

# MONITORING OF VOLCANIC ACTIVITY FROM SATELLITE AS PART OF GSE PROMOTE

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## ABSTRACT

One of the services in GSE PROMOTE Stage II is the Support to Aviation Control Service, SACS for short. The aim of SACS is to deliver in near-real-time data derived from satellite measurements regarding SO<sub>2</sub> and aerosol emissions possibly related to volcanic eruptions, and where possible to track volcanic plumes. In case of "exceptional SO<sub>2</sub> concentrations", SACS will issue a notification by e-mail to interested parties.

Together with information from other sources, data from SACS can assist official organisations – the Volcanic Ash Advisory Centres (VAACs) – when issuing alerts regarding volcanic activity to air traffic control and airline organisations, so as to help them to decide whether to reroute aeroplanes in case of volcanic clouds.

This paper gives an overview of the background and structure of SACS and presents a few example results. More information and links to the data products (maps and data files) can be found via the SACS web portal <http://sacs.aeronomie.be/> or via the PROMOTE website <http://www.gse-promote.org/> under "special services".

Key words: Volcanism, SO<sub>2</sub>, volcanic ash.

## 1. INTRODUCTION

Volcanic eruptions may eject large amounts of ash (aerosols; cf. Fig. 1) and trace gases such as sulphur dioxide (SO<sub>2</sub>) into the atmosphere. These ejecta can have considerable impact on the safety of air traffic and on human health. Ground-based monitoring is carried out at only a limited number of volcanoes: most volcanoes are not monitored on a regular basis, in particular the remotely located volcanoes.

Global observations of SO<sub>2</sub> and aerosols derived from satellite measurements in near-real-time may therefore



Figure 1. Ash cloud of the Grímsvötn volcano eruption, November 2004. [Image: Matthew J. Roberts; Source: [http://hraun.vedur.is/ja/englishweb/eruption\\_grimsvotn.html](http://hraun.vedur.is/ja/englishweb/eruption_grimsvotn.html)]

provide useful complementary information to assess possible impacts of volcanic eruptions on air traffic control and public safety.

The Support to Aviation Control Service (SACS) will focus on the timely delivery of SO<sub>2</sub> data derived from different satellite instruments, such as SCIAMACHY, OMI and GOME-2. This will allow for monitoring the occurrence and extension of volcanic eruptions and plumes.

On the basis of selection criteria of exceptional SO<sub>2</sub> emissions, the Service will send notifications by e-mail to interested parties, with a reference to specific pages at the website. In addition to this, high-resolution images taken with a 15 min scan cycle by the SEVIRI instrument of Europe and Africa will provide information to trace volcanic ash plumes by way of a volcanic aerosol indicator.

In the event of an exceptional SO<sub>2</sub> concentration, the location of the SO<sub>2</sub> peak value will be used to start backward and forward trajectories on the basis of meteorological data (wind, temperature, pressure, etc.). These trajectories will facilitate the interpretation of the satellite



Figure 2. Part of an B-747 engine after flying through an ash plume, June 1982. [Source: <http://www.geo.mtu.edu/departments/classes/ge404/gcmayber/engine.html>]

observations, will provide an indication of the location of the source of the  $\text{SO}_2$  and of the height of the plume, and will forecast the motion of the volcanic plume.

## 2. HAZARD TO AVIATION

Volcanic eruptions can emit large quantities of rock fragments and fine particles (ash) into the atmosphere, as well as several gases, such as  $\text{CO}$ ,  $\text{SO}_2$ ,  $\text{BrO}$ , and water vapour. The rock fragments usually fall back to Earth quite quickly. The ash and the gases, however, can rise high up into the troposphere and even reach the lower stratosphere, up to 15 or even 20 km. The elevation reached by the material depends on the strength of the volcanic eruption, which in turn depends on the kind of volcano that erupts.

The ash emitted by volcanic eruptions is a major hazard to aviation. The ash can, for example, severely damage the material of the aircraft, it can clog its sensors, it can limit the view of its pilots, and it can severely scratch ("sandblast") the windows of the aircraft. And when it enters the aircraft's engines, the ash can melt (it has a melting point of about  $1100^\circ\text{C}$ ), as a result of which the engine may fail (Fig. 2).

More than 90 aircraft have sustained damage after flying through volcanic ash clouds. In at least 7 cases this resulted in temporary loss of power on one or more of the engines during flight. In three cases, a Boeing 747 lost all four engines (1982 and 1989); fortunately the engines could be restarted once outside the ash cloud, but meanwhile the aircraft had dropped several km. The ash emitted during the eruption of the Pinatubo volcano (1991) has damaged aircraft as far away from the volcano as 1000 km.

Every year there are about 60 volcano eruptions. On average the ash cloud of 10 of these eruptions reach flight level along major aircraft routes. The total cost of the

damage sustained by aircraft due to volcanic ash clouds in the period 1982-2000 is estimated at 250 million US dollar. So far none of the incidents have resulted in fatal accidents or of people being injured.

Of the gases emitted during a volcano eruption, sulphur dioxide ( $\text{SO}_2$ ) is in itself also a hazard to aircraft, as  $\text{SO}_2$  reacts with water vapour to form sulphuric acid ( $\text{H}_2\text{SO}_4$ ), which is corrosive and can therefore scratch the paint and the windows of the aircraft, and it can create sulphate deposits in the engines. Depending on the kind of eruption, the  $\text{SO}_2$  may be inside the ash cloud, but it may also be above or below the ash cloud. In general the ash will drop due to gravity effects faster than the  $\text{SO}_2$ , so that some distance away from the volcano the ash and  $\text{SO}_2$  clouds may be separated.

From all these considerations it is clear that the safest procedure for aircraft is to stay clear of volcanic clouds. Pilots cannot always see an ash cloud (e.g. at night) and the ash does not show up on radar. And  $\text{SO}_2$  and  $\text{H}_2\text{SO}_4$  are colourless gases, and therefore invisible. If it penetrates into the aircraft; sulphuric acid is noticed easily because of its strong smell, but then the aircraft is already inside the cloud. Hence, it is of major importance to know in advance where volcanic clouds are and what elevation they reach.

Observations by satellite based instruments can assist in this. On the one hand, some satellite instruments can detect volcanic ash directly, though this technique is still under development. On the other hand, the detection of  $\text{SO}_2$  does not only show where  $\text{SO}_2$  clouds are, but can also help pinpoint volcanic ash clouds.

In addition it is known that some volcanoes emit  $\text{SO}_2$  prior to a (major) eruption. This so-called passive degassing will not send the  $\text{SO}_2$  high up in the atmosphere, because the emissions are not explosive, and the emission will usually be only in low concentrations. It is quite difficult to detect low concentrations of  $\text{SO}_2$  near ground level or in the lower troposphere. But if it is possible to detect these emissions, it will provide additional information for early warning systems of upcoming volcano eruptions.

## 3. USERS OF SACS

The Volcanic Ash Advisory Centres (VAACs) are the official organisations to gather information on volcanic ash clouds and on the basis of that issue advices and alerts to air line and air traffic control organisations on the possible danger of volcanic clouds.

The VAACs are part of an international system set up by the International Civil Aviation Organization (ICAO) called the International Airways Volcano Watch (IAVW), which was founded at an ICAO meeting in 1995. VAAC responsibilities to aviation users include:

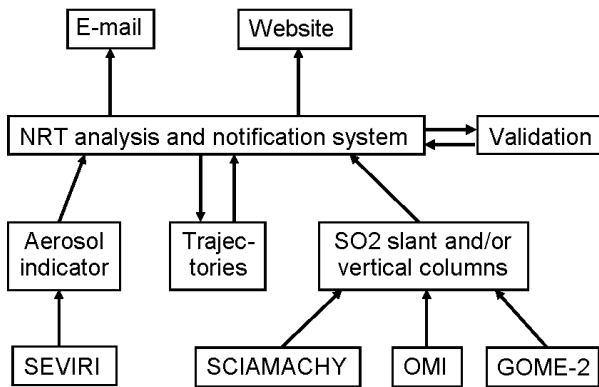


Figure 3. Schematic overview of the structure of SACS.

- Utilise satellite data, pilot reports, and other sources of information to detect and track ash clouds.
- Use trajectory/dispersion models to forecast the motion of ash plumes.

The core users of the SACS data are the London and Toulouse VAACs, who cover Europe and Africa. The data from SACS will, however, not be restricted to Europe and Africa because the number of active volcanoes in Europe and Africa is too small for validation of the Service, and other regions in the world may be of interest to future users.

For more information on the VAACs, the reader is referred to <http://www.metoffice.gov.uk/aviation/vaac/>

#### 4. OVERVIEW OF THE SERVICE

This section provides a short overview of the structure and geographic coverage of SACS and the way the data is presented via the website. At the same time some example results are shown.

##### 4.1. Processing system

The structure of SACS is schematically represented in Fig. 3. The near-real-time analysis system gathers  $\text{SO}_2$  data derived from measurements of several satellite instruments. The service is being set up using  $\text{SO}_2$  data from SCIAMACHY; in the near future  $\text{SO}_2$  data from OMI and GOME-2 will be added. The system stores the data and images (maps) of all the geographic regions on a website and in an archive.

As mentioned above, the geographic coverage of SACS is in principle world-wide. For this reason,  $\text{SO}_2$  is retrieved for all satellite orbits available and plotted in global maps. To facilitate users, close-up maps of pre-defined geographic regions are made available as well. For the service a total of 42 geographic regions of 30 by 30 degrees

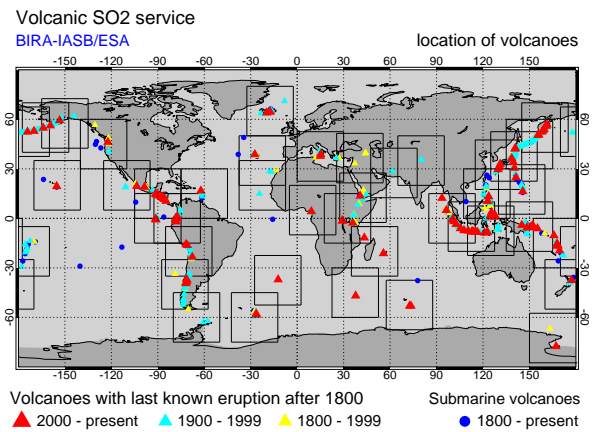


Figure 4. The location of the 42 geographic regions of 30 by 30 degree which have been pre-defined for SACS.

are defined, centred around volcanoes that have erupted since the year 1800, as shown in Fig. 4.

This does not mean that volcanoes that have been silent for longer are no threat: volcanoes that have erupted last, say, 3000 years ago can still be a threat. But those volcanoes can always be found in one of the pre-defined regions. The volcanoes not covered by the regions shown in Fig. 4 are submarine volcanoes, which is not a problem, since we are unlikely to ever measure  $\text{SO}_2$  emitted by submarine volcanoes.

Images (maps) of  $\text{SO}_2$  data for each of the pre-defined regions are made and put on the website. Fig. 5 shows as example an  $\text{SO}_2$  map based on SCIAMACHY data. In view of the way SCIAMACHY measures, the "natural entity" of the data is one nadir state. For each nadir state the maps that present the near-real-time data show the begin and end time of the measurement in UTC.

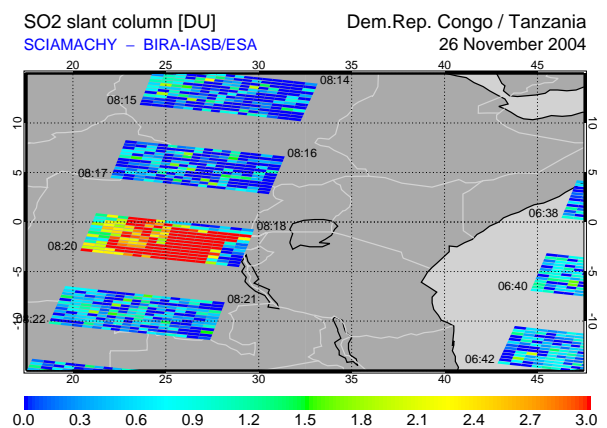


Figure 5.  $\text{SO}_2$  slant column densities in Dobson Units over part of the Democratic Republic of Congo, as derived from SCIAMACHY observations on 26 November 2004. The  $\text{SO}_2$  is related to an eruption of the Nyiragongo volcano, which started on 22 November.

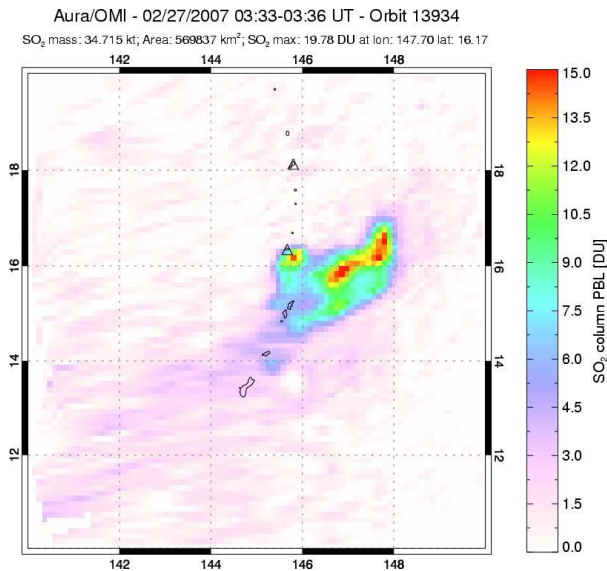


Figure 6.  $SO_2$  concentrations in Dobson Units near the Anatahan volcano (bottom triangle) on the Mariana Islands as derived from OMI observations on 27 February 2007. The largest island to the south is Guam. [Image: Simon Carn, University of Maryland / OMI]

From Fig. 5 it is clear that the geographic coverage of SCIAMACHY data is rather poor. Yet, SCIAMACHY data is very useful to set up the processing system of the service. OMI and GOME-2 data have a much better geographic coverage, with global coverage in one day. GOME-2 measures at 09:30 local time and OMI measures at 13:30 locale time, thus giving at least two measurements per day, instead of just one, even in the tropics. Combining the information from the instruments will therefore provide more and better information on the  $SO_2$  concentrations. Note that OMI has a very high spatial resolution, as can be seen from Fig. 6, better than SCIAMACHY and GOME-2.

In addition to the  $SO_2$  data, SACS will also provide a volcanic ash indicator based on measurements of the SEVIRI instrument, aboard MSG (Meteosat-8). This geostationary satellite does not cover the whole world: roughly said it covers Europe and Africa, the regions of interest of the core users of SACS (see Section 3). While the  $SO_2$  data are available only along the orbits the satellite makes (and each orbits takes about 1.5 hours), SEVIRI measurements are available every 15 minutes, and they have a high spatial resolution. SACS will provide images of SEVIRI derived aerosols focussing on volcanoes within the field-of-view of MSG along side the  $SO_2$  images. Fig. 7 shows an example image of volcanic ash emitted by the Etna volcano.

#### 4.2. Notification system

Using archived  $SO_2$  data and lists of known volcano eruptions of April 2005, a set of criteria for "exceptional  $SO_2$

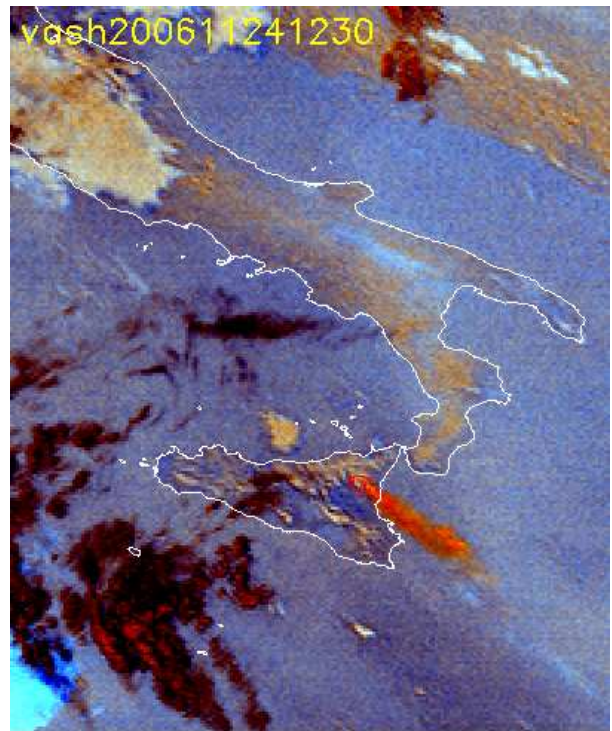


Figure 7. Volcanic ash from the Etna eruption on 24 November 2006 as seen by the SEVIRI instrument at 12.30 UTC that day.

concentrations" is set up, considering all ground pixels of one nadir state in the SCIAMACHY measurements at a time. Similar criteria for the OMI and GOME-2 data will be set up once these data source have been integrated in the processing and analysis system of SACS.

In case the  $SO_2$  data at a given moment satisfies the criteria of an "exceptional  $SO_2$  concentration", the near-real-time system will issue a notification by e-mail to users who have registered for this. The e-mail message contains in a few lines the basic information regarding the event. In case of SCIAMACHY data, for example, the systems looks at individual nadir states and the e-mail provides the start time of the nadir state, the (approximate) location of the middle of the state, and the peak  $SO_2$  concentration in the state.

Furthermore, the e-mail lists the geographic region(s) one of the corners of the nadir state lies in, plus the URL of a dedicated web page that shows images (maps) of the geographic regions: the  $SO_2$  concentration, the cloud cover fraction and some geographic information (such as the location of volcanoes). The dedicated web pages, which are in principle generated automatically, offer room for adding additional information by hand, such as linking different measurements of the same  $SO_2$  event.

In case of an "exceptional  $SO_2$  concentration" the plan is to feed the coordinates of the  $SO_2$  peak value to a trajectory model. This model will be used to backtrace the  $SO_2$  over a few days starting tracers at a few selected el-

NOAA HYSPLIT MODEL  
 Backward trajectories ending at 22 UTC 27 Apr 05  
 CDC1 Meteorological Data

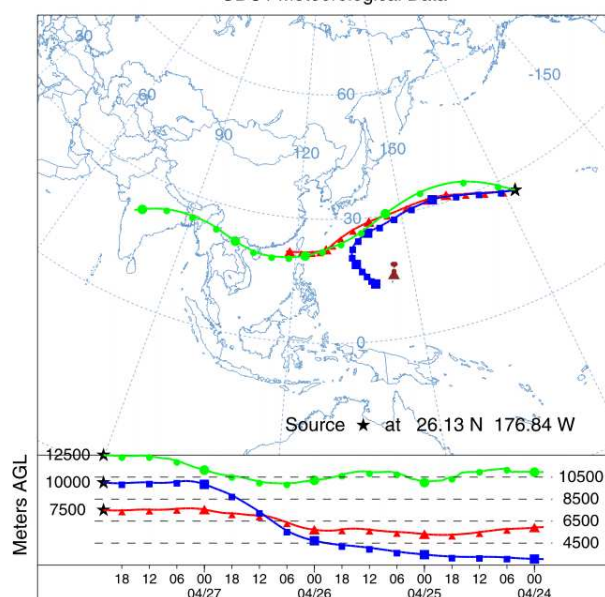


Figure 8. Backward trajectories starting at three elevations from a location just west of Hawaii, as detected by SCIAMACHY on 27 April 2005. See the text for more information.

evations, to see where the  $\text{SO}_2$  may come from, and at the same time this provides an estimate of the elevation of the  $\text{SO}_2$  cloud at the moment it is measured.

The forward motion of the tracers, based on forecast meteorological fields, and again starting from a few selected elevations, can be used to indicate where the volcanic  $\text{SO}_2$  cloud may travel to, depending on the actual elevation of the  $\text{SO}_2$  when it is measured.

An example of backward trajectories is shown in Fig. 8. The trajectories were started from a location just west of Hawaii, where a peak  $\text{SO}_2$  value of unknown origin was seen in SCIAMACHY measurements on 27 April 2005, and go backward for four days. The trajectory that started at 10km elevation (blue) shows that the  $\text{SO}_2$  may have come from the Anatahan volcano (with a top at nearly 800m) on the Mariana Islands, which is known to have erupted on 23 April.

Fig. 8 also shows, however, that the  $\text{SO}_2$  may have come from completely different sources. In fact, when starting trajectories at lower elevations (not shown), the trajectories trace back to China, Japan or Russia. Clearly, it will *not* be possible to identify in an automatic way the origin of an  $\text{SO}_2$  cloud. But placing graphs such as Fig. 8 on the website will facilitate the users in identifying possible sources of  $\text{SO}_2$  and ash.

## 5. VALIDATION

The service of SACS aims to provide in near-real-time  $\text{SO}_2$  and ash data derived from satellite measurement so as to enable the early detection and mapping of abrasive ashes and corrosive sulphur compounds emitted by volcanoes and transported by winds. In the event of an "exceptional  $\text{SO}_2$  concentration", the aim is to send out notifications by e-mail to interested parties, with images and data accessible via dedicated web pages. At the same time, the  $\text{SO}_2$  peak value will be used to start backward and forward trajectories to facilitate the interpretation of the satellite observations and by providing an indication of the location of the source of the  $\text{SO}_2$  and of the height of the plume.

Validation of this two-faceted service should take into consideration the following two tasks: first, a validation of the service components and related geophysical data products, based on classical correlative analysis and information content studies; second, a validation of alert-related aspects. Quantitative validation of  $\text{SO}_2$  and aerosol data products of volcanic origin is not straightforward, due to:

1. the difficulty to plan correlative measurement long-term programmes or even campaigns for – nearly – unpredictable eruptions;
2. safety and practical issues to get correlative measurements in the vicinity of an erupting volcano;
3. the current lack of suitable devices to perform accurate  $\text{SO}_2$  column measurements from the ground.

A major experimental support is expected from the FP6-funded Network for Observation of Volcanic and Atmospheric Change (NOVAC), which will operate DOAS instruments at observatories of 15 volcanoes on five continents, including some of the most active and strongest degassing volcanoes in the world. The geographical development of plumes of volcanic ash can be confronted to images provided by satellite instruments like Envisat MERIS and EOSAqua MODIS. Aerosol lidars operated in the context of networks like the NDACC can provide correlative information on the vertical structure of the plume and on its temporal development (overpass of station at a given time).

In a first stage, the validation of the SACS will be its demonstration for a sufficient amount of past volcanic eruptions in long-term satellite data records. The study of alert-related aspects should address the following logical cases (if possible in terms of probability and of detection threshold):

- a potentially hazardous eruption occurs and SACS reports it;
- a potentially hazardous eruption occurs and SACS does not report it;



Figure 9. The logo symbolises the aim of the service.

- a potentially hazardous eruption does not occur but SACS emits an alert.

More quantitative might be envisaged in a later stage, using ground-based  $\text{SO}_2$  and aerosol measurements as well as satellite data. Suitable validation methods are still in their infancy and should be further developed.

## 6. CONCLUDING REMARKS

The Support to Aviation Control Service (SACS for short) will deliver in near-real-time data derived from satellite measurements regarding  $\text{SO}_2$  and aerosol emissions possibly related to volcanic eruptions, and where possible track volcanic plumes.

With this SACS is an additional source of information for the official organisations, the Volcanic Ash Advisory Centres (VAACs), responsible for issuing alerts of the potential danger of volcanic eruptions to aviation. This aim is symbolised in cartoon-form by the logo of SACS (Fig. 9).

At the moment of writing,  $\text{SO}_2$  data derived from the SCIAMACHY instrument is being used to set up the basic structure of SACS. At a later stage,  $\text{SO}_2$  data derived from the OMI and GOME-2 instruments will be included.

The  $\text{SO}_2$  data covers the whole world and is presented in the form of maps of geographic regions of 30 by 30 degrees covering known volcanoes. Furthermore, a volcanic ash indicator based on SEVIRI measurements – which covers Europe and Africa only – will be supplied in the form of maps focussing on selected volcanoes.

In the event of an "exceptional  $\text{SO}_2$  concentration", a notification will be sent by e-mail to interested parties, referring to dedicated web pages with images and further information.

In addition to this, the location of such a  $\text{SO}_2$  peak value will be used to start backward and forward trajectories on the basis of meteorological data (wind, temperature, pressure, etc.). These trajectories will facilitate the interpretation of the satellite observations and will provide an indication of the location of the source of the  $\text{SO}_2$  and of the height of the plume. And the trajectories will provide an indication of the destination of the volcanic plume.

More information, including an on-line product description and some downloadable documents, can be found via the SACS web portal <http://sacs.aeronomie.be/> or via the PROMOTE website <http://www.gse-promote.org/> under "special services".

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