Measuring volcanic SO2 emission using IASI

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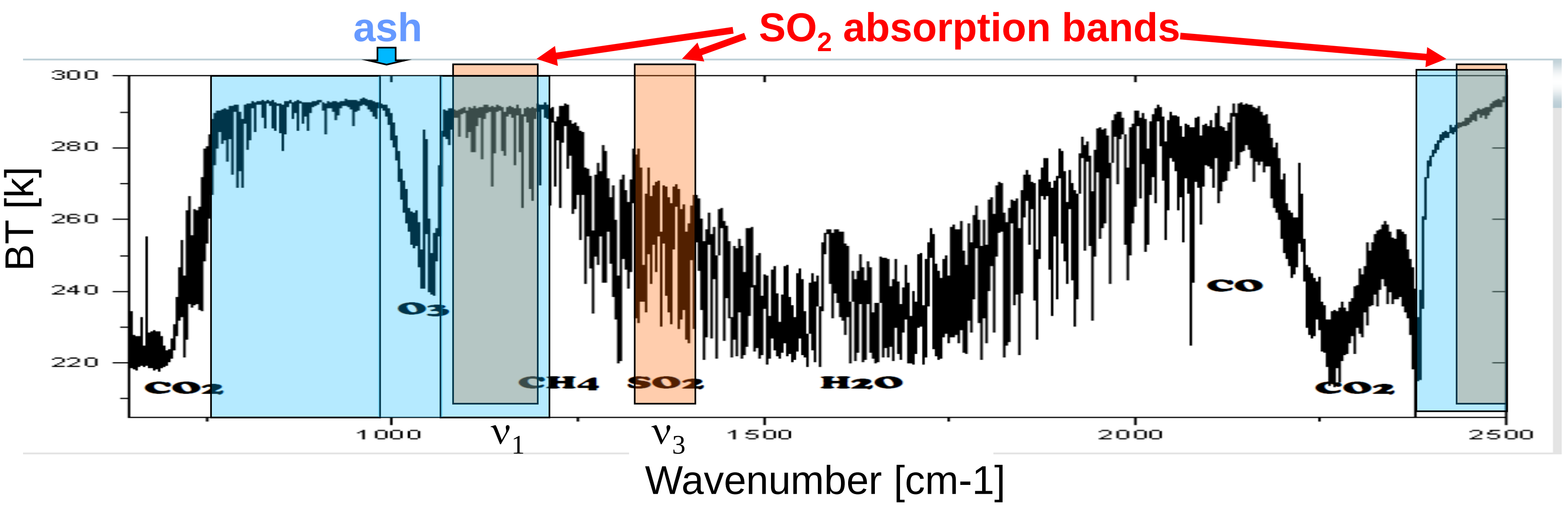
Infrared Atmospheric Sounding Interferometer - IASI

IASI is on board of METeorological OPerational satellite program (METOP-A and METOP-B), a European meteorological satellite that has been operational since 2007.

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.**

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.



SO_2 linear (ν3)

Assume:

SO2 vertical profile,
atmospheric profiles,
Jacobian

It is mainly a 'measurements' of the SO2 signal

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

Retrieve:

SO2 column amount [DU]

(1)

Used for: (i) plume detection, (ii) identify where there is a signal

SO_2 iterative (all ν1 and ν3)

comprehensive error budget for every pixel

Require auxiliary data (ECMWF profiles), radiative transfer (RTTOV) called iteratively

Used for:

Volcanic plume,
study SO2 mass and vertical distribution

Retrieve:

SO2 column amount [DU]
SO2 plume altitude [mb, km]

(2)

(3) Low signal case: degassing, pollution
Results are average in time (monthly means)

(3)

Assume:

SO2 altitude

Retrieve:

SO2 column amount [DU]

(1) SO_2 linear retrieval (detection) theory

[Rodger 2000]

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

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

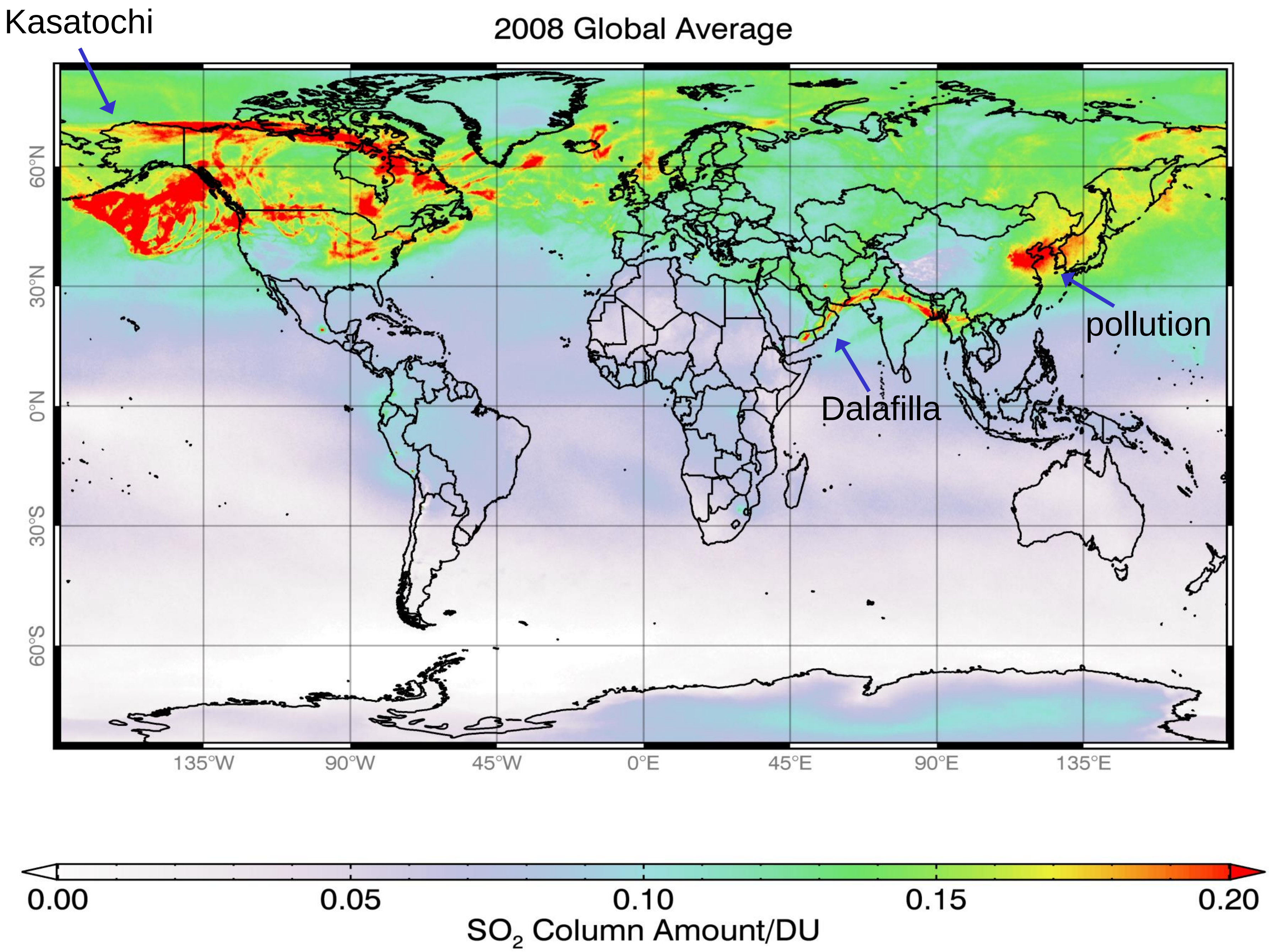
Create a generalized error covariance S_y^{tot} that contains not only the instrument noise, but noises due to interfering gases and broadband scatterers (using IASI spectra only).

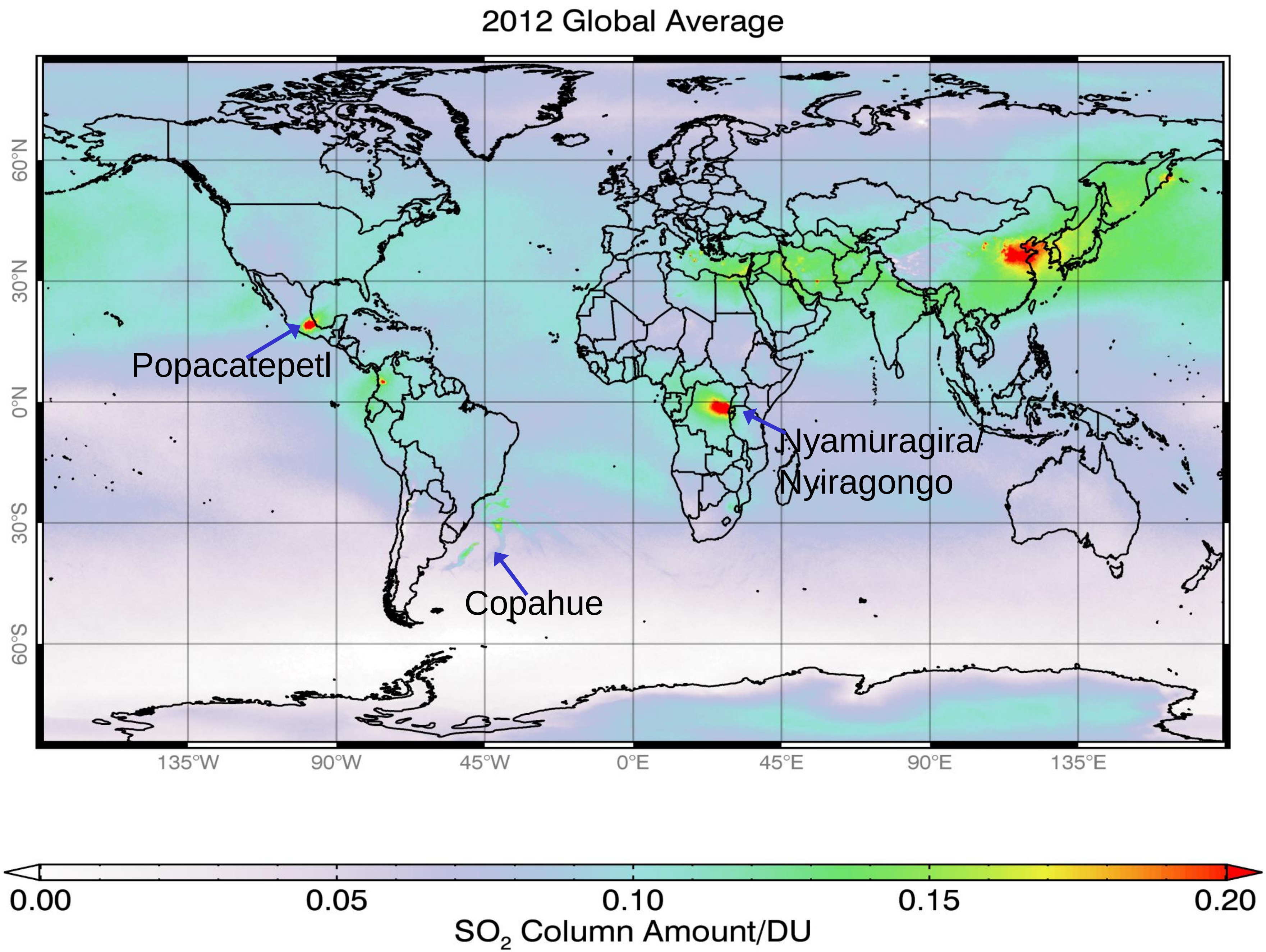
S_y^{tot} is computed considering an appropriate ensemble of N measured spectra to construct an estimate of total measurement error variance-covariance S_y^{obs}

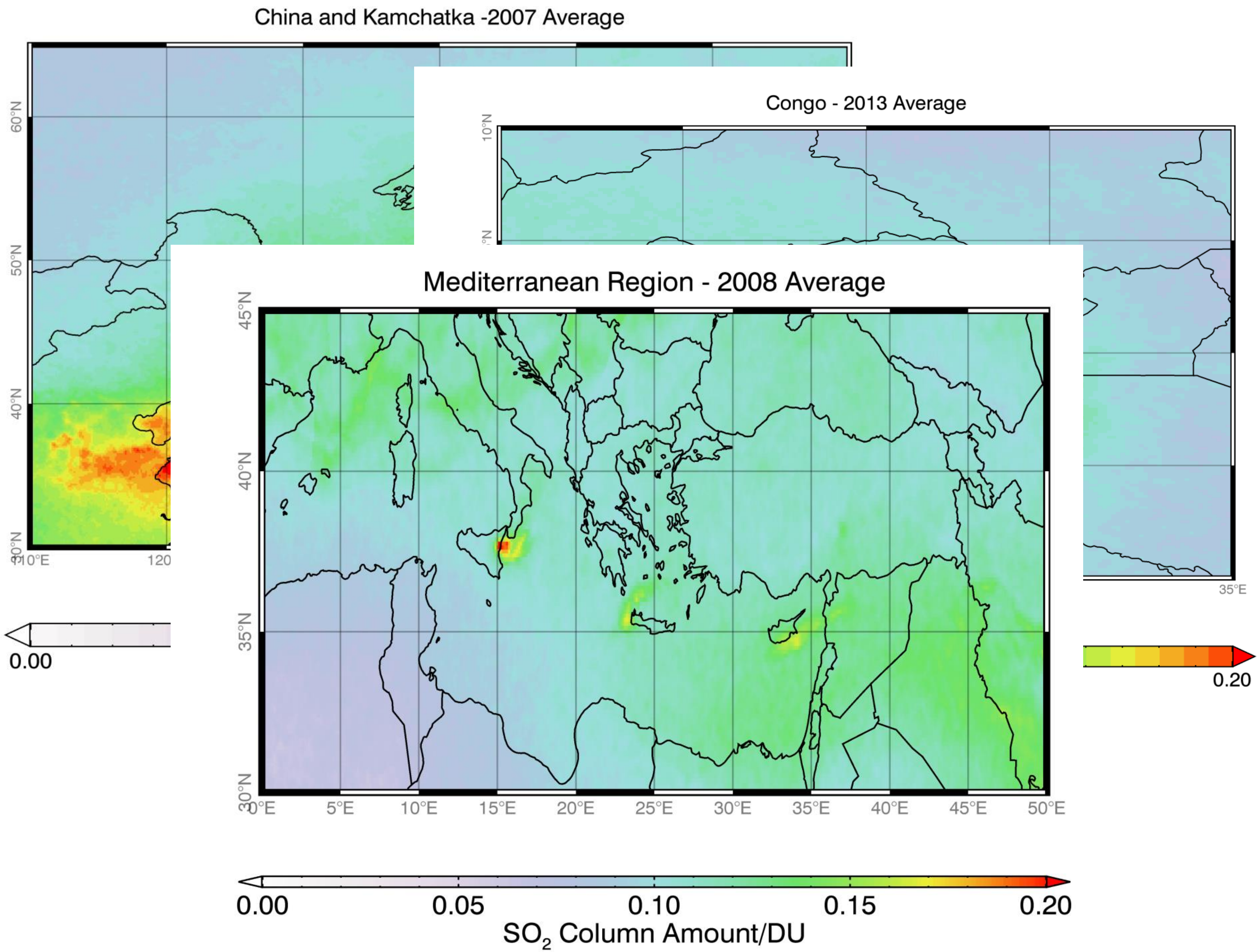
$$\mathbf{S}_y^{\mathrm{tot}} \approx \mathbf{S}_y^{\mathrm{obs}} = \frac{1}{N} \sum_{i=1}^{N} (\mathbf{y}_i - \bar{\mathbf{y}})(\mathbf{y}_i - \bar{\mathbf{y}})^T$$

$$\bar{\mathbf{y}} = \frac{1}{N} \sum_{i=1}^{N} \mathbf{y}_i$$

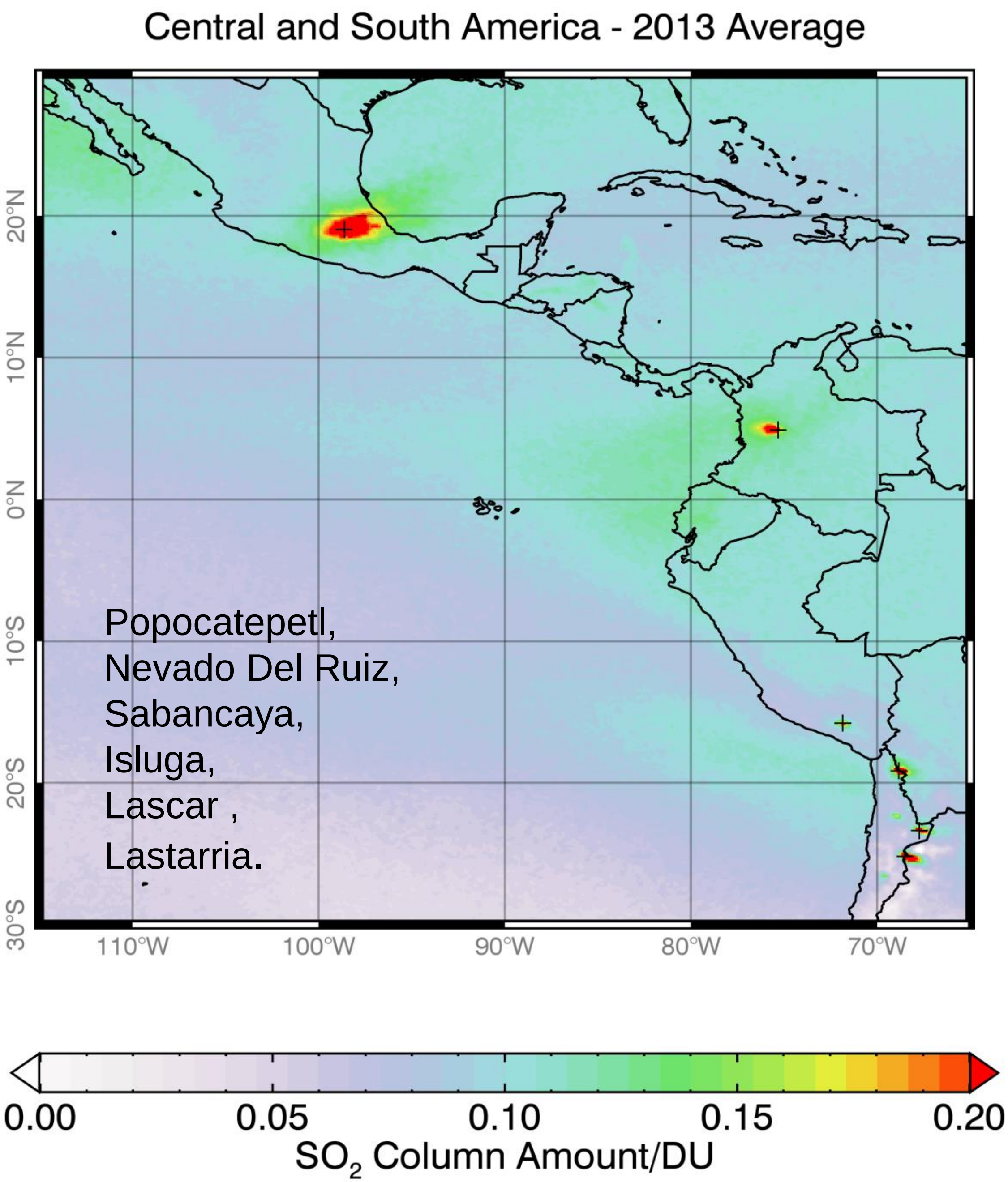
[Walker, Dudhia, Carboni, Atmos. Meas. Tech., 2011]

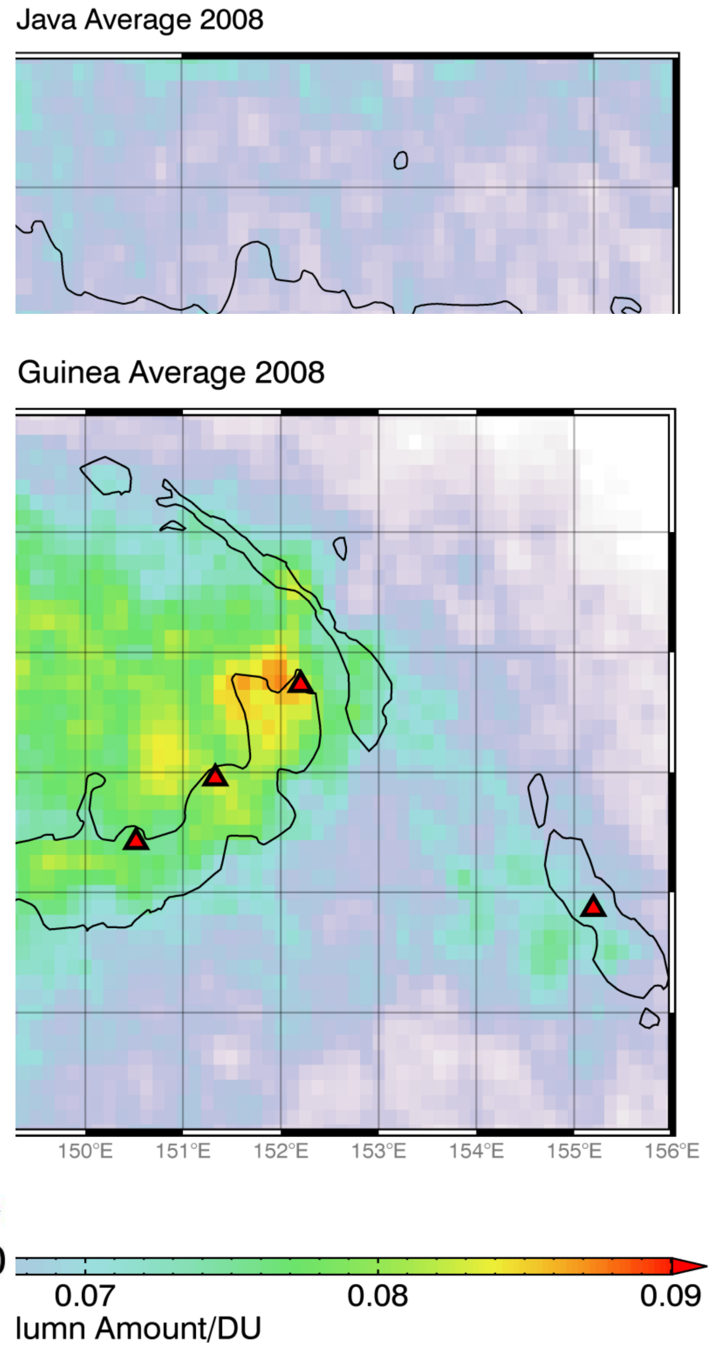

Kasatochi
2008 Global Average
pollution
Dalafilla
60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
0°E
45°E
90°E
135°E
0.00
0.05
0.10
0.15
0.20
SO2 Column Amount/DU


2012 Global Average
60°N
30°N
0°N
30°S
60°S
135°W
90°W
45°W
0°E
45°E
90°E
135°E
Popacatepetl
Nyamuragira/
Nyiragongo
Copahue
0.00
0.05
0.10
0.15
0.20
SO2 Column Amount/DU

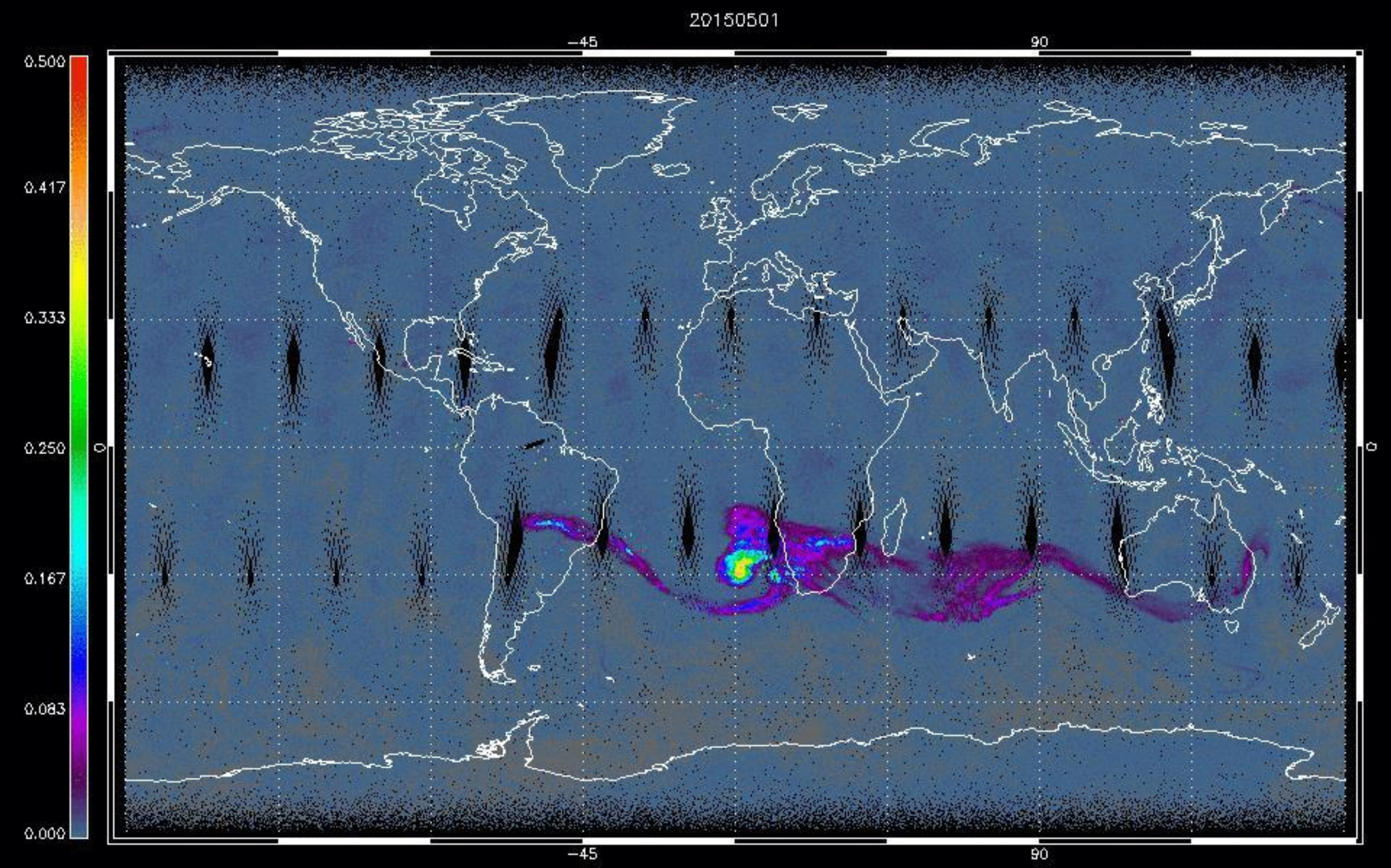


China and Kamchatka -2007 Average
Congo - 2013 Average
Mediterranean Region - 2008 Average
45°N
40°N
35°N
30°N
0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
50°E
0.00
0.05
0.10
0.15
0.20
SO_2 Column Amount/DU

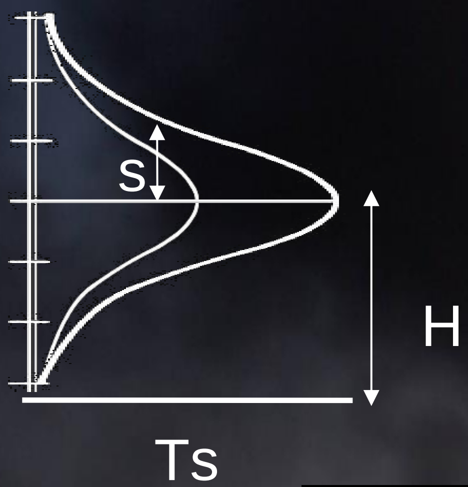

Central and South America - 2013 Average
20°N
10°N
0°N
10°S
20°S
30°S
110°W
100°W
90°W
80°W
70°W
Popocatepetl,
Nevado Del Ruiz,
Sabancaya,
Isluga,
Lascar ,
Lastarria.
0.00
0.05
0.10
0.15
0.20
SO2 Column Amount/DU


Java Average 2008
Guinea Average 2008
150°E
151°E
152°E
153°E
154°E
155°E
156°E
0.07
0.08
0.09
lumn Amount/DU

NRT IASI-A SO2 linear – plume detection - Calbuco



(2) SO_2 iterative - Retrieval scheme



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 + SO2 RAL coefficients)

IASI simulated spectra

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

IASI measurements

OE retrieval

$$J = (y - F(x))^T S_y^{-1} (y - F(x)) + (x - x_a)^T S_a^{-1} (x - x_a)$$

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

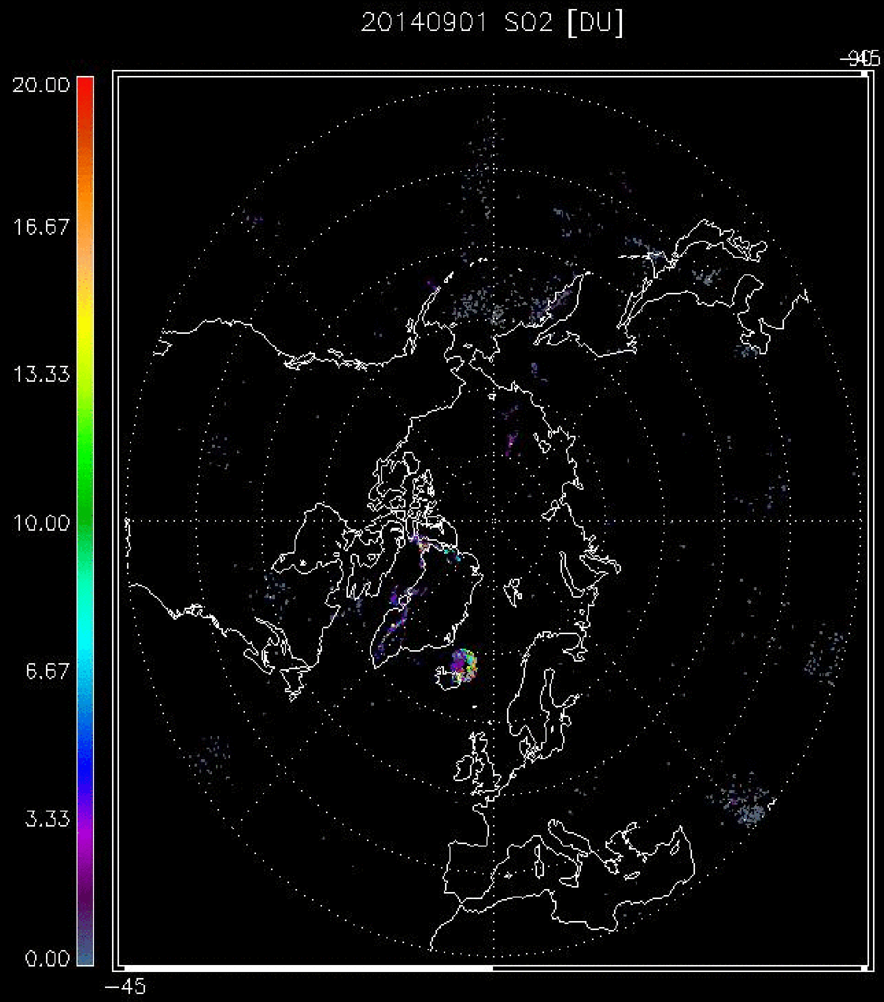
$$S_y(i,j) = <(y_{mi}-y_{si})-\overline{(y_{mi}-y_{si})}><(y_{mj}-y_{sj})-\overline{(y_{mj}-y_{sj})}>$$

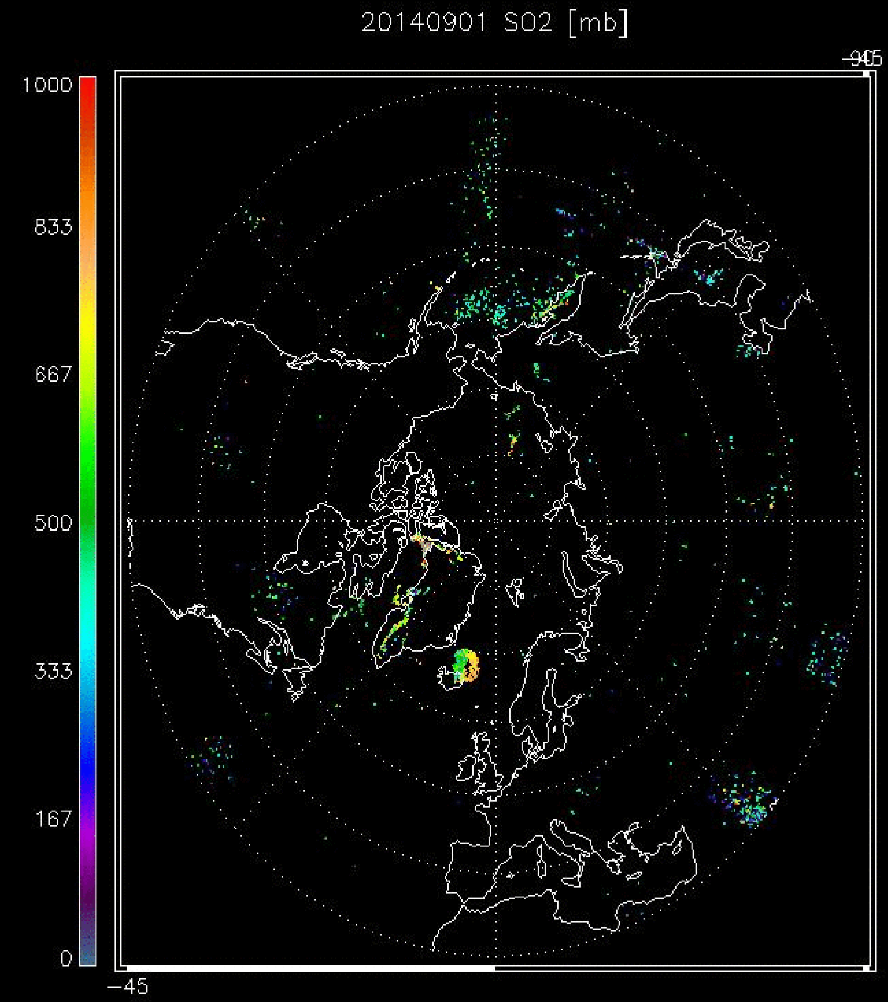
$y_s = F(SO_2{=}0)$

Sy Computed with billions pixels

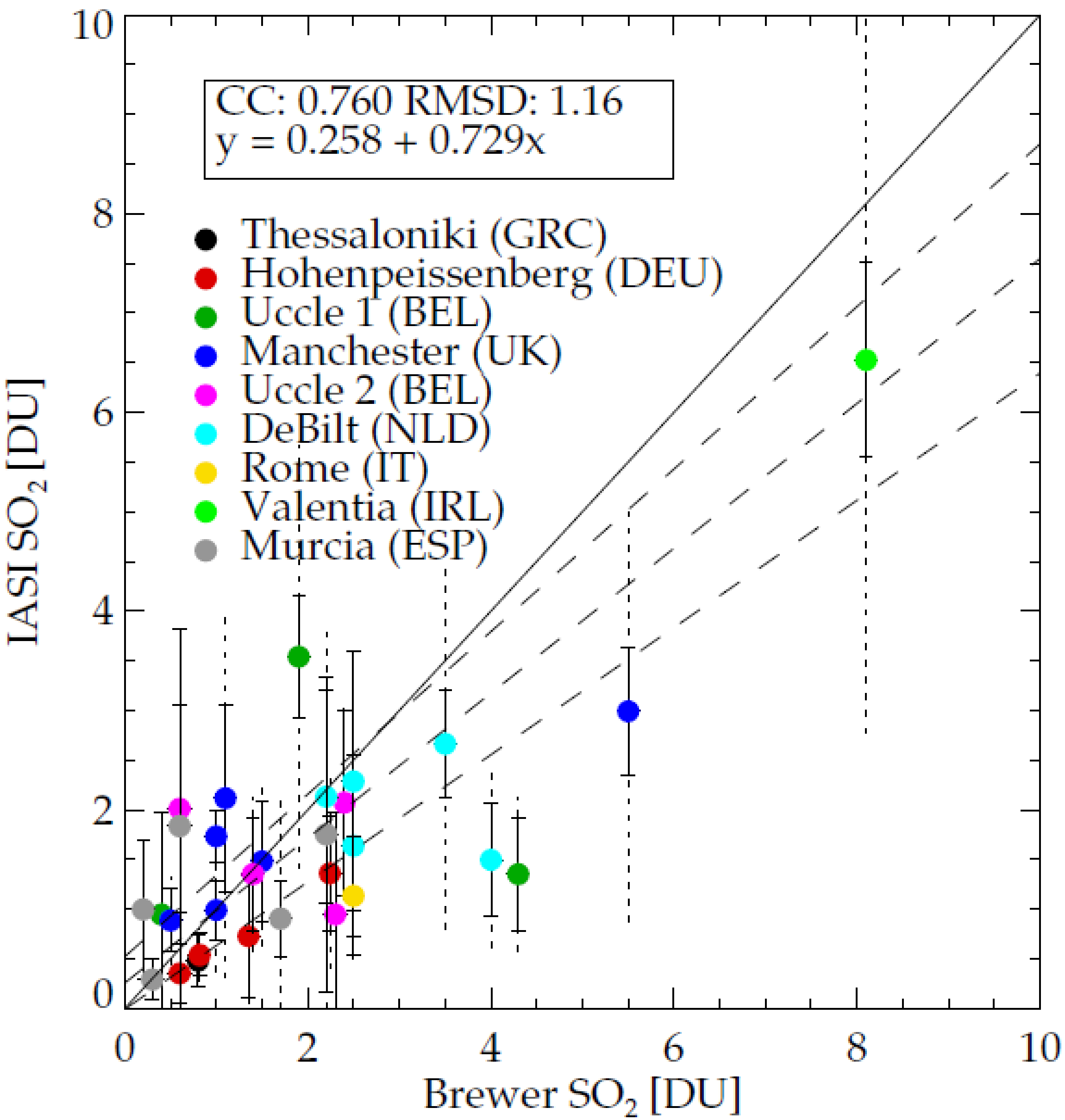
S_y, is defined to represent the effects of atmospheric variability not represented in the forward model (FM), as well as instrument noise (cloud and trace-gases…).
The matrix is constructed from differences between FM calculations (for clear-sky) and actual IASI observations for wide range of conditions, when we are confident that negligible amounts of SO_2 are present.

SO2 iterative – Bardarbunga





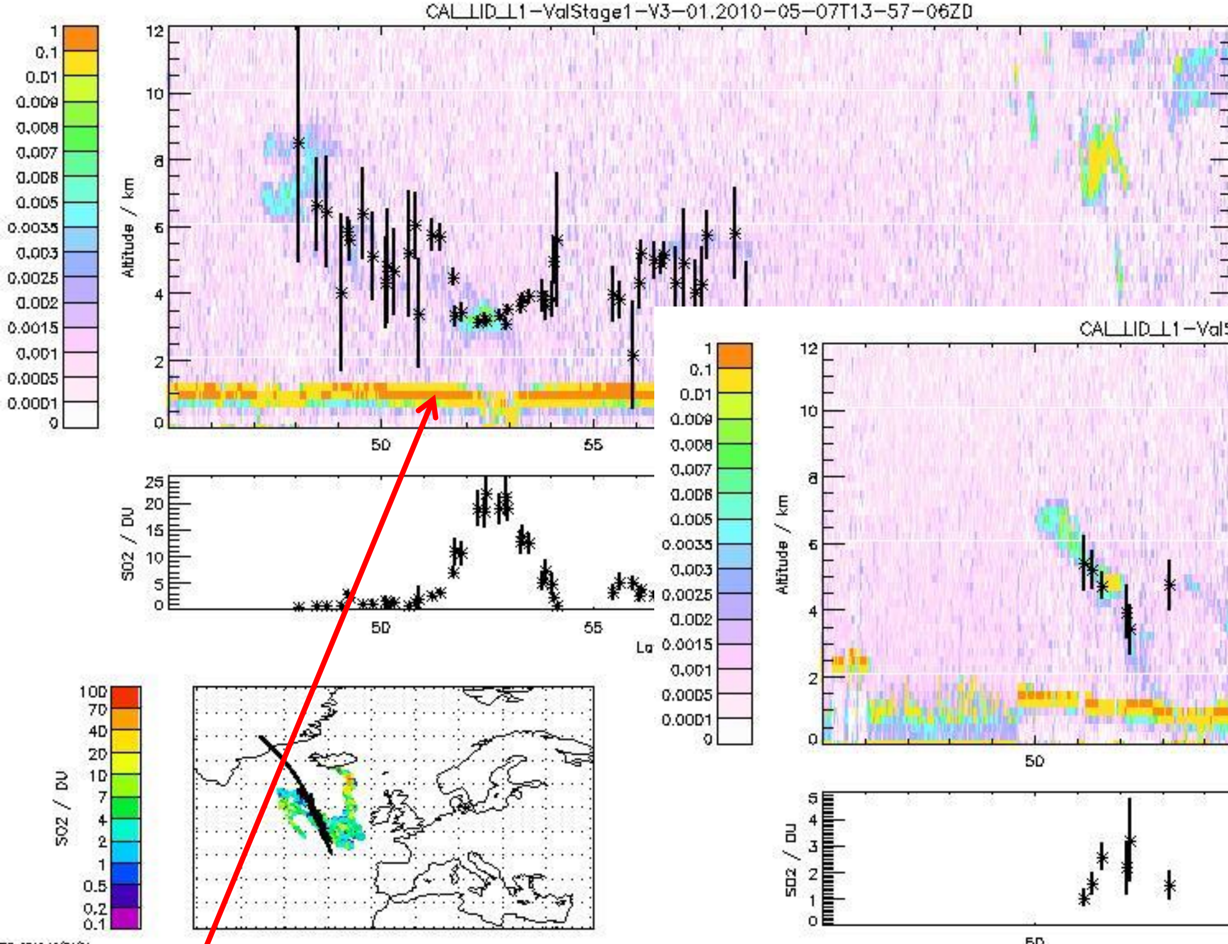
SO2 iterative – Comparison with Brewer ground data

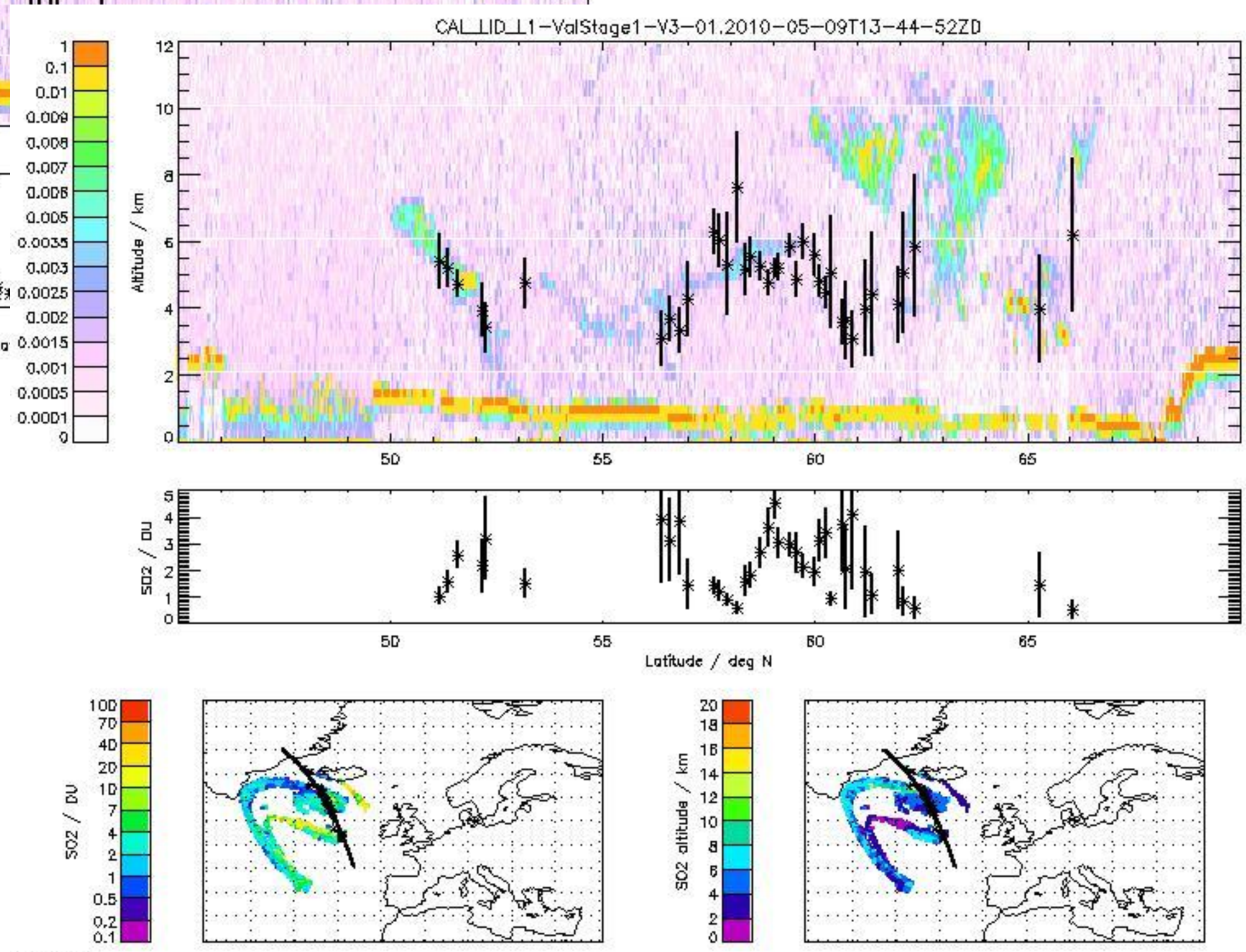


Scatter plot of IASI SO2 measurements, averaged within a distance of 200 km from the ground station, versus the daily SO2 column amount, measured from Brewer spectrometers. Different colours correspond to a different ground station. Black error-bars are the IASI average errors; dotted error-bars are the standard deviation of the IASI data within the selected distance. Black lines represent the ideal line y=x; dotted lines are the best fits with error in the best fit

SO2 iterative – Height comparison with CALIOP

Eyjafjallajökull eruptions

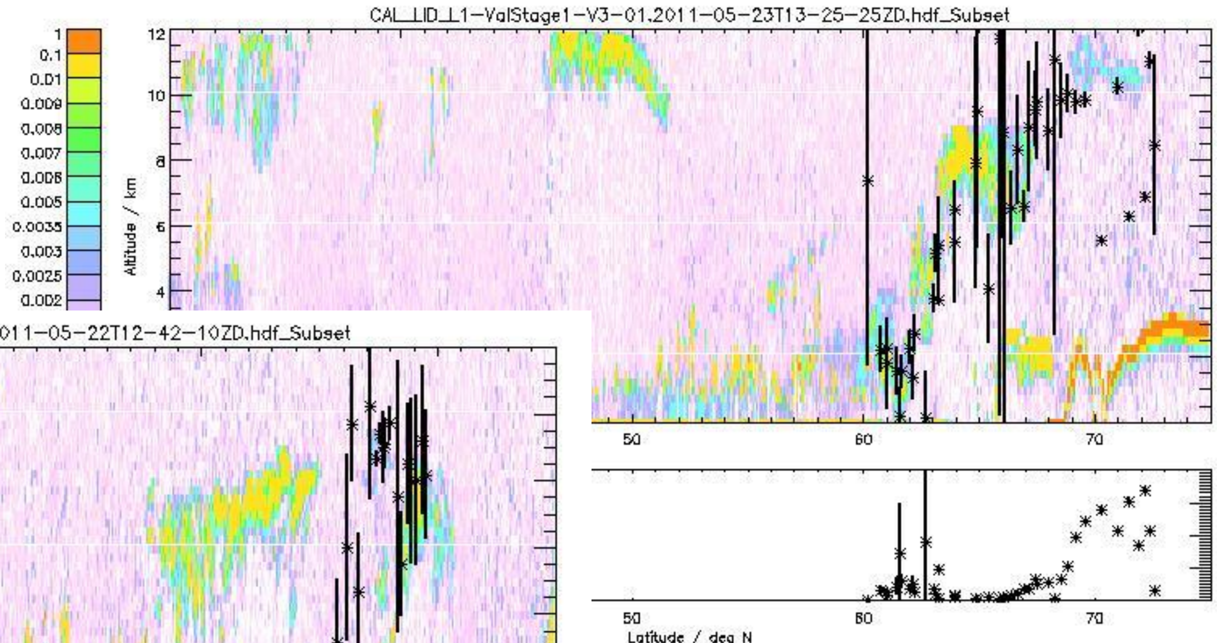


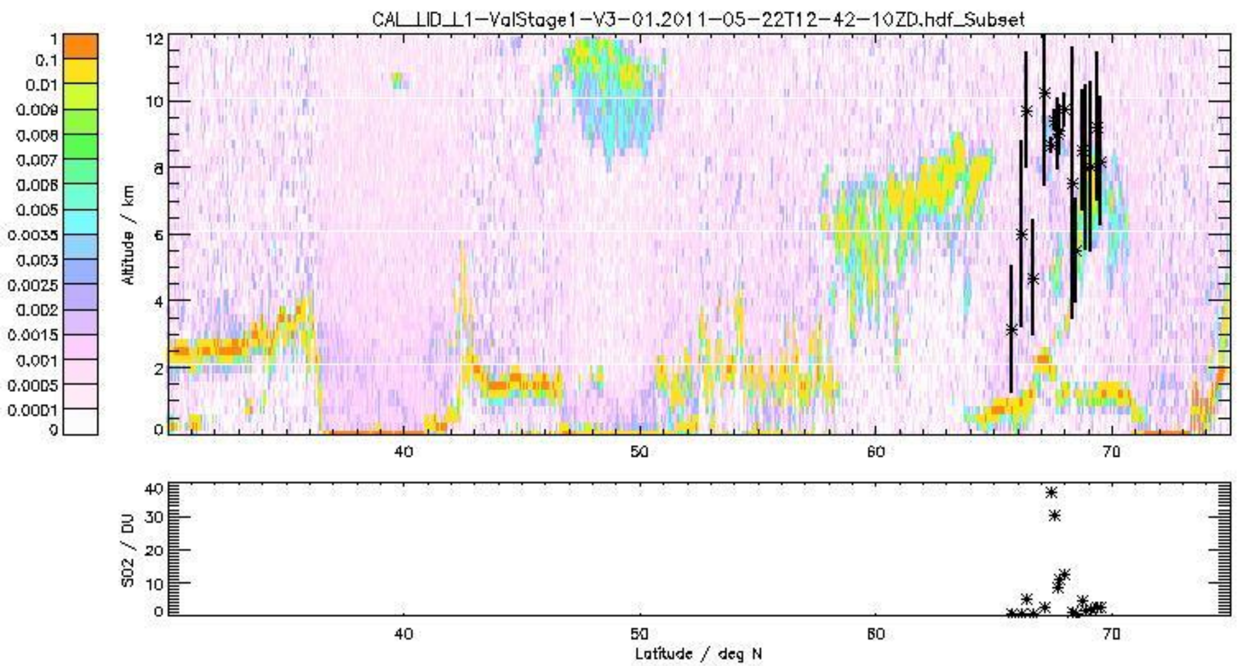


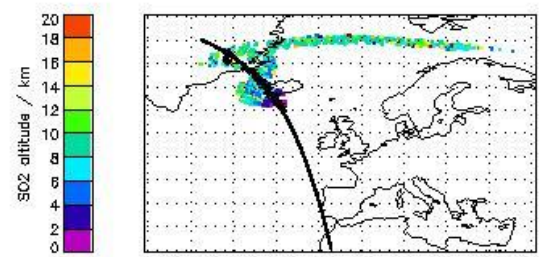
Note that underlying cloud doesn't affect the retrieval

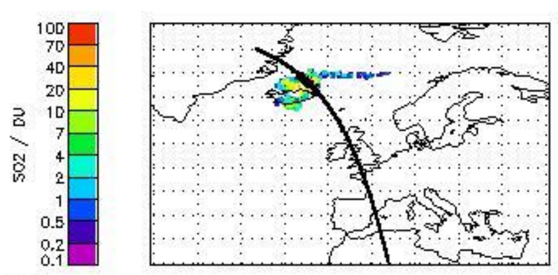
SO2 iterative – Height comparison with CALIOP

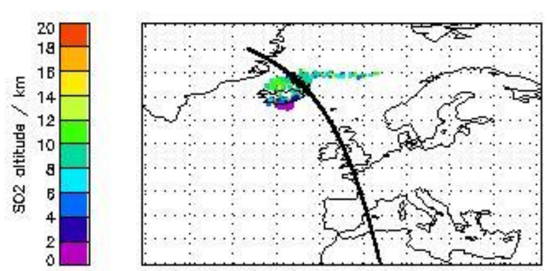
Grímsvötn eruption

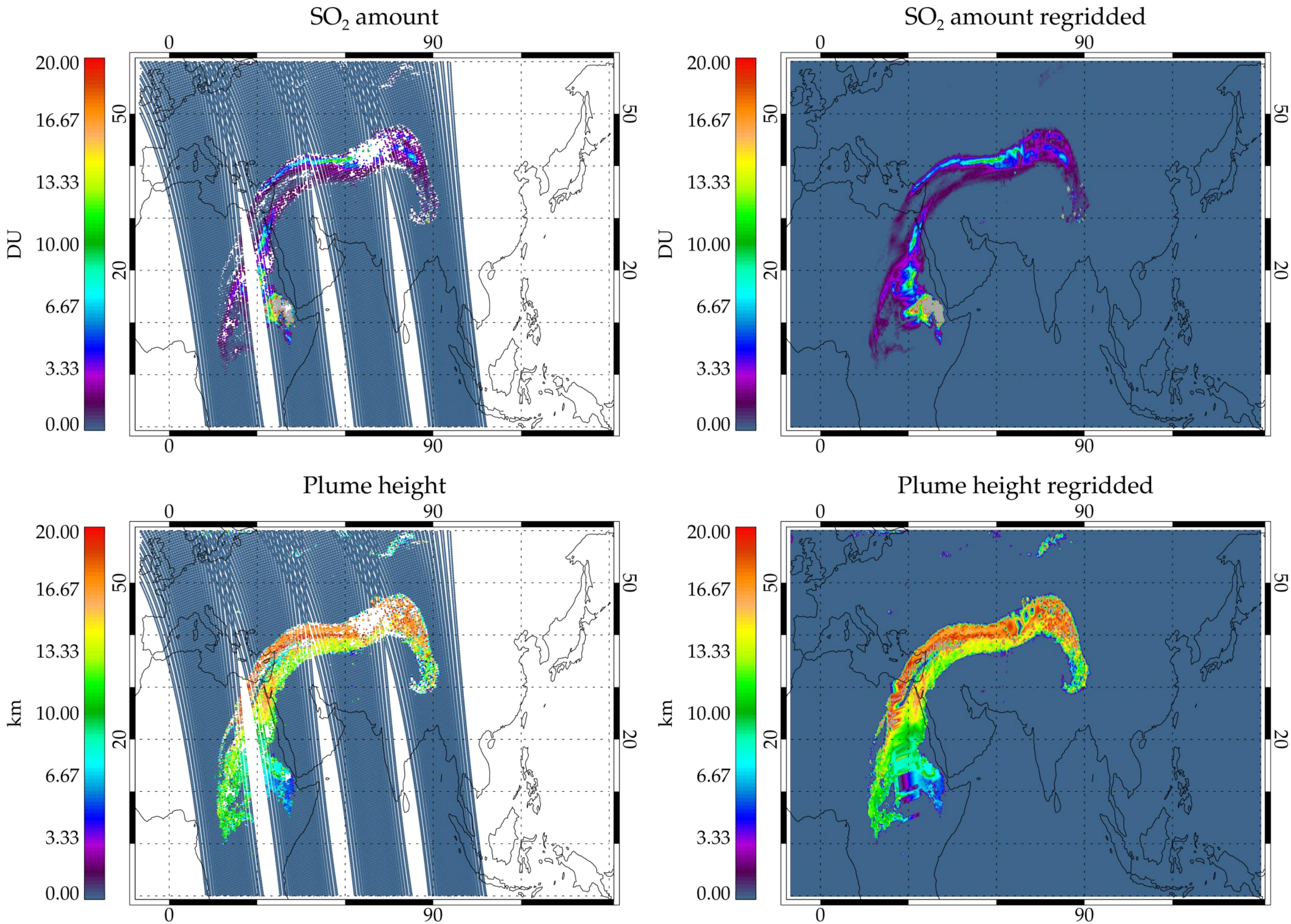




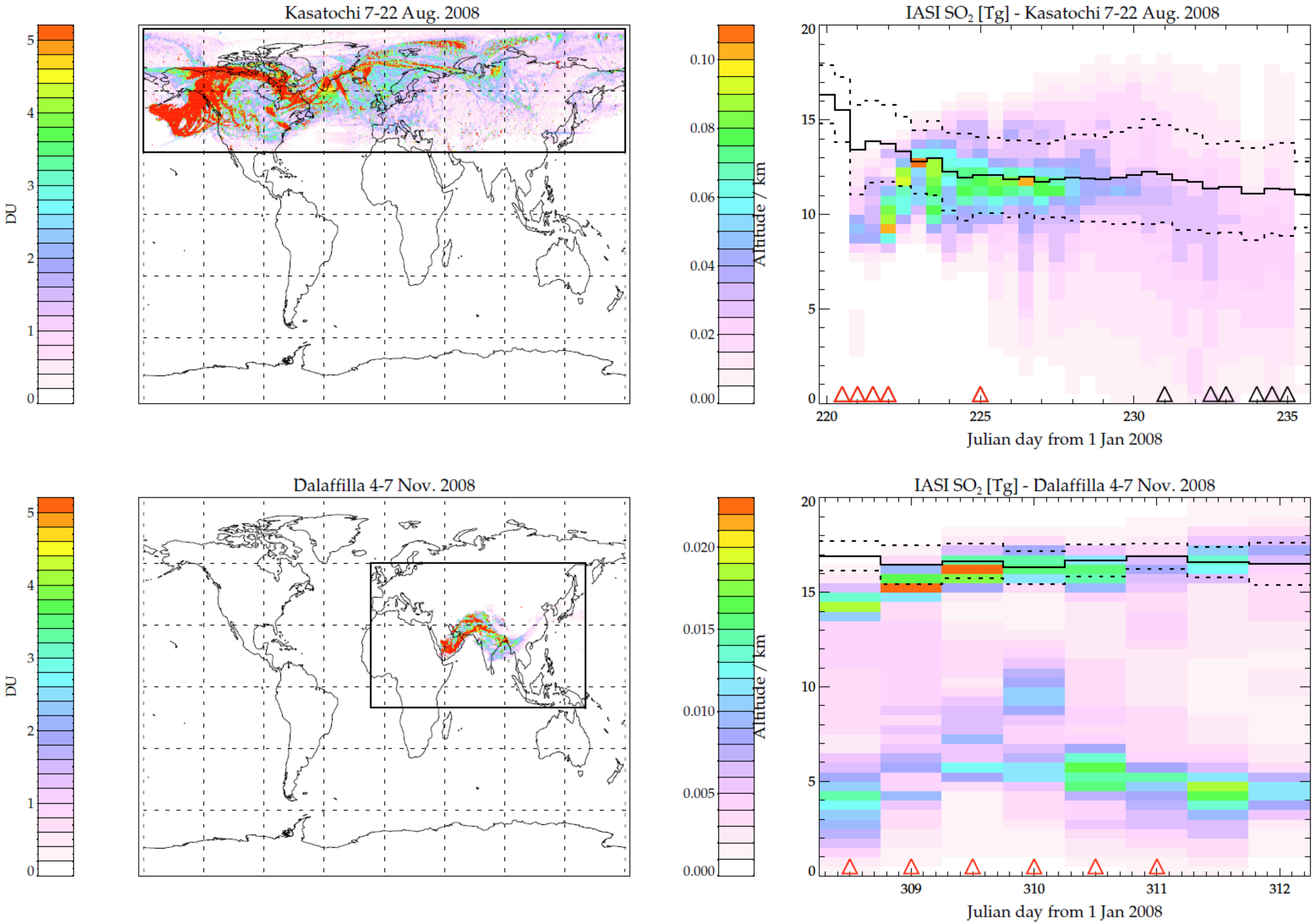




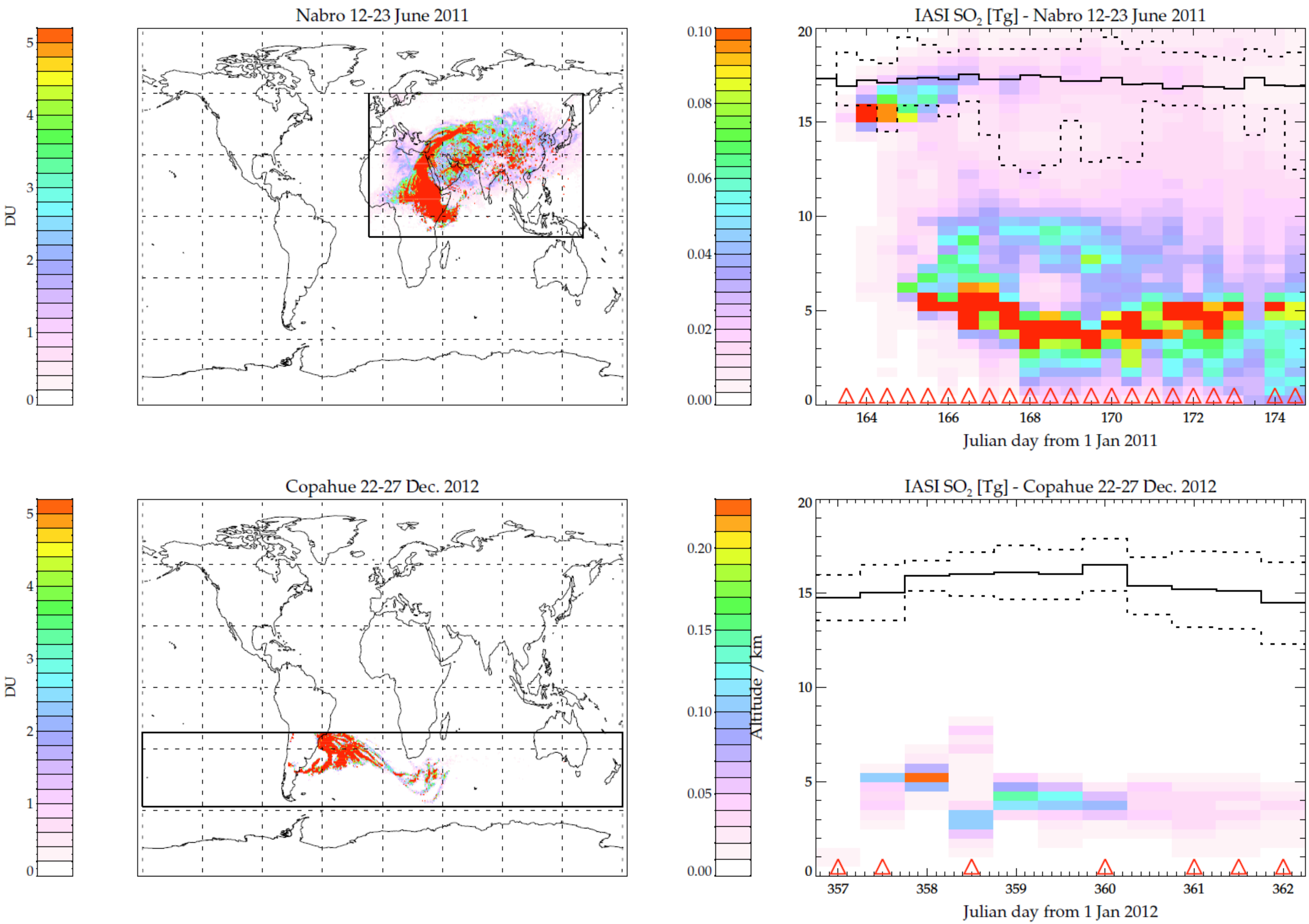




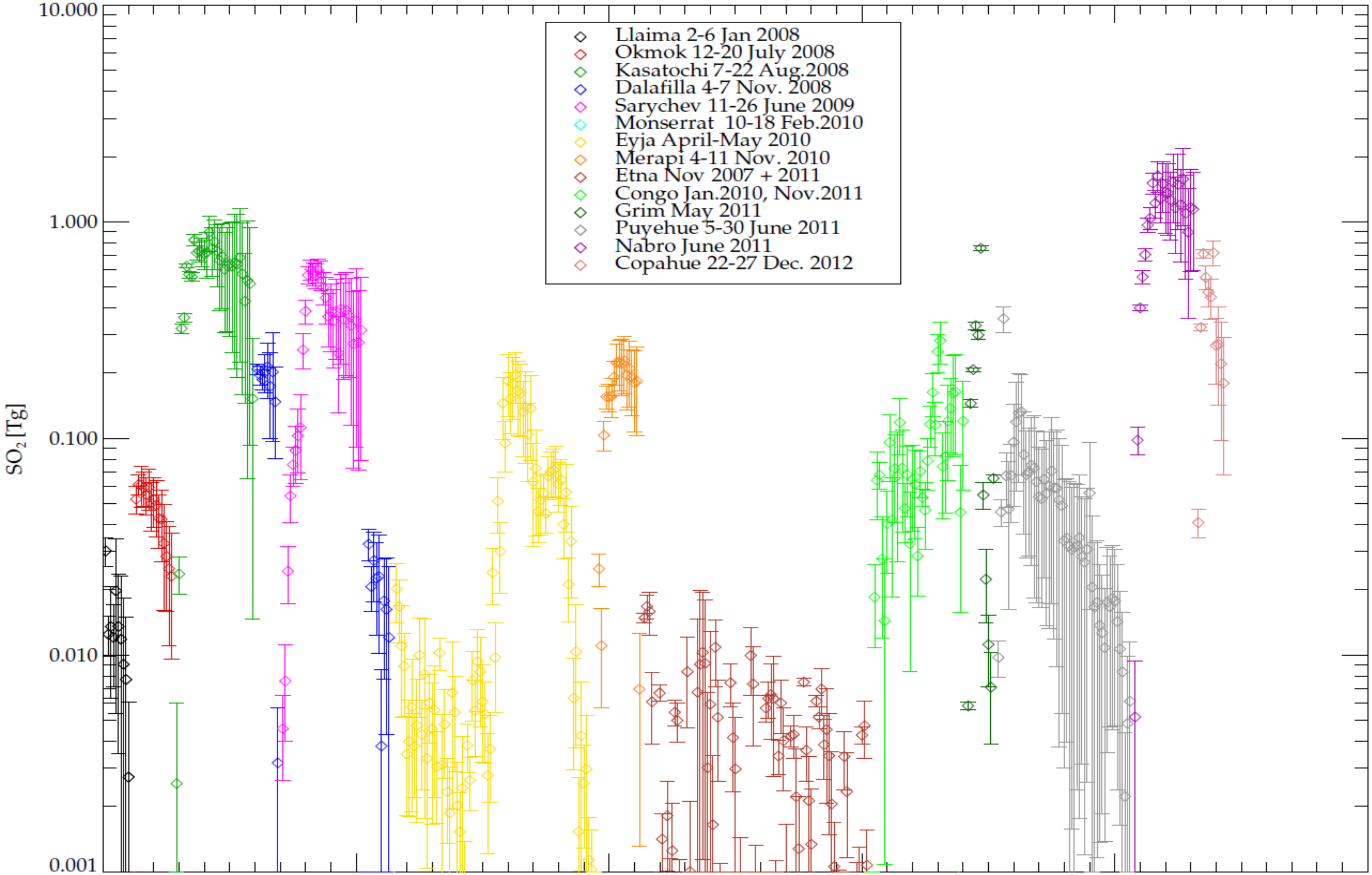
SO$_2$ amount
SO$_2$ amount regridded
Plume height
Plume height regridded
DU
km
20.00
16.67
13.33
10.00
6.67
3.33
0.00
0
90
50
20



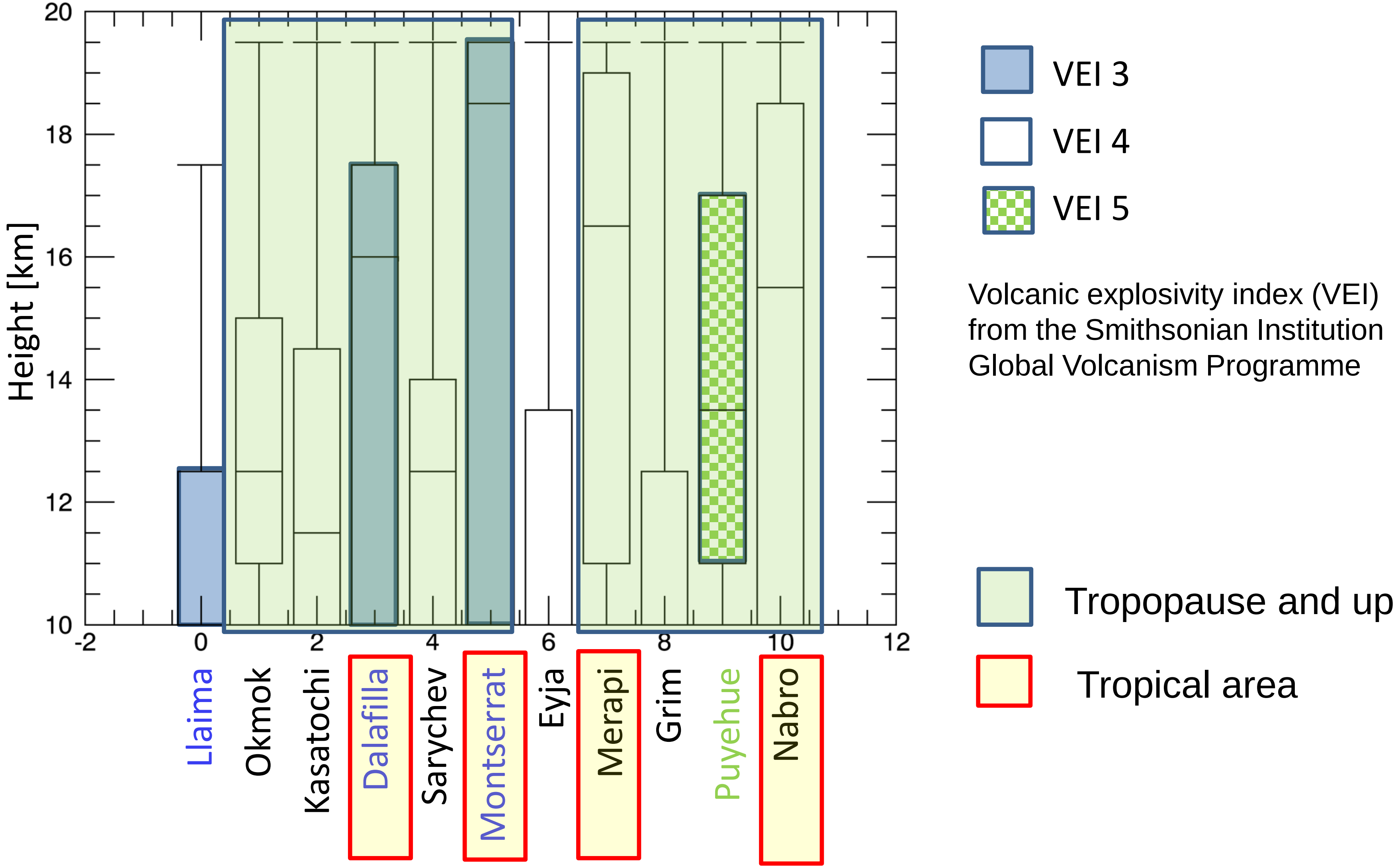
Kasatochi 7-22 Aug. 2008
DU
Altitude / km
IASI SO$_2$ [Tg] - Kasatochi 7-22 Aug. 2008
Julian day from 1 Jan 2008
Dalaffilla 4-7 Nov. 2008
DU
Altitude / km
IASI SO$_2$ [Tg] - Dalaffilla 4-7 Nov. 2008
Julian day from 1 Jan 2008


Nabro 12-23 June 2011
IASI SO_2 [Tg] - Nabro 12-23 June 2011
Julian day from 1 Jan 2011
Copahue 22-27 Dec. 2012
IASI SO_2 [Tg] - Copahue 22-27 Dec. 2012
Julian day from 1 Jan 2012
DU
Altitude / km

SO2 iterative – total mass



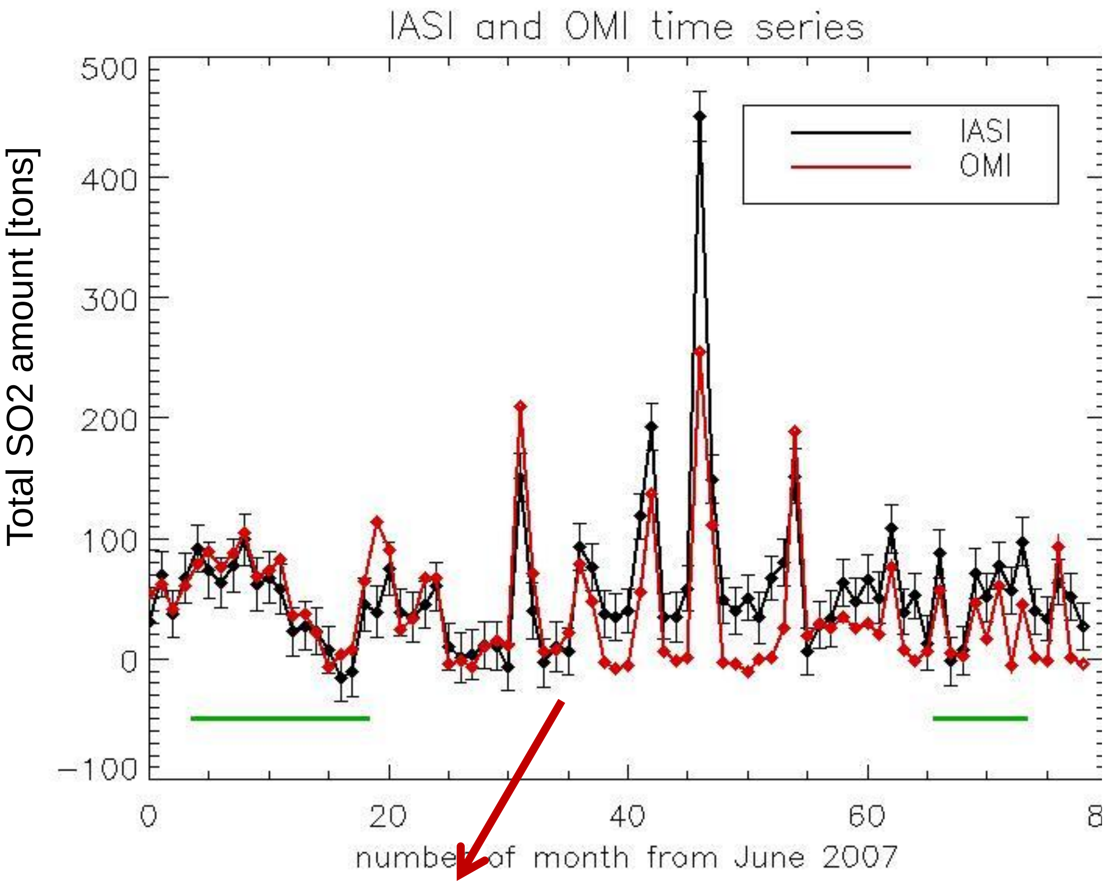
SO_2 retrieved from IASI data. The values are the measured amount on a particular day and vary with volcanic emission, gas removal and satellite sampling. Points are separated by ~12 hours.

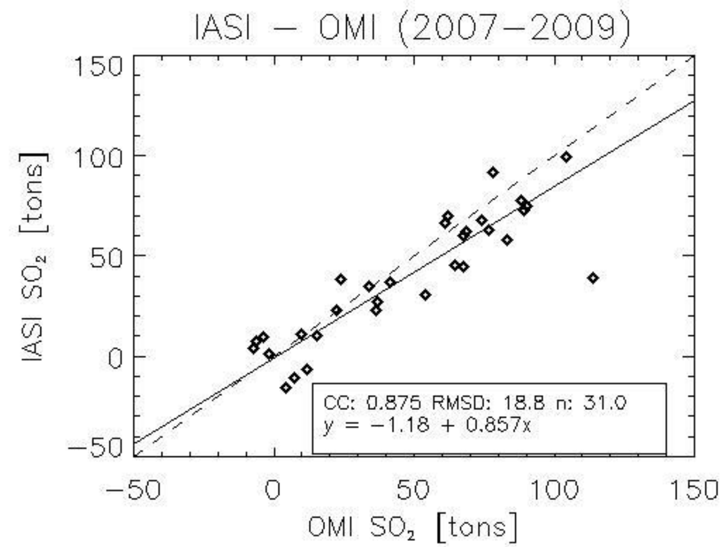


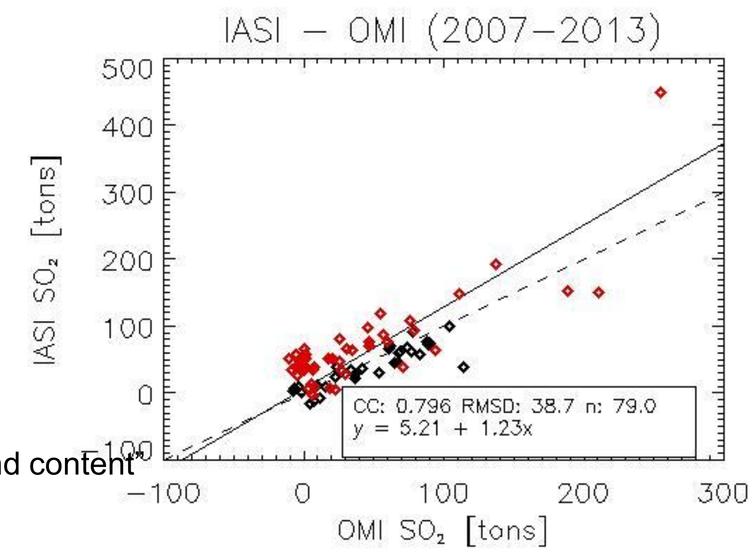
VEI is a poor index of the potential height to which volcanic SO2 is injected.

All of the eruptions in the tropics (except Nyamuragira, VEI 1,2), reached the tropopause.

(3) SO2 iterative – Ecuador monthly average - degassing







May 2010, anyone know if something happen to IASI l1c data?

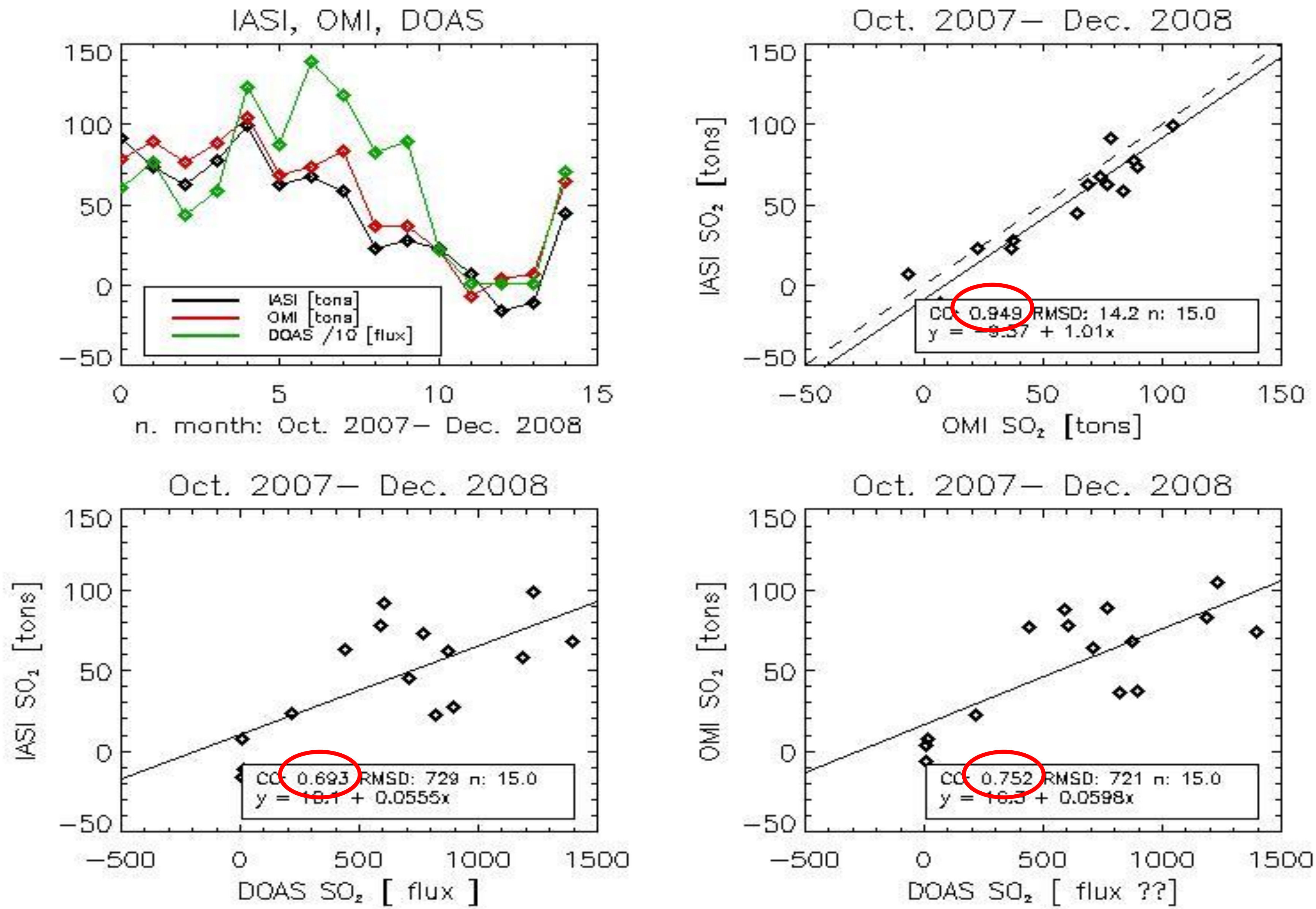
"18/05/2010 IASI lev 1C EO:EUM:DAT:METOP:IASIL1C change of format and content"

From eumetsat web page – 'product history'

OMI – BIRA – N. Thyes

IASI SO2 [tons]

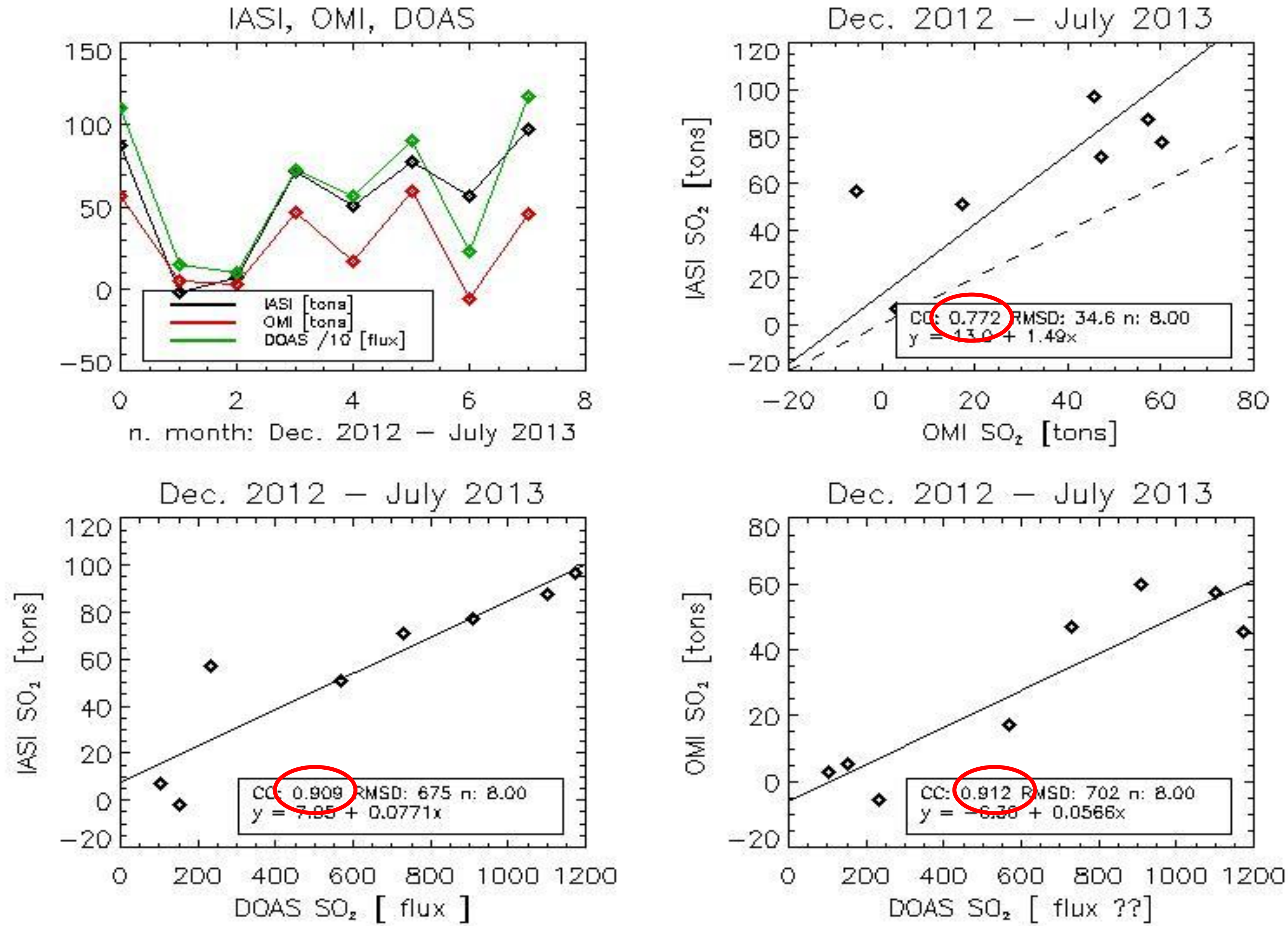
(3) SO2 iterative – Ecuador monthly average - degassing



OMI – BIRA – N. Thyes

Ground base DOAS from Hidalgo et al (2015)

(3) SO2 iterative – Ecuador monthly average - degassing



OMI – BIRA – N. Thyes

Ground base DOAS from Hidalgo et al (2015)

Summary

SO2 linear: (AMT Walker et al 2011, JRL Walker et al 2012)

Very fast => global survey tool

⇒ show emission from volcanic eruptions, anthropogenic source and degassing.

- IASI archive 2007-2014
- NRT processing

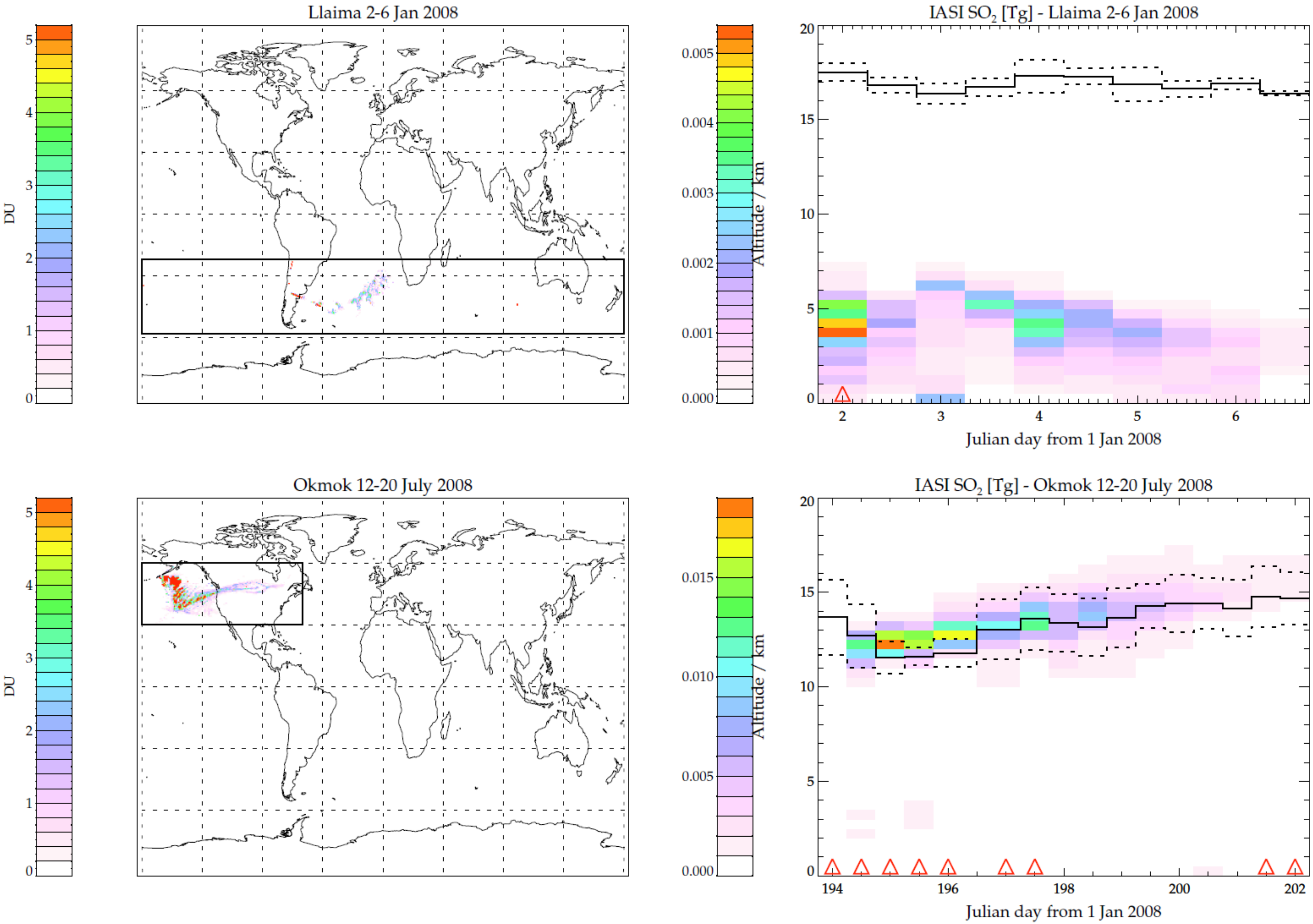
SO2 iterative: (ACP Carboni et al 2012, ACP Carboni et al. 2016)

We use simultaneously cannel between 1000-1200 cm-1 and 1300-1410 cm-1 (v1 and v3 SO2 absorption band)

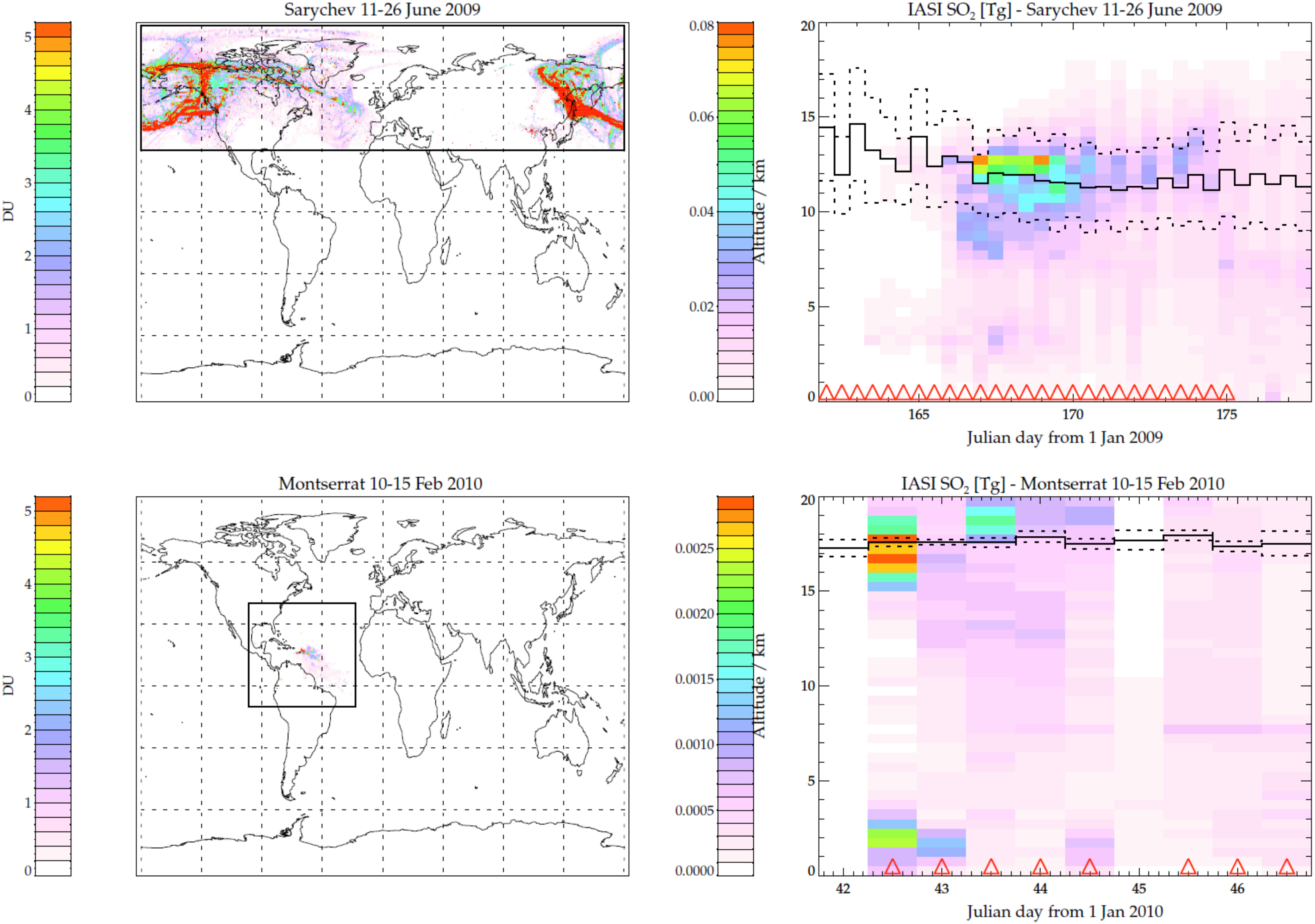
- retrieve both column amount and altitude for volcanic plume.
- we can study the plume vertical distributions, and evolution in time.
- Volcanic degassing look promising (vs, OMI and ground data)

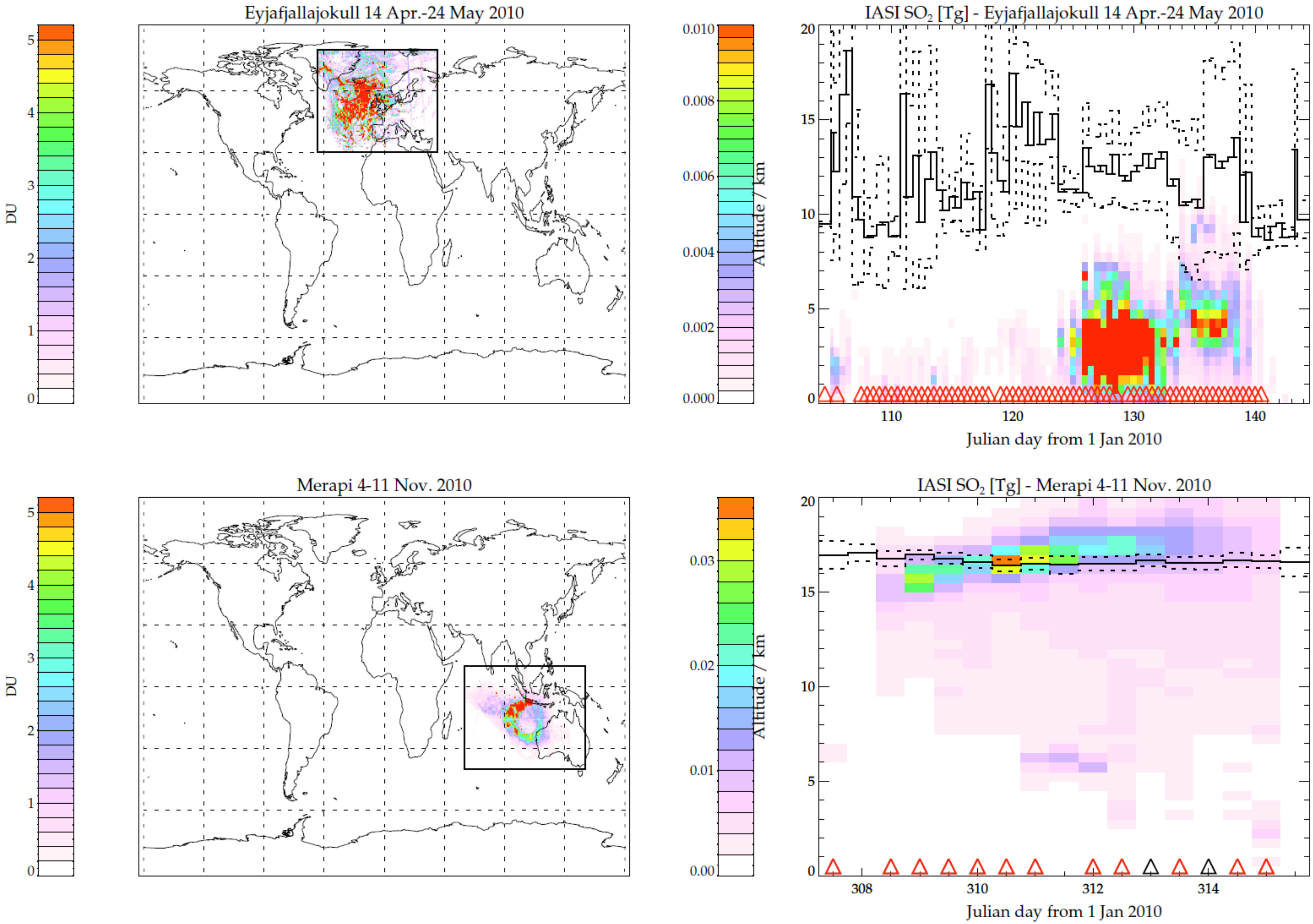
Thank you!

+ Lucy poster on IASI ash retrieval:
Optical depth, effective radius (=> ash mass) and altitude
In clear and cloudy atmosphere (cloud below the plume)

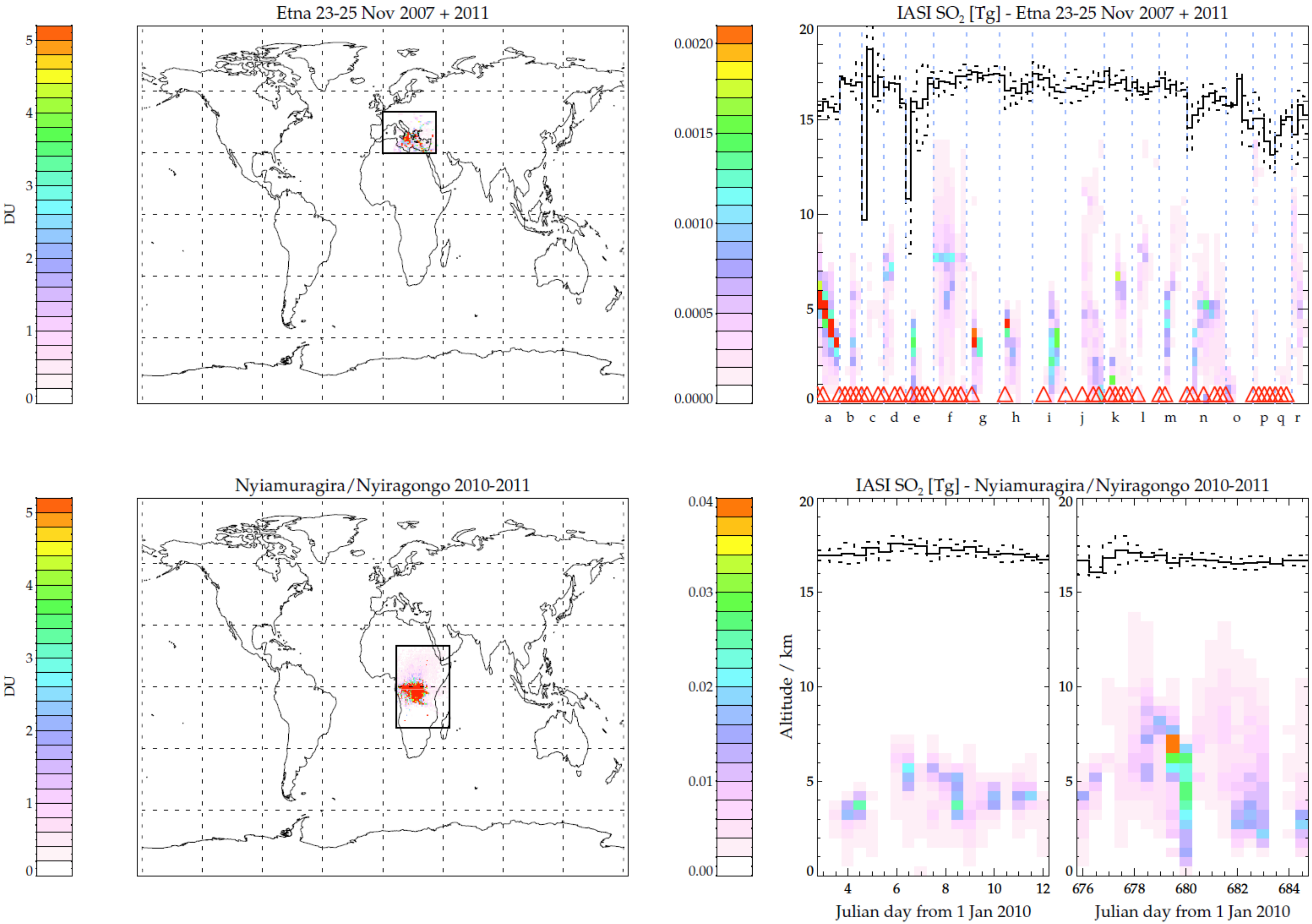


Llaima 2-6 Jan 2008
IASI SO2 [Tg] - Llaima 2-6 Jan 2008
DU
Altitude / km
Julian day from 1 Jan 2008
Okmok 12-20 July 2008
IASI SO2 [Tg] - Okmok 12-20 July 2008
DU
Altitude / km
Julian day from 1 Jan 2008

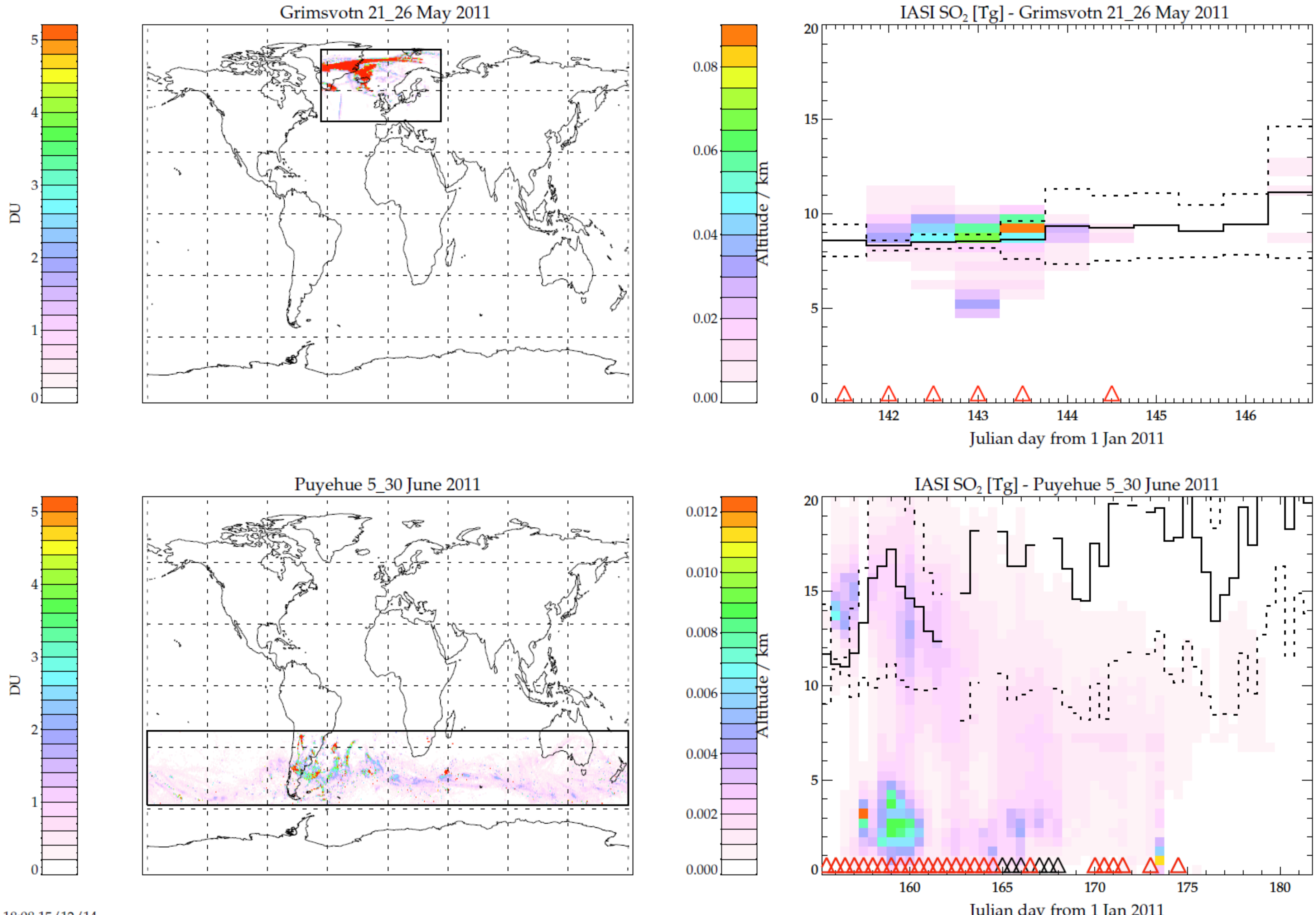

Sarychev 11-26 June 2009
DU
IASI SO$_2$ [Tg] - Sarychev 11-26 June 2009
Altitude / km
Julian day from 1 Jan 2009
Montserrat 10-15 Feb 2010
DU
IASI SO$_2$ [Tg] - Montserrat 10-15 Feb 2010
Altitude / km
Julian day from 1 Jan 2010



Eyjafjallajokull 14 Apr.-24 May 2010
DU
0
1
2
3
4
5
IASI SO$_2$ [Tg] - Eyjafjallajokull 14 Apr.-24 May 2010
Altitude / km
0.000
0.002
0.004
0.006
0.008
0.010
0
5
10
15
20
110
120
130
140
Julian day from 1 Jan 2010
Merapi 4-11 Nov. 2010
DU
0
1
2
3
4
5
IASI SO$_2$ [Tg] - Merapi 4-11 Nov. 2010
Altitude / km
0.00
0.01
0.02
0.03
0
5
10
15
20
308
310
312
314
Julian day from 1 Jan 2010



Etna 23-25 Nov 2007 + 2011
DU
0 1 2 3 4 5
0.0000 0.0005 0.0010 0.0015 0.0020
IASI SO2 [Tg] - Etna 23-25 Nov 2007 + 2011
0 5 10 15 20
a b c d e f g h i j k l m n o p q r
Nyiamuragira/Nyiragongo 2010-2011
DU
0 1 2 3 4 5
0.00 0.01 0.02 0.03 0.04
IASI SO2 [Tg] - Nyiamuragira/Nyiragongo 2010-2011
Altitude / km
0 5 10 15 20
4 6 8 10 12
676 678 680 682 684
Julian day from 1 Jan 2010
Julian day from 1 Jan 2010



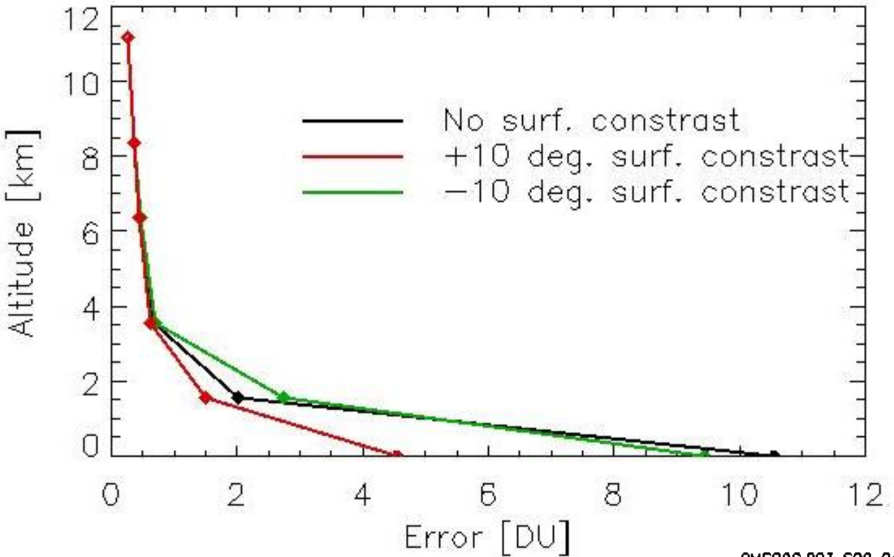
E.C. 18:08 15/12/14.

SO_2 degassing

assumption: we know the altitude of the plume

1 DU = 0.0285 g/m²

Minimum error



considering 60 overpass a month => error reduced of 1/sqrt(60)

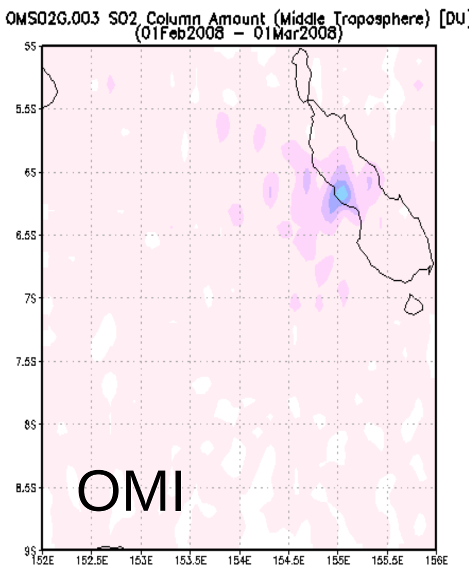
SO_2 monthly errors

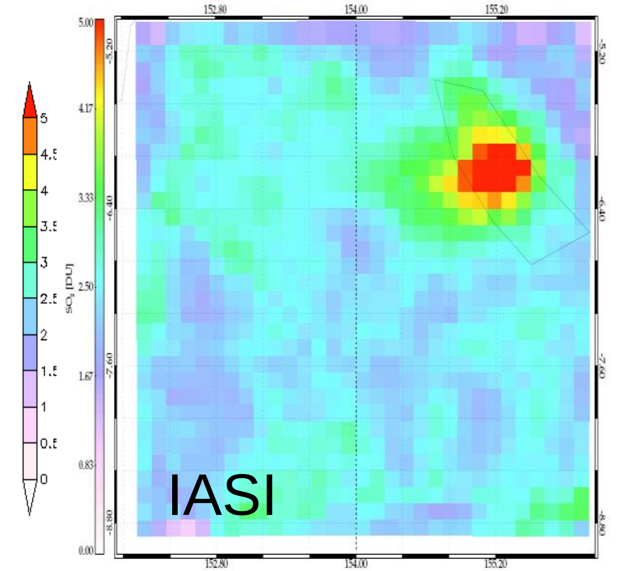
[km]	[g/m2]
11	$9\ 10^{-4}$
8.3	$13\ 10^{-4}$
6.4	$17\ 10^{-4}$
3.5	$24\ 10^{-4}$
1.5	$73\ 10^{-4}$
0	$388\ 10^{-4}$

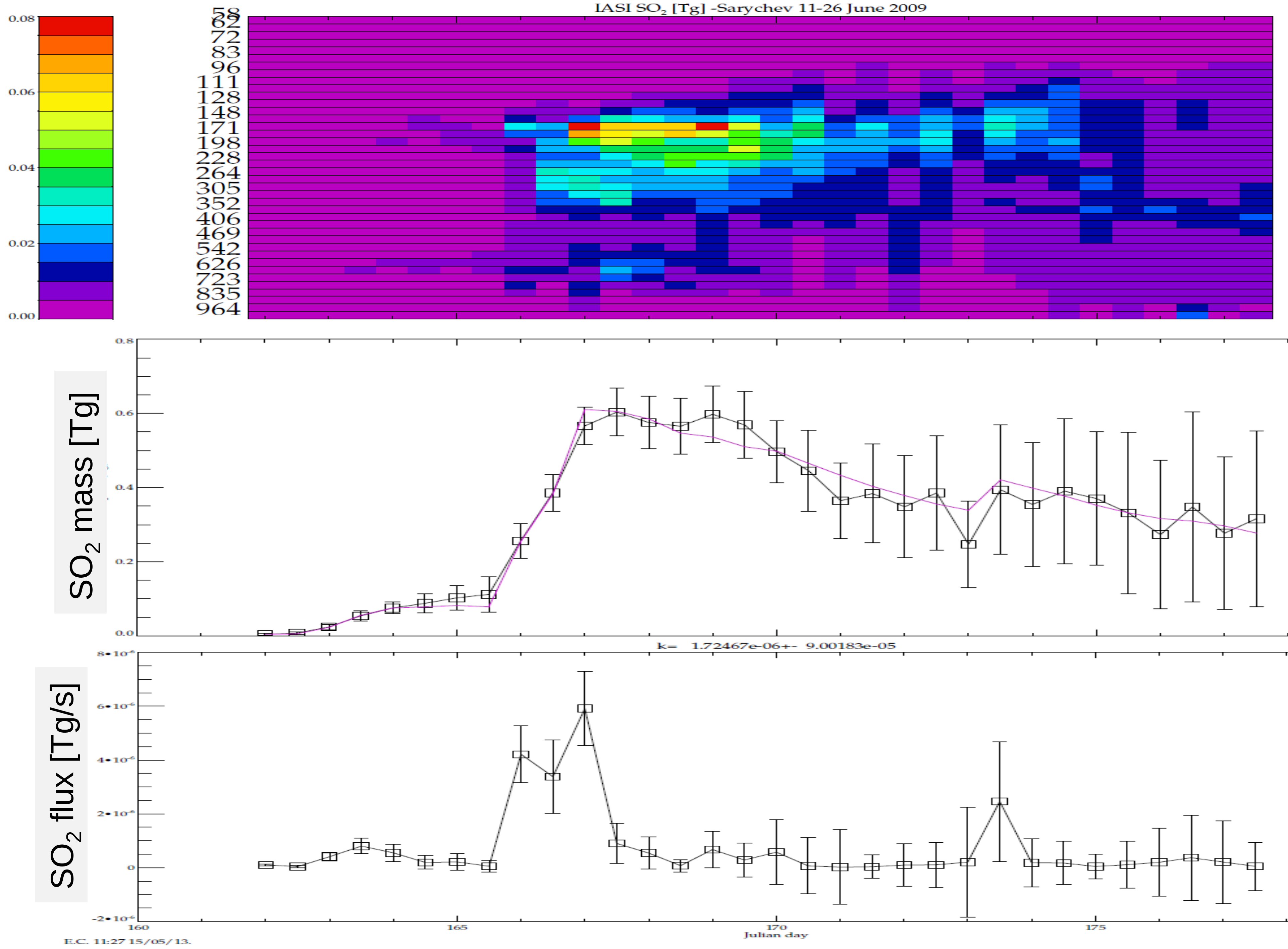
Bagana - February 2008

IASI detect between 2 and 4 time more SO_2 then OMI for Bagana degassing on Feb. 2008

OMI monthly mean is produced with the Giovanni online data system, developed and maintained by the NASA GES DISC: http://gdata2.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=omil2g







IASI SO₂ [Tg] -Sarychev 11-26 June 2009
SO₂ mass [Tg]
SO₂ flux [Tg/s]
k= 1.72467e-06+- 9.00183e-05
Julian day
E.C. 11:27 15/05/13.