The use of IASI in the measurement of volcanic SO2: degassing and lower tropospheric emission

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Abstract

Sulphur dioxide (SO2) is an important atmospheric constituent that plays a crucial role in many atmospheric processes. Volcanic eruptions are a significant source of atmospheric SO2 and its lifetime and impact depend on the SO2 injection altitude. Measurements of volcanic SO2 emissions can offer critical insight into the current and near-future activity of volcanoes, however, the majority of active volcanoes lack regular ground-based monitoring.
We exploit the spectral range of IASI, from 1000 to 1200 cm-1 and from 1300 to 1410 cm-1 (the 7.3 and 8.7 mm SO2 absorption bands), to study volcanic SO2.
The IASI-A dataset was analysed using a rapid linear retrieval algorithm as a global survey tool to show that IASI observations detect SO2 emissions from anthropogenic sources, volcanic eruptions and certain persistently degassing volcanoes over the IASI time series. Using this linear retrieval hundreds of potential degassing volcanoes are identified around the world.
An iterative optimal estimation retrieval scheme was then employed to produce a more detailed analysis of the data, with a comprehensive error budget. This algorithm is significantly more computationally intensive but allows for the estimation of both the SO2 amount and altitude of volcanic plume from recent explosive and effusive eruptions.
Thermal infrared spectrometers are particularly valuable in regions where shorter wavelength observations are limited, such as during polar winter.
In particular here we present two case studies:
1) The vertical distribution of SO2 during the Bardabunga eruption from September 2014 to February 2015.
2) The monthly mean trends in SO2 emission over Ecuador. Over Ecuador, Tungurahua showed the most persistent signal, with a strong correlation between IASI, ground-based and OMI datasets. Over Kamchatka, IASI detected clear peaks in SO2 emissions coincident with reports of elevated volcanic activity.

SO2 linear retrieval (detection) theory

The optimal estimate of x taking into account total measurement error may be computed as:

$$\hat{\mathrm{x}} = \mathrm{x}_0 + (\mathrm{K}^T \mathrm{S}_y^{\mathrm{tot}-1}\mathrm{K})^{-1}\mathrm{K}^T\mathrm{S}_y^{\mathrm{tot}-1}(\mathrm{y}-\bar{\mathrm{y}})$$

$$\mathrm{G} = (\mathrm{K}^T \mathrm{S}_y^{\mathrm{tot}-1}\mathrm{K})^{-1}\mathrm{K}^T\mathrm{S}_y^{\mathrm{tot}-1}$$

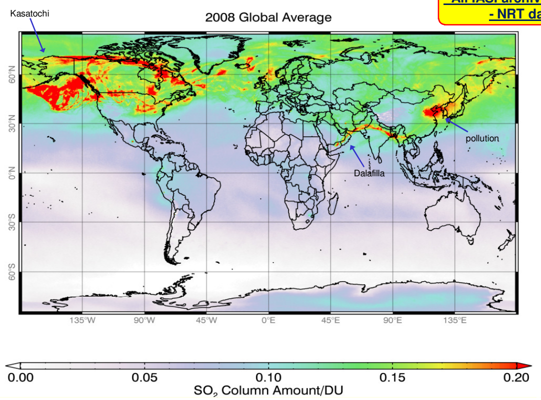
Sy^{tot} is computed considering an appropriate ensemble of N measured spectra to construct an estimate of total measurement error variance-covariance Sy^{obs}

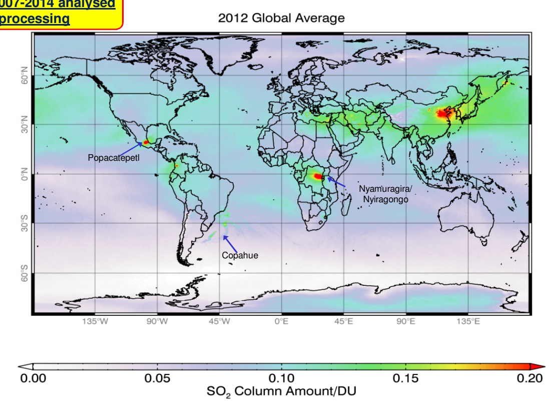
$$\mathrm{S}_y^{\mathrm{tot}} \approx \mathrm{S}_y^{\mathrm{obs}} = \frac{1}{N}\sum_{i=1}^{N}(\mathbf{y}_i-\bar{\mathbf{y}})(\mathbf{y}_i-\bar{\mathbf{y}})^T \qquad \bar{\mathrm{y}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{y}_i$$

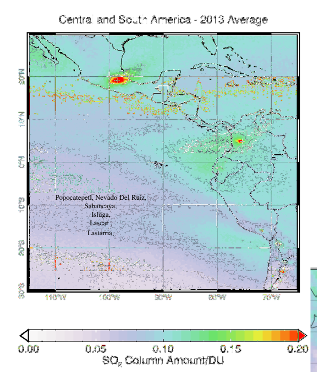
Create a generalized error covariance Sy^{tot} that contains not only the instrument noise, but noises due to interfering gases and broadband scatterers (using IASI spectra only).

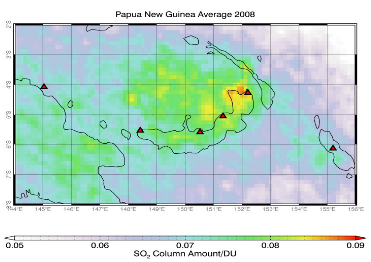
It is mainly a 'measurement' of the SO2 signal. Assume SO2 vertical profile, atmosphere profiles, jacobian. Used for: (i) plume detection, (ii) identify where there is a signal

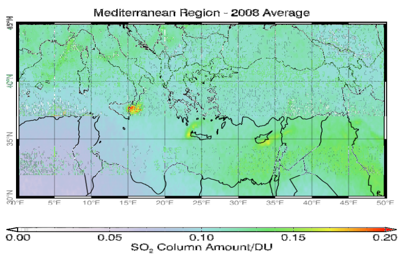
- All IASI archive 2007-2014 analysed
- NRT data processing

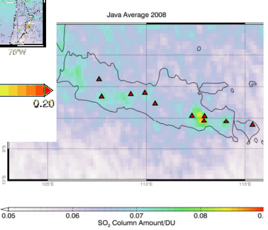


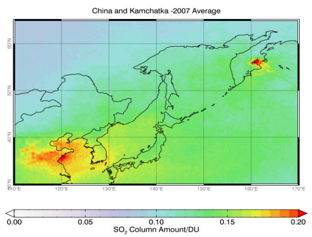


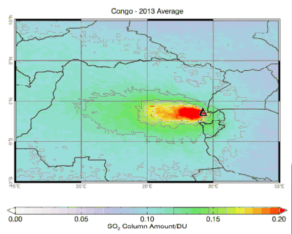










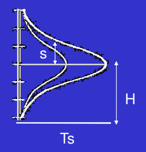


SO2 iterative (all v1 and v3) - Retrieval scheme

The SO_2 retrieval algorithm uses measurements from 1000 to 1200 cm^{-1} and from 1300 to 1410 cm^{-1} (the 7.3 and 8.7 µm SO2 bands) made by IASI (Carboni et al., 2012). Uses the detection scheme (Walker et al. 2012) applied to pixels for the full retrieval (Carboni et al 2012).

This retrieval scheme determines the column amount and effective altitude of the SO_2 plume with high precision (up to 0.3 DU error in SO_2 amount if the plume is near the tropopause) and can retrieve informations in the lower troposphere.

There are several advantages of the IASI retrievals:
(1) IASI makes measurements both day and night (so has **global coverage every 12 hours**),
(2) the IASI retrieval does not assume plume height but **retrieves an altitude for maximum SO_2 amount** (under the assumption that the vertical concentration of SO_2 follows a Gaussian distribution).
(3) IASI retrievals is **not affected by underlying cloud** (if the SO_2 is within or below an ash or cloud layer its signal will be masked and the retrieval will underestimate the SO_2 amount, in the case of ash this is a posteriori discernible by the cost function value)
(4) A **comprehensive error budget for every pixel** is included in the retrieval. This is derived from an error covariance matrix that is based on the SO_2-free climatology of the differences between the IASI and forward modelled spectra.



State vector:
- Total column amount of SO_2
- Altitude H
- Thickness s
- Surface temperature Ts

+ ECMWF profile (temperature, h2o, p, z)

F(x) — Forward model: fast radiative transfer (RTTOV + SO_2 RAL coefficients)

IASI simulated spectra

IASI measurements → OE retrieval

$$J = (\mathbf{y}-F(\mathbf{x})-\mathbf{b})^T\mathbf{S}_e^{-1}(\mathbf{y}-F(\mathbf{x})-\mathbf{b}) + (\mathbf{x}-\mathbf{x}_a)^T\mathbf{S}_a^{-1}(\mathbf{x}-\mathbf{x}_a)$$

y is the measurement vector, **x** the state vector, **F(x)** forward model, **Se** error covariance matrix

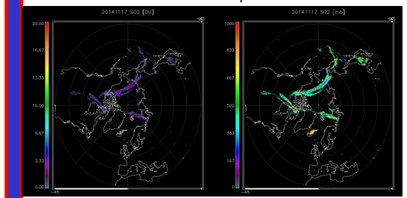
best estimate of stare vector:
SO_2 amount, plume altitude, Ts

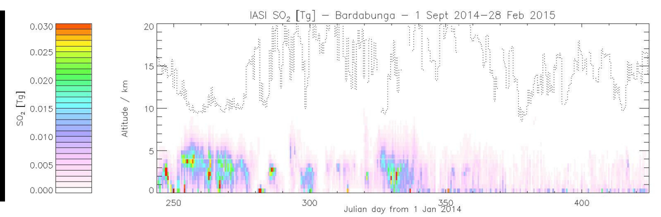
Note that the measurement covariance, $\mathbf{S_e}$, is defined to represent the effects of atmospheric variability not represented in the forward model (FM), as well as instrument noise. This includes the effects of cloud and trace-gases which are not explicitly modelled. The matrix is constructed from differences between FM calculations (for clear-sky) and actual IASI observations for wide range of conditions, when we are confident that negligible amounts of SO_2 are present.

Bardabunga eruption from September 2014 to February 2015

Every ~12 hours we produce maps of IASI retrieved SO2 amount and altitude. Example here:

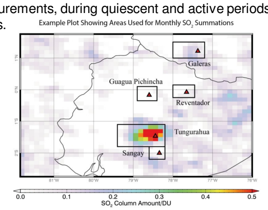
The colour represents the total mass of SO2 in Tg between two vertical step, dark-red represent values higher the colour-bar.
Every column of the plots come from an IASI map (one every 12h). Black line is the mean altitude of tropopouse compute at the plume pixels.

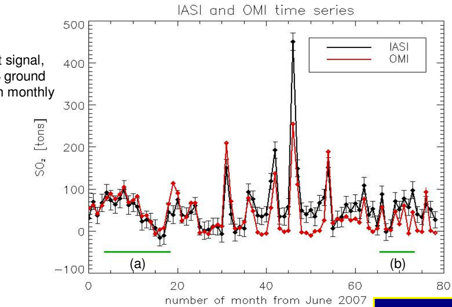


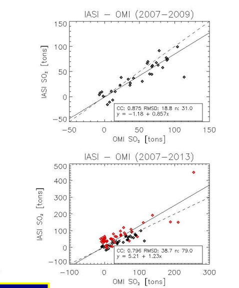


Ecuador monthly average - degassing

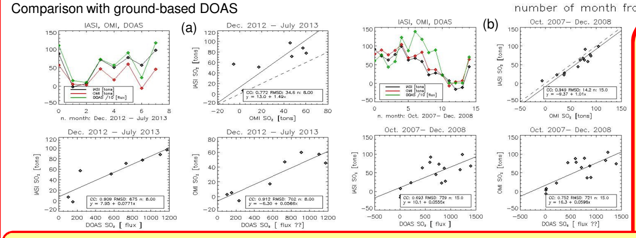
Over Ecuador, Tungurahua showed the most persistent signal, with a strong correlation between IASI, OMI and DOAS ground measurements, during quiescent and active periods, on monthly scales.







Comparison with ground-based DOAS



Summary

Linear retrieval clearly indicated areas where IASI detects persistent emissions. Individual eruptions were also apparent in this data, alongside anthropogenic pollution (China and the Middle East).
The IASI scheme can be used twice a day to follow the vertical distribution of SO2 as a function of time for low altitude plume and during winter time with low solar radiation (Bardabunga eruption).
Monitoring trends in volcanic emissions using the IASI retrieval shows promise for variations in Tungurahua-scale persistent activity. The IASI retrieval may have value in monitoring trends at similar active volcanoes where ground-based monitoring is limited.

Iterative retrieval
Carboni, E., R.G. Grainger, T.A. Mather, D.M. Pyle G.E. Thomas, R. Siddans, A.J.A. Smith, A. Dudhia, M.E. Koukouli and D. Balis, The vertical distribution of volcanic SO2 plumes measured by IASI, Atmospheric Chemistry and Physics, 16, 4343–4367, 2016. (doi:10.5194/acp-16-4343-2016)
Carboni, E., Grainger, R., Walker, J., Dudhia, A., and Siddans, R.: A new scheme for sulphur dioxide retrieval from IASI measurements: application to the Eyjafjallajökull eruption of April and May 2010, Atmos. Chem. Phys., 12, 11417-11434, doi:10.5194/acp-12-11417-2012, 2012.
Detection scheme:
Walker, J.C., E. Carboni, A. Dudhia, R.G. Grainger: Improved Detection of Sulphur Dioxide in Volcanic Plumes using Satellite-based Hyperspectral Infra-red Measurements: Application to the Eyjafjallajokull 2010 Eruption, J. Geophys. Res., 117, doi:10.1029/2011JD016810, 2012.
Walker, J.C., A. Dudhia and E. Carboni, An effective method for the detection of trace species demonstrated using the MetOp Infrared Atmospheric Sounding Interferometer, Atmospheric Measurement Techniques, 4, 1567–1580, 2011.