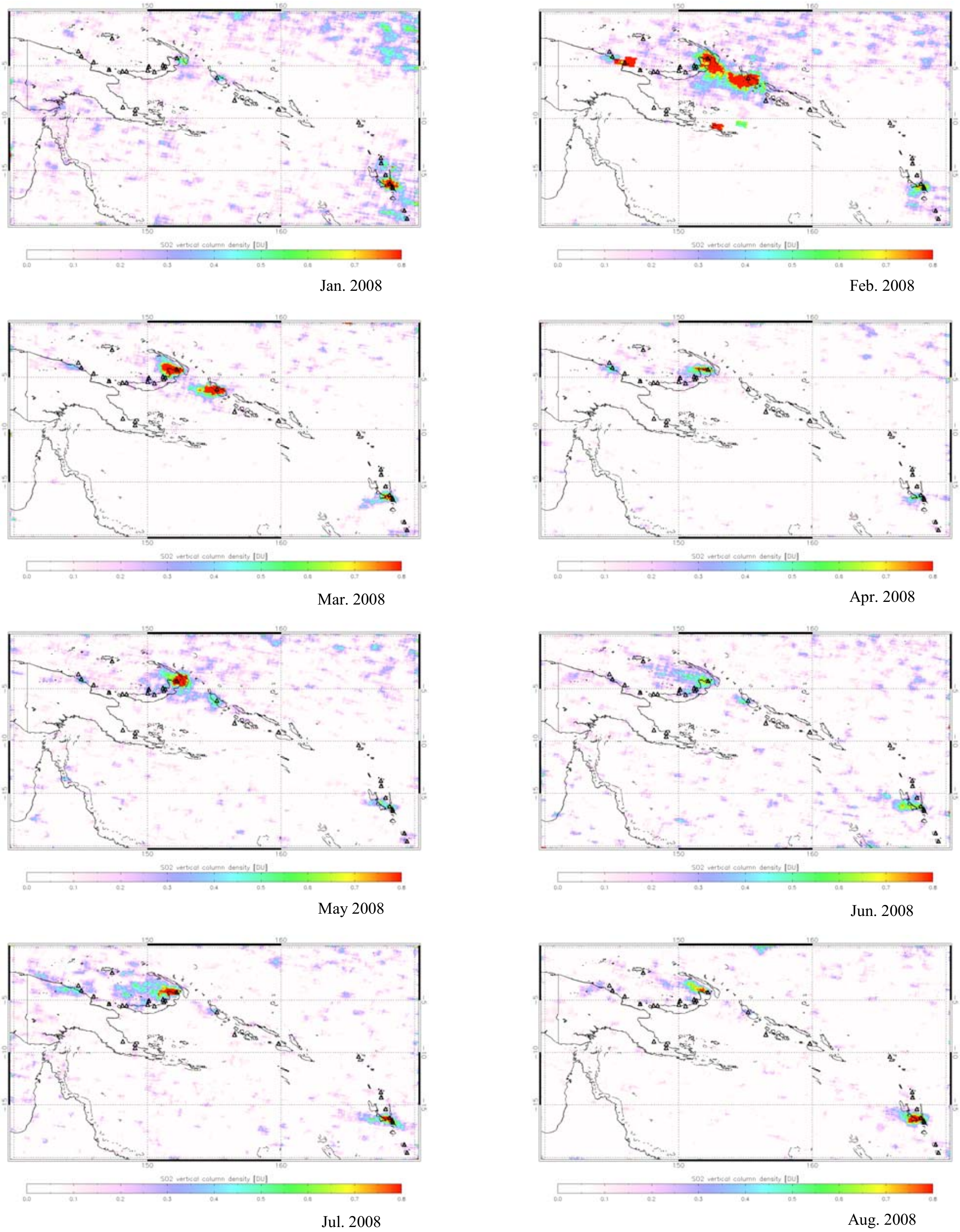

Fig. 2: Monthly averaged SO_2 column amounts measured by GOME-2 from passively degassing volcanoes in the volcanic region Papua New Guinea/ Vanuatu, January 2008 – August 2008

IV. APPLICATIONS IN VOLCANIC EARLY WARNING SYSTEMS

The SO_2 data from the GOME-2 are used in several volcanic early warning services. The GOME-2 SO_2 measurements of are being implemented into the new Volcano Fast Response System (VFRS), Exupéry, developed within the framework of the German Geotechnology Program [3]. Within Exupéry different monitoring techniques applied to volcanoes, including satellite observations, are combined into a prototype of a new mobile VFRS. This system can be deployed on any volcano worldwide in case of volcanic unrest. Another project that makes use of the GOME-2 SO_2 data is the ESA/ DUE project GlobVolcano. Within this project the focus lies on demonstrating the use of EO based information services to support observatories and other users in monitoring volcanic activity. In both projects the daily GOME-2 SO_2 data are being used to detect possible changes in volcanic degassing behavior prior to an eruption. The data will be stored in a GIS database that can be accessed by local authorities and observatories to provide additional daily information in case of volcanic unrest. Within the framework of the Support to Aviation Control Service (SACS) of GSE-PROMOTE the GOME-2 data is used in combination with SCIAMACHY and OMI to monitor the occurrence and development of volcanic eruption plumes. In the case of large SO_2 and ash plumes VAAC (Volcanic Ash Advisory Centre) and other interested parties will be automatically informed, as volcanic ash is a danger to aircrafts and can lead to engine failure. In addition daily volcanic activity maps for different volcanic regions worldwide are supplied in NRT using the GOME-2 SO_2 data at http://wdc.dlr.de/sensors/gome2/.

V. CONCLUDING REMARKS

GOME-2 has proven its ability to detect and monitor daily SO_2 emissions from volcanic eruptions as well as from passive degassing, which makes it a valuable tool for monitoring volcanoes and early warning of volcanic risk.

It is planned to use the GOME-2 SO_2 data in combination with ground-based SO_2 measurements to estimate the detection limit of GOME-2 for volcanic SO_2. In this context we will further optimize the retrieval for the low SO_2 concentrations typically observed in passive degassing situations. Observed patterns of volcanic degassing will be related to other volcanic activity parameters to achieve a better understanding of the processes responsible for volcanic eruptions and make optimal use of the data for early warning purposes. Furthermore the method to estimate the total emitted mass of SO_2 from eruptions and passive degassing will be improved.

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REFERENCES

[1] H.-F. Graf, J. Feichter, B. Langmann, “Volcanic sulfur emisions: Estimates of source strength and its contribution to the global sulfate distribution”, J. Geophys. Res. 1997, 102, 10727 - 10738

[2] S.A. Carn, A.J. Krueger, S. Arellano, N.A. Krotkov, K. Yang, “Daily monitoring of Ecuadorian volcanic degassing from space”, J. Volcanol. Geotherm. Res. (2008), in press, doi:10.1016/j.jvolgeores.2008.01.029

[3] M. Hort, K. Zaksek, “Exupery: the mobile volcano fast response system”, IEEE proceedings of 2nd USEReST workshop, 2008

[4] U. Platt, “Differential optical absorption spectroscopy (DOAS)”, in Air Monitoring by Spectroscopic Techniques. Chem. Anal. Ser. 127, 27-84, John Wiley, New York, pp. 27 – 84, 1994

[5] P. Valks, D. Loyola, “Algorithm Theoretical Basis Document for GOME-2 Total Column Products of Ozone, Minor Trace Gases and Cloud Properties (GDP 4.2 for O3M-SAF OTO and NTO)”, DLR/GOME-2/ATBD/01, Iss./Rev.: 1/D, 26 September 2008

[6] R. J. D.Spurr, T. P. Kurosu, K.V. Chance, “A linearized discrete ordinate radiative transfer model for atmospheric remote sensing retrieval”, J. Quant. Spectrosc. Radiat. Transfer, 68, 689 – 735, 2001

[7] A. Stohl, L. Haimberger, M. Scheele, H. Wernli, “An intercomparison of results from three trajectory models“, Meteorol. Applications 8, 127 – 135, 1999

[8] C. Maerker, K. Seidenberger, T.Erbertseder, M. Rix, P. Valks, J. van Geffen, “ Trajectory matching and dispersion modelling of volcanic plumes utilizing space-based SO2 observations,” IEEE proceedings of 2nd USEReST workshop, 2008.

[9] Smithonian Institution, 2008, Global Volcanism Program, SI/ USGS Weekly Volcanic Activity Reports, http://www.volcano.si.edu/