The vertical distribution of volcanic SO2 plumes measured by IASI

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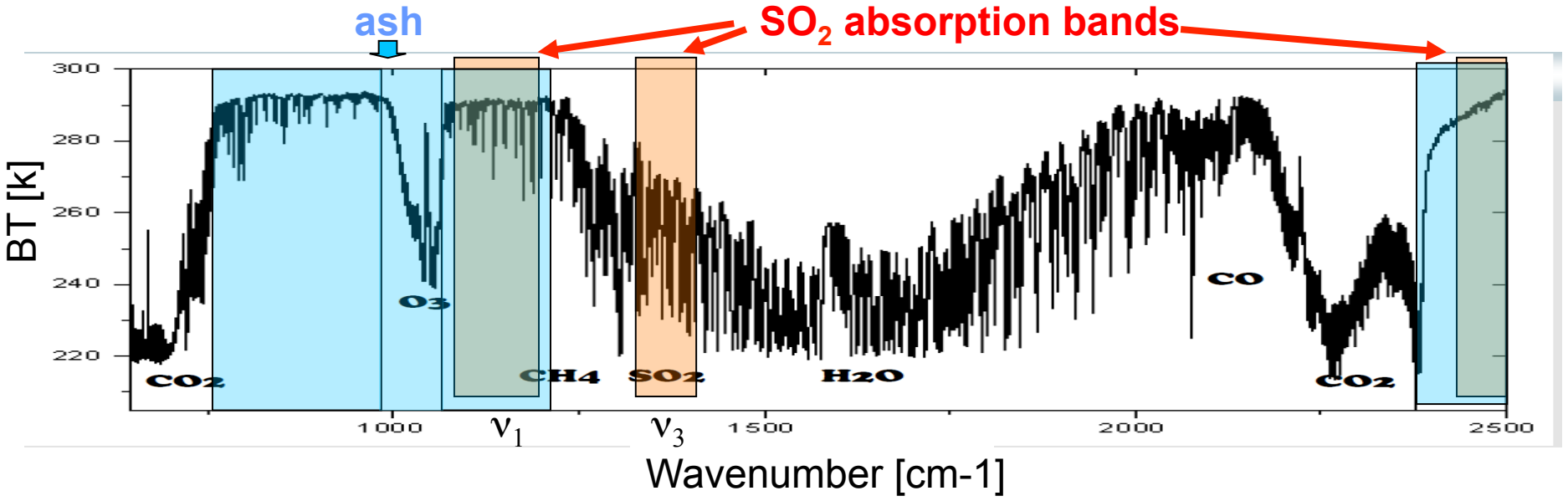
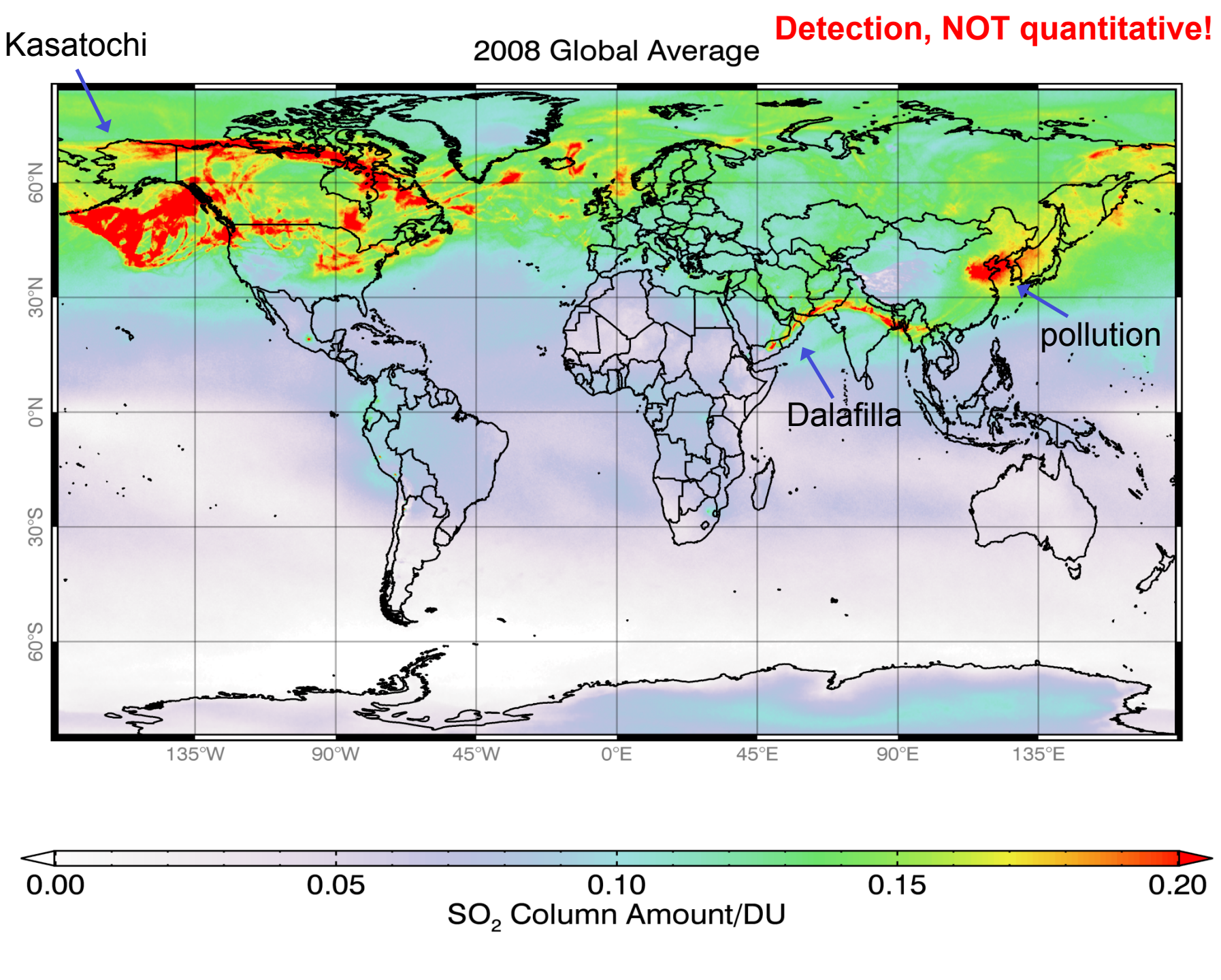
Infrared Atmospheric Sounding Interferometer - IASI

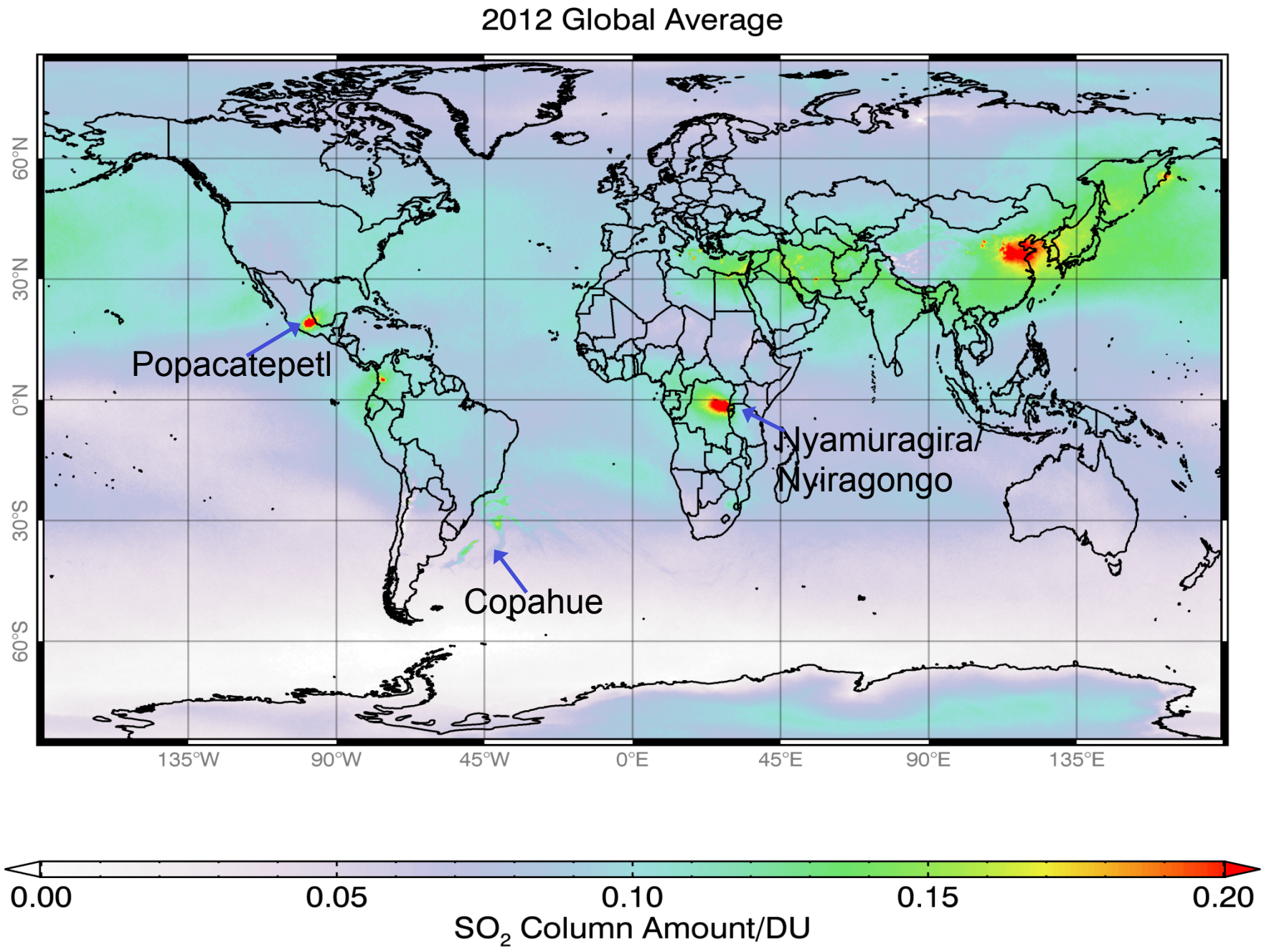
IASI is on board of METeorological OPerational satellite program (METOP-A and METOP-B), a European meteorological satellite that has been operational since 2007.

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.**

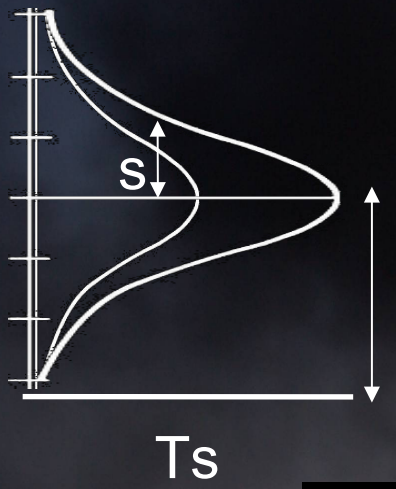
It has a 2000 km swath and nominally can achieved **global coverage in 12 hours** (although there are some gaps between orbits at tropical latitudes). Radiances are collocated with the Advanced Very High Resolution Radiometer (AVHRR) that provides complementary visible/near infrared channel, for cloud and aerosol retrievals.




Kasatochi
2008 Global Average
Detection, NOT quantitative!
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

SO_2 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

IASI measurements → OE retrieval

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

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

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

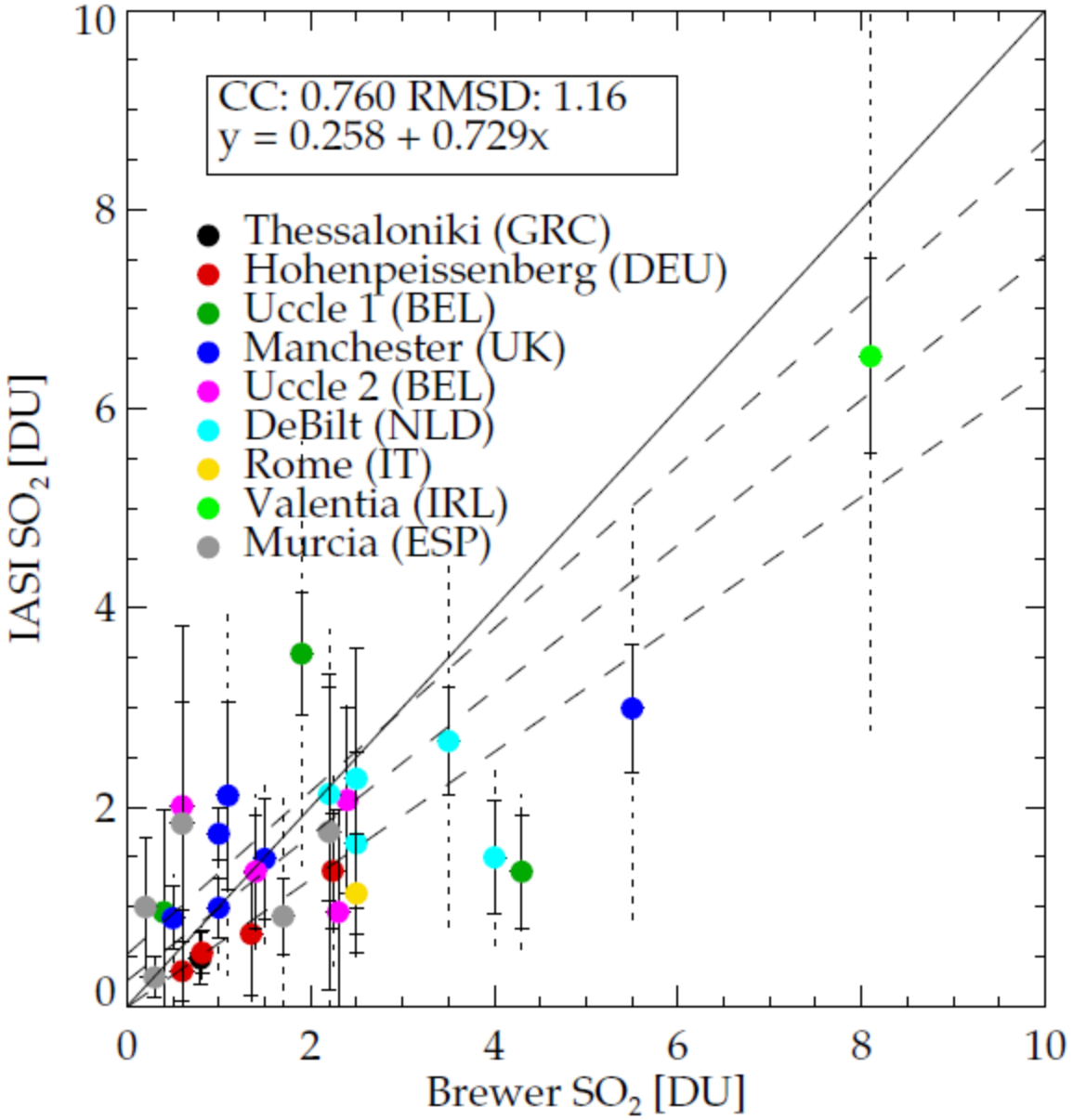
$$S_y(i,j) = \langle (y_{mi} - y_{si}) - \overline{(y_{mi} - y_{si})} \rangle \langle (y_{mj} - y_{sj}) - \overline{(y_{mj} - y_{sj})} \rangle$$

$y_s = F(SO_2=0)$

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.

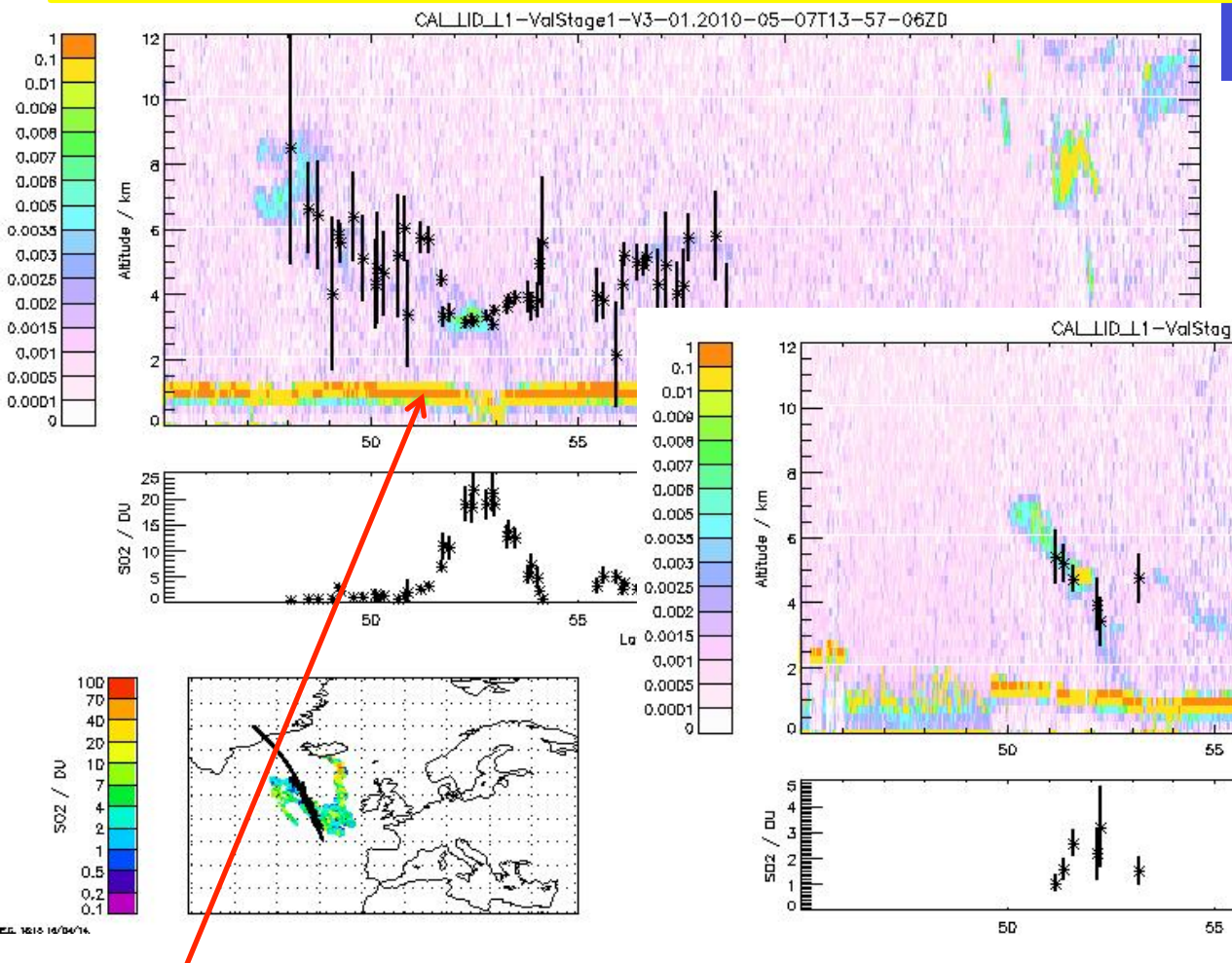
Comparison with Brewer ground data

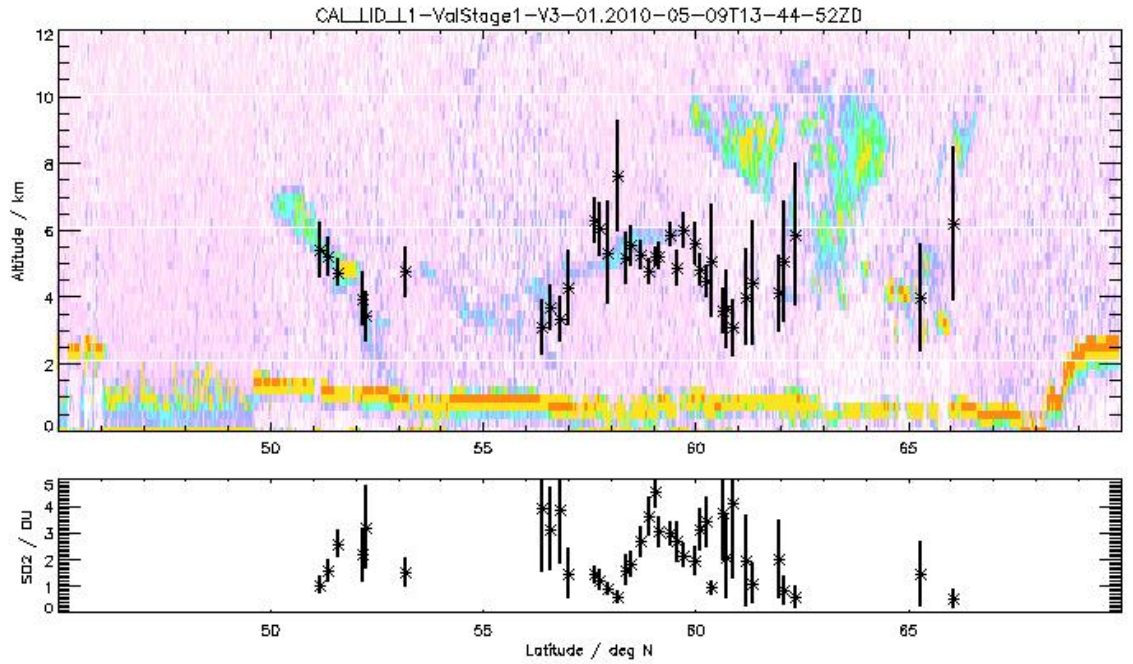


Scatter plot of IASI SO2 measurements, averaged within a distance of 200 km from the ground station, versus the daily SO2 column amount, measured from Brewer spectrometers. Different colours correspond to a different ground station. Black error-bars are the IASI average errors; dotted error-bars are 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

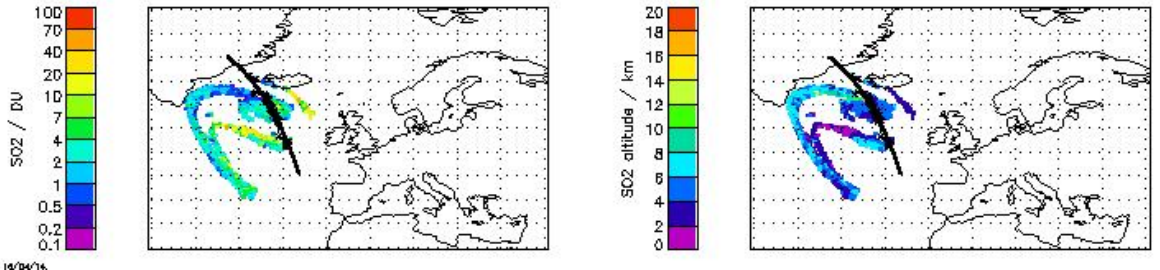
Height comparison with CALIOP

Eyjafjallajökull eruptions



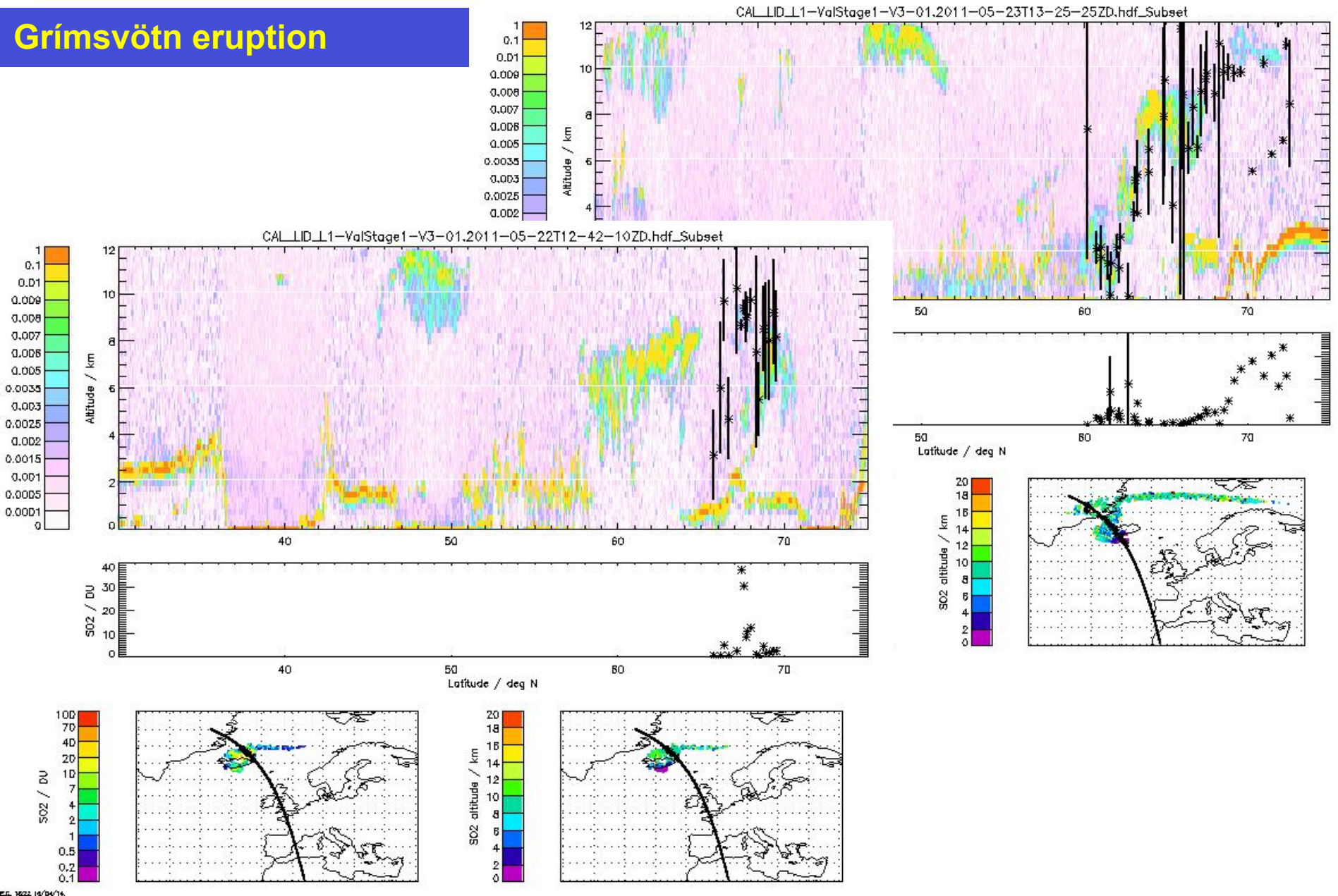


Note that underlying cloud doesn't affect the retrieval

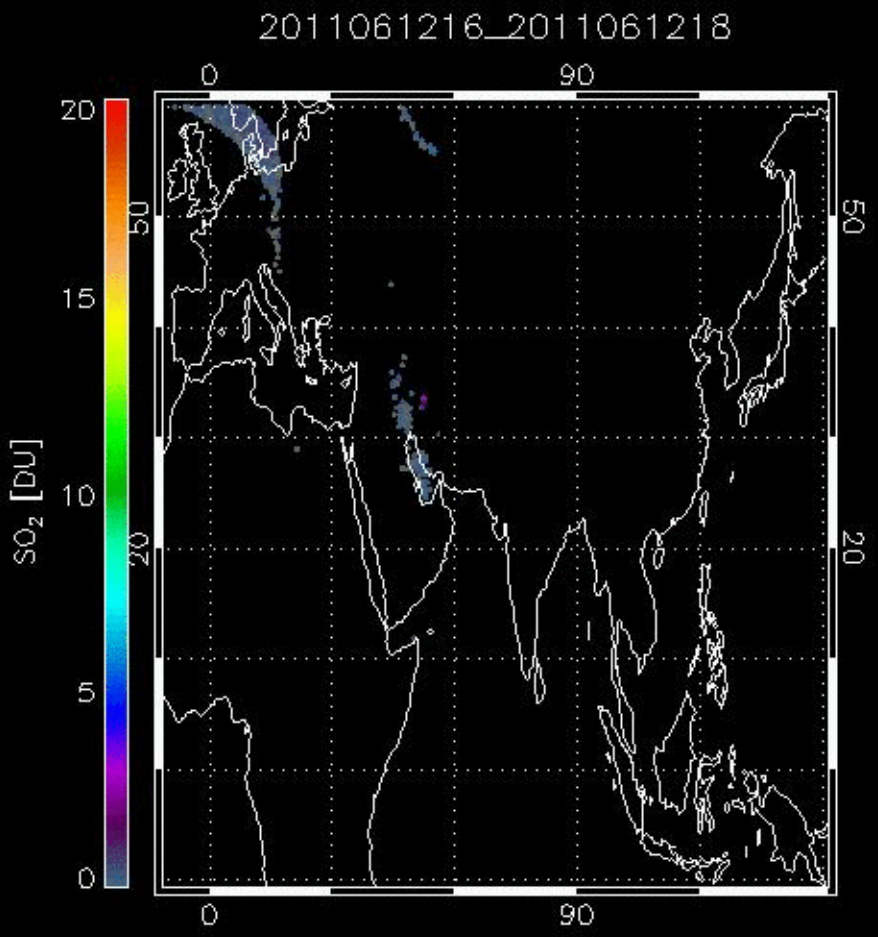


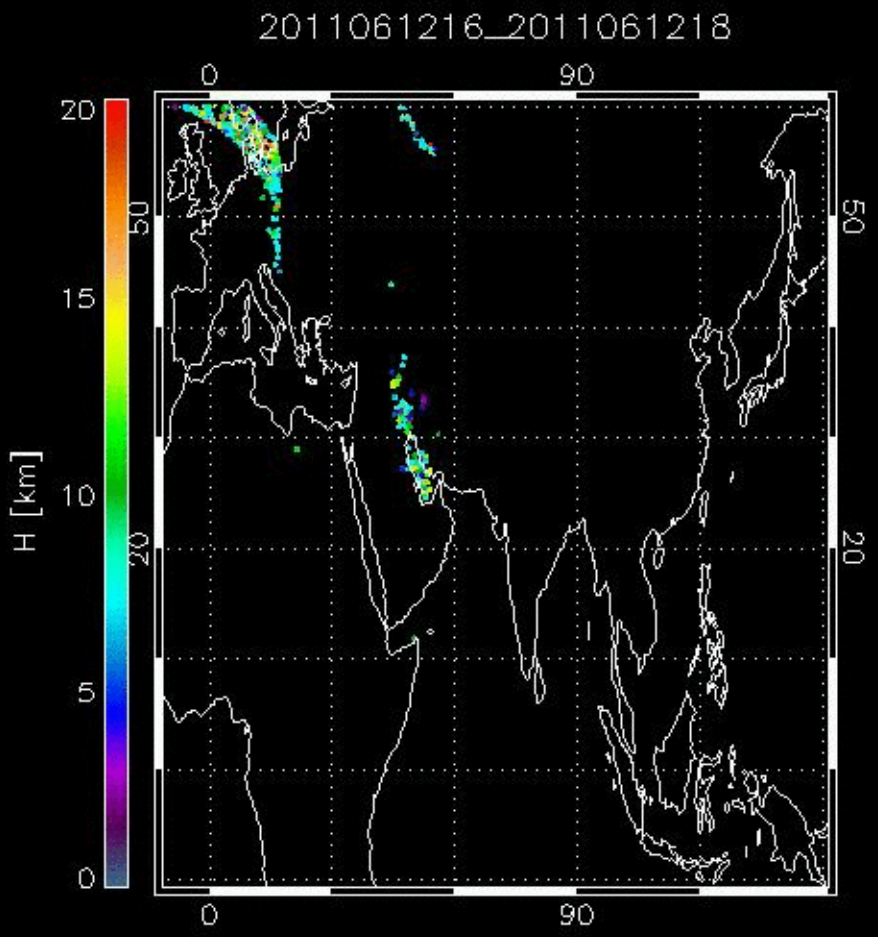
Height comparison with CALIOP

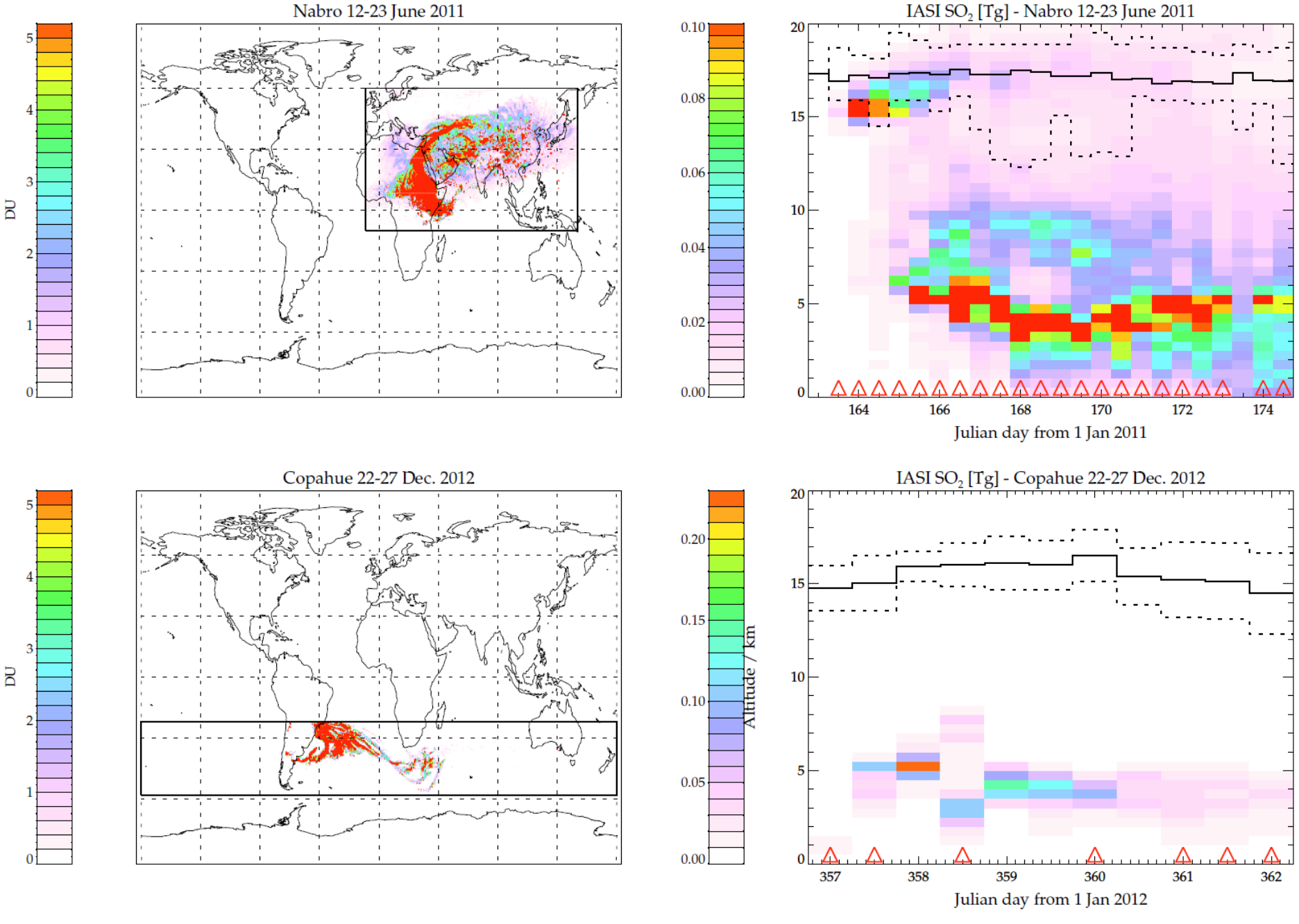
Grímsvötn eruption

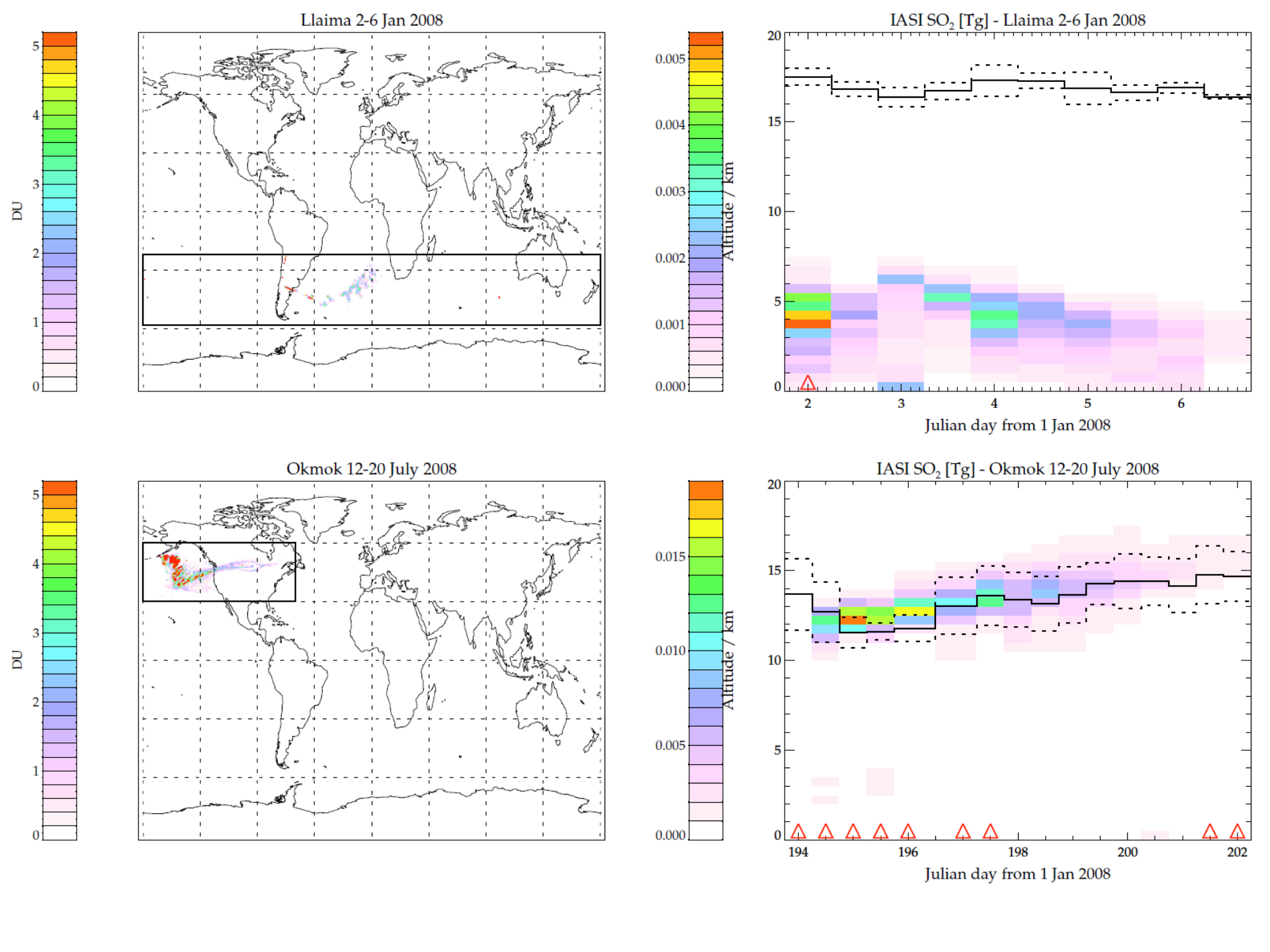


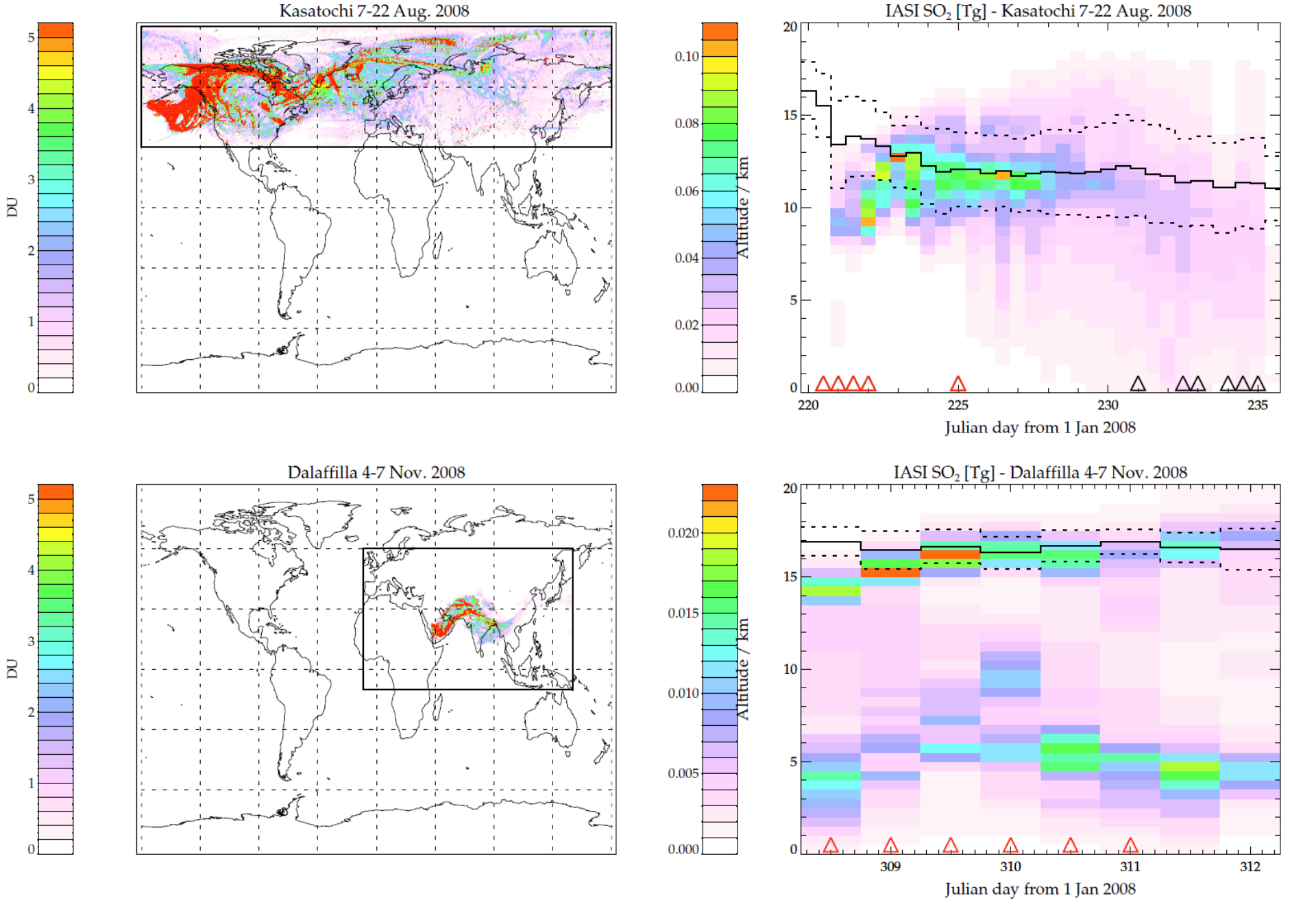
Nabro eruption 13-24 June 2011

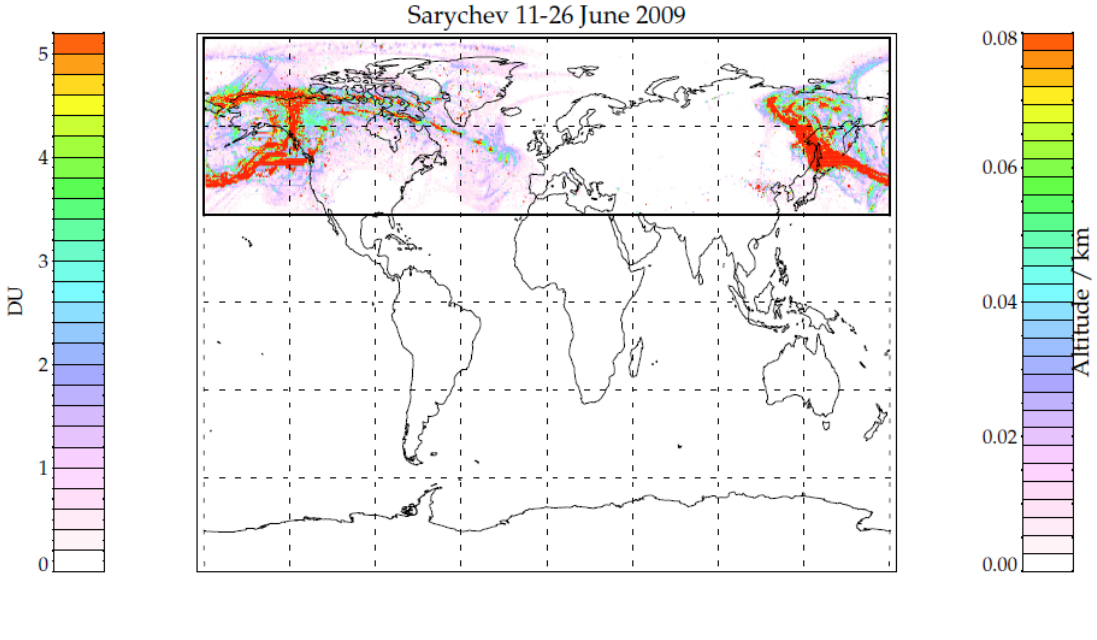


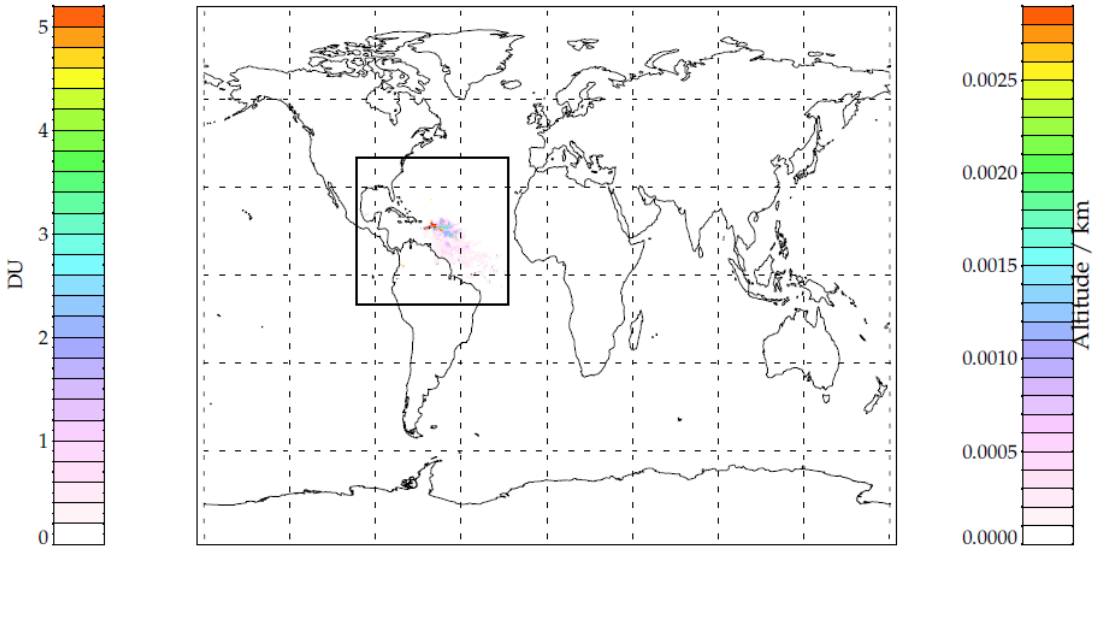


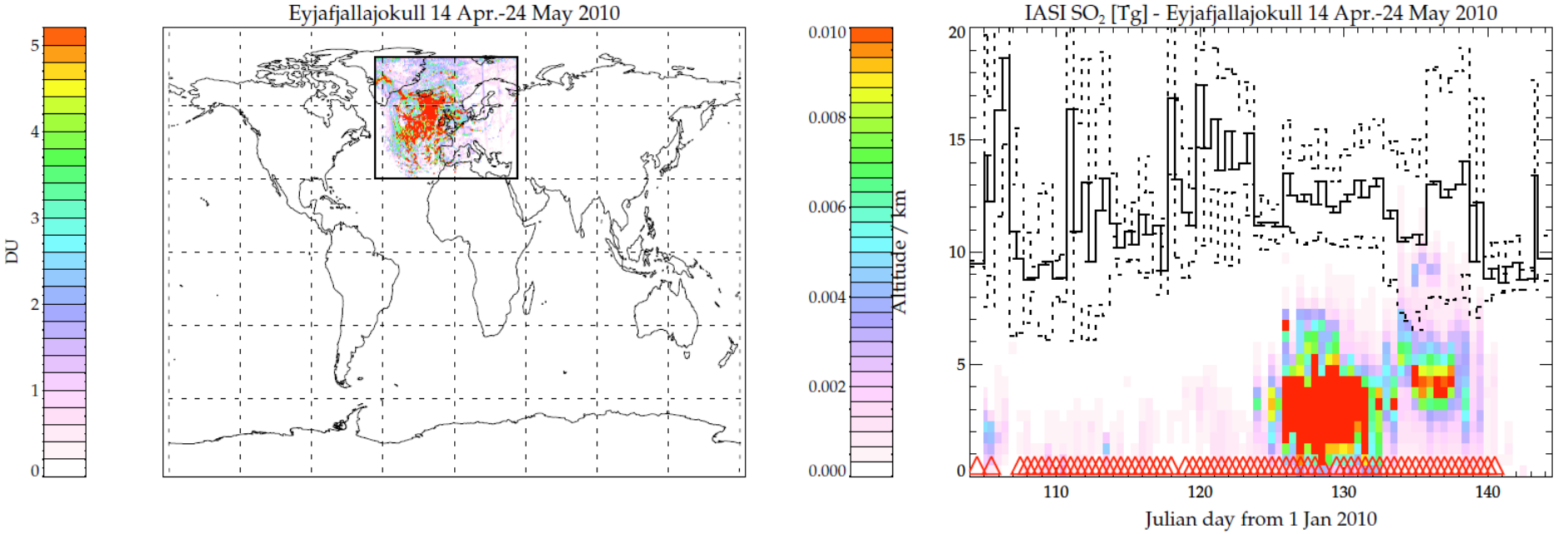

Nabro 12-23 June 2011
DU
0
1
2
3
4
5
IASI SO2 [Tg] - Nabro 12-23 June 2011
0.00
0.02
0.04
0.06
0.08
0.10
0
5
10
15
20
164
166
168
170
172
174
Julian day from 1 Jan 2011
Copahue 22-27 Dec. 2012
DU
0
1
2
3
4
5
IASI SO2 [Tg] - Copahue 22-27 Dec. 2012
Altitude / km
0.00
0.05
0.10
0.15
0.20
0
5
10
15
20
357
358
359
360
361
362
Julian day from 1 Jan 2012

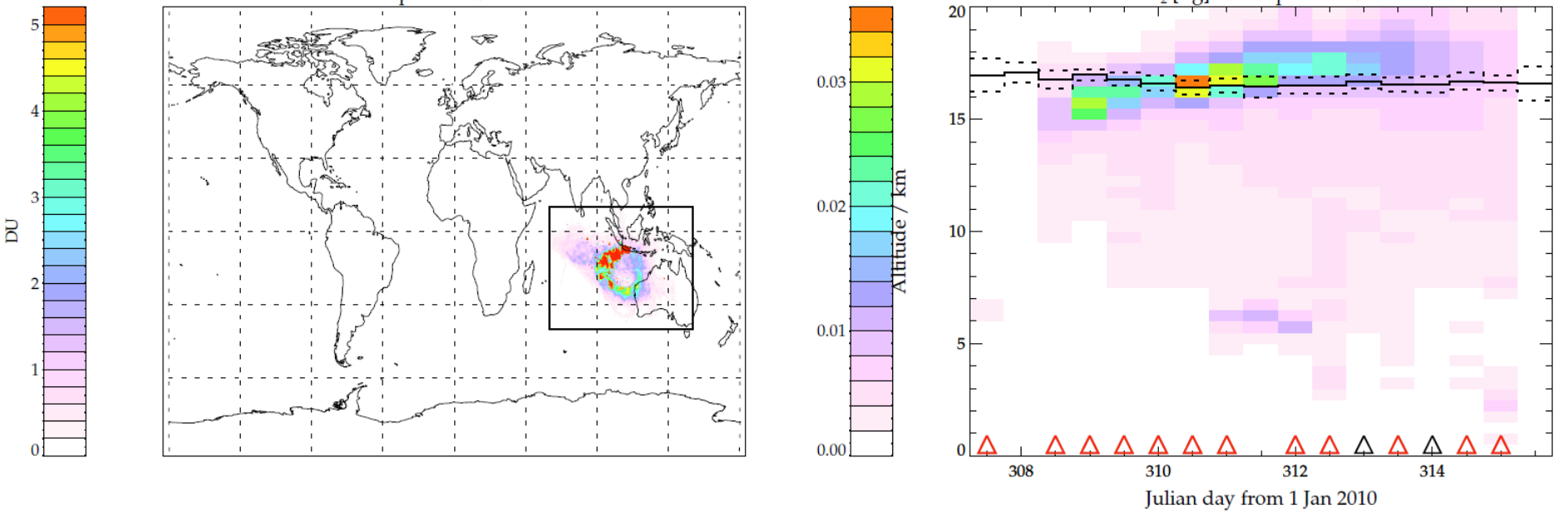

Llaima 2-6 Jan 2008
DU
0
1
2
3
4
5
IASI SO2 [Tg] - Llaima 2-6 Jan 2008
Altitude / km
0.000
0.001
0.002
0.003
0.004
0.005
0
5
10
15
20
2
3
4
5
6
Julian day from 1 Jan 2008
Okmok 12-20 July 2008
DU
0
1
2
3
4
5
IASI SO2 [Tg] - Okmok 12-20 July 2008
Altitude / km
0.000
0.005
0.010
0.015
0
5
10
15
20
194
196
198
200
202
Julian day from 1 Jan 2008

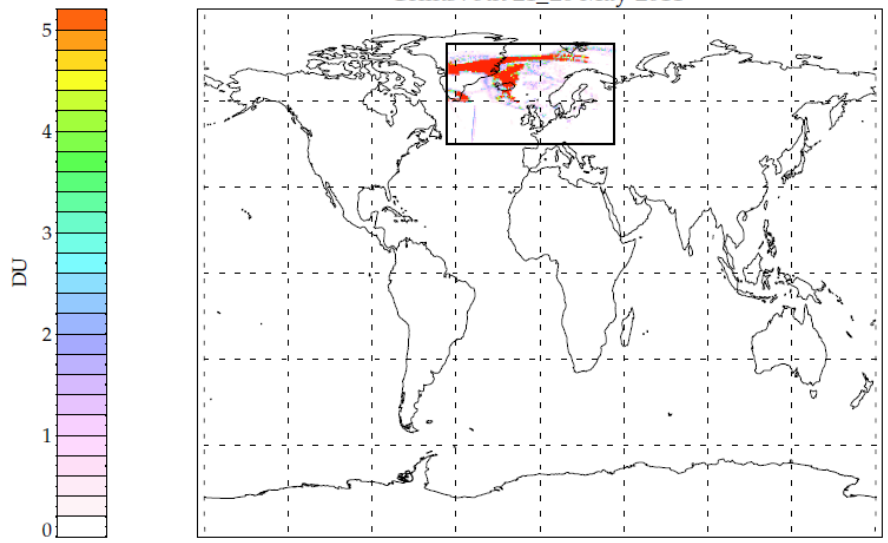

Kasatochi 7-22 Aug. 2008
DU
0
1
2
3
4
5
0.00
0.02
0.04
0.06
0.08
0.10
Altitude / km
IASI SO2 [Tg] - Kasatochi 7-22 Aug. 2008
0
5
10
15
20
220
225
230
235
Julian day from 1 Jan 2008
Dalaffilla 4-7 Nov. 2008
DU
0
1
2
3
4
5
0.000
0.005
0.010
0.015
0.020
Altitude / km
IASI SO2 [Tg] - Dalaffilla 4-7 Nov. 2008
0
5
10
15
20
309
310
311
312
Julian day from 1 Jan 2008

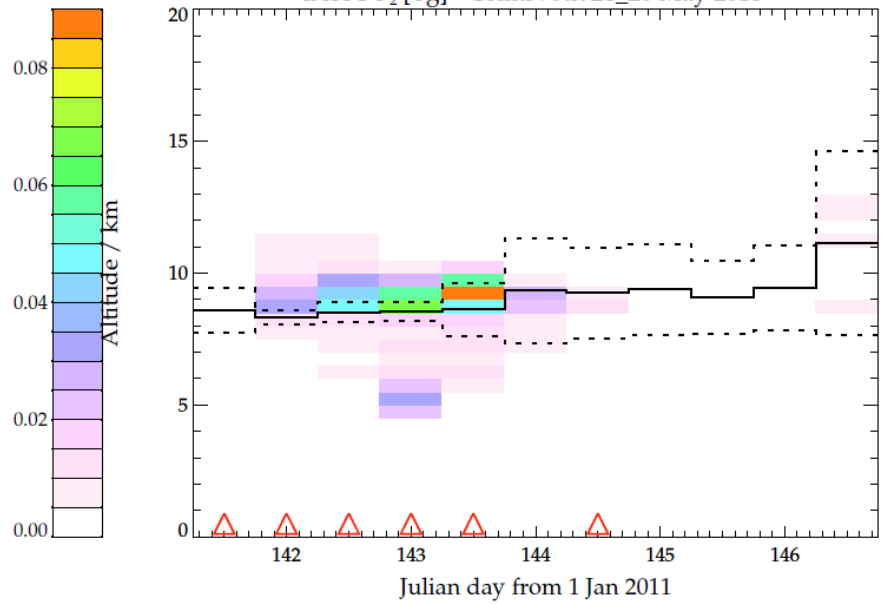

Sarychev 11-26 June 2009
DU
0
1
2
3
4
5
0.00
0.02
0.04
0.06
0.08
Altitude / km
IASI SO2 [Tg] - Sarychev 11-26 June 2009
0
5
10
15
20
165
170
175
Julian day from 1 Jan 2009

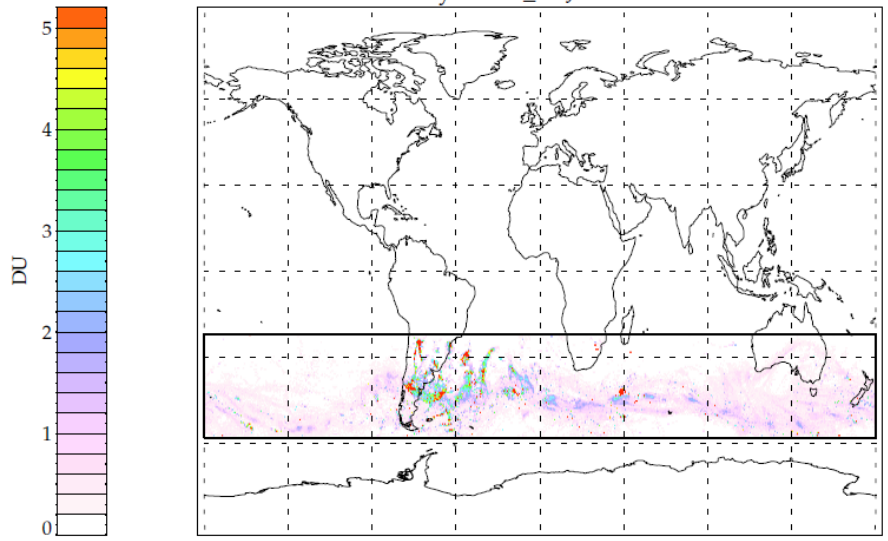

Montserrat 10-15 Feb 2010
DU
0
1
2
3
4
5
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
Altitude / km
IASI SO2 [Tg] - Montserrat 10-15 Feb 2010
0
5
10
15
20
42
43
44
45
46
Julian day from 1 Jan 2010

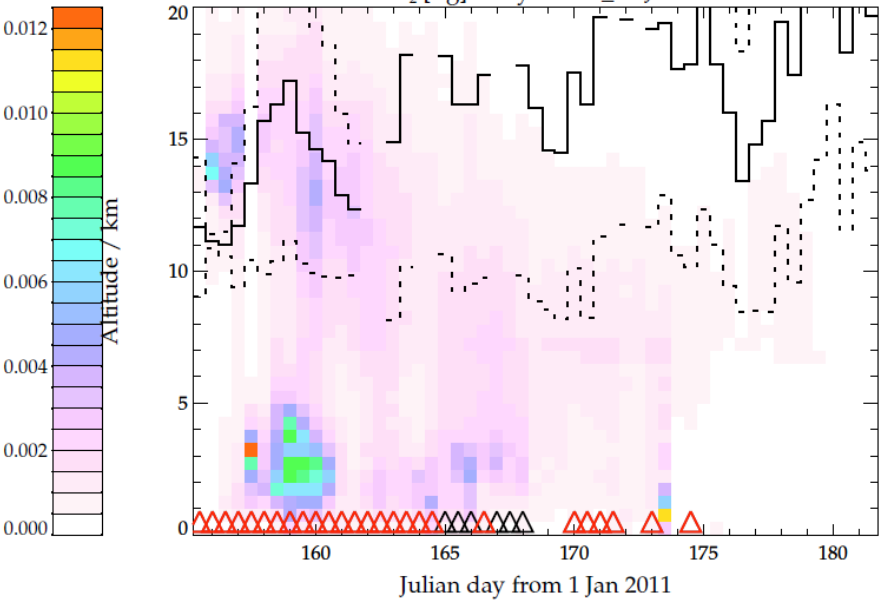

Eyjafjallajokull 14 Apr.-24 May 2010
DU
0
1
2
3
4
5
IASI SO2 [Tg] - Eyjafjallajokull 14 Apr.-24 May 2010
Altitude / km
0.000
0.002
0.004
0.006
0.008
0.010
0
5
10
15
20
110
120
130
140
Julian day from 1 Jan 2010


Merapi 4-11 Nov. 2010
DU
0
1
2
3
4
5
IASI SO2 [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



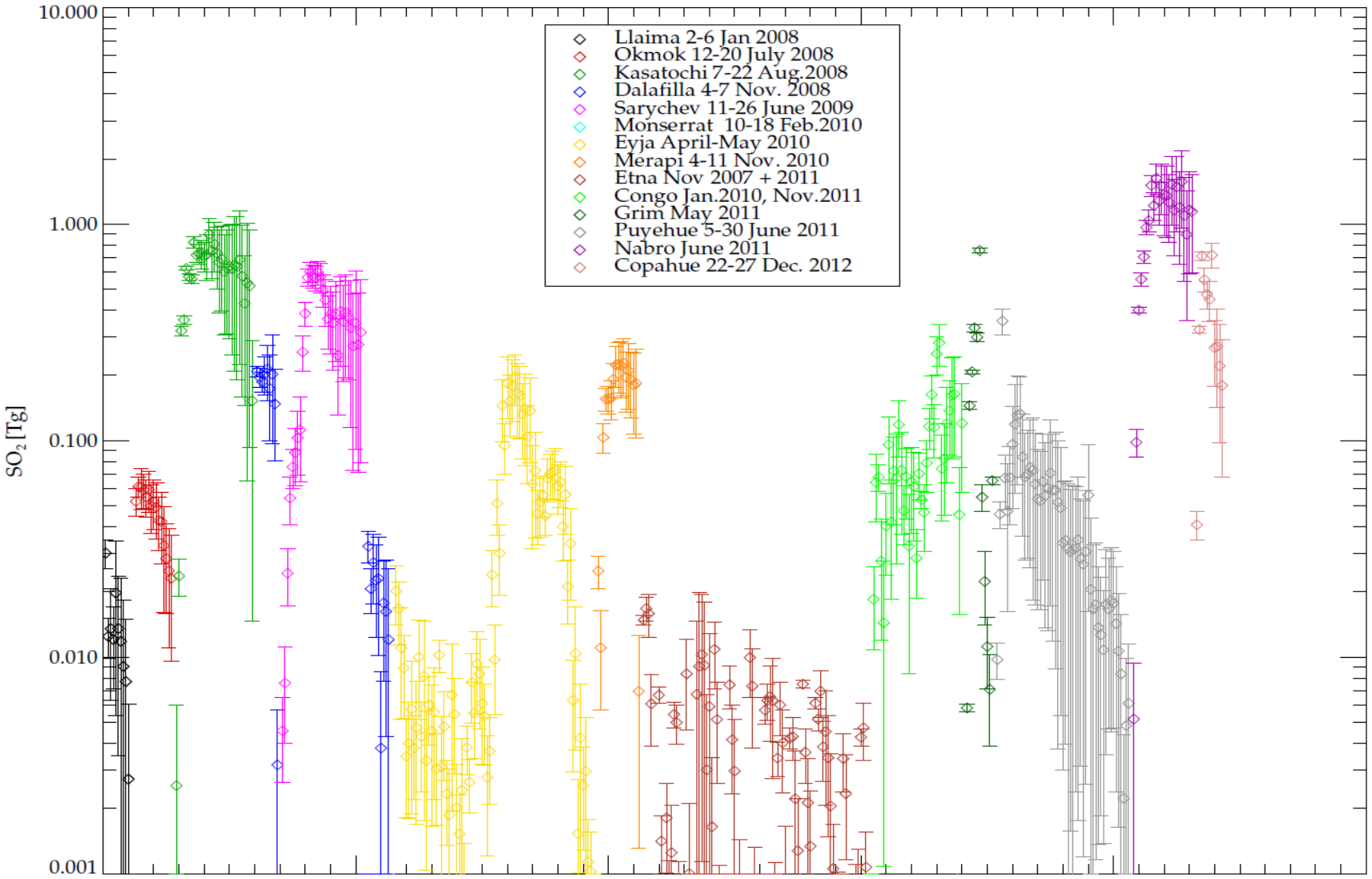




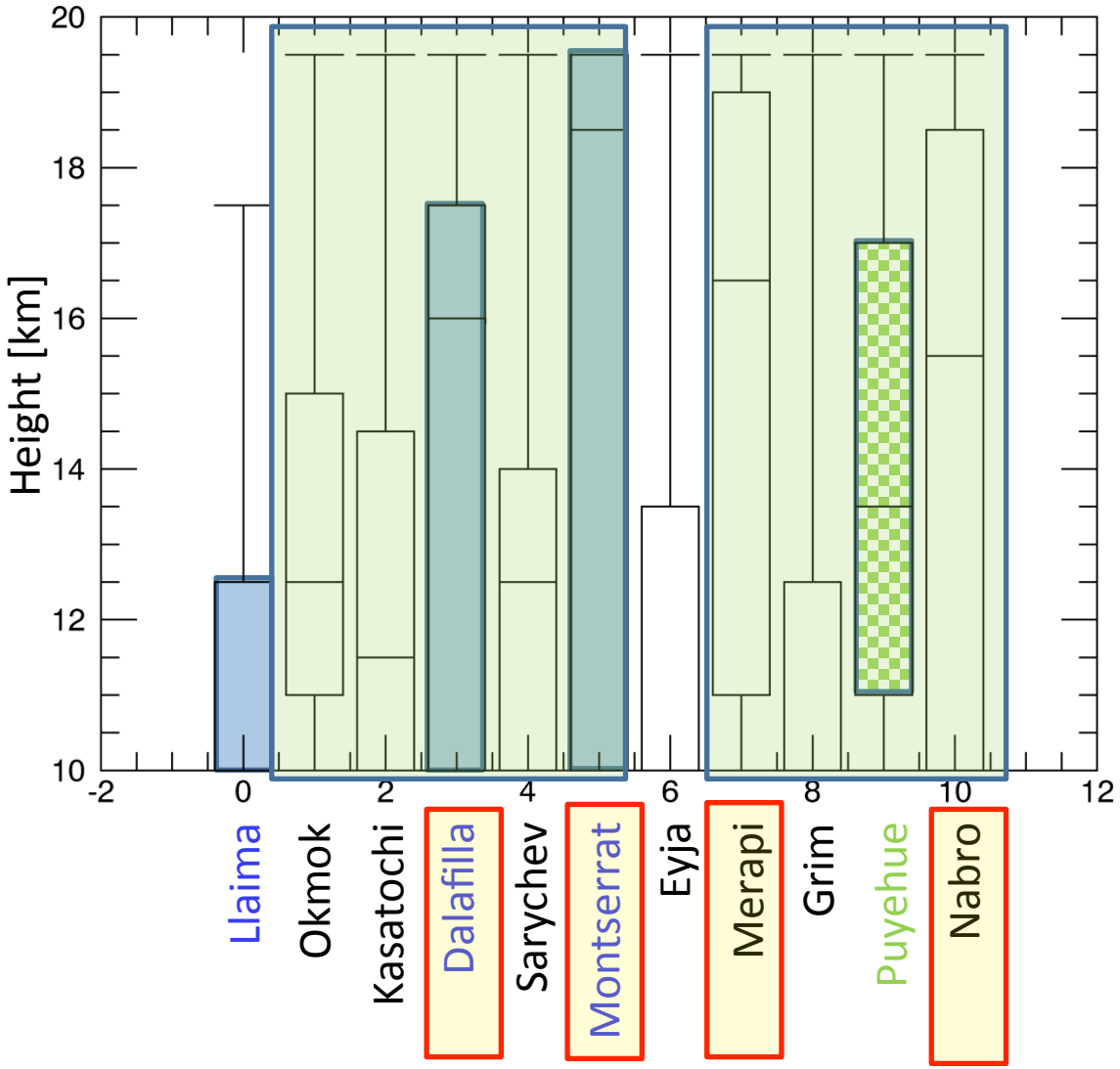


E.C. 18:08 15/12/14.

SO2 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 3

VEI 4

VEI 5

Volcanic explosivity index (VEI) from the Smithsonian Institution Global Volcanism Programme

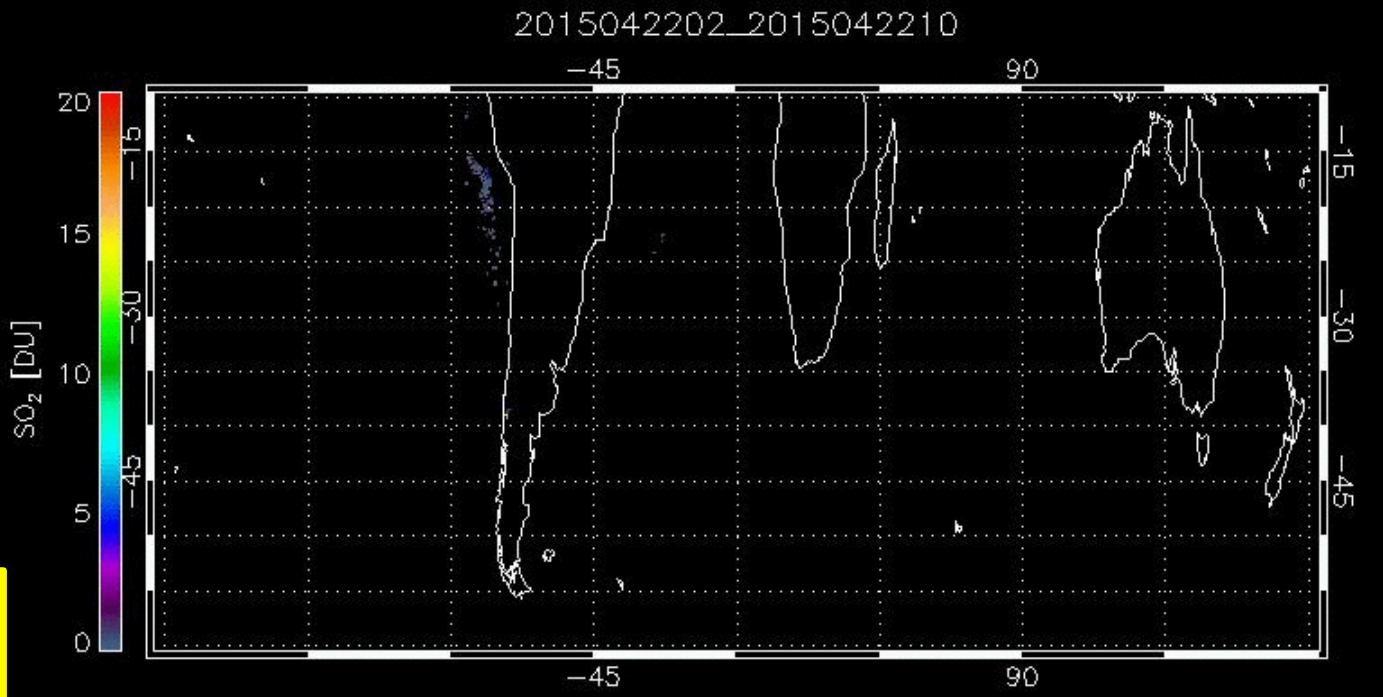
Tropopause and up

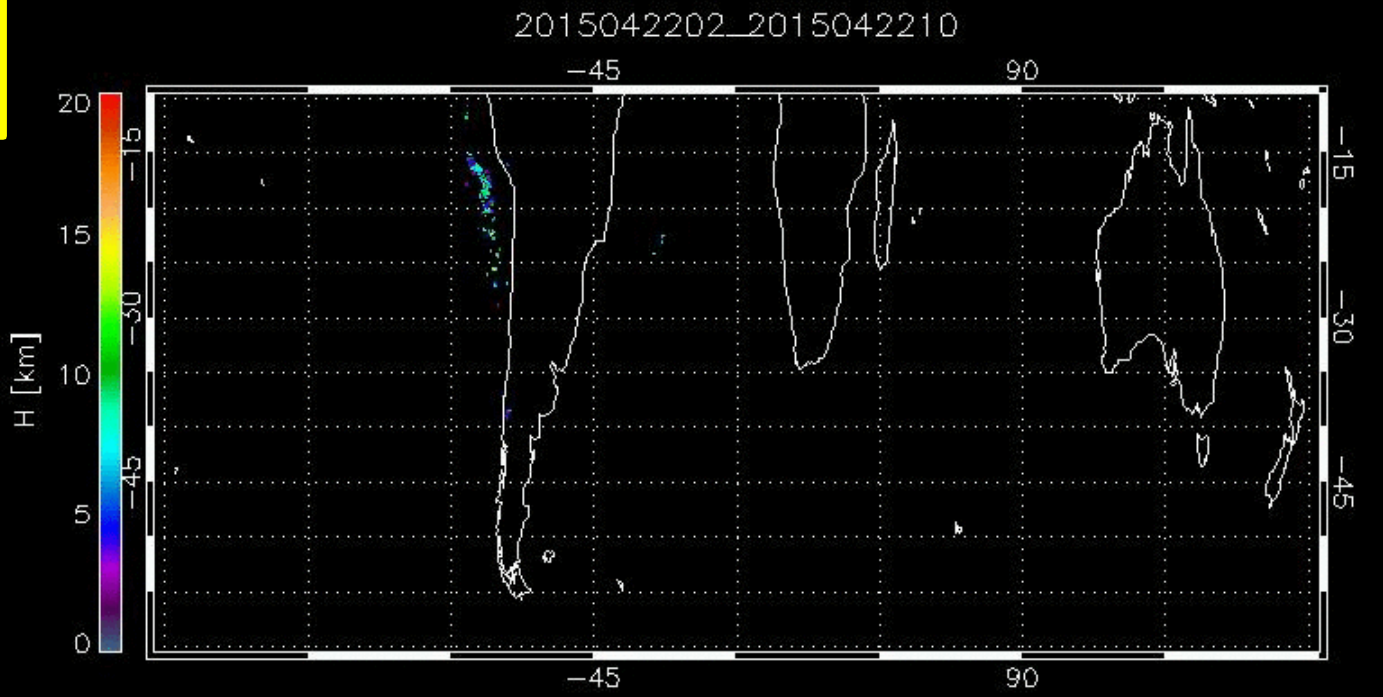
Tropical area

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.

Calbuco
22 April -
20 May 2015





Summary

SO2 detection: (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.
- IASI retrieved values are consistent with CALIPSO altitudes and Brewers column amount
- we can study the plume vertical distributions, and evolution in time.
- There is a tendency for volcanic SO2 plumes to reach the tropopause. (All of the eruptions in the tropics (except Nyamuragira) reached the tropopause).

More papers using this IASI SO2:

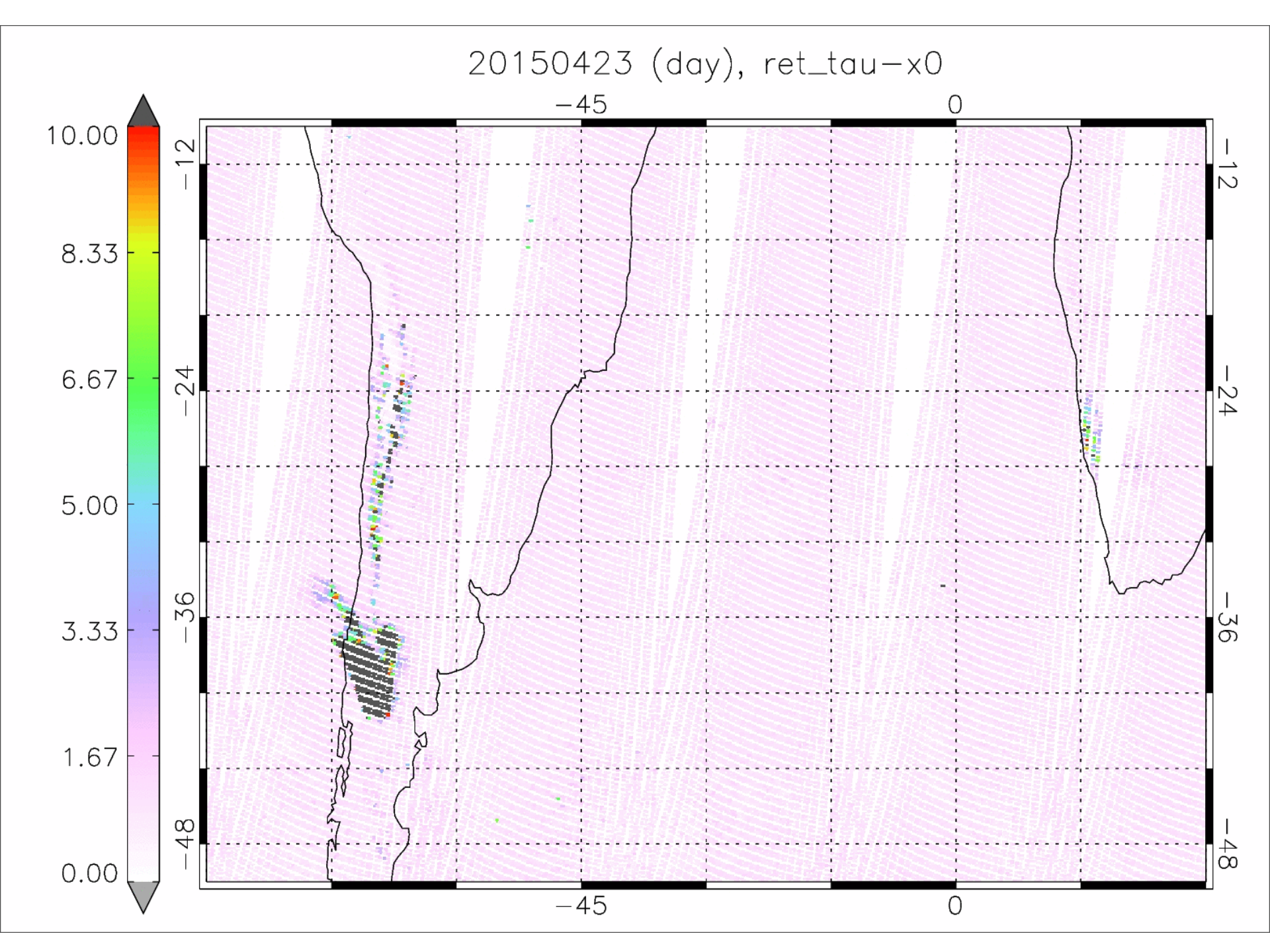
Schmidt et al. 2015 - Bardabunga

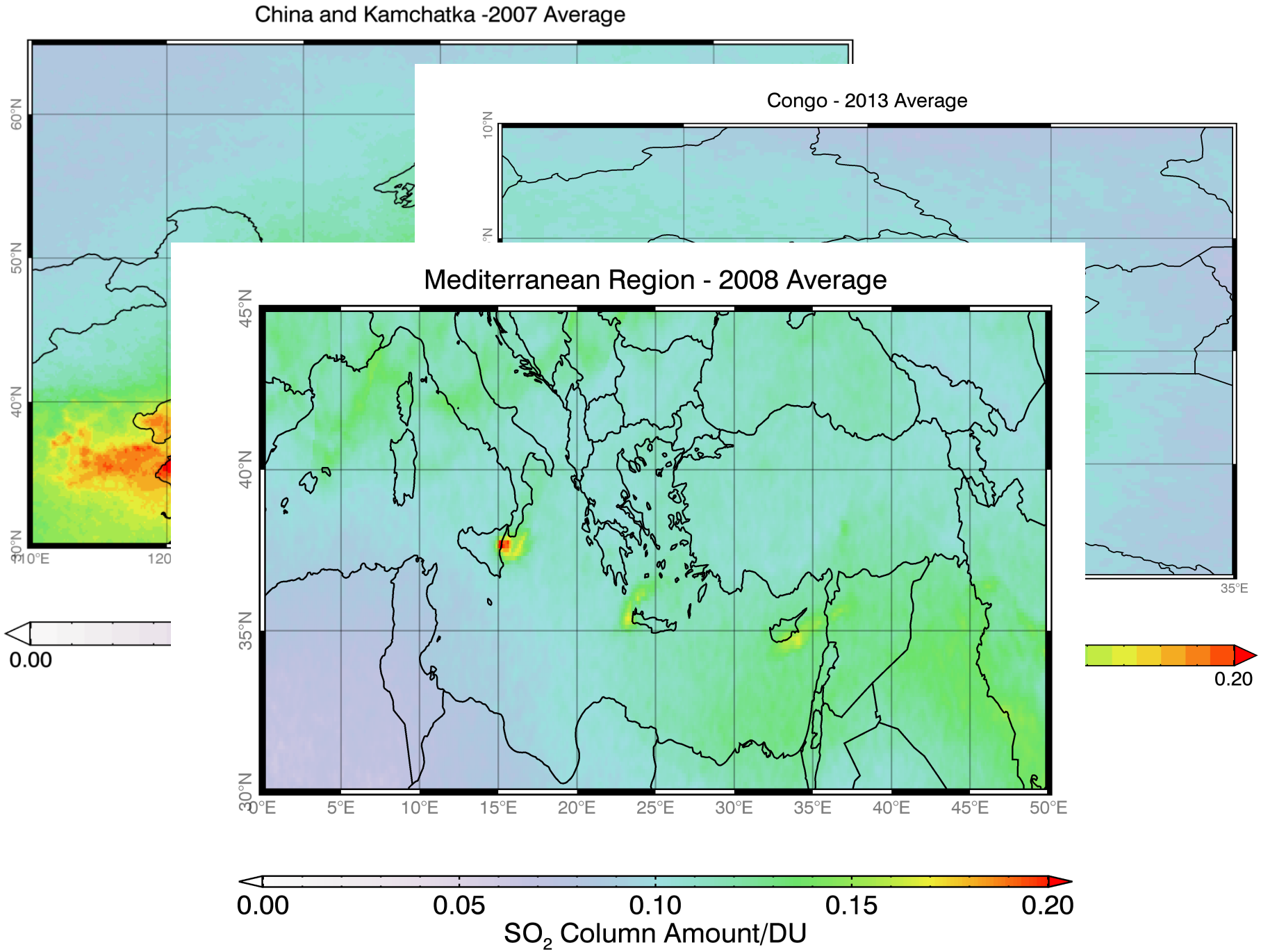
Fromm et al 2014 – Nabro

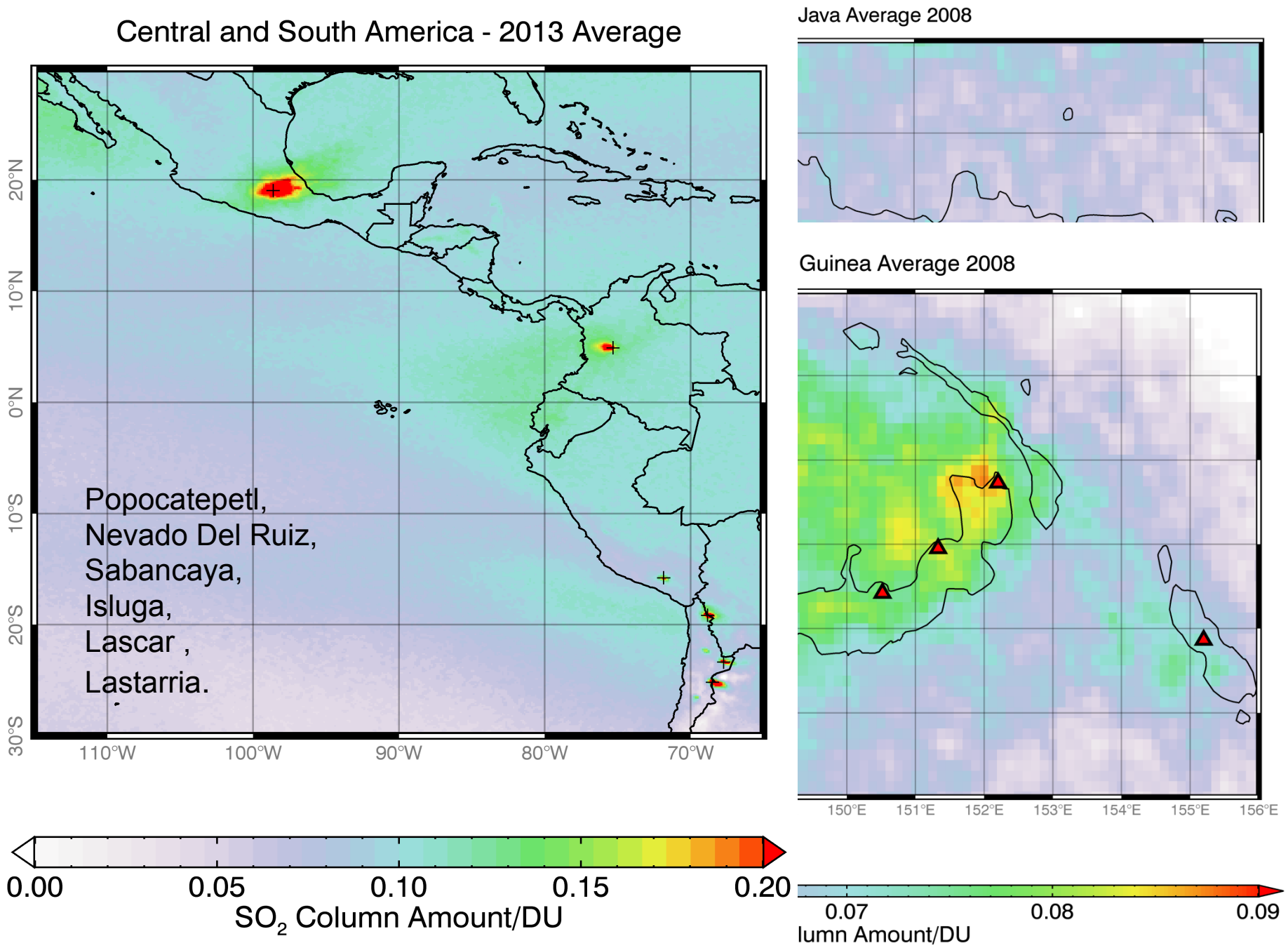
Koukouli et al 2015, Spinetti et al 2015, Sears et al. 2013

Dataset is available (elisa@atm.ox.ac.uk)

Thank you!


20150423 (day), ret_tau−x0
10.00
8.33
6.67
5.00
3.33
1.67
0.00
−45
0
−12
−24
−36
−48

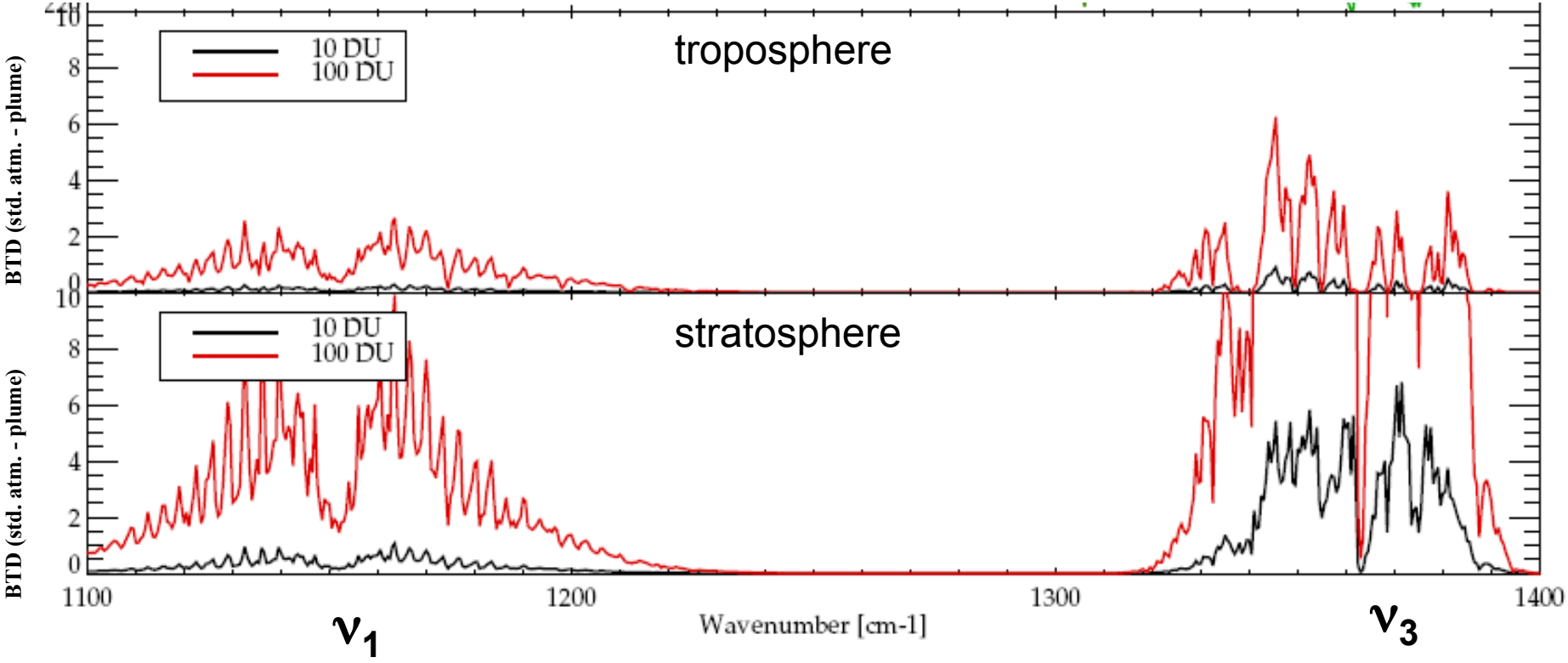

China and Kamchatka -2007 Average
60°N
50°N
40°N
30°N
110°E
120
0.00
Congo - 2013 Average
10°N
°N
35°E
0.20
Mediterranean Region - 2008 Average
45°N
40°N
35°N
30°N
0°E
5°E
10°E
15°E
20°E
25°E
30°E
35°E
40°E
45°E
50°E
0.00
0.05
0.10
0.15
0.20
SO2 Column Amount/DU


Central and South America - 2013 Average
Popocatepetl,
Nevado Del Ruiz,
Sabancaya,
Isluga,
Lascar ,
Lastarria.
20°N
10°N
0°N
10°S
20°S
30°S
110°W
100°W
90°W
80°W
70°W
Java Average 2008
Guinea Average 2008
150°E
151°E
152°E
153°E
154°E
155°E
156°E
0.00
0.05
0.10
0.15
0.20
SO2 Column Amount/DU
0.07
0.08
0.09
lumn Amount/DU

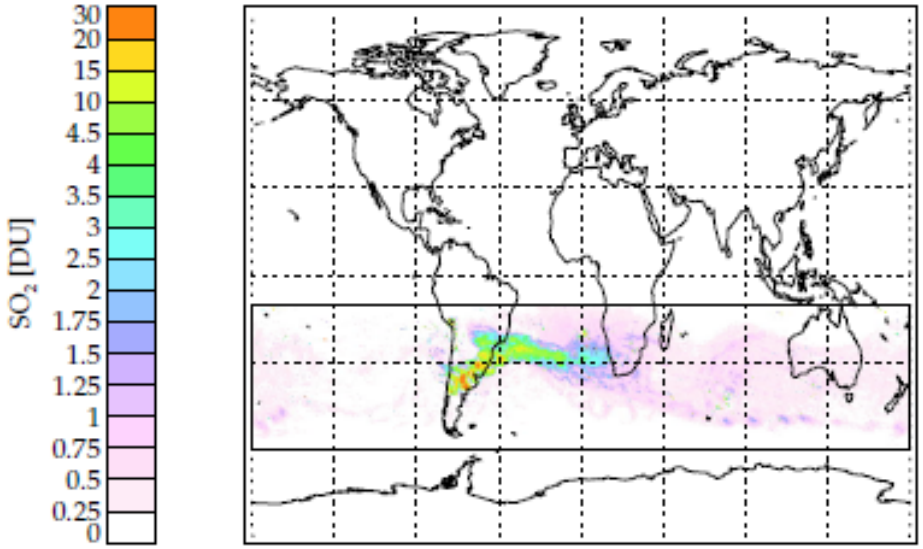
SO_2 thermal infrared spectra

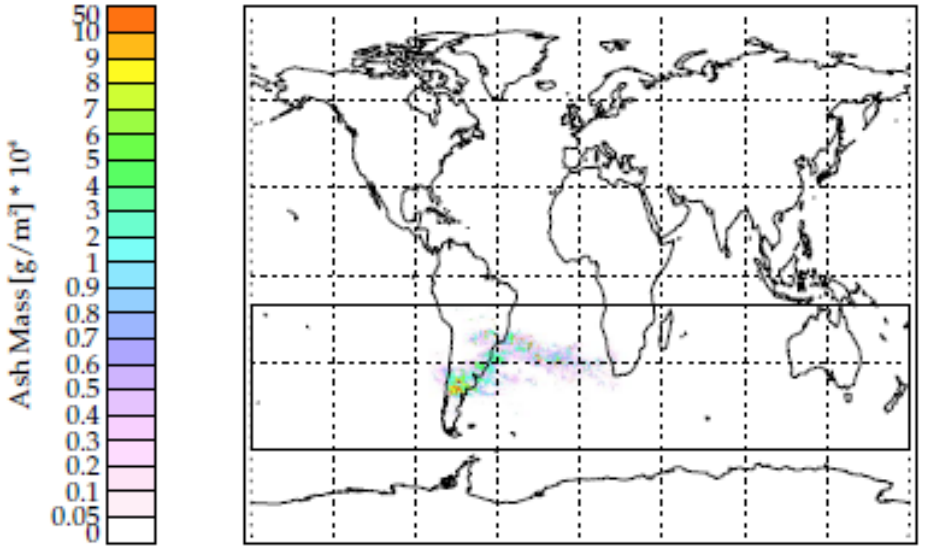
Brightness temperature differences (BTD) between the clear atmosphere and the atmosphere with enhanced tropospheric/stratospheric (top/bottom) SO_2 containing a total column amount of 10DU (black line) or 100DU (red line) of SO_2;

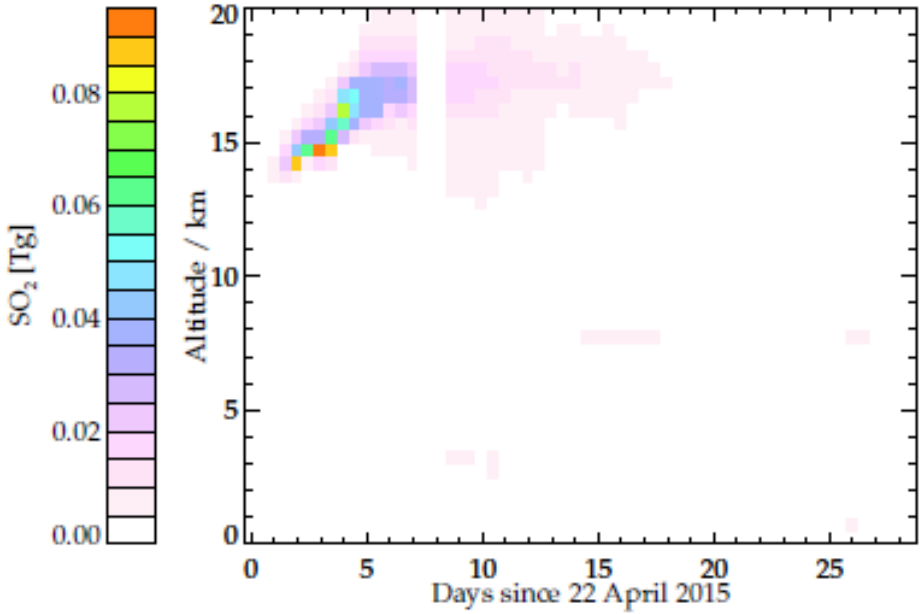
SO_2 absorption around 7.3 (ν3) and 8.7 (ν1) mm.

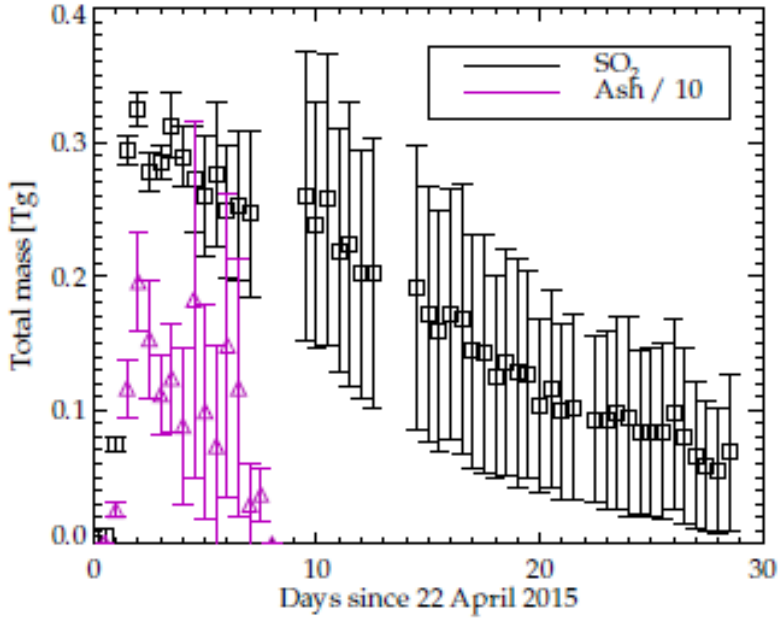


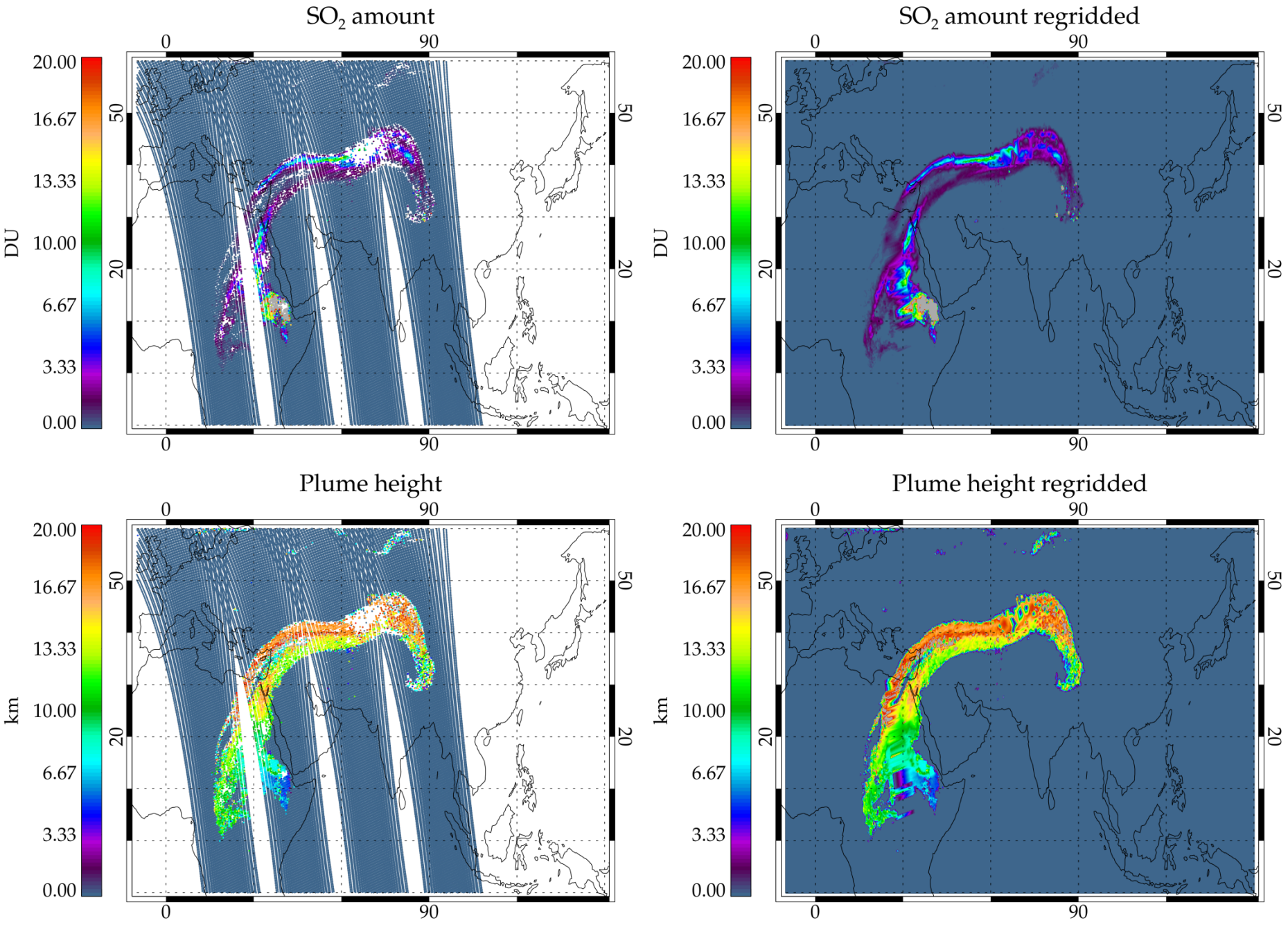
IASI is sensitive to both the amount of SO_2 and the altitude of the plume => getting the altitude correct is important in order to get the correct *amount* of SO_2, since the signal depends strongly on altitude.


SO2 [DU]
30
20
15
10
4.5
4
3.5
3
2.5
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0


Ash Mass [g/m²] * 10⁴
50
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.05
0


SO2 [Tg]
0.08
0.06
0.04
0.02
0.00
Altitude / km
20
15
10
5
0
0
5
10
15
20
25
Days since 22 April 2015


Total mass [Tg]
0.4
0.3
0.2
0.1
0.0
SO2
Ash / 10
0
10
20
30
Days since 22 April 2015


SO2 amount
SO2 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

Error analysis

linear error on the 'true' state obtained as:

$$S_x = (K^T S_y^{-1} K + S_a^{-1})^{-1}$$

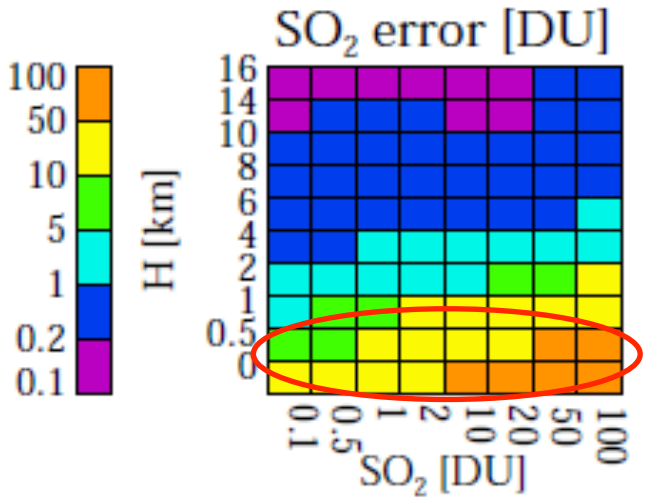
$$A = S_x S_x^{-1} - S_a^{-1}$$

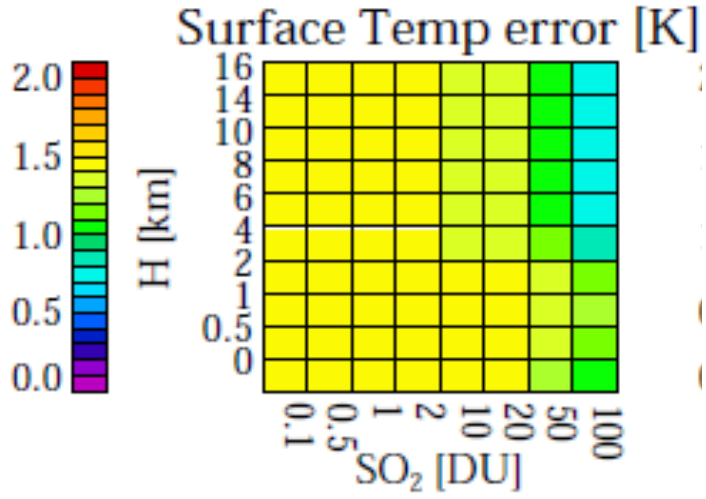
A priori values

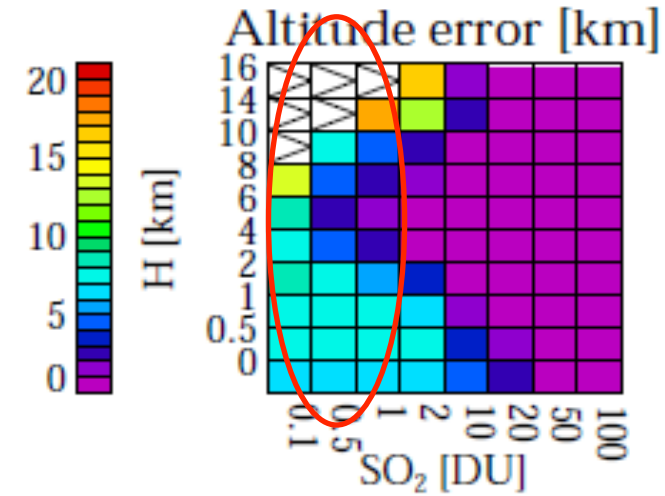
SO2, H, s, Ts

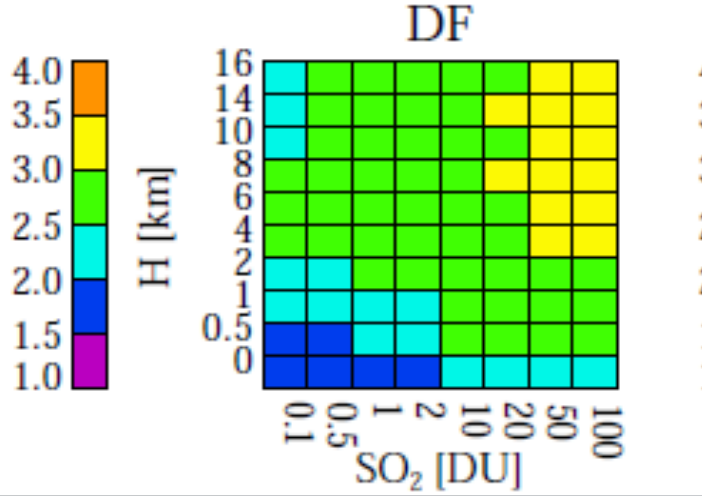
Xa=[0.5, 400, 100, 290]

DXa=[100, 1000, 1, 20]





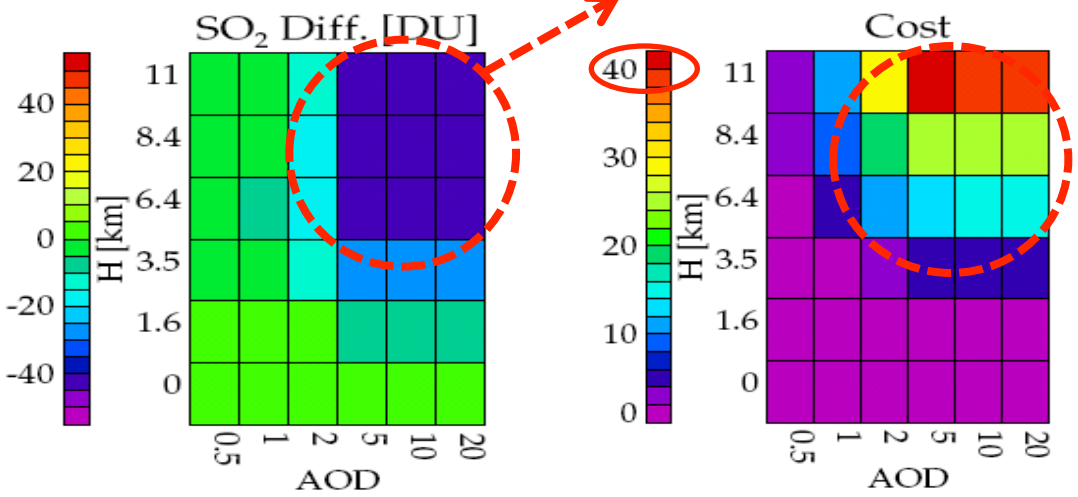




Sensitivity of retrieval to presence of ash and cloud

Type: ash, Re=2um

SO2 underestimate for thick ash



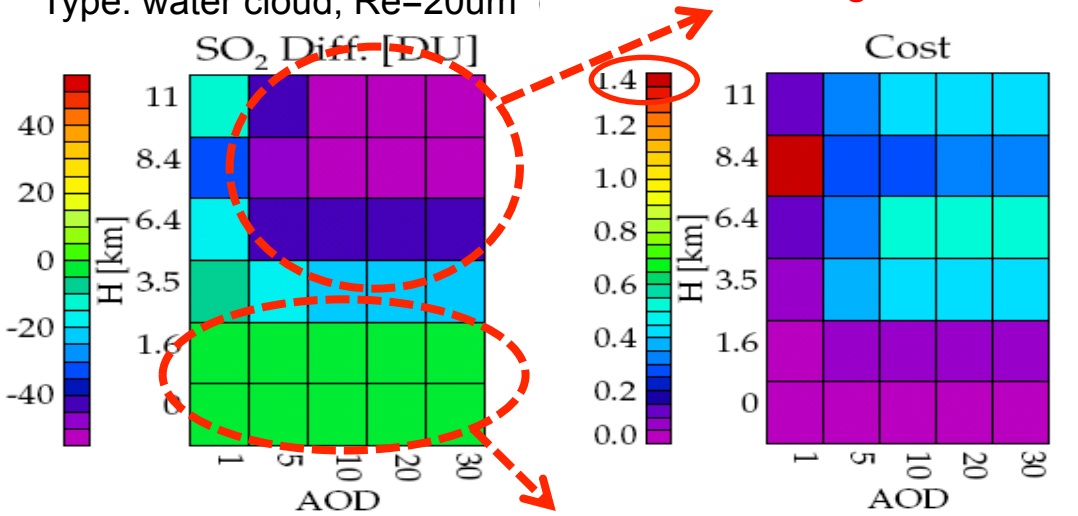
high cost !!

Retrieval using simulations with ash and water cloud at different optical depth and altitude

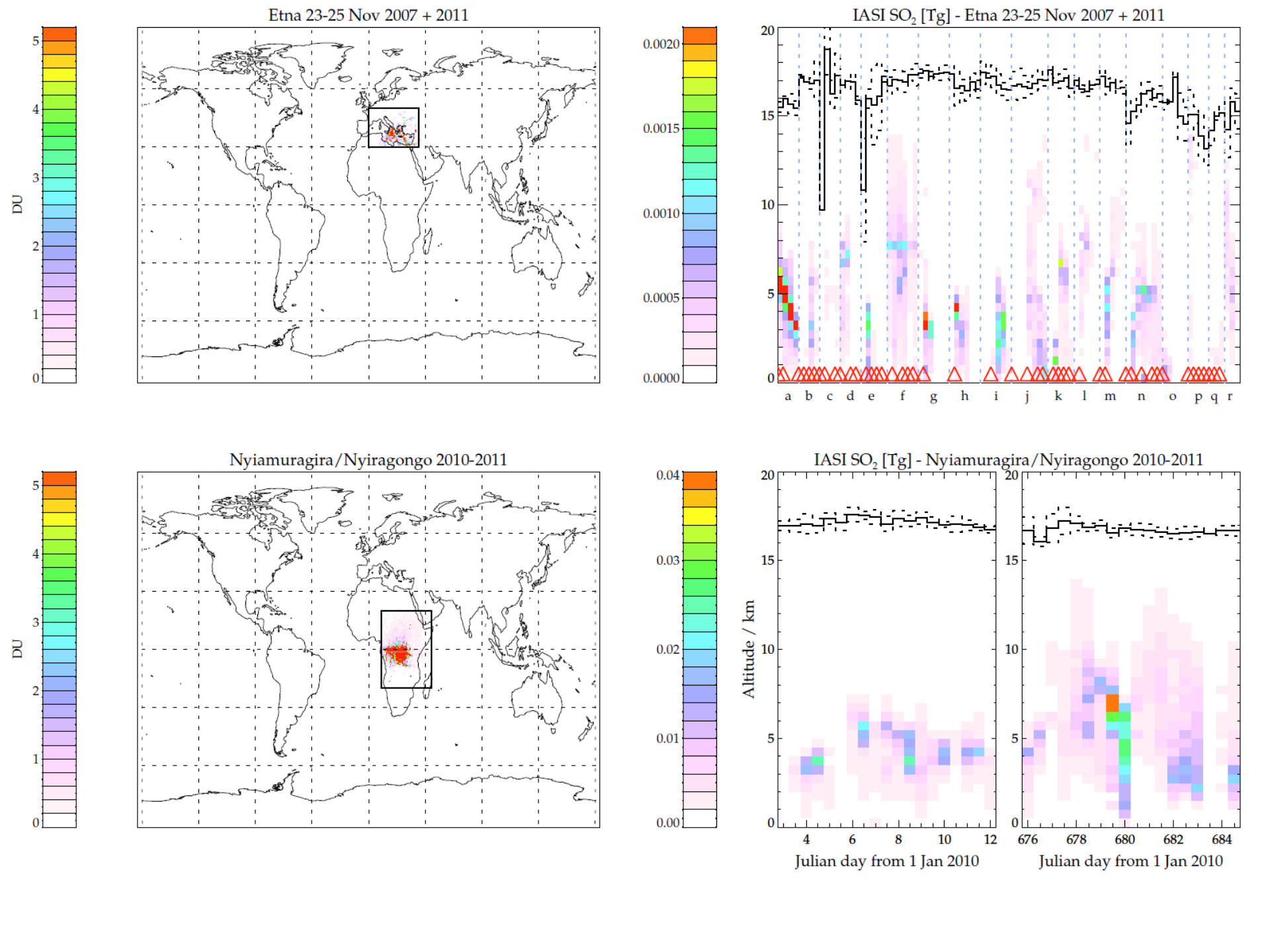
	DU	hPa	T [K]
Tru	50	400	
Ap	0.5	400	290
Ap err	100	1000	20

Type: water cloud, Re=20um

SO2 signal 'covered' from cloud within or above the plume



OK for cloud below the plume!!!


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
0.00
0.01
0.02
0.03
0.04
IASI SO2 [Tg] - Nyiamuragira/Nyiragongo 2010-2011
Altitude / km
4
6
8
10
12
676
678
680
682
684
Julian day from 1 Jan 2010
Julian day from 1 Jan 2010

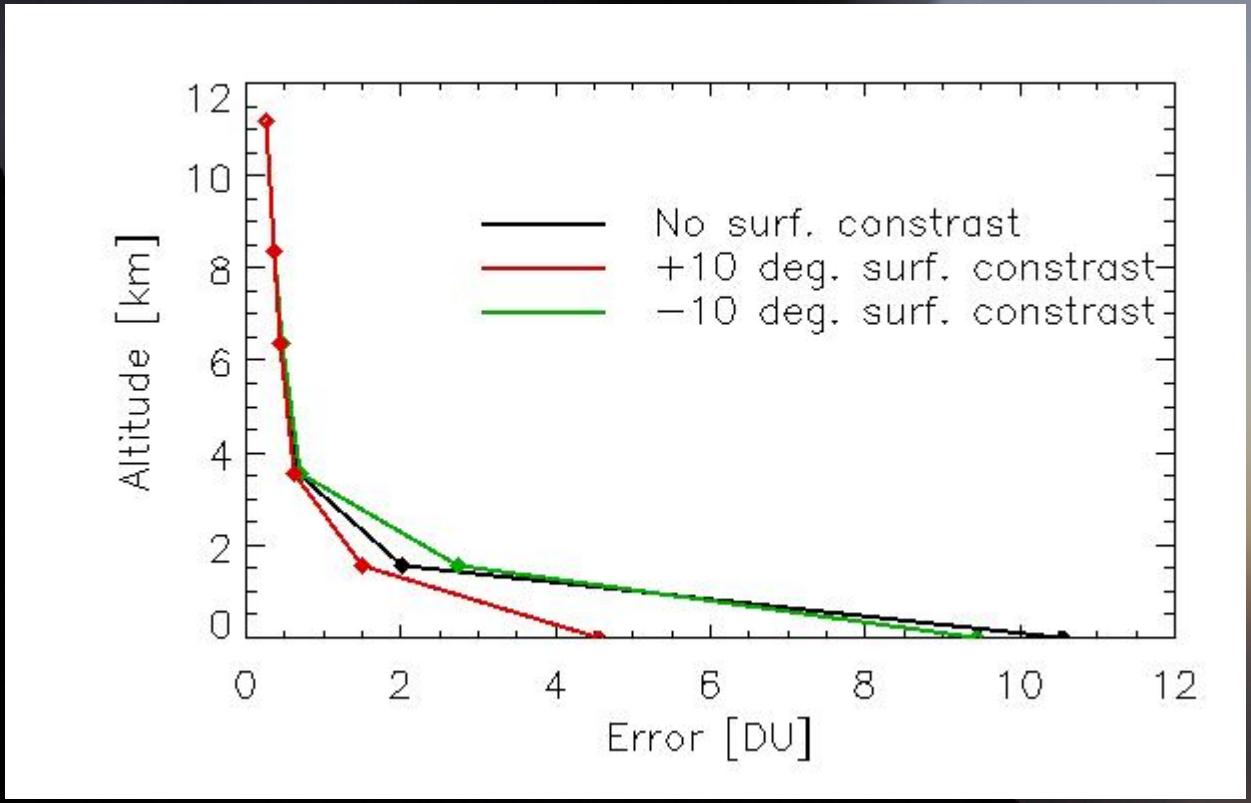
Minimum error estimate

surface contrast = skin temperature - temperature of the first atm. layer

std. atm. profiles
assumption: we know the altitude of the plume.

1 DU = 0.0285 g/m^2

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	$388\ 10^{-4}$

SO_2 linear (ν3)

It is mainly a 'measurements' of the SO2 signal

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

Assume:

SO2 vertical profile, atmospheric profiles, Jacobian

Retrieve:

SO2 column amount [DU]

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

(1)

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:

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

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

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}

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

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

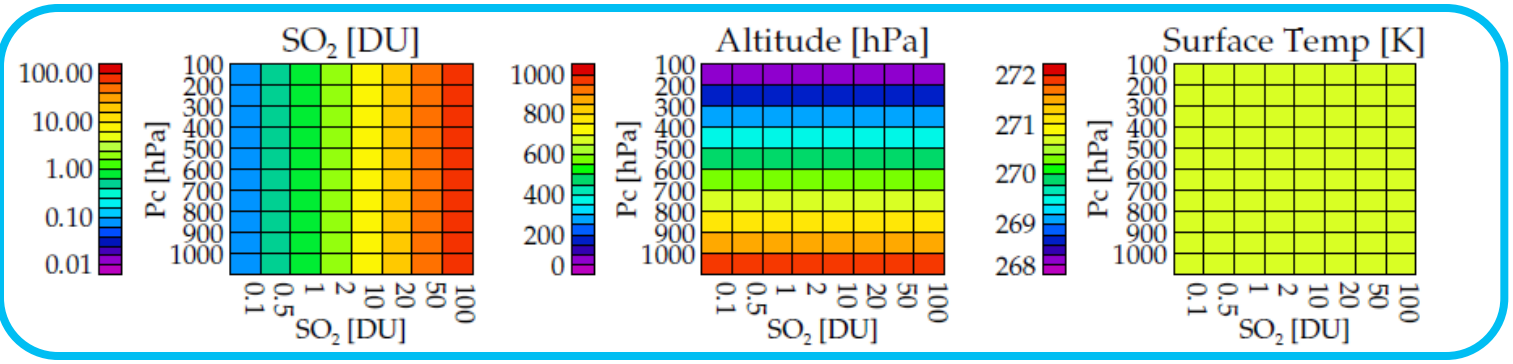
[Walker, Dudhia, Carboni, Atmos. Meas. Tech., 2011]

Error analysis

linear error on the ‘true’ state obtained as:

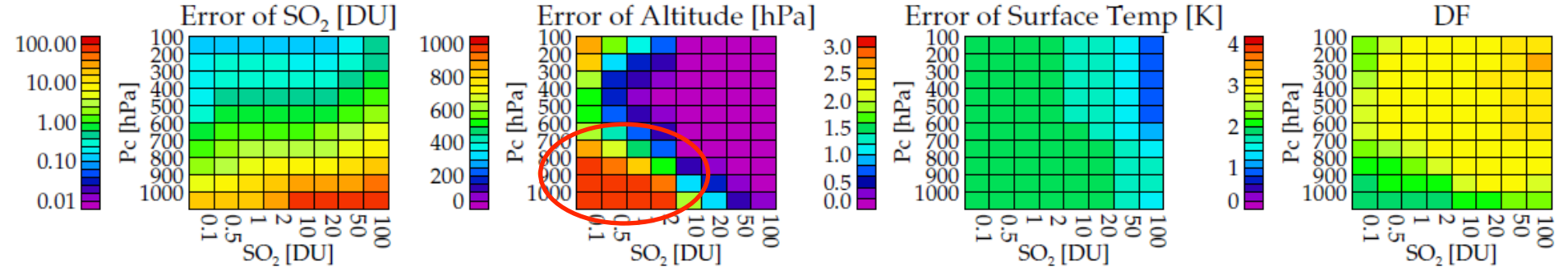
$$S_x = (K^T S_y^{-1} K + S_a^{-1})^{-1} \qquad A = S_x S_x^{-1} - S_a^{-1}$$

SO2, H, s, Ts
Xa=[0.5, 400, 100, 290]
DXa=[100, 1000, 1, 20]

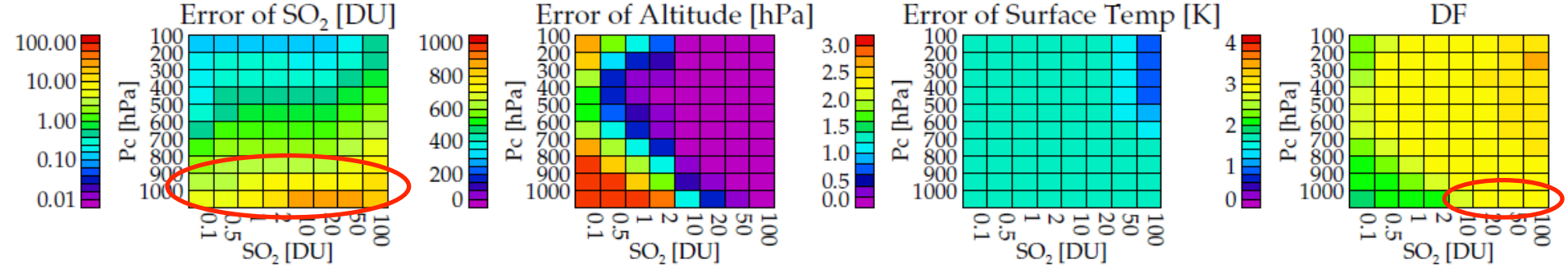


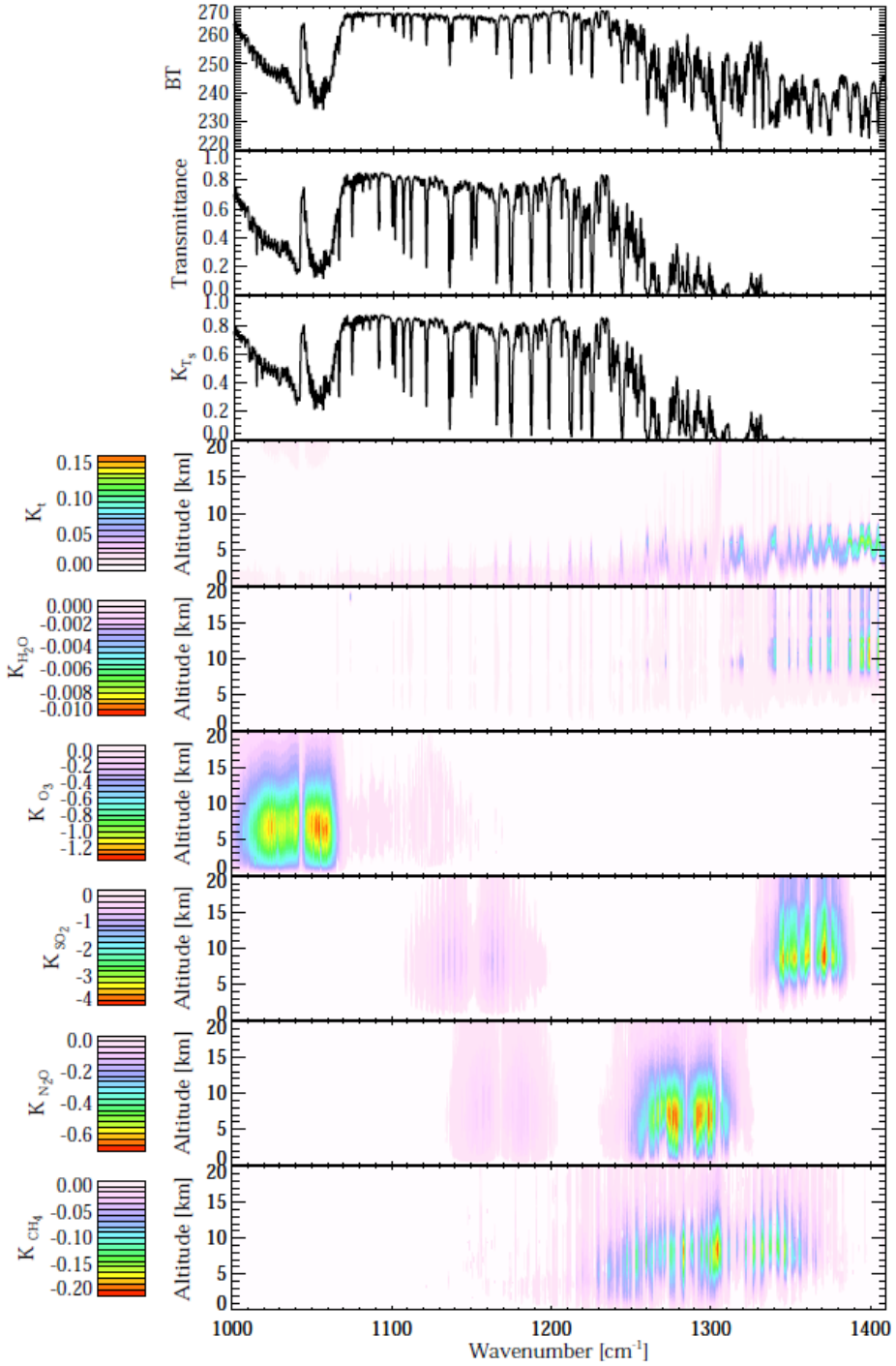
‘true state’

NO thermal contrast



+10° thermal contrast





Radiative transfer model

Radiative transfer model based on RTTOV (plus SO2 coefficients computed by RAL using the line by line model RFM).

When used in proper retrieval RTTOV is driven by ECMWF profile interpolated at IASI pixel location and time

IASI FORWARD MODEL

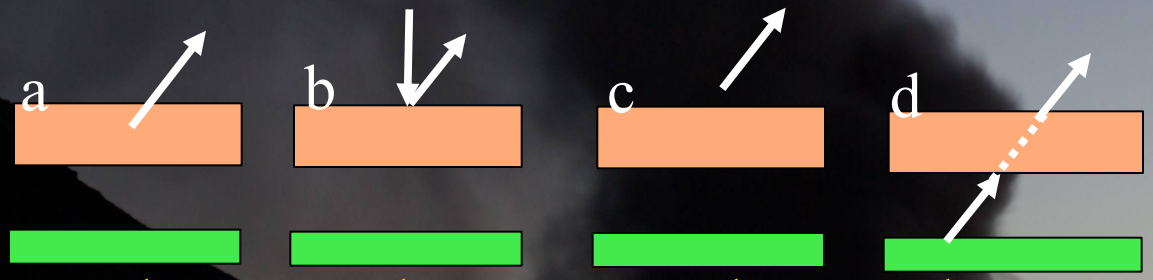
The RTTOV output for a clean atmosphere (containing gas but not cloud or aerosol/ash) is combined with an ash layer using the same scheme as for the Oxford-RAL Retrieval of Aerosol and Cloud (ORAC) algorithm.

atm. above $I^{\uparrow}_{ac}$ $I^{\downarrow}_{ac}$ T_{ac}

aerosol layer R_c, e_c, T_c, B_c The suffix 'c' refers to clou aerosol layer

atm. belowe $I^{\uparrow}_{bc}, T_{bc}$

surface R_s, e_s, B_s

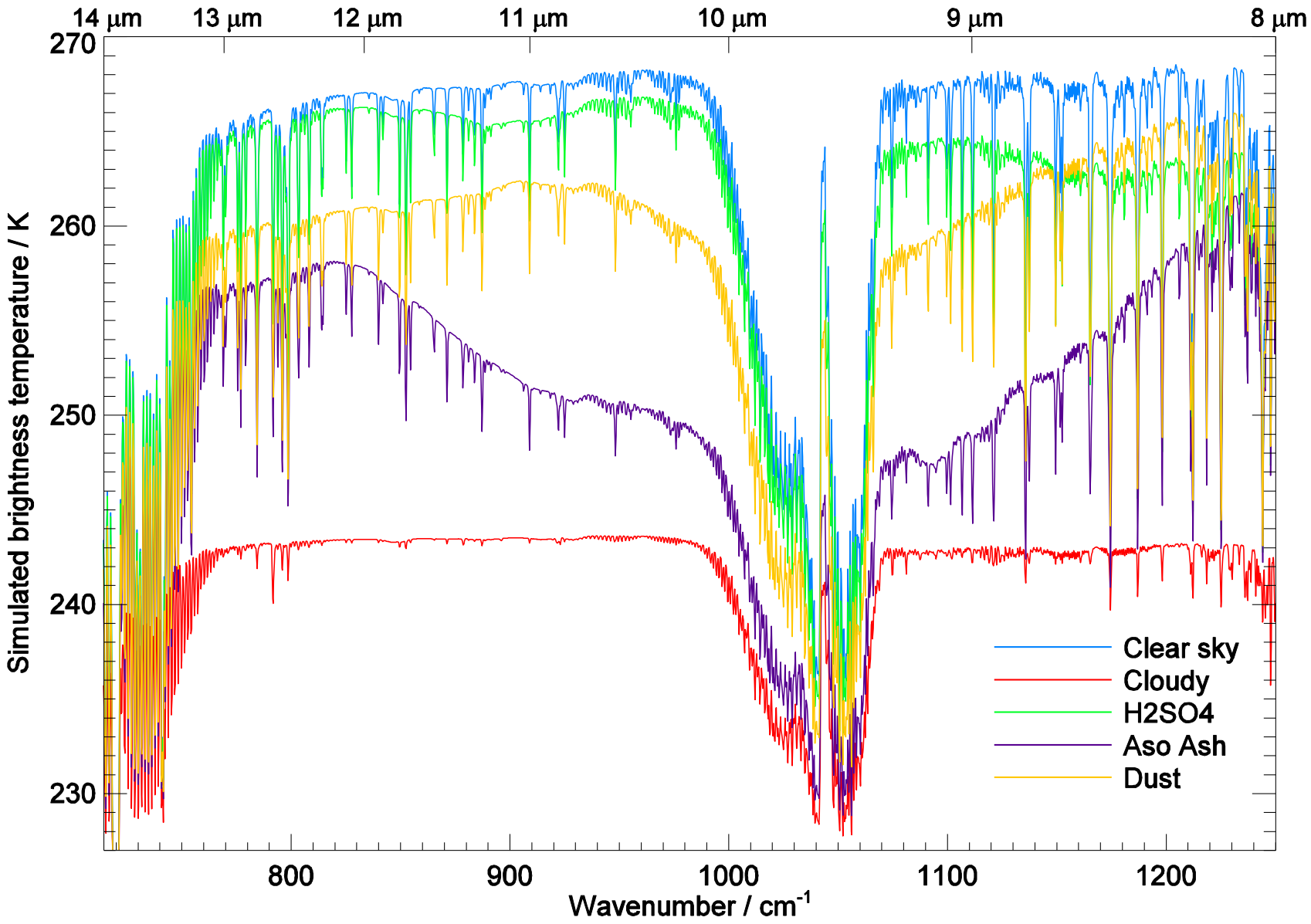


$$I^{\uparrow}_{\bullet} = B_c \epsilon_c T_{ac} + I^{\downarrow}_{ac} R_c T_{ac} + I^{\uparrow}_{ac} + B_s \epsilon_s T_{bc} T_c T_{ac} + I^{\uparrow(atm)}_{bc} T_c T_{ac}$$

LUTs for aerosol layer parameters (aerosol optical properties + DISORT)

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

IASI simulated spectra

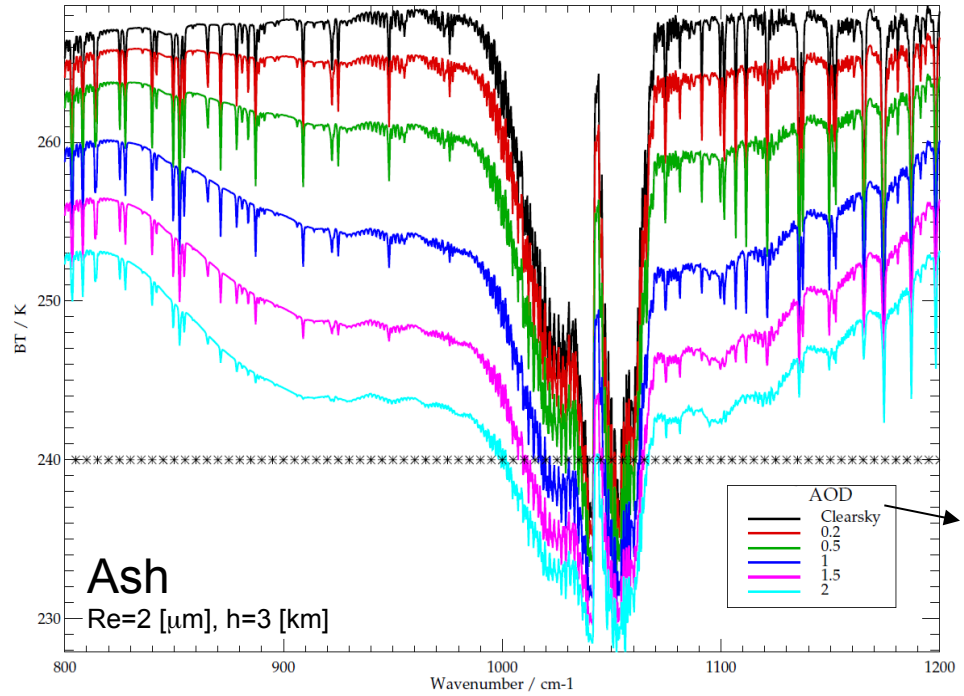


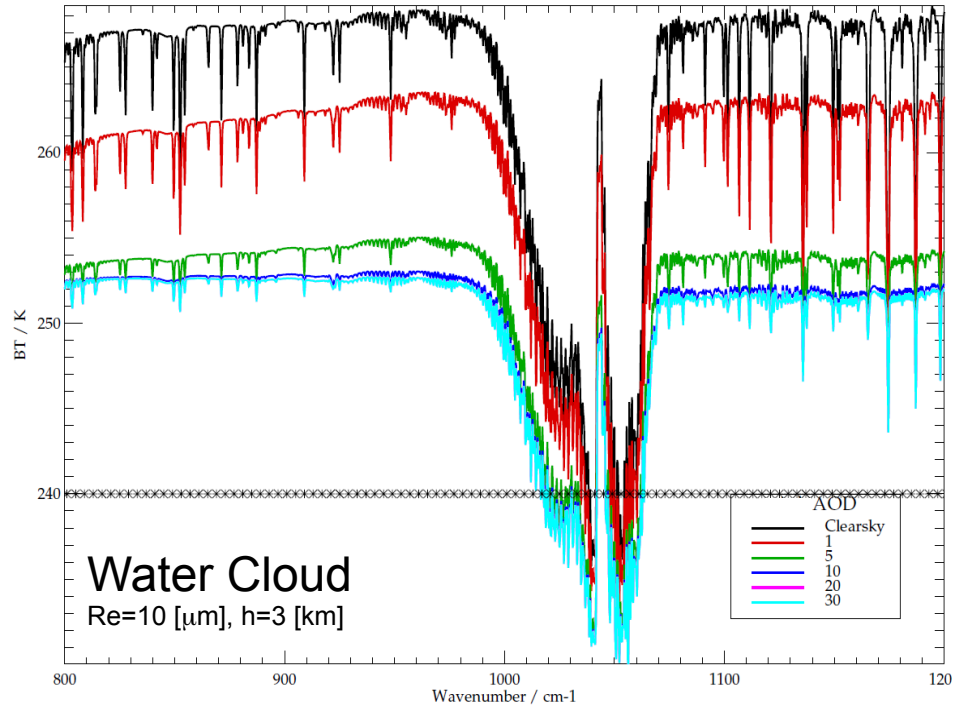
Ash and cloud effects?

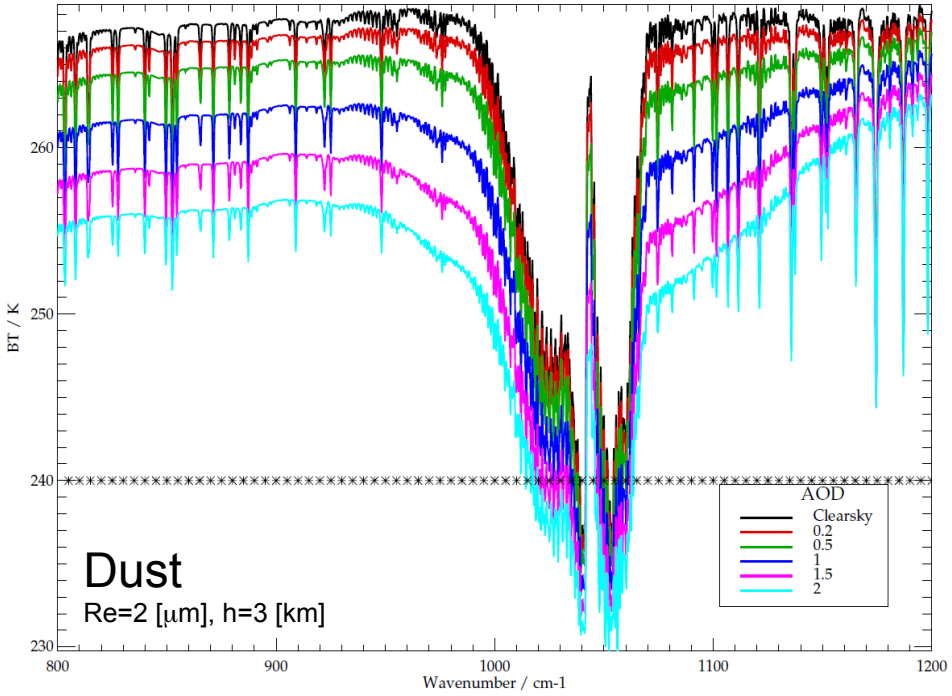
To test if the retrieval is sensitive to ash/cloud etc...

IASI forward model can include aerosol and cloud.

Obtained with refractive index measured by Daniel Peters (see poster VA-5).







Sensitivity of retrieval to presence of ash and cloud

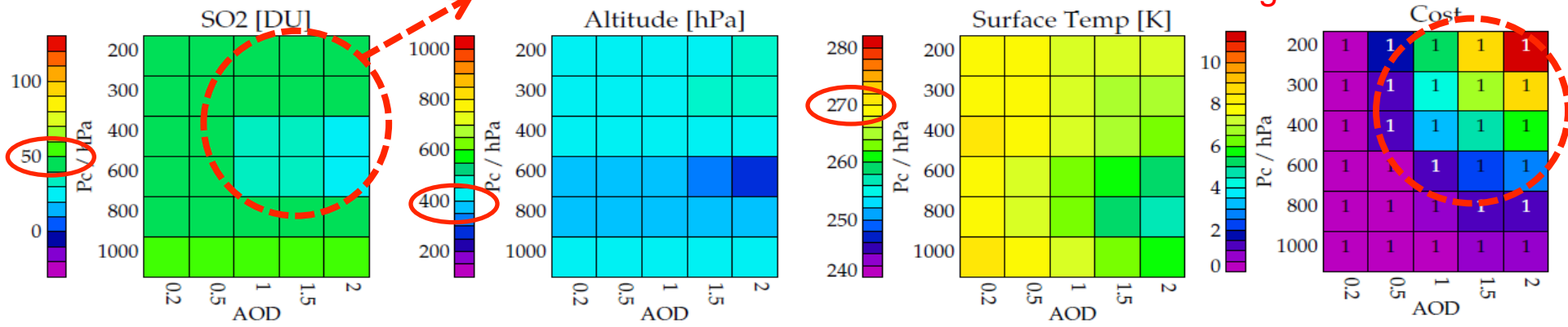
Retrieval using simulations with ash and water cloud at different optical depth and altitude

	DU	hPa	T [K]
Tru	50	400	
Ap	0.5	400	290
Ap err	100	1000	20

Type: ash, Re / microns = 2

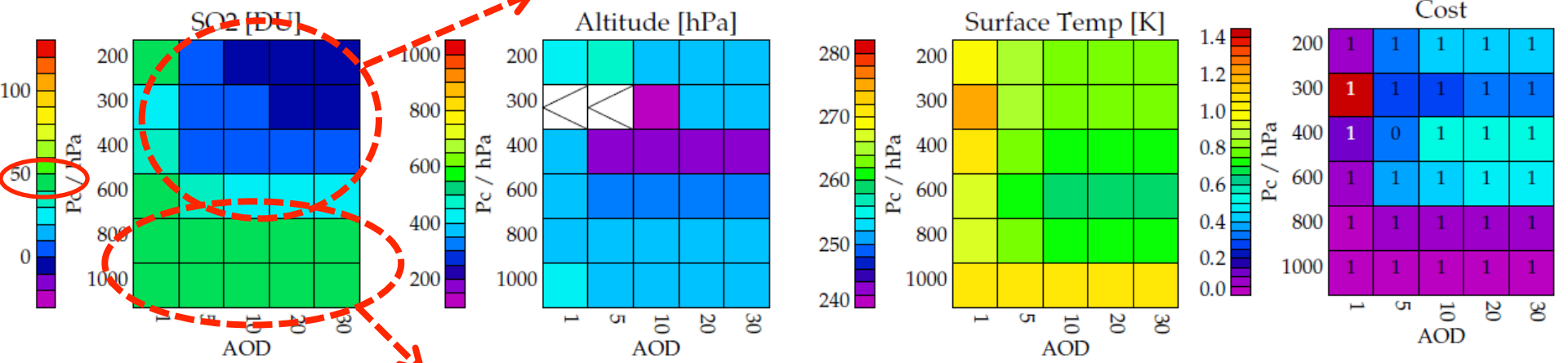
SO2 underestimate for thick ash

high cost !!



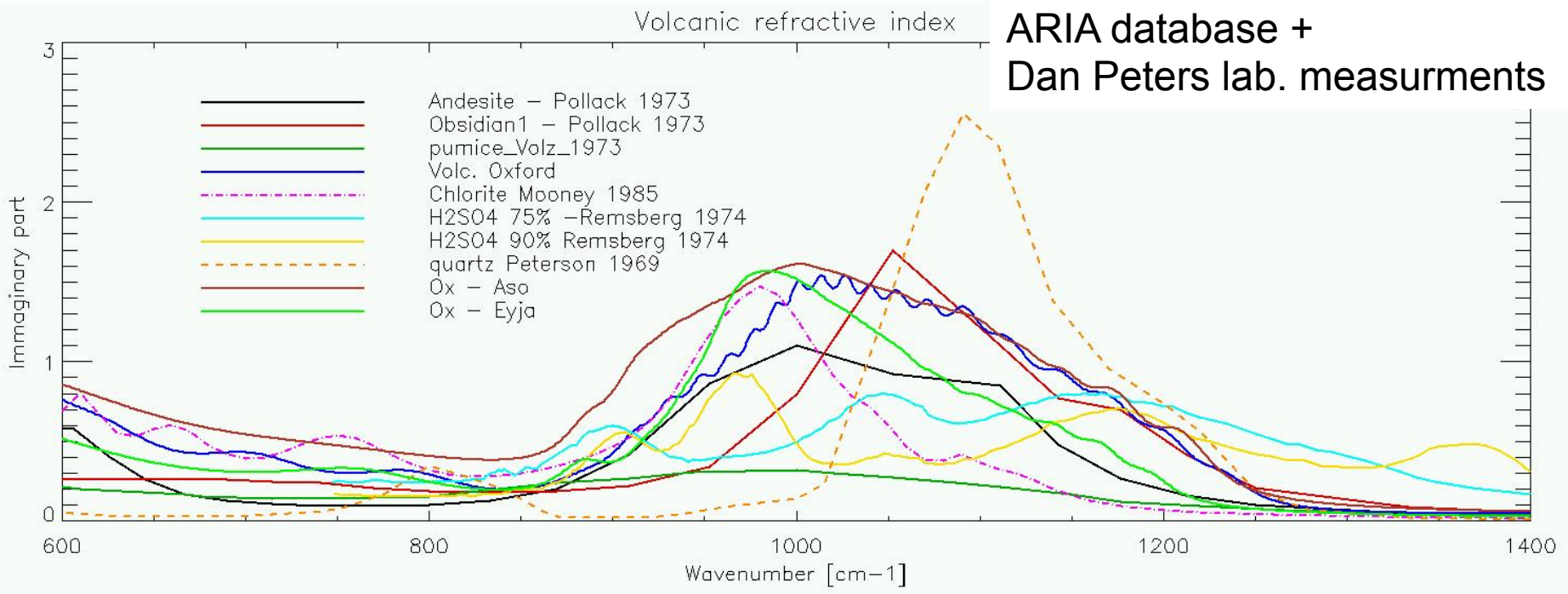
Type: wat, Re / microns = 15

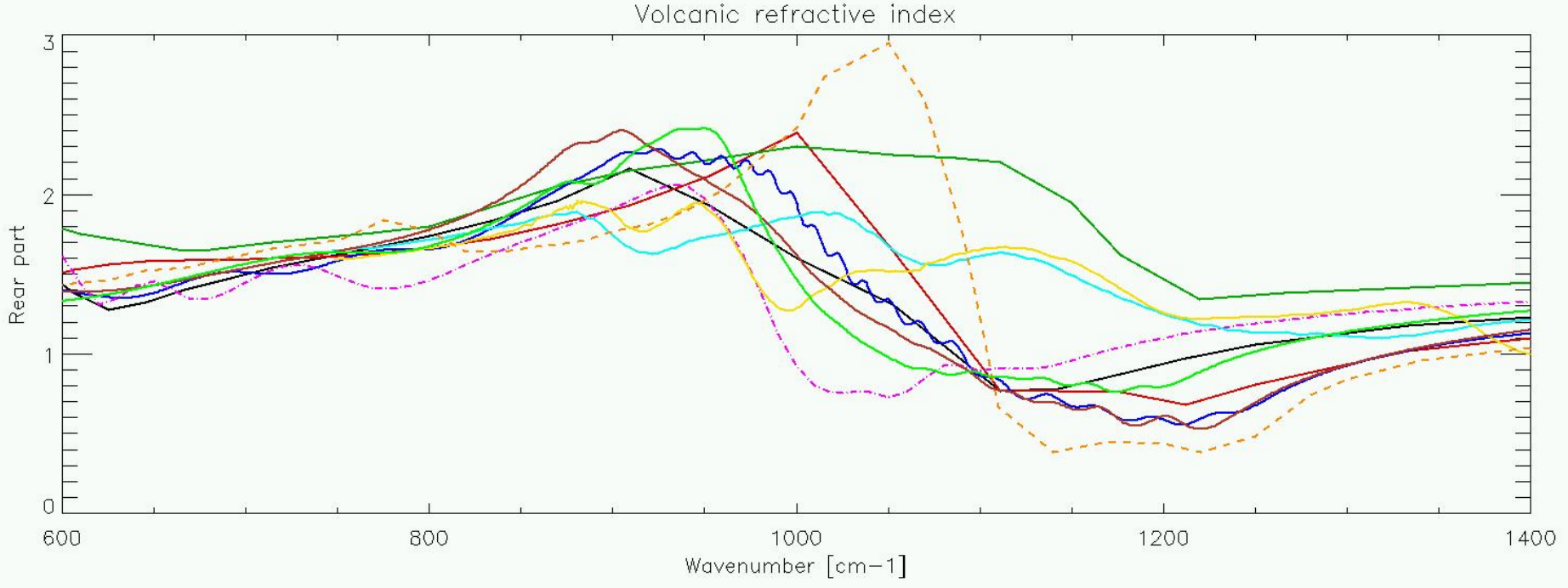
SO2 signal 'covered' from cloud within or above the plume



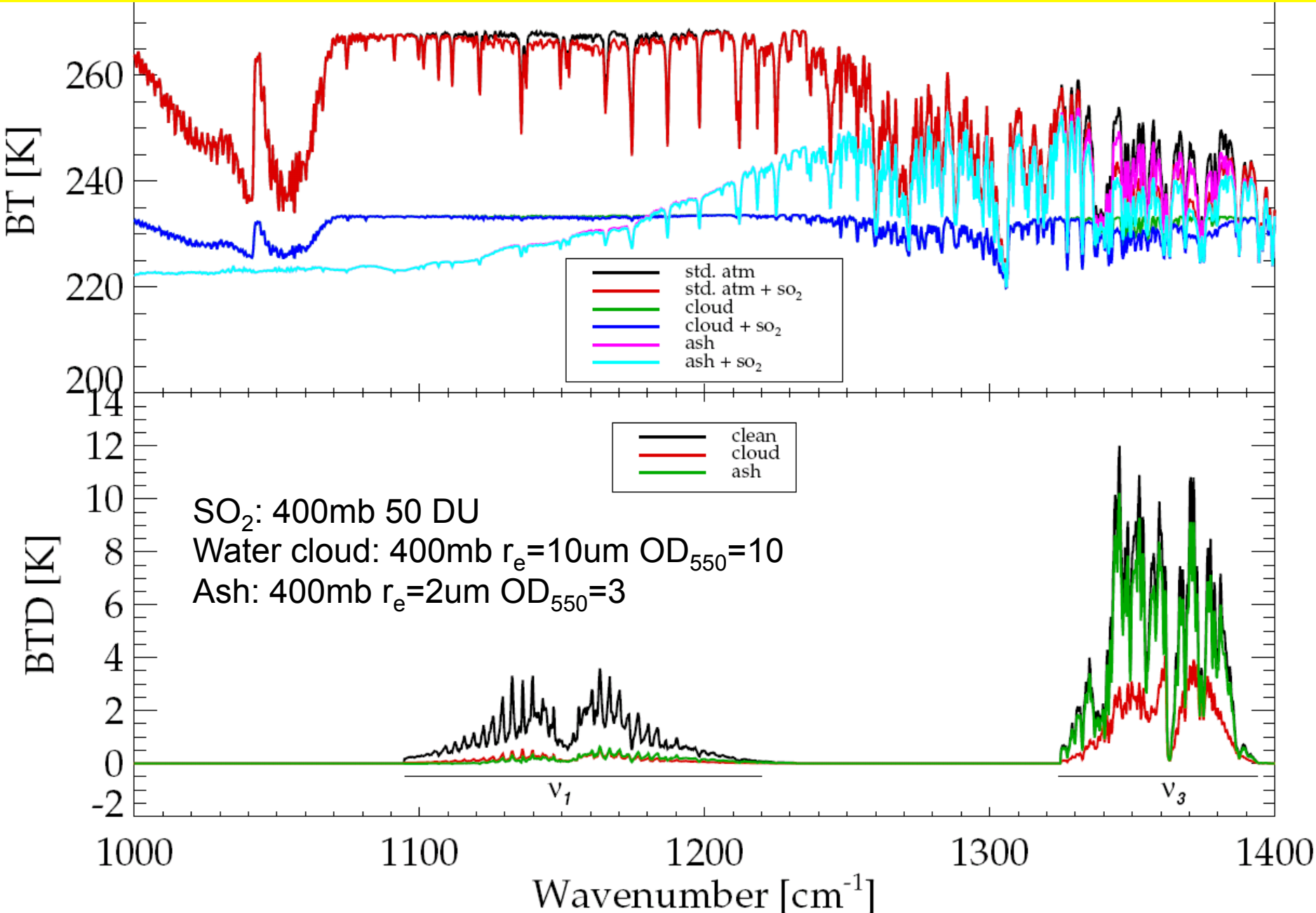
OK for cloud below the plume!!!

ARIA database +
Dan Peters lab. measurments





Ash and cloud effects?



Nabro - starts 12 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