Satellite Monitoring of Ash and Sulphur Dioxide for the mitigation of Aviation Hazards: Part II. Validation of satellite-derived Volcanic Sulphur Dioxide Levels.

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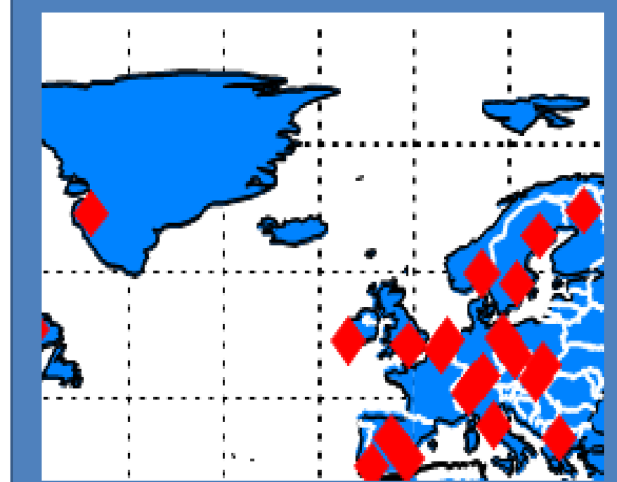
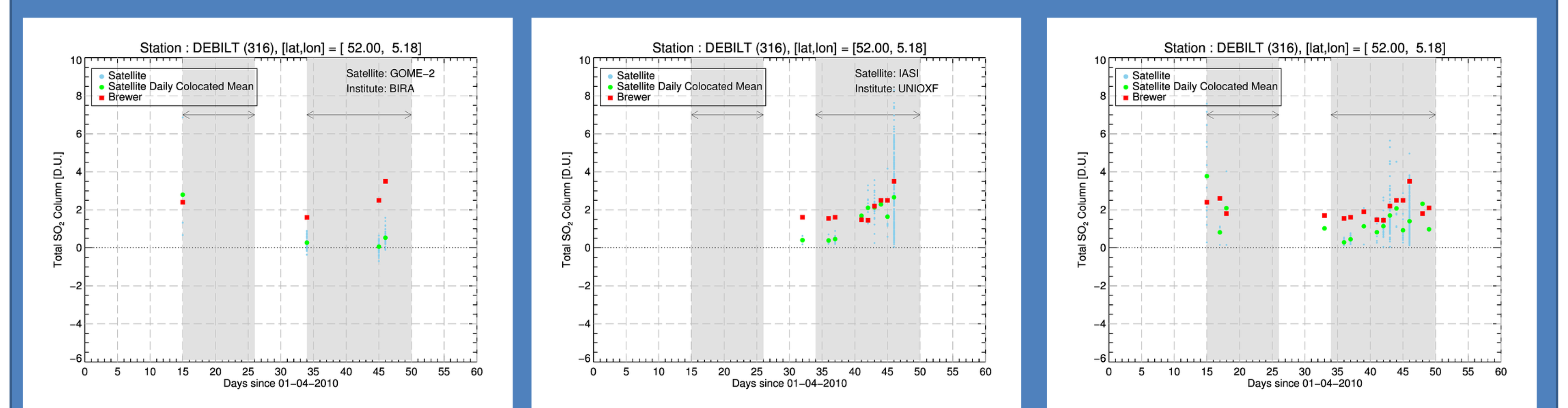
Satellite to Brewer comparisons



Locations of the Brewer stations considered in this work.

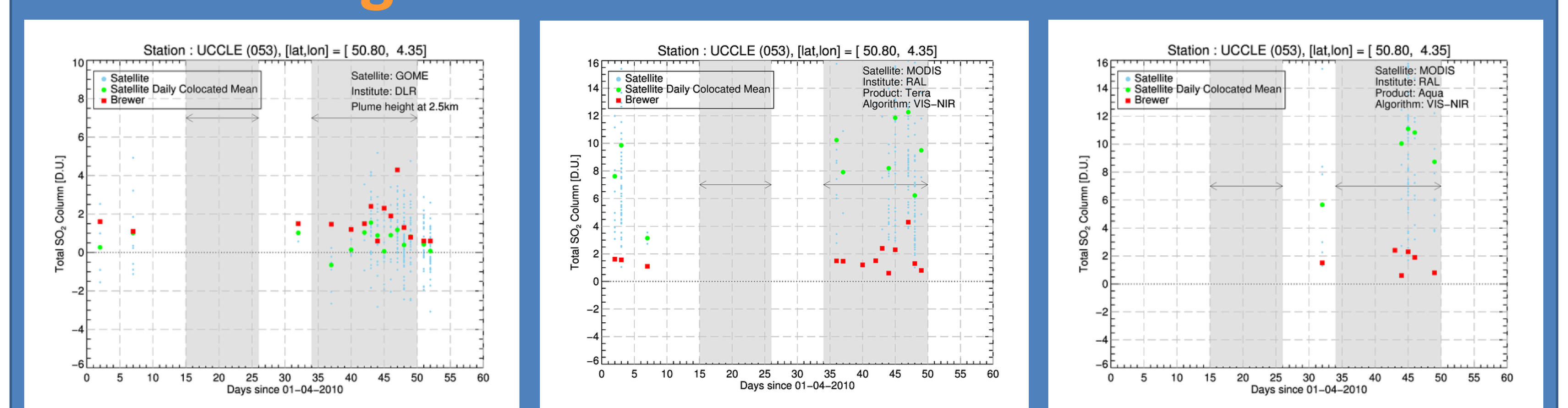
•The ground-based data that has been used for comparison with the satellite columnar SO_2 products are the daily mean values of total SO_2 columns observed by the global Brewer spectrophotometer network and distributed through the World Ozone and Ultraviolet Data Centre, WOUDC, database found in www.woudc.org.
•SO_2 is a bi-product of Brewer spectrophotometer measurements, once O_3 is extracted from the data.
•Since the signal-to-noise is quite low, very well-calibrated instruments are required to monitor nominal SO_2 levels.
•In extreme [e.g. volcanic] cases SO_2 levels rise well above instrumental noise which was not **our case.**

De Bilt – The Netherlands



BIRA/GOME-2 [left panel], the Oxford nominal algorithm/IASI [middle panel] and the ULB/IASI [right panel] co-locations between the satellite overpasses and the De Bilt, Netherlands, Brewer measurements for the Eyjafjallajökull 2010 eruptions. In green, the daily mean SO_2 levels estimated by the satellite and in red, the daily mean SO_2 Brewer measurements. The grey zones denote the eruptive periods.

Uccle - Belgium



DLR/GOME-2 [left panel], the RAL VIS-NIR algorithm/MODIS-Terra [middle panel] and the RAL VIS-NIR algorithm/MODIS-Aqua [right panel] co-locations between the satellite overpasses and the Uccle, Belgium, Brewer measurements for the Eyjafjallajökull 2010 eruptions. In green, the daily mean SO_2 levels estimated by the satellite and in red, the daily mean SO_2 Brewer measurements. The grey zones denote the eruptive periods. Note that the y-axis scale differs between the GOME-2 and the MODIS comparisons.

Table 1. Summary of mean satellite and ground-based SO_2 level estimates, as well as their mean difference.

Institute	Instrument & algorithm	Mean Satellite SO_2 levels [D.U.]	Mean Brewer SO_2 Levels [D.U.]	Mean difference [D.U.]	Number of common obs
BIRA	SCIA/GOME				Too few
DLR	GOME2/MetopA	0.18 1.53	1.22 1.07	1.06 1.83	493
Oxford	IASI/MetopA Nominal Algorithm	**1.57 1.53**	**1.78 1.25**	0.80 1.85	44
Oxford	IASI/MetopA Fast Algorithm	0.62 0.55	1.58 1.28	1.22 1.19	87
ULB	IASI/MetopA	**1.09 0.95**	**1.50 1.09**	1.13 1.41	80

Abstract – Project description

The eruption of the Icelandic volcano Eyjafjallajökull in the spring of 2010 turned the attention of both the public and the scientific community to the susceptibility of the European airspace to the outflows of large volcanic eruptions. The ash-rich plume from Eyjafjallajökull drifted towards Europe and caused major disruptions of European air traffic for several weeks affecting the everyday life of millions of people and with a strong economic impact. This unparalleled situation revealed limitations in the decision making process due to the lack of information on the tolerance to ash of commercial aircraft engines as well as limitations in the ash monitoring and prediction capabilities.

The European Space Agency project *Satellite Monitoring of Ash and Sulphur Dioxide for the mitigation of Aviation Hazards*, was introduced to facilitate the development of an *optimal End-to-End System for Volcanic Ash Plume Monitoring and Prediction.* This system is based on comprehensive satellite-derived ash plume and sulphur dioxide [SO_2] level estimates, as well as a widespread validation using supplementary satellite, aircraft and ground-based measurements. The validation of volcanic SO_2 levels extracted from the sensors GOME-2/MetopA and IASI/MetopA are shown here with emphasis on the total column observed right before, during and after the Eyjafjallajökull 2010 eruptions. Co-located ground-based Brewer Spectrophotometer data extracted from the World Ozone and Ultraviolet Radiation Data Centre, *WOUDC*, were compared to the different satellite estimates. The findings are presented at length, alongside a comprehensive discussion of future scenarios.

Satellite products shown in this work

The GOME-2/MetopA observations were analyzed by:
1. Belgian Institute of Aeronomie, hereafter ***BIRA***
2. German Space Agency, hereafter ***DLR***

The IASI/MetopA observations were analyzed by:
1. Université Libre de Bruxelles, hereafter **ULB**
2. Oxford University, hereafter ***Oxford***

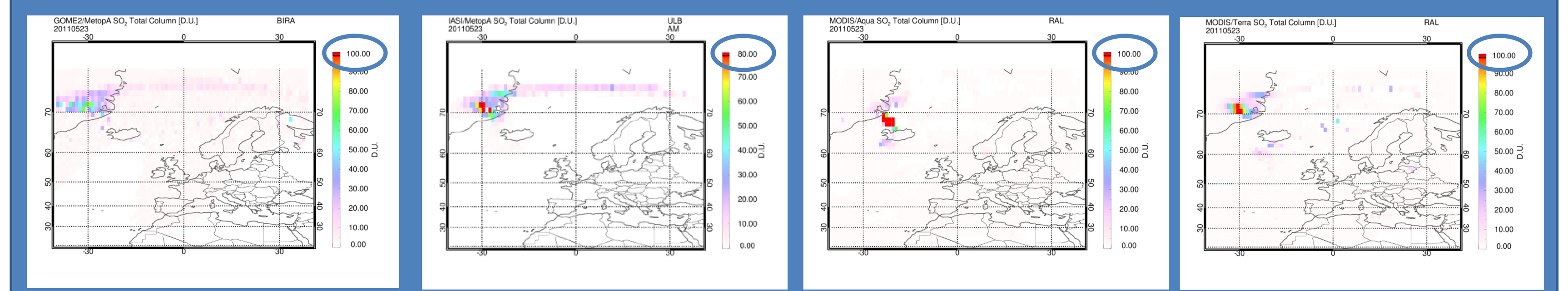
The MODIS/Terra & MODIS/Aqua observations were analyzed by:
1. Rutherford Appleton Laboratory, hereafter ***RAL***
2. Istituto Nazionale di Geofisica e Vulcanologia, hereafter ***INGV***

Main Findings - Conclusions

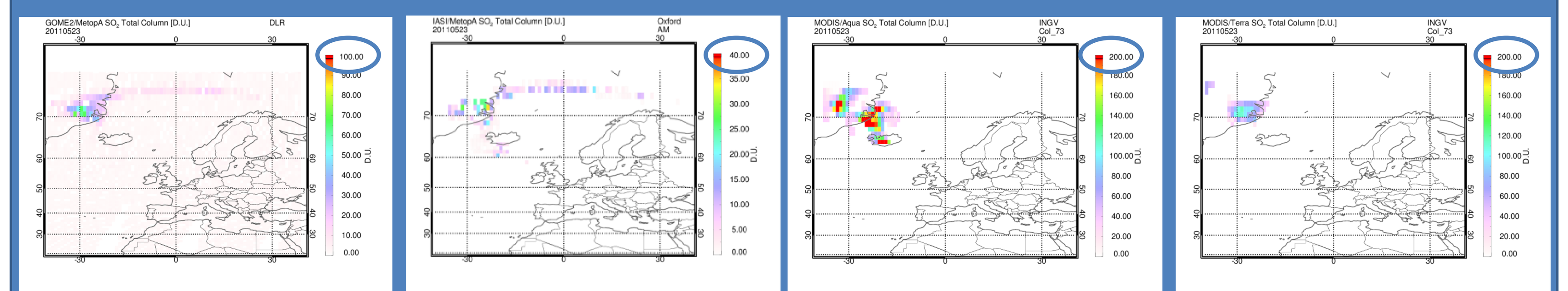
For the Comparisons with the Brewer spectrophotometers we may say that:
▪The BIRA/SCIAMACHY and BIRA/GOME-2 data set had too few co-locations.
▪The DLR/GOME-2 total SO_2 column for the 2.5km plume height show distinct signal during the main eruptive period. A moderate correlation, R^2, was found for some of the ground-based stations, with values between 0.3 and 0.5.
▪The Oxford_nominal/IASI algorithm total SO_2 columns are quite promising when there is a strong signal.
▪The Oxford_Fast/IASI algorithm provides smaller (≈2 DU) total SO_2 column compared to the nominal algorithm.
▪The ULB/IASI total SO_2 columns are very promising when there is a strong signal with correlations R^2 for some of the ground-based stations between 0.3 and 0.7.
▪The RAL MODIS/Terra & MODIS/Aqua IR & VIS/NIR algorithms largely the total SO_2 column relative to the other (differences > 6 DU), however consistent spatial patterns are observed.
For the Inter-Comparisons between satellite products we may say that:
▪The BIRA and DLR GOME2/MetopA algorithms produce very similar patterns for the SO_2 loading as well as very similar absolute SO_2 column levels providing the SO_2 signal is high enough.
▪The ULB and Oxford IASI/MetopA algorithms produce very similar patterns for the SO_2 plume height [where given] however the absolute SO_2 levels vary dramatically. There is an order of magnitude difference between the two Oxford algorithms, with the nominal algorithm providing absolute SO_2 columns within the same order of magnitude to the ULB findings and the GOME2 findings.
▪The INGV and RAL MODIS/Terra & /Aqua algorithms deviate quite a bit, both in the magnitude of the estimates SO_2 column but also in the geographical extend of the loading, which bares further investigation.

Satellite to Satellite comparisons

The case of the Grimsvötn 23rd of May 2011 eruption: Columnar SO_2 estimates

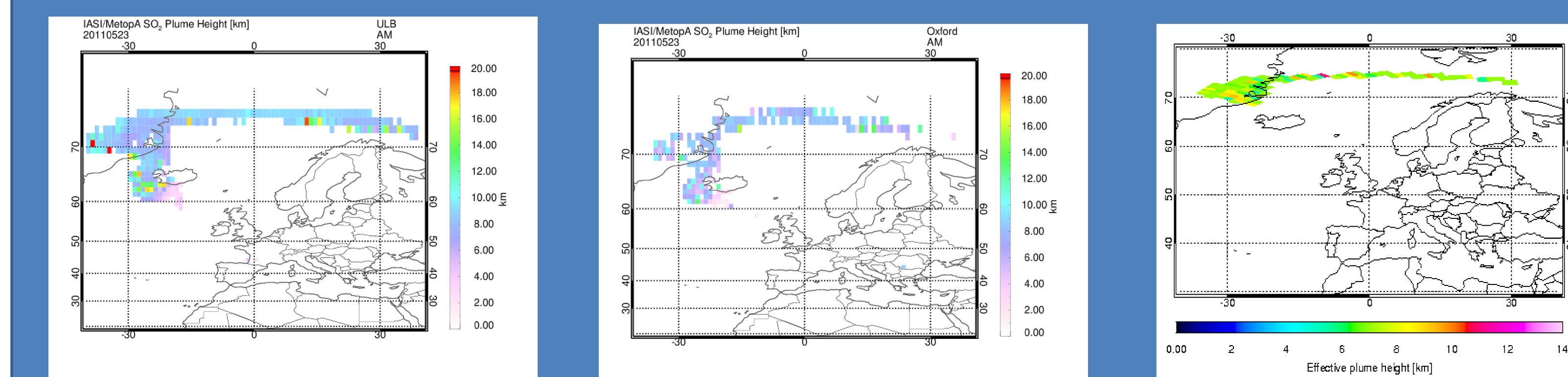


BIRA/GOME-2 [leftmost panel], the ULB/IASI AM overpass [second to the left panel], the RAL MODIS/Aqua [third to the left panel] and the RAL MODIS/Terra [right panel] map of Europe during the 23rd of May 2011 Grimsvötn eruption. Note that the colour bars are **slightly** different between the different products.



DLR/GOME-2 [leftmost panel], the Oxford/IASI AM overpass [second to the left panel], the INGV MODIS/Aqua [third to the left panel] and the INGV MODIS/Terra [right panel] map of Europe during the 23rd of May 2011 Grimsvötn eruption. Note that the colour bars are **quite** different between the different products.

The case of the Grimsvötn 23rd of May 2011 eruption: SO_2 plume height estimates



ULB/IASI AM overpass [left panel], the Oxford/IASI AM overpass [middle panel] and the BIRA/GOME2 [right panel] estimated SO_2 effective plume height for the 23rd of May 2011 Grimsvötn eruption. Note that the colour bars are **somewhat** different between the different products.

References

▪Carboni, E., Grainger, R., Walker, J., et al., (2012), A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010, Atmos. Chem. Phys., doi:10.5194/acp-12-11417-2012.
▪Clarisse, L., Coheur, P.-F., Prata, F., et al., (2013), A unified approach to infrared aerosol remote sensing and type specification, Atmos. Chem. Phys., doi:10.5194/acp-13-2195-2013.
▪Clerbaux, C., Boynard, A., Clarisse, L., et al., (2009), Monitoring of atmospheric composition using the thermal infrared IASI/MetOp sounder, Atmos. Chem. Phys., doi:10.5194/acp-9-6041-2009.
▪Koukouli, M. E., Balis, D. S., Dimopoulos, S., et al., (2014), SACS-2/SMASH Validation Report on the Eyjafjallajökull and Grimsvötn eruptions, European Space Agency.
▪Rix, M., Valks, P., Hao, N., et al. (2012): Volcanic SO_2, BrO and plume height estimations using GOME-2 satellite measurements during the eruption of Eyjafjallajokull in May 2010, J. Geophys. Res., doi:10.1029/2011JD016718.
▪Theys, N., Campion, R., Clarisse, L., et al., (2013), Volcanic SO_2 fluxes derived from satellite data: a survey using OMI, GOME-2, IASI and MODIS, Atmos. Chem. Phys., doi:10.5194/acp-13-5945-2013.
▪van Gent, J. Spurr, R., Theys, N., et al., (2014), Towards operational retrieval of SO_2 plume height from GOME-2 radiance measurements, manuscript in preparation for Atmos. Meas. Tech., 2014.

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