Retrieval of SO_2 from high spectral resolution measurements: AIRS and IASI

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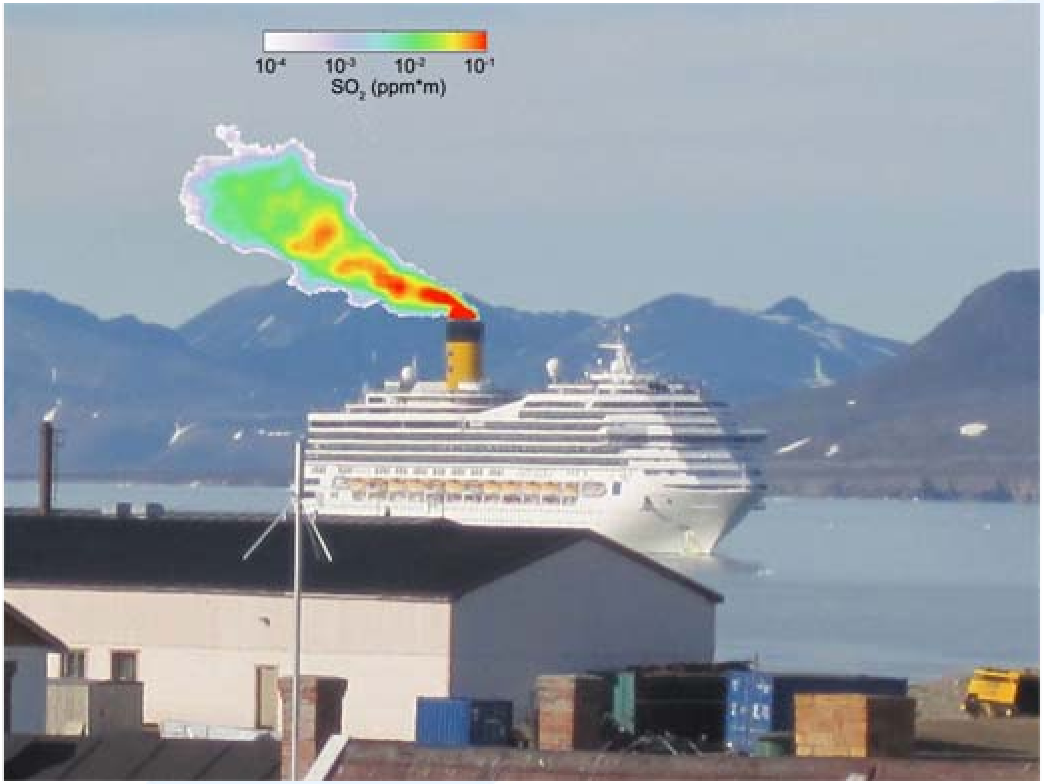
NILU Norsk institutt for luftforskning

Why measure SO_2?

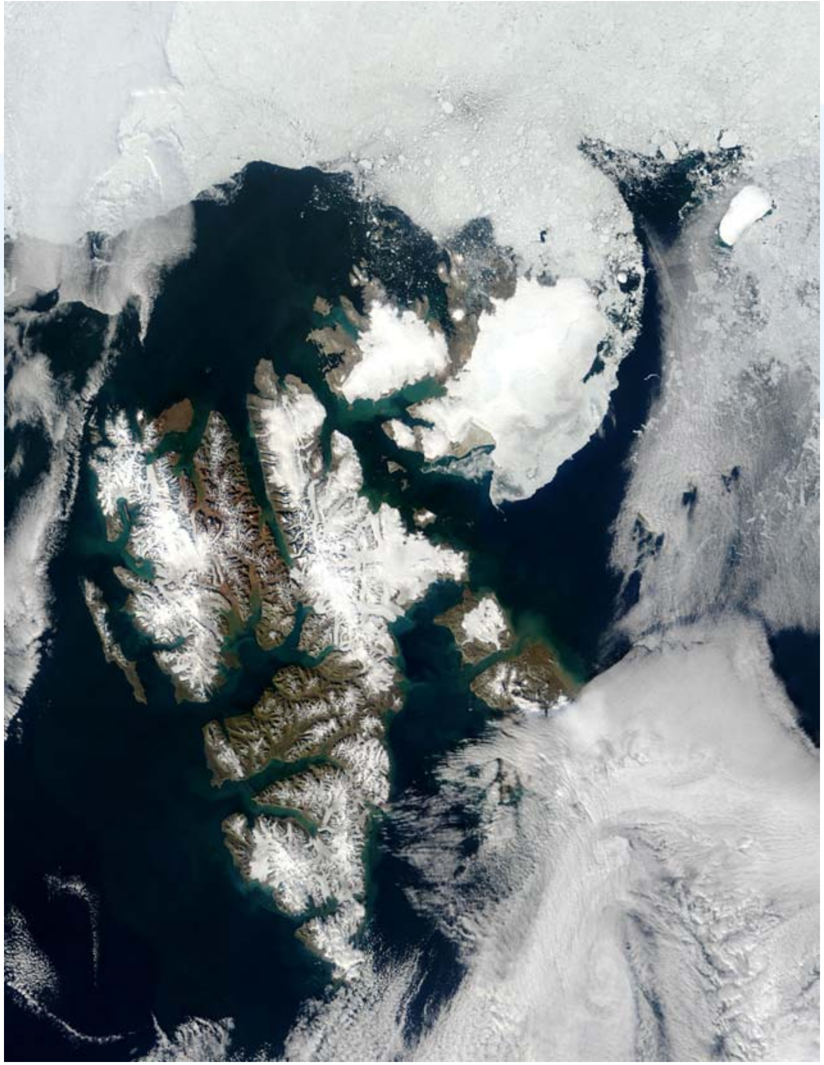
Atmospheric pollution ***Effects on climate*** ***Hazards to aviation***

- Background levels generally low $<10^{-4}$ ppmV
- Man-made emissions from industry, mining operations, shipping
  - emission rates from 10 gs^{-1} to >1000 kgs^{-1}
- Large natural emissions from volcanoes
  - passive degassing >10 kgs^{-1}
  - explosive volcanism $>10^3$ kgs^{-1}

Atmospheric Pollution



Measurements from NILU's ground-based UV camera – EnviCam



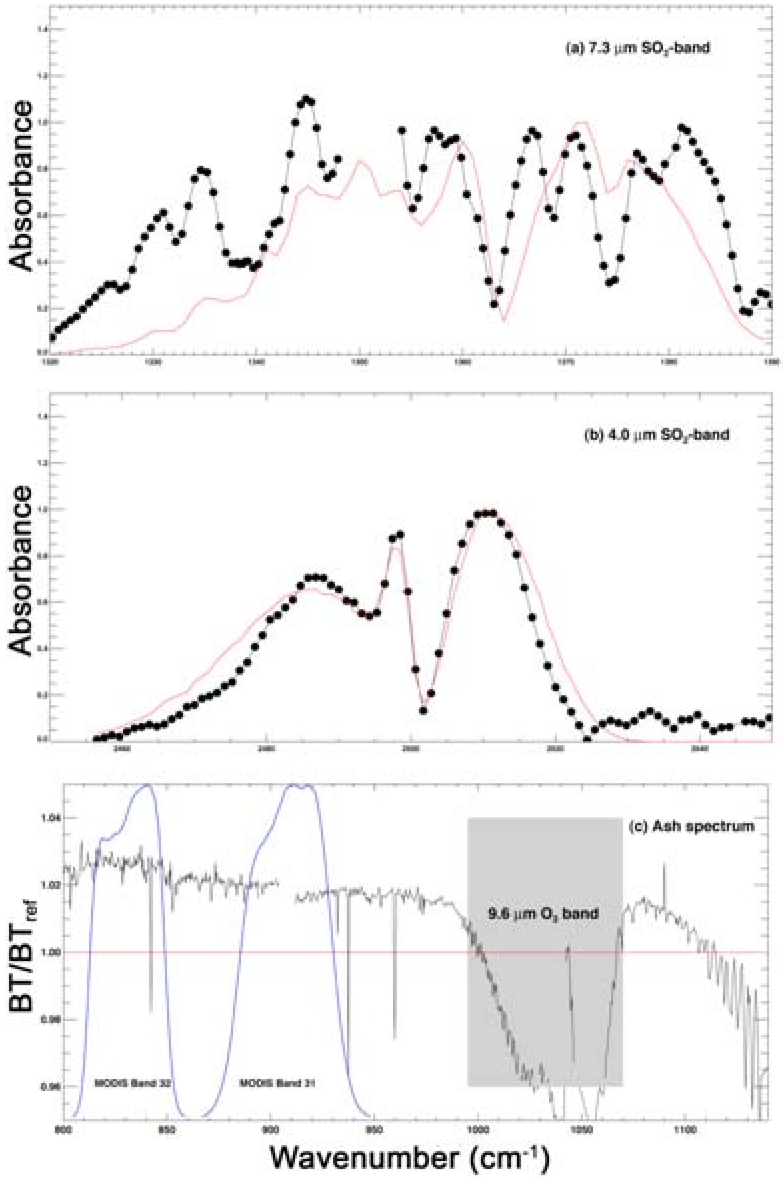
SO_2 ship emissions from a large cruise ship entering Kongsfjorden, Ny Ålesund, Svalbard.

Volcanic emissions

Soufriere Hills, Montserrat explosive eruption, 11 February 2010

Villarica volcano, Chile.
Passive degassing

Ground-based IR camera (CyClops) at Tavurvur volcano, New Britain.



AIRS and IASI can measure SO_2 absorption in the strong ν_3 (1363 cm^{-1}/7.3 µm) band of SO_2

AIRS and IASI can also measure SO_2 absorption in the weak combination band $\nu_1+\nu_3$ 2500 cm^{-1}/4 µm) band of SO_2

Ash can be measured between 800–1130 cm^{-1}

Retrieval scheme

$$I_\nu \approx \int_0^{z_1} B_\nu[T(z)]\left(\frac{\partial\tau_\nu[z, q_2(z)\ldots q_n(z)]}{\partial z}\right)dz$$
$$+ \int_{z_1}^{z_2} B_\nu[T(z)]\left(\frac{\partial\tau_\nu[z, q_1(z), q_2(z)\ldots q_n(z)]}{\partial z}\right)dz$$
$$+ \int_{z_2}^{\infty} B_\nu[T(z)]\left(\frac{\partial\tau_\nu[z, q_2(z)\ldots q_n(z)]}{\partial z}\right)dz.$$

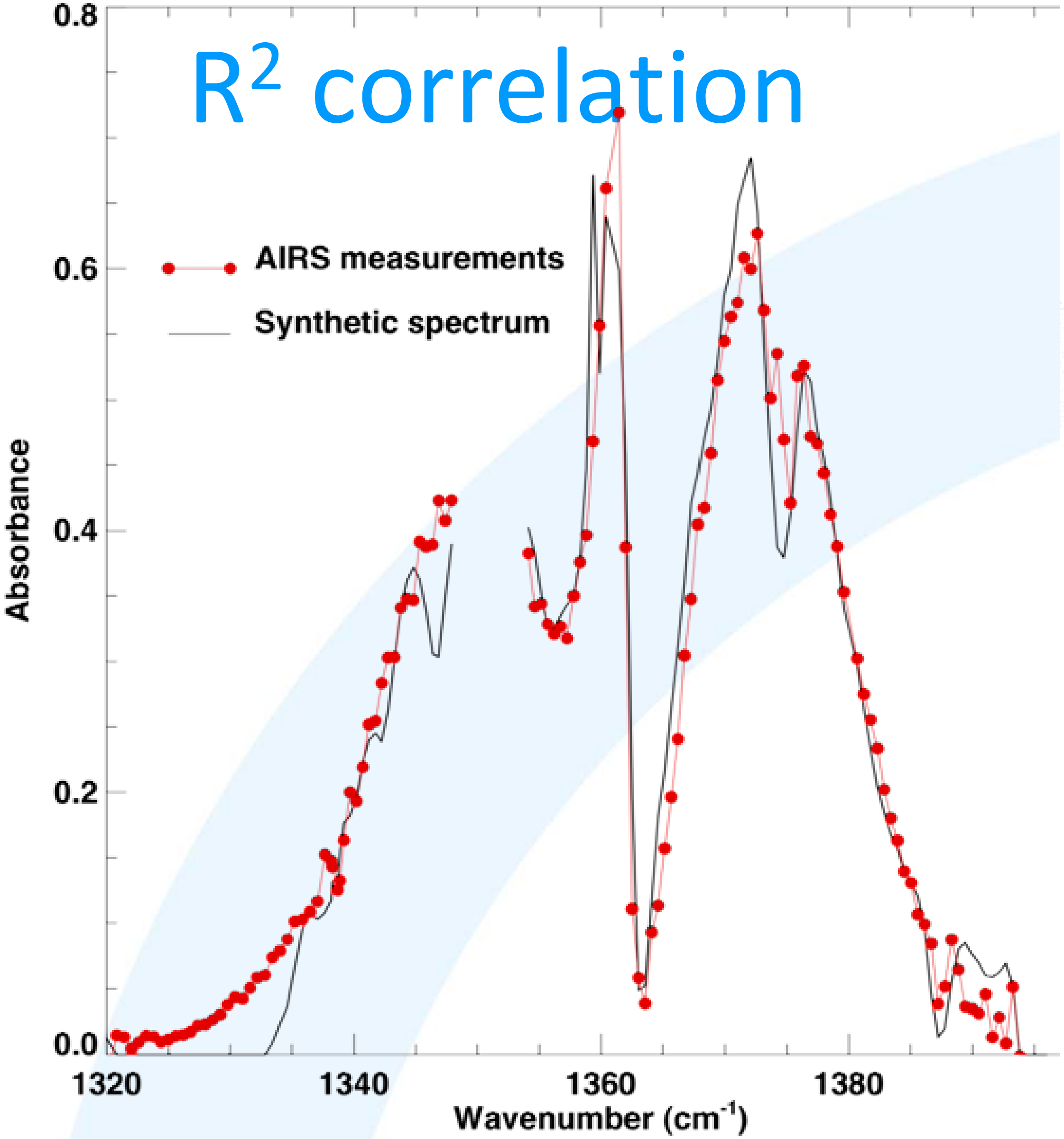
$$I'_\nu = I_{\nu,0}\exp\left\{-\int_o^\infty k_\nu(z)q(z)dz\right\} \quad A_\nu = -\ln\left\{\frac{I'_\nu}{I_{o,\nu}}\right\} = \int_o^\infty k_\nu(z)q(z)dz.$$

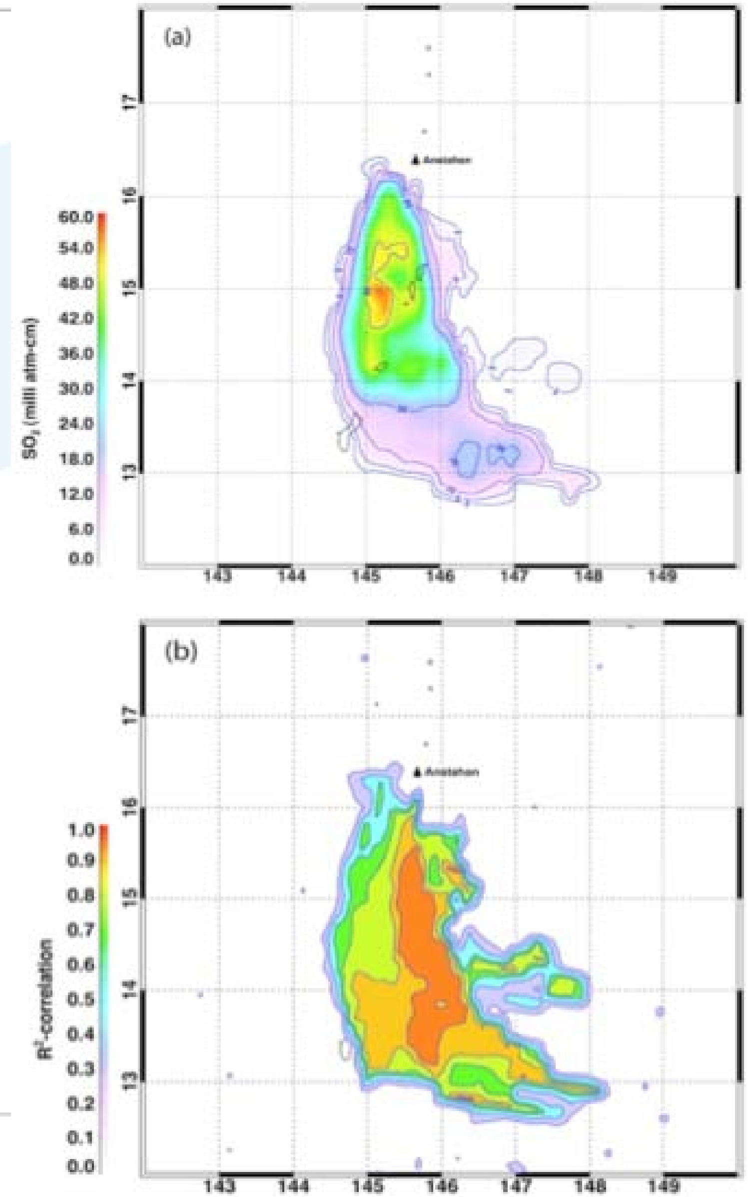
Absorbing layer only

$$A_\nu = -Ln\left\{\frac{I_{p_t,l_t}}{I_{p_r,l_r}}\right\} \qquad S_\nu = -Ln\left\{\frac{I_s}{I_0}\right\}$$

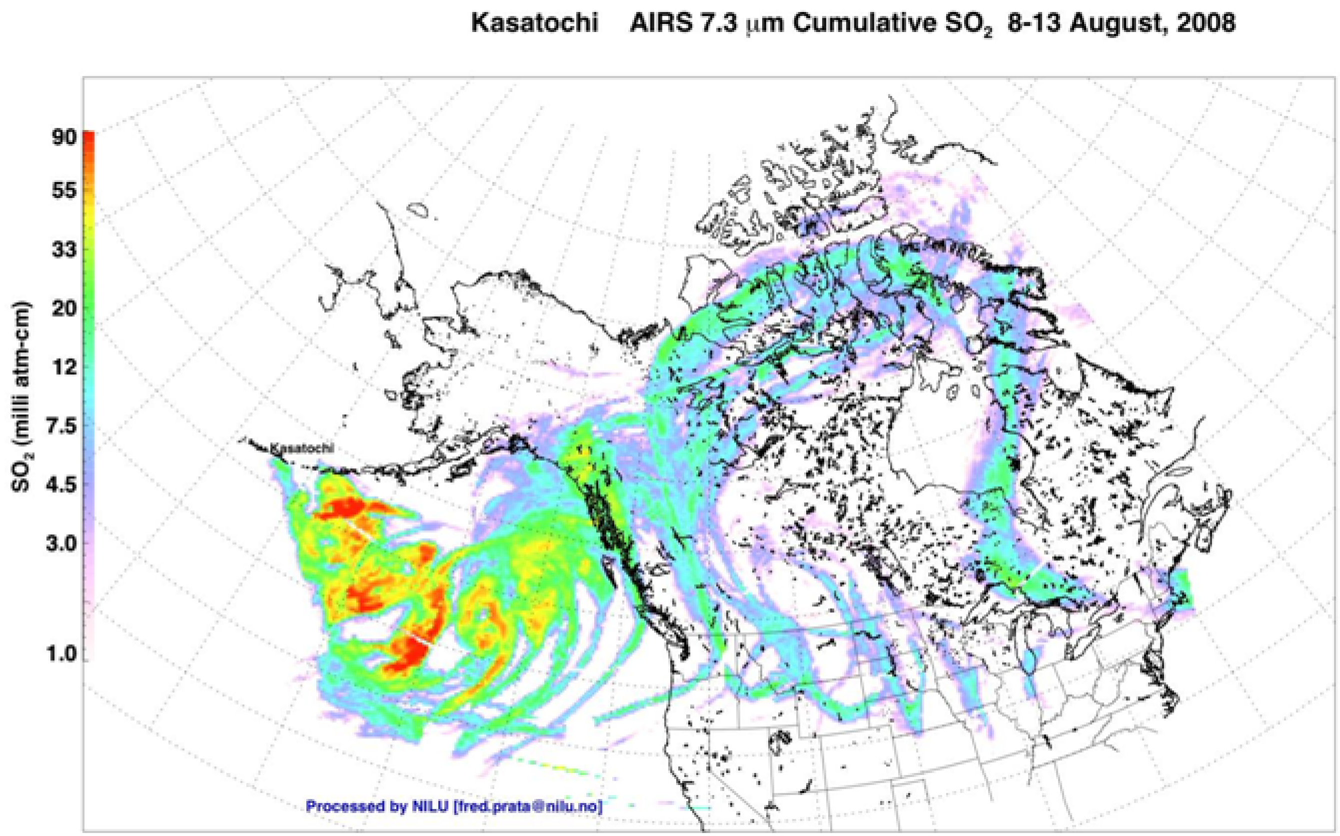
$$R = \frac{\frac{1}{n-1}\sum_{i=0}^{n-1}\tilde{A}_i\tilde{S}_i}{\sqrt{\frac{1}{n-1}\sum_{i=0}^{n-1}\tilde{A}_i^2}\sqrt{\frac{1}{n-1}\sum_{i=0}^{n-1}\tilde{S}_i^2}}.$$

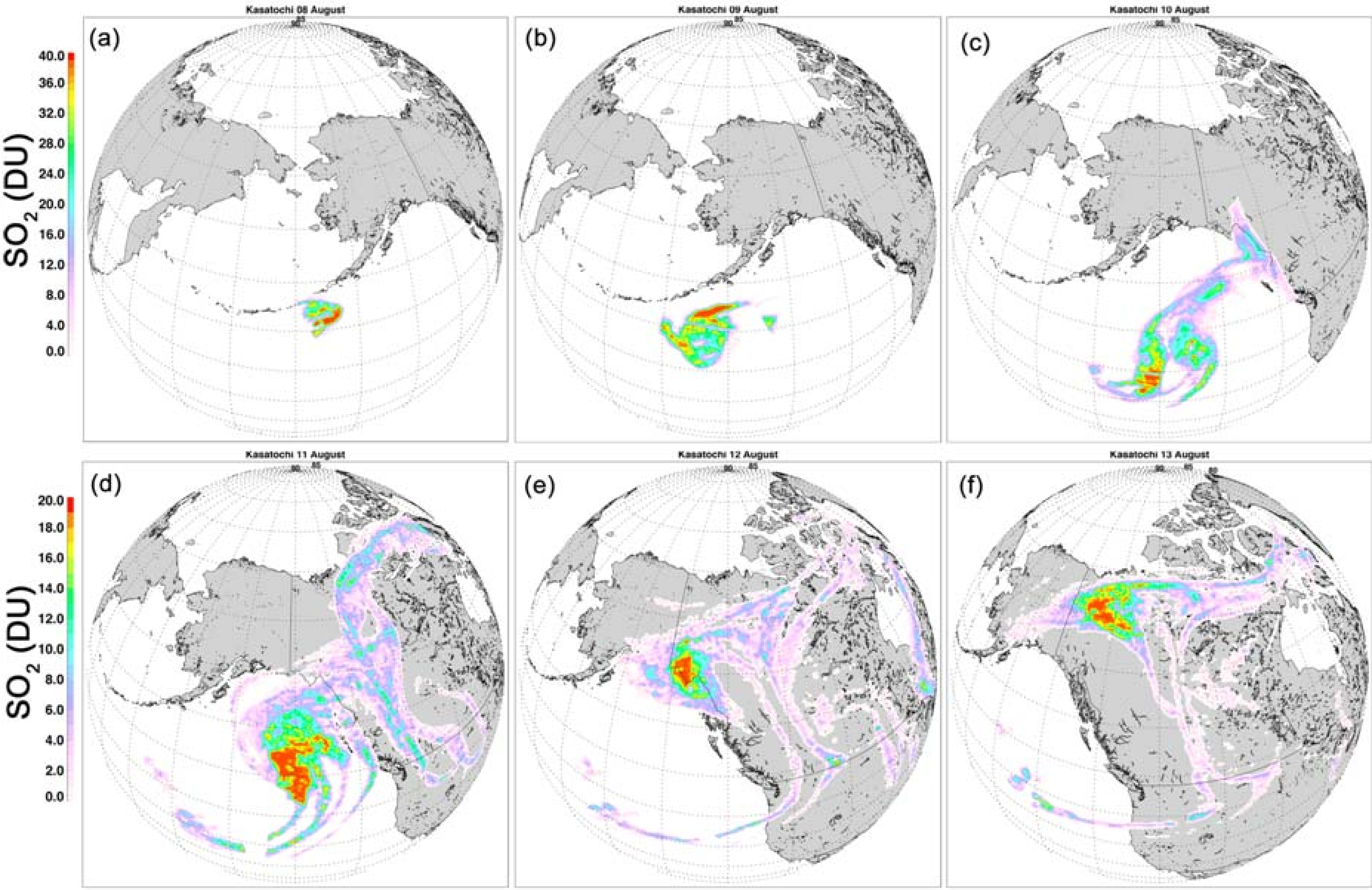
R^2 correlation





AIRS SO_2 using the strong ν_3 (7.3 µm band)

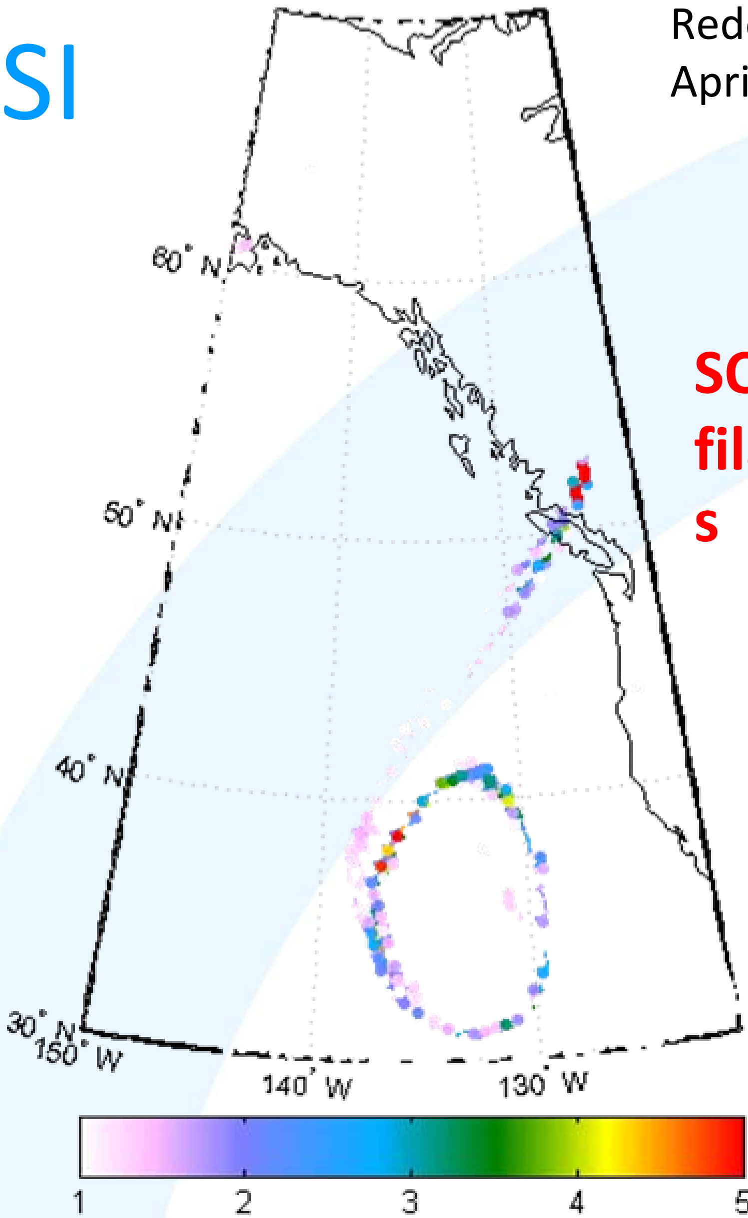




Kasatochi AIRS retrievals: 8–13 August 2008. >1.2 Tg (SO_2)

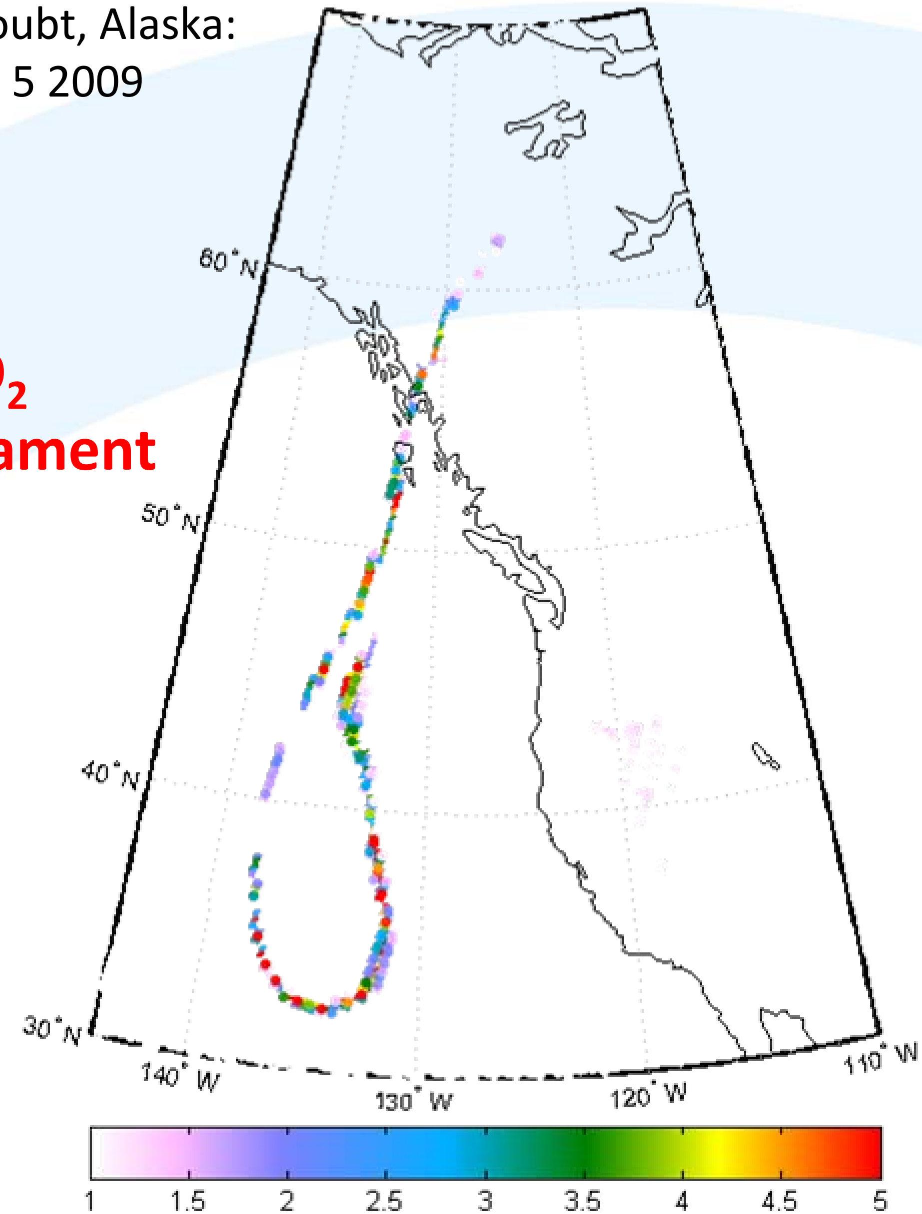
IASI

Redoubt, Alaska:
April 5 2009

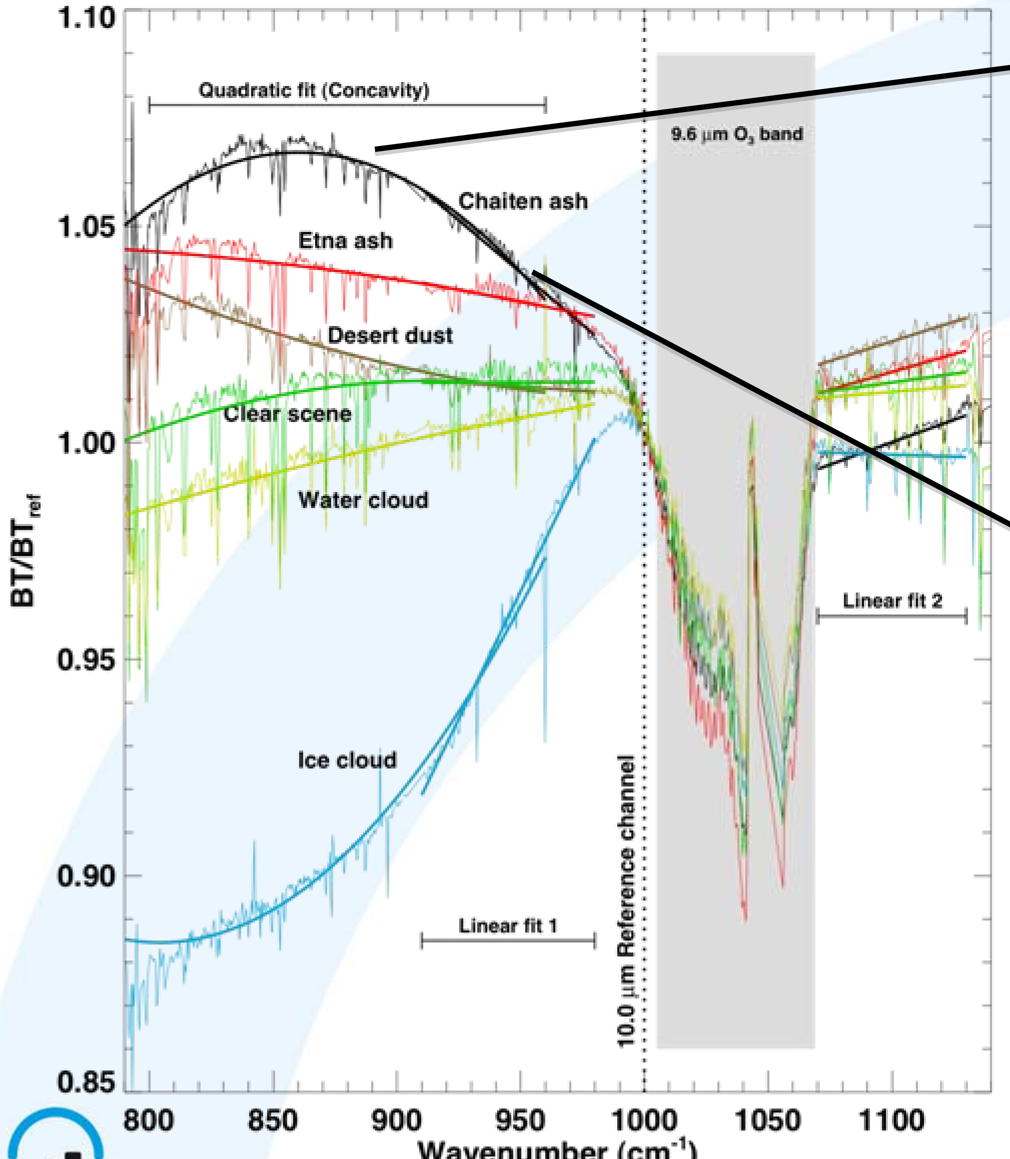


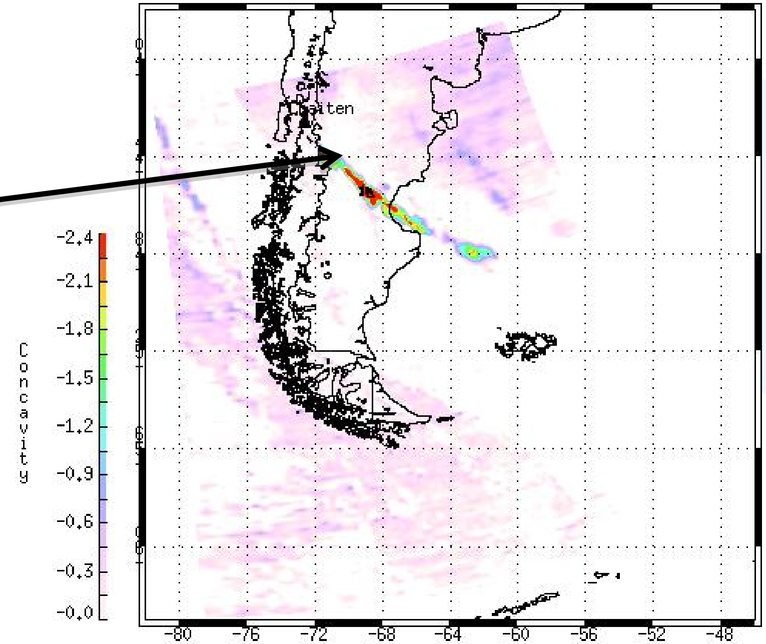
ΔBT (K)

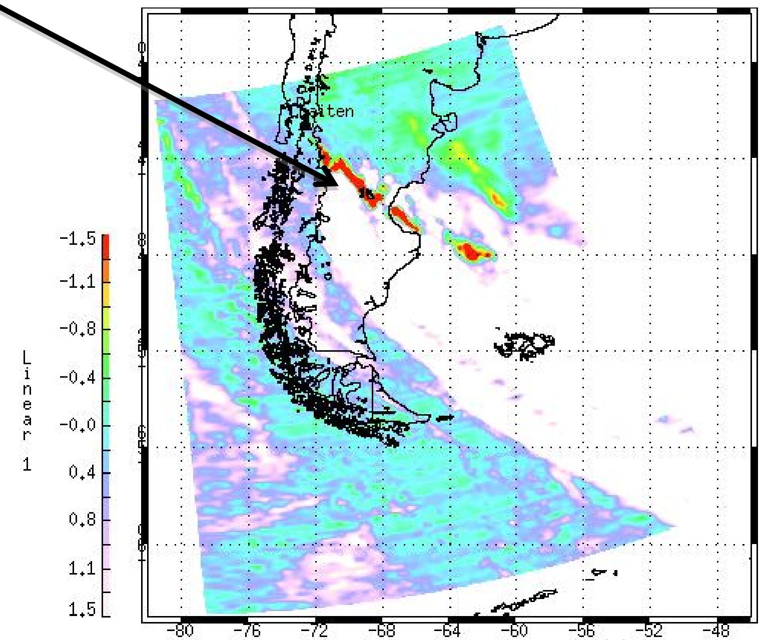
SO_2 filament s



Spectral Signatures







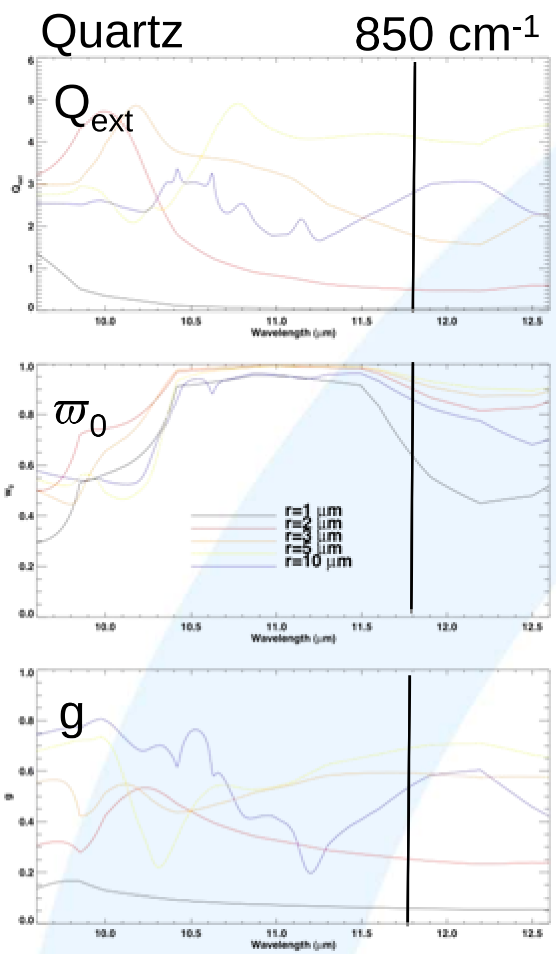
Microphysics retrieval

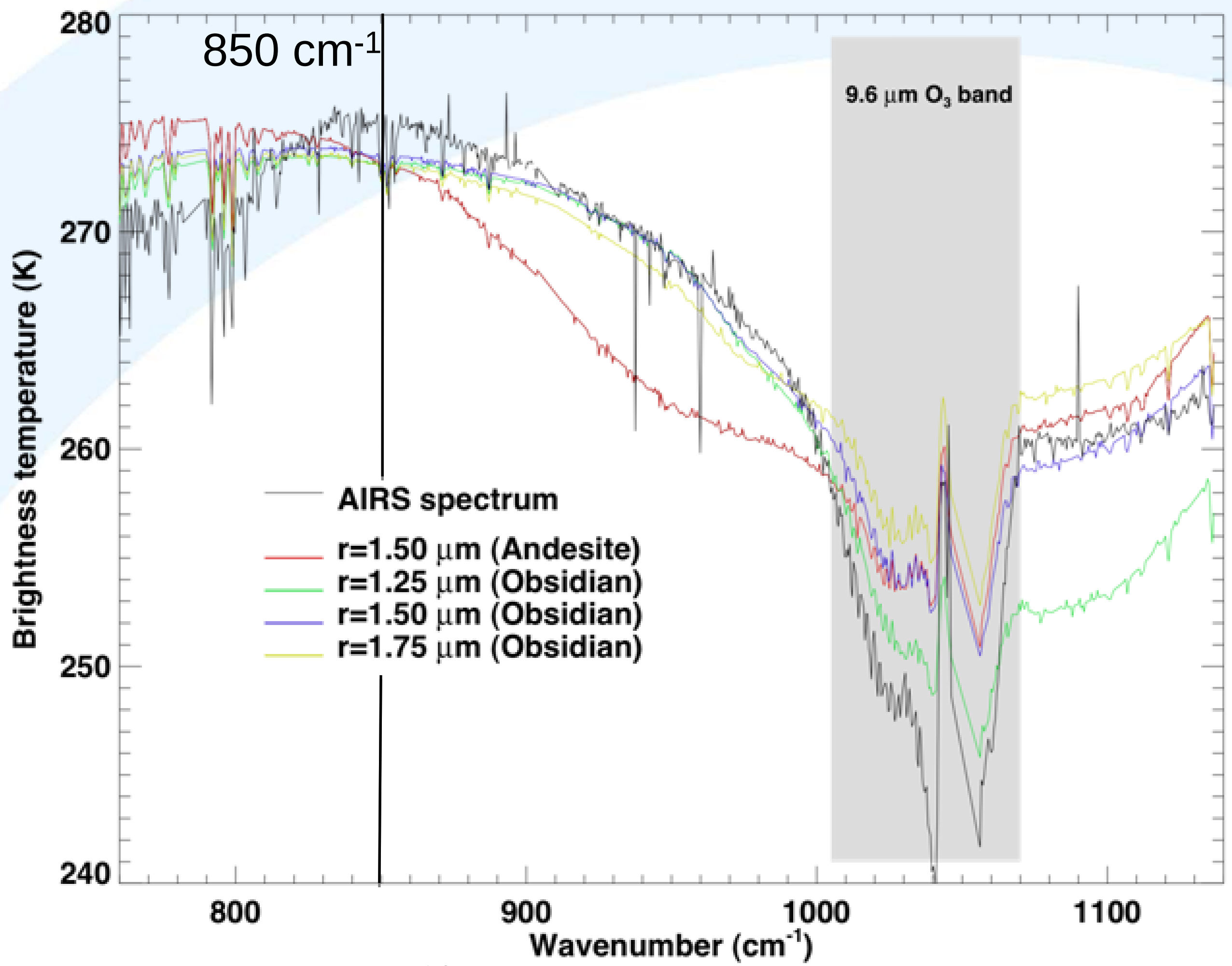
r_e– effective particle radius

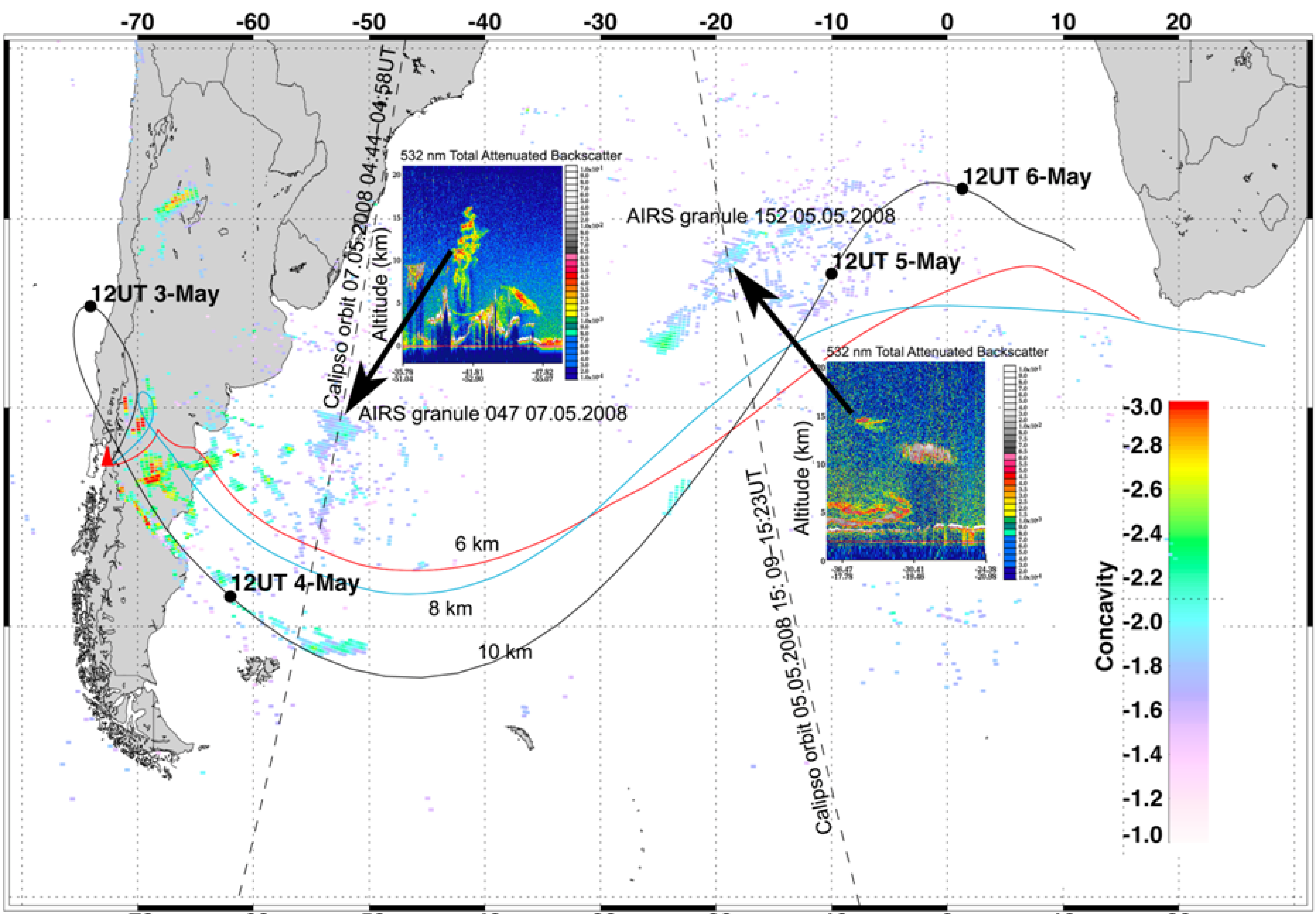
τ–infrared optical depth

M–mass loading

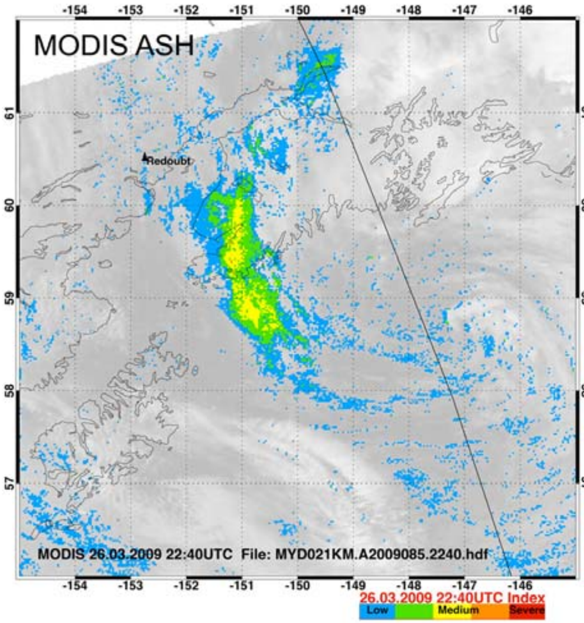
Si–silicate composition

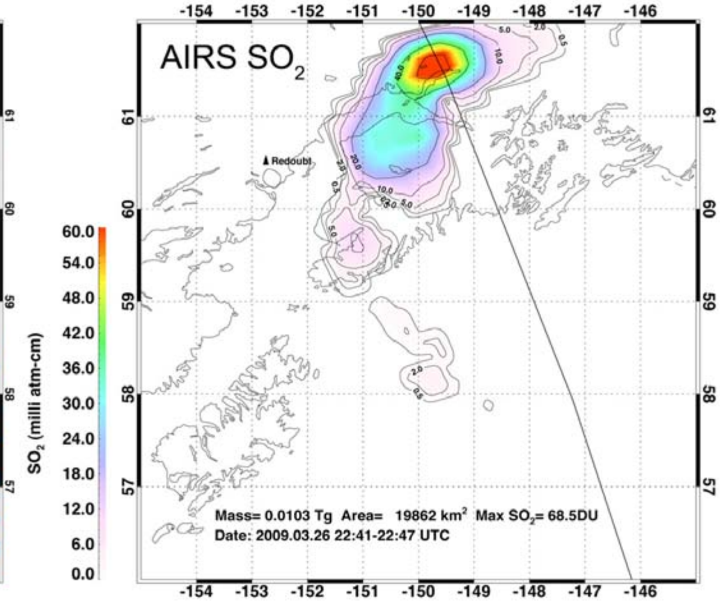


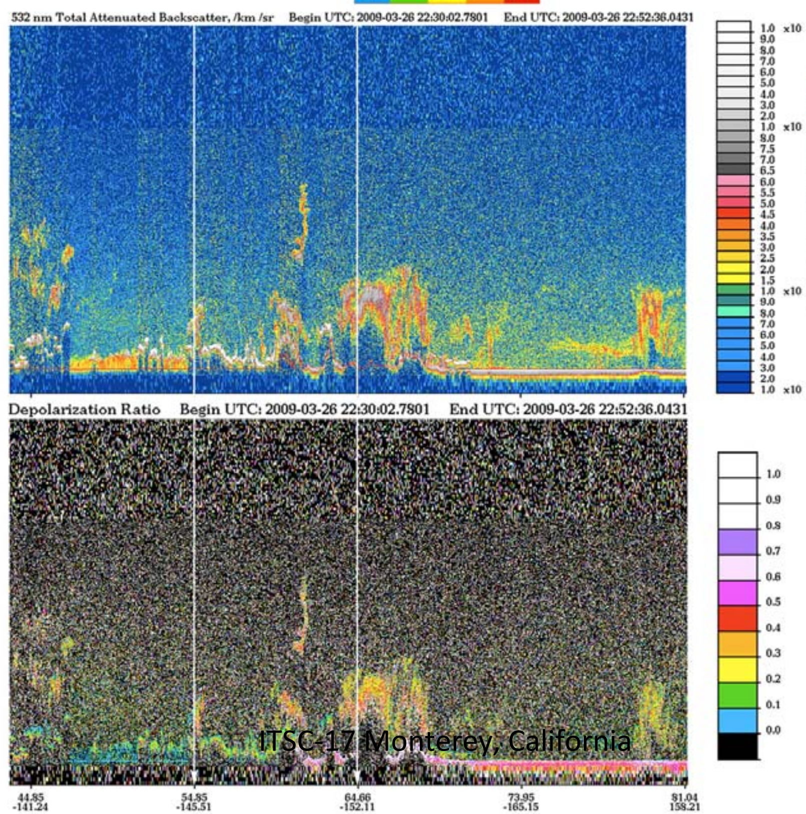



12UT 3-May
12UT 4-May
12UT 5-May
12UT 6-May
AIRS granule 152 05.05.2008
AIRS granule 047 07.05.2008
Calipso orbit 07.05.2008 04:44–04:58UT
Calipso orbit 05.05.2008 15:09–15:23UT
532 nm Total Attenuated Backscatter
Altitude (km)
6 km
8 km
10 km
Concavity
-3.0
-2.8
-2.6
-2.4
-2.2
-2.0
-1.8
-1.6
-1.4
-1.2
-1.0

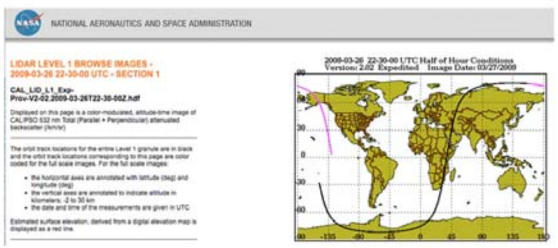
MODIS
AIRS
CALIOP
Comparisons



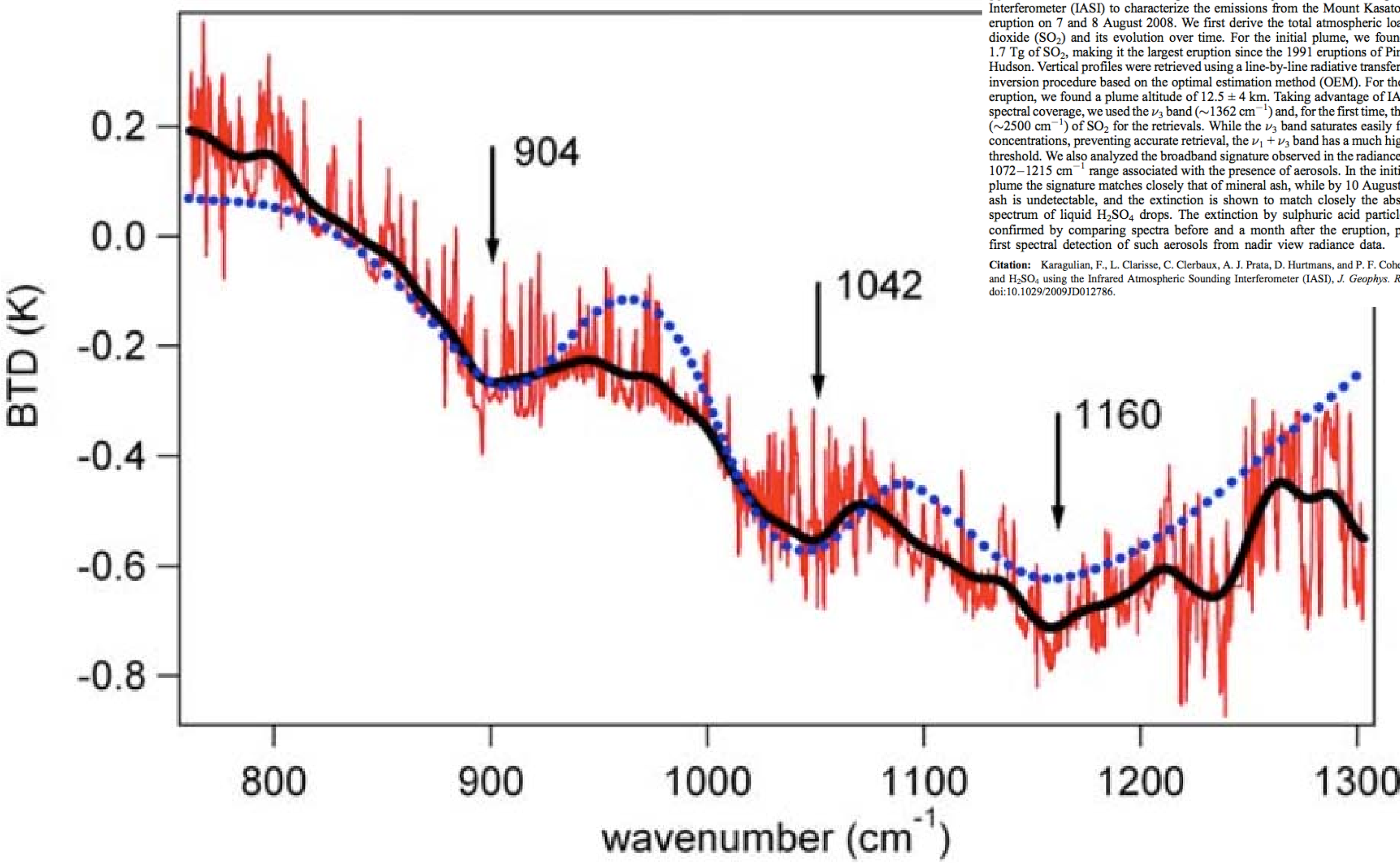




CALIPSO



IASI H_2SO_4 detection



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D00L02, doi:10.1029/2009JD012786, 2010

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Detection of volcanic SO_2, ash, and H_2SO_4 using the Infrared Atmospheric Sounding Interferometer (IASI)

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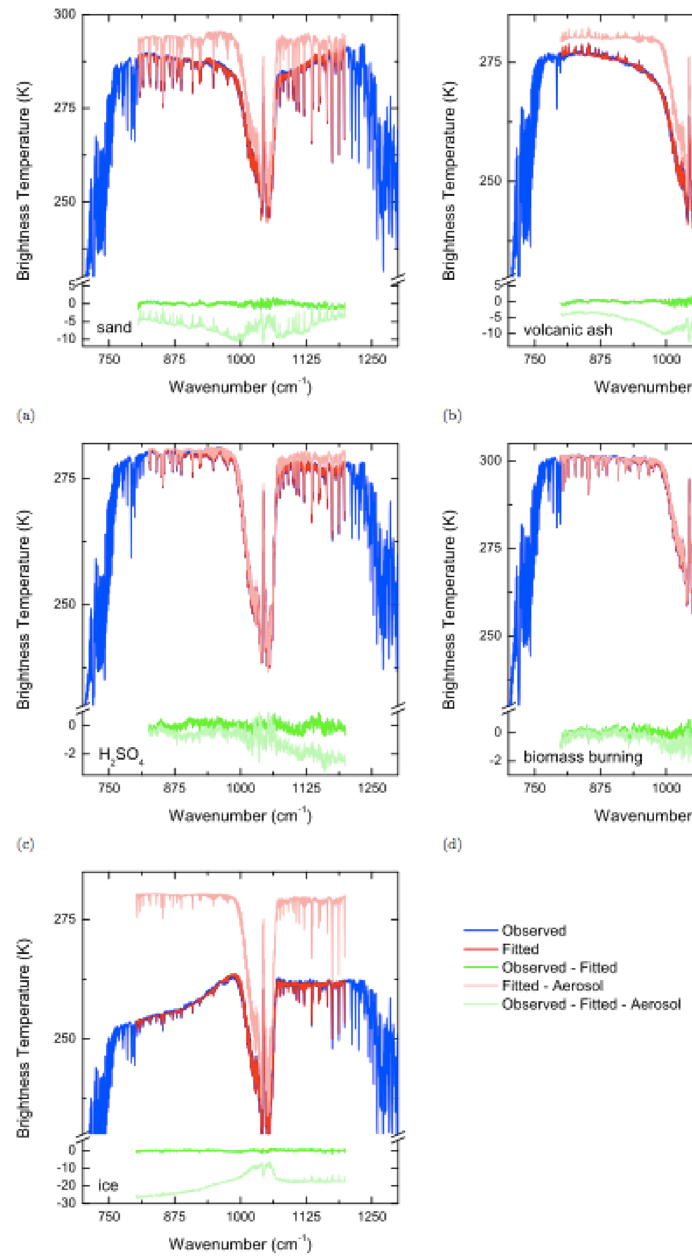
[1] In this work we use infrared spectra recorded by the Infrared Atmospheric Sounding Interferometer (IASI) to characterize the emissions from the Mount Kasatochi volcanic eruption on 7 and 8 August 2008. We first derive the total atmospheric load of sulfur dioxide (SO_2) and its evolution over time. For the initial plume, we found values over 1.7 Tg of SO_2, making it the largest eruption since the 1991 eruptions of Pinatubo and Hudson. Vertical profiles were retrieved using a line-by-line radiative transfer model and an inversion procedure based on the optimal estimation method (OEM). For the Kasatochi eruption, we found a plume altitude of 12.5 ± 4 km. Taking advantage of IASI's broad spectral coverage, we used the ν_3 band (~1362 cm^{-1}) and, for the first time, the $\nu_1 + \nu_3$ band (~2500 cm^{-1}) of SO_2 for the retrievals. While the ν_3 band saturates easily for high SO_2 concentrations, preventing accurate retrieval, the $\nu_1 + \nu_3$ band has a much higher saturation threshold. We also analyzed the broadband signature observed in the radiance spectra in the 1072–1215 cm^{-1} range associated with the presence of aerosols. In the initial volcanic plume the signature matches closely that of mineral ash, while by 10 August most mineral ash is undetectable, and the extinction is shown to match closely the absorption spectrum of liquid H_2SO_4 drops. The extinction by sulphuric acid particles was confirmed by comparing spectra before and a month after the eruption, providing the first spectral detection of such aerosols from nadir view radiance data.

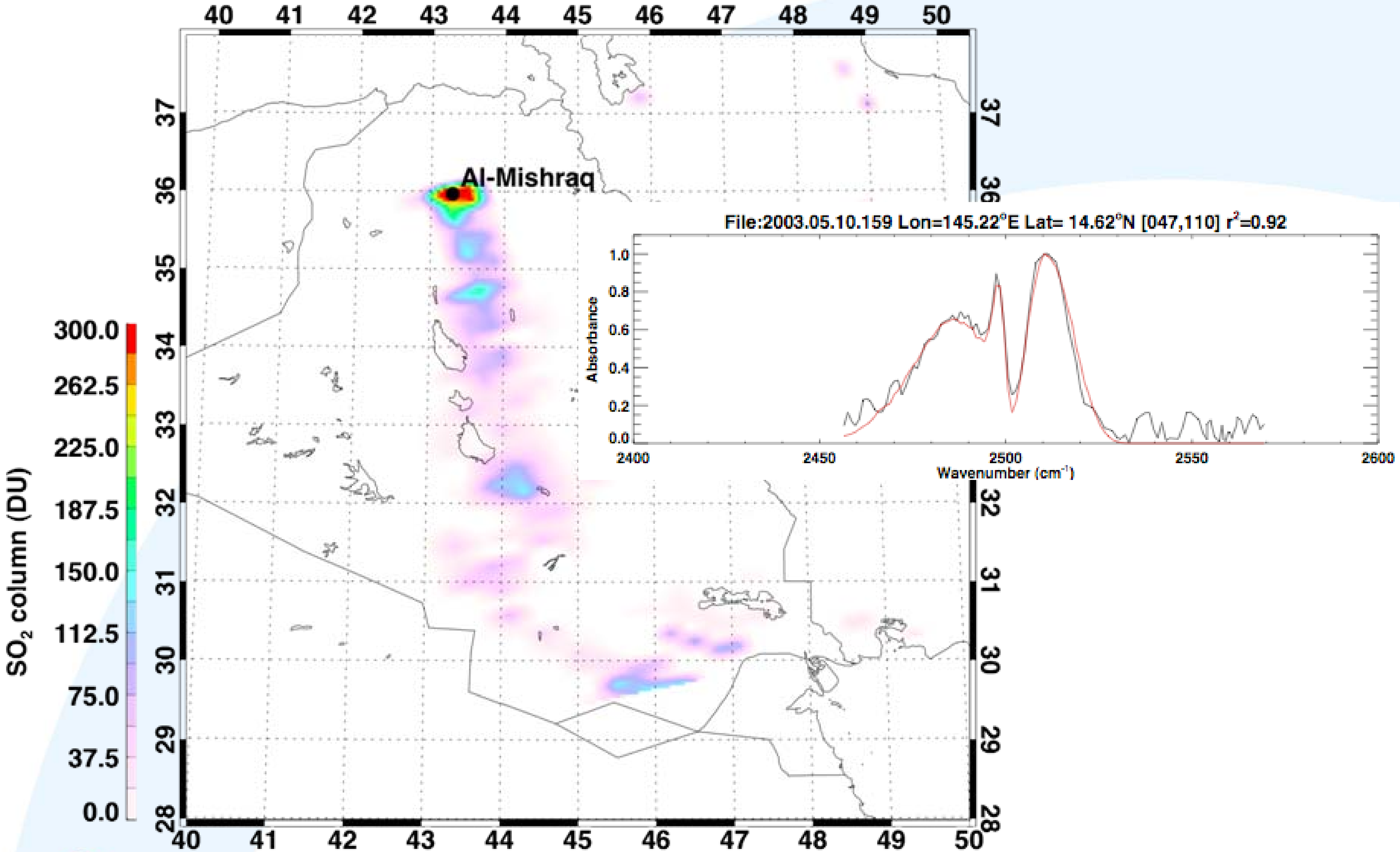
Citation: Karagulian, F., L. Clarisse, C. Clerbaux, A. J. Prata, D. Hurtmans, and P. F. Coheur (2010), Detection of volcanic SO_2, ash, and H_2SO_4 using the Infrared Atmospheric Sounding Interferometer (IASI), *J. Geophys. Res.*, *115*, D00L02, doi:10.1029/2009JD012786.

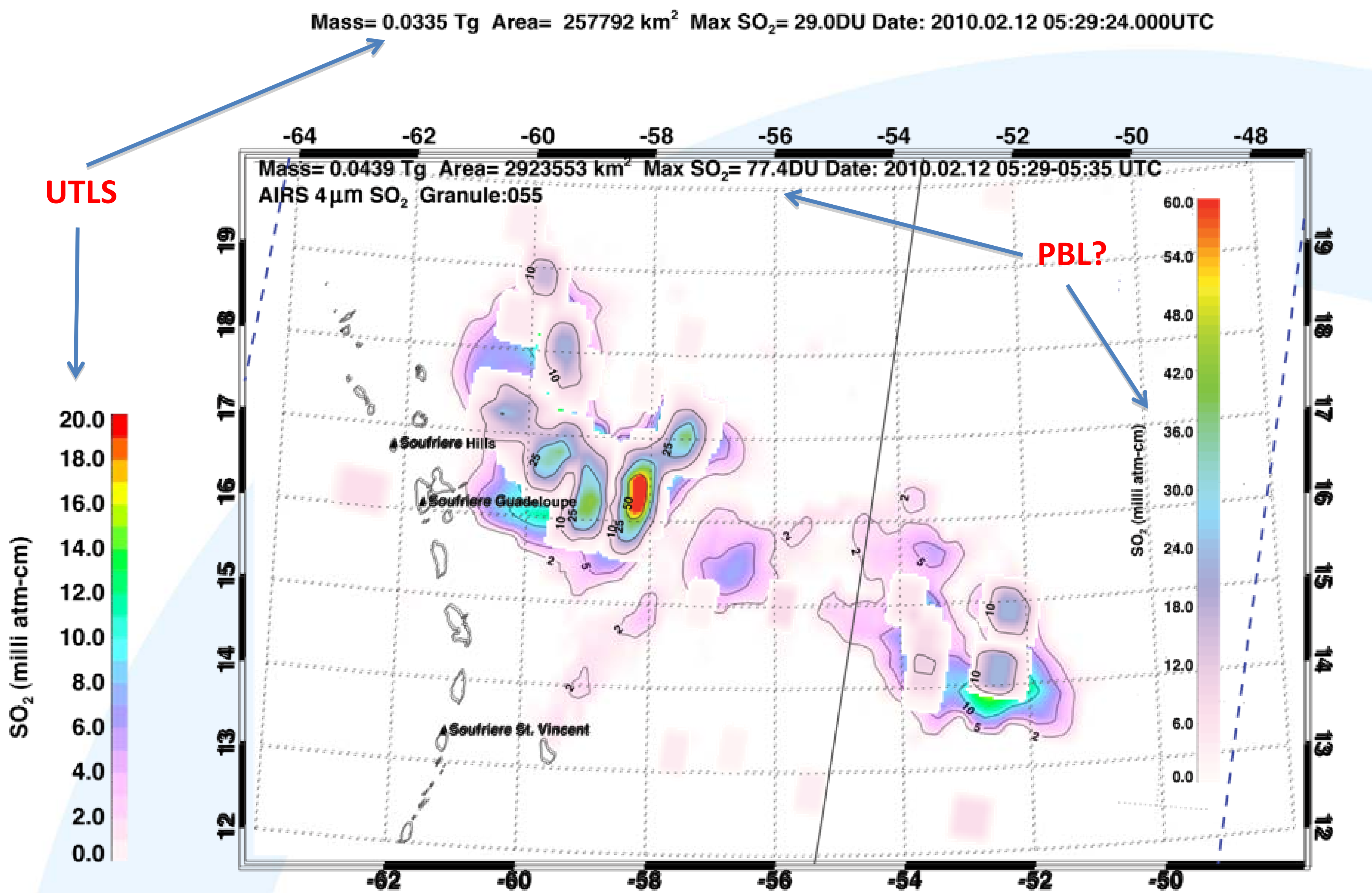
Detection of other species



L. Clarisse, D. Hurtmans, A.J. Prata, F. Karagulian, C. Clerbaux, M. De Mazi`ere and P.-F. Coheur, Retrieving radius, concentration, optical depth and mass of different types of aerosols from high resolution infrared nadir spectra, *Submitted to Applied Optics, 2010.*

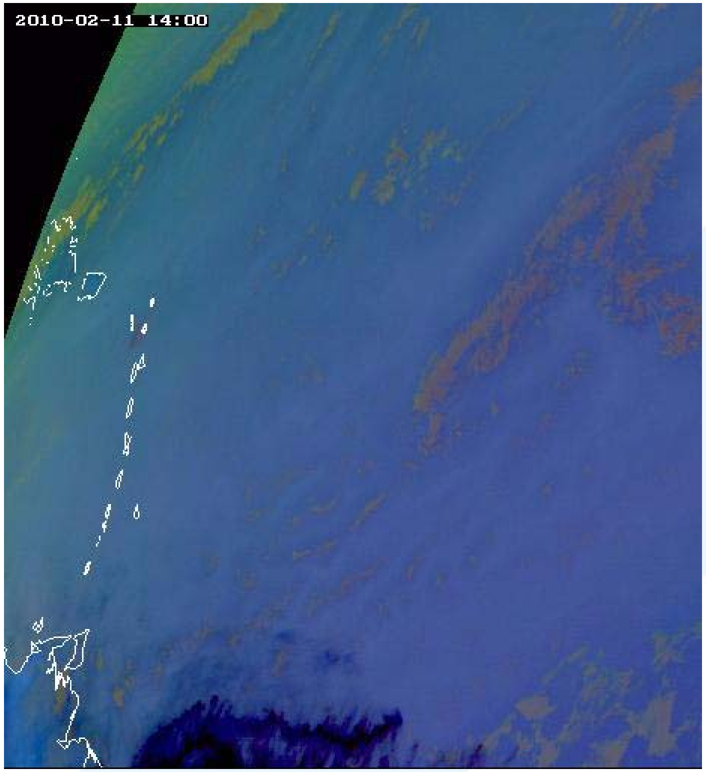
Boundary layer SO_2 at 4 µm

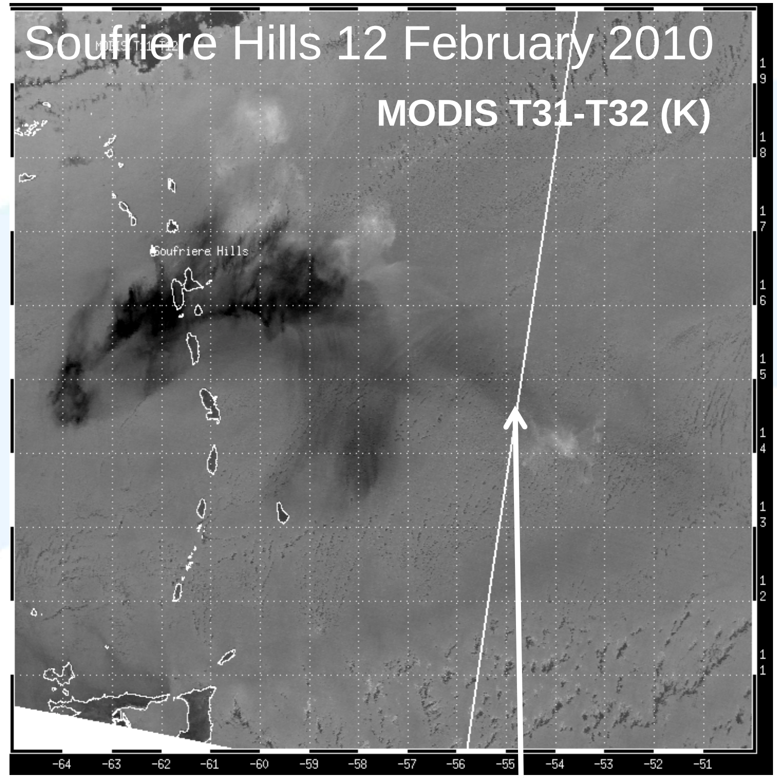


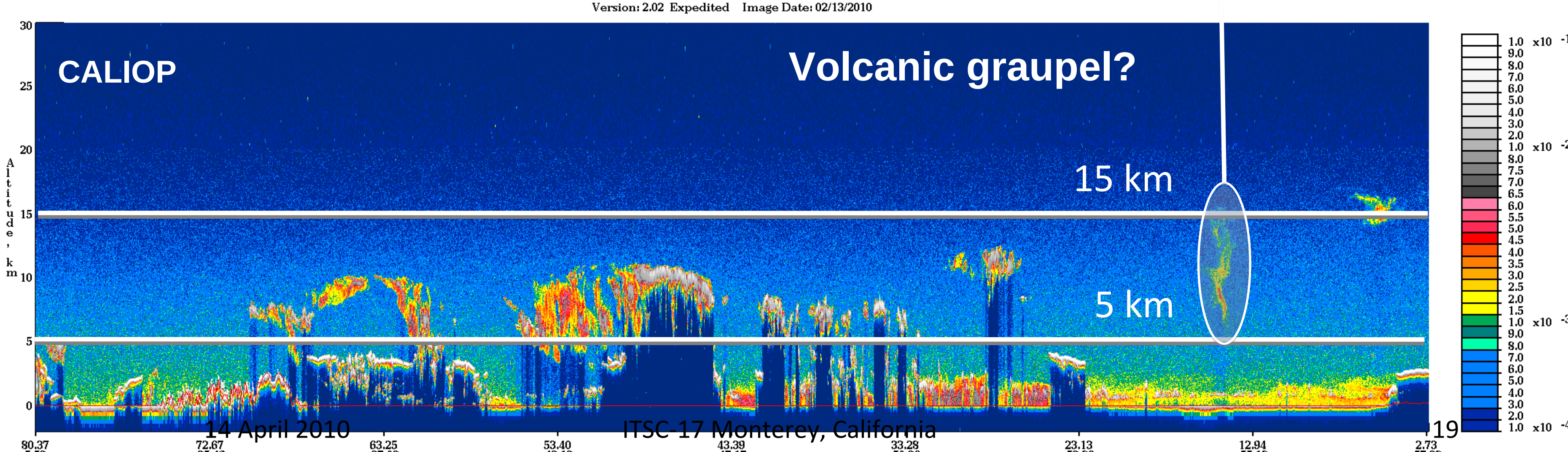


Soufriere Hills, 12 February 2010

SEVIRI


2010-02-11 14:00


Soufriere Hills 12 February 2010
MODIS T31-T32 (K)
Soufriere Hills
-64 -63 -62 -61 -60 -59 -58 -57 -56 -55 -54 -53 -52 -51


532 nm Total Attenuated Backscatter, /km /sr Begin UTC: 2010-02-12 05:15:12.6771 End UTC: 2010-02-12 05:37:45.9742
Version: 2.02 Expedited Image Date: 02/13/2010
CALIOP
Volcanic graupel?
15 km
5 km
Altitude, km
30
25
20
15
10
5
0
80.37 5.53
72.67 -25.49
63.25 -37.02
53.40 -43.12
43.39 -47.17
33.28 -50.26
23.13 -52.86
12.94 -55.18
2.73 -57.38
1.0 x10 -1
1.0 x10 -2
1.0 x10 -3
1.0 x10 -4

Combining satellite data with a Lagrangian dispersion model

- Volcanic ash and SO_2 can be placed into the atmosphere at different levels

- Wind shear ensures that ash and SO_2 travel in different directions and at different speeds

- Is there a better way to utilise dispersion models and satellite data to provide predictions for aviation?

Inverse Modelling- Analytic method

Source-receptor matrix calculation with a Lagrangian particle dispersion model in backward mode, P. Seibert and A. Frank, ACP, 4, 51-63, 2004.

Sources $\mathbf{x}$ (1..n) $\mathbf{x}^a$ a priory profile

Satellite observation $\mathbf{y}^0$ (1..m)

M Emission sensitivity Matrix (m × n), as obtained from FLEXPART

σ standard error of observation

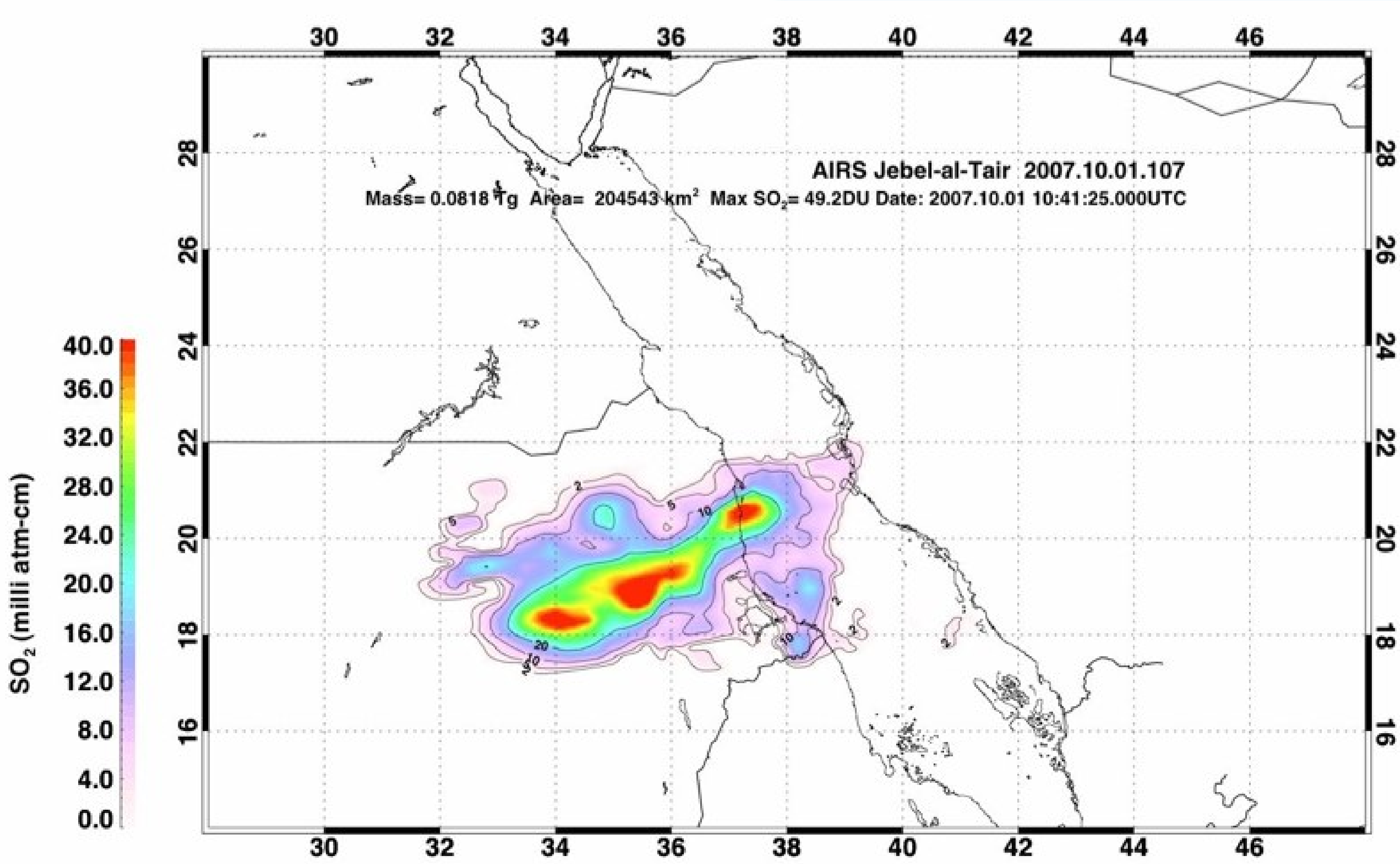
$$\mathbf{M}(\mathbf{x}-\mathbf{x}^a) \approx \mathbf{y}^o - \mathbf{M}\mathbf{x}^a$$

$$\mathbf{M}\tilde{\mathbf{x}} \approx \tilde{\mathbf{y}}\,.$$

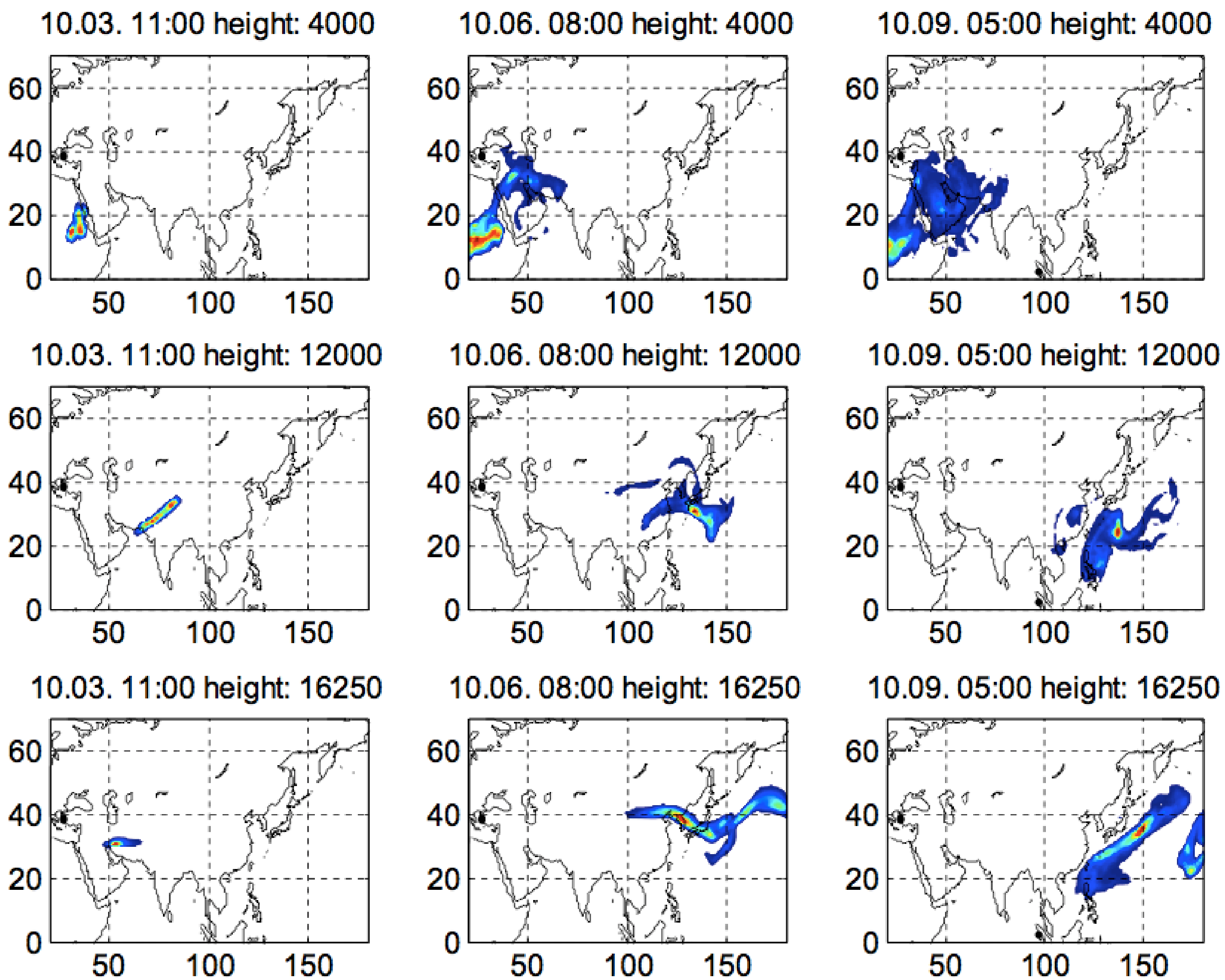
$$J = \underbrace{(\mathbf{M}\tilde{\mathbf{x}}-\tilde{\mathbf{y}})^T \mathbf{diag}(\sigma_o^{-2})(\mathbf{M}\tilde{\mathbf{x}}-\tilde{\mathbf{y}})}_{\text{I) misfit model – observation}}$$

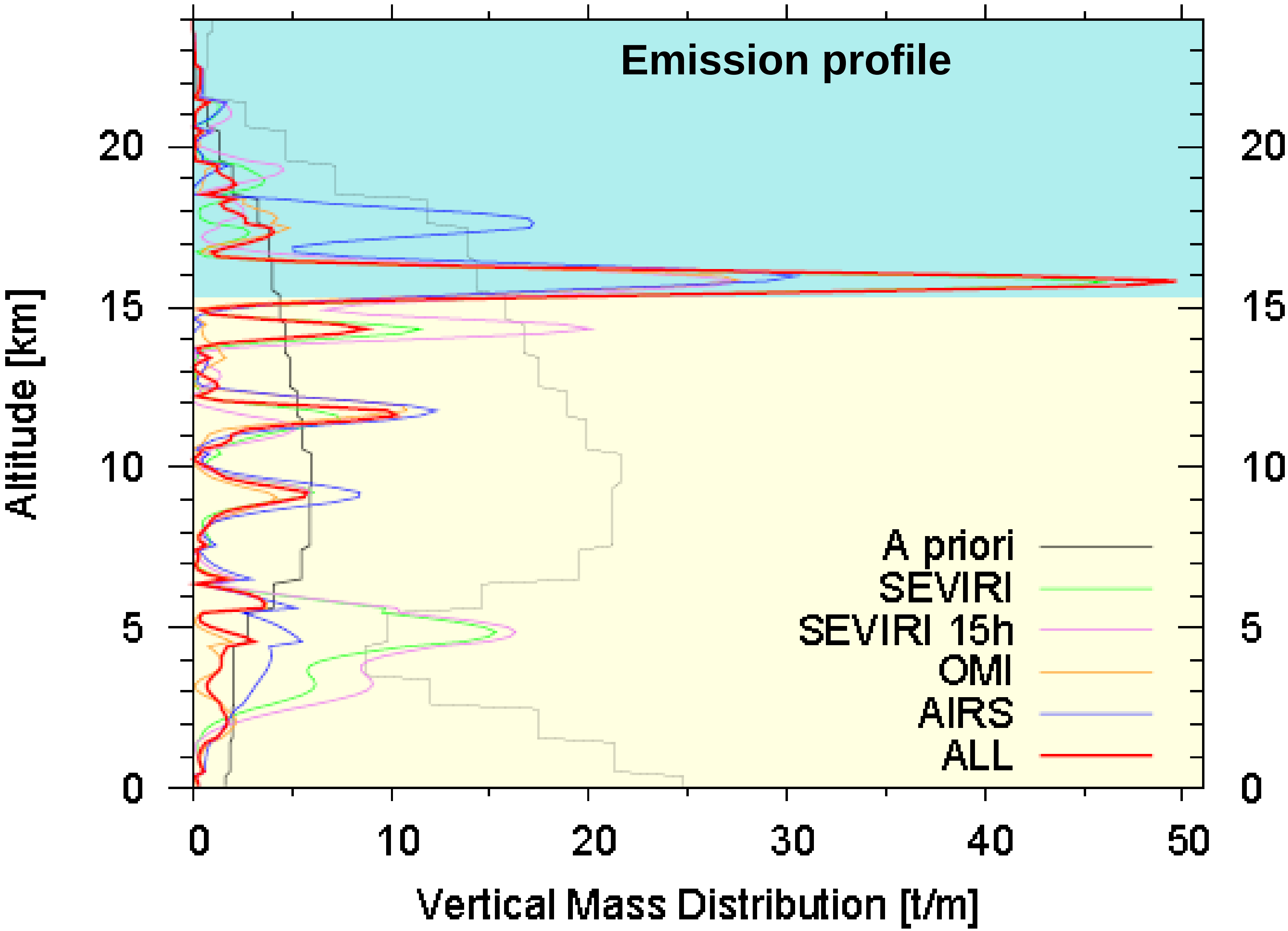
$$+ \underbrace{\tilde{\mathbf{x}}^T \mathbf{diag}(\sigma_{\mathbf{x}}^{-2})\,\tilde{\mathbf{x}}}_{\text{II) deviation from first guess}} + \underbrace{\epsilon\,(\mathbf{D}\tilde{\mathbf{x}})^T \mathbf{D}\tilde{\mathbf{x}}}_{\text{III) smoothness condition}}.$$

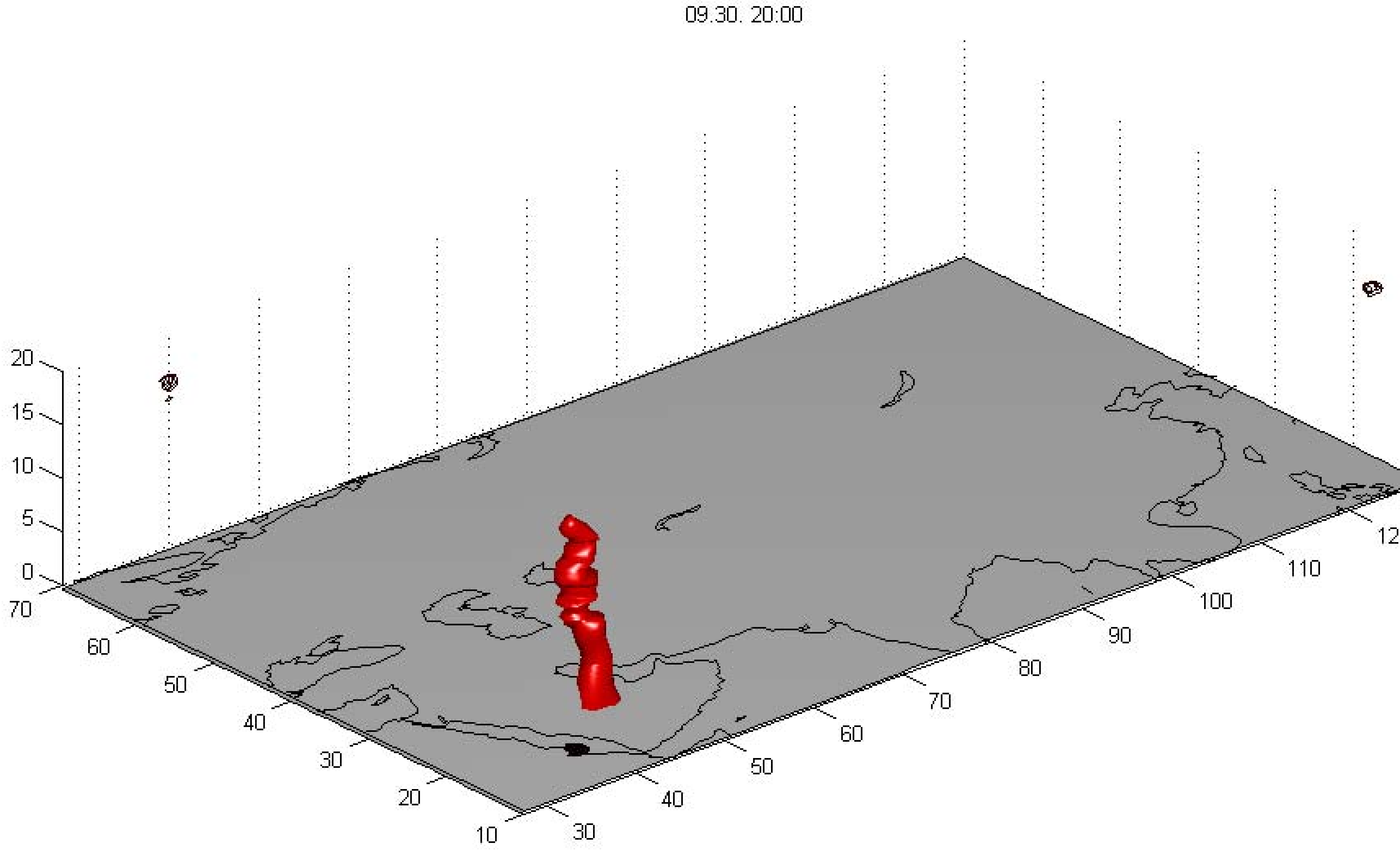
Satellite Data–AIRS



Model–FLEXPART




Emission profile
Altitude [km]
Vertical Mass Distribution [t/m]
0
10
20
30
40
50
0
5
10
15
20
A priori
SEVIRI
SEVIRI 15h
OMI
AIRS
ALL


09.30. 20:00
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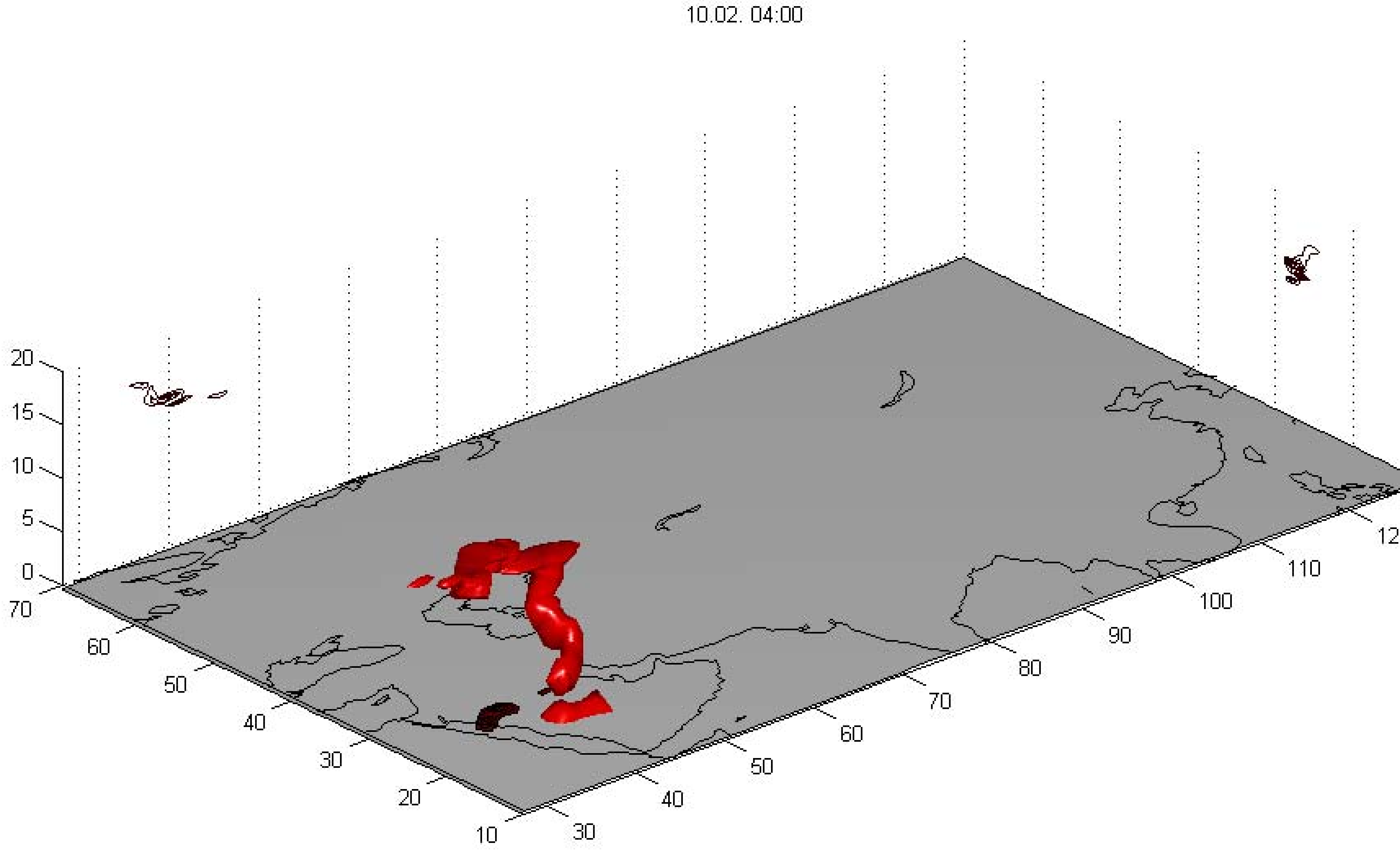
12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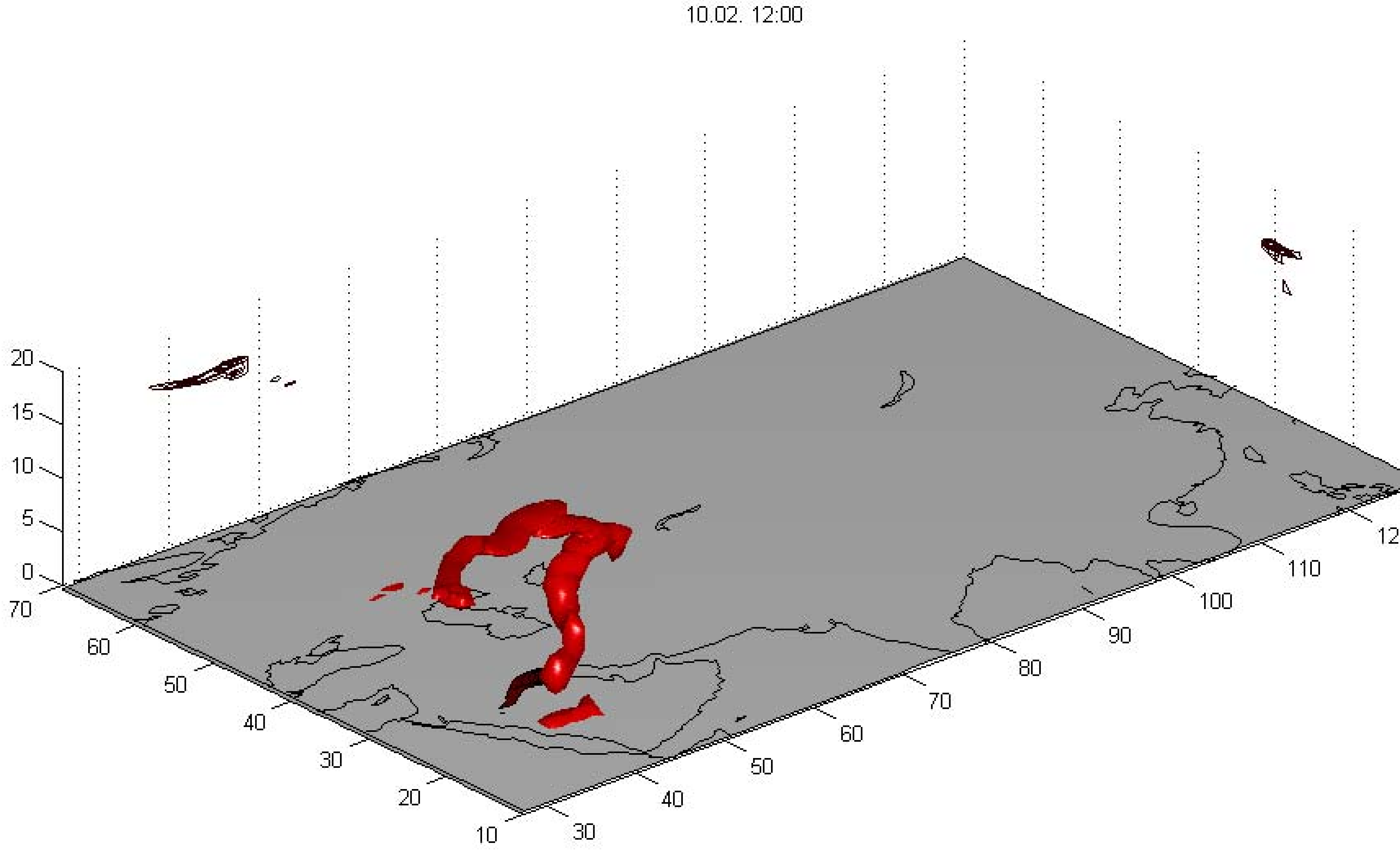
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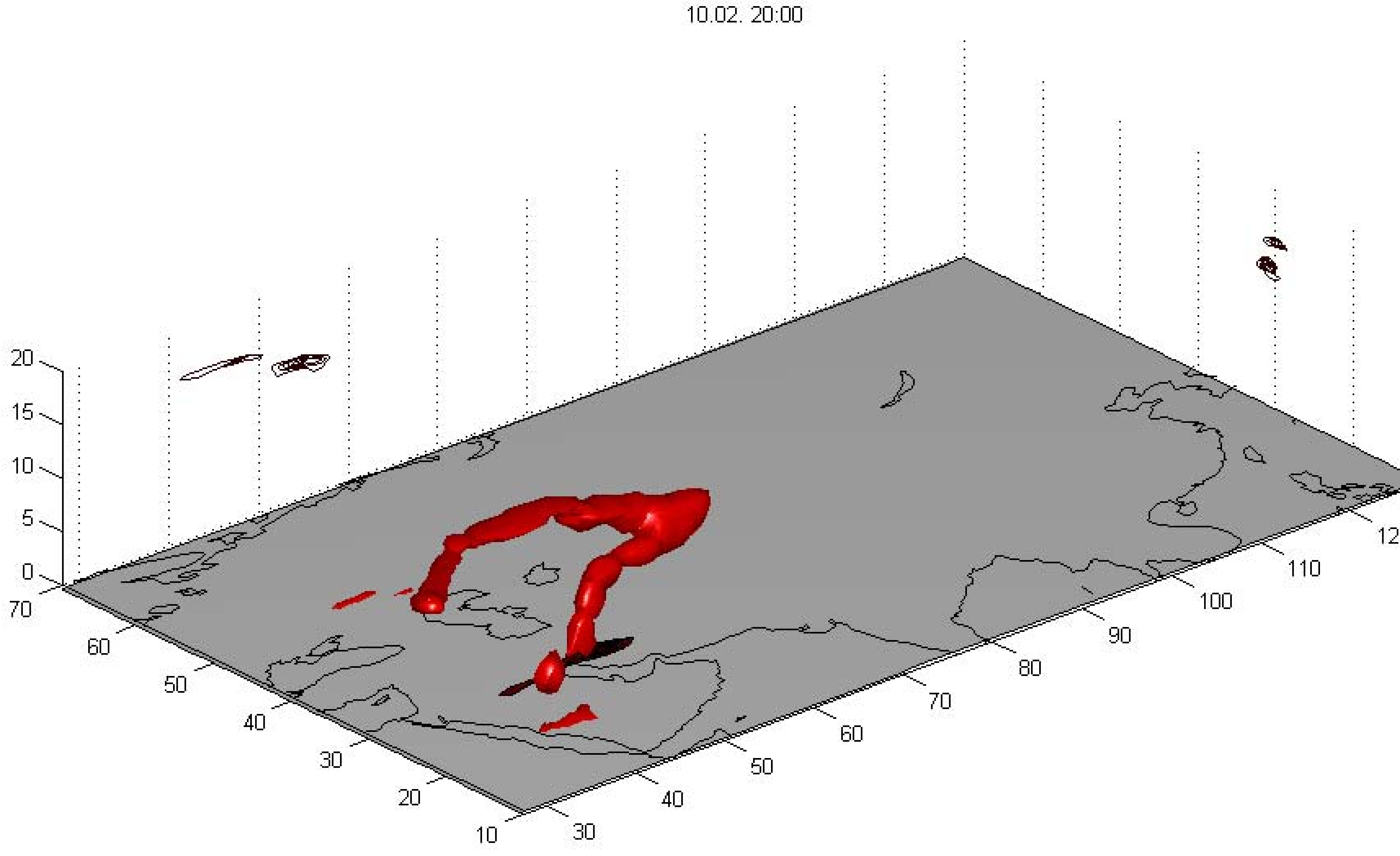
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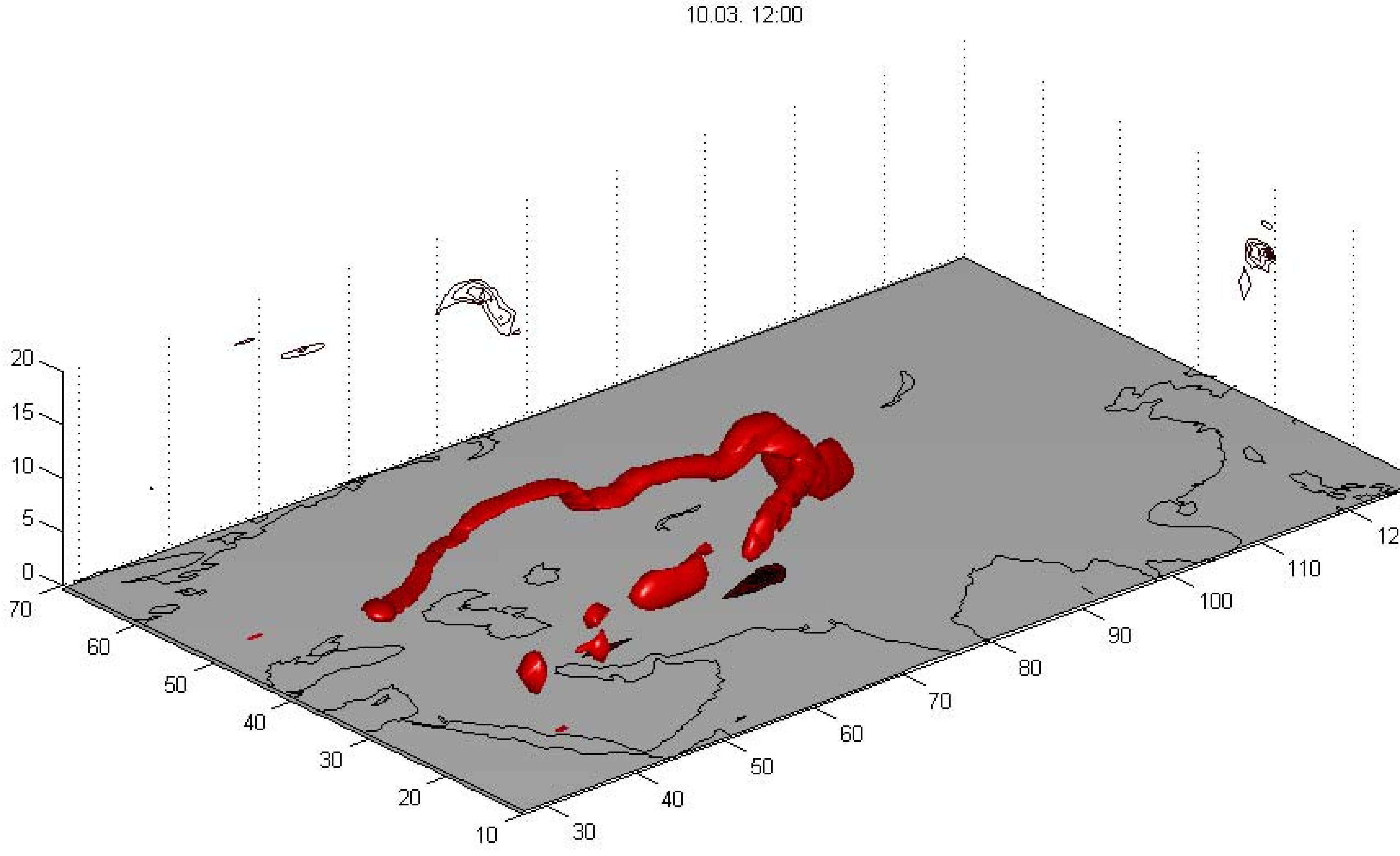

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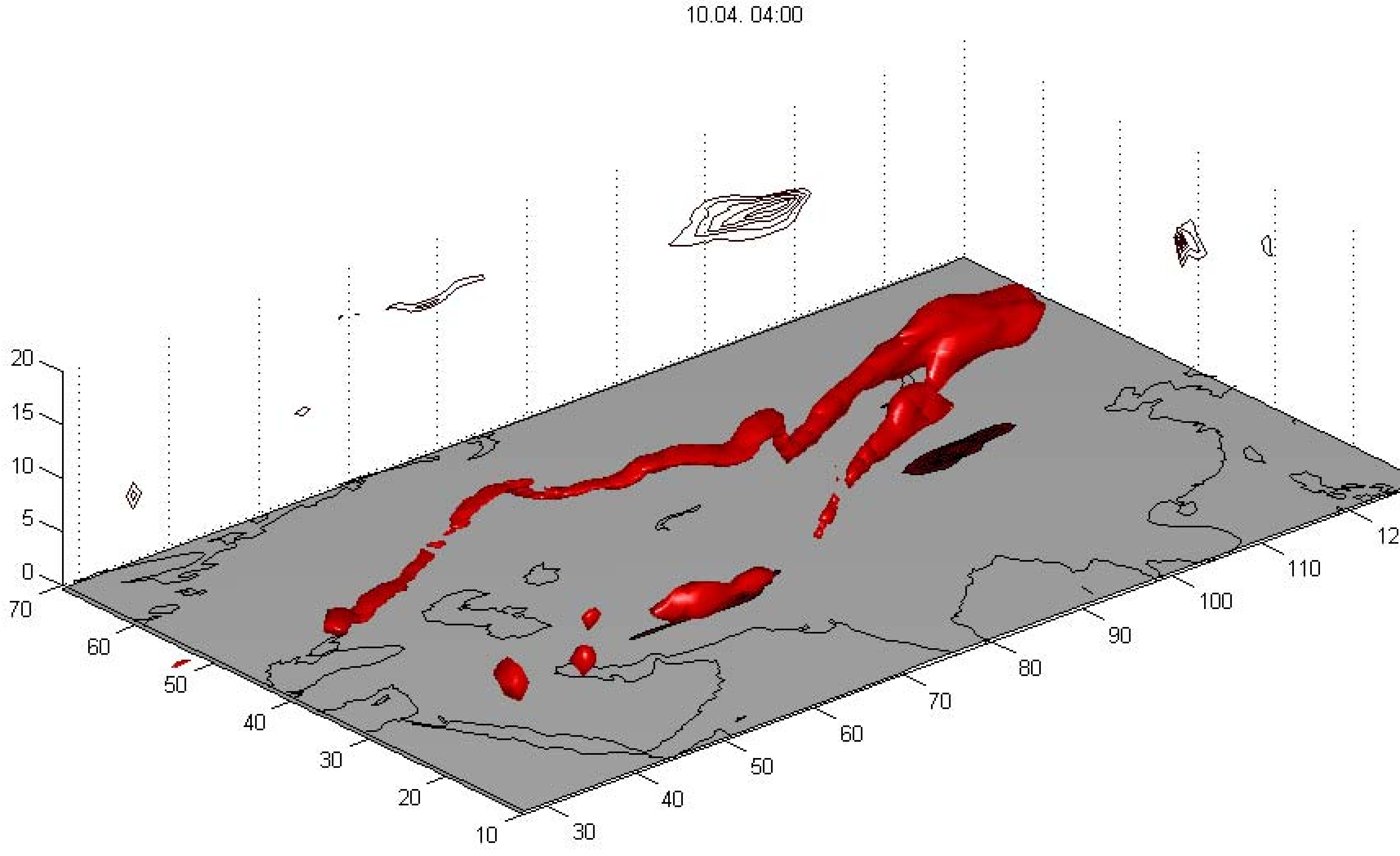
10.04. 04:00
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