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 nm SO2 absorption bands), to study volcanic SO2. The IASI-A dataset was analyzed 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 plumes from recent explosive and effusive eruptions.

Thermal infrared spectroscopy is particularly valuable in regions where shorter wavelength observations are limited, such as during polar winters. In particular here we present two case studies:

1. The vertical distribution of SO2 during the Bardarbunga 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 a taking into account total measurement error may be computed as:

\[ S_y = \begin{pmatrix} x_0 + (K_y \Sigma_y^{-1} k) \end{pmatrix} \]

where \( x_0 \) is the a priori estimate of SO2, \( K_y \Sigma_y^{-1} k \) is the Kalman gain matrix, and \( \Sigma_y \) is the measurement error covariance matrix. A common example of using this equation is the SO2 retrieval from IASI measurements using the IASI retrieval scheme presented in Walker et al. (2012).

Sy is computed considering an appropriate ensemble of N measured spectra to construct an estimate of total measurement error variance-covariance \( \Sigma_y \). Create a generic cloud error covariance \( \Sigma_y \) that contains not only the instrument noise, but also that due to interfering gases and broadening mechanisms (using IASI spectra only).

SO2 iterative (all y1 and y3) - Retrieval scheme

The SO2 retrieval algorithm uses measurements from 1000 to 1200 cm⁻¹ and from 1300 to 1410 cm⁻¹ (the 7.3 and 8.7 nm 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 SO2 plume with high precision (up to 0.3 DU error in SO2 amount if the plume is near the tropopause) and can retrieve information 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 SO2 retrieval does not assume plume height but retrieves an altitude for maximum SO2 amount (under the assumption that the vertical concentration of SO2 follows a Gaussian distribution).
3. IASI retrievals are not affected by underlying cloud if the SO2 is within or below an ash or cloud layer its signal will be masked and the retrieval will underestimate the SO2 amount, in the case of ash this is a posteriori determined 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 SO2-free climatology of the differences between the IASI and forward modeled spectra.

Summary

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

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 retrieval scheme can be used twice a day to follow the vertical distribution of SO2 as a function of time for low plume altitude and during winter time with low solar radiation (Bardarbunga example). 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.