AN ALERT SYSTEM FOR VOLCANIC SO2 EMISSIONS USING SATELLITE MEASUREMENTS

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Abstract

Satellite measurements of sulphur dioxide (SO_2) concentrations are used to set up an automated service which issues notifications by e-mail in case of exceptional SO_2 concentrations. Such "SO_2 events" could signify volcanic activity, as SO_2 is one of the major trace gases released during volcanic eruptions. Most eruptions also release ash and in that case SO_2 can serve as a marker for the presence of volcanic ash. Volcanic ash, when transported high up in the troposphere, poses a great hazard to aviation: aircraft flying through a volcanic ash cloud may suffer major damage, including engine failure. The SO_2 alert service – named the Support to Aviation Control Service (SACS) – thus provides information to the Volcanic Ash Advisory Centres (VAACs), whose official task is to gather information regarding volcanic ash clouds and to assess the possible hazard to aviation. Other users of SACS are volcanological observatories, health care organisations, scientists, etc. Currently SACS uses measurements of the SCIAMACHY, GOME-2 and OMI instruments for SO_2 data. This will be extended with an Absorbing Aerosol Index (AAI) from these instruments, as well as SO_2 data and an aerosol flag from the IASI instrument. Maps, data and product information can be found at the SACS website: http://sacs.aeronomie.be/

A HAZARDOUS ENCOUNTER

It is evening over Asia when on 24 June 1982 the scheduled British Airways flight 009, carrying 248 passengers and 15 crew, flies over Indonesia at an altitude of 11 km, on its way from London Heathrow to Perth in Australia and then further to New Zealand. An hour and a half or so before the Boeing 747 had picked a fresh crew in Kuala Lumpur. The weather looks perfect, no meteorological problems are forecast, and the weather radar shows no echoes. [Wikipedia, 2009a; GVP 2009a; Diamond, 1986; Hanstrum and Watson, 1983.]

The aircraft has just passed the Indonesian island Java when at 20:40 Jakarta time (13:40 UTC) the first signs show up that something may be wrong: flares are visible on the wind screen, like St. Elmo's fire, smoke starts entering the passenger cabin, and the engines look unusually bright. Then at 20:42 engine number four surges and flames out. The crew starts the standard shut-down procedure for engine four, while there is a yellow glow visible around the other engines. Less than a minute later engine two flames out, and immediately after that also engines one and three.

Without any engine working, the Boeing 747 has become a glider. Given that it started from an altitude of 11 km, the crew knows it can glide for about 23 minutes and cover about 170 km before reaching the surface. The closest airport is Jakarta, but to reach that the aircraft has to pass the coastal mountain range at an altitude of at least 3.5 km. Restarting at least one the engines does not succeed, and therefore the crew heads for a gliding landing at the surface of the ocean – something no-one had ever attempted before with a 747, nor has it been done since.

Cabin pressure falls and automatically the oxygen masks drop from the ceiling. But at the altitude of the aircraft there is not enough air to have all oxygen masks work, so the captain decides to descend rapidly (1.8 km in a minute) to an altitude with sufficient air pressure to make the oxygen masks work. This manoeuvre most likely saved everyone on board ...

Figure 1: **Part of one of the Boeing-747 engines of flight BA-009 after flying through the volcanic ash plume, June 1982. [Photo by captain Eric Moody, British Airways.]**

Figure 2: **Photograph of Redoubt's North face taken about 35 minutes after the ash burst of 15 March 2009 during a monitoring flight. A dark area of fresh ash deposits lies on top of the snow on the sloping crater floor. In front of that a gas plume escapes from a vent near the crater rim. The sinuous dark stripe in the foreground is a watery debris flow that emerged from beneath the ice about 20 minutes after the ash event. [Photo by Heather Bleick; GVP, 2009b.]**

Suddenly, at 20:56, engine four comes back to life and shortly after that engine three, allowing the crew to increase the altitude slowly. Then also the other two engines restart, and the aircraft climbs to 4.5 km. But then the flaring on the windscreens reappears, and engine two surges again, forcing it to be shut down. The crew takes the aircraft back down to an altitude of 3.6 km and heads for Jakarta airport. Visibility there is good, but the crew can see very little through the windscreens and the landing lights do not seem to give any light, so they have to land almost entirely on the instruments.

Upon inspection of the engines (*Figure 1*), the windscreens, etc. of the aircraft it was found that the problems had been caused by an encounter with a volcanic ash cloud, released by the 2168-m high volcano Galunggung (7.25ºS, 108.06ºE), which had erupted some time before 19:00 Jakarta time. At the moment of the encounter with the ash cloud, the aircraft was some 150 km from the volcano at an altitude of about 11 km. The aircraft's radar had not picked up the dry volcanic ash, as the radar is designed to pick up drops of moisture from clouds. The sharp drop of the aircraft to get to an altitude with more air pressure for the oxygen masks had brought the aircraft back into clean air, making a restart of some of the engines possible.

Flight BA-009 was not the first to encounter an ash cloud from Galunggung: on 5 April 1982 – the day the volcano erupted for the first time since 64 years – a DC-9 of Garuda Airlines, on an internal Indonesian flight, experienced problems related to volcanic ash. After that first eruption, there were several eruption episodes, the tenth being from 24-27 June. Another eruption took place on 13 July that year and caused another major hazardous encounter: a Singapore Airlines Boeing 747 – on its way from Singapore to Melbourne, carrying 230 passengers – passed through an ash cloud at an altitude of 9 km. Three of the four engines failed and the aircraft descended some 3.5 km, after which one of those three engines restarted and the aircraft made it safely to Jakarta airport. After this second incident, the air space around Galunggung was closed for a while. Galunggung has been quiet again since early 1983.

On 15 December 1989 there was another major incident: KLM Flight 867, on its way from Amsterdam to Tokyo, was descending into Anchorage airport when the Boeing 747, carrying 231 passengers and 14 crew, flew through a thick ash cloud released by the 3108-m high volcano Redoubt (152.74ºW, 60.49ºN) at about 10:15 Alaska time, some 200 km away from the point of encounter. Again the volcanic cloud did not show up on the on-board radar. All four engines failed at 11:50 Alaska time (23:50 UTC). Eight minutes later, after a descent of more than 4 km, the crew managed to restart the engines and safely land. The windshields were damaged, as were internal aircraft systems, avionics and electronics. The costs of repairing the damage amounted to more than 80 million USD. Redoubt erupted on 14 December for the first time since 1966-68, and remained active until June 1990. [Wikipedia, 2009b; GVP, 2009b; Dean, et al., 1994; Carn et al., 2008.] The following eruption phase started on 15 March 2009 (*Figure 2*).

VOLCANIC ERUPTIONS: HAZARDS TO AVIATION

Per year there are some 55 to 60 volcano eruptions, and some cases the volcanic ash reaches the altitudes of scheduled flights. Once high up in the troposphere, volcanic ash can travel over large distances. An ash cloud released by the Pinatubo eruption on 15 June 1991, for example, travelled in three days more than 7000 km, to the east coast of Africa. This ash cloud damaged more than 20 aircraft, most flying more than 1000 km away from the volcano [USGS, 1997]. Over 90 encounters with a volcanic ash cloud have lead to damage to aeroplanes. The economic costs of this have been estimated at 250 million USD for the period 1982-2000.

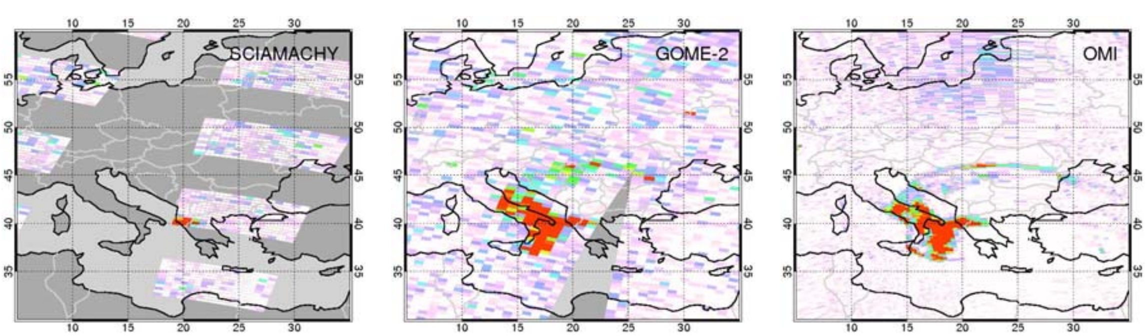
When flying through a volcanic ash cloud, ash particles enter the jet engines and this may immediately lead to a deterioration of the engine's performance and possibly to engine failure, because the ash particles deposit in the hot sections of the engine. The molten ash will coat fuel nozzles, combustor and turbine, which reduces the efficiency of the fuel mixing and restricts air passing through the engine, leading to surging, a flame out and loss of engine thrust. Furthermore, the ash may also seriously erode moving parts in the engine. [USGS, 2009; Diamond, 1986]

Volcanic ash is highly abrasive and any forward-facing surface of an aeroplane is likely to be damaged ("sandblasted" as it where): cockpit windows, landing light covers, leading edges of wings and tail, etc. The cockpit windows may become so scratched that pilots cannot see the runway anymore when they land, as in the case of the BA-009 flight described above. Furthermore, the ash may also end up in the ventilation system en eventually spread throughout the cabin. Any gases that are in the volcanic cloud, such as sulphur dioxide (SO_2), may also end up in the cabin. Smoke and a strong odour of sulphur filled the cockpit and cabin of the B-747s mentioned above when they passed through the volcanic cloud. [USGS, 1997; Diamond, 1986.]

SO_2 itself is toxic and can seriously affect human health. In combination with water vapour (also present in volcanic clouds) it forms sulphuric acid (H_2SO_4), which is toxic and corrosive. It is at the moment unclear to what extent these compounds form a direct hazard to aviation [Bernard and Rose, 1990]. But their presence at flight level may be a tell-tale sign of volcanic activity [Carn et al., 2008].

THE VOLCANIC ASH ADVISORY CENTRES (VAACS)

The three incidents of the encounters in 1982 and 1989 of a Boeing 747 with a volcanic ash cloud changed the views on aviation safety forever, leading to awareness of the hazard to aviation of volcanic ash clouds and to Volcanic Ash Advisory Centres (VAACs). The VAACs were established in September 1995 at a meeting of the International Civil Aviation Organisation (ICAO). To ensure that volcanic cloud hazards were addressed, the VAACs would form an interface between volcano observatories, meteorological agencies and air traffic control centres. [USGS, 2009] The VAACs – there are nine, based at meteorological agencies, and covering most of the world – are part of the International Airways Volcano Watch (IAVW), which was set up in the early 1980s.



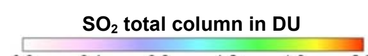


***Figure 3*: SO_2 concentrations in Dobson Units (DU) measured by three UV/Visible satellite instruments on 14 May 2008. The SO_2 was released during an eruption of Etna (Sicily). High SO_2 values were measured by SCIAMACHY (left) around 08:50 UTC, by GOME-2 (centre) around 09:16 UTC, and by OMI (right) around 12:23 UTC. With its limited geographic coverage SCIAMACHY clearly misses most of the SO_2 cloud.**

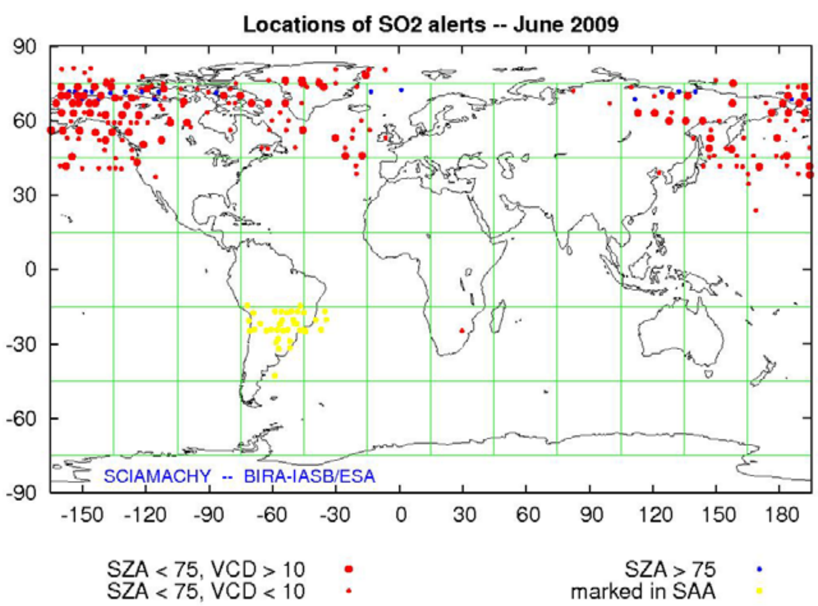
THE SUPPORT TO AVIATION CONTROL SERVICE (SACS)

Though SO_2 clouds released by volcanic eruptions are not part of the VAAC tasks, monitoring SO_2 can be useful, as SO_2 is often a good marker for the presence of volcanic ash [Carn et al., 2008; Krueger et al, 2008], notably during the first day or two of an eruption. After some time the two will separate due to gravitational effects: ash sinks faster to the surface than the SO_2 or the sulphuric aerosols it forms into. SO_2 is the third major trace gas released into the atmosphere during volcanic eruptions, after water vapour and carbon dioxide (CO_2).

The aim of the Support to Aviation Control Service (SACS) is to monitor in near-real time SO_2 concentrations worldwide using satellite instruments and in case of exceptional SO_2 concentrations, i.e. "SO_2 events", to issue alerts by e-mail to the VAACs and other users, pointing them to dedicated web pages with maps and related information. In addition, SACS has an archive for case studies, for validation of the notification criteria, and for inter-comparison of satellite data. The near-real time and archive data, as well as the alerts of "SO_2 events" are available at http://sacs.aeronomie.be/

Current SACS data products and alert service

At the moment of writing, Sept. 2009, SACS employs SO_2 data from three satellite instruments that measure in the UV/Visible, namely SCIAMACHY aboard ENVISAT, GOME-2 aboard MeTop-A, and OMI aboard EOS-Aura (*Figure 3*). Of these, the data from SCIAMACHY is currently in use for the alert service that notifies subscribers of an "SO_2 event". Criteria for alerts based on GOME-2 and OMI data will be implemented in the near future. For each alert a dedicated map of a 30 by 30 degree region around the location of the SO_2 peak value that triggered the alert is made and put on a dedicated web page, mentioned in the email sent to the subscribers. The near-real time and archive data is presented in the form of 60 detailed maps of 30 by 30 degree regions plus two maps for the poles, thus covering the whole world (these predefined regions are marked by the green lines in *Figure 4*). As the presence of clouds is an important issue when observing volcanic ash clouds, maps of the cloud cover fraction are provided alongside the SO_2 maps.



Category	Number of alerts
SZA ≤ 75 ° VCD > 10 DU	81
SZA ≤ 75 ° VCD < 10 DU	119
SZA > 75 ° all VCD	60
In SAA area, all VCD, SZA	37
Total	256

***Figure 4*: Map of the location of SO_2 alerts for June 2009 based on data from the SCIAMACHY instrument. Different sized or coloured symbols are used for different categories; numbers of alerts for each are given in the table on the right. Measurements taken at high solar zenith angle and over the area known as the South Atlantic Anomaly (SAA) are difficult and often lead to false alerts (data is limited to SZA ≤ 80º). A large number of the alerts over a part of the Northern Hemisphere is related to the eruption of the Sarychev Peak volcano (48.1º N, 153.2º E) on one of the Kuril Islands, which started on 12 June and continued for several days. The eruptions released a relatively large amount of SO_2 in the atmosphere, which was subsequently transported by stratospheric winds across the Northern Hemisphere. Alerts triggered by this SO_2 continued well into July.**

Concentrations of SO_2 are derived from SCIAMACHY and GOME-2 data with a Differential Optical Absorption Spectroscopy (DOAS) technique [e.g. Khokhar et al. 2005; Thomas et al., 2005; Richter et al., 2006; Rix et al., 2009]. Determination of SO_2 concentrations involves taking into account the absorption by ozone in the same wavelength window (315 – 325 nm). In addtion a background correction is applied, based on a relationship between the thus determined O_3 and SO_2 concentrations, such that on average and away from emission sources there is no SO_2. An initial validation showed that GOME-2 and SCIAMACHY data are consistent [Van Geffen et al, 2008].

The SO_2 data product based on OMI measurements uses different subsets of calibrated residuals of the NASA operational ozone retrieval algorithm at selected UV wavelengths: four in the range 310.8 – 314.4 nm and two non-absorbing wavelengths at 345 and 370 nm [e.g. Krotkov et al., 2006; Carn et al., 2007]. According to intercomparisons performed within SACS, the method used for OMI leads to SO_2 total columns consistent with those derived from SCIAMACHY and GOME-2.

Planned extension of the SACS data products

GOME-2 and SCIAMACHY measure in the local morning (09:30 and 10:00 local solar time, resp.) and OMI in the local early afternoon (13:45), all on the day-side of the Earth, thus providing basically two data points per day. For the benefit of aviation safety, the more data points the better. An additional data point will be available with the incorporation of SO_2 data derived from measurements in the Infrared by IASI aboard MetOp-A: it measures in the morning at the same time as GOME-2, and also at the local night side of the Earth 12 hours later, thus providing a third data point (*Figure 5*).

The detection of SO_2 by IASI is based on the presence of absorption features in the thermal infrared, notably in the ν_3 band. The retrieval provides an SO_2 index in terms of a brightness-temperature difference in Kelvin units [e.g. Clarisse et al., 2008; Clerbaux et al., 2009]. The approach is currently implemented at ULB and used with a special filter for issuing alerts (see http://cpm-ws4.ulb.ac.be/Alerts/). This alert service will be incorporated in the system of SACS and SO_2 maps similar to those of the UV/Visible instruments will be provided.

The system set up under SACS is primarily concentrating on SO_2 data, based on the idea that SO_2 may serve as a marker for the presence of volcanic ash, in particular in the early hours to days after an eruption. To provide some additional information that may help to identify volcanic ash clouds, SACS plans to provide maps of the Absorbing Aerosol Index (AAI), based on UV/Visible observations, and an Aerosol Flag (AF), based on IASI data. As a start, the SACS near-real time web pages already provide maps of the OMI AAI. The AAI – determined from the radiance difference at two wavelengths, usually around 340 and 390 nm – is positive (negative) for absorbing (scattering) aerosols. It remains to be investigated whether the AAI is a good indicator of the presence of volcanic ash. The AF is determined from broad spectral features of volcanic aerosol in the wavelength range 700 to 1300 cm^{-1}, though the retrieval may be hindered by the presence of meteorological clouds and other aerosol.

Elevation and extension of the volcanic plume

For their tasks to assess the possible hazard of volcanic ash clouds, the VAACs determine the motion of the ash clouds with dispersion models. These models currently rely on rather crude assumptions of the horizontal and vertical extent of the ash cloud, as little is known about this in near-real time. To improve their advices, the VAACs need more accurate information of in particular the altitude and vertical size of an ash plume. This is the main topic of the SAVAA – Support to Aviation for Volcanic Ash Avoidance – project: SAVAA aims to set up a demonstration system able to ingest satellite data and meteorological wind fields, in order to compute the injection height profile of volcanic emissions, using trajectory and inverse modelling [Prata et al., 2008]. SACS will set up a close link with SAVAA: SO_2 data and alerts will be input for the SAVAA system, and results of the SAVAA analysis in case of "SO_2 events" will be added to the dedicated alert web pages.

Complementary information on the altitude of an SO_2 cloud can also be derived directly from UV/Visible measurements by applying a more advanced retrieval scheme, based on a direct fit of SO_2, ozone and other absorbers that play a role in the selected wavelength window. The possibilities of this approach – probably in combination with a first guess provided by the DOAS retrieval mentioned above – will be investigated under SACS. It is likely that this will provide at least a rough estimation (in terms of a few km) of the altitude of the SO_2 plume.

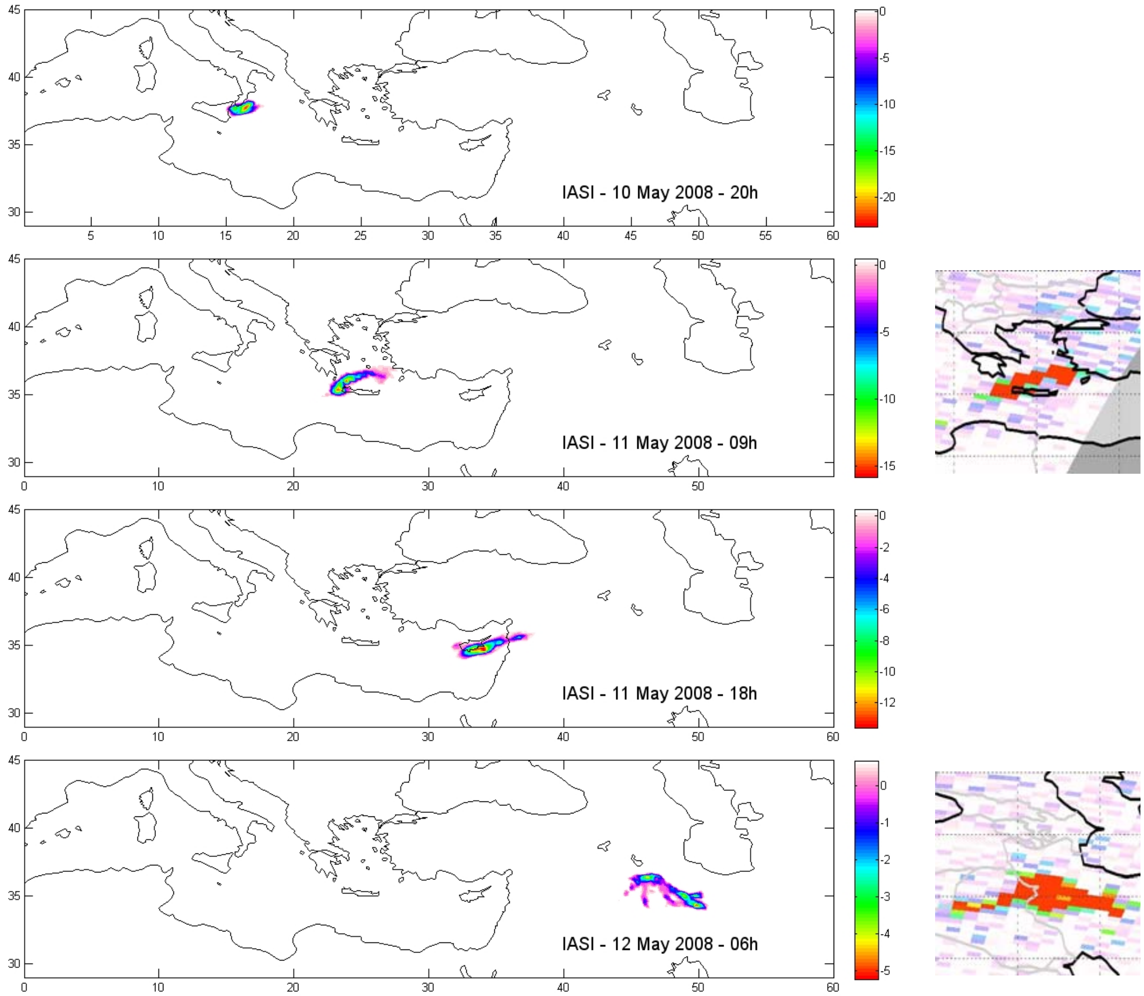


***Figure 5*: Maps of an SO_2 concentration index from IASI data, in terms of a temperature-brightness difference, after an eruption of Etna (Sicily) in the afternoon of 10 May 2008, showing the motion of the SO_2 cloud to the east. The times given are the times in UTC of the measurement of the SO_2 patch. Note that the colour scale changes between the successive maps. The small pictures on the right are cuts from GOME-2 SO_2 maps at the times corresponding to the IASI maps on the left; the colour bar of these maps is that of Figure 3.**

Likewise, the high spectral resolution of IASI allows for the retrieval of vertical profiles to estimate the altitude of peak concentration using a line-by-line inversion method [Clarisse et al., 2008]. These estimates will typically be better for larger eruptions. For the moderate Jebel at Tair eruption, for instance, the peak altitude was estimated to be 16.5 ± 2 km (*Figure 6*). With this approach also SO_2 at lower altitudes can be detected.

CONCLUDING REMARKS

Volcanic ash clouds pose a hazard to aviation: when crossing through such a cloud, the ash can seriously hamper the functioning of aircraft systems and damage its structure. The best policy for aircraft is to stay clear from volcanic ash clouds. The Volcanic Ash Advisory Centres (VAACs) have the task to gather information on the location, altitude and motion of volcanic ash clouds and to issue advices to aviation control and airline organisations in case of possible threads to aviation.

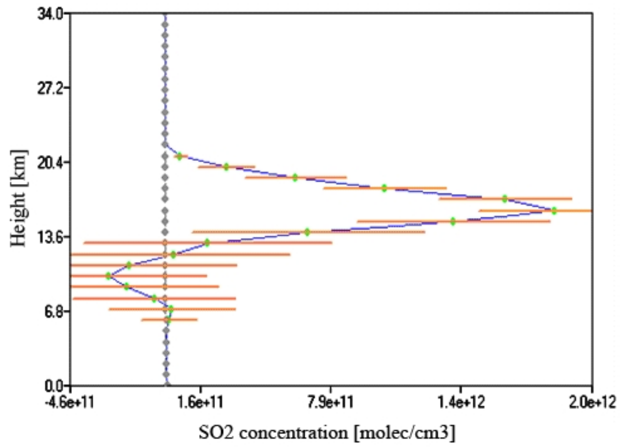


***Figure 6*: Vertical profile of SO_2 concentrations derived from IASI measurements for the eruption of Jebel at Tair, a volcano on a small island in the Red Sea, on 30 September 2007.**

The Support to Aviation Control Service (SACS) is set up to assist the VAACs in their tasks by monitoring world-wide concentrations of sulphur dioxide (SO_2) from satellite and issuing alerts in case of exceptional concentrations (“SO_2 events”). Knowledge of the presence of SO_2 itself is not part of the VAAC tasks, but SO_2 may serve as a marker for the presence of volcanic ash clouds, since SO_2 is one of the major trace gases released during volcanic eruptions.

The present paper describes the implemented and planned elements of SACS. The main focus of SACS lies on providing SO_2 data and maps of instruments onboard polar-orbiting satellites, measuring in the UV/Visible (SCIAMACHY, OMI, GOME-2) and the Infrared (IASI), and issuing alerts in case of “SO_2 events” by e-mail, pointing the subscribers to dedicated web pages with additional information (such as the altitude and motion of the cloud). Further, there will be data and maps of the Absorbing Aerosol Index (AAI) from the UV/Visible instruments and an Aerosol Flag from IASI.

Though SACS is in first instance set up to support the VAACs in their tasks, the data, maps and alerts are also of use to others, notably to local volcanological and public safety organisations. In this respect the potential of detecting so-called passive degassing of SO_2 prior to eruptions, known to take place at some types of volcanoes, is very promising. SACS will collaborate closely with the SAVAA project [Prata et al., 2008], which focuses on determining origin, elevation and motion of volcanic clouds.

The SACS data and map archive can be used for case studies to further the knowledge of SO_2 emissions during volcanic eruptions and the subsequent motion and lifetime of SO_2 clouds through the atmosphere. Maps, data, alerts and product information can be found at the SACS website: http://sacs.aeronomie.be/

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