Satellite remote sensing of volcanic plume from Infrared Atmospheric Sounding Interferometer (IASI): results for recent eruptions.

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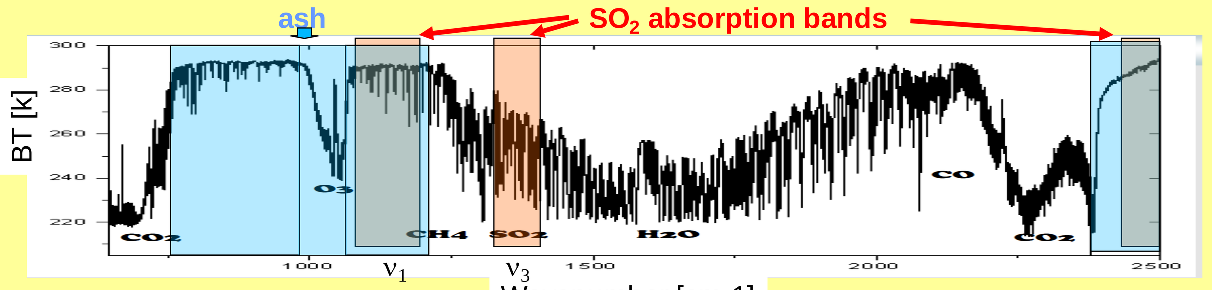
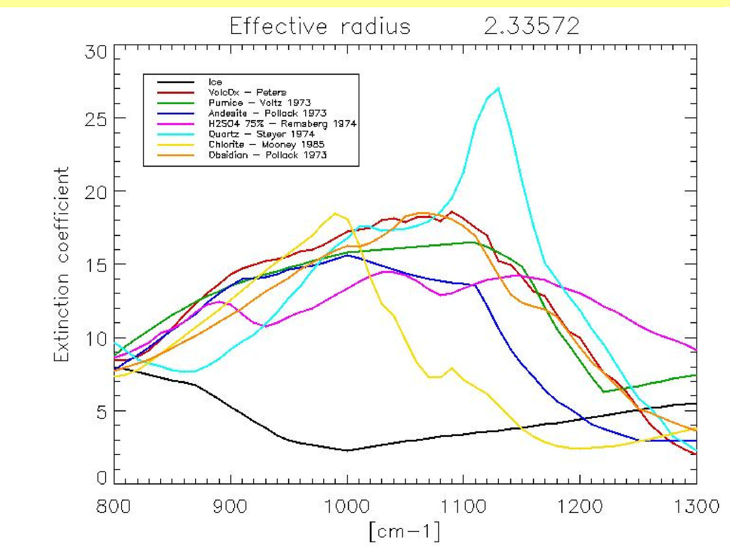
Infrared Atmospheric Sounding Interferometer - IASI

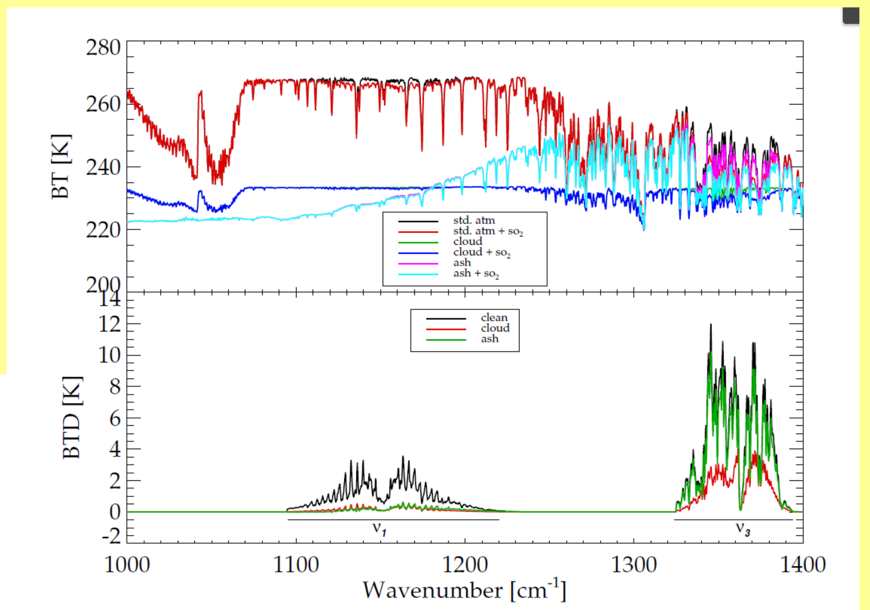


IASI is on board of METeorological OPerational satellite program (METOP), a European meteorological satellite that has been operational since 2007. METOP-A is the first of three polar satellites planned for the next fourteen years. It crosses the equator at the local time of 9.30. IASI is a Fourier transform spectrometer, that measures the spectral range 645 to 2760 cm^{-1} (3.62–15.5μm) with a spectral sampling of 0.25 cm^{-1} and an apodised spectral resolution of 0.5 cm^{-1}. Radiometric accuracy is 0.25-0.58K. The IASI field of view (FOV) consists of four circles of 12 km diameter (at nadir) inside a square of 50 x 50 km, step-scanned across track (30 steps). It has a 2000 km swath and nominally can achieved global coverage in 12 hours (although there are some gaps between orbits at tropical latitudes). Radiances are collocated with the Advanced Very High Resolution Radiometer (AVHRR) that provides complementary visible/near infrared channel, for cloud and aerosol retrievals.

The thermal infrared spectra of volcanic plumes shows a rapid variation with wavelength due to absorption lines from atmospheric and volcanic gases as well as broader scale features due to particulate absorption.
IASI spectra also contain information about the atmospheric profile (temperature, gases, aerosol and cloud) and radiative properties of the surface. In particular the ash signature depends on the composition and size distribution of ash particles as well on their altitude. The signature of sulphur dioxide depends on its amount and vertical profile.

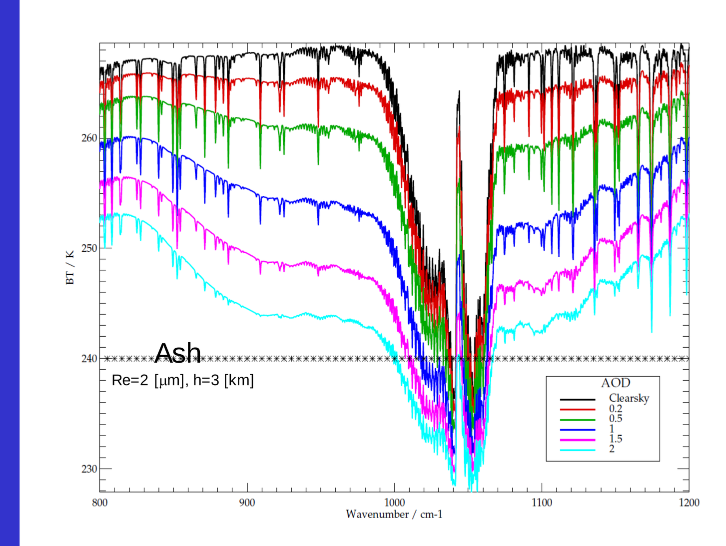


Extinction coefficients obtained using the same size-distribution (with an effective radius of 2 μm) and different refractive indexes of volcano-related ash and rock: ice, volcanic ash (Peters, 2013), pumice, andesite, H_2SO_4, quartz, chlorite, obsidian. The large variability, presumably because changing ash composition reflect the variability of IR spectra measured from satellites for different volcanoes and eruptions.



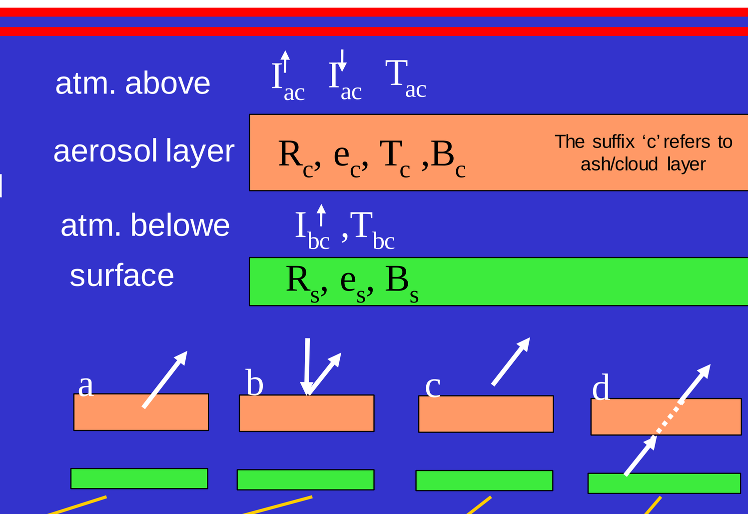
The influence of ash or cloud layers on simulated IASI spectra. The spectra for a thick water cloud and an ash layer suppresses the SO_2 signal in the ν1 band, but in the ν3 band ash has a smaller impact than cloud.
Water cloud: R_{eff} = 20 μm; AOD_{550}=10; h =400 mb
Ash layer: R_{eff} = 2 μm; AOD_{550}= 3; h =400 mb

IASI FAST FORWARD MODEL FOR ASH



IASI spectra simulated using refractive index measured in lab by Daniel Peters from an Aso ash sample, for different ash optical depths (at the reference wavelength of 550 nm)

The RTTOV output for a clean atmosphere (containing gas but not cloud or aerosol/ash) is combined with an ash layer using the same scheme as for the Oxford-RAL Retrieval of Aerosol and Cloud (ORAC) algorithm.

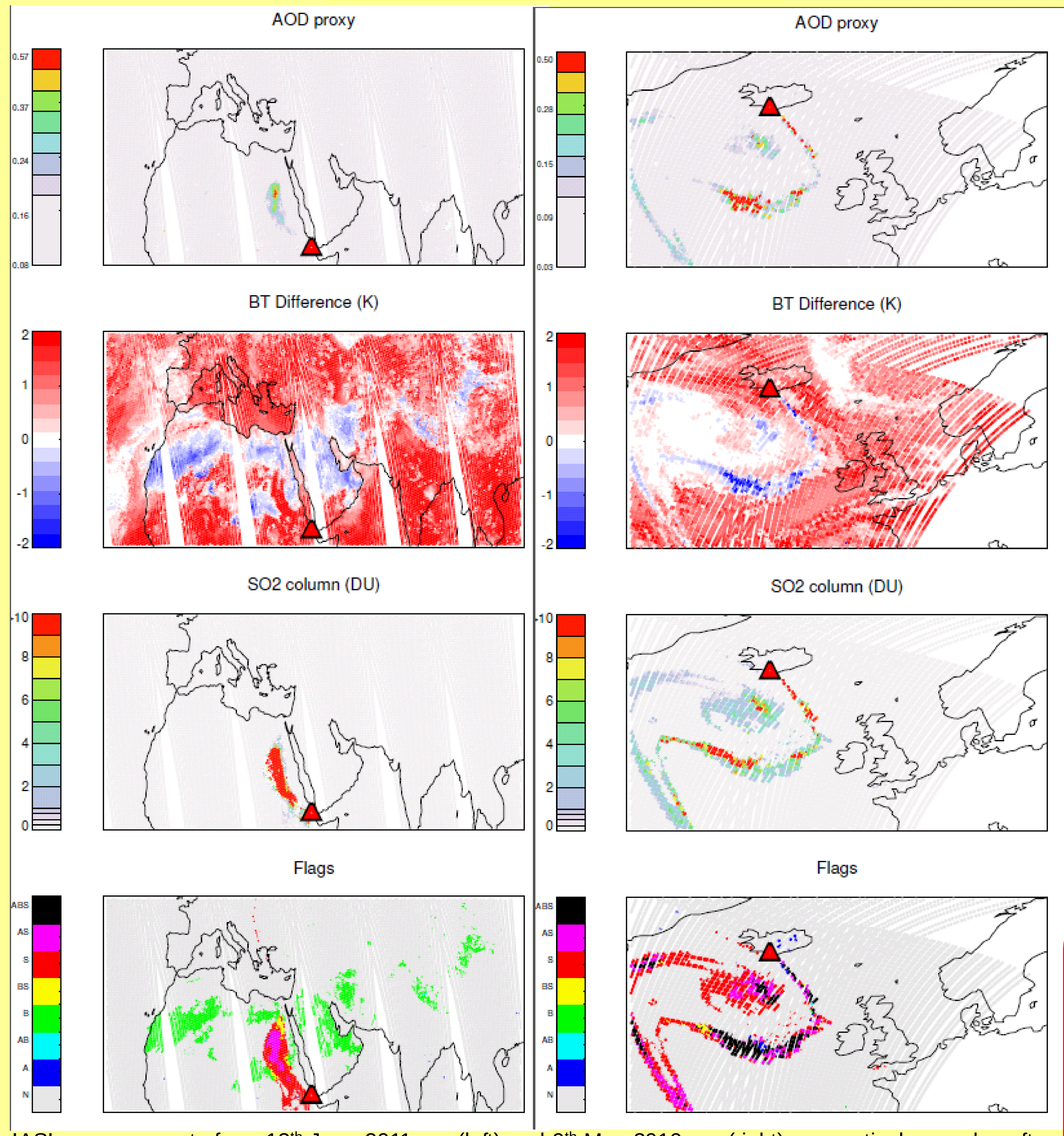


$$I^{\uparrow}_{\bullet} = B_c \epsilon_c T_{ac} + I^{\downarrow}_{ac} R_c T_{ac} + I^{\uparrow}_{ac} + B_s \epsilon_s T_{bc} T_c T_{ac} + I^{\uparrow(atm)}_{bc} T_c T_{ac}$$

LUTs for aerosol layer parameters

Other atmospheric parameters (radiances above/below aerosol layer going up/down) are computed with RTTOV using ECMWF atmospheric profiles.

Volcanic ash flag



IASI measurements from 13th June 2011 pm (left) and 9th May 2010 am (right), respectively one day after the begin of Nabro (Eritrea) eruption, and during the more active phase of Eyja (Iceland) eruption.
From top-bottom, Ash optical depth proxy (top), brightness temperature difference, SO_2 column amount are shown along with a flag showing where each method indicate plumes: A=Ash; B=BTD; S=SO_2; N=none: Colours show different combinations e.g. "AS" (pink) indicates both ash and SO_2 flagged.

Ash flagging uses a methodology based on that of Walker et al (2011) and Walker et al (2012), designed to detect trace gases in IASI data. The principle idea is to use a generalised error covariance that contains not only the instrument noise, but covariance due to interfering trace gases and broadband scatterers (such as aerosols and clouds) that should be unrelated to the required retrieved property. Since these signals are included in the covariance, they need not be retrieved or their variance taken account of in the forward model of the atmosphere.

A proxy optical depth is retrieved by linearisation about some background level, τ_0, so that a least squares estimate of τ can be obtained by

$$\tau = \tau_0 + \left(\mathbf{K}^T \mathbf{S}_\epsilon^{-1} \mathbf{K}\right)^{-1} \mathbf{K}^T \mathbf{S}_\epsilon^{-1} \left(\mathbf{y} - \bar{\mathbf{y}}\right).$$

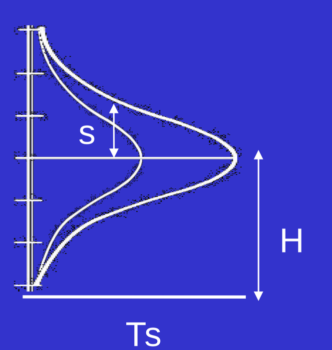
where $\mathbf{y}$ is a measurement, and $\mathbf{K}$ is the Jacobian of the measurement with respect to optical depth $\frac{\partial y}{\partial \tau}$
The error covariance matrix, $\mathbf{S_e}$, is built up from IASI measurements in the days preceding the eruption and in the same geographical area (so that it contains the variation for this location, and time of year, but no volcanic covariance).
Proxy optical depth values are not accurate, but for cases where there is no volcanic signal, they lie very close to τ_0. Volcanic signals stand out above the noise by several standard deviations and can be flagged as being of suspected volcanic origin.

The figure to the left shows comparisons of τ, brightness temperature difference (BTD) between 11 and 12 um, and column SO_2. Ash and SO_2 plumes match well, but the BTD method shows issues over desert.

SO2 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 SO_2 bands) made by IASI (Carboni et al., 2012).
This retrieval scheme (based on optimal estimation) 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 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 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 retrieval 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, H_2O, p, ...)

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

IASI simulated spectra

IASI measurements → OE retrieval

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

y is the measurement vector, **x** the state vector, **F(x)** forward model, **Sy** 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 modeled. 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.

$$S_e(i,j) = \langle (y_{mi}-y_{si})-(\overline{y_{mi}-y_{si}}) \rangle \langle (y_{mj}-y_{sj})-(\overline{y_{mj}-y_{sj}}) \rangle$$

$$y_s = F(SO_2=0)$$

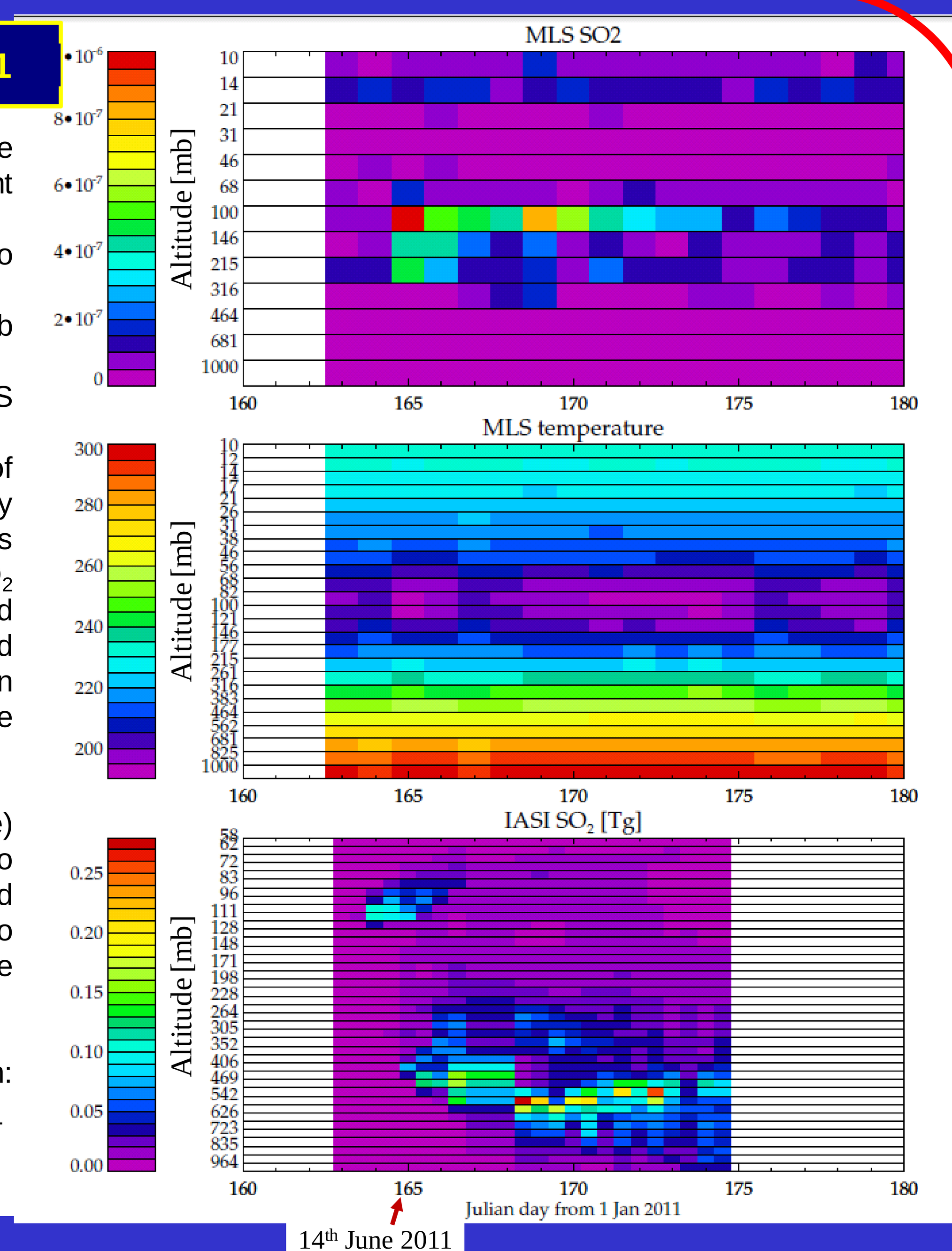
Se Computed with billions pixels

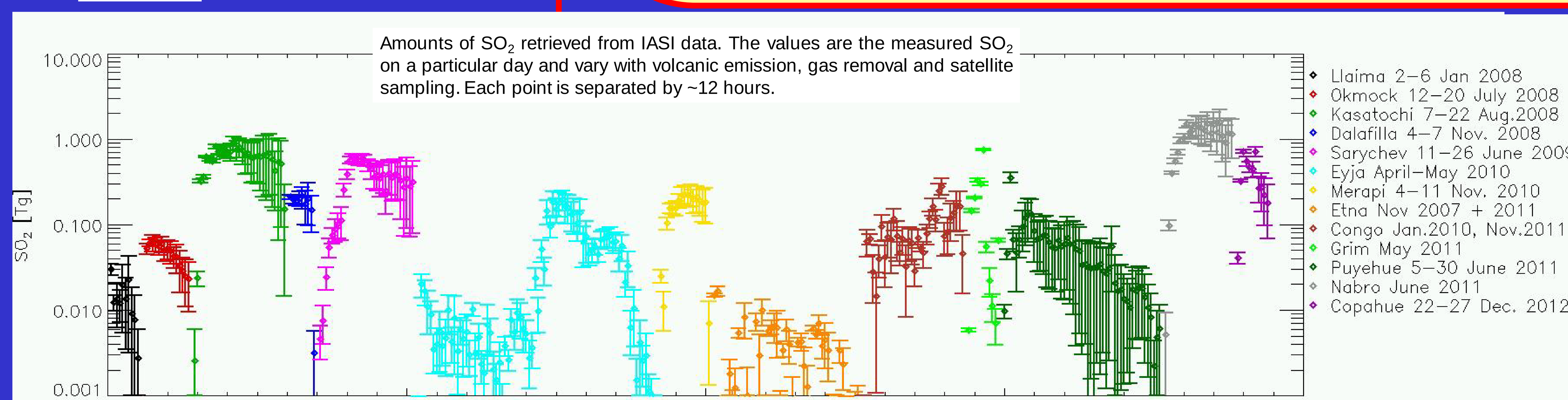
Nabro - starts 12 June 2011

Twice a day it is possible to have IASI maps of retrieved SO_2 amount and altitude.
This figure shows data for Nabro (Eritrea) eruption in June 2011:
a)The MLS (microwave limb sounder) retrieval of SO_2,
b)The corresponding MLS temperature profile retrieval,
c)The IASI SO_2 mass as function of altitude and time (one column every half day). Each column of this plot is obtained summing all the SO_2 amounts (regridded), with retrieved altitude between the indicated vertical levels. In this way we can follow the evolution of the SO_2 plume in the vertical.

As measured from MLS (14th June) and IASI (13th June) the initial Nabro SO2 plume was injected at around 100m, and this altitude correspond to the minimum of the temperature profile as measured by MLS.

MLS data from: http://mls.jpl.nasa.gov/products/so2_product.php





Amounts of SO_2 retrieved from IASI data. The values are the measured SO_2 on a particular day and vary with volcanic emission, gas removal and satellite sampling. Each point is separated by ~12 hours.

SUMMARY

- IASI SO_2 scheme (Carboni et al 2012) retrieves the height and amount of SO_2 and error estimates for every pixel.
- Retrieved uncertainties increase with the decreasing altitude, nevertheless it is possible to retrieve information in the lower troposphere and monitor volcanic degassing (Wednesday, yellow poster, Z143).
- Thick ash can affect the retrieval, recognizable from cost >2 (see Carboni et al. 2012)
- Underlying cloud does not affect the retrieval, though cloud at the same altitude or above masks the SO_2 signal.
- Comparison with other satellite retrievals is shown in Corradini talk; Thursday at 14:45, Room G6
- Full optimal estimation retrievals of ash and SO_2 using the fast ash forward model are currently under development. The ash retrieval scheme development will be carried out within the new NERC SHIVA and ESA SMASH projects.

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