COMPARISON OF VOLCANIC SO_2 FLUX MEASUREMENTS FROM SATELLITE AND FROM THE NOVAC NETWORK

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Abstract

The main objective of the NOVAC project (Network for Observation of Volcanic and Atmospheric Change) is to establish a global network of stations for the quantitative measurement of volcanic gas emissions (in particular SO_2 and BrO) by UV absorption spectroscopy.
The data from the network (more than 21 volcanoes are currently monitored) are primarily used for risk assessment and volcanological research, but the data are also valuable for the study of tropospheric and stratospheric gas composition (SO_2, NO_2, CH_2O, BrO and O_3). Since volcanic SO_2 is also monitored from satellite (e.g. the SACS service, http://sacs.aeronomie.be/) the NOVAC project provides an excellent opportunity to explore and inter-compare the different satellite SO_2 data-sets under volcanic conditions. Furthermore the NOVAC ground-based data can be used to validate satellites estimates of gas flux emissions.
In this work, we present an investigation focusing on GOME-2 and OMI SO_2 data sets. Their mutual consistency is analysed and comparisons are performed with the NOVAC ground-based network measurements. A statistical study on the whole NOVAC dataset is performed, comparing mass estimation from satellites and flux measurements from the ground. A case study over Etna involving OMI (Ozone Monitoring Instrument) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) illustrates the impact of spatial inhomogeneities in the SO_2 field inside the area covered by an OMI pixel. Moreover, this study illustrates the importance of external information (such as the height of the volcanic plume) to reduce the error on the SO_2 estimation.

1. CONTEXT / VOLCANIC SO_2 DATASETS

Within the NOVAC project (Galle et al., 2010) a network of ground-based automated instruments for the measurement of volcanic SO_2 emissions has been set up. An overview of the volcanoes monitored in Latin America is presented in figure 1. The possibility of monitoring volcanoes activity from space with UV-Vis sounders like OMI and GOME-2 has been shown, both for explosive eruptions and for degassing cases (e.g., Yang et al., 2007, Carn et al., 2008, Rix et al., 2009 and references therein). More information on the instruments, the main retrieval settings and references for the data used in this work are given in table 1.

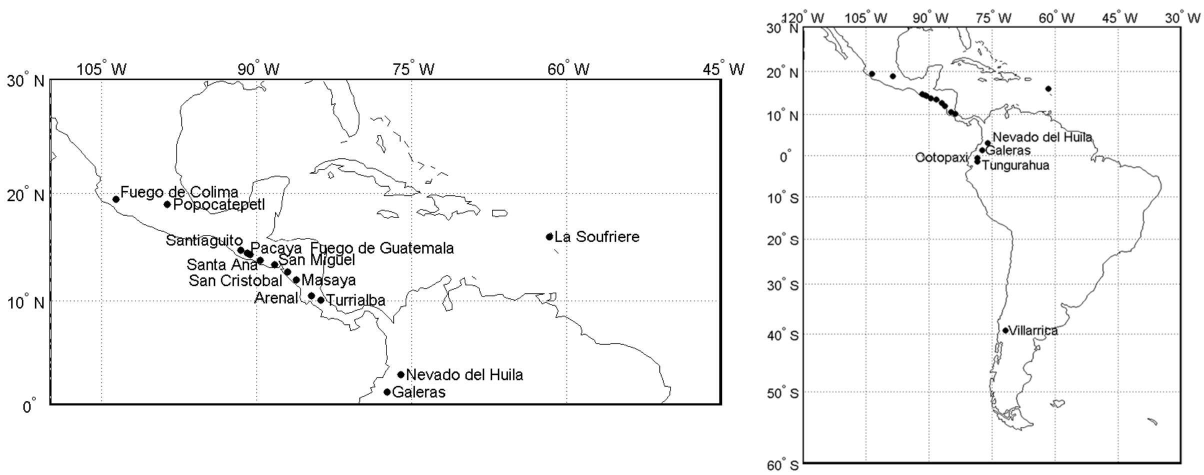

Figure 1: **Location of the NOVAC volcanoes in Latin America.**

	GOME-2 Global Ozone Monitoring Experiment	**OMI** Ozone Monitoring Instrument	**ASTER** Advanced Spaceborne Thermal Emission and Reflection Radiometer
Instrument reference	(Munro et al., 2006)	(Levelt et al., 2006)	(Pieri and Abrams, 2004)
Platform and launch	On MetOp-A, since 2006	On AURA, since 2004	On Terra, since 1999
Overpass time	~9h30 UT	~12h-13h30 UT	9h59 GMT
Pixel resolution	**80x40km²** (at nadir – swath of 1920km)	**13x24km²** (at nadir -swath of 2600 km, CTP from 1 to 60)	**0.09x0.09km²** (whole image 60x60km²)
SO_2 data origin	Operational product from O_3M-SAF. Columns given for SO_2 content at 2km, **6km,** 15km	OMSO2 operational product from NASA. Columns given for SO_2 content at 0.9km (PBL, pollution), 2.5km (TRL), **7.5km (TRM)** , 17km (STL)	Data obtained from Robin Campion (ULB), personal communication.
SO_2 detection limit	3σ noise: ~3e+16 molec/cm² (1.15DU)	3σ noise: ~1.61e+16 molec/cm² (0.6DU)	1σ noise: ~5e+17 molec/cm^2
SO_2 retrieval reference	Valks et al., 2010 Rix et al., 2009	Yang et al., 2007 PBL: Krotkov 2006	Campion et al., 2010

Table 1: **Details about the different satellite SO_2 data used in this study.**

SO_2 data from OMI and GOME-2 instruments are extracted in the vicinity of the NOVAC volcanoes, from 2007 onward, with the aim to (1) investigate the possibilities of using satellites for monitoring volcanic gas emissions and (2) assess the quality of the data compared to the NOVAC ground-based network. In this study, the consistency of the two satellite data sets is explored for a few volcanic eruption cases, and the SO_2 columns are transformed into SO_2 masses and compared with the NOVAC fluxes. A case study comparing OMI data to high resolution ASTER data (see table 1) is also presented here, in order to further explore the spatial gradients within an OMI pixel (case over Etna) and to calculate and compare fluxes from the 2 instruments.

2. OMI AND GOME-2 COMPARISONS

SO_2 data from OMI and GOME-2 are extracted and daily maps are created around every NOVAC station. An example is shown in figure 2. This type of maps allows a first visualisation of the coherence between the retrievals of the two satellites and of the possible transport of the volcano plume between the two overpass times (a few hours). The information on the daily maximum SO_2 column value of OMI and GOME-2 is included in the map, as well as an estimation of the total SO_2 mass in the area. The calculation of the SO_2 mass is performed by selecting all the pixels that are above a threshold value (designated with the "*fi*" index), and by transforming the vertical columns [molec/cm²] into mass through equation (1):

$$Mass = (VCD_{fi} - mean(VCD_{notfi})) \cdot AirPix_{fi} \cdot \frac{M_{SO2}}{N_A} \quad (1)$$

[Kg] [molec/cm²] [cm²] [kg/molec]

M_{SO2} and N_A are respectively the molar mass of SO_2 and the Avogadro number (M_{SO2}= 64 g/mol and N_A= 6.022e23 mol/molec). The threshold values for OMI and GOME-2 (respectively 0.6 DU and 1.15 DU) have been defined as the noise level of the SO_2 VCD over a clean area in the Pacific Ocean (-30° lat, -120° long) over one month. The value found fo r OMI is coherent with previous literature studies (Carn et al., 2008). GOME-2 data are noisier than OMI data which, is partly due to instrumental characteristics and partly to differences in the SO_2 algorithms (e.g., different fitting windows).

Figure 3 presents two examples of the comparisons of OMI and GOME-2 SO_2 data over Nevado del Huila and Tungurahua volcanoes, during 2008, showing a good agreement of columns and masses. However, the OMI data suffer from the so-called "row anomalies", affecting L1B and L2 data (http://www.temis.nl/docs/omi_warning.html, http://www.knmi.nl/omi/research/product/rowanomaly-background.php, Claas et al. 2010), which results in a progressive degradation of the SO_2 data product. An example of how this degradation affects the SO_2 field is presented in figure 4 for a case over Nevado del Huila in November 2009. The main difficulty in handling these OMI-anomalies is that they are not stable in time, and several major changes occurred since the first appearance in June 2007. Efforts to flag and correct the affected data are currently on-going, but so-far not implemented in the OMSO2 product. The different evolution of the affected cross-track positions (CTP) over time do not allow a simple removal of pre-defined pixels (a manual check of the scene is needed) and the global comparisons can still be affected by an incorrect removal.

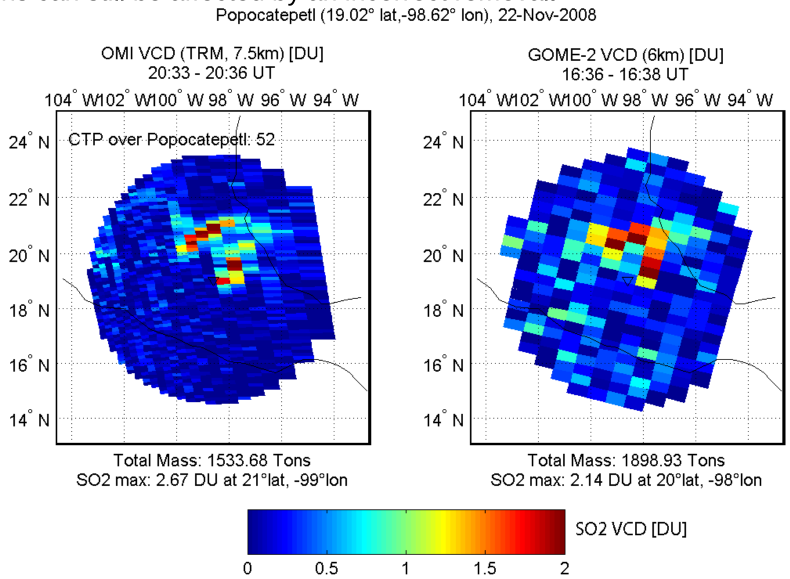

Figure 2: **Map of the SO_2 column values (in DU) around Popocatepetl volcano (Mexico) on 22 November 2008, from OMI instrument (left panel) and GOME-2 instrument (right panel).**

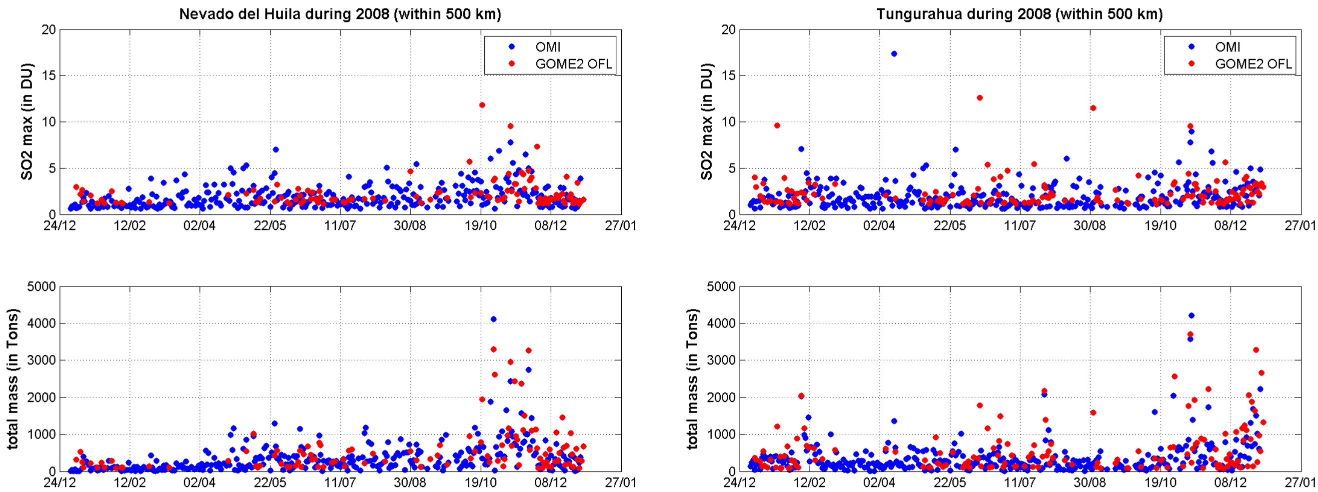

Figure 3: **Examples of the comparison of OMI and GOME-2 over Nevado del Huila (Colombia) and Tungurahua (Ecuador) in 2008. The upper panels present the daily maximum SO_2 column values, and the lower panel the corresponding SO_2 masses.**

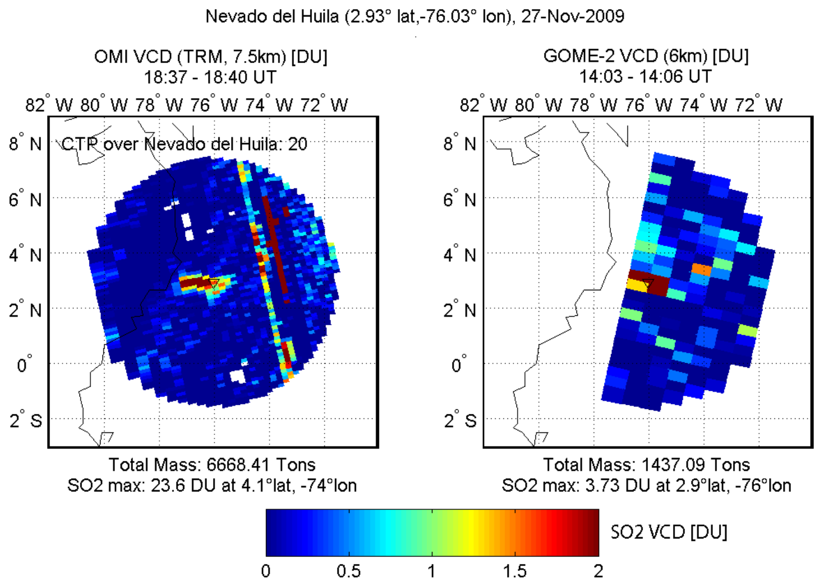

Figure 4: **as figure 2, but around Nevado del Huila volcano (Colombia) on 27 November 2009. Part of the OMI data are affected by the „cross-track row anomaly“ and should be excluded from the mass calculation (in this case, pixels with a cross-track position (CTP) from 27 to 40).**

3. PRELIMINARY COMPARISONS WITH NOVAC

The masses calculated from the satellite data are then compared with the SO_2 flux measured from ground-based NOVAC stations. So far, only data from ScanDOAS instrument at Tungurahua during February 2008, MobileDOAS data from Nevado del Huila since 2007 and ScanDOAS data at Vulcano island since 2008 have been investigated. Preliminary results are presented in figure 5, showing e.g. good agreement in Tungurahua for OMI, GOME-2 and NOVAC data. Over Nevado del Huila the mobileDOAS fluxes are often much larger than the mass seen by the satellites. Very good agreement in conditions of very low SO_2 emission (Vulcano Island) is obtained for OMI, but larger differences are obtained with GOME-2, which probably reflects the higher noise level of GOME-2 than OMI. Moreover, GOME-2 has larger pixels than OMI (40x80km² vs 13x40km² at best) and can therefore be contaminated by Etna emissions (which is at ~50km of Vulcano Island). Note also that both satellite datasets have been retrieved with the TRM SO_2 columns, assuming a plume height at 6 or 7.5 km, while Vulcano is a degassing volcano and a lower emission height would probably be more realistic.

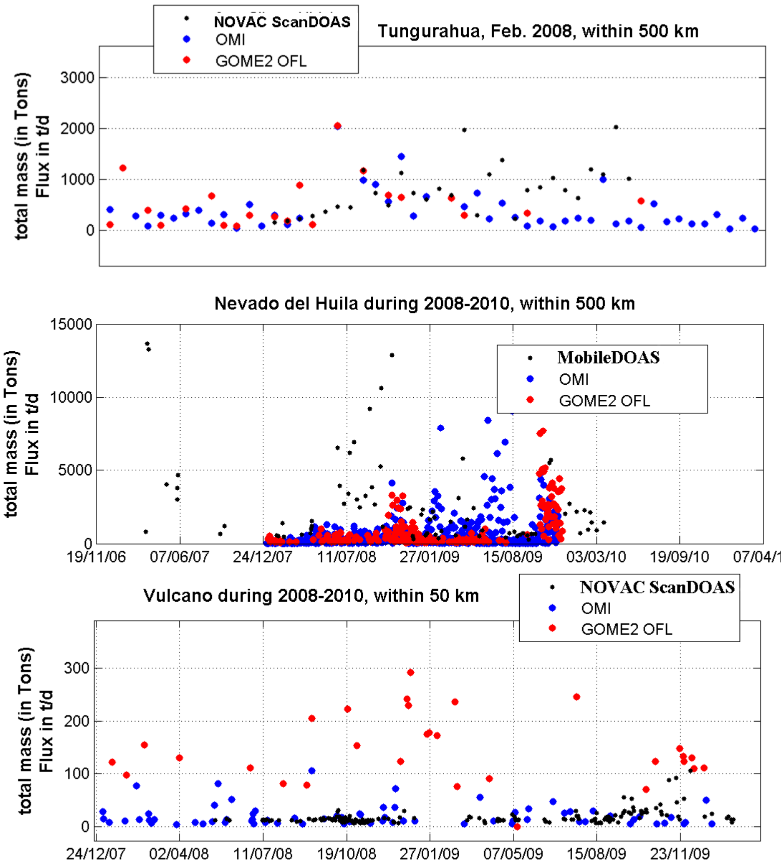

Figure 5: **Time series of OMI and GOME-2 masses comparisons vs ground-based SO_2 fluxes over Tungurahua in Feb. 2008, Nevado del Huila since 2007 and Vulcano Island since 2008.**

From these preliminary comparisons it is difficult to conclude on the validity of the comparison of the satellite-based masses with the ground-based fluxes. More ground-based data are necessary to extend this comparison. Moreover, large uncertainties on both types of data exist: ground-based fluxes depend strongly on wind speed and plume altitude choices (Galle et al. 2010, Salerno et al. 2009), while for the satellites, clouds can mask part of the scene, and an assumption has to be made for the plume altitude (both OMI and GOME-2 datasets provide at least 3 types of SO_2 VCD, with different assumed SO_2 altitude depending on the assumed eruption type – see table 1). Uncertainties in the mass calculation also exist (related to data re-gridding, inclusion of a possible second OMI overpass orbit and choices of the CTP for the elimination of anomalies; Carn et al., 2008), and different values can be obtained for the same scene (e.g. http://so2.umbc.edu/omi).

4. OMI AND ASTER COMPARISONS

A study focusing on the comparison of the OMI SO_2 values with the high resolution ASTER data has been started, focusing on the different perception of the volcanic plume by the two instruments. ASTER has a pixel resolution of 90x90m² which allows the exploration of the spatial inhomogeneities in the SO_2 plume inside the area covered by an OMI pixel (13x24 km² at best). ASTER also gives a stereoscopic estimation of the height of the volcanic plume and this external information can be used to reduce the error on the SO_2 column retrieval from OMI. Figure 6 shows the plume emitted by Etna on 3 August 2006, as seen by OMI and by ASTER. The maximum SO_2 columns retrieved are respectively 4.8×10^{16} molec/cm² for OMI and 1.4×10^{19} molec/cm² for ASTER. In order to compare these two different types of measurements, we need to resample the ASTER data on the OMI pixel size, in order to counterbalance the spatial gradients that are smoothed within the OMI pixel. On the right panel of figure 6 the area of the OMI pixels close to the ASTER measurements is plotted as black rectangles. The resampled ASTER data over these 3 OMI pixels (1.1×10^{17}, 7.6×10^{16} and 8.1×10^{16} molec/cm²) are now of the same order of magnitude as the OMI SO_2 standard TRM column (assuming the SO_2 is around 7.5km, see table 1). An even better agreement is obtained when interpolating the OMI columns at the height of the plume derived from the ASTER data (3.4km in this case). Moreover, considering the transport of the plume between the different overpass times (~2h) and thus comparing the total column over the 3 pixels, an even better agreement is found, with 2.66×10^{17} molec/cm² for ASTER and 1.91×10^{17} molec/cm² for OMI.

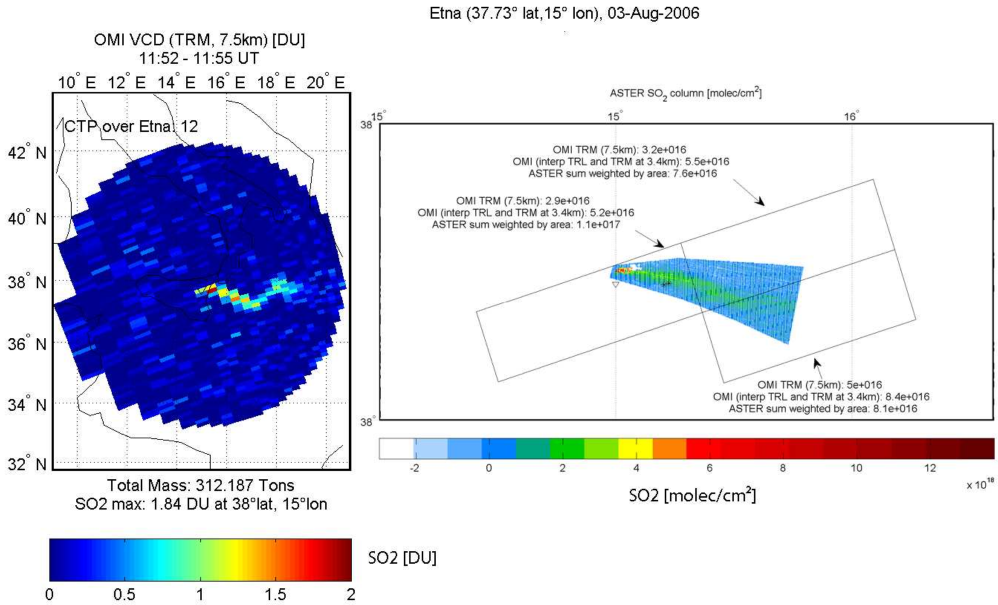

Figure 6: **Maps of the SO_2 plume distribution over Etna on 3 August 2006 as seen by OMI (left panel) and as seen by ASTER (right panel). In the latter, the edges of the OMI closest pixels are also plotted in black.**

A flux calculation routine has been developed for ASTER data (Campion et al., 2010) and is applied also on OMI data for different eruptions. The flux-routine uses the SO_2 columns amounts, an estimation of plume altitude, wind speed and wind direction as input, and calculates the fluxes along parallel transects at increasing distance of the volcano (see figure 7a). The fluxes measured with OMI at the different transects for the Etna case study are presented in figure 7. The mean value is of 22 kg/s (figure 7b), which is slightly lower than what measured 2 hours before by ASTER (48 kg/s).

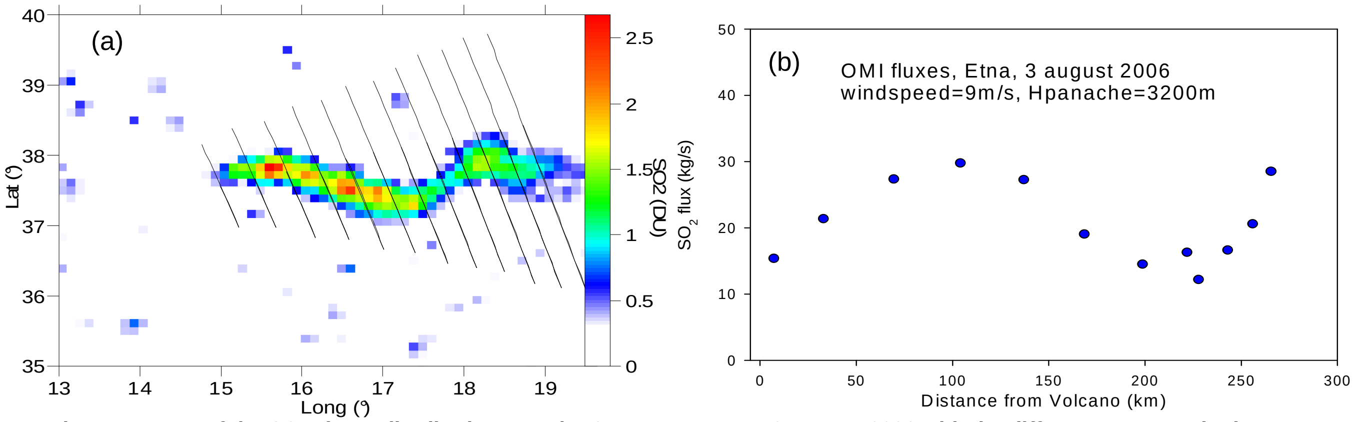

Figure 7: **Maps of the SO_2 plume distribution seen by OMI over Etna on 3 August 2006 with the different transects in the (left panel), and results of the flux calculation with respect to the distance from the volcano (right panel).**

Another example of OMI and ASTER flux calculations is presented in figures 8 and 9 for the Anatahan eruption in June 2005. Figure 8 shows the OMI scene (1000km around the volcano), and the wind speed and direction as extracted from ECMWF data over the volcano. Figure 9 shows the evolution of the fluxes as a function of the distance from the vent, both for ASTER and for OMI. A good agreement between the fluxes calculated from the two instruments is found.

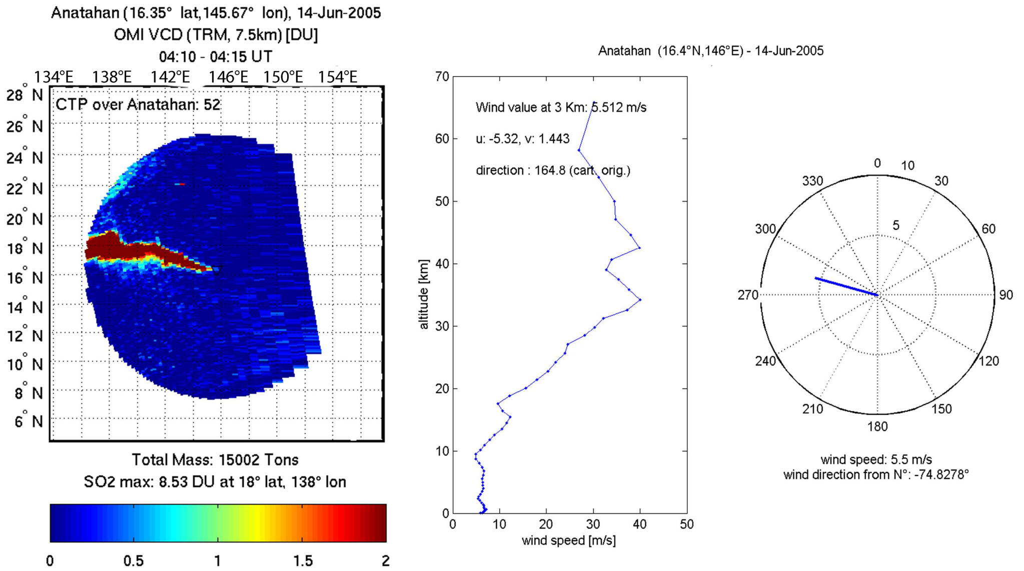

Figure 8: **Maps of the SO_2 plume distribution over Anatahan on 14 June 2005 as seen by OMI on the left panel, and ECMWF wind speed and direction over the volcano on the right panel.**

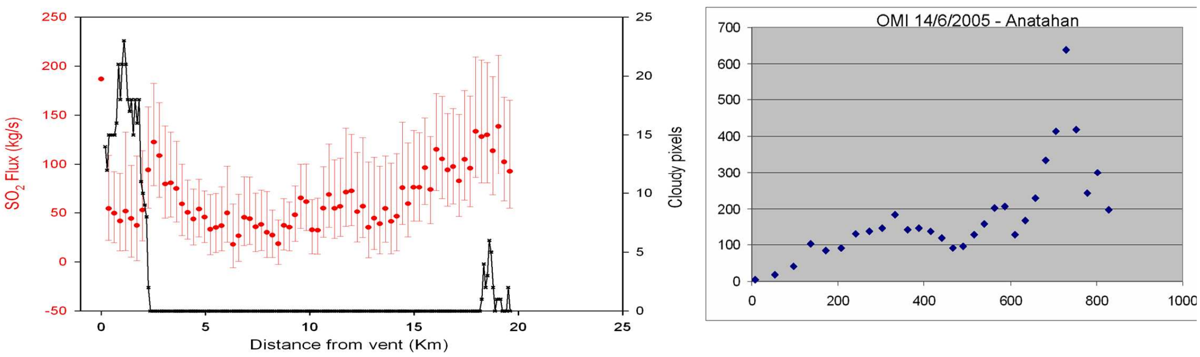

Figure 9: **Results of the flux calculation around Anatahan on the 14 June 2005. The fluxes are plotted as a function of the distance from the volcano for ASTER on the left panel and from OMI on the right panel.**

Several flux calculations have been performed on both ASTER and OMI data, for volcanic plumes from Etna, Nyriagongo, Nyamuragira and Anatahan and the results are compared in figure 10. A good general agreement is found, with a correlation coefficient of R = 0.95, a slope of 0.99 and an intercept of -8kg/s for the linear regression line fit. OMI fluxes are generally slightly smaller than those retrieved by ASTER. More eruptions are currently being analysed and will be included in this comparison exercise.

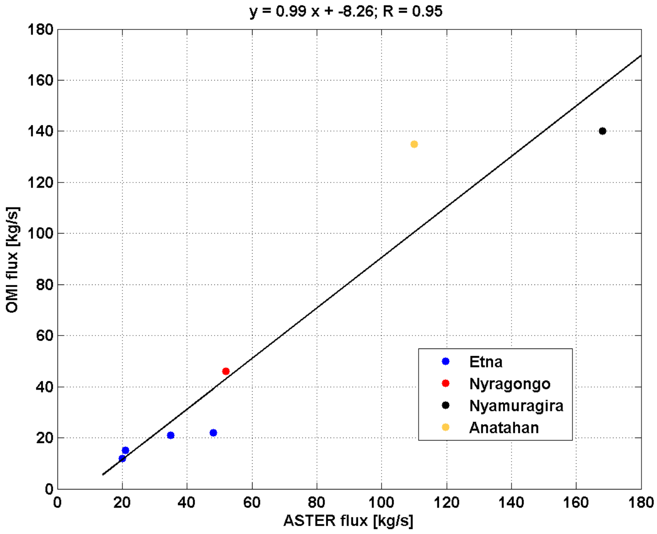

Figure 10: **Scatter plot of the fluxes obtained from ASTER and OMI data over Etna (3/8/2006, 12/8/2006, 16/9/2007, 21/6/2008), Nyriagongo (18/1/2010), Nyamuragira (19/6/2007) and Anatahan (14/6/2005).**

5. CONCLUSIONS AND FUTURE WORK

The data from OMI and GOME-2 operational products have been extracted over the different NOVAC stations since 2007. The coherence of the two datasets has been tested by looking at the maximum SO_2 column within a radius of 500km around the volcanoes and total daily SO_2 masses have been calculated and compared. OMI pixels affected by the cross-track position (CTP) anomalies have been excluded at best from the mass calculation, but the continuous degradation and spreading to other CTP is still in part affecting the calculations. Comparisons of the satellite-based masses with ground-based fluxes have been performed at 3 stations showing a reasonable agreement for some of them (Tungurahua, Feb. 2008, and Vulcano, 2008-2009), but also large differences over some time periods (Nevado del Huila, July 2008) with much larger ground-based fluxes. More NOVAC data are needed to conclude on the validity of the exercise. Moreover, uncertainties on the SO_2 columns and masses exist, related to the way the calculation is done and to the importance of unknown external parameters (like the SO_2 plume height) that largely affect the SO_2 column values.
The comparison of OMI columns with the ASTER instrument shows good results: a study over Etna, smoothing the SO_2 column within an OMI pixel, highlights the importance of averaging the spatial horizontal inhomogeneities within an OMI pixel. Also the plume altitude estimation is important to get the best SO_2 column. A method to calculate SO_2 fluxes from OMI (and possibly GOME-2 as well) has been developed for the comparisons with ASTER. Its application to several case studies showed a good agreement. Preliminary results indicate that in most cases OMI seems to slightly underestimate ASTER.
In the future, the reprocessing of the NOVAC database will allow for a more extended comparison with the satellite data-sets, including more accurate information on winds and plume altitude. Moreover, the use of trajectory analysis on case studies will help linking satellite-based masses and ground-based fluxes. For plumes containing high SO_2 columns it is known that the current operational products underestimate the volcanic SO_2; and more accurate – but time-consuming – retrievals exist (Yang et al., 2009, Yang et al., 2010) that will be used for specific test cases.

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