Satellite Monitoring of Volcanic Sulfur Dioxide Emissions for Early Warning of Volcanic Hazards

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***Abstract*—Satellite-based remote sensing measurements of volcanic sulfur dioxide (SO_2) provide critical information for reducing volcanic hazards. This paper describes the use of SO_2 measurements from the thermal infrared sounder IASI and the UV-VIS instrument GOME-2 in services related to aviation hazard and early warning of volcanic unrest. The high sensitivity of both instruments to SO_2 allows the detection and global tracking of volcanic eruption plumes and makes them a valuable tool for volcanic aviation hazard mitigation. The GOME-2 and IASI SO_2 data are produced in near-real time and distributed to the Volcanic Ash Advisory Centers (VAACS) to assist them in issuing alerts to airlines and air traffic control organizations. Examples of recent eruptions affecting air traffic are presented including Jebel al Tair (Yemen, September 2007), Mount Okmok (Alaska, July 2008), and Mount Kasatochi (Alaska, August 2008). In addition, GOME-2 can detect changes in the SO_2 emissions from passively degassing volcanoes and, therefore, provide critical information for hazard assessment. The monitoring of pre-eruptive degassing by GOME-2 is used in early warning of volcanic activity by a mobile volcano fast response system in combination with numerous other parameters, such as seismicity, deformation, and thermal anomalies.**

***Index Terms*—GOME-2, IASI, MetOp, satellite applications, SO_2 atmospheric measurements.**

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I. Introduction

VOLCANIC eruptions pose a major danger to people living in the vicinity of volcanoes. The fast growing population more, more people living close to active volcanoes, and the growing developments in infrastructure and transportation systems make societies more vulnerable [1]. The region surrounding the volcano is directly affected by the eruption, e.g, due to lava flows, pyroclastic flows, and lahars. 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.

An important indicator for volcanic activity is the emission of trace gases, such as sulfur dioxide (SO_2). Volcanic eruptions and passive degassing of volcanoes are the most important natural source of SO_2 [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. In addition, SO_2 is also produced by anthropogenic activities like power plants, refineries, metal smelting and burning of fossil fuels, but its atmospheric background level is usually very low. The lifetime of atmospheric SO_2 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 directly 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), and as sulfuric aerosols it can also have a cooling effect on the atmosphere (e.g, Pinatubo eruption, 1991) [3].

Satellite-based instruments operating in the ultraviolet (UV) spectral region have played an important role in monitoring and quantifying volcanic 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 [4]. The detection sensitivity for SO_2 was limited to large SO_2 amounts due to the discrete wavelengths that were designed for ozone measurements [5]. The detection limit to measure volcanic and anthropogenic SO_2 greatly improved for the Global Ozone Monitoring Experiment (GOME) [6] launched 1995 onboard the ERS-2 satellite and the Scanning Imaging Spectrometer for Atmospheric Cartography (SCIAMACHY) [7] launched in 2002 onboard the ENVISAT satellite [8]–[11]. 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) [12] on EOS-Aura since 2004 and GOME-2 on MetOp-A since 2006 make it possible to monitor volcanic activity and eruptions on a global scale and daily basis. Both sensors have also proven their ability to detect passive degassing of volcanoes [13], which is particularly valuable for early warning services.

Recently, thermal infrared sounders onboard satellites, such as the Atmospheric Infrared Sounder (AIRS) [14] on EOS-AQUA since 2002 and the Tropospheric Emission Spectrometer (TES), onboard EOS-Aura, have demonstrated their ability to provide an alternative in monitoring volcanic plumes from space [15], [16]. Last but not least, the Infrared Atmospheric Sounding Interferometer (IASI) [17] on MetOp-A is also able to detect SO_2 with an excellent global coverage in combination with small footprints [18]. All these instruments can add valuable information to UV measurements to derive the SO_2 atmospheric loading, as they provide additional nightly measurements, as well as plume altitude estimation.

In this paper, we discuss the global operational SO_2 monitoring with the satellite-based instruments IASI and GOME-2 and the use of these SO_2 measurements in the framework of two important applications related to early warning of volcanic hazard.

First, we give a short overview about the IASI and GOME-2 satellite instruments, followed by a description of the retrieval algorithms for the SO_2 columns and profiles.

The first application focuses on the threat volcanic eruption clouds pose to aviation. Satellite-based observations provide valuable information for detecting and tracking eruption plumes and, therefore, minimize the risk of aircraft encounter with hazardous volcanic clouds [19], [20]. Although volcanic ash is the main hazard to aviation, SO_2 has proven to be an excellent tracer for volcanic eruption clouds, especially if ash detection techniques fail. SO_2 is always released during volcanic eruptions and is a robust marker for the onset of volcanic activity. Therefore, satellite SO_2 observations are frequently being used in addition to ash measurements for aviation hazard mitigation. We describe the use of satellite SO_2 data in the Support to Aviation Control Service (SACS) which is part of the GMES Service Element for the Atmosphere (PROMOTE) [21]. The service has been developed to provide volcanic plume information to the Volcanic Ash Advisory Centers (VAACs), which are the official organizations to issue alerts to airlines and air traffic control organizations of the potential danger of volcanic eruption plumes. In the case of exceptional SO_2 concentrations, SACS sends notifications to the VAACs. As an example, the Kasatochi eruption (Alaska, August 2008), that caused widespread disturbance to aviation operations, is discussed.

In the last part of the paper, we focus on the danger volcanoes pose to their immediate surroundings and the local population. In this context, the use of satellite SO_2 measurements of degassing volcanoes in early warning of volcanic activity is discussed. We describe the application of GOME-2 passive degassing measurements within the Exupéry service, which is concerned with early warning of volcanic unrest [22]. The main focus of Exupéry is on the development of a mobile volcanic fast response system (VFRS) that can be deployed on any volcano worldwide and will assist countries in case of a volcanic crisis.

II. GOME-2 and IASI Instruments

The GOME-2 and IASI instruments on the MetOp-A satellite, launched in October 2006, are part of the EUMETSAT Polar System (EPS) with three polar-orbiting operational MetOp satellites. MetOp-A is flying on a sun-synchronous orbit and has a equator crossing time of 9:30 local time. Further MetOp satellites are to be launched in 2011 and 2015. They will provide a continuous time series of trace gas measurements until 2020. Both GOME-2 and IASI perform operational long-term monitoring of ozone and other atmospheric trace gas columns, including SO_2.

A. GOME-2 Instrument

The Second Global Ozone Monitoring Experiment (GOME-2) on MetOp-A is an improved version of the GOME instrument on the ERS-2 satellite [23]. 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 $\times$ 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 provided 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. The focus of the O3M-SAF is to process, archive, validate and disseminate atmospheric data products of ozone, various trace gases, aerosols and surface ultraviolet radiation. The first step in the processing chain is the production of calibrated and geolocated level 1 radiances (Level 0-to-1 processing), which is performed at EUMETSAT in the Core Ground Segment (CGS). The level 1 products are delivered to DLR and other users via the EUMETCast broadcast system approximately 1:45 h after sensing. The operational level 1-to-2 processing of the SO_2 product is then performed at DLR with UPAS (Universal Processor for Atmospheric Spectrometers), a new generation system for the processing of operational trace gas and cloud property products in near-real time and off-line [24]. UPAS takes as input level 1 irradiances from different sensors. The ground-segment at DLR needs less than 15 min for acquiring the input data, retrieving the trace gas total columns and disseminating the resulting products, which means the level 2 near-real time SO_2 products are delivered via EUMETCast to the end-users approximately 2:00 hours after sensing. The German National Remote Sensing Data Library stores the GOME-2 SO_2 data for enabling the long-term monitoring of global change, and data reprocessing (http://wdc.dlr.de/sensors/gome2) [25].

B. IASI Instrument

IASI measures the outgoing thermal infrared radiation emitted from the Earth and the atmosphere. It records in the nadir mode, complemented by a scan reaching 48.3° degrees on both sides. IASI provides global coverage of the Earth twice daily (around 9:30 a.m. and 21:30 p.m. local time), with a on-ground pixel size of 12 km (four simultaneous pixels) at nadir. It has a large spectral coverage (extending from 645 to 2760 cm^{-1} without gaps) and a relatively good spectral resolution (0.5 cm^{-1}, apodized). The high spatial and temporal sampling, associated with the small pixel size and good radiometric performances makes it a candidate sounder for identifying and tracking local events on the globe. These include among others, volcanic activities through the sounding of SO_2, for which two strong spectral signatures are available in the infrared spectral range. They are the ν_1 band (centered at 1152 cm^{-1}) and the ν_3 band (centered at 1362 cm^{-1}), both covered completely by IASI [26].

As for GOME-2 the IASI Level 0-to-1 processing is performed at EUMETSAT CGS delivering calibrated and geolocated level 1C radiances. IASI calibrated level 1C are routinely processed at the Université Libre de Bruxelles (ULB) both on a near-real time basis (in collaboration with the LATMOS-CNRS in Paris) and in a research mode to provide concentration distributions of climate (e.g, H_2O, CH_4) and chemistry trace gases (e.g, O_3, CO, HNO_3, SO_2). Whenever possible, vertically-resolved information is also extracted.

III. Retrieval of Sulfur Dioxide

A. GOME-2 Retrieval Algorithm

SO_2 columns are retrieved from GOME-2 UV backscatter measurements of sunlight in a two-step procedure [27]. In a first step, slant column densities (SC) of SO_2 are determined using the well established Differential Optical Absorption Spectroscopy (DOAS) method [28] 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) [29]. Fig. 1 illustrates the SO_2 absorption features in the backscattered Earthshine radiance used in the DOAS slant column retrieval, as measured by GOME-2 for the Kasatochi eruption on 8 August 2008.

In the 315–326 nm wavelength range used for the retrieval, there is a strong interference of the SO_2 and ozone absorption signals, especially at high solar zenith angles. Therefore, an interference correction needs to be applied to the SO_2 slant column values [27].

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 $\mathrm{VC} = \mathrm{SC}/\mathrm{AMF}$.

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

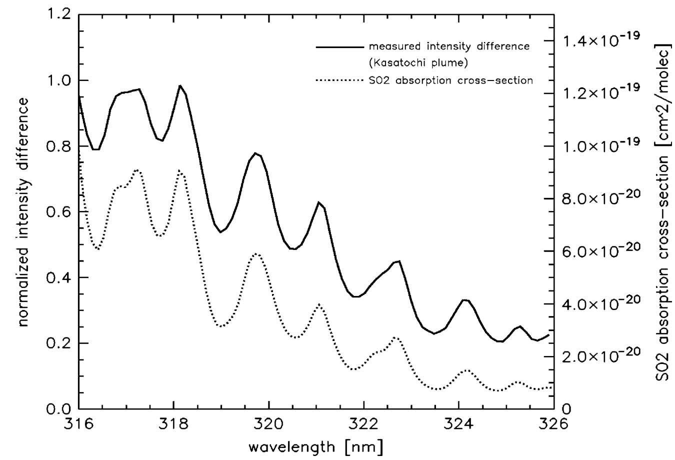

Fig. 1. Normalized intensity difference $(\ln(\mathrm{I}/\mathrm{I}_0)_{\text{inside plume}} - \ln(\mathrm{I}/\mathrm{I}_0)_{\text{outside plume}})$ for the Kasatochi eruption on 8 August 2008, as measured by GOME-2 (solid line) illustrating the strong SO_2 absorption features used by the DOAS retrieval method. The dashed line denotes the SO_2 absorption cross-sections in the UV wavelength region.

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 volcanic plume heights: 2.5, 6, 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 [30].

An initial validation of the GOME-2 total SO_2 columns with ground-based observations and other satellite measurements has been carried out [31]. 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. 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. [31].

B. IASI Retrieval Algorithm

Recently, a fast and efficient volcanic mask was developed for IASI, using the SO_2 signatures of the ν_3 band [17]. With the latter, all major eruptions since IASI was launched in October 2006 have been successfully captured and tracked in space and time, while totally avoiding false alerts. The detection of SO_2 is based on the direct detection of absorption lines of SO_2 in the thermal radiance spectra of IASI; it gives an SO_2 index as a

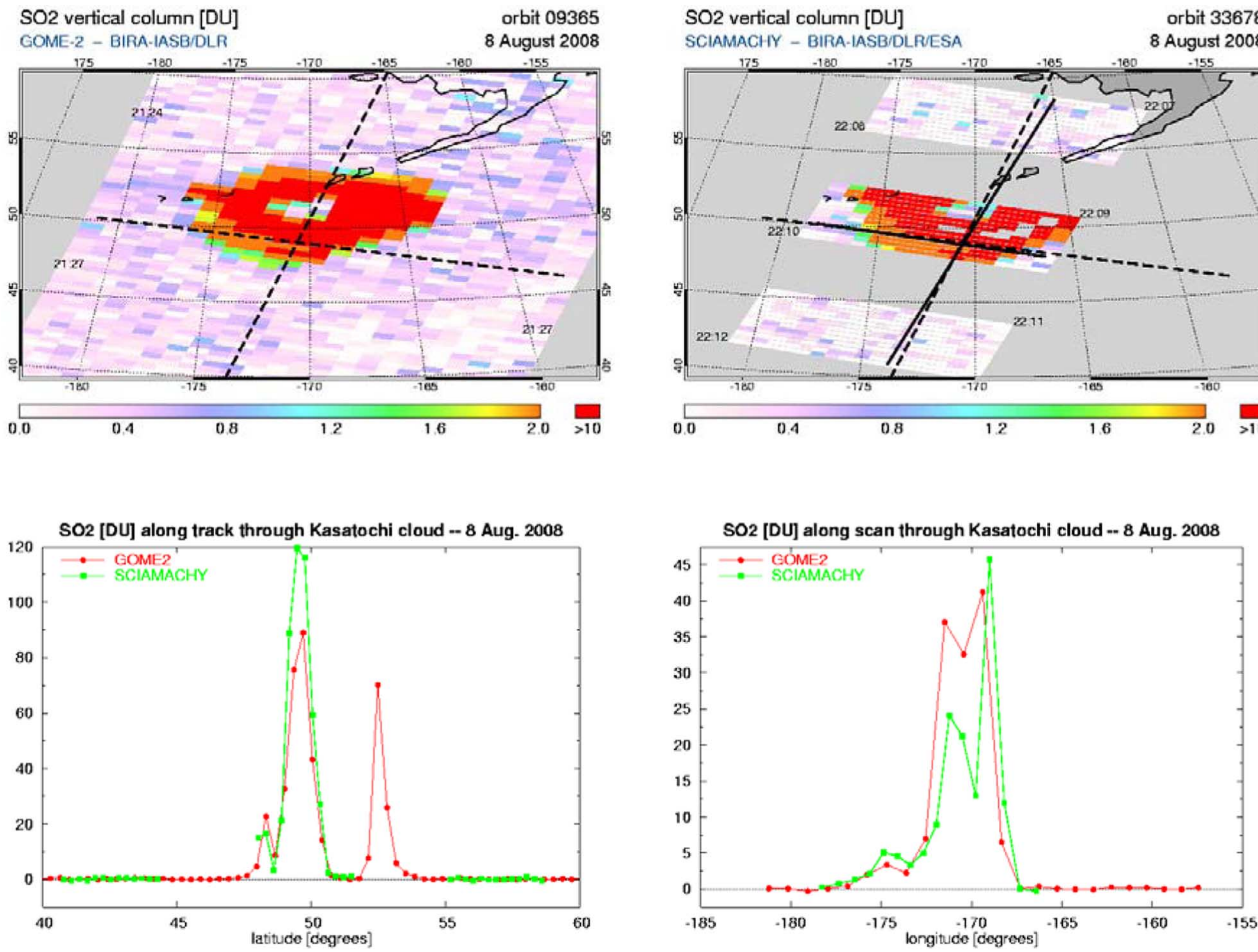

Fig. 2. Along-track and along-scan lines in the GOME-2 (dashed) and SCIAMACHY (solid) orbit used for a direct pixel-to-pixel comparison of data on 8 August 2008 (top) and comparison of the total SO_2 column (bottom). Differences in the observed total SO_2 columns can mostly be explained by differences in the retrieval methods for the two instruments [31]. 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.

brightness temperature difference (in Kelvin units). The advantage of this approach is that it is computational very fast. The absorption and reference channels were chosen as to maximize the sensitivity above 3 km. The downside of this approach is that it only provides an index, and not total columns. In off-line mode, concentrations and vertical profiles of SO_2 can be retrieved using *Atmosphit*, a sophisticated line-by-line radiative transfer model, which can do inverse retrievals using the optimal estimation method. The optimal estimation method is a constrained inverse calculation, where a simulated spectrum is fitted to the observed spectrum by adjusting relevant atmospheric constituents (such as SO_2). Full details of the algorithm and its implementation for nadir-viewing satellites can be found in [17] and [32]. A major advantage of this method is that it can also be used to extract vertical profiles of SO_2 (and, hence, can be used to estimate the altitude of a plume) as illustrated in Fig. 3. This method can also be used to detect and retrieve concentrations of SO_2 at relatively low altitudes, as shown in Fig. 4, which illustrates the passive degassing of the Kilauea volcano (Hawaii).

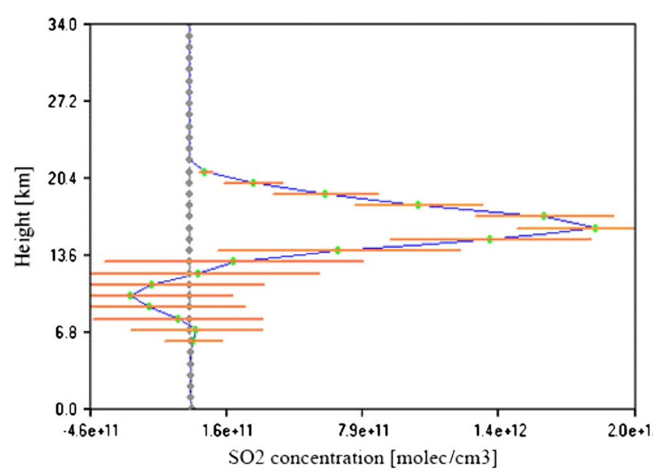

Fig. 3. Sample vertical profile of SO_2 for the Jebel at Tair eruption (Red Sea) on 30 September 2007, retrieved from an IASI spectrum using the optimal estimation method.

C. Back Trajectories Calculations

For both instruments the detected SO_2 plume can be tracked to the emission source using the FLEXTRA model [33]. Calculating ensembles of trajectories allows determination of the origin of the SO_2 plume and the effective emission height [34]. The estimation of the plume height is particularly important for the correct quantitative determination of the SO_2 loading. For this purpose, an ensemble of $\sim$1000 trajectories is started at the

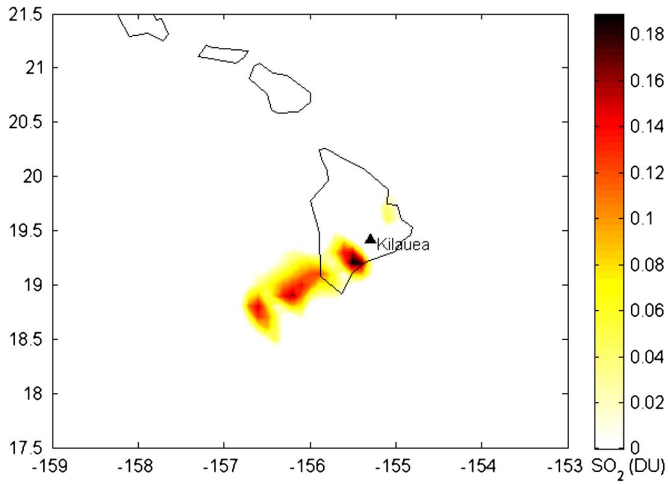

Fig. 4. Passive degassing from Kilauea (Hawaii), 26 May 2008, as measured from IASI observations.

location of the GOME-2 pixel containing the maximum SO_2 amount. Trajectory density maps are calculated using ECMWF 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 plume height. Trajectory and dispersion modeling for volcanic eruptions will be discussed in detail in a separate paper currently in preparation.

IV. Aviation Hazard Mitigation

Volcanic eruptions can inject large quantities of volcanic ash and gases into the atmosphere. Depending on the strength of the eruption the height of the emissions can vary between the summit height of the volcano up to 20 km or higher (e.g, Pinatubo, Philippines, 1991). The ash emitted by volcanic eruptions is known to be the primary hazard to aviation in volcanic clouds. The ash can cause severe damages to aircraft from disrupting avionics and navigation systems, limiting the view of the pilots and severely scratching forward facing surfaces of aircraft to stalling engines as a result of ash melting in the aircraft's engines [35]. Most dangerous are explosive magmatic eruptions where the thermal energy allows the eruption plume to reach the cruising altitudes of jet aircraft. Effusive eruptions are less energetic but the eruption plumes can sometimes reach altitudes of 9–11 km where they become hazardous for aviation, e.g, eruption of Jebel al Tair, September, 2007 [36] and Mount Etna, May, 2008. Atmospheric winds can transport the ash and gases rapidly over long distances; especially within the jet stream. Volcanic clouds occupying the jet stream are particularly hazardous as aircrafts use the same phenomenon to reduce their travel times and fuel consumption. Besides ash, volcanic eruption clouds contain large amounts of gases as these are the driving forces during explosive eruptions. Typically the dominant gases are water vapor, carbon dioxide, and sulfur dioxide. Of these gases SO_2 is itself a hazard to aircraft as it reacts with water to form sulfuric acid (H_2SO_4), which is highly corrosive and may, therefore, damage the paint and windows of aircraft and can create sulfate deposits in the engines. The latter can block the cooling holes and lead to engine overheating [37], [38].

With approximately 60 eruptions per year and increasing volumes of jet aircraft traffic, more than 90 aircraft are known to have suffered severe damage after the encounter with volcanic ash clouds. In some cases, this resulted in the temporary loss of one or more engines during the flight. Since the threshold ash concentration that poses a threat to aircraft is currently unknown [39], the safest procedure for aircraft is to stay clear of volcanic clouds. Many airlines operate a "zero tolerance policy" regarding volcanic ash [40]. Onboard detection of volcanic ash clouds is not possible, as aircraft radar cannot detect micron size particles and SO_2 is a colorless gas.

Of the main components of volcanic clouds, SO_2 is the most robust indicator for volcanic activity. Direct measurements of volcanic aerosol using IR sensors or the aerosol absorption index are also being used to track hazardous eruption clouds. However, these techniques can fail if for example the ash particles at higher altitudes are encased in ice or if the volcanic cloud is very dilute. Further, it can be difficult to distinguish between volcanic aerosols and other types of aerosols; hence, SO_2 is used as a marker for eruptive activity. For example, GOME-2's high sensitivity to low SO_2 amounts and its almost daily global coverage make it possible to detect most volcanic eruptions regardless of magnitude. As described in Section II-A DLR provides GOME-2 SO_2 products in near-real time (2 hours after sensing). A web-based navigation tool (http://wdc.dlr.de/sensors/gome2) allows searching for events in user selected regions, time period and SO_2 amounts. Being less sensitive to SO_2 especially at lower altitudes, IASI has the advantage of providing night time images and offers a higher spatial resolution due to smaller pixel size. In addition, the IASI measurements can be used to retrieve profile information. The capability of both instruments to track volcanic SO_2 over long distances has been demonstrated for several recent eruptions, e.g, Jebel al Tair in 2007, Okmok and Kasatochi in 2008. Although the SO_2 and ash may separate into distinct clouds as the ash drops to lower altitudes due to gravity effects [41], [42] and may be transported into different directions under conditions of vertical wind shear, the presence of SO_2 is a good indicator for volcanic eruption plumes and the presence of ash.

A. *Support to Aviation Control Service*

The Support to Aviation Control Service (SACS) has been designed as a service based on satellite measurements to provide volcanic plume information to the Volcanic Ash Advisory Centres (VAACs) [21]. The aim of SACS is the near-real time delivery of SO_2 and ash data related to volcanic eruptions derived from satellite measurement, and the tracking of volcanic plumes. The data will assist the VAACs in advising airlines on rerouting aircraft and flight cancellations. The main users are the VAACs in London and Toulouse covering Europe and Africa, but in principle the geographical coverage of the service is world-wide.

SACS uses SO_2 data derived from SCIAMACHY, GOME-2, and OMI, which allows multiple measurements a day, and rapid detection of volcanic SO_2 clouds. The SO_2 data and images are stored in a database, and are accessible to the VAACs and other

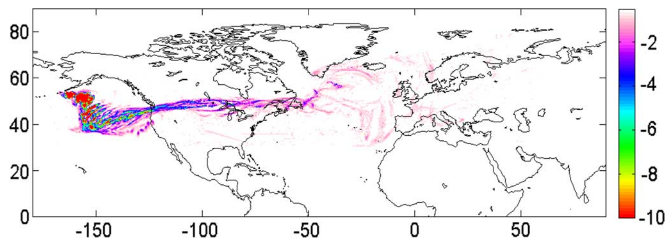

Fig. 5. Two-week integrated view of the SO_2 flag (in Kelvin units) from the eruption of Mount Okmok, Aleutian Islands, on 12 July 2008 as seen from IASI/ MetOp-A.

users via the internet. The SO_2 is plotted in global maps with close-up maps for a total of 62 predefined geographical regions covering all active volcanoes.

Criteria for "exceptional SO_2 concentrations" were set up using archived SO_2 data together with a list of known volcanic eruptions. In case "exceptional SO_2 concentrations" are detected by the satellite instruments, the near-real time system will provide a notification via e-mail to the VAACs. The notification contains basic information regarding the detected event, start time and location of the observation and the peak SO_2 value observed. In addition, the user has access to images of the affected geographical regions with SO_2 concentrations, cloud cover fraction and information on the location of volcanoes via an internet link (http://sacs.aeronomie.be).

SACS plans to use backward trajectories to determine the origin and the plume height of the SO_2. Forward trajectories, based on forecast meteorological fields, will provide information on the motion of the volcanic cloud.

Based on the IASI SO_2 retrieval system, ULB is also running in near-real time an SO_2 alert system since November 2008. The alerts are sent out by email and complemented by images directly available on the web (http://cpm-ws4.ulb.ac.be/Alerts/index.php). This website can also be consulted to retrieve information on older events. As the retrieval technique is negligibly affected by SO_2 in the boundary layer (eg pollution or passive degassing of volcanoes) it is an ideal tool to be used for aviation hazard mitigation. The IASI early detection filter is currently being implemented in the Toulouse VAAC. As an illustration, Fig. 5 shows a two-week integrated view of the SO_2 flag after the eruption of Mount Okmok on 12 July 2008.

B. *Eruption of the Kasatochi Volcano*

The eruption of the Kasatochi volcano on 7 August 2008 is a good example on how satellite measurements can provide valuable information on an eruption posing a danger to aviation, as in the region of the Aleutian Island chain the density of volcanoes is very high but most of these volcanoes are not regularly monitored. Three major eruptions emitted large amounts of volcanic ash and gas into the atmosphere that rose to a height of at least 10 km (Fig. 6 and Fig. 7), an altitude where they are a major hazard to aircraft. Low levels of ash concentration made it difficult to use ash absorption features to track the cloud using satellite instruments. Therefore, satellite SO_2 measurements were used to trace the eruption cloud. Due to the high altitude of the eruption plume, the SO_2 was located above the clouds.

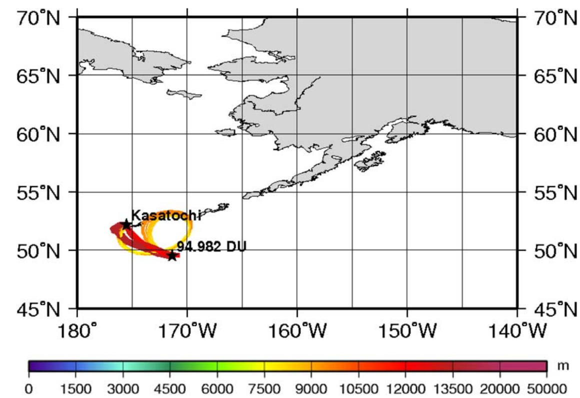

Fig. 6. FLEXTRA analysis for plume height determination for the Kasatochi eruption on 7 August 2008. The trajectories show, that the volcanic eruption plume reached altitudes of more than 10 km.

The SO_2 plume was first detected during the GOME-2 overpass on 8 August. GOME-2 measured maximum SO_2 column amounts of $\sim$150 DU the first day after the eruption. (1 DU corresponds to a total mass of approximately 91.5 tons of SO_2, for a GOME-2 pixel size of 40 km $\times$ 80 km). A first estimate from the GOME-2 data of the total erupted mass of SO_2 during the Kasatochi eruption yields about 1.2×10^6 tons of SO_2. The volcanic cloud was transported across North America intersecting some of the main air traffic routes in that region, as most intercontinental flights from the USA to Asia fly over Alaska. One week after the eruption the SO_2 cloud reached Spain on 14 August (Fig. 7). The SO_2 cloud could be tracked for several weeks as it was distributed all over the northern hemisphere, during this time it triggered multiple SACS alerts.

The eruption of the Kasatochi volcano caused 44 Alaska Airline flights to be cancelled between Anchorage and the US West Coast leaving about 6000 passengers stranded. Flights from other US airlines had to be cancelled or diverted as well. In addition several aircraft encounters with the volcanic cloud from the Kasatochi eruption were reported. Numerous pilots reported smelling sulfurous odors and a hazy, brown cloud at cruise altitudes as long as two weeks after the eruption. Flights had to be diverted around the cloud or their flight level had to be changed to fly above or below the volcanic cloud [43].

V. Monitoring Volcanic Unrest

Most of the world's potentially active volcanoes are not monitored on a regular basis, of the ones known to have erupted in historic times, less than 25% have basic monitoring and little more than 20 volcanoes have a well established monitoring network [44]. Furthermore many of the most explosive eruptions since 1800 have occurred at volcanoes that had not shown any activity for several thousand years [45]. The danger associated with volcanoes is not restricted to eruptions, further volcanic hazards are earthquakes, dangerous gases (e.g, Lake Nyos, Cameroon) [46], flank movements and ground deformation, tsunamis (e.g, Stromboli, Italy) [47] landslides and climatic changes (e.g, eruption of Mount Pinatubo, Philippines, 1991) [3]. Monitoring and forecasting of volcanic activity in combination with early warning of volcanic risk is, therefore, of major importance.

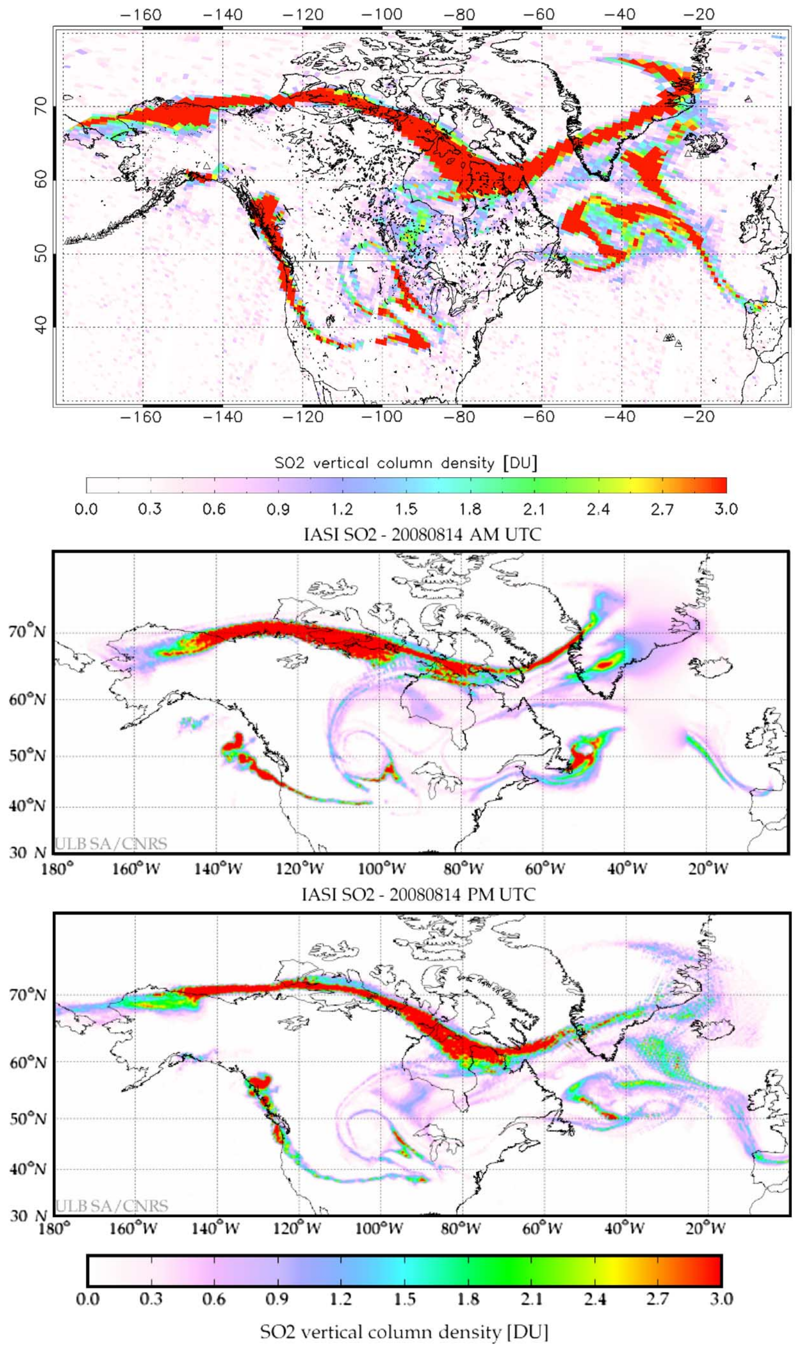

Fig. 7. Volcanic SO_2 plume from the Kasatochi eruption (Aleutian Islands) as measured on 14 August 2008, by GOME-2 (top) and by IASI, once in the morning (middle panel) and once in the evening (bottom panel). Kasatochi volcano erupted on 7 August 2008. The SO_2 cloud had been transported over North America and reached Europe one week after the eruption.

The project Exupéry, as part of the German GEOTECHNOLOGIEN program, aims at developing a mobile volcano fast response system in order to support countries in case of a volcanic crises if help is requested. The system is especially dedicated to supporting third world countries in dealing with volcanic risk. In the past response teams for volcanic crisis have proven to be very successful. The first rapid response system Volcano Disaster Assistance Program (VDAP) [44] was successful in managing the crisis connected to the Pinatubo eruption (Philippines, 1991). Other successfully predicted eruptions include Mt. St. Helens, USA, in 1980 [48] and Merapi, Indonesia, in 2006.

The Exupéry system (www.exupery-vfrs.de) is designed for operating standalone or as a supplement to an existing monitoring network providing additional information on volcanic activity parameters that are not routinely observed (i.e., SO_2 measurements, thermal anomalies, deformation measurements). Using this additional information further insight into the volcanic processes is possible. Apart from traditional monitoring techniques like seismology, the system includes ground-based observations of gas fluxes and surface deformation. One of the novelties of the system is the utilization of space-based observations, including monitoring of ground deformation, thermal anomalies and volcanic SO_2 emissions,

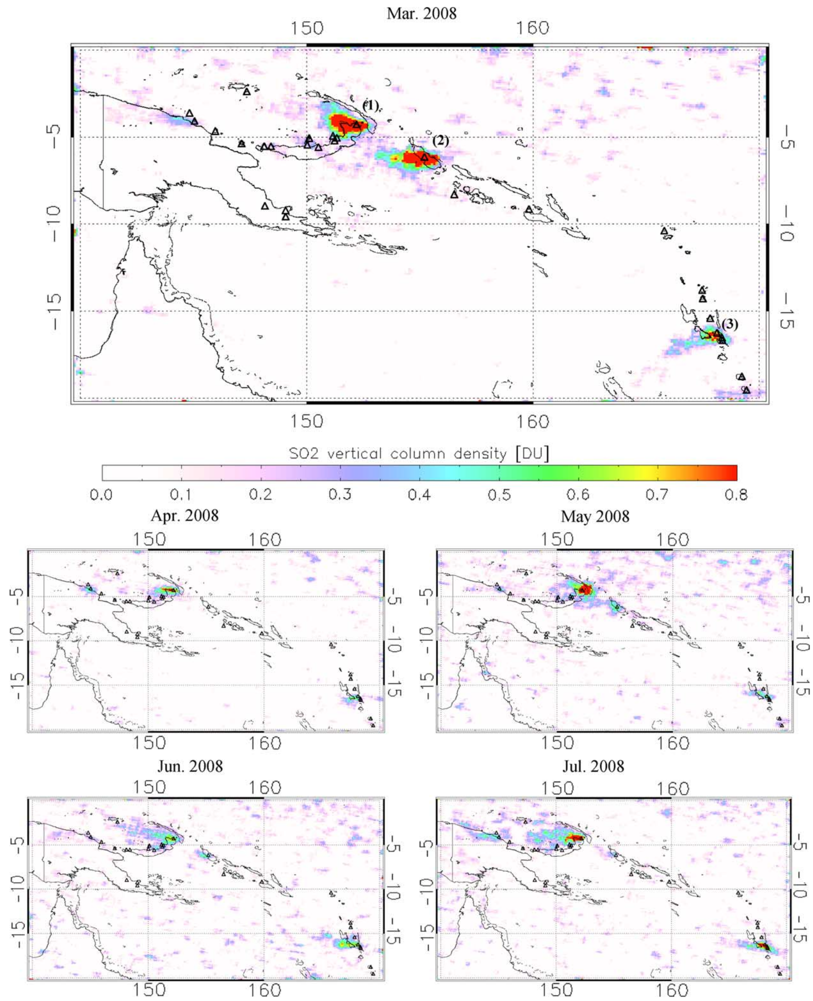

Fig. 8. Monthly averaged SO_2 column amounts measured by GOME-2 from passively degassing volcanoes in the volcanic region Papua New Guinea/Vanuatu, March 2008–July 2008. The degassing volcanoes are Rabaul (1), Bagana (2), and Ambrym (3).

using GOME-2. The Exupéry system can be installed quickly due to intelligent cable free communication between the different stations and the data center, which is a major advantage. All acquired data are stored in a central data base together with data from an existing monitoring network. The data are then partially analyzed in near-real time and visualized via a GIS system. Activity parameters, such as automatically estimated alert levels, are derived from the data using various models and data evaluation is carried out including recommendations for crisis management. The whole system undergoes a test phase on the Azores from April–August, 2009.

As Exupéry focuses on early warning of volcanic risk, the ability of satellite instruments to detect volcanic degassing prior to an eruption is of great importance. Increasing activity at many volcanoes is indicated by increased gas fluxes at the surface. Rising high-temperature magma releases SO_2 and, therefore, increased SO_2 degassing can often be a precursor of a magmatic eruption. This connection between gas flux and eruption has been exploited in ground-based UV remote sensing measurements [49]. Detection of pre-eruptive passive degassing with satellite measurements is challenging as the emission plumes are typically of low altitude, because the emissions are noneruptive and the concentrations of SO_2 will be relatively low. However, the newest satellite instruments, OMI and GOME-2, have proven their ability to detect passive degassing patterns for several volcanoes. For example, it has been possible to relate daily measurement of passive SO_2 degassing at Ecuadorian volcanoes to eruptive activity at these volcanoes [13]. In addition to the detection of the degassing patterns, one major task is to link the observed SO_2 patterns to the volcanic activity in combining them with measurements of other volcanic parameters. Within Exupéry, daily images of SO_2 are provided in near-real time for volcanic regions worldwide. The daily GOME-2 SO_2 data are being used to detect possible changes in volcanic degassing behavior prior to an eruption. Threshold levels for the SO_2 are determined to yield special SO_2 alerts in case of high SO_2 amounts, indicating exceptional SO_2 degassing levels. Furthermore additional information concerning location and maximum observed SO_2 value is supplied.

An example for the ability of the GOME-2 instrument to monitor changes in the degassing behavior of volcanoes is provided in Fig. 8 where monthly averaged SO_2 maps for the geographical region of Papua New Guinea/Vanuatu are shown. The three main degassing volcanoes in this area are clearly visible in the March 2008 image (Fig. 8, 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. Of these three volcanoes, Rabaul shows the most frequent SO_2 emission and 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. From January to August 2008 Rabaul volcano emitted approximately 2.5×10^5 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 [50]. The other two volcanoes show a higher variability in the SO_2 emissions, with a total emitted amount of $\sim 1.7 \times 10^5$ tons SO_2 for Bagana and $\sim 1.9 \times 10^5$ tons for Ambrym.

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.

VI. Concluding Remarks

We have presented the use of satellite-based detection of volcanic SO_2 for the early warning of volcanic risk. The GOME-2 and IASI instruments provide a new tool in monitoring long-range transport of volcanic clouds, detection of small eruptions and investigation of pre-eruptive degassing. GOME-2 has the higher sensitivity especially for SO_2 at lower altitudes, whereas IASI also offers night-time observations, a higher spatial resolution and an estimation of the altitude of the plume.

These measurements provide valuable information in reducing volcanic hazard to aviation and in managing volcanic unrest. With commercial and freight air traffic growing globally the risk of aircraft encounter with hazardous volcanic clouds is increasing, as many volcanoes are not regularly monitored and atmospheric winds can rapidly distribute ash and gas. The GOME-2 and IASI instruments have demonstrated the ability to track volcanic clouds for a range of eruption magnitudes and for extended time periods. The near-real time SO_2 data are distributed to the Volcanic Ash Advisory Centers to assist them in advising airlines and air traffic control organizations.

GOME-2's ability to monitor pre-eruptive degassing from volcanoes gives new possibilities in early warning of eruptive activity, as increased gas fluxes are often an indicator for increased volcanic activity [49]. Space-based SO_2 measurements of volcanic degassing provide regular information on remotely located volcanoes and supplement existing observations, for example from seismic networks. For optimal interpretation, in the framework of the Exupéry volcanic fast response system the GOME-2 SO_2 measurements are combined with numerous other observations, including seismicity, deformation, thermal anomalies and ground-based trace gas measurements.

The applications presented in this paper show the value of space-based monitoring of volcanic SO_2 in early warning of volcanic hazards. For effective aviation hazard mitigation plume height information is crucial; therefore, we envisage a combined estimation of the height of the observed volcanic plume from the GOME-2 and IASI measurements. With Exupéry it is possible to achieve a better understanding of the processes responsible for volcanic eruptions and to make optimal use of data for early warning purposes by relating patterns of volcanic degassing to other volcanic activity parameters. We expect to further improve the GOME-2 measurements of SO_2 degassing by optimizing the retrieval methods for low SO_2 concentrations typically observed in passive degassing situations and by synergetic use of ground-based measurements.

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