Exploiting high-spectral resolution satellite data for studies of volcanic emissions: AIRS and IASI retrievals of SO2 and fine ash particles

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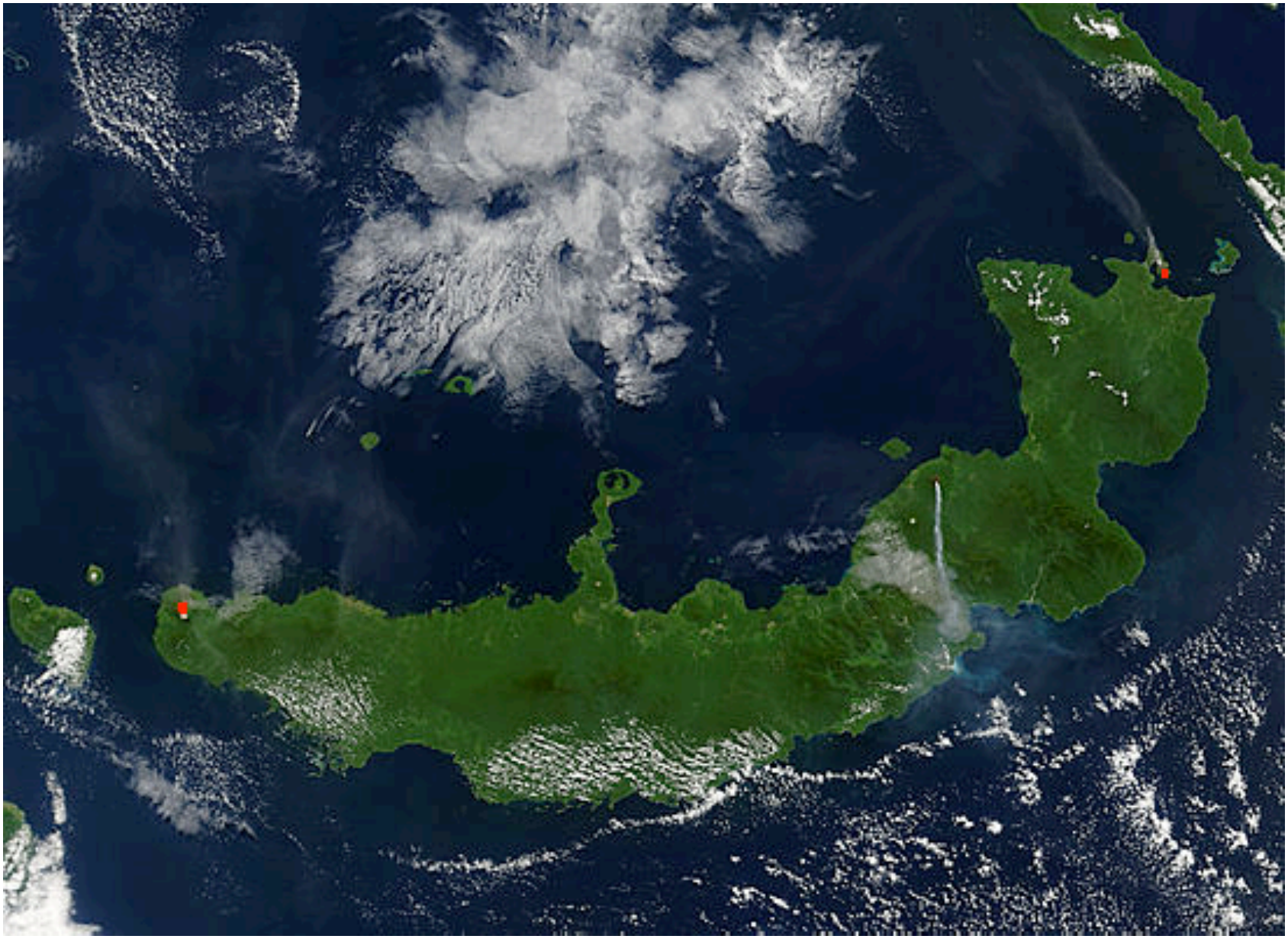
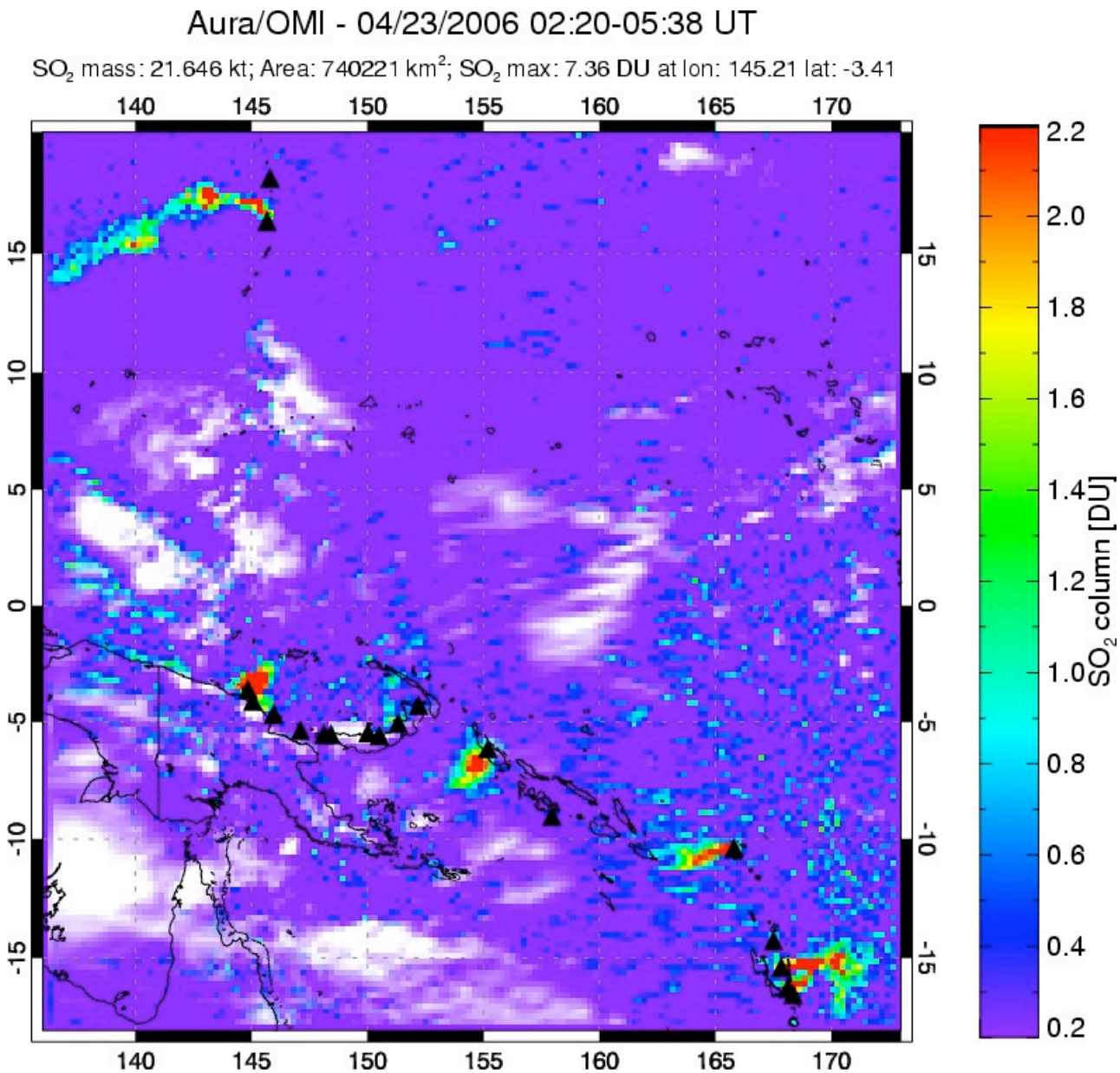
Air Niugini




Aura/OMI - 04/23/2006 02:20-05:38 UT
SO2 mass: 21.646 kt; Area: 740221 km2; SO2 max: 7.36 DU at lon: 145.21 lat: -3.41
140
145
150
155
160
165
170
15
10
5
0
-5
-10
-15
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
SO2 column [DU]

Frequency of Eruptions

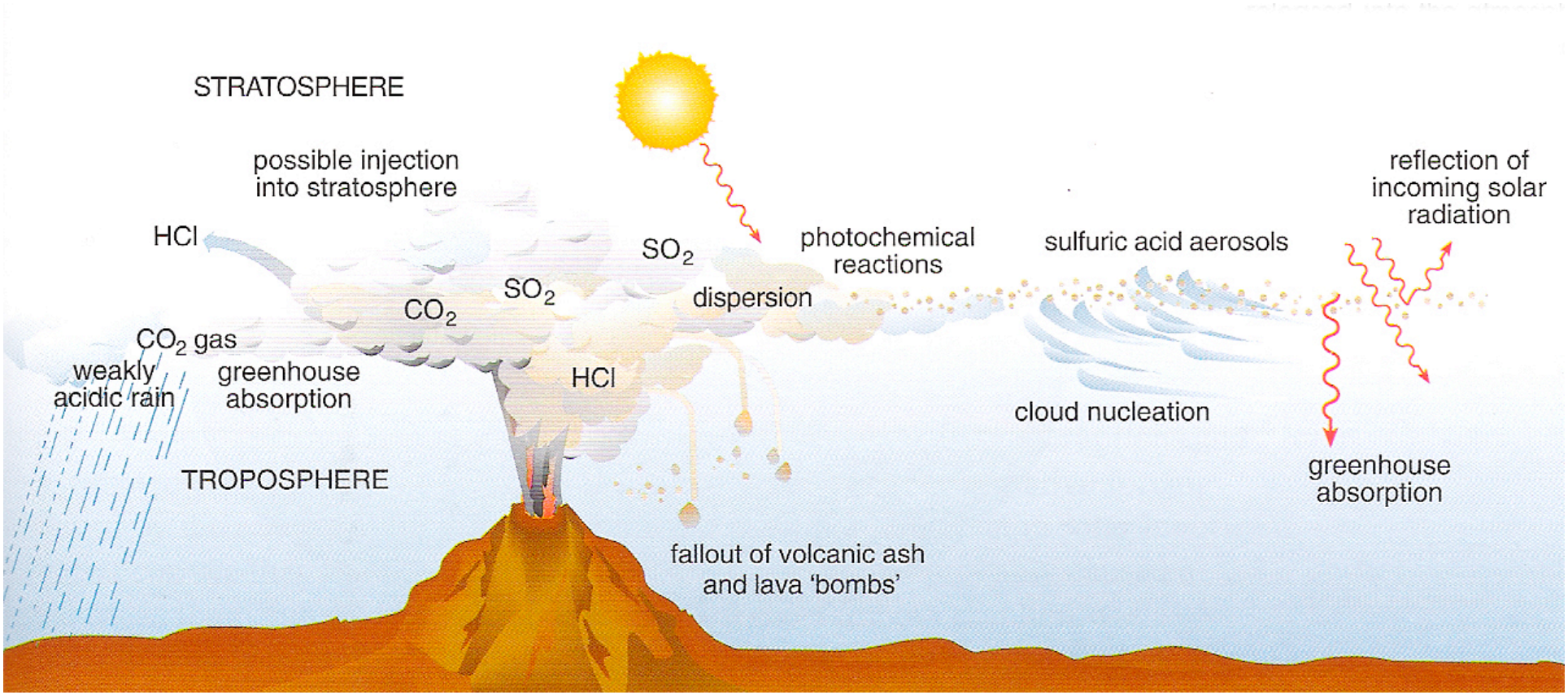
Mt St Helens (5) 1 in 10 years

Krakatau (6) 1 in 100 years

Tambora (7) 1 in 1000 years

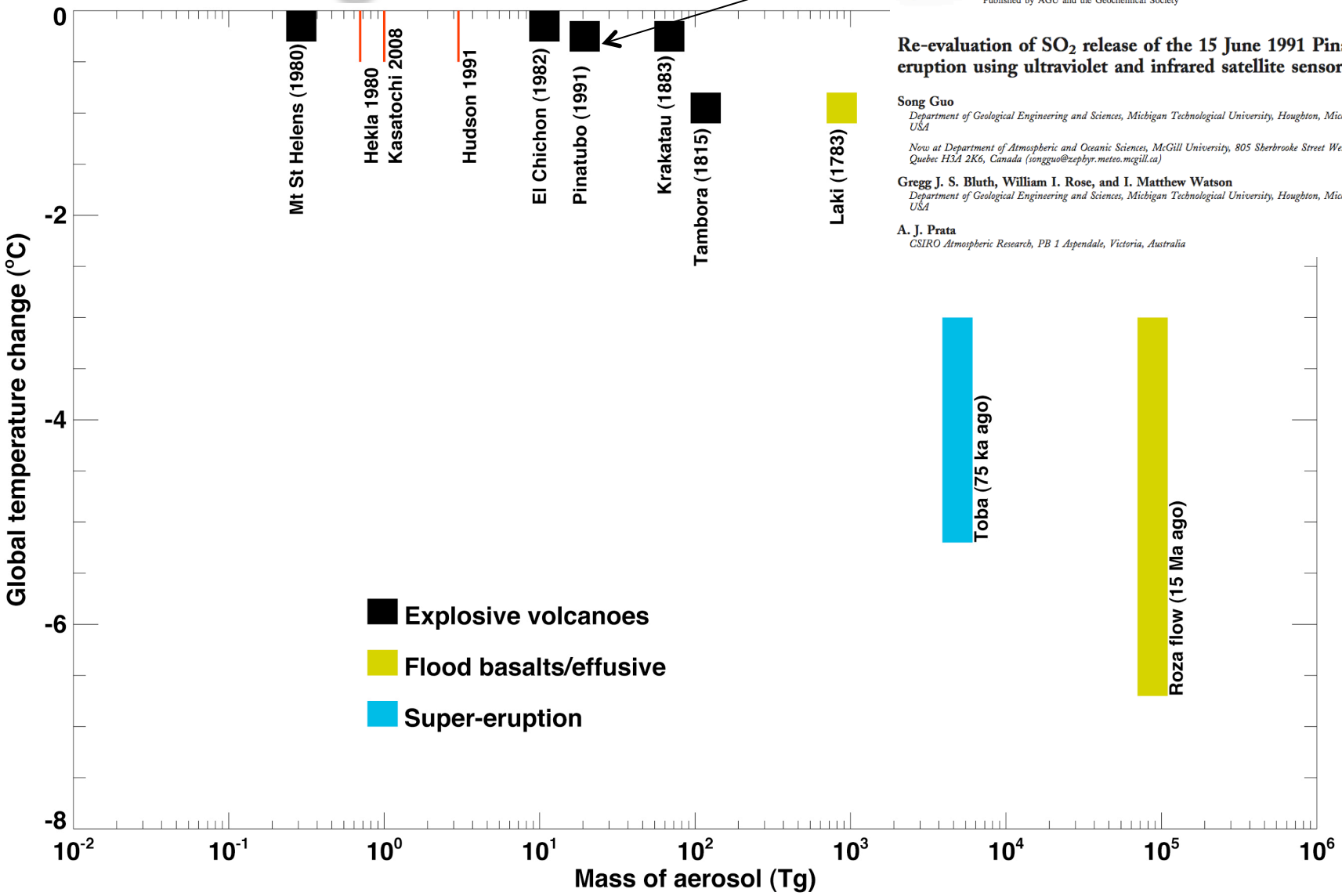
VEI ~ 2 1 every 2 weeks
VEI > 7 (~100,000 years - Toba)

Volcanoes and Climate



Cooling Effects

~18 Tg



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Article
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ISSN: 1525-2027

Re-evaluation of SO_2 release of the 15 June 1991 Pinatubo eruption using ultraviolet and infrared satellite sensors

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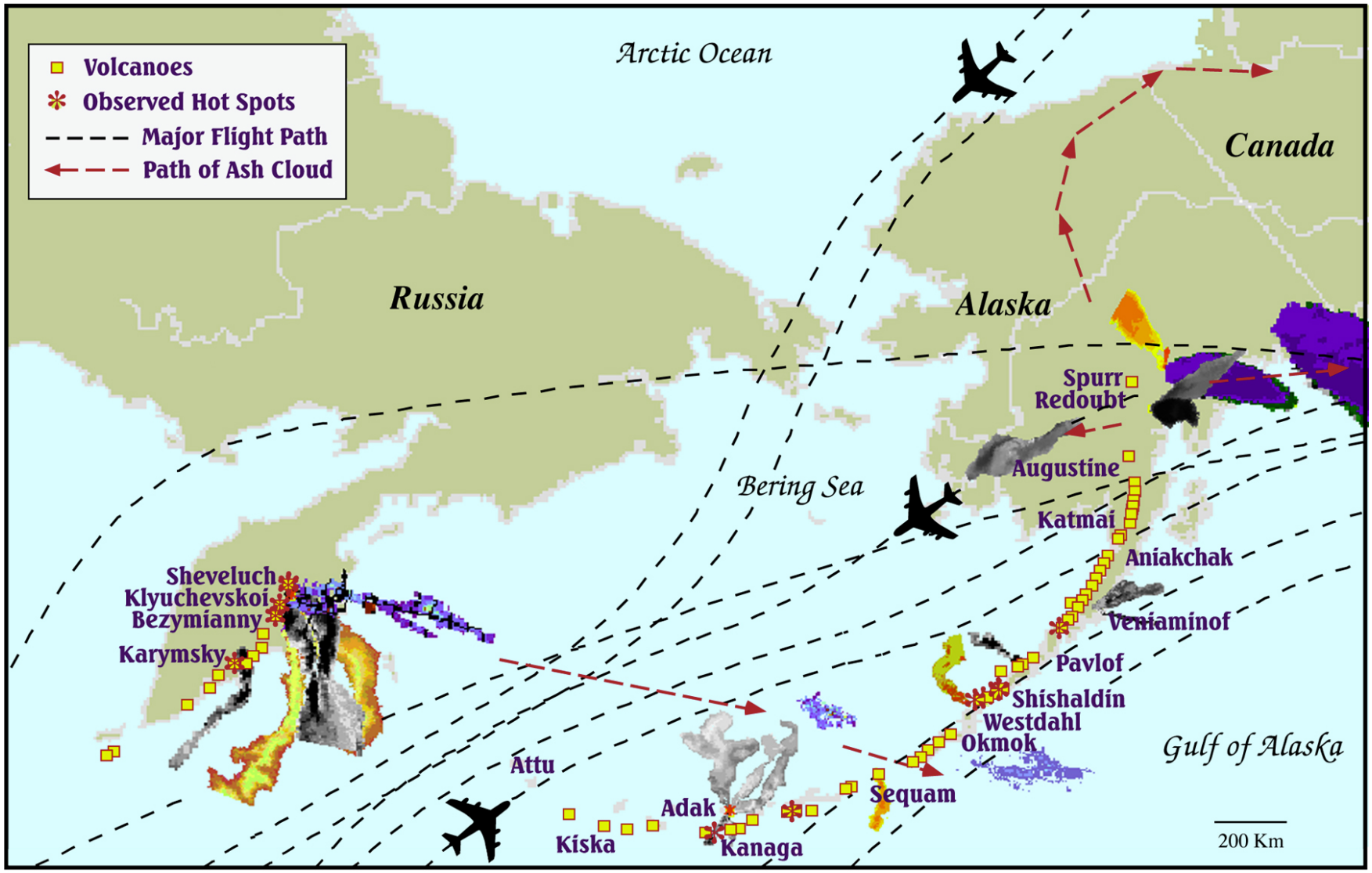
Aviation Hazards

- Plugged cooling holes
- Erosion of edges
- Ash build-up

Eruptions Affecting North Pacific Air Routes During the 1990's



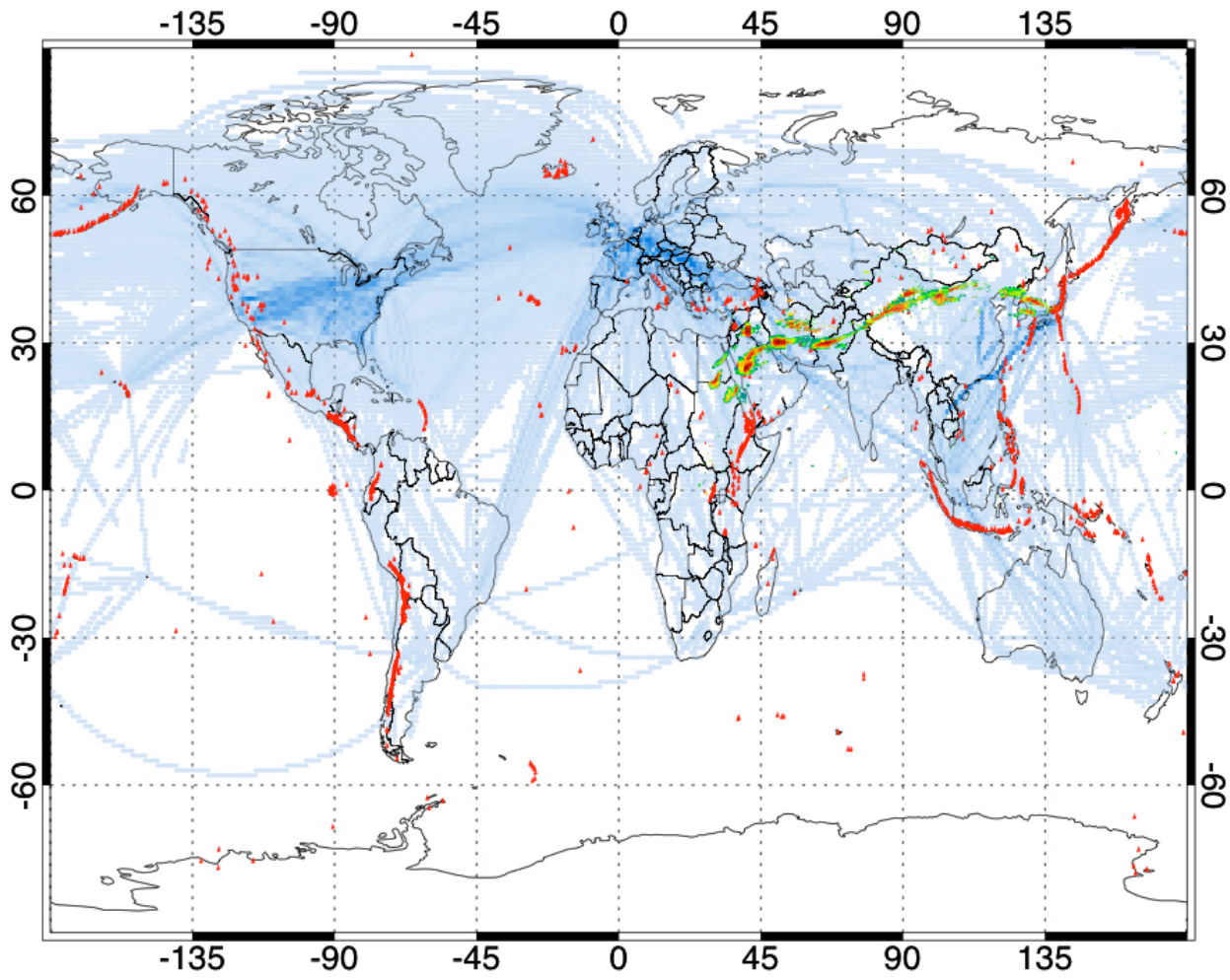
Growth in aviation traffic

Region	Annual average growth rate of passengers (percentage) 2001-2005	
Europe	2.3	4.5
Africa	3.3	5.0
Middle East	6.4	4.0
Asia and Pacific	4.1	7.5
North America	1.8	5.0
Latin America and Caribbean	2.9	4.5
World	2.7	6.0

Freight & mail
(% change in ton-km)

Source: International Civil Aviation Organisation

Global aviation threat



SO_2 measurements from satellites

INSTRUMENT	From
• TOMS	1979
• TOVS	1979
• MLS	1991
• MODIS	1999
• ASTER	1999
• *ACE*	*2003*
• *TES*	*2004*
• SCIAMACHY/GOME	1998
• AIRS	2002
• OMI	2004
• SEVIRI	2005
• IASI	2005

Measuring SO_2 from satellites

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, D20204, doi:10.1029/2006JD007955, 2007

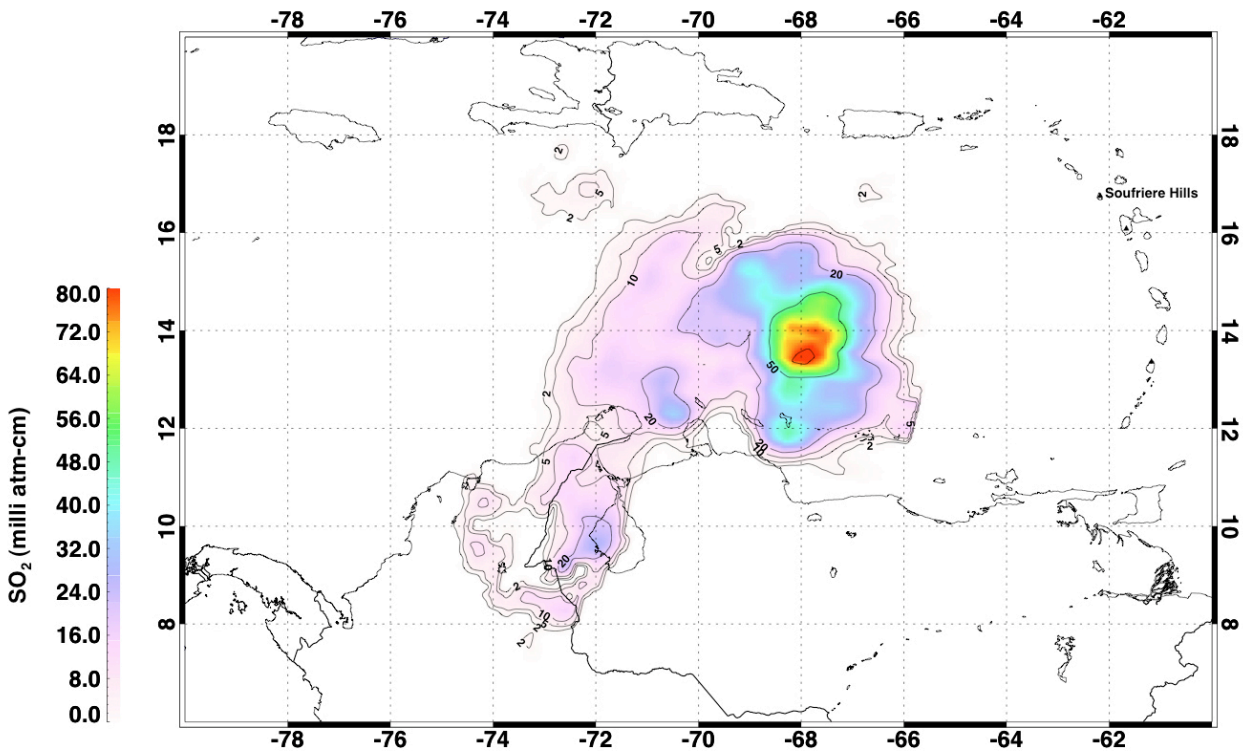
Click Here for Full Article

Retrieval of volcanic SO_2 column abundance from Atmospheric Infrared Sounder data

A. J. Prata[1] and C. Bernardo[2]

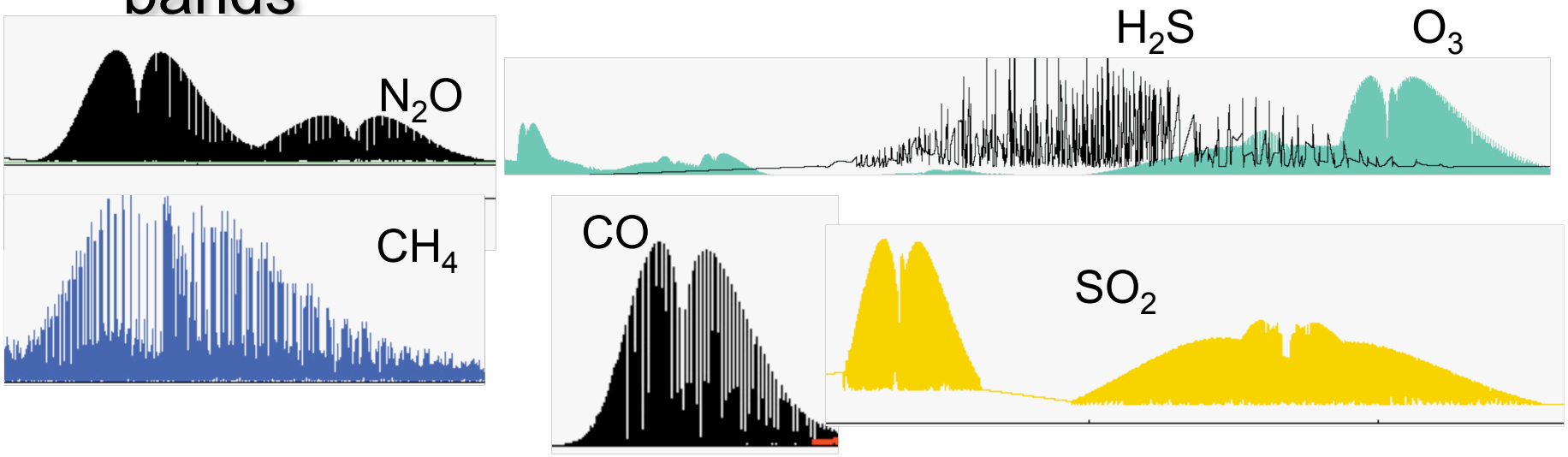
Received 23 August 2006; revised 25 June 2007; accepted 16 July 2007; published 19 October 2007.

[1]Norwegian Institute for Air Research, Kjeller, Norw
[2]Auspace Ltd., Mitchell, ACT, Australia.



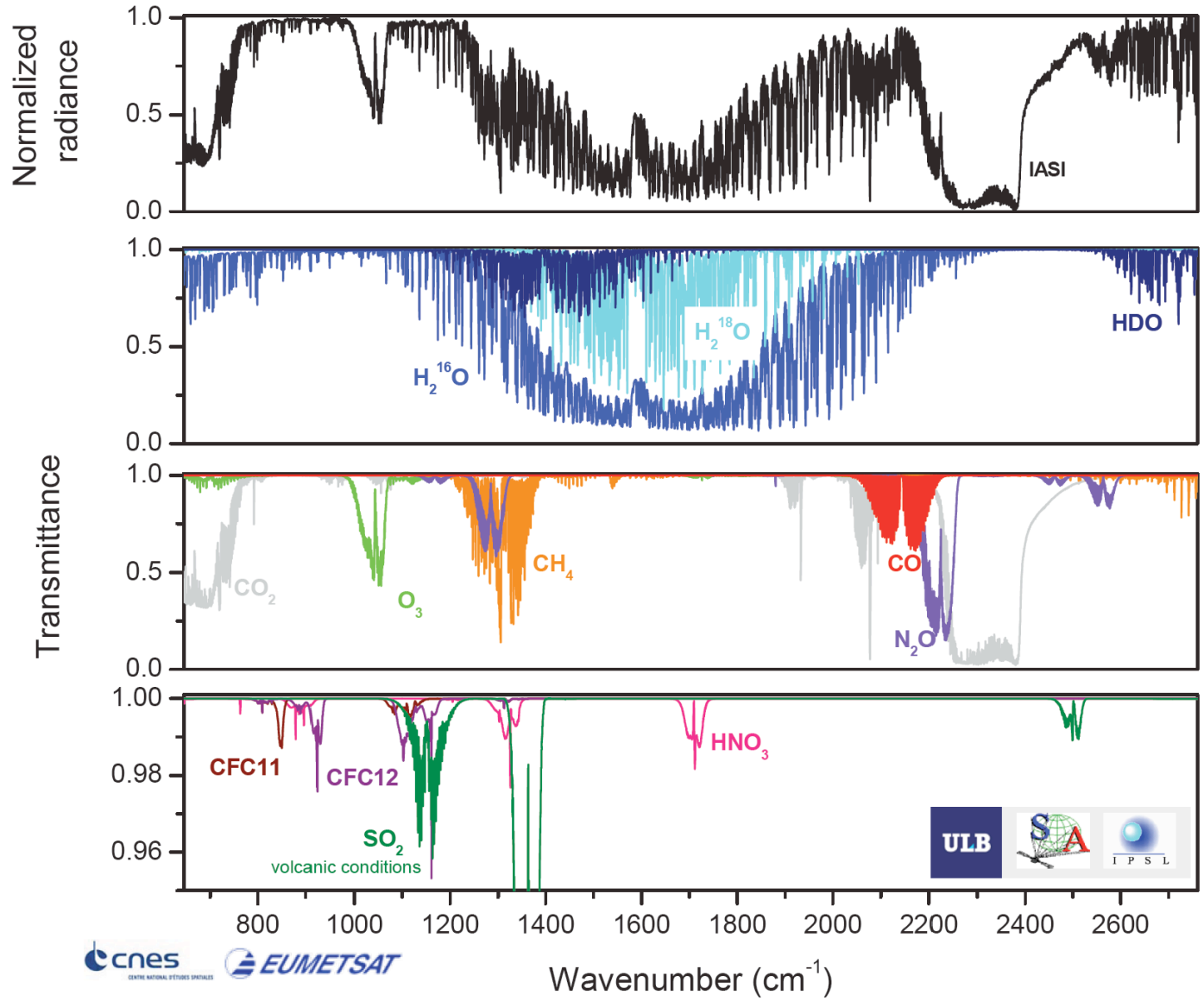
Spectral matching

- Many molecules have distinctive absorption bands



- Using theoretically-derived spectral shapes, molecules can be identified by comparing (or matching) the observed shape with theory.

Courtesy Pierre Coheur



Spectral matching (1)

Radiative transfer equation

$$I_\nu = I_{\nu,s} + \int_0^\infty B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_1(z), q_2(z) ... q_n(z)]}{\partial z} \right) dz,$$

Choose absorption region and split integral into 3 parts:

$$\begin{aligned} I_\nu \approx & \int_0^{z_1} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_2(z) ... q_n(z)]}{\partial z} \right) dz && \text{Below gas layer} \\ + & \int_{z_1}^{z_2} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_1(z), q_2(z) ... q_n(z)]}{\partial z} \right) dz && \text{In gas layer} \\ + & \int_{z_2}^{\infty} B_\nu[T(z)] \left(\frac{\partial \tau_\nu[z, q_2(z) ... q_n(z)]}{\partial z} \right) dz. && \text{Above gas layer} \end{aligned}$$

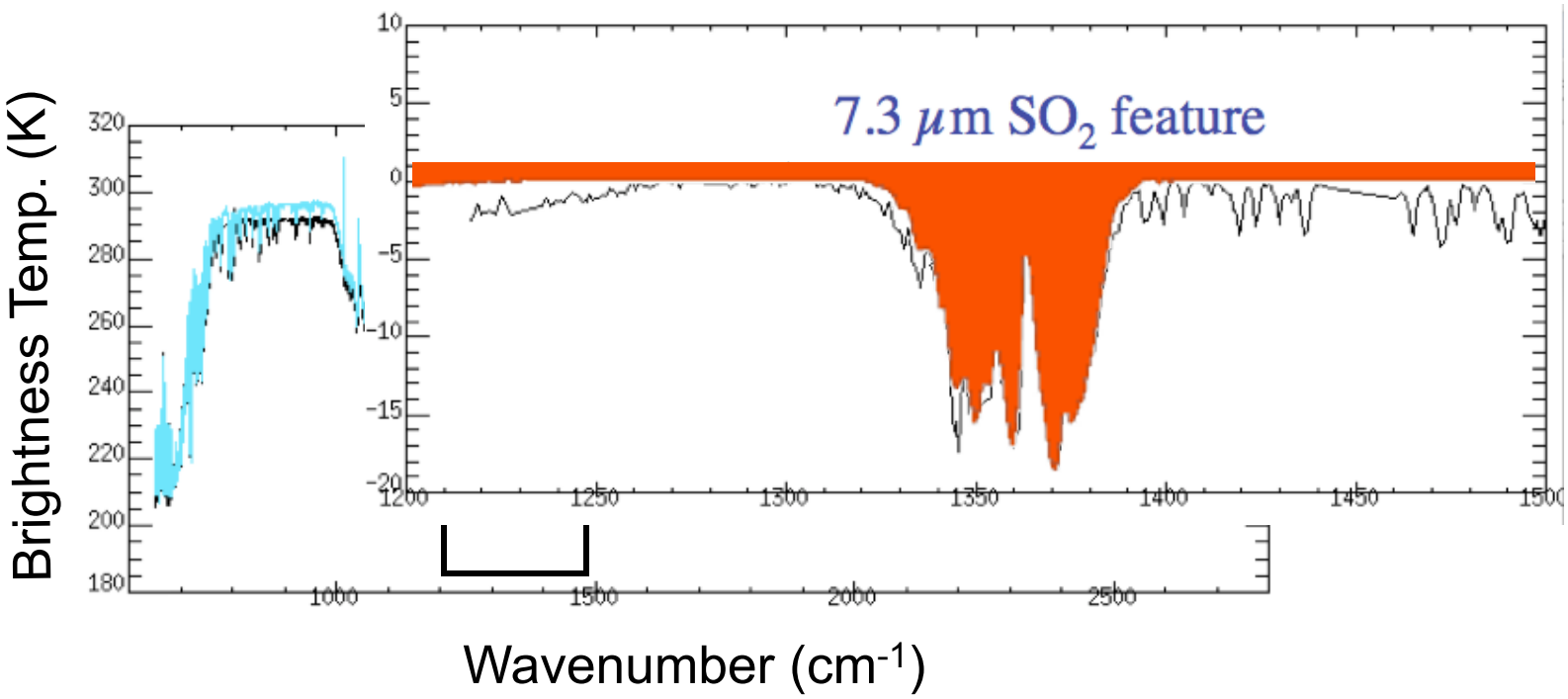
Spectral matching (2)

$$I'_\nu = I_{\nu,0} \exp\left\{-\int_o^\infty k_\nu(z)q(z)dz\right\}$$

Beer-Bougier-Lambert law

$$A_\nu = -\ln\left\{\frac{I'_\nu}{I_{o,\nu}}\right\} = \int_o^\infty k_\nu(z)q(z)dz.$$

Absorbance spectrum



Spectral matching (3)

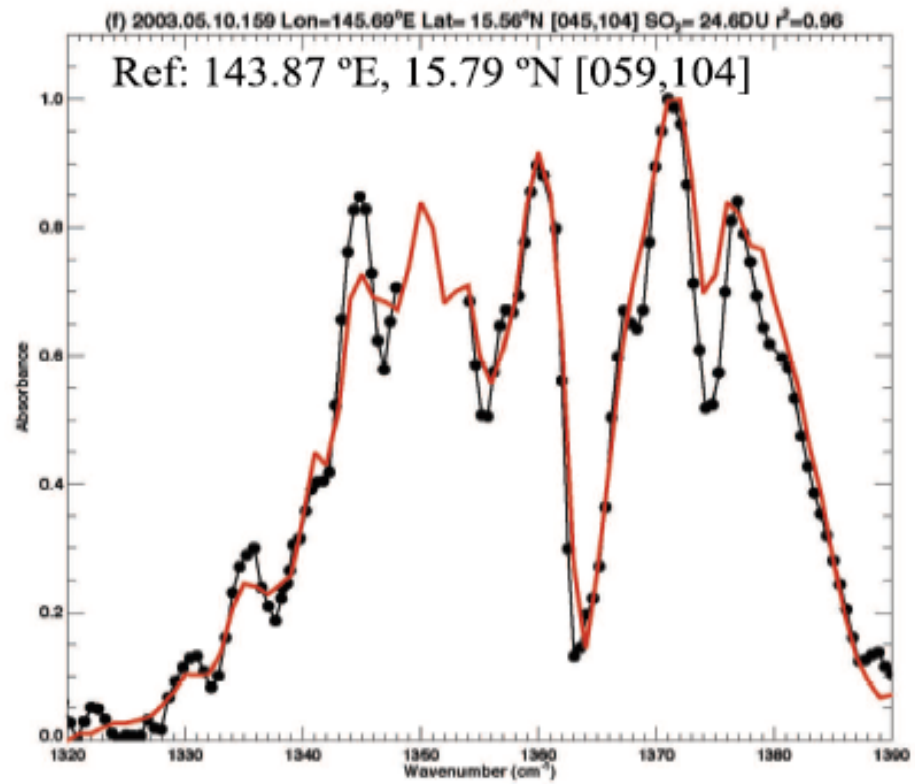
Problem: How do you find the “best” reference pixel?

Solution: Search all pixels for best spectral match

$$R = \frac{\frac{1}{n-1}\sum_{i=0}^{n-1} \tilde{A}_i \tilde{S}_i}{\sqrt{\frac{1}{n-1}\sum_{i=0}^{n-1} \tilde{A}_i^{\,2}}\sqrt{\frac{1}{n-1}\sum_{i=0}^{n-1} \tilde{S}_i^{\,2}}}.$$

$$\tilde{A}_i = \frac{A_i - \min(A_i)}{\max(A_i) - \min(A_i)},$$

$$\tilde{S}_i = \frac{S_i - \min(S_i)}{\max(S_i) - \min(S_i)}.$$



Retrieval

Single Lorentz line

$$A\Delta\nu = \int_{\Delta\nu} \left\{ 1 - \exp[-\frac{1}{\pi} \int_{z_1}^{z_2} \frac{\alpha q(z)}{(\nu - \nu_0)^2 + \alpha^2} dz] \right\} d\nu,$$

$$A\Delta\nu = 2\pi\alpha\psi[L_0(\psi) + L_1(\psi)] \exp\{-\psi\},$$

$$\psi = \frac{Su}{2\pi\alpha},$$

For a band with temperature dependent line strengths and line broadening, an “off-line” radiative transfer model is needed

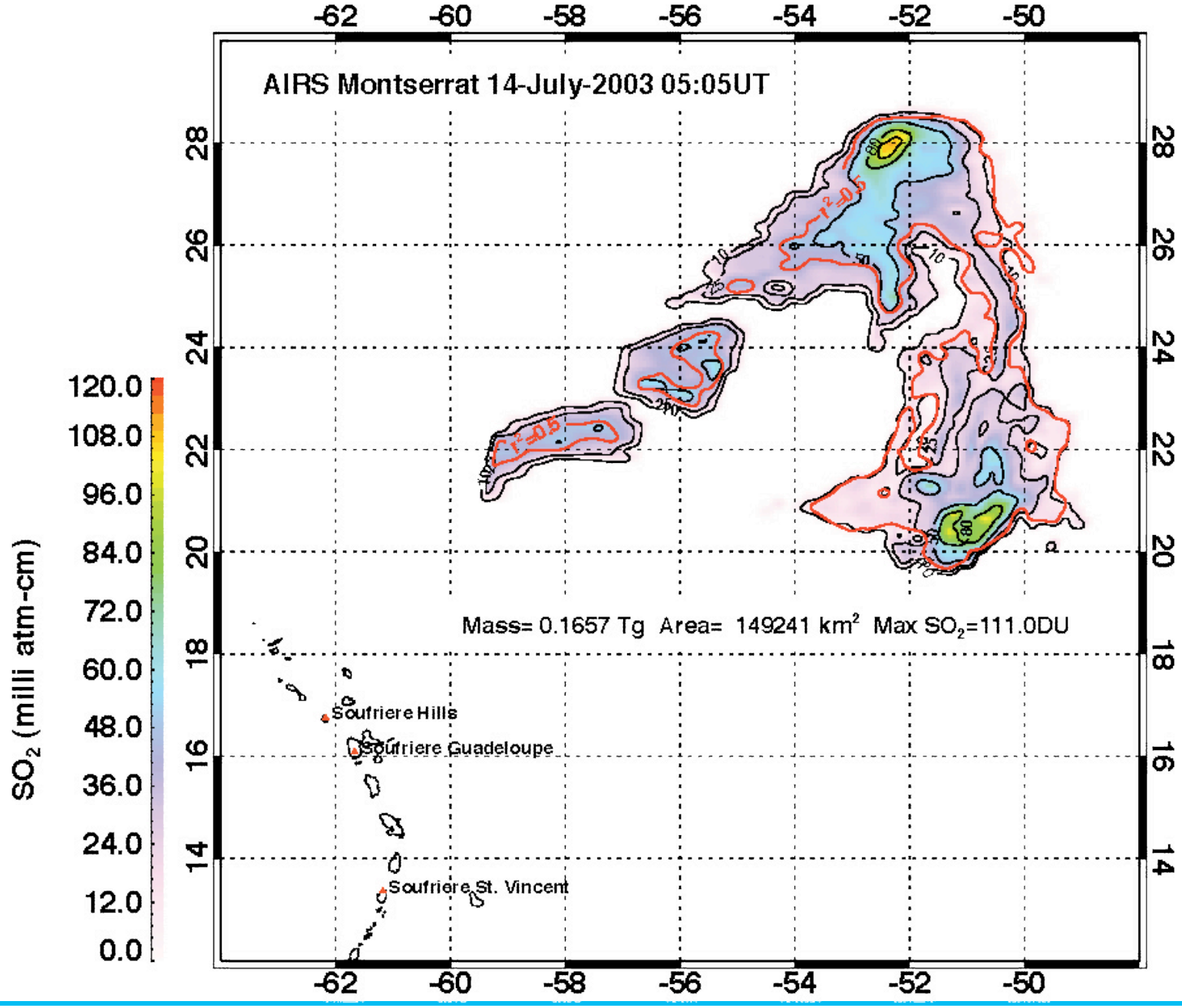
$$\vec{x} = (\mathrm{K}^T\mathrm{K})^{-1}\mathrm{K}^T\vec{y}.$$

Least squares solution

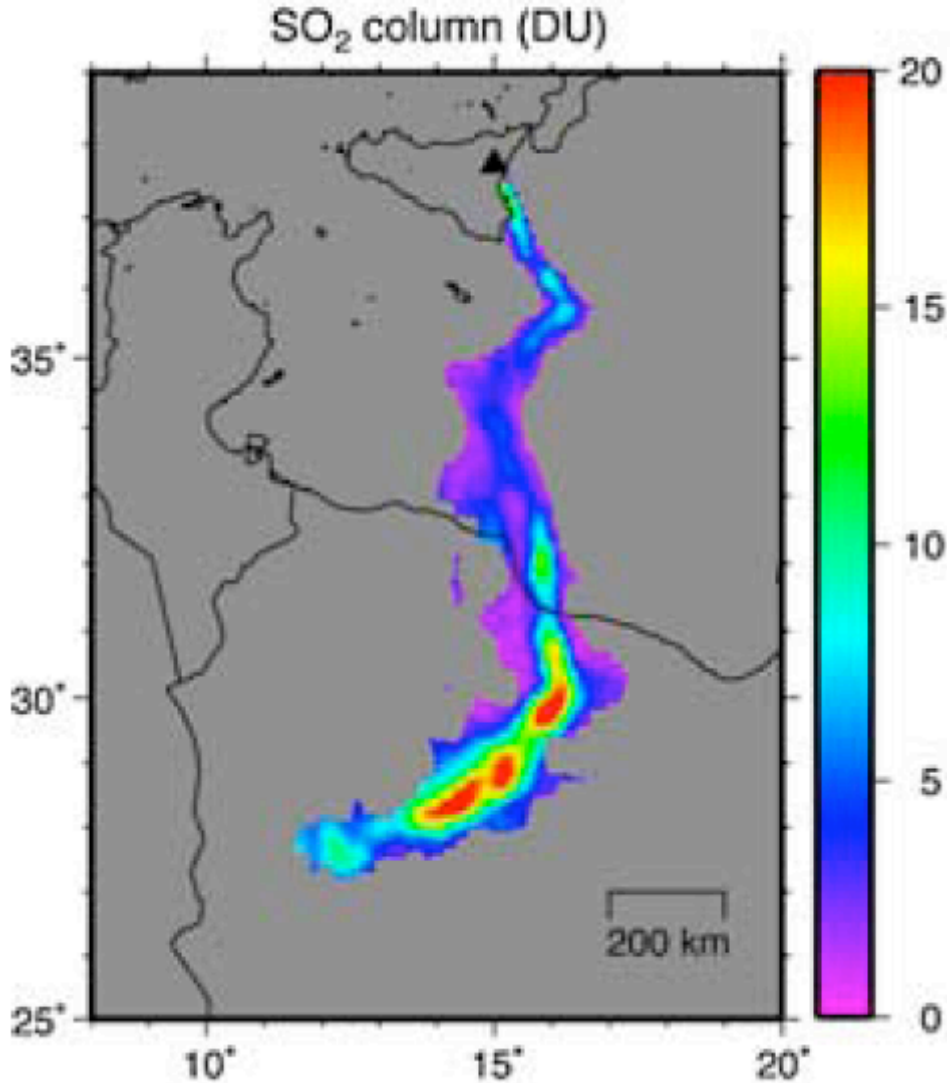
$\vec{x}$: layer absorber amounts (N layers)

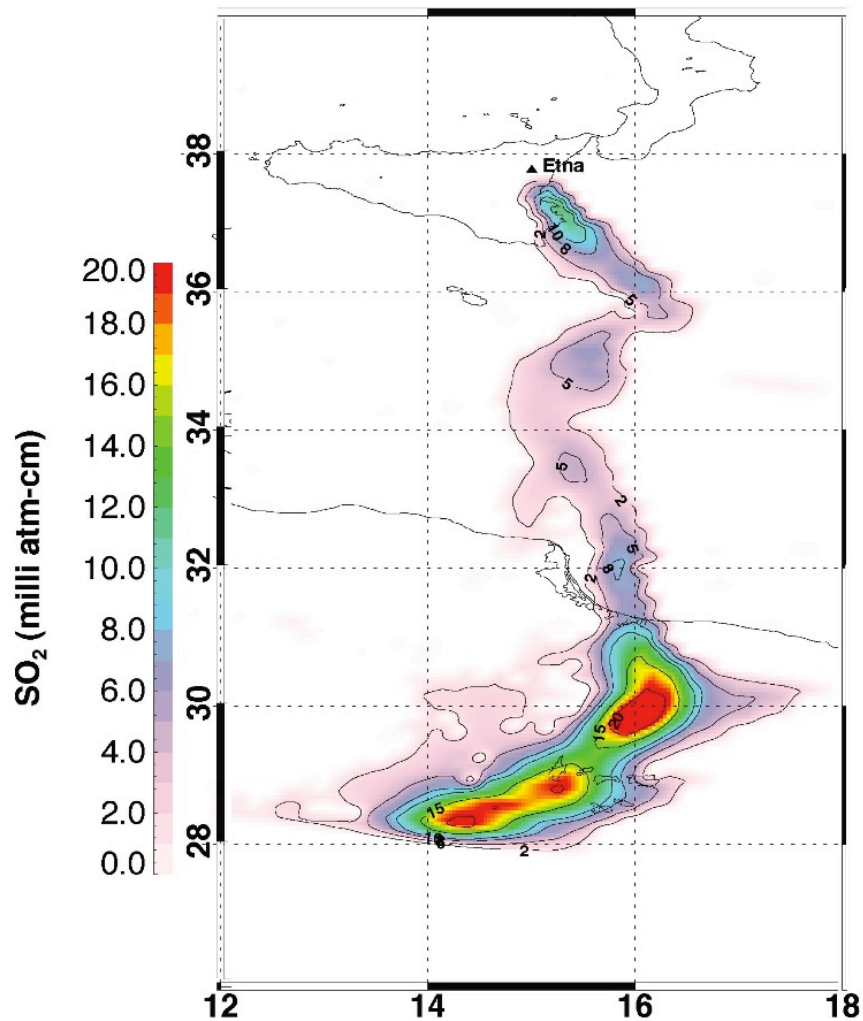
$\vec{y}$: observed absorbances (M wavenumbers)

K: is an MxN matrix of absorption cross sections


AIRS Montserrat 14-July-2003 05:05UT
Mass= 0.1657 Tg Area= 149241 km² Max SO₂=111.0DU
Soufriere Hills
Soufriere Guadeloupe
Soufriere St. Vincent
SO₂ (milli atm-cm)
120.0
108.0
96.0
84.0
72.0
60.0
48.0
36.0
24.0
12.0
0.0
-62
-60
-58
-56
-54
-52
-50
28
26
24
22
20
18
16
14

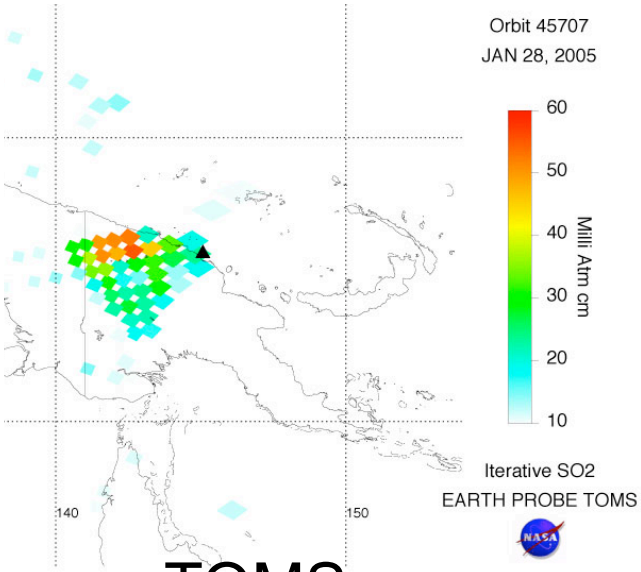
Validation



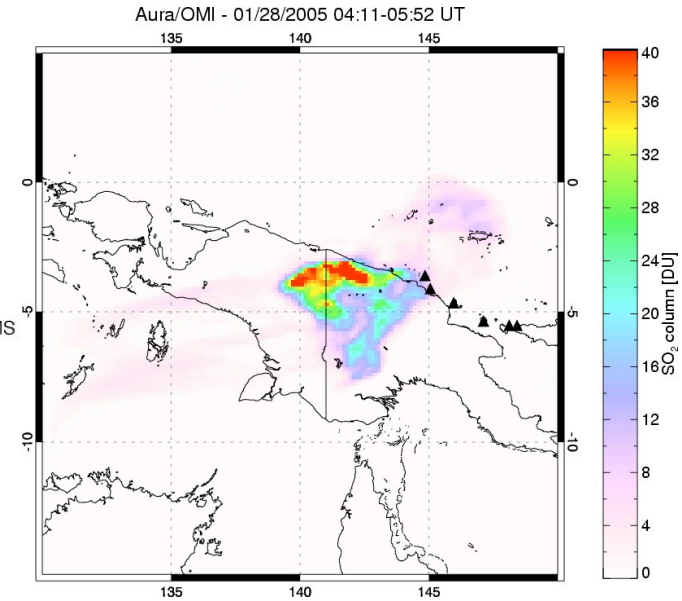


Carn et al., GRL, 32, L02301, doi:10.1029/2004GL021034, 2005

Manam Eruption Jan 28 2005

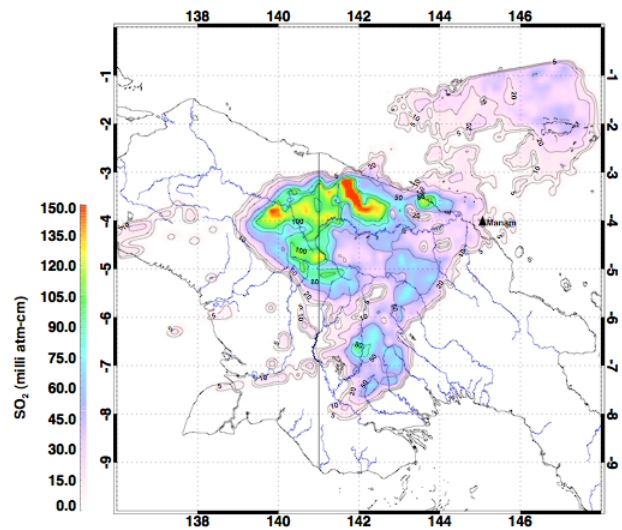


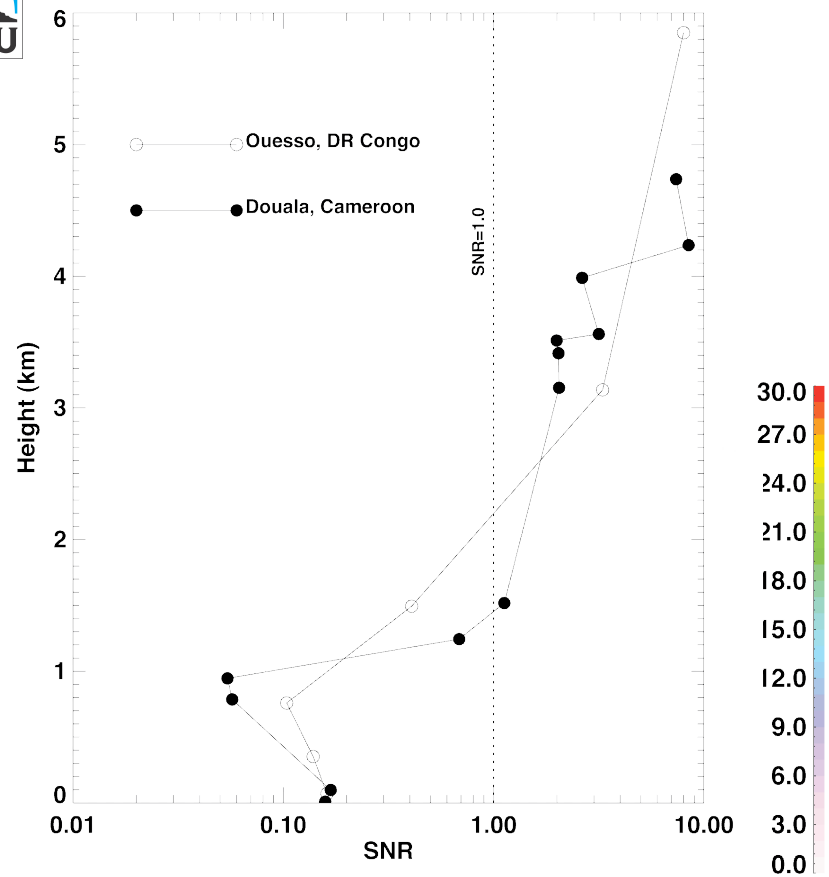
TOMS



OMI

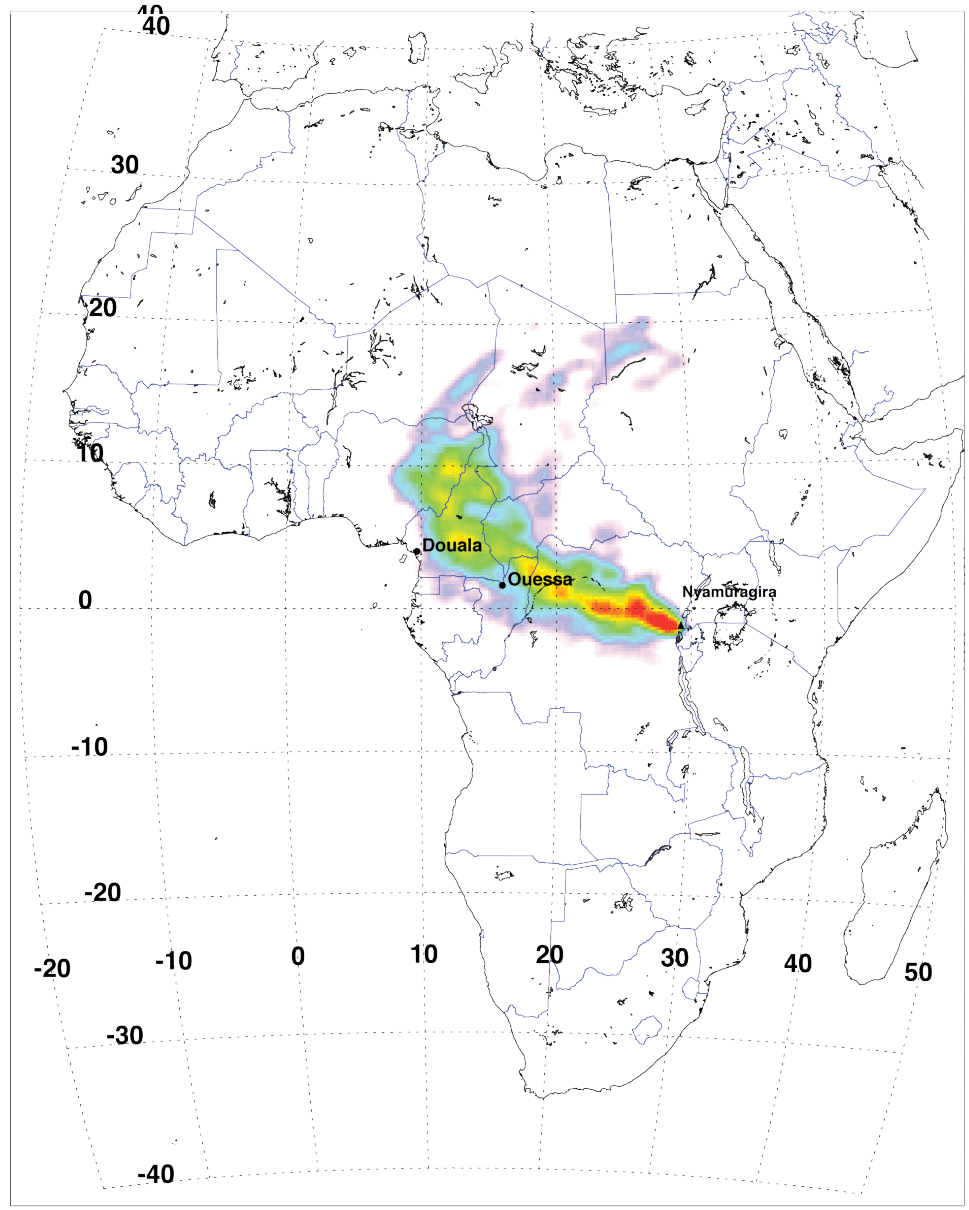
AIRS

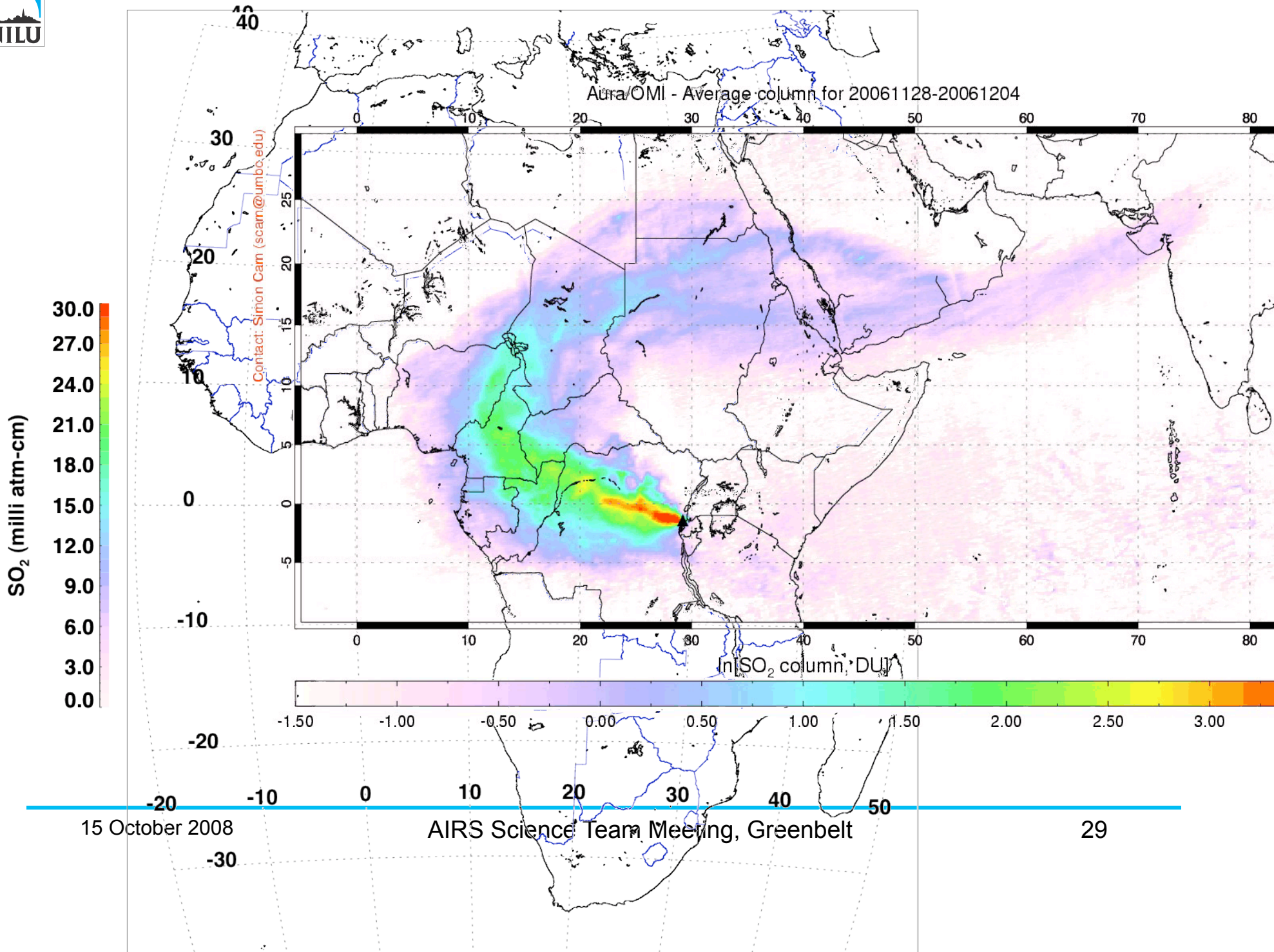


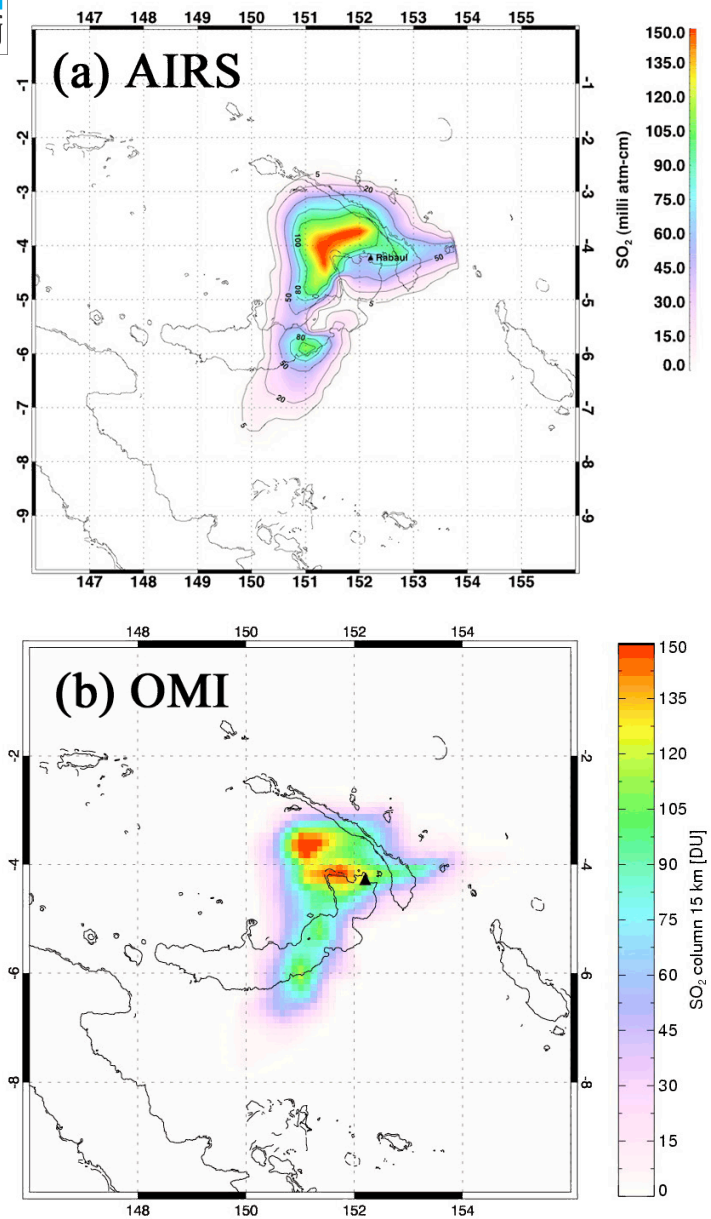


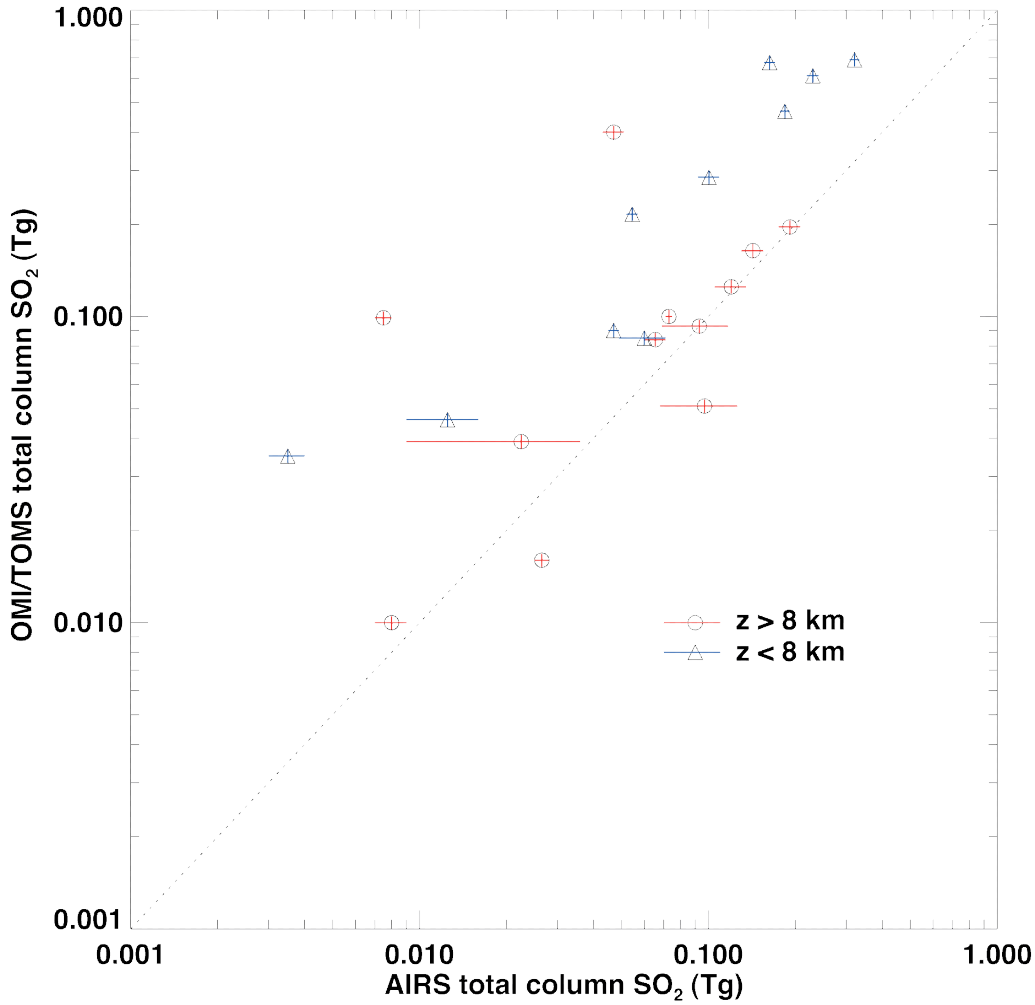
$$SNR = \frac{\sqrt{\frac{1}{\Delta\nu}\int_{\Delta\nu} \Delta S_\nu^2 d\nu}}{NE\Delta I}.$$

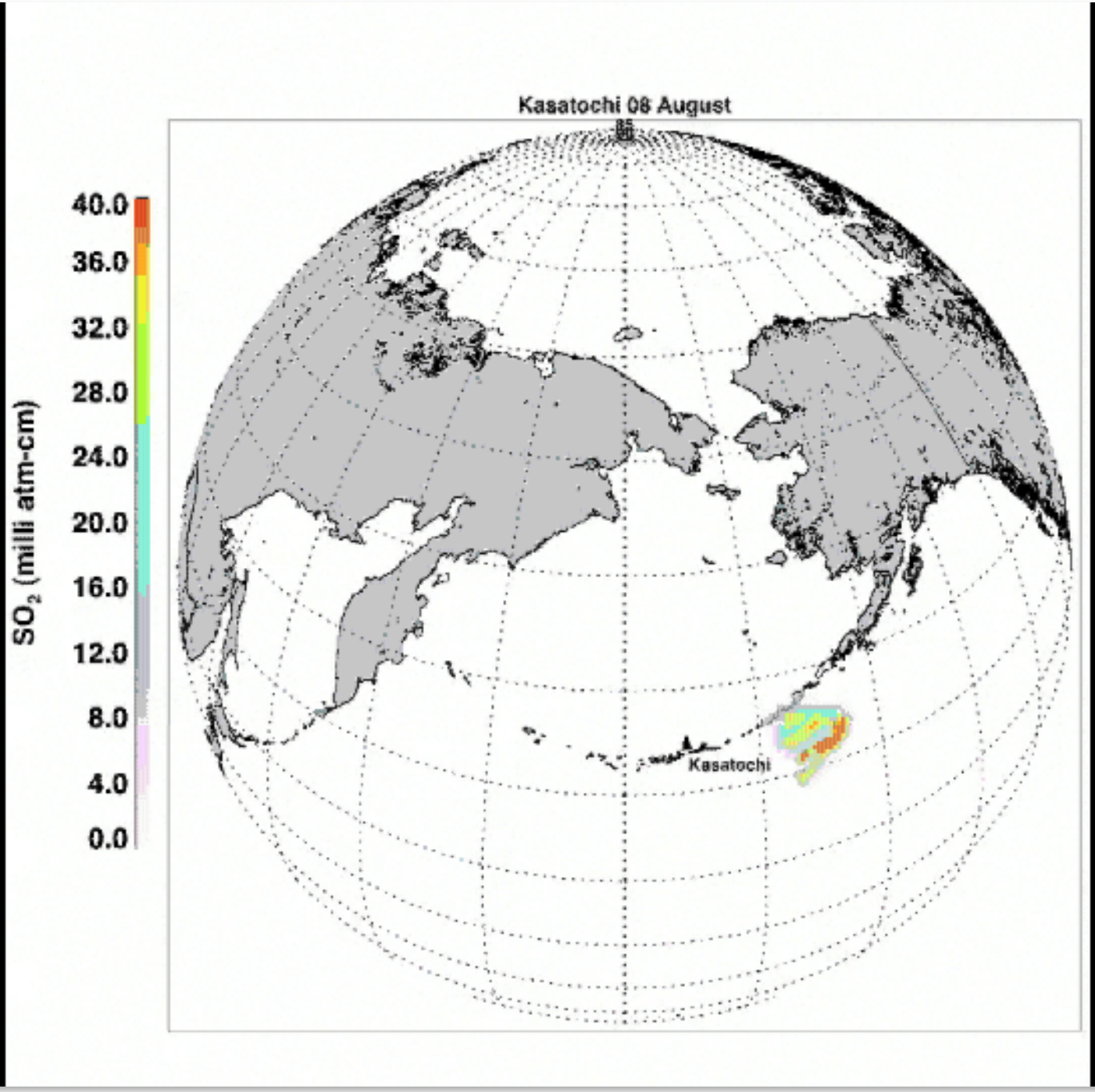
$$\Delta S_\nu = |I_{\nu,z'} - I_{\nu,0}|,$$



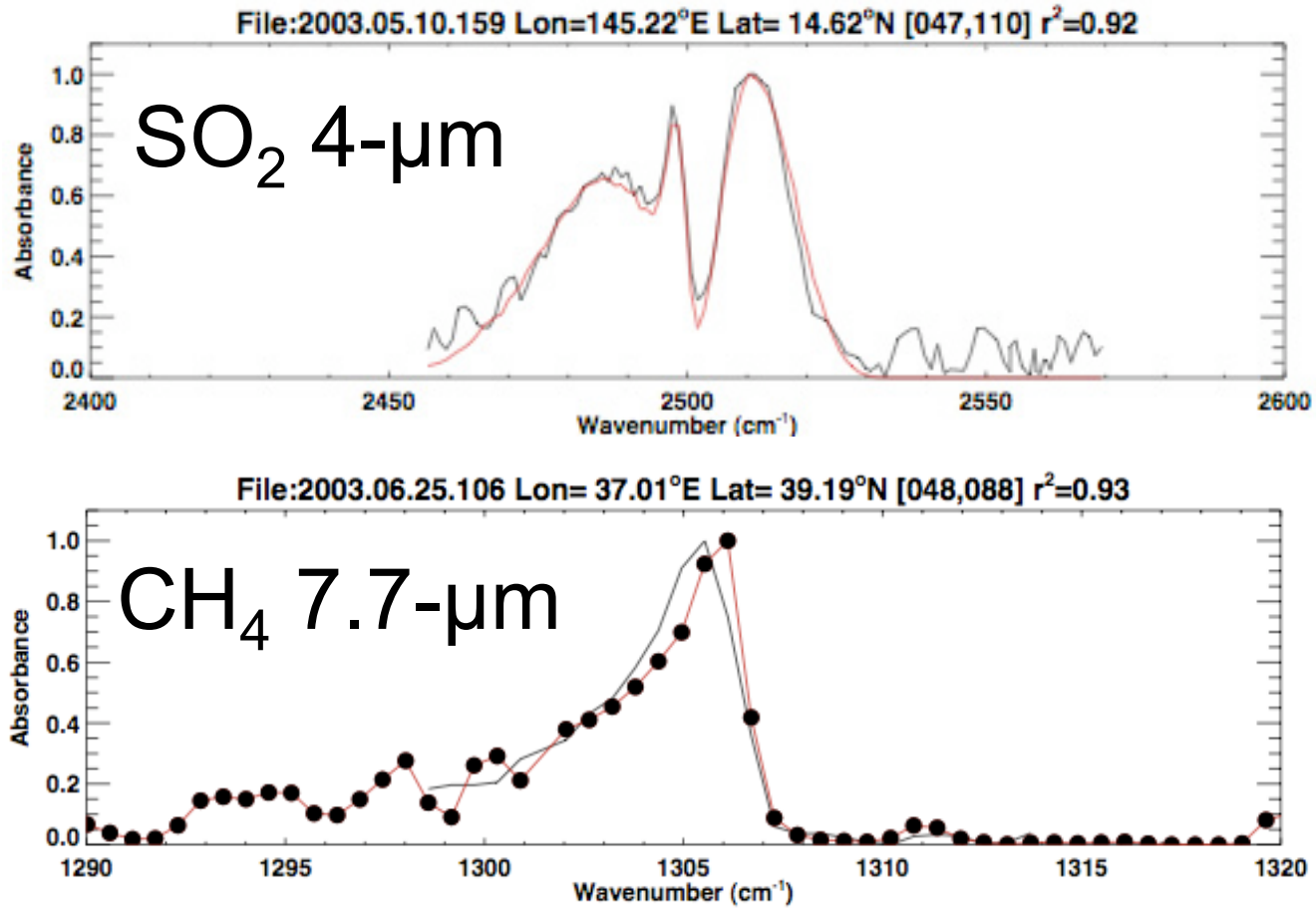

Aura/OMI - Average column for 20061128-20061204
Contact: Simon Carn (scarn@umbc.edu)
SO_2 (milli atm-cm)
30.0
27.0
24.0
21.0
18.0
15.0
12.0
9.0
6.0
3.0
0.0
ln[SO_2 column, DU]
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
3.00


(a) AIRS
Rabaul
SO2 (milli atm-cm)
(b) OMI
SO2 column 15 km [DU]


OMI/TOMS total column SO2 (Tg)
AIRS total column SO2 (Tg)
z > 8 km
z < 8 km

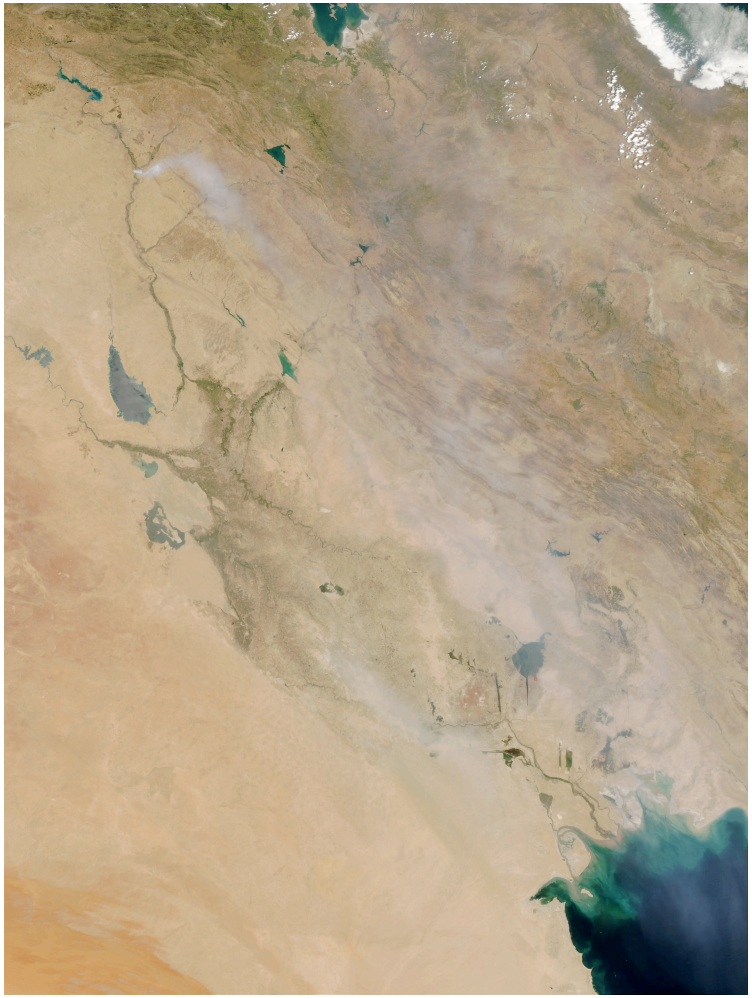

Kasatochi 08 August
SO_2 (milli atm-cm)
40.0
36.0
32.0
28.0
24.0
20.0
16.0
12.0
8.0
4.0
0.0
Kasatochi

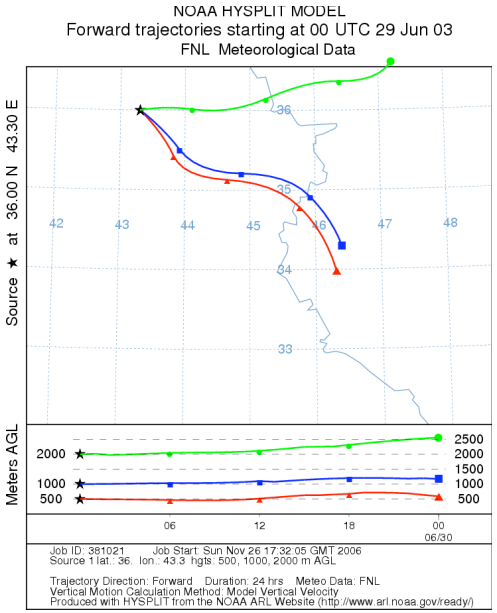
Other spectral regions

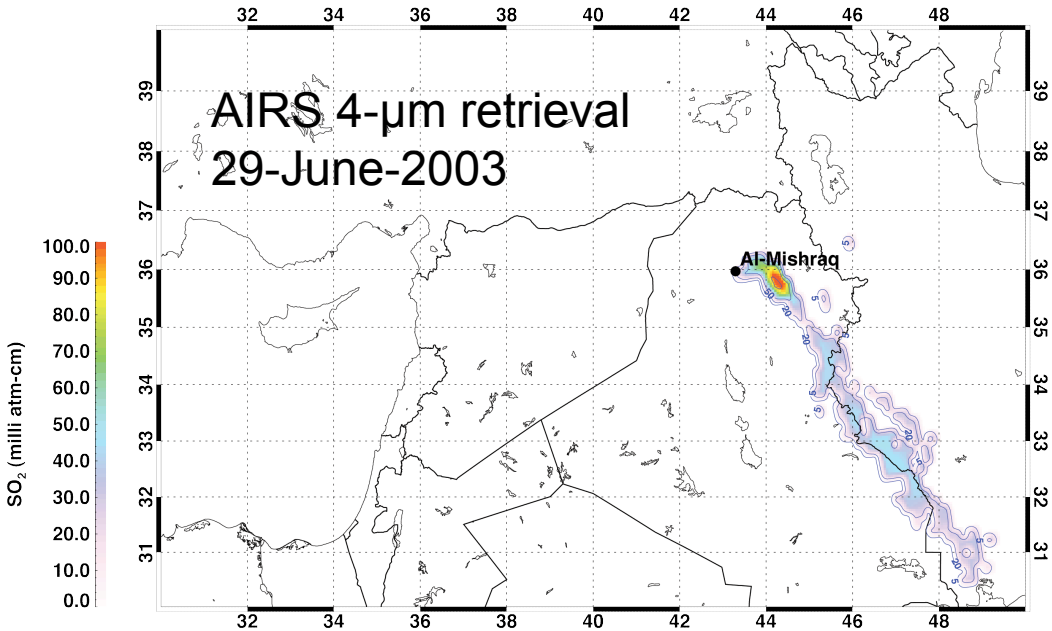


H_2S: 1332–1344 cm^{-1}

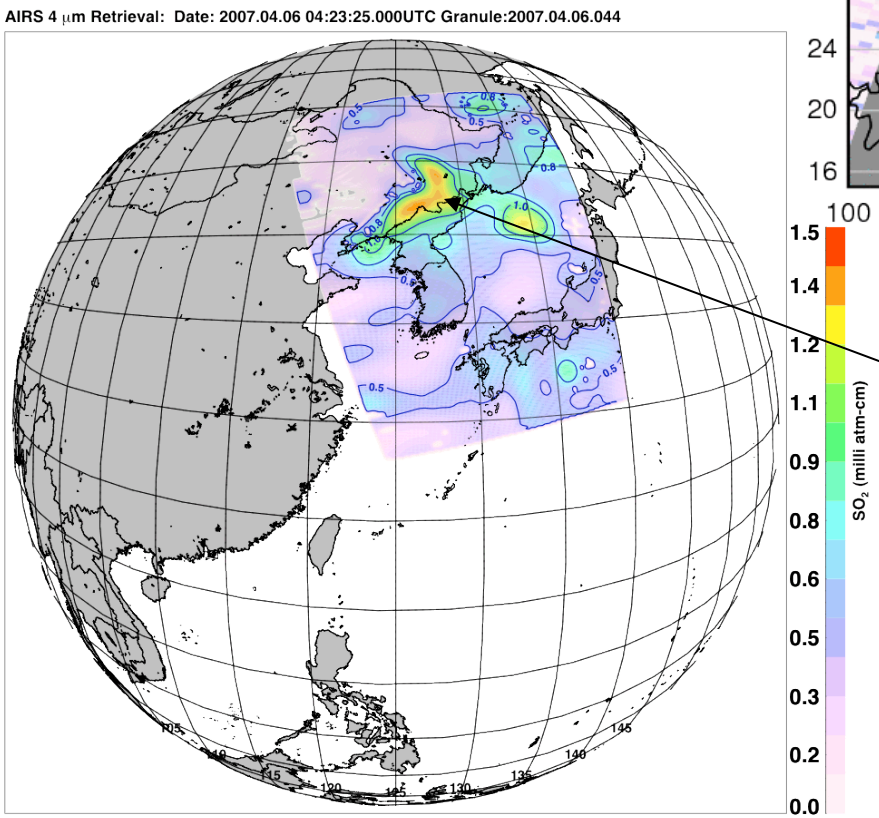
Al Mishraq Sulphur fire





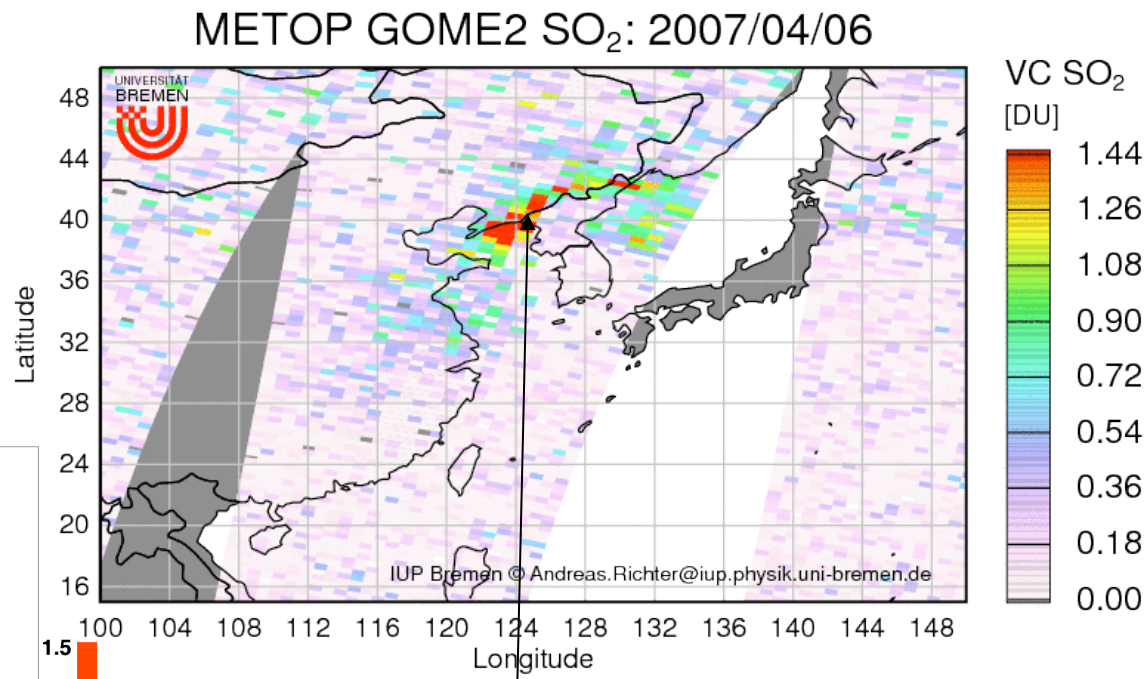


AIRS 4 µm



AIRS Lower Tropospheric SO_2.

Produced by: Dr Fred Prata, NILU, [fred.prata@nilu.no]



Anthropogenic SO_2 emissions

IASI

Atmos. Chem. Phys. Discuss., 8, 16917–16949, 2008
www.atmos-chem-phys-discuss.net/8/16917/2008/
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Atmospheric Chemistry and Physics Discussions

This discussion paper is/has been under review for the journal *Atmospheric Chemistry and Physics (ACP)*. Please refer to the corresponding final paper in *ACP* if available.

Tracking and quantifying volcanic SO_2 with IASI, the September 2007 eruption at Jebel at Tair

L. Clarisse[1], P. F. Coheur[1], A. J. Prata[2], D. Hurtmans[1], A. Razavi[1], T. Phulpin[3], J. Hadji-Lazaro[4], and C. Clerbaux[4,1]

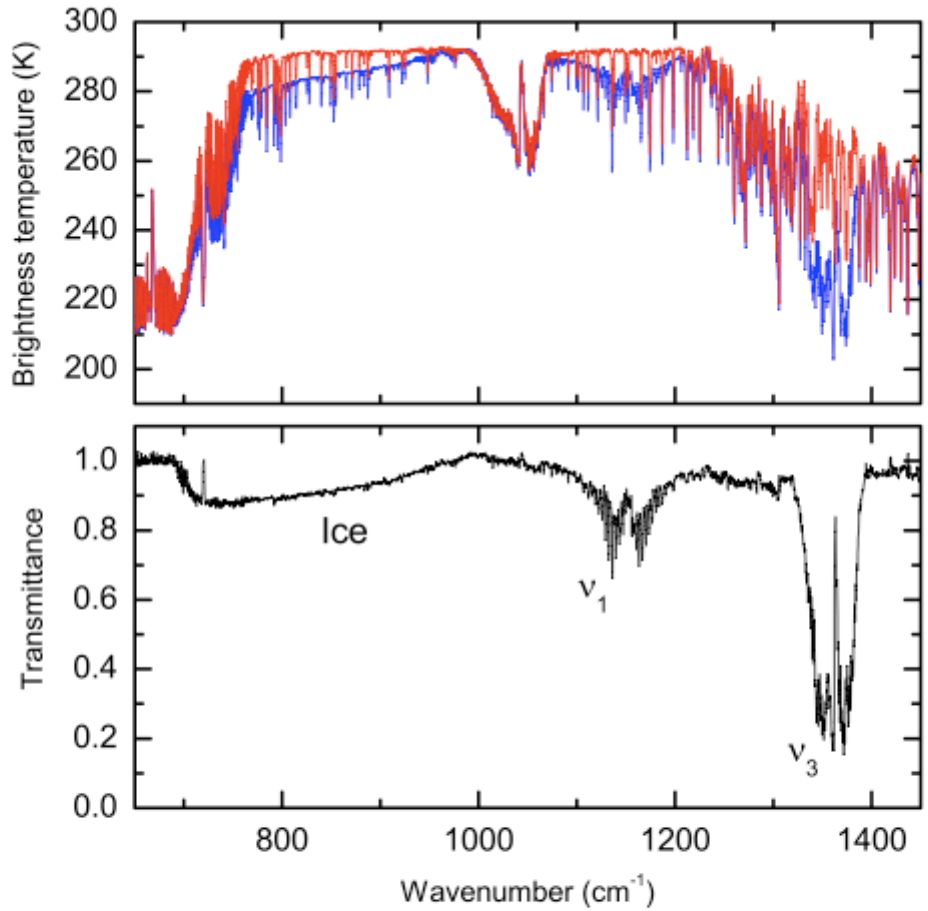
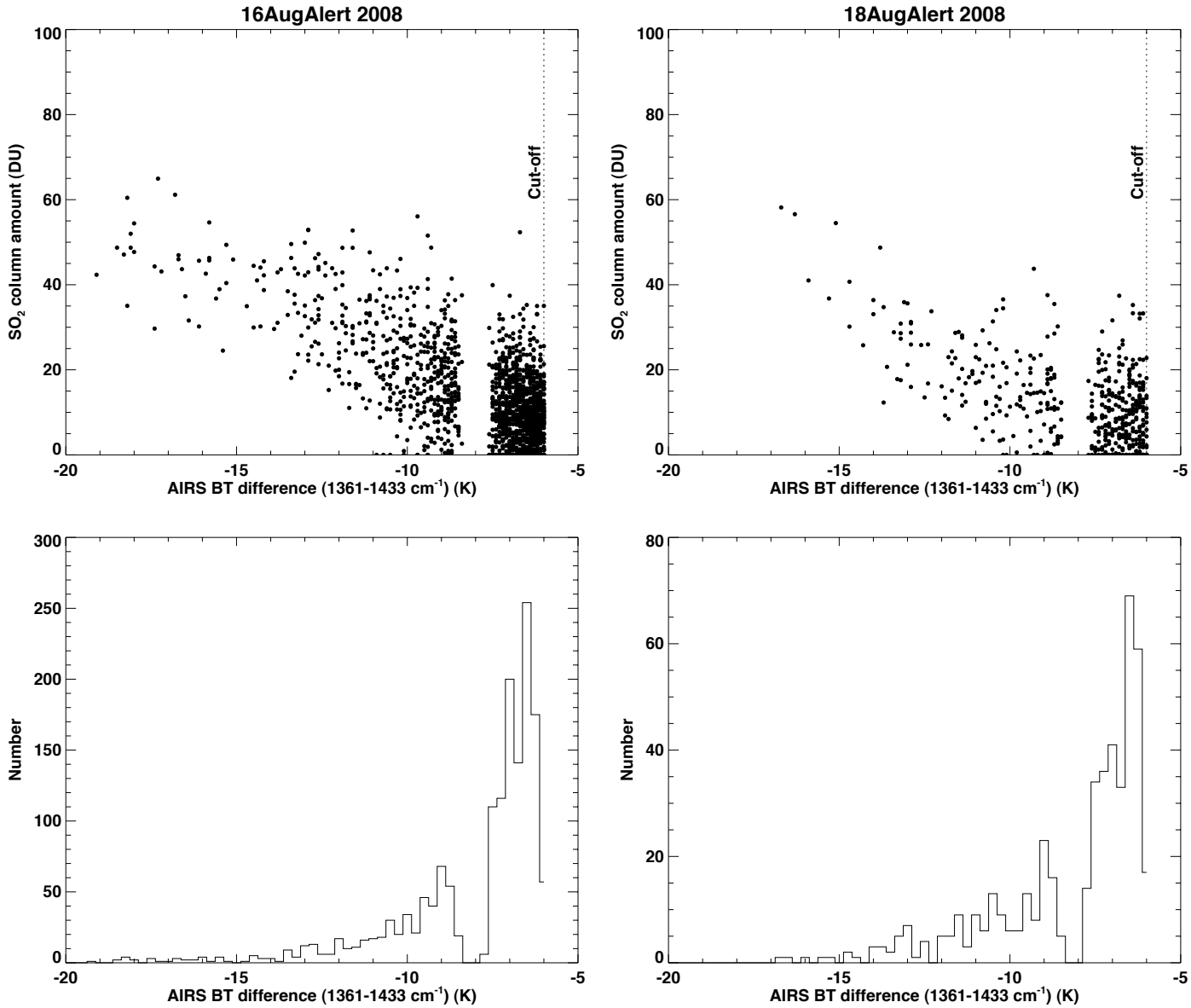


Fig. 1. Top panel. Two spectra (in brightness temperature) from 30 September 2007. The spectrum in blue is taken from inside the initial plume of the Jebel at Tair eruption, the spectrum in red is from a nearby pixel, just outside the plume. Bottom panel. Ratio of the two spectra from the top panel.



IASI uses 1407.25, 1408.75, 1371.50 and 131.75 cm $^{-1}$

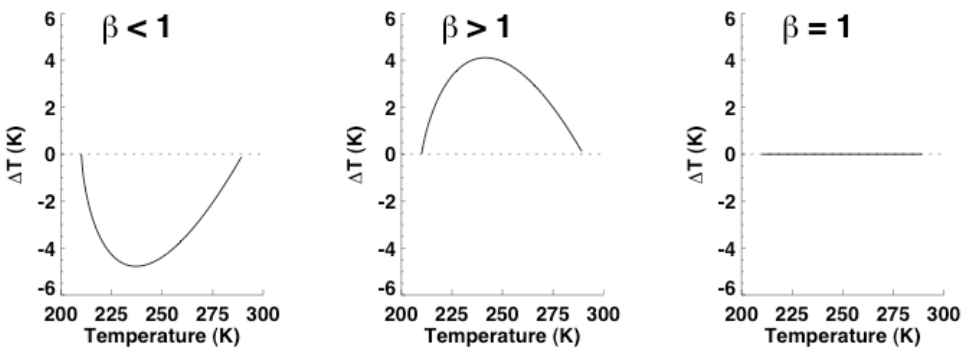
Volcanic ash – Detection and discrimination

Prata, A. J., 1989, Infrared radiative transfer calculations for volcanic ash, Geophys. Res. Lett., 16(11), 1293-1296

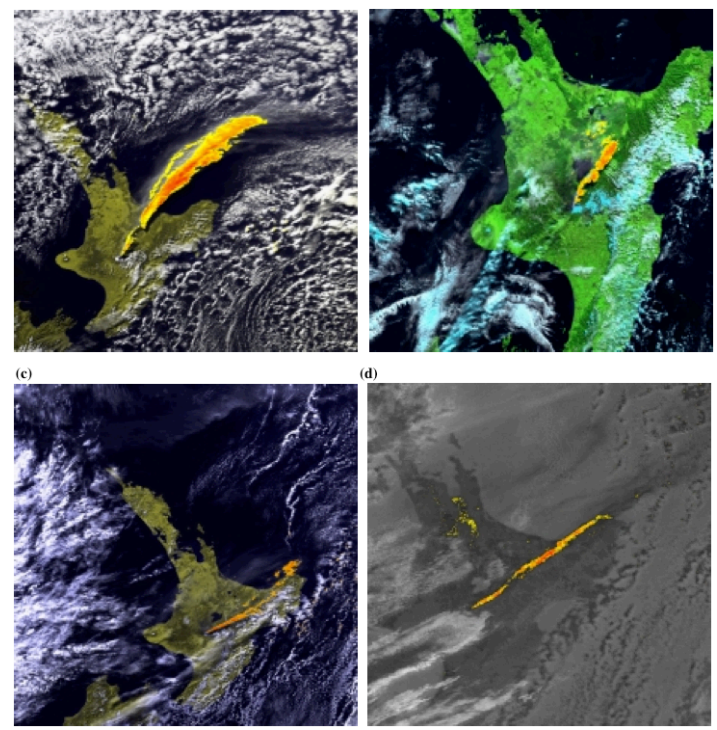
$$\Delta T = \Delta T_c [X - X^{\beta}],$$

$$X = 1 - \frac{\Delta T_4}{\Delta T_c},$$

$$\Delta T = T_4 - T_5, \quad \Delta T_c = T_s - T_c, \quad \Delta T_4 = T_s - T_4.$$

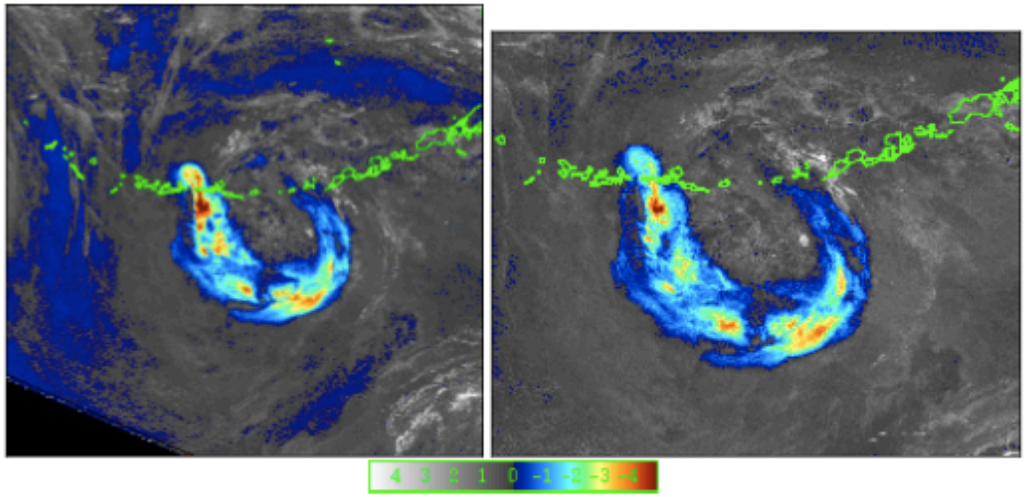


$T_4 - T_5 < 0$

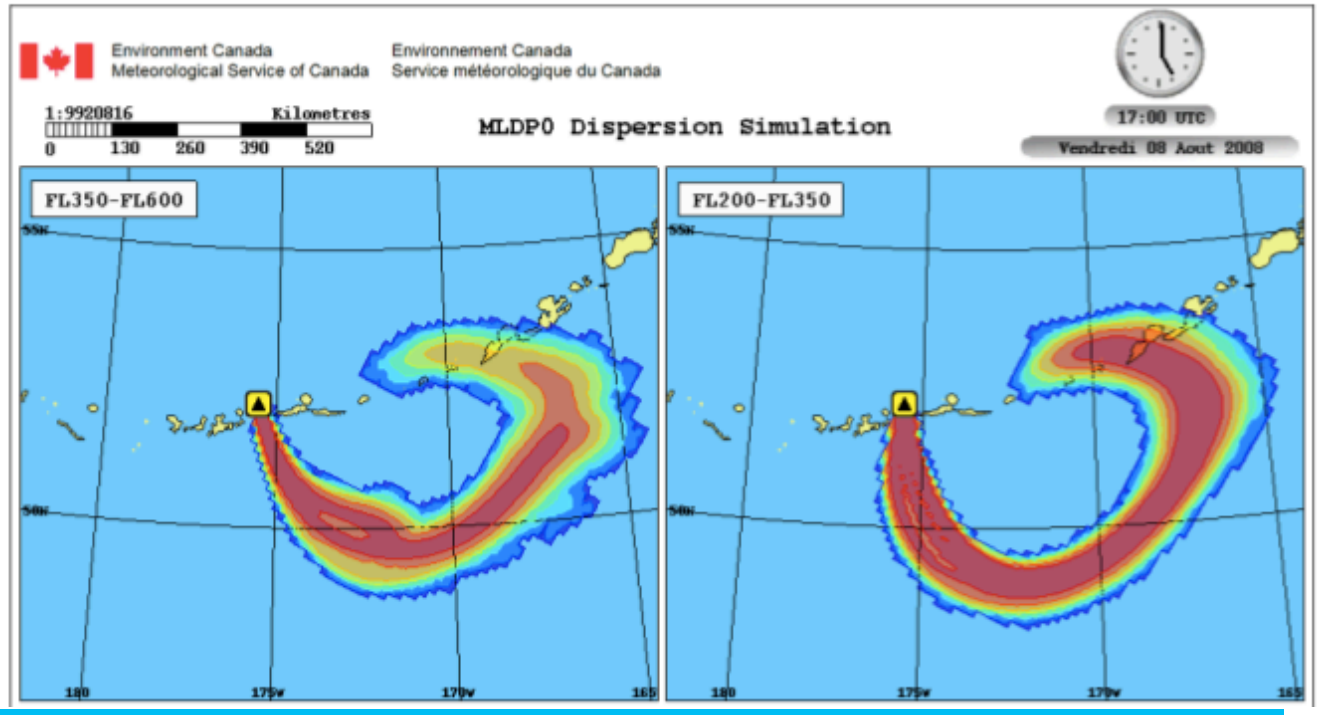


Operational use of the "reverse absorption" algorithm

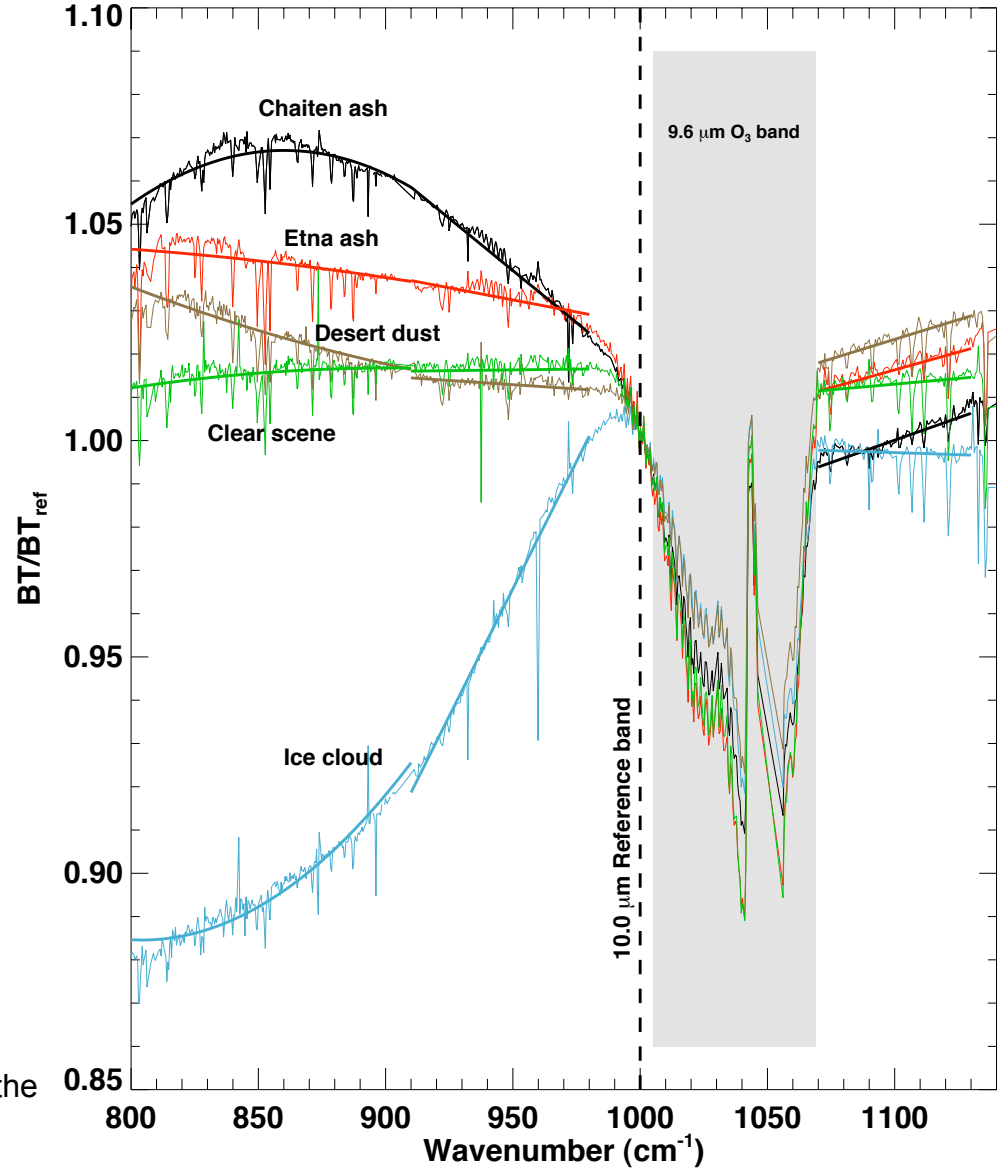
Kasatochi eruption



AVHRR 4m5 – Left: NOAA-15 2008/08/08 16:41 UTC
AVHRR 4m5 – Right: NOAA-16 2008/08/08 17:09 UTC



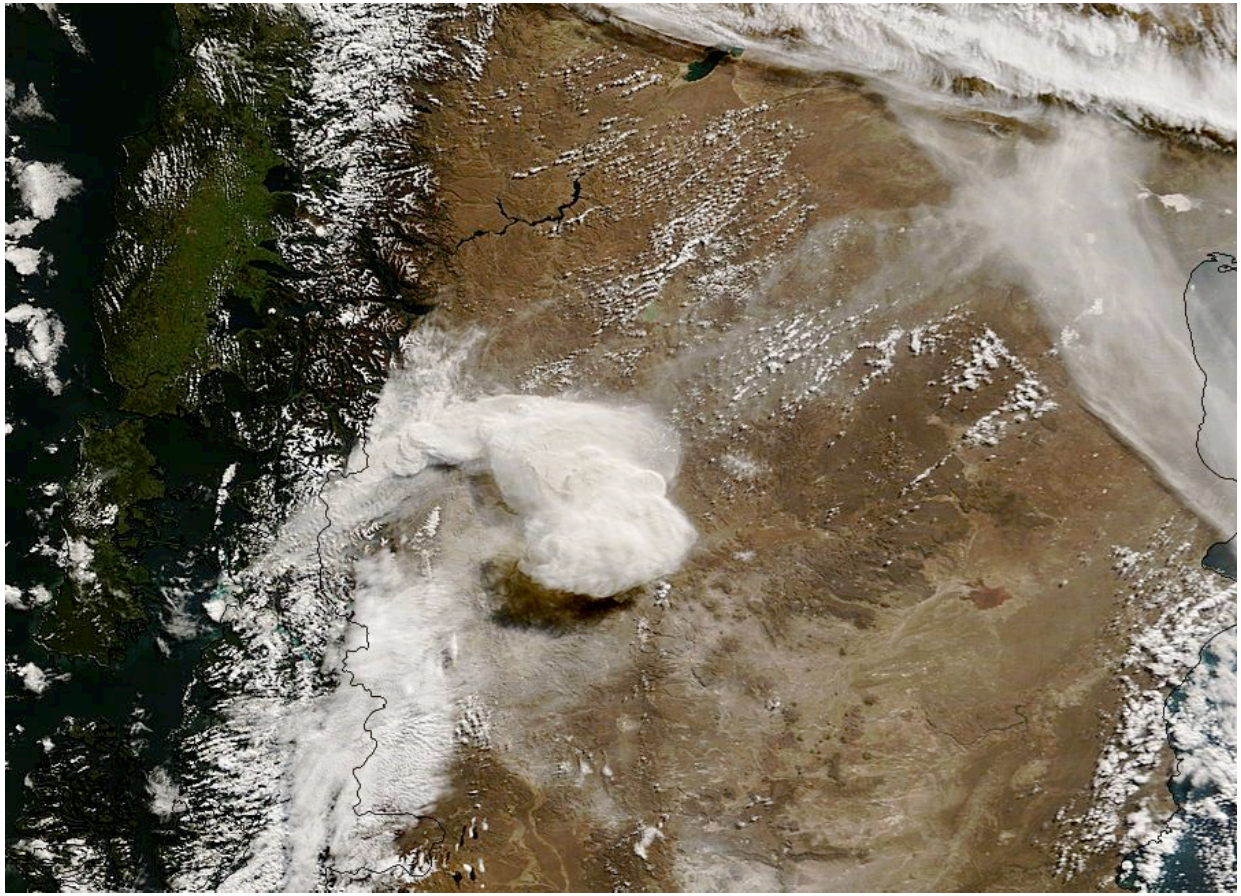
Spectral signature of volcanic ash



Prata, A.J., Gangale, G., and L. Clarisse, 2008, On the spectral signature of volcanic ash, *Submitted to JGR Atmos*.

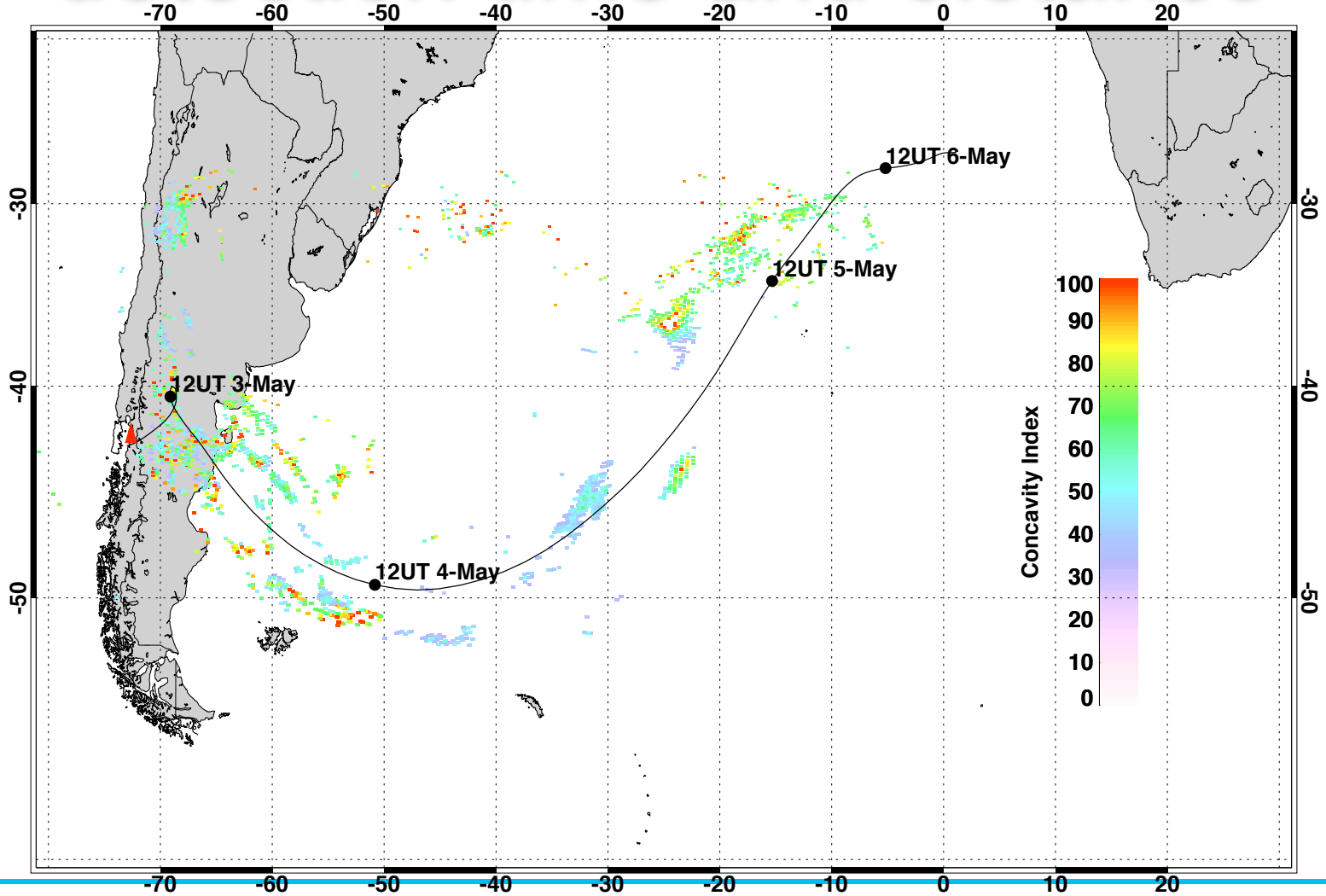
Chaitén, Chile

First rhyolitic ash eruption in the satellite era (~30 years)

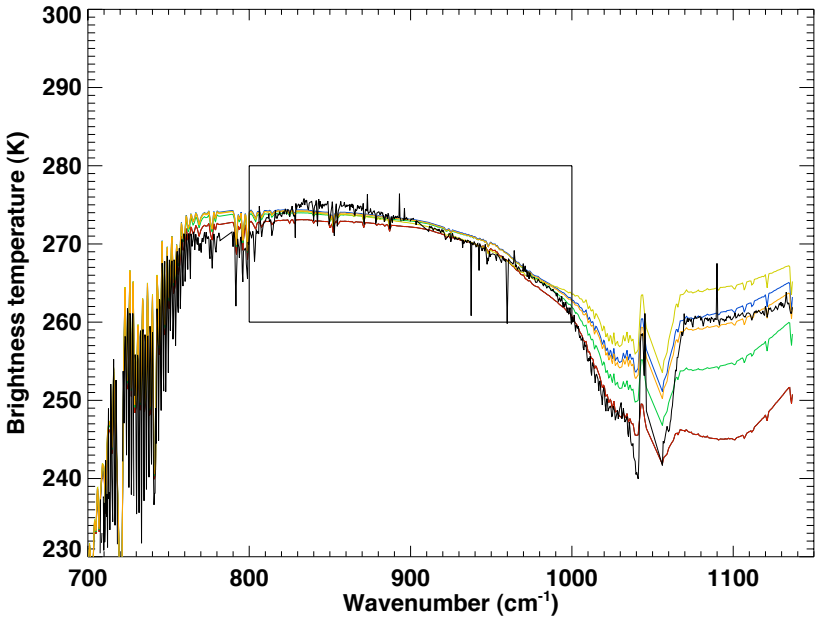


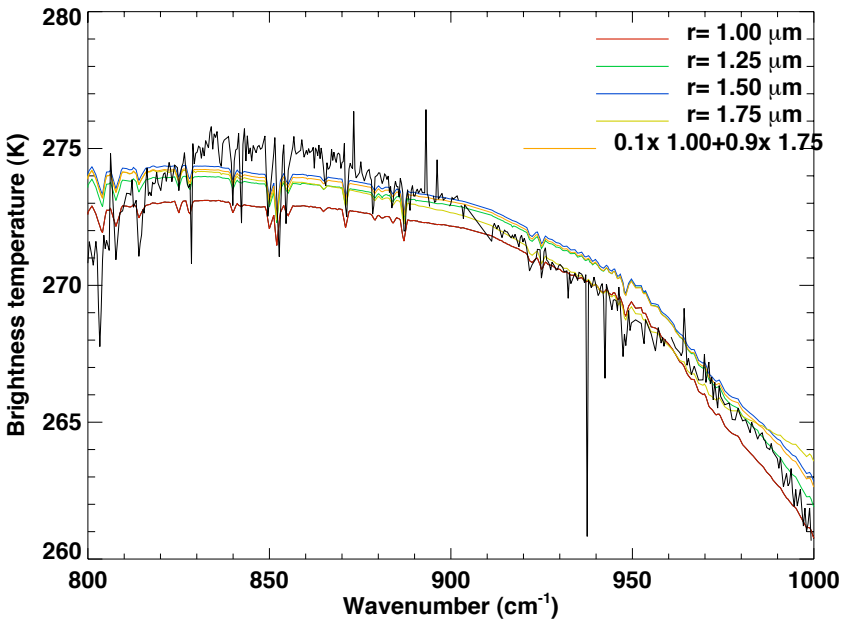
S.A. Carn, J.S. Pallister, L. Lara, J. Ewert, G. Villarosa, M. Fromm, S. Watt, A.J. Prata, D.M. Pyle, T.A. Mather, N. Matthews, R.S. Martin, A. Pavez, R. Aguilera, R. Thomas, W. Rison, P. Krehbiel, J. Johnson, A. Folch, D. Basualto, T.J. Casadevall, M. Guffanti, C. Benitez, J.G. Viramonte, 2008, **The awakening of Chaitén volcano, Chile**, EOS Trans. (to appear).

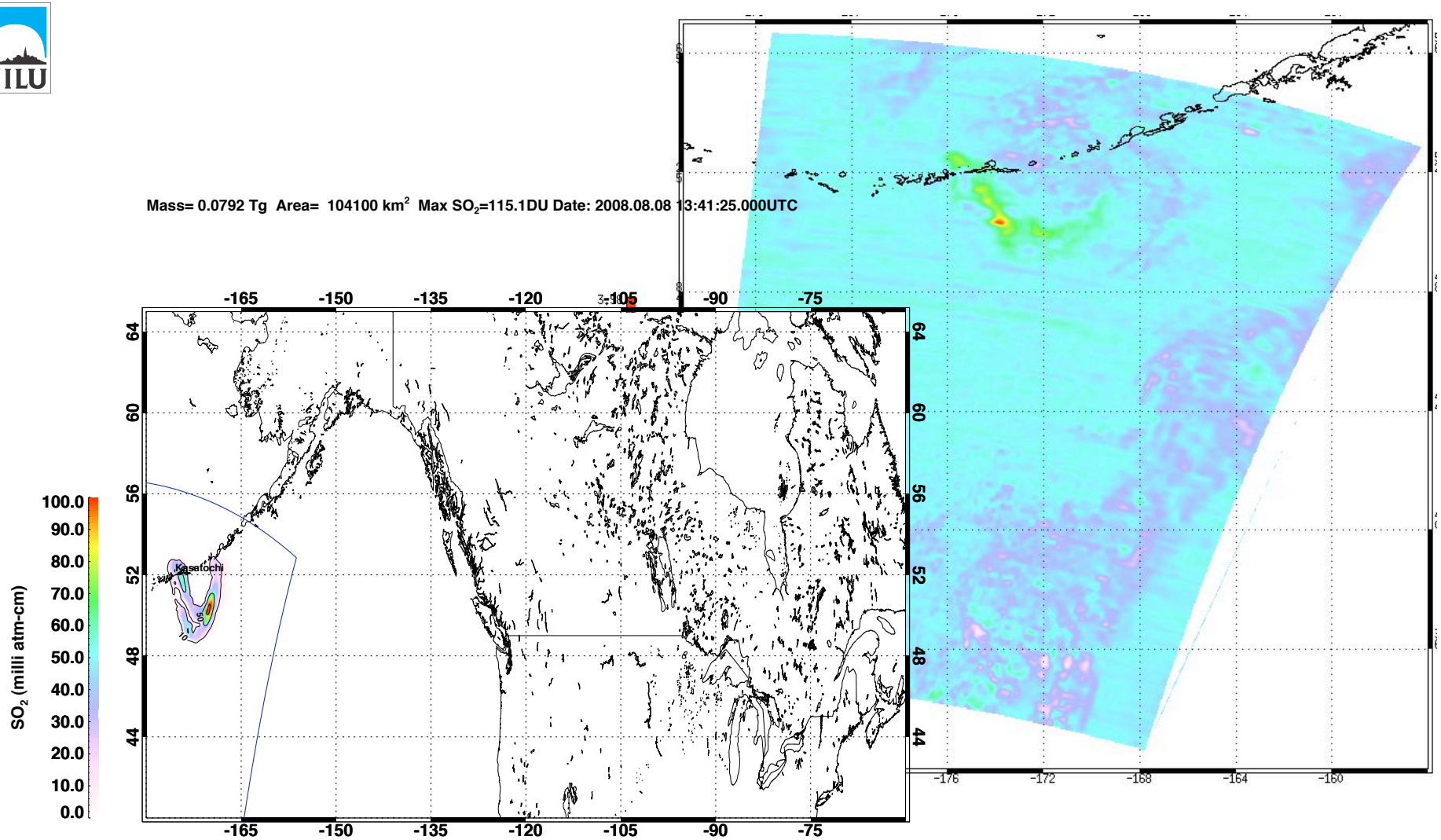
Concavity index increases detection time and distance



Sensitivity to particle size and composition



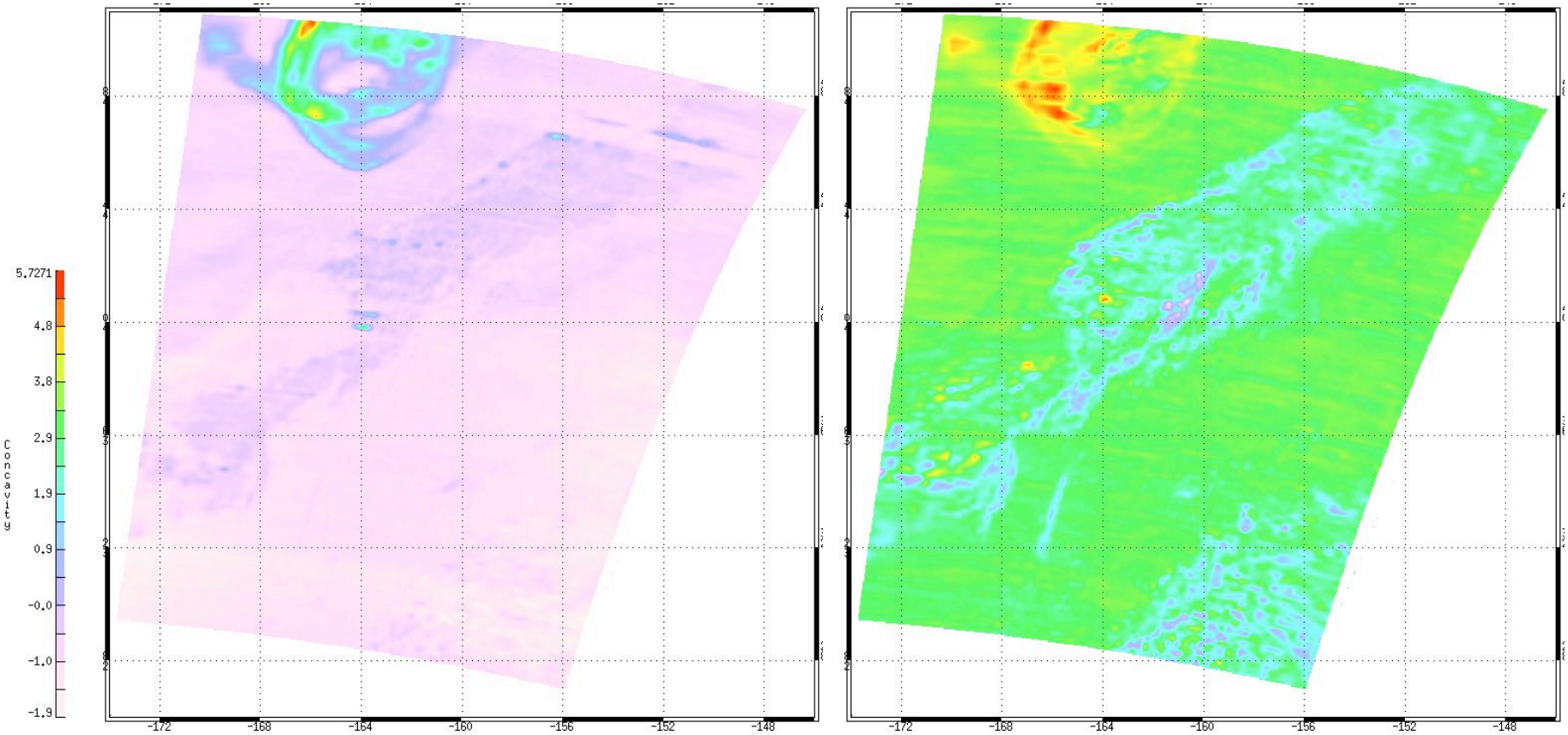




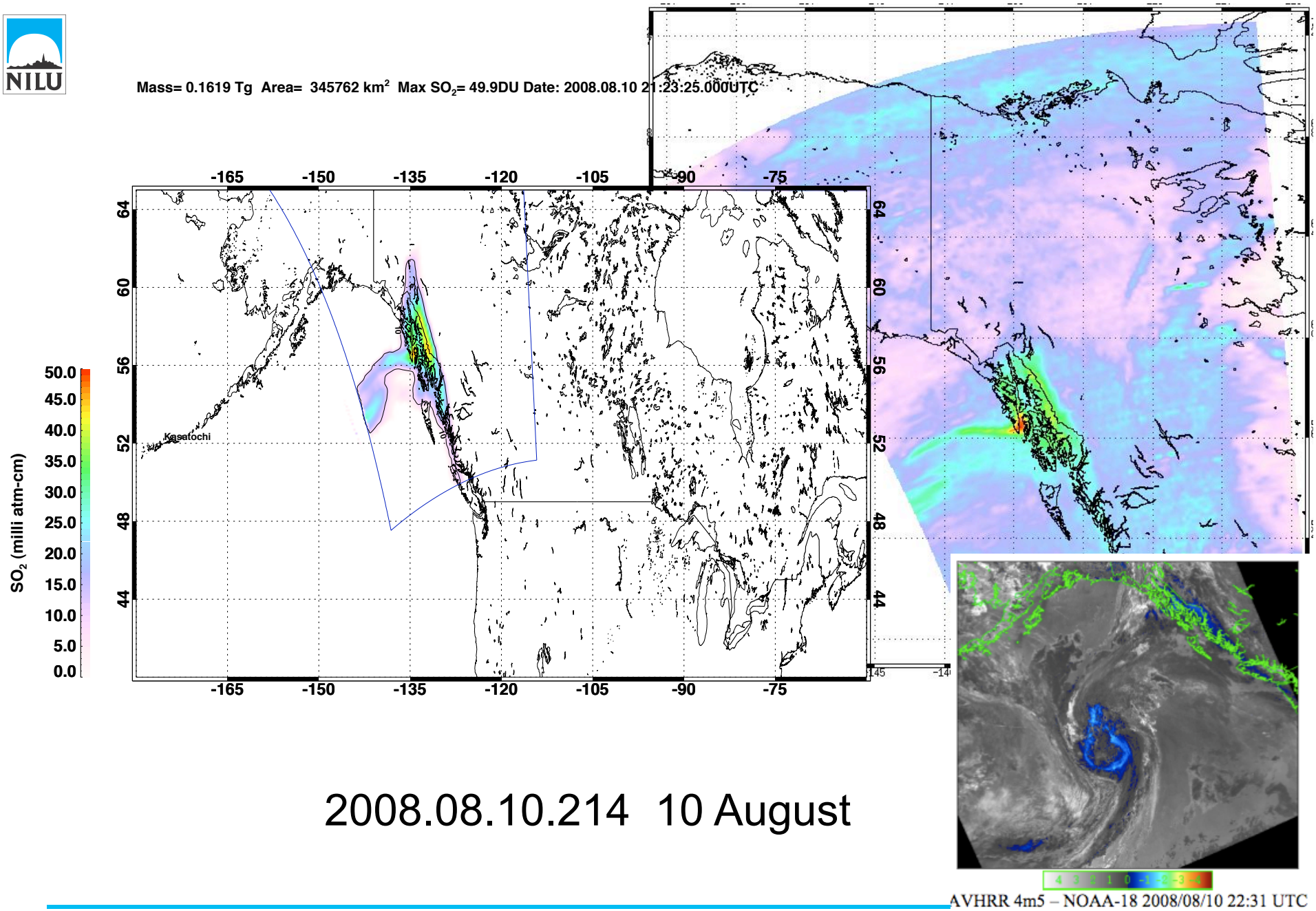
2008.08.08.137 08 August

1070-1130 cm^{-1}

820-960 cm^{-1}

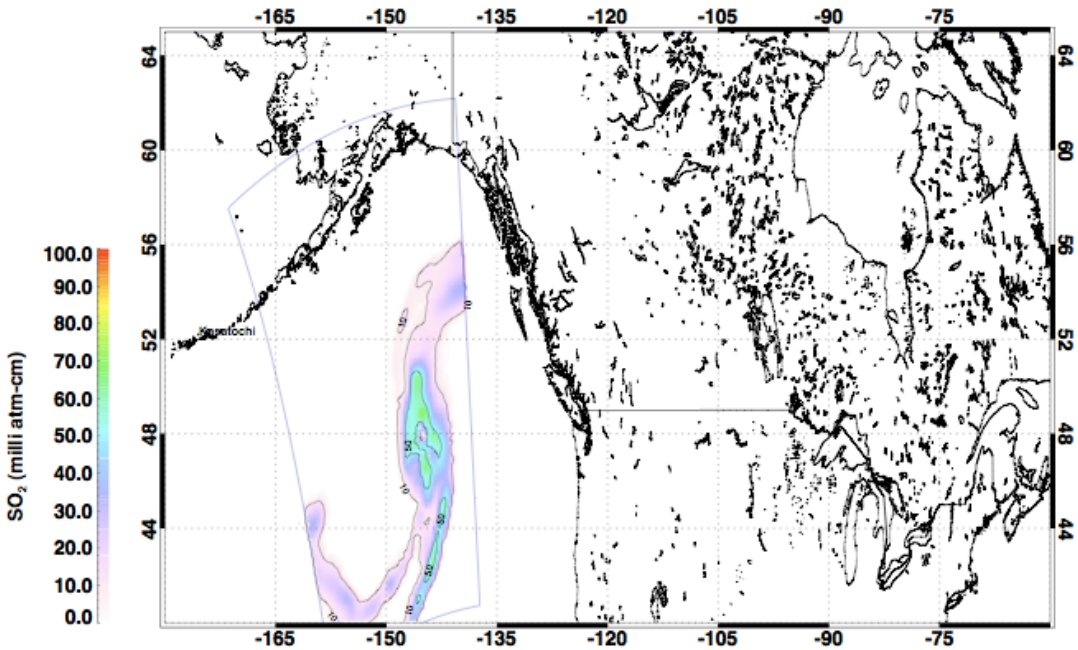


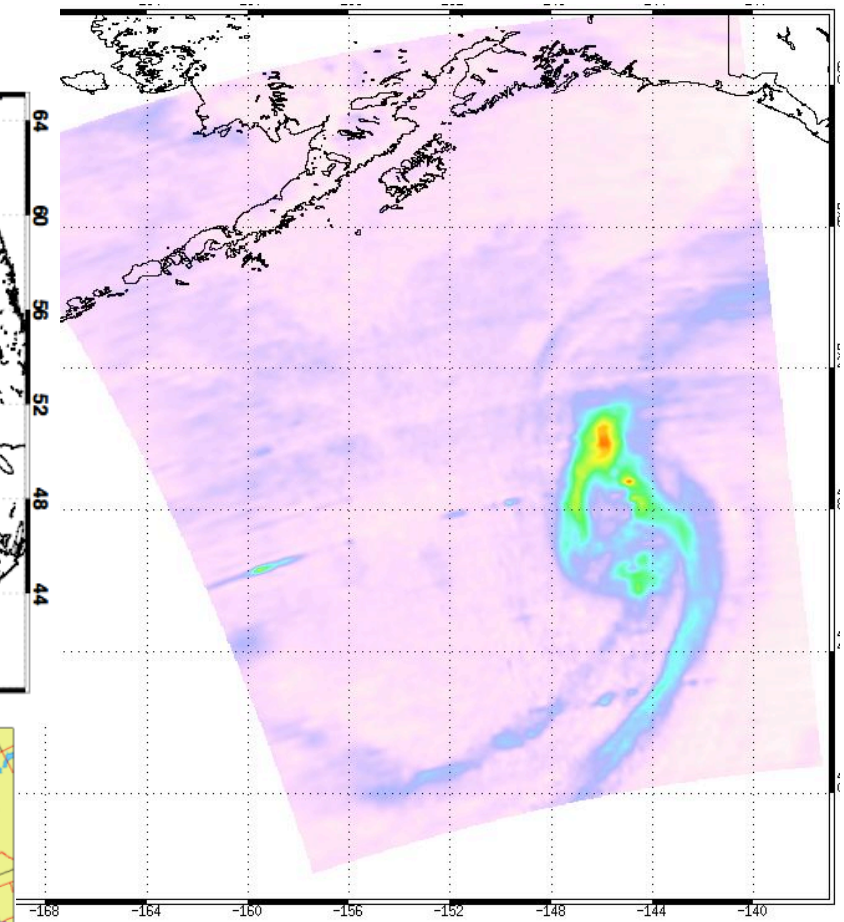
2008.08.09.128 09 August 2008

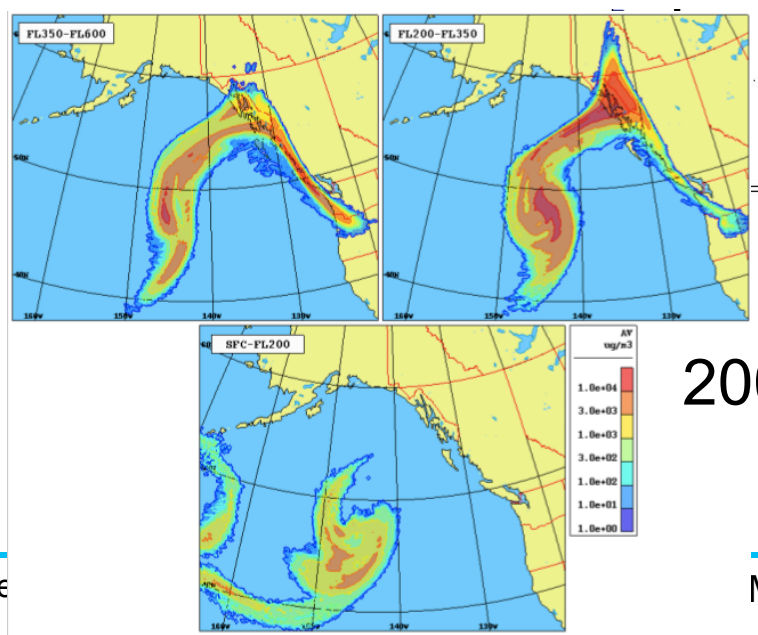


2008.08.10.214 10 August

Mass= 0.4997 Tg Area= 733087 km^2 Max SO_2= 70.1DU Date: 2008.08.10 22:59:25.000UTC

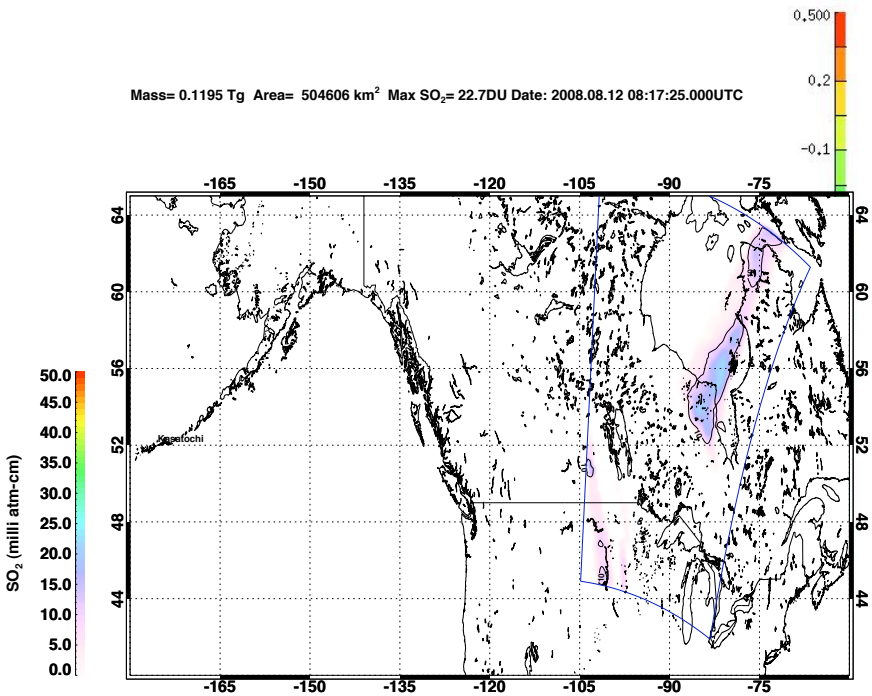


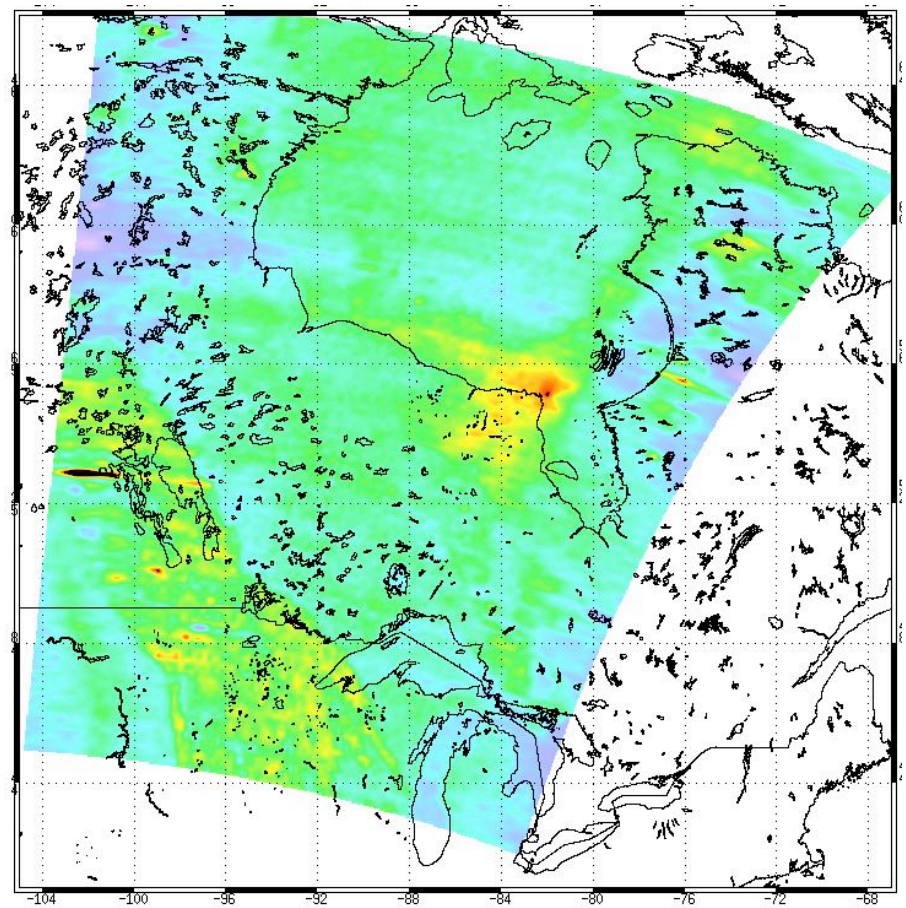




2008.08.10.230 10 August

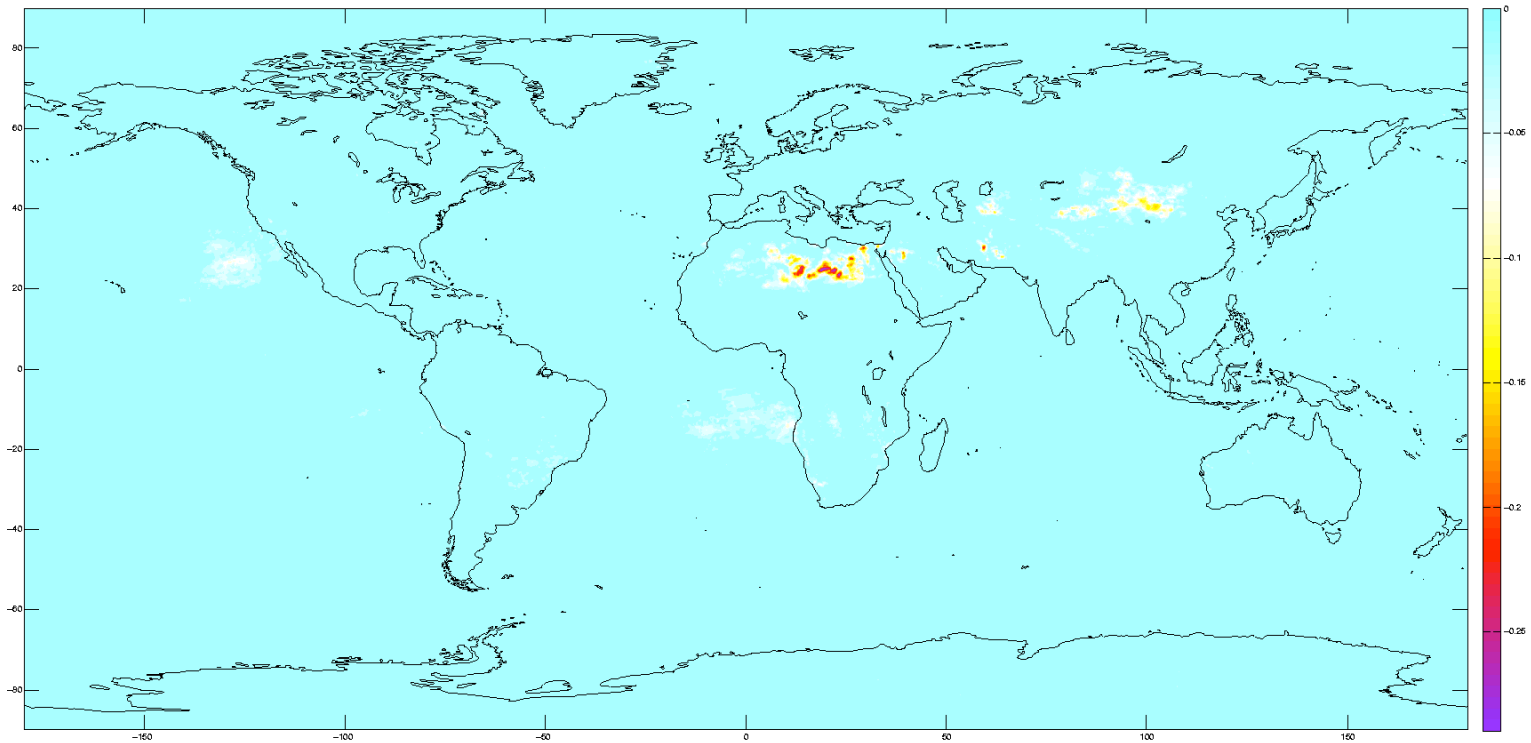
4 days later





2008.08.12.083 12 August

IASI – Dust detection (based on the concavity index)



August 2008 pm.

(Courtesy Levien Clarisse)

Further information

AIRS

Transport

OMI

SEVIRI

Aviation

UV imager

SO_2 Pinatubo

TOVS

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- **Prata, A. J.,** S. A. Carn, A. Stohl, and J. Kerkmann, 2007, Long range transport and fate of a stratospheric volcanic cloud from Soufri`ere Hills volcano, Montserrat, ***Atmos. Chem. Phys.,*** 7, 5093–5103.
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- **Prata, A. J.,** Rose, W. I., Self, S., and D. M. O'Brien, Global, long-term sulphur dioxide measurements from TOVS data: A new tool for studying explosive volcanism and climate, In *Volcanism and the Earth's Atmosphere* (ed. Robock and Oppenheimer), ***Geophysical Monograph***. 139, 75-92, 2003.