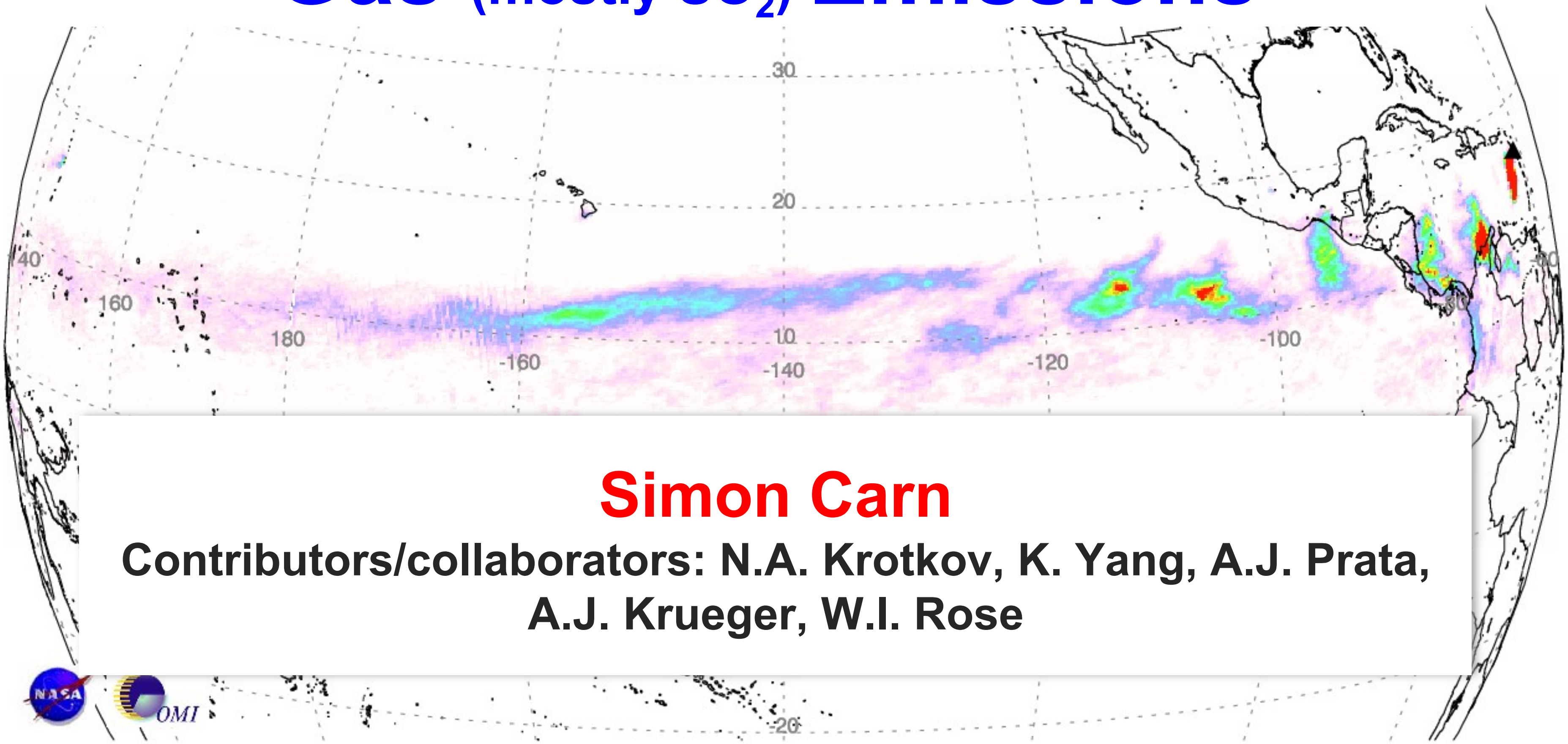
Remote Sensing of Volcanic Gas (mostly SO_2) Emissions



Simon Carn

Contributors/collaborators: N.A. Krotkov, K. Yang, A.J. Prata, A.J. Krueger, W.I. Rose

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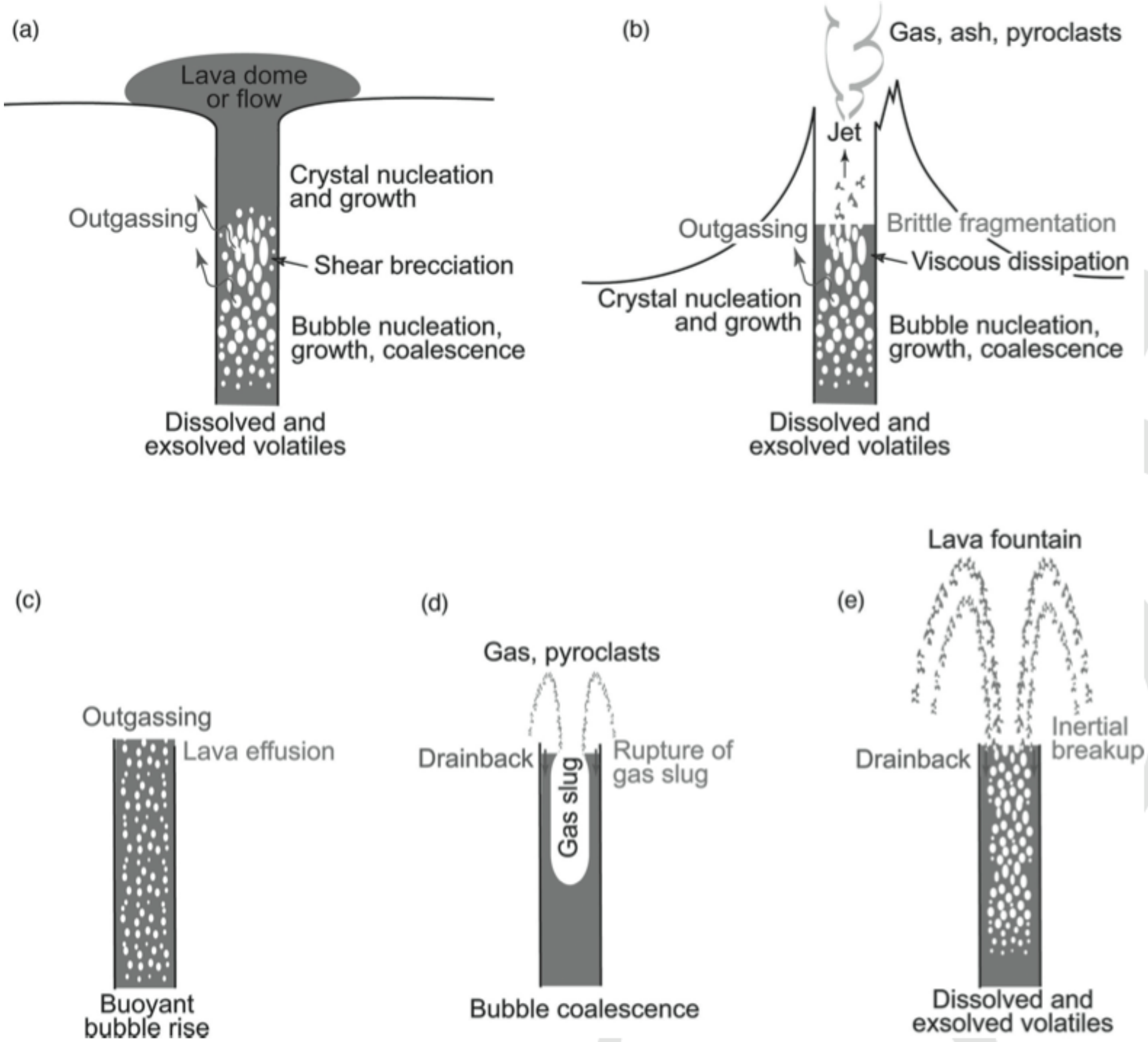
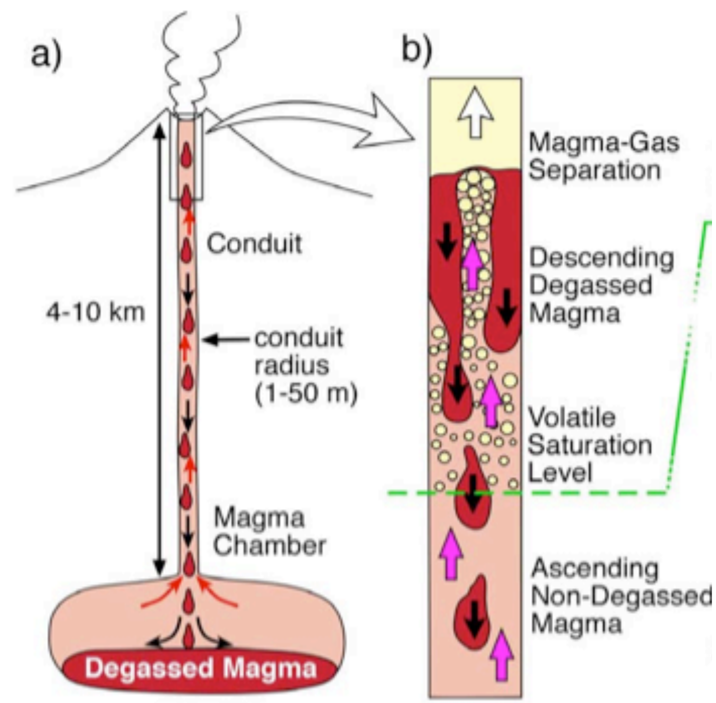
Volcano Monitoring Techniques workshop, COV7, Colima, Nov 2012

Ascent and degassing of magma



Gonnermann and Manga (2012)

Conduit convection



Shinohara (2008)

Goal: elucidate conduit processes using geochemical (gas) and geophysical data

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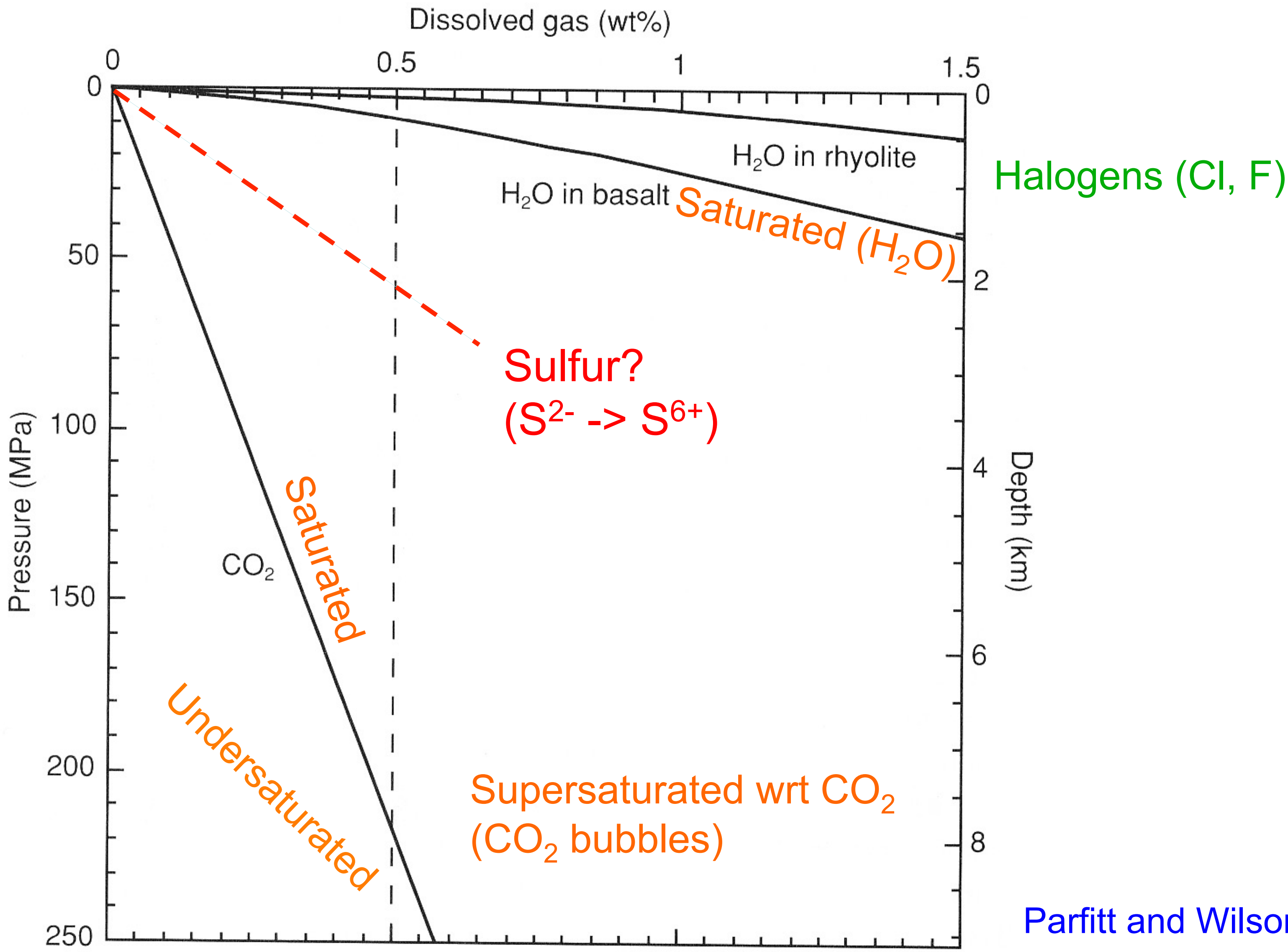
Volcanic gas compositions

mol%	Nyiragongo (DR Congo) RIFT	Kilauea* (Hawaii) HOTSPOT	Merapi* (Indonesia) SUBDUCTION	Etna* (Sicily) SUBDUCTION
H_2O	70	37	91	48
CO_2	24	49	5	20
SO_2	5	12	1	31
CO	1	2	0.1	0.4
HCl	0.3	0.08	0.6	-
HF	0.1	-	0.04	-

Trace constituents: CH_4, N_2, BrO, Zn, Cu, Hg, Au, As, Re, He, Ne, Ar…..

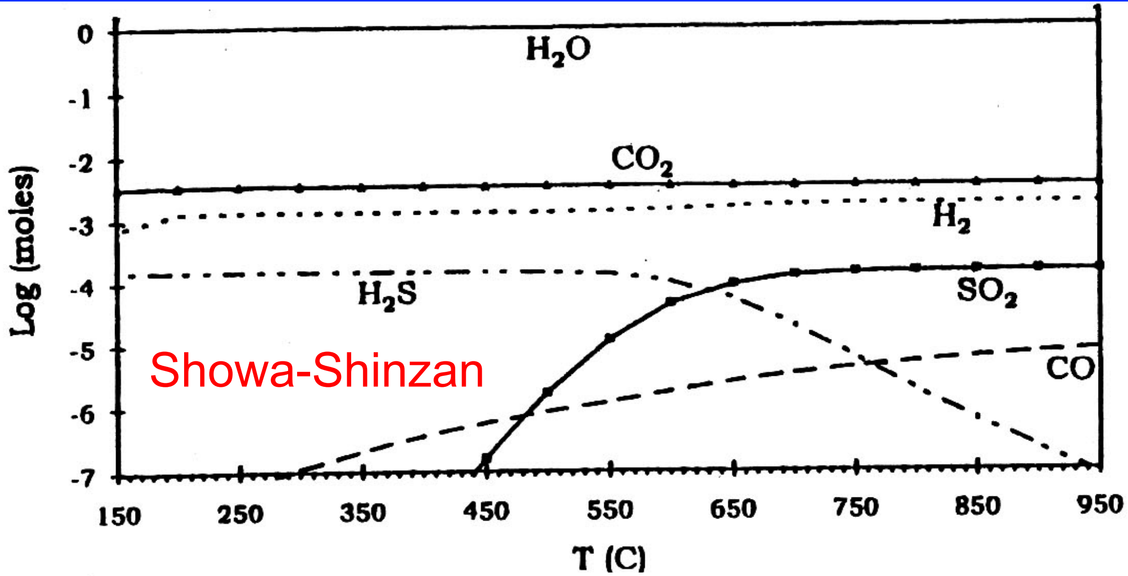
*Symonds *et al.* [1994]

Volatile solubility in magma



Parfitt and Wilson

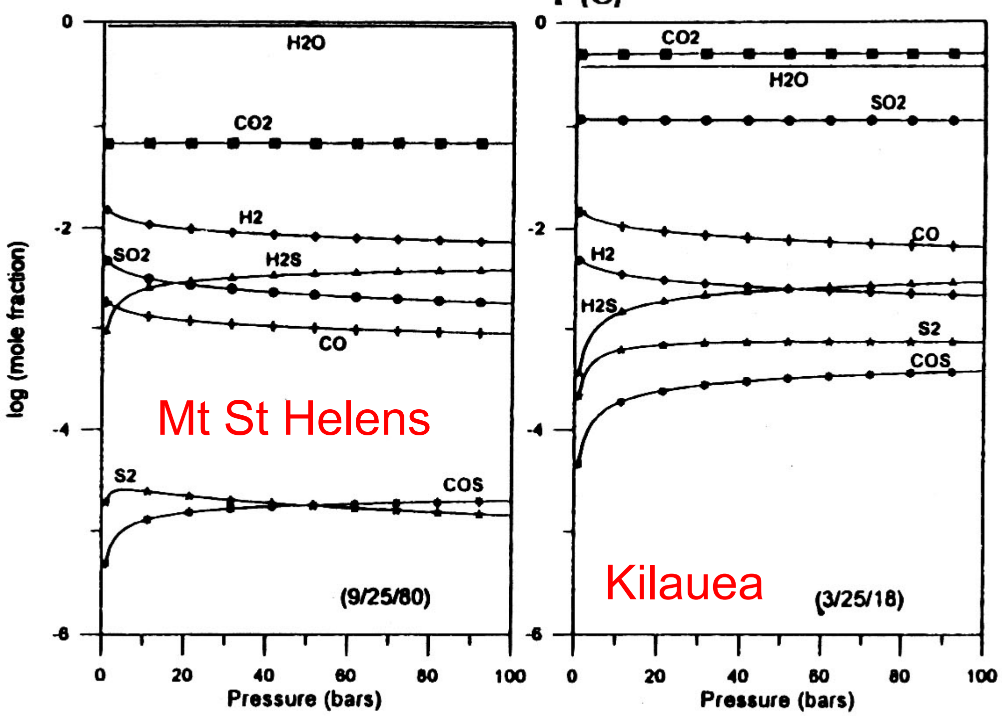
Temperature and pressure effects on volcanic gas species



Pressure →

$$SO_2 + 3H_2 = H_2S + 2H_2O$$

← Temperature



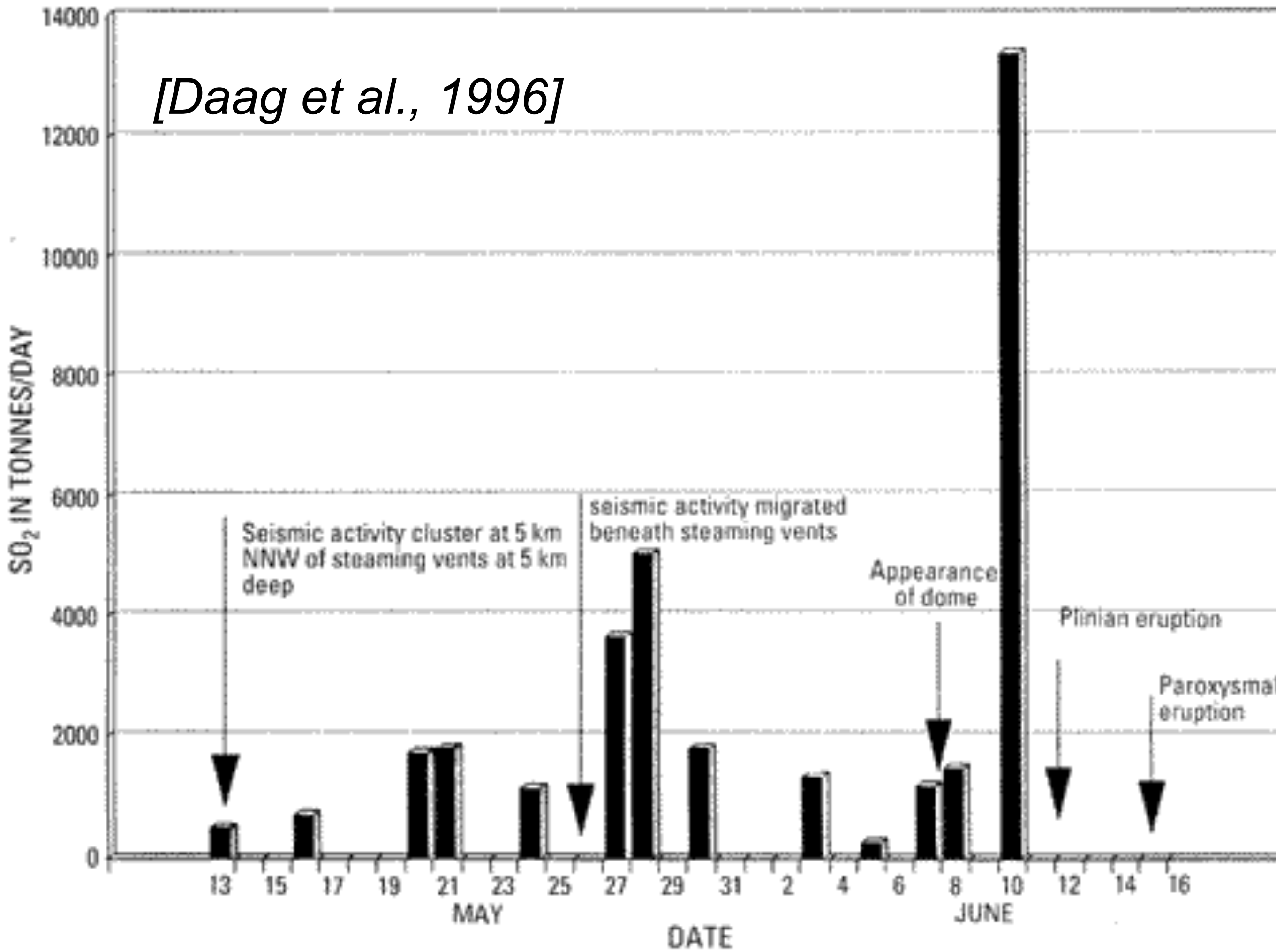
$\log (SO_2/H_2S) =$

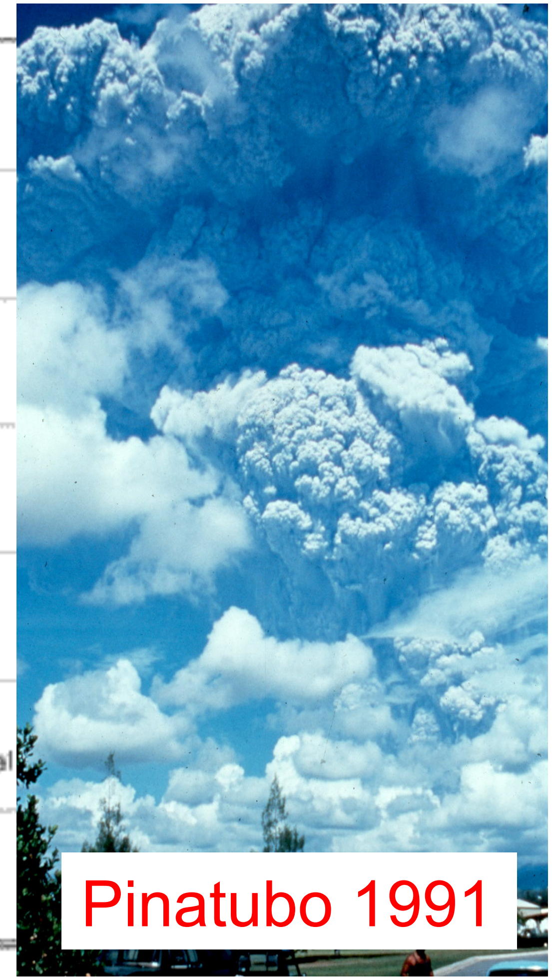
$\log K_T - 3 \log (H_2/H_2O) -$

$\log P \,.\, X_{H2O}$

[Symonds et al., Rev. Mineral., 1994; Aiuppa et al., 2004]

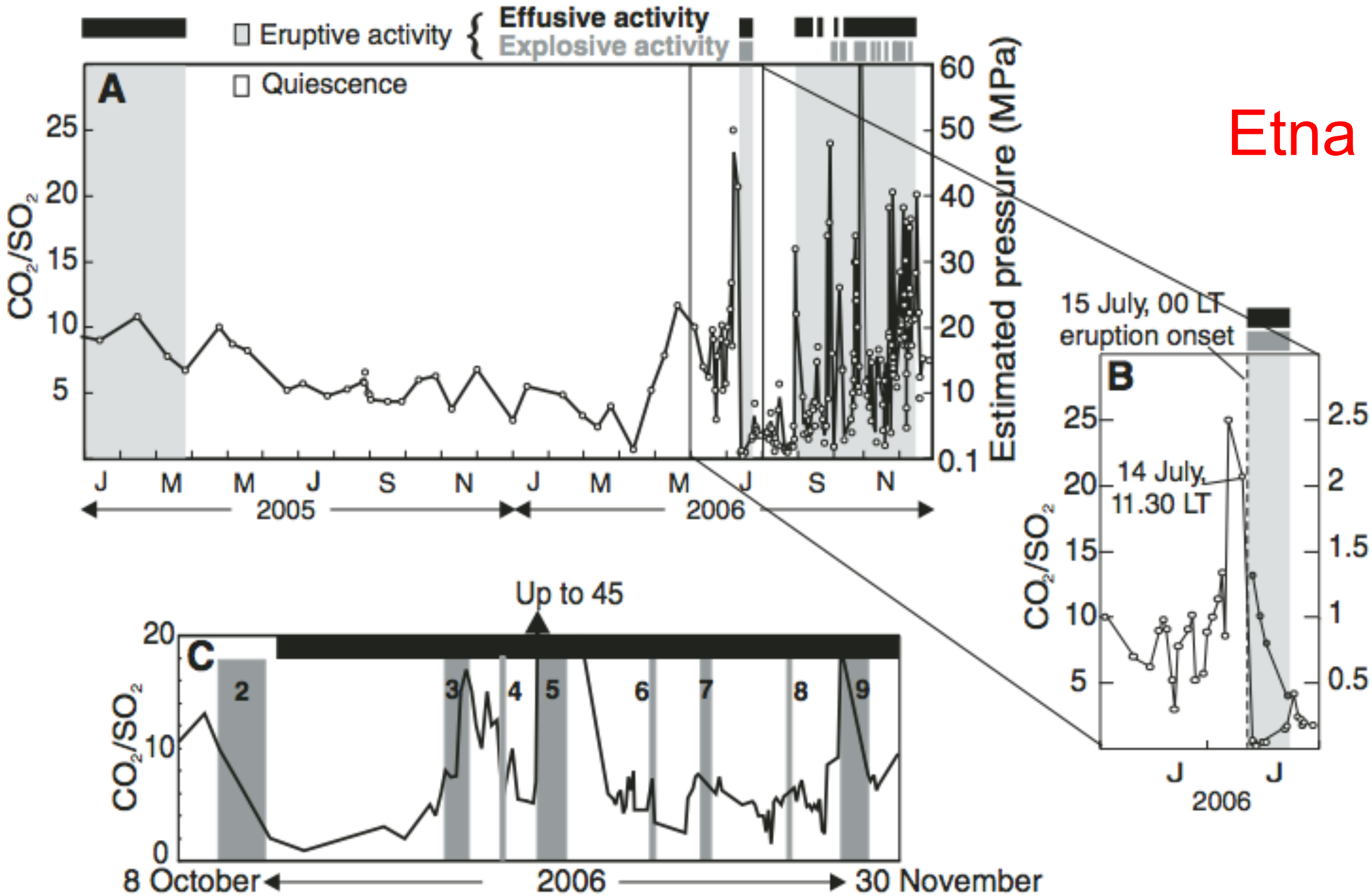
Pre-eruptive volcanic SO_2 degassing





- Increase in SO_2 emissions prior to a major eruption
- Reduced SO_2 emissions prior to eruptions have also been observed

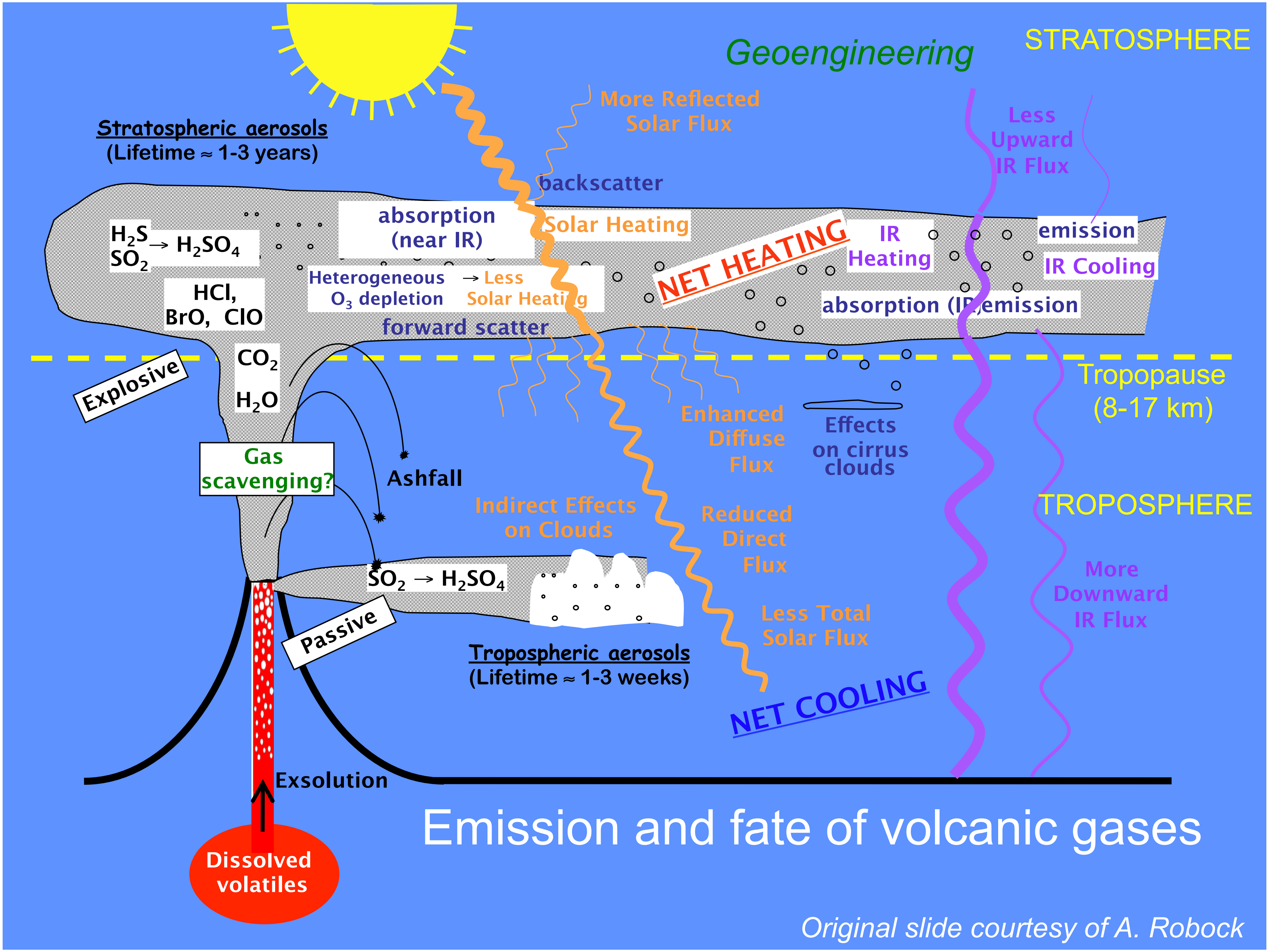
Changes in gas ratios prior to eruptions



Etna (Sicily)

Figure 2. A: Time evolution of CO_2/SO_2 molar ratios in Etna central crater's plume. Right axis shows estimated pressures (in MPa) evaluated by combining volcanic gas data with model results. Timing of 2004–2005 and 2006 eruptions are also shown. B: Detail of June–July 2006 period. Gray dots refer to composition of plume released at eruptive vent (right scale). LT—local time. C: Detail of the October–November 2006 period. Dark gray bars indicate timing of Strombolian events 2–9 that occurred at south-east summit crater (SEC).

[Aiuppa et al., Geology, 2007]

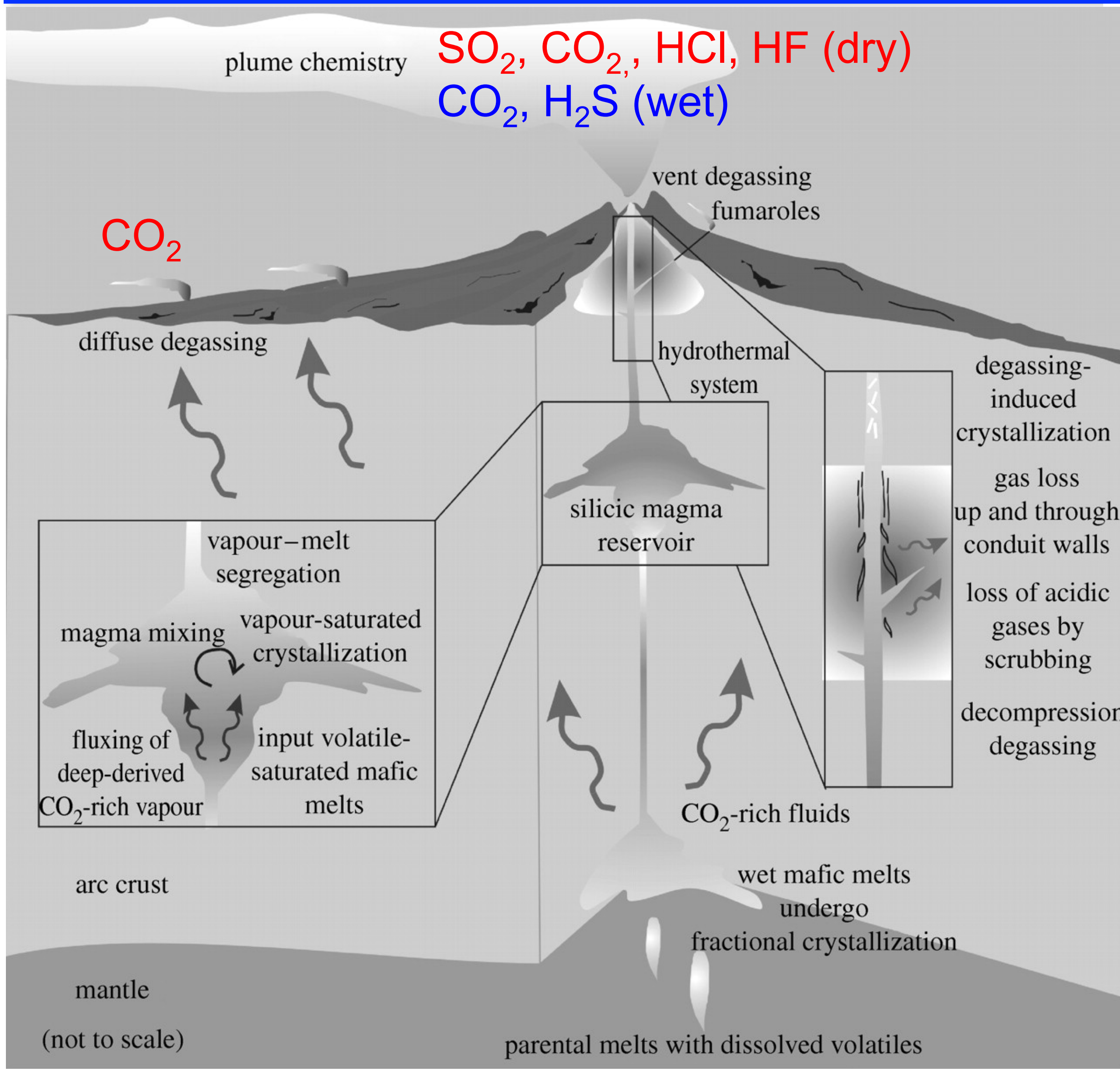


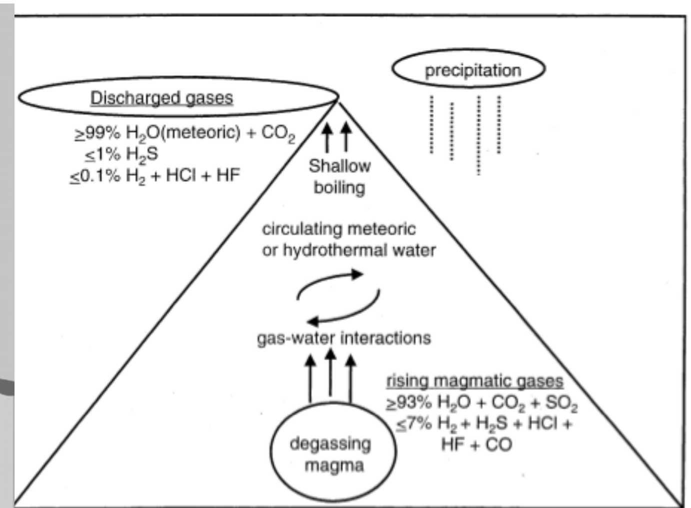
Geoengineering
STRATOSPHERE
More Reflected Solar Flux
Less Upward IR Flux
Stratospheric aerosols
(Lifetime ≈ 1-3 years)
backscatter
absorption (near IR)
Solar Heating
H_2S
SO_2 → H_2SO_4
NET HEATING
IR Heating
emission
IR Cooling
Heterogeneous O_3 depletion → Less Solar Heating
HCl, BrO, ClO
absorption (IR) emission
forward scatter
CO_2
H_2O
Explosive
Tropopause (8-17 km)
Enhanced Diffuse Flux
Effects on cirrus clouds
Gas scavenging?
Ashfall
Indirect Effects on Clouds
Reduced Direct Flux
TROPOSPHERE
SO_2 → H_2SO_4
More Downward IR Flux
Passive
Less Total Solar Flux
Tropospheric aerosols
(Lifetime ≈ 1-3 weeks)
NET COOLING
Exsolution
Emission and fate of volcanic gases
Dissolved volatiles
Original slide courtesy of A. Robock

Motivation for volcanic SO_2 measurements

- SO_2 is the most abundant gas in volcanic emissions that can be easily measured using remote sensing techniques
  - Low background concentrations (cf. H_2O, CO_2)
  - No other major sources above the planetary boundary layer (PBL)
  - Well-characterized spectral absorption bands (UV, IR, microwave)
- Released from magma at high temperature and low pressure
  - Can indicate fresh magma rising within a volcanic system
  - Signature of magmatic eruptions with potential for high altitude eruption columns
  - H_2S (hydrogen sulfide) is the more stable sulfur species at high pressures and low temperatures (e.g., fumarole fields)
- Environmental, health and climate impacts (sulfate aerosol)

Temperature, pressure and scrubbing effects on volcanic gases





[Symonds et al., 2001; Edmonds, 2008]

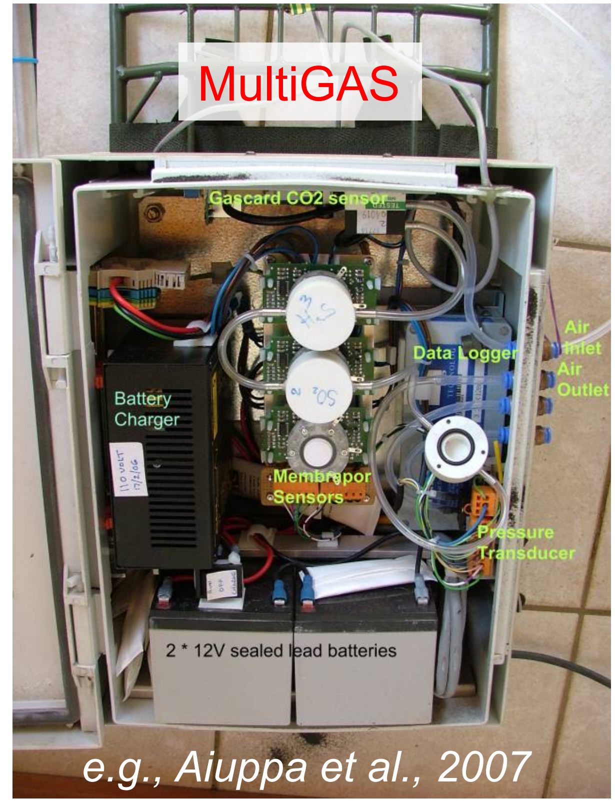
Gas monitoring at 'wet' volcanoes

Precursory stage:
CO_2, H_2S

Eruptive stage:
CO_2, SO_2, H_2S, HCl, HF

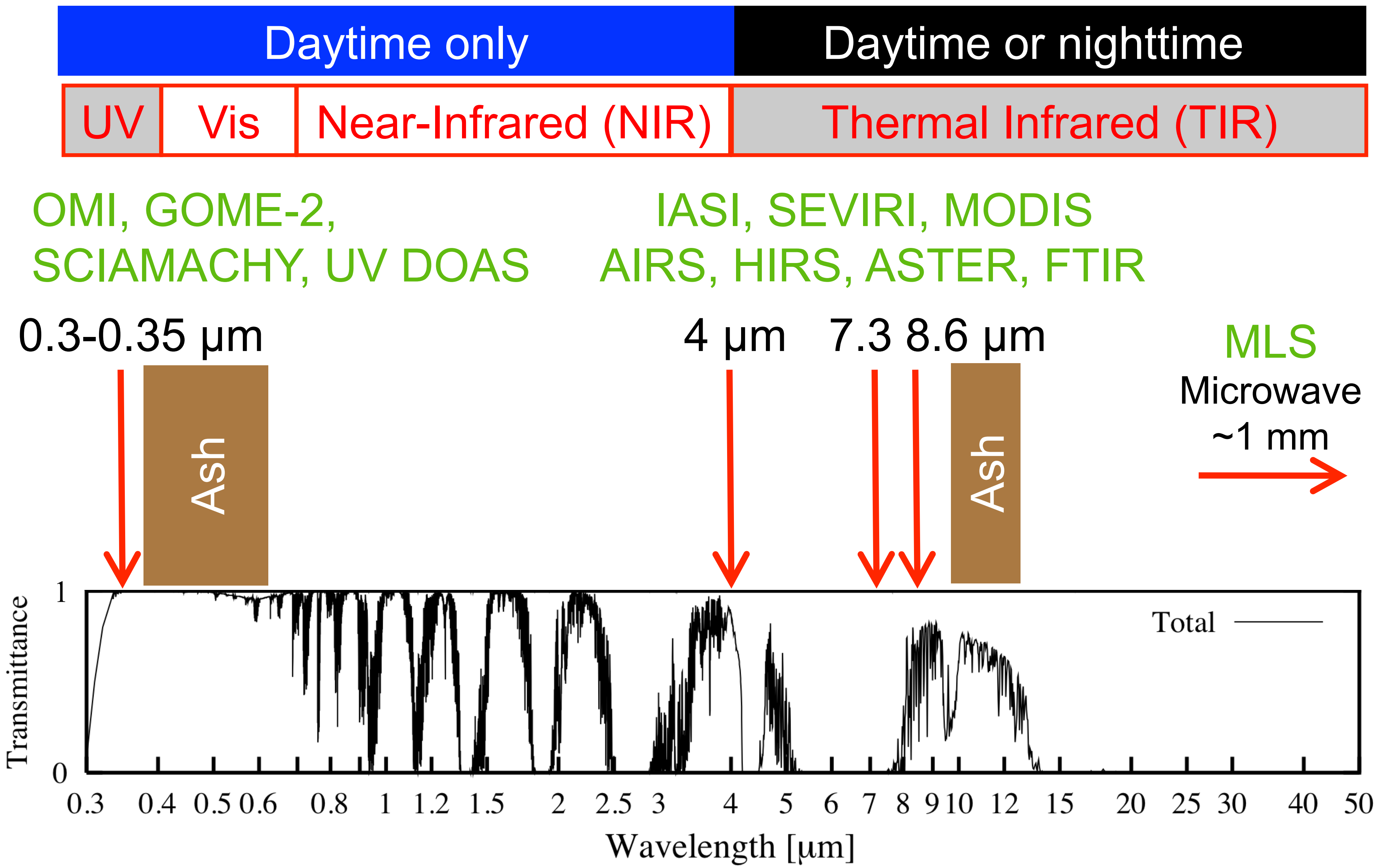
Waning stage:
CO_2, H_2S

In-situ gas monitoring techniques (ground-based)



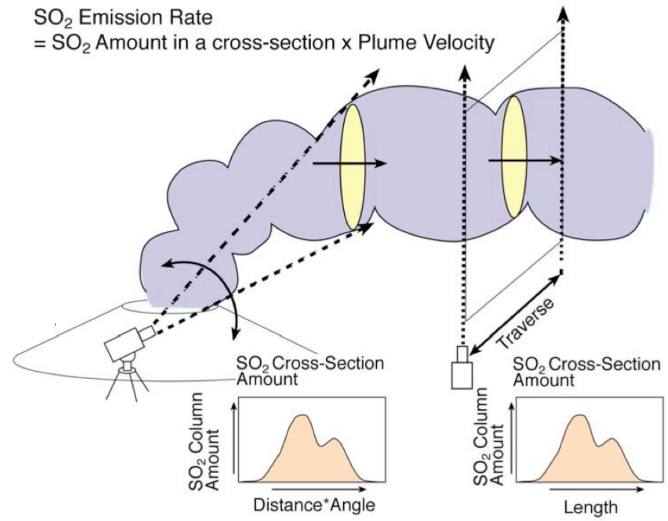
- Direct gas sampling: complete chemical and isotopic composition
- Hazardous, corrosive environment, low temporal resolution
- MultiGAS sensor packages: SO_2, CO_2, H_2S, H_2O, CO gas ratios
- Autonomous, telemetered networks

Electromagnetic spectrum – SO_2 absorption



Volcanic SO_2 flux measurements via UV spectroscopy

Figure 9. NOVAC Version I instrument installed at San Cristóbal volcano, Nicaragua.



[Galle et al., JGR, 2010]

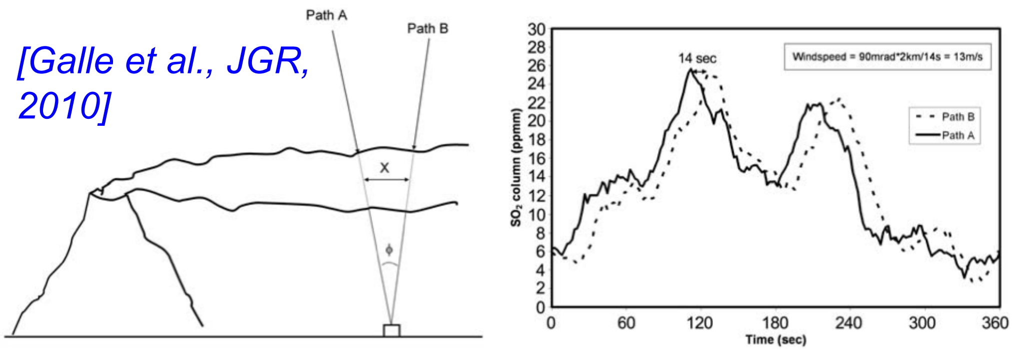
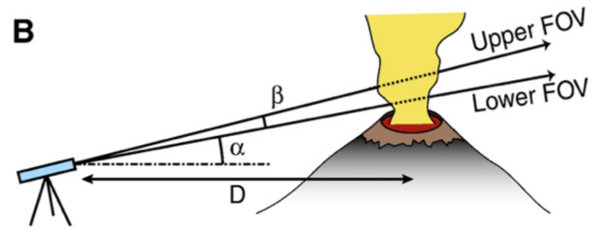
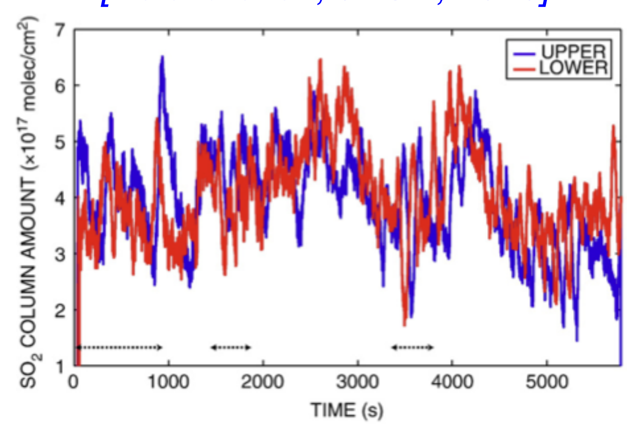


Figure 5. (left) The speed of the plume can be determined by collecting two time series of column data, one farther upwind than the other. (right) Measurement of the speed of the SO_2 plume from San Cristóbal volcano, Nicaragua [*Galle et al.*, 2006].

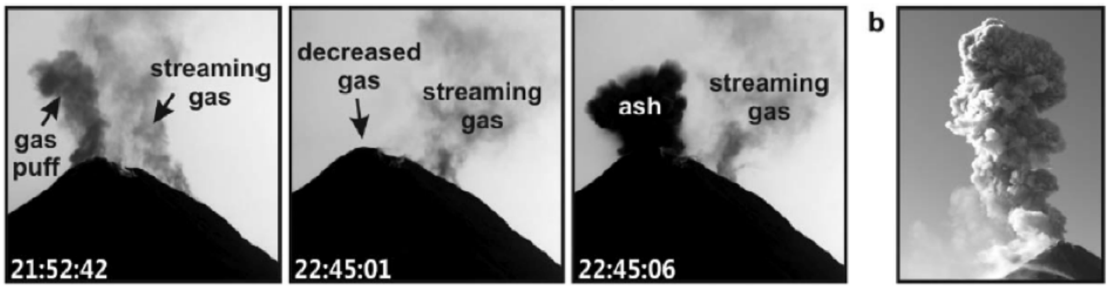


[Boichu et al., JVGR, 2010]

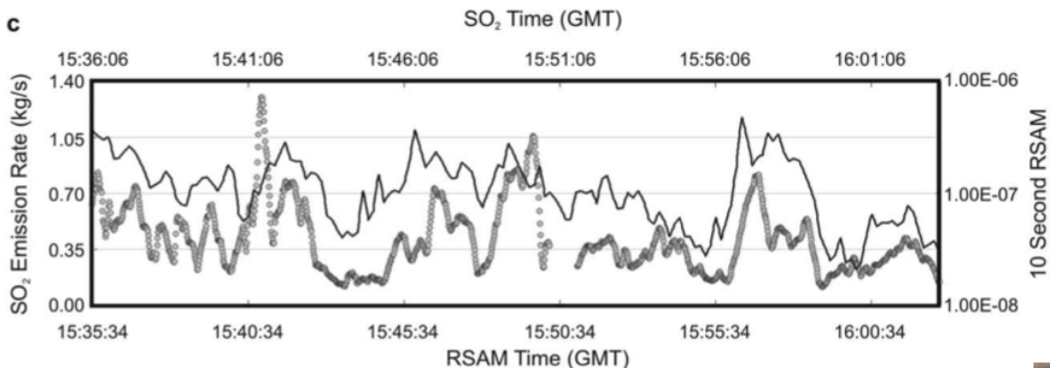


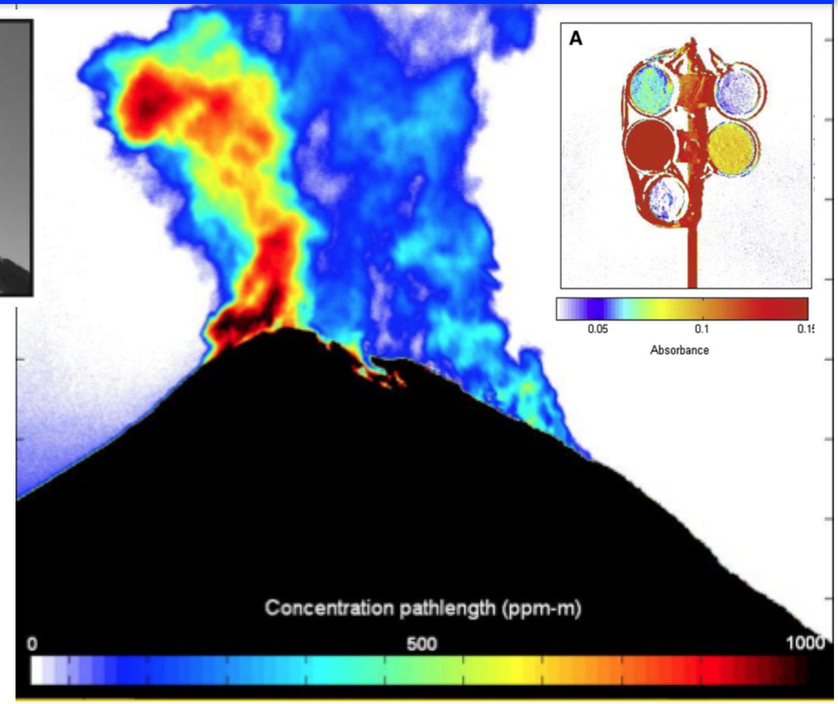
- Mainstay of volcanic gas monitoring since 1970s
- UV Differential Optical Absorption Spectroscopy (DOAS)
- Yields emission rates of SO_2 (also BrO, NO_2, ClO)

Ultraviolet imaging cameras

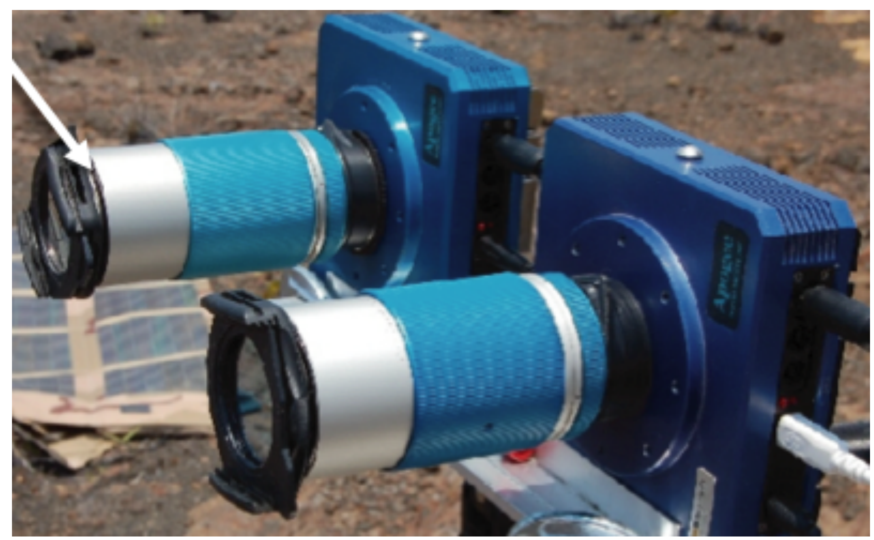


Fuego (Guatemala); *Nadeau et al.*, GRL, 2011



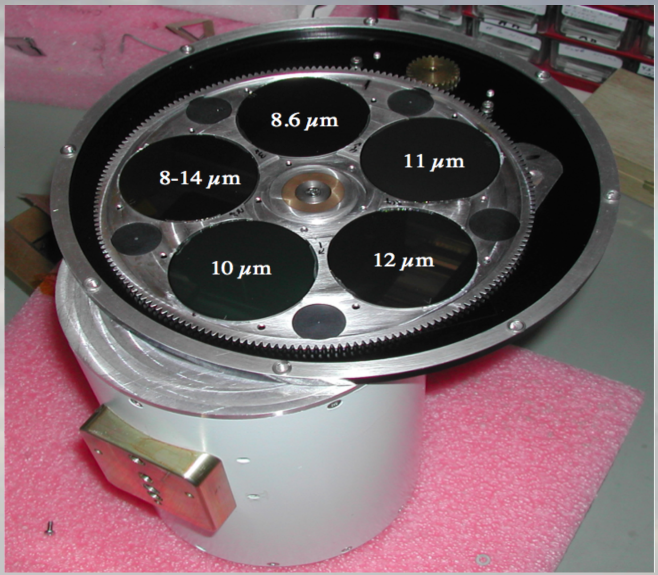


- High temporal resolution (~1 Hz) SO_2 emission data – comparable to other geophysical data (e.g., seismic)
- Plume dynamics and wind speed
- UV spectroscopic data required for corrections
- Plume tomography with multiple cameras

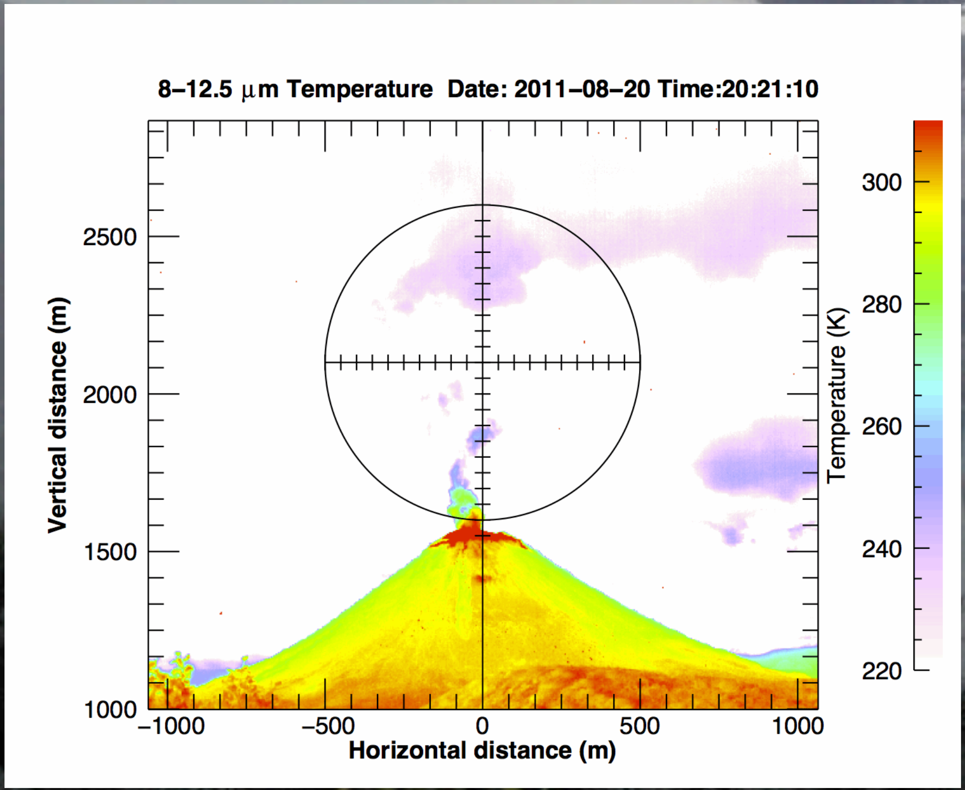


Mori and Burton, 2006; *Bluth et al.,* 2007; *Dalton et al.*, 2009; *Kern et al*., 2010; Nadeau *et al.*, 2011

Thermal Infrared imaging cameras



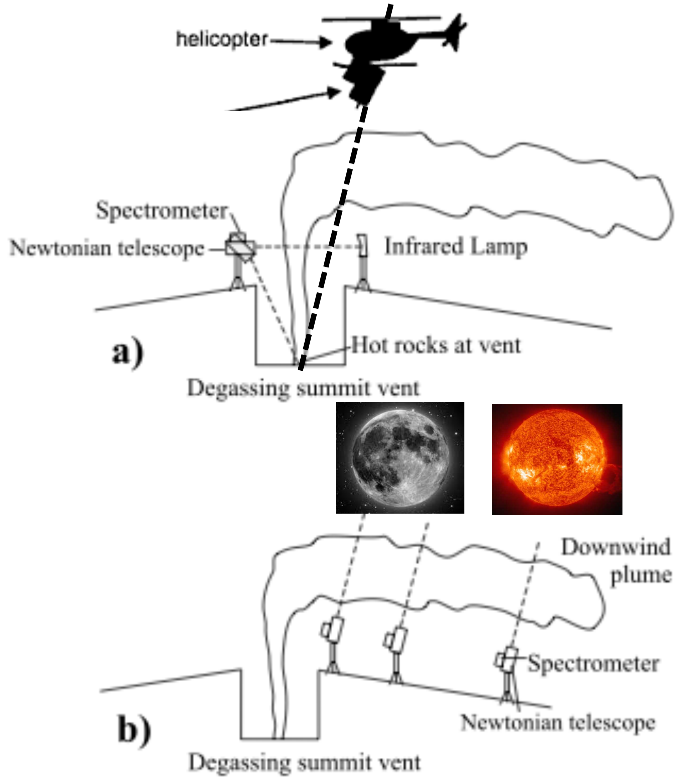
Karymsky (Kamchatka)



- SO_2 and ash detection
- Day/night operation
- ~50 Hz sampling

Courtesy Fred Prata and David Fee

Fourier-Transform Infrared (FTIR) spectroscopy



- Simultaneous quantification of multiple IR-active volcanic gases (H_2O, CO_2, SO_2, CO, HCl, HF, OCS)
- High temporal resolution gas ratios
- Volatile solubility data needed to interpret FTIR measurements (F/Cl ≥ H_2O > SO_2 > CO_2)
- Autonomous FTIR deployed at Stromboli (INGV)

Volcanic gas monitoring techniques

Technique	Gases measured	Hazard	Cost	Frequency
Direct sampling	Total gas composition	High	Low	Low
In-situ sensors	SO_2, H_2S, CO_2, H_2O, CO	High	Low	High
COSPEC	SO_2	Moderate	$10k	≥ Minutes
Mini-DOAS	SO_2, BrO, NO_2, ClO	Moderate	$10k	1 Hz
FTIR	SO_2, CO_2, H_2O, HCl, HF	Moderate	$40k	1 Hz
UV camera	SO_2	Low-Mod	$20k	>1 Hz
IR camera	SO_2	Low-Mod	$20k	Seconds
Satellites	SO_2, HCl (strat.), CO_2?	None	Free*	≥15 minutes

**Not including satellite launch*

- In addition, variation in spatial coverage and atmospheric interference

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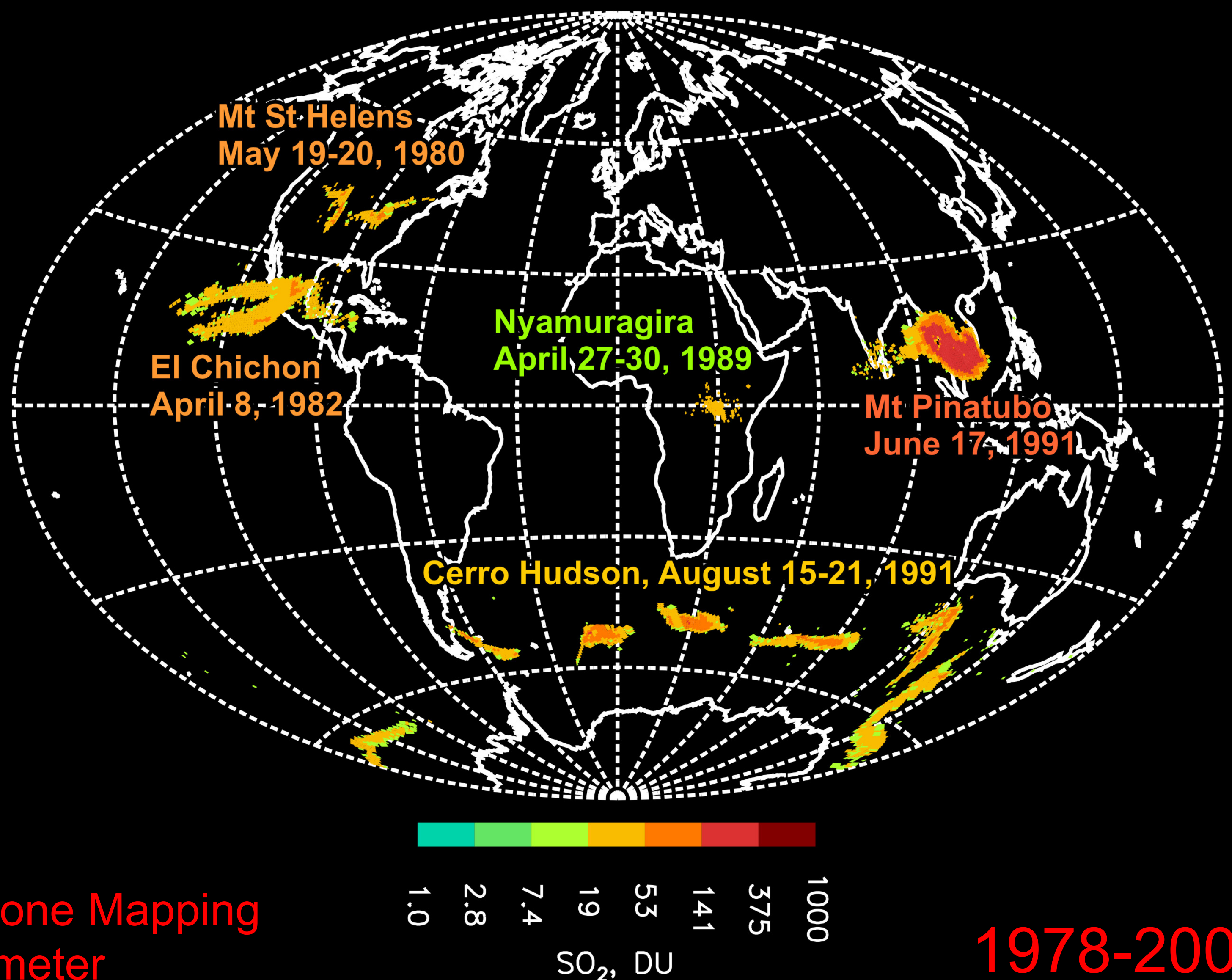
Volcanic SO_2 clouds measured by TOMS

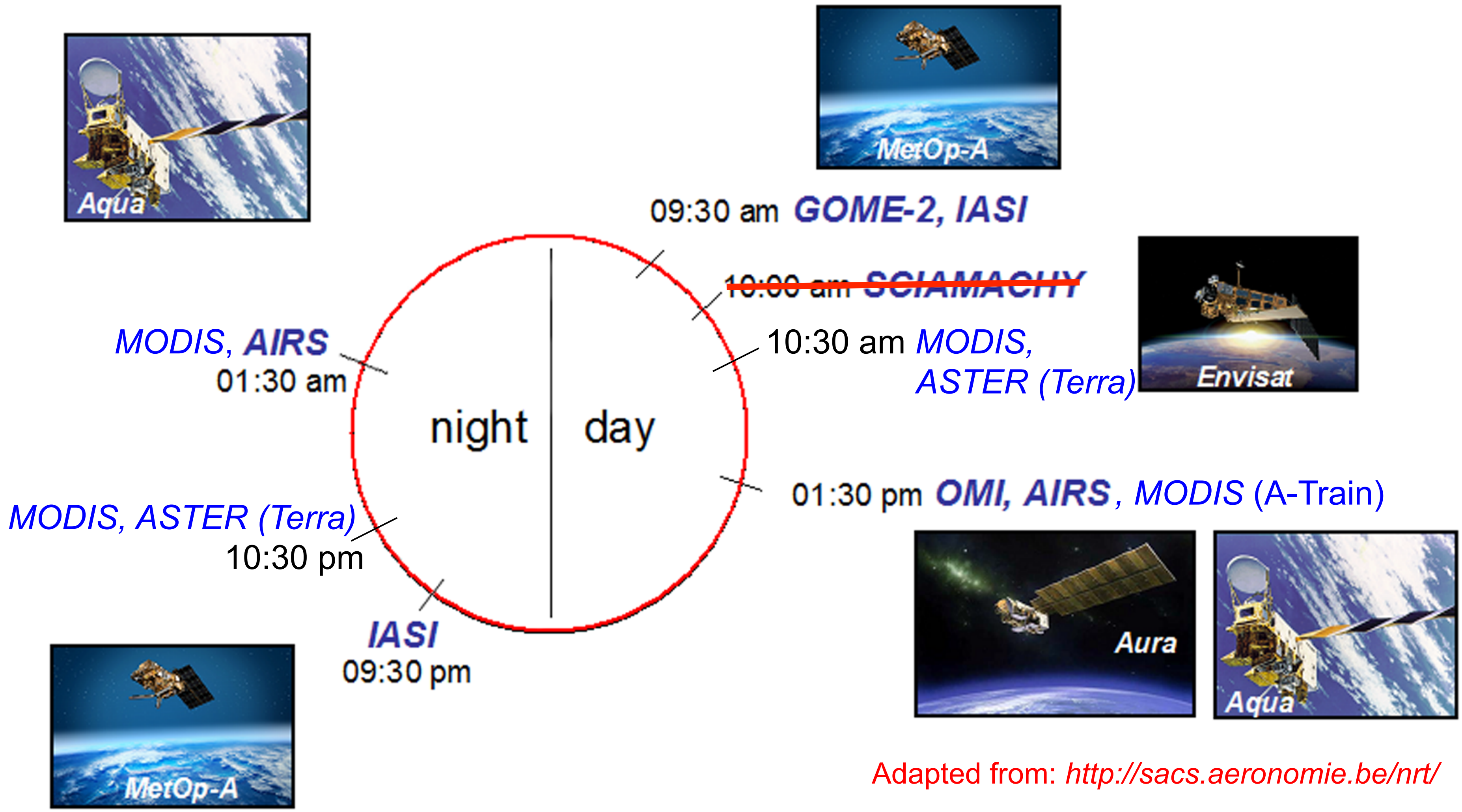


Total Ozone Mapping Spectrometer

1978-2005

An unprecedented era of satellite SO_2 measurements

Up to ~15 daily overpasses by ultraviolet (UV) and infrared (IR) sensors

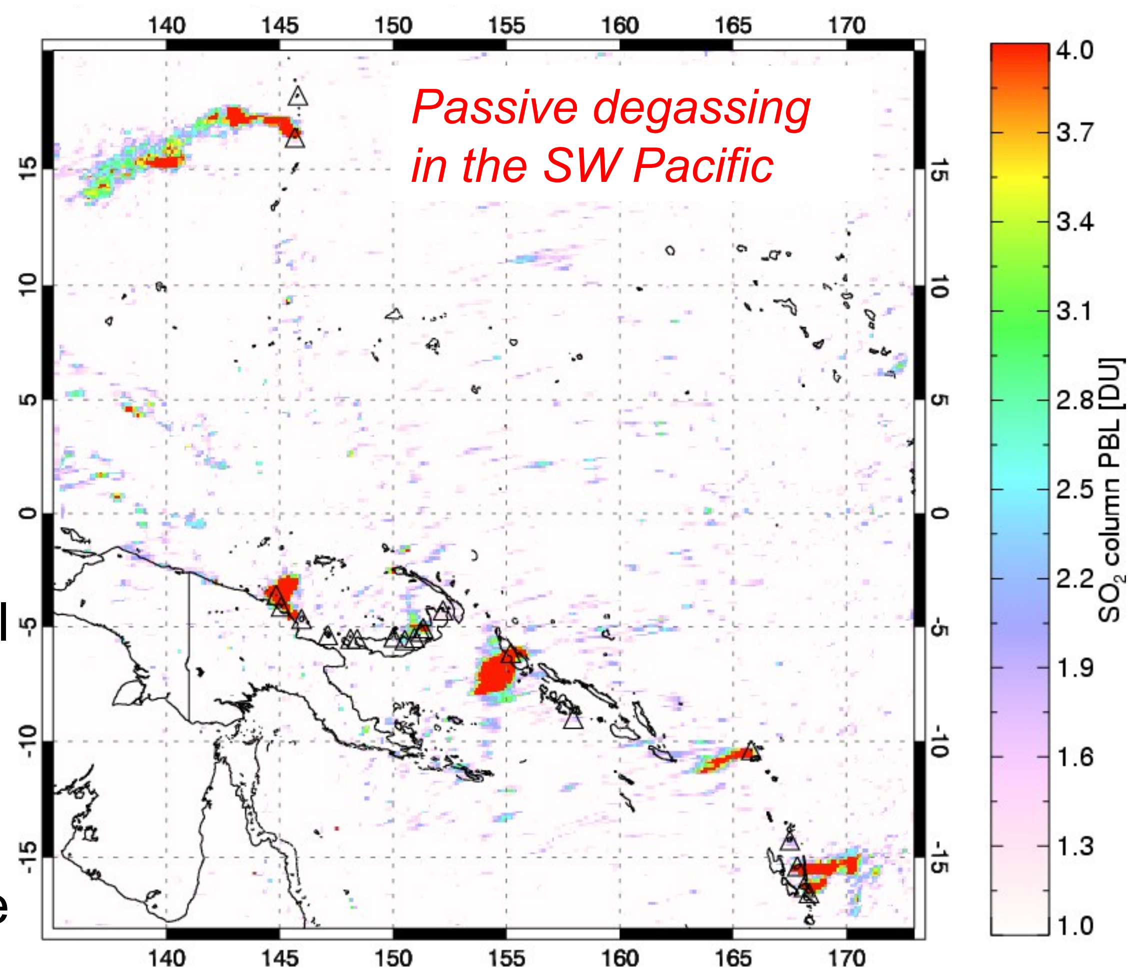


Adapted from: *http://sacs.aeronomie.be/nrt/*

+ TOVS/HIRS, MSG/SEVIRI (Europe/Africa)

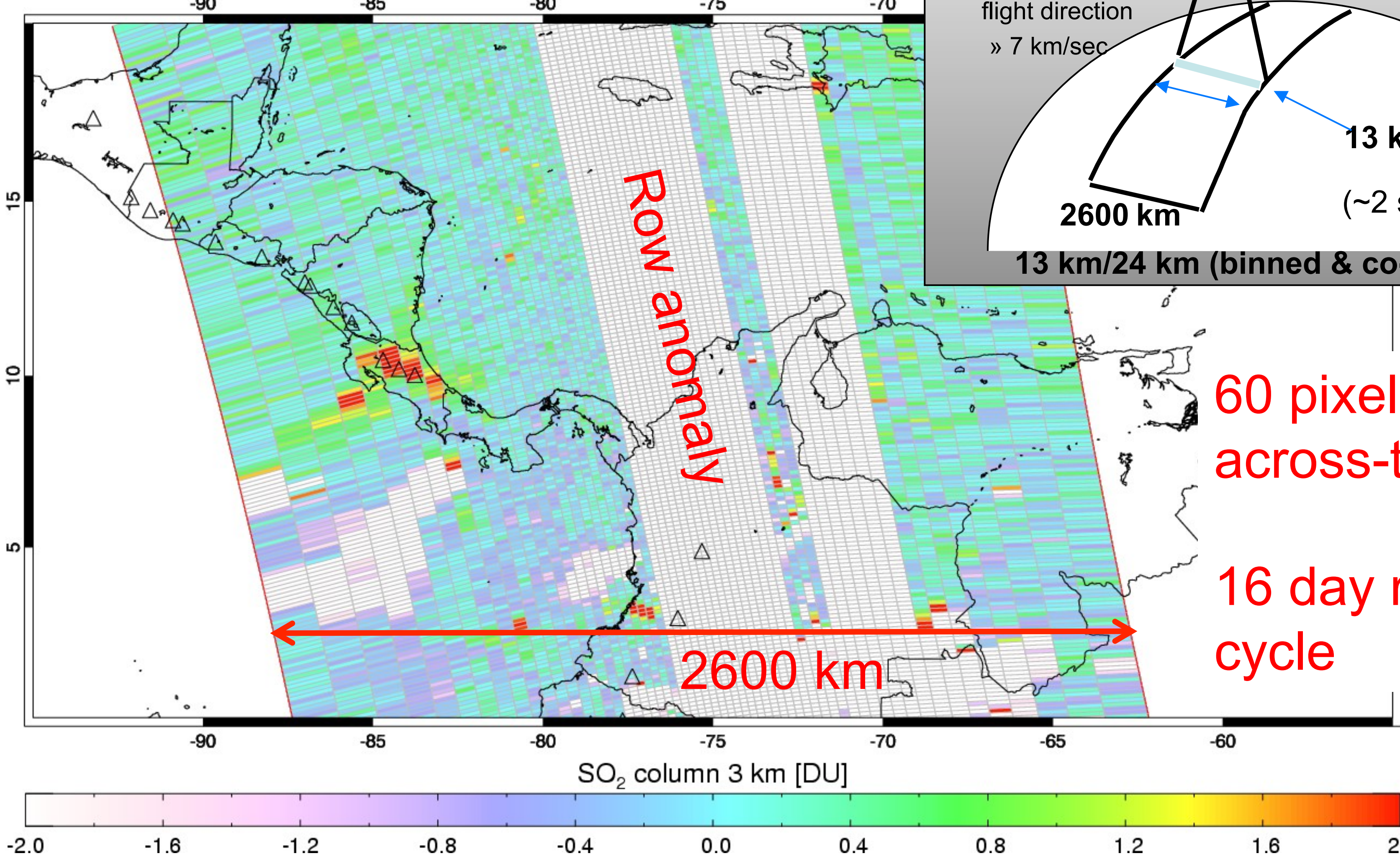
Ozone Monitoring Instrument (OMI)

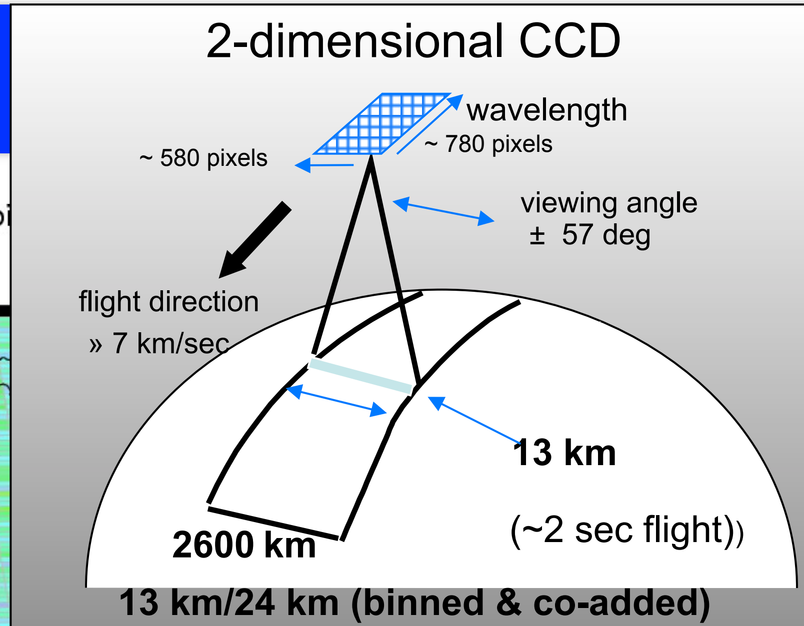
- UV/Visible sensor
- On NASA/Aura satellite (polar orbit)
- Launched July 2004
- Daily contiguous global coverage (until late 2008)
- 13 x 24 km nadir pixel
- Overpass at 1:30-2:00 pm local time
- Measures SO_2 total column (plus other gases and aerosols)
- Data publicly available and free



- Near real-time (NRT) OMI SO_2 data produced within 3 hours of satellite overpass (http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html)

OMI SO_2 measurements





60 pixels across-track

16 day repeat cycle

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Satellite instruments - UV

Instrument	Satellite(s)	Data coverage dates	Daily global coverage?
Total Ozone Mapping Spectrometer (**TOMS**)	Nimbus-7, Meteor-3, ADEOS, Earth Probe	Nov 78 – Dec 94 Jul 96 – Dec 2005	Yes
Global Ozone Monitoring Experiment (**GOME**)	European Remote Sensing Satellite (ERS-2)	July 95 – present	No
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (**SCIAMACHY**)	European Environmental Satellite (Envisat-1)	Sept 03 – Apr 2012	No
Ozone Monitoring Instrument (**OMI**)	NASA EOS Aura	Sept 2004 – present	Yes (until late 2008)
Global Ozone Monitoring Experiment-2 (**GOME-2**)	MetOp A, B, C	Oct 2006 - present	No
Ozone Mapping and Profiler Suite (**OMPS**)	National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP)	Apr 2012 - present	Yes

Operational SO_2 data products

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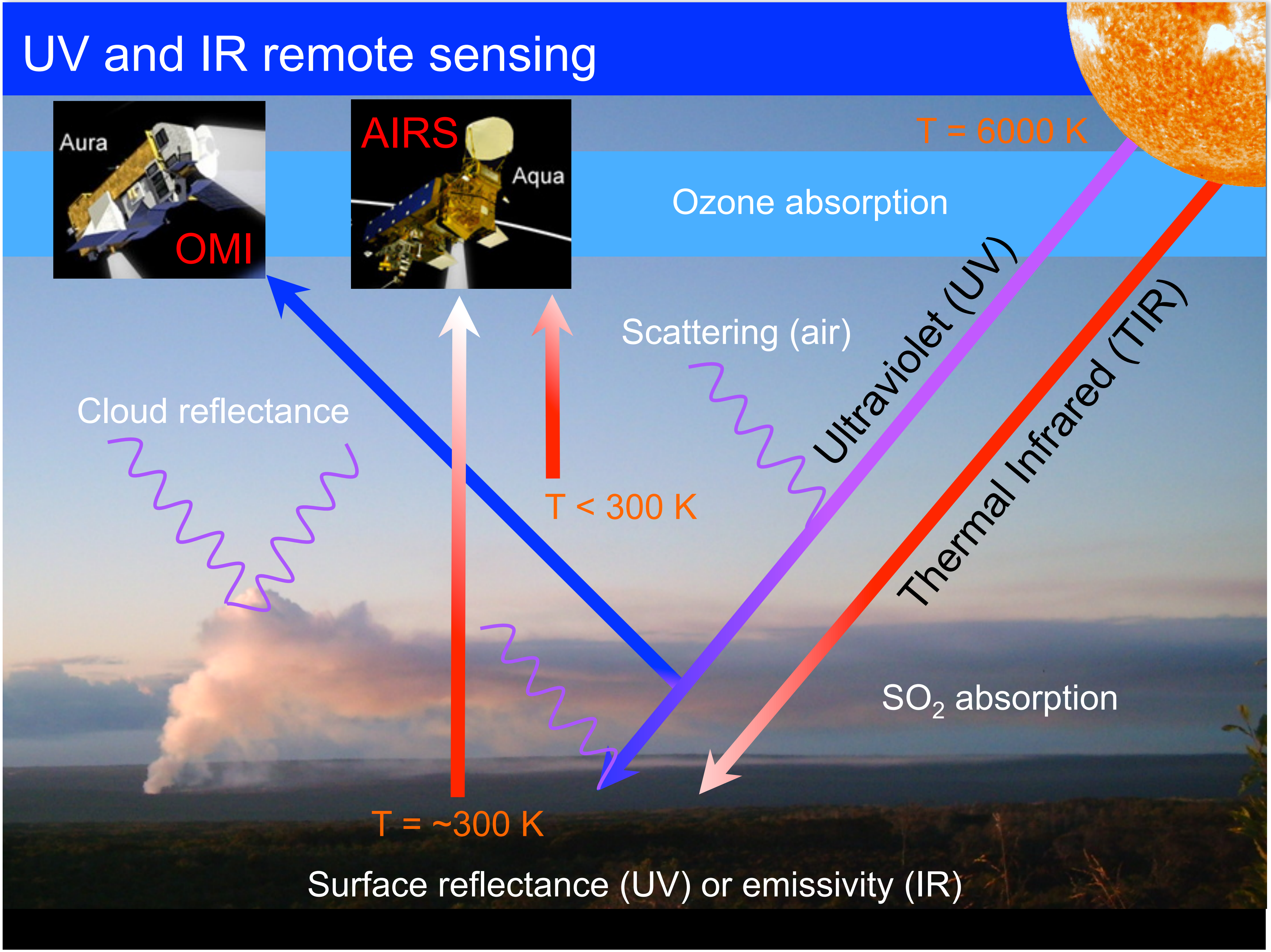
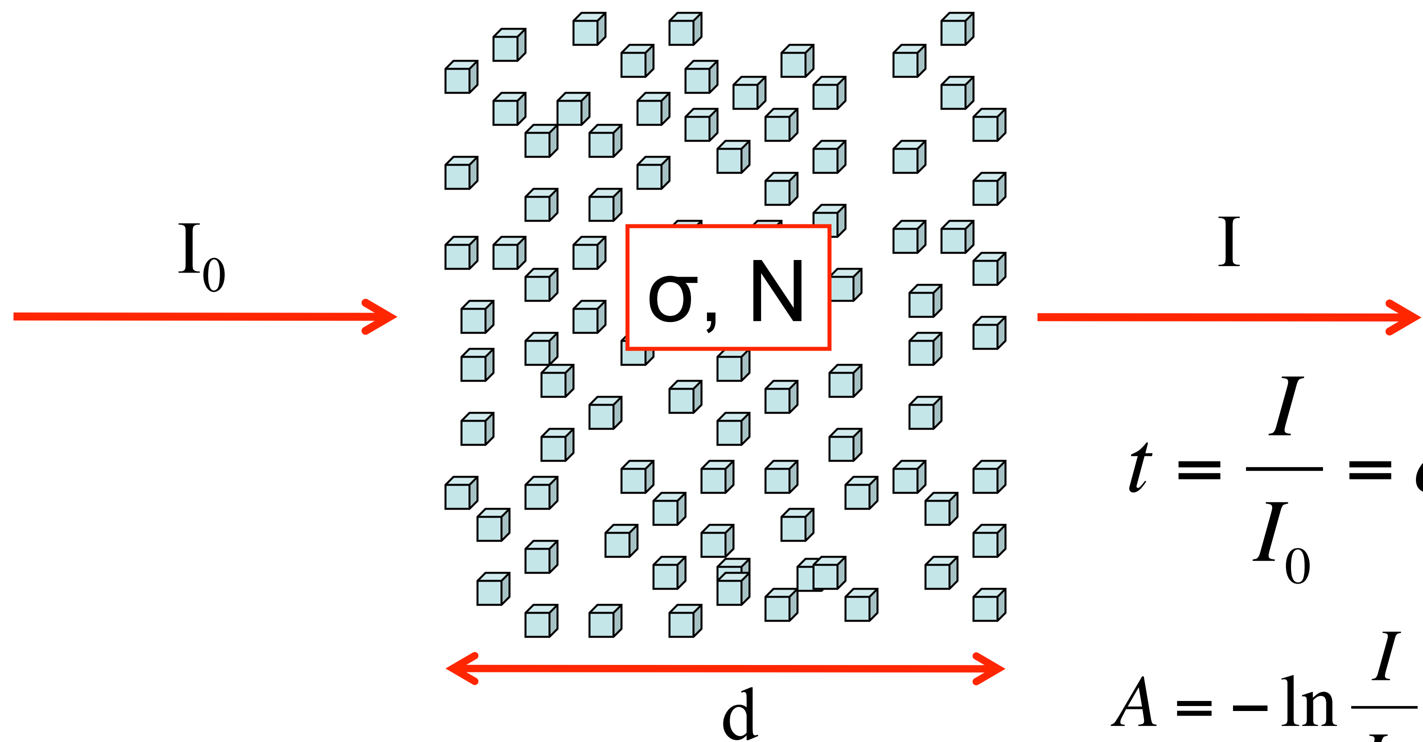
Satellite instruments – Microwave & IR

Instrument	Satellite(s)	Data coverage dates	Daily global coverage?
Microwave Limb Sounder (**MLS**)	Upper Atmosphere Research Satellite (UARS), EOS Aura	1991 – 1994 (UARS) 2004 – (EOS Aura)	No
High Resolution Infrared Radiation Sounder (**HIRS, HIRS/2**)	TIROS-N, NOAA-6-14	Oct 78 – present	Yes (day/night)
Moderate Resolution Imaging Spectroradiometer (**MODIS**)	EOS Terra, Aqua	Feb 2000 –	Yes (day/night)
Advanced Spaceborne Thermal Emission & Reflection Radiometer (**ASTER**)	EOS Terra	Feb 2000 – (request only)	No
Atmospheric Infrared Sounder (**AIRS**)	EOS Aqua	Sept 2002 –	No
Spinning Enhanced Visible and Infrared Imager (**SEVIRI**)	Meteosat Second Generation (MSG)	2004 –	No
Infrared Atmospheric Sounding Interferometer (**IASI**)	MetOp A, B, C	Oct 2006 -	No


UV and IR remote sensing
Aura
OMI
AIRS
Aqua
T = 6000 K
Ozone absorption
Scattering (air)
Ultraviolet (UV)
Thermal Infrared (TIR)
Cloud reflectance
T < 300 K
SO2 absorption
T = ~300 K
Surface reflectance (UV) or emissivity (IR)

Beer-Bouguer-Lambert (Beer's) Law

For a gaseous absorber, the absorption coefficient (β) is written as the product of an absorption cross-section (σ, cm^2) and the number density of absorbers (N, molecules cm^{-3}):

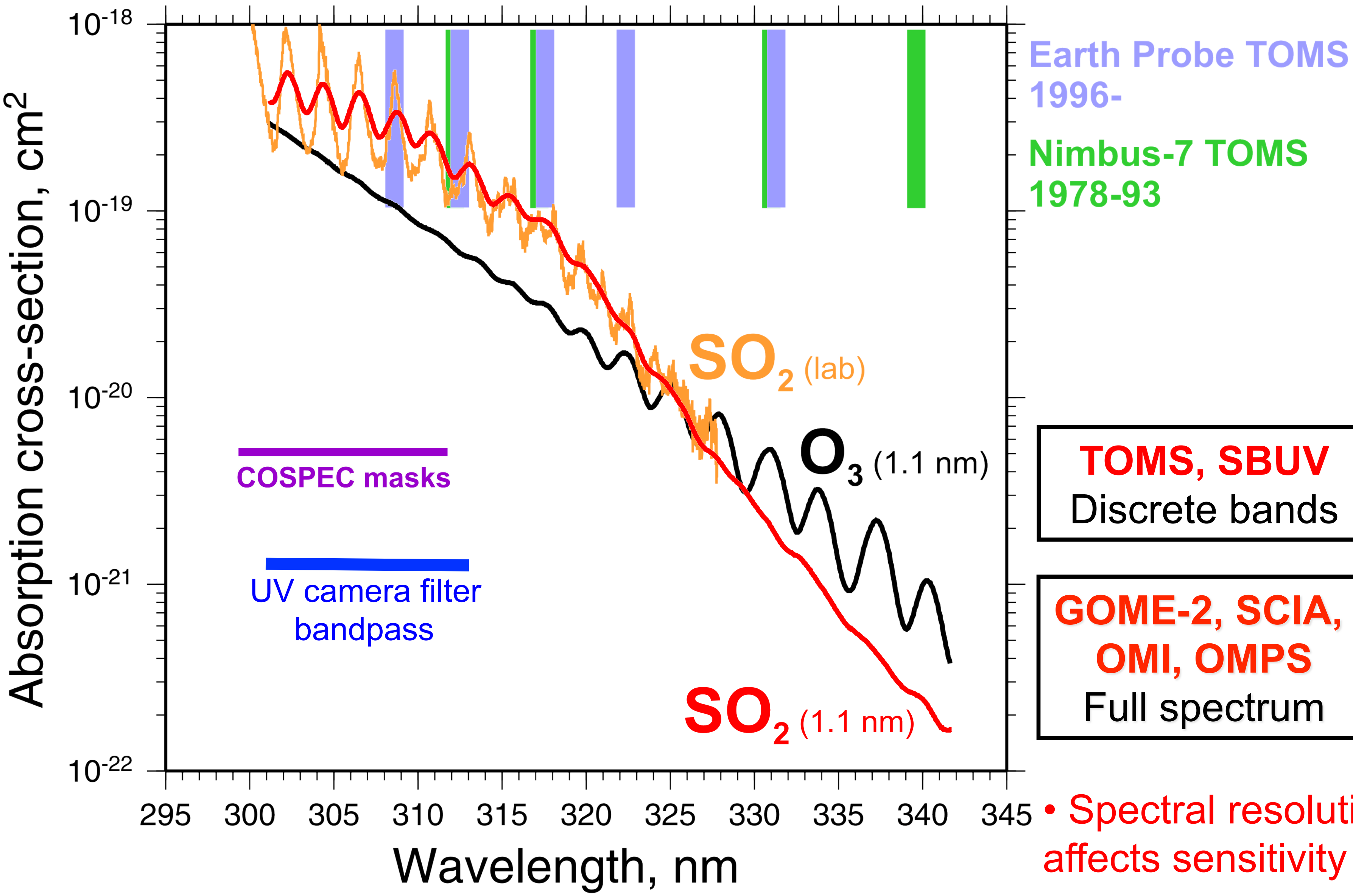


$$t = \frac{I}{I_0} = e^{-\sigma N d}$$

$$A = -\ln\frac{I}{I_0} = \sigma N d$$

- Beer's Law applies to direct beam only
- Deviations from Beer's Law occur at high concentrations

UV SO_2 and O_3 absorption spectra and instrument bands

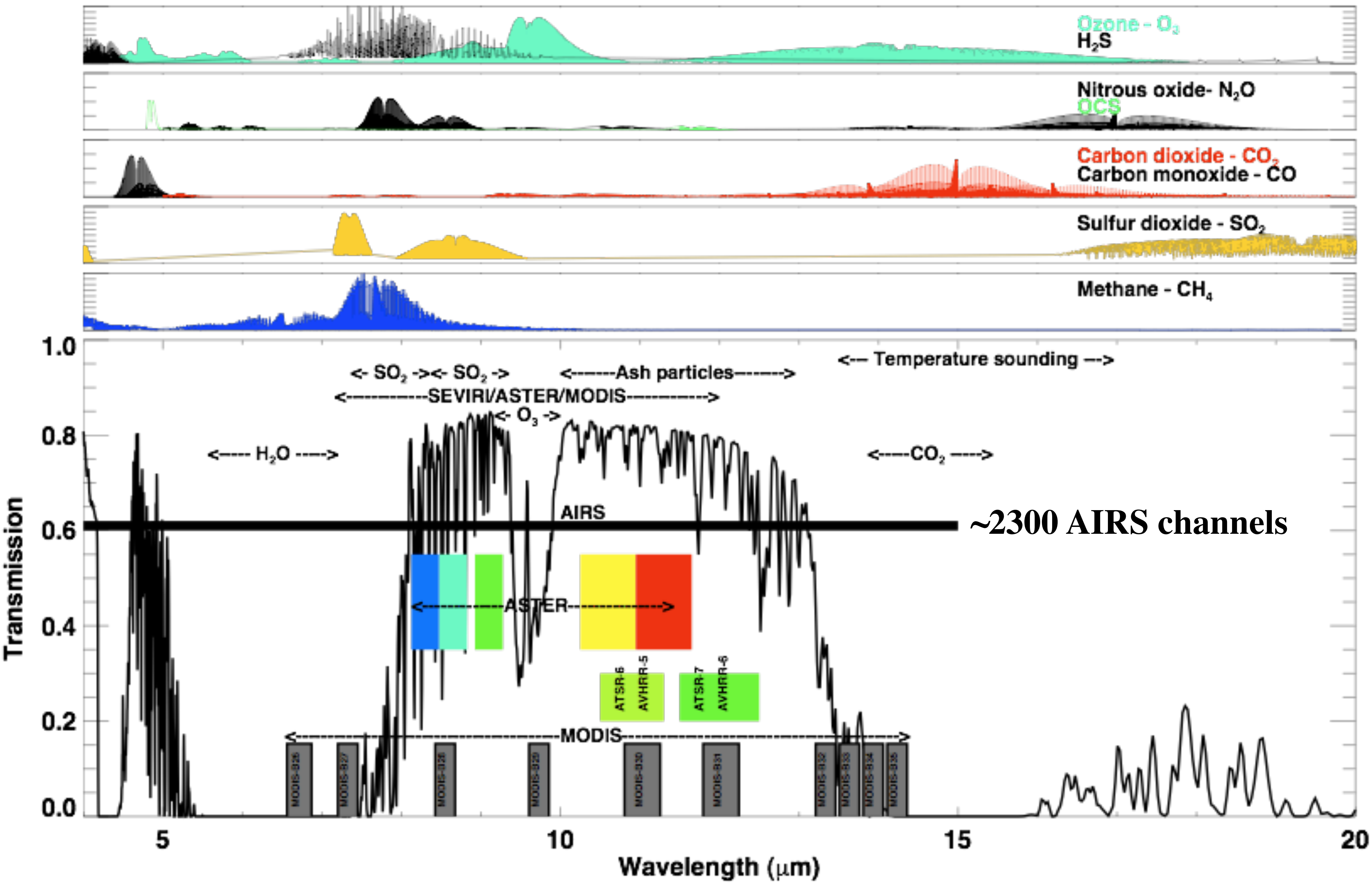


TOMS, SBUV
Discrete bands

GOME-2, SCIA, OMI, OMPS
Full spectrum

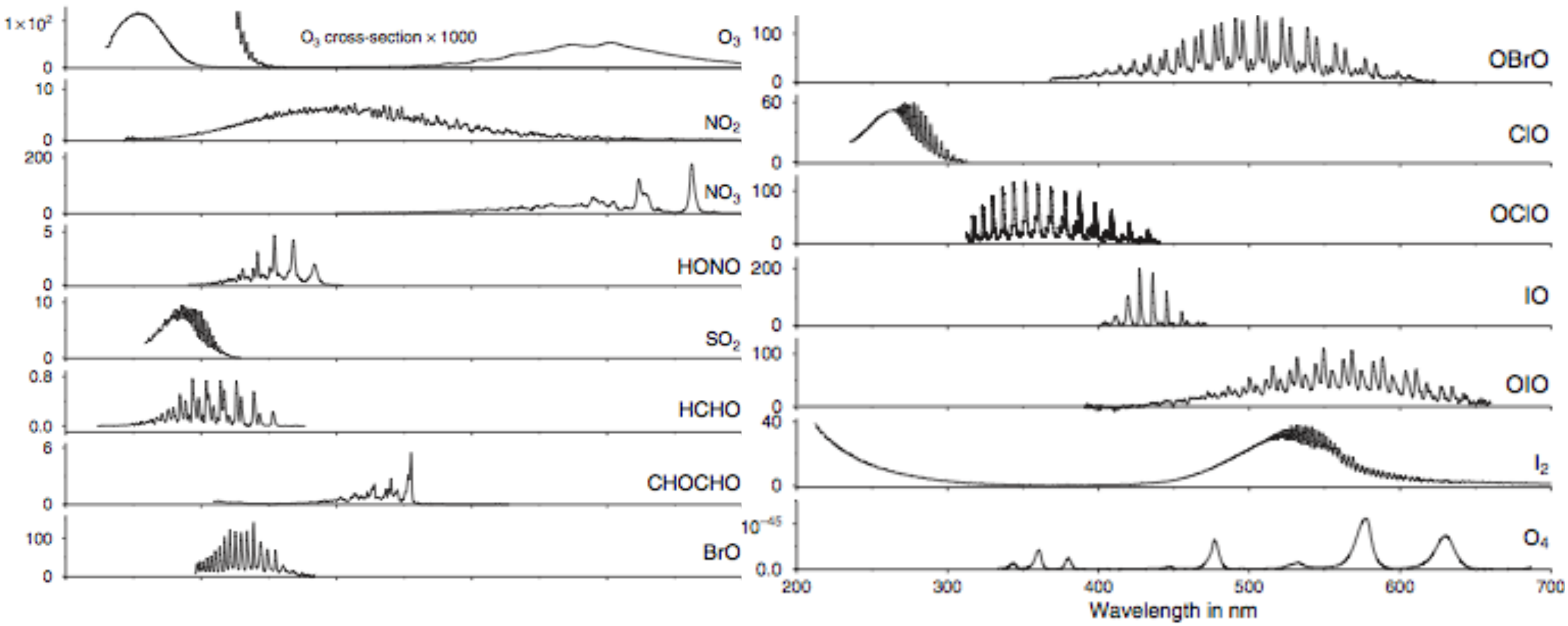
- Spectral resolution affects sensitivity

IR-active trace gases and instrument channels



Differential Optical Absorption Spectroscopy (DOAS)

Measured UV-visible spectra contain overlapping structures due to the solar spectrum (Fraunhofer lines), elastic scattering, trace gas absorption, aerosol absorption and the Ring effect (inelastic Raman scattering)



Absorption cross-sections of trace gases in the 200-700 nm wavelength range

- Alternative technique: forward modeling of UV radiances with a radiative transfer model, and comparison with observations

UV backscatter measurements

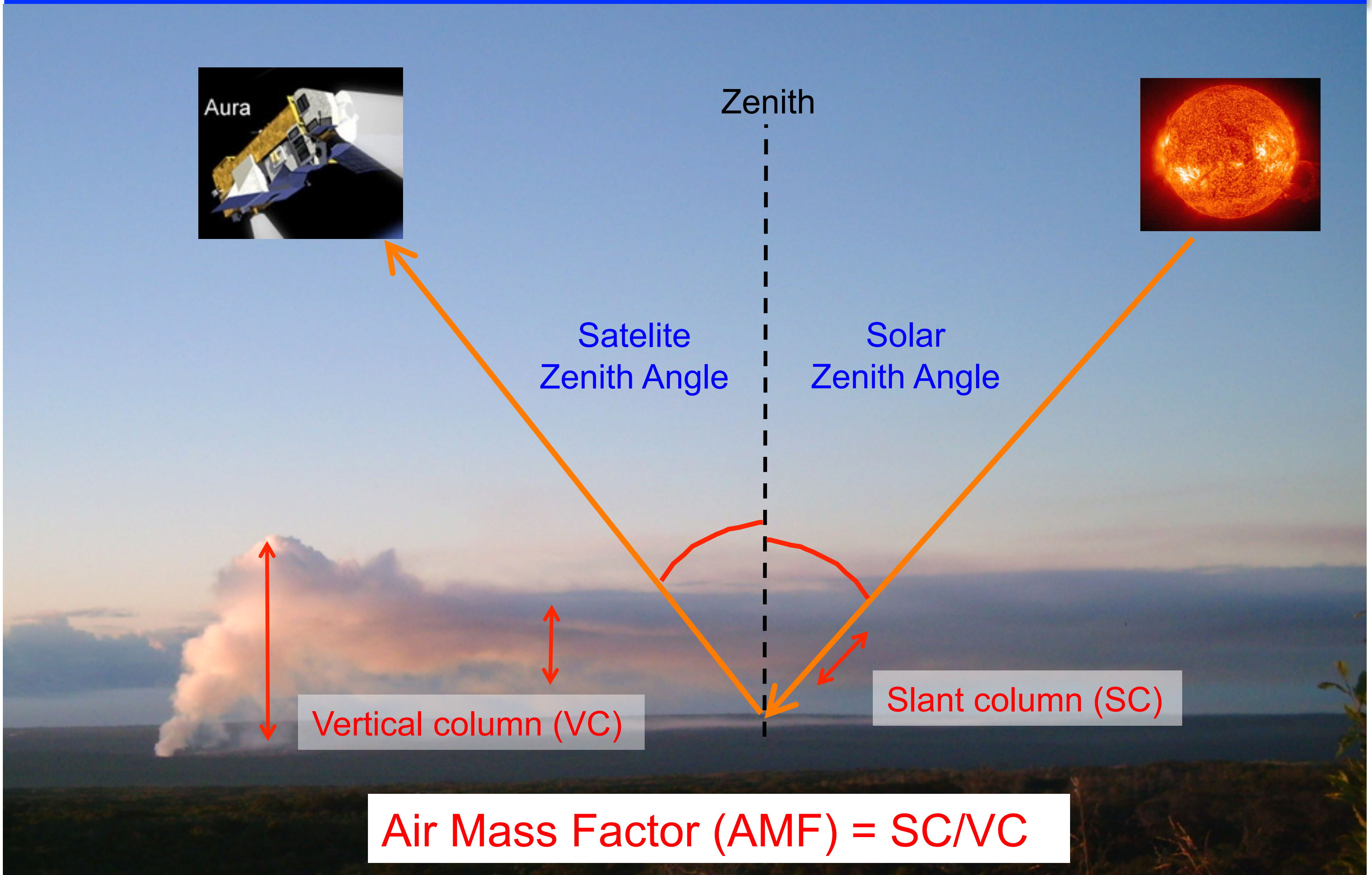
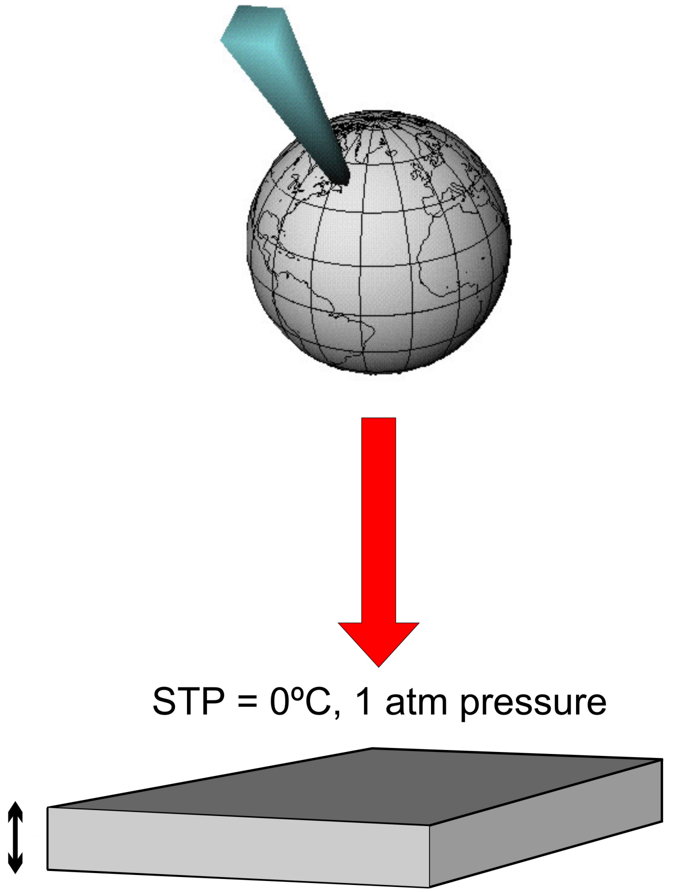


Image courtesy Matt Patrick (HVO)

SO_2 column amount measurements

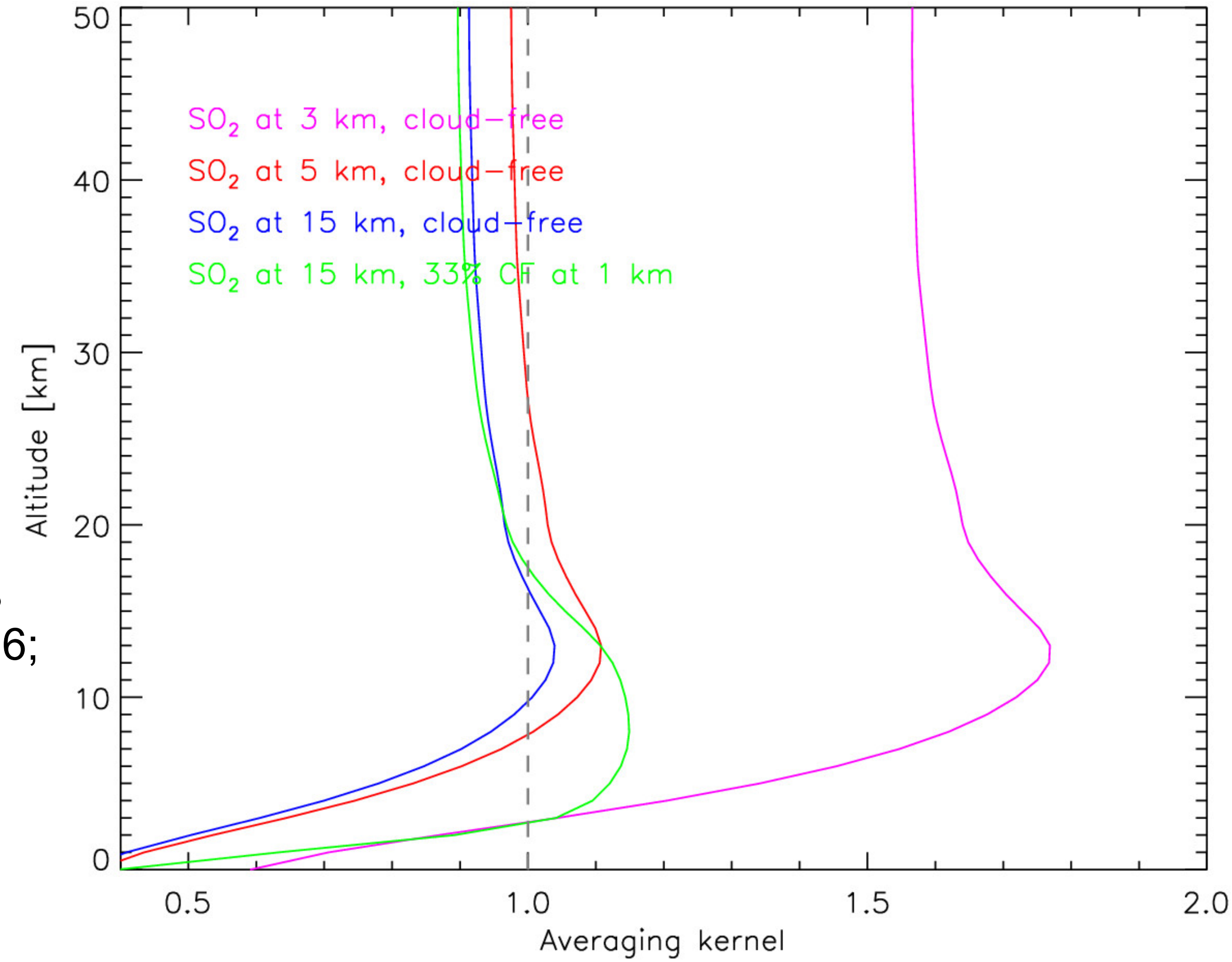


1 Dobson Unit (DU) = 1 Milli Atm cm
1 DU = 0.01 mm thickness at STP
e.g. 800 DU = 8 mm thick layer
1 DU = 10 ppmm at STP

- Satellites provide measurements of ‘column amount’ or ‘total column’ SO_2
  - US units: Dobson Unit (DU)
  - 1 DU = 2.69×10^{16} molecules cm^{-2} = 0.0285 g m^{-2} SO_2
  - European units: molecules cm^{-2}
  - *Milli atm cm* also used (same as DU)
- Typical values in volcanic clouds
  - Fresh eruption cloud: 100s – 1000+ DU
  - Passive degassing: <20 DU
  - Measured column amount depends on spatial resolution of sensor
  - Can be converted to mass or concentration (if cloud thickness is known)
- Emission rate not directly measured

Effect of volcanic plume altitude on SO_2 retrievals

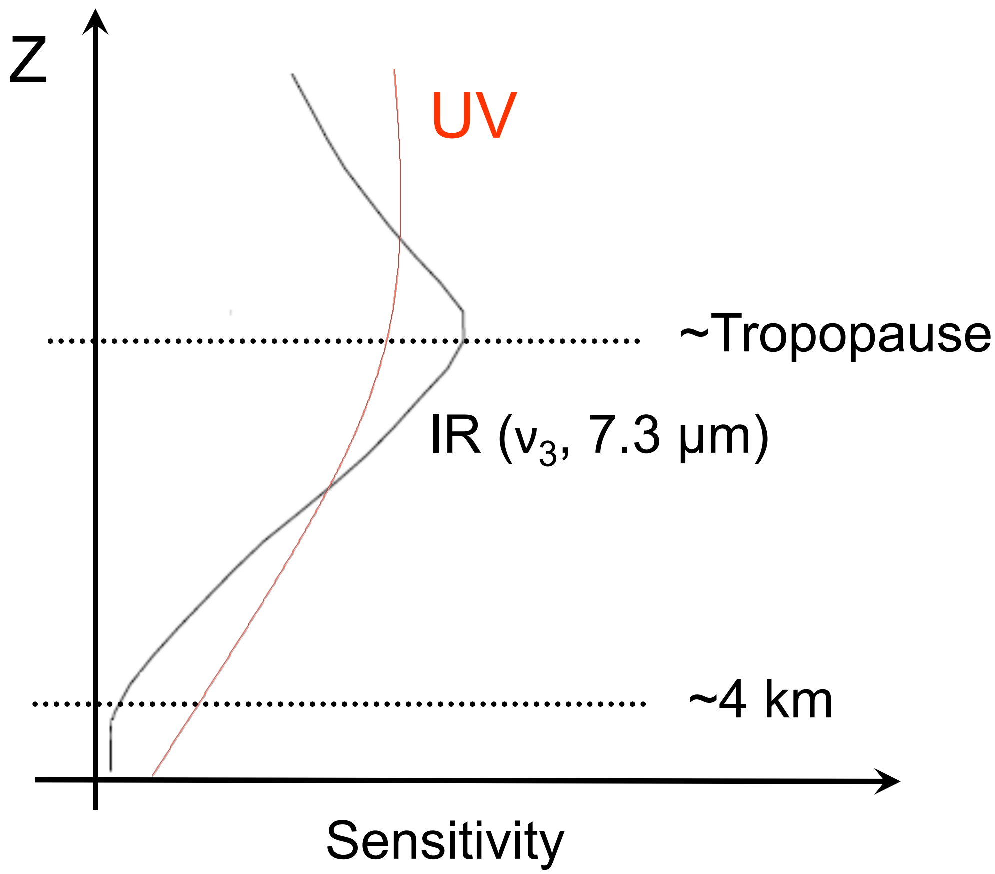
- OMI SO_2 product
- 4 *prescribed* SO_2 profiles:
  - PBL (<3 km)
  - TRL (0-5 km)
  - TRM (5-10 km)
  - STL (15-20 km)
  - 2 SO_2 algorithms [Krotkov *et al.*, 2006; Yang *et al.*, 2007]



- Knowledge of SO_2 cloud altitude is critical for accurate SO_2 retrieval
- Satellite sensitivity increases with altitude in the troposphere

[Krotkov *et al.*, IEEE TGRS, 2006; Yang *et al.*, JGR, 2007]

Relative sensitivity of UV and IR measurements



Courtesy of L. Clarisse, ULB

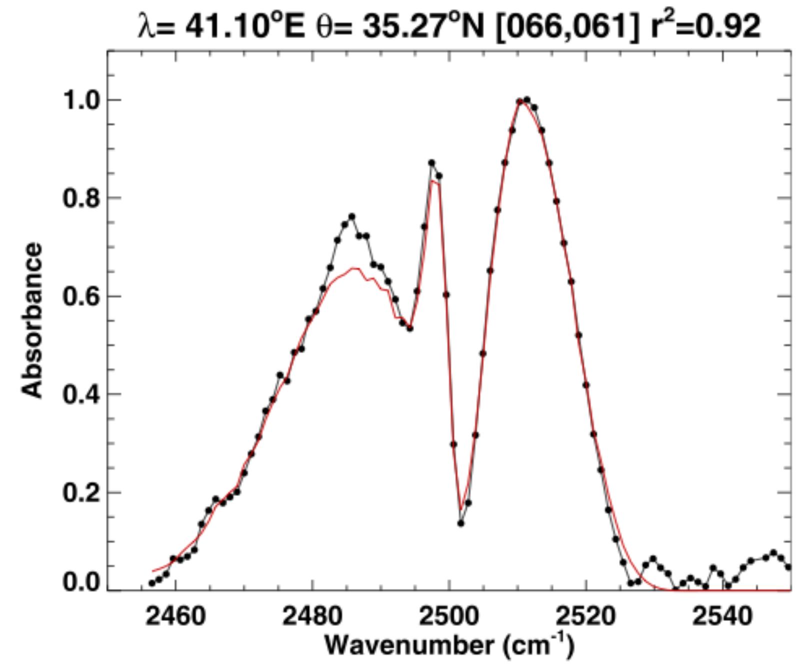


Figure 15. Spectral matching plot for the 4 μm band of SO_2. The red line shows a synthetic absorbance spectrum and the black line shows AIRS measurements. The data are for an AIRS image of the Al-Mishraq (Iraq) SO_2 plume on 25 June 2003.

Prata and Bernardo, 2007

- IR channels at ~4 μm and ~8.6 μm can detect lower tropospheric SO_2

UV instrument SO_2 sensitivity

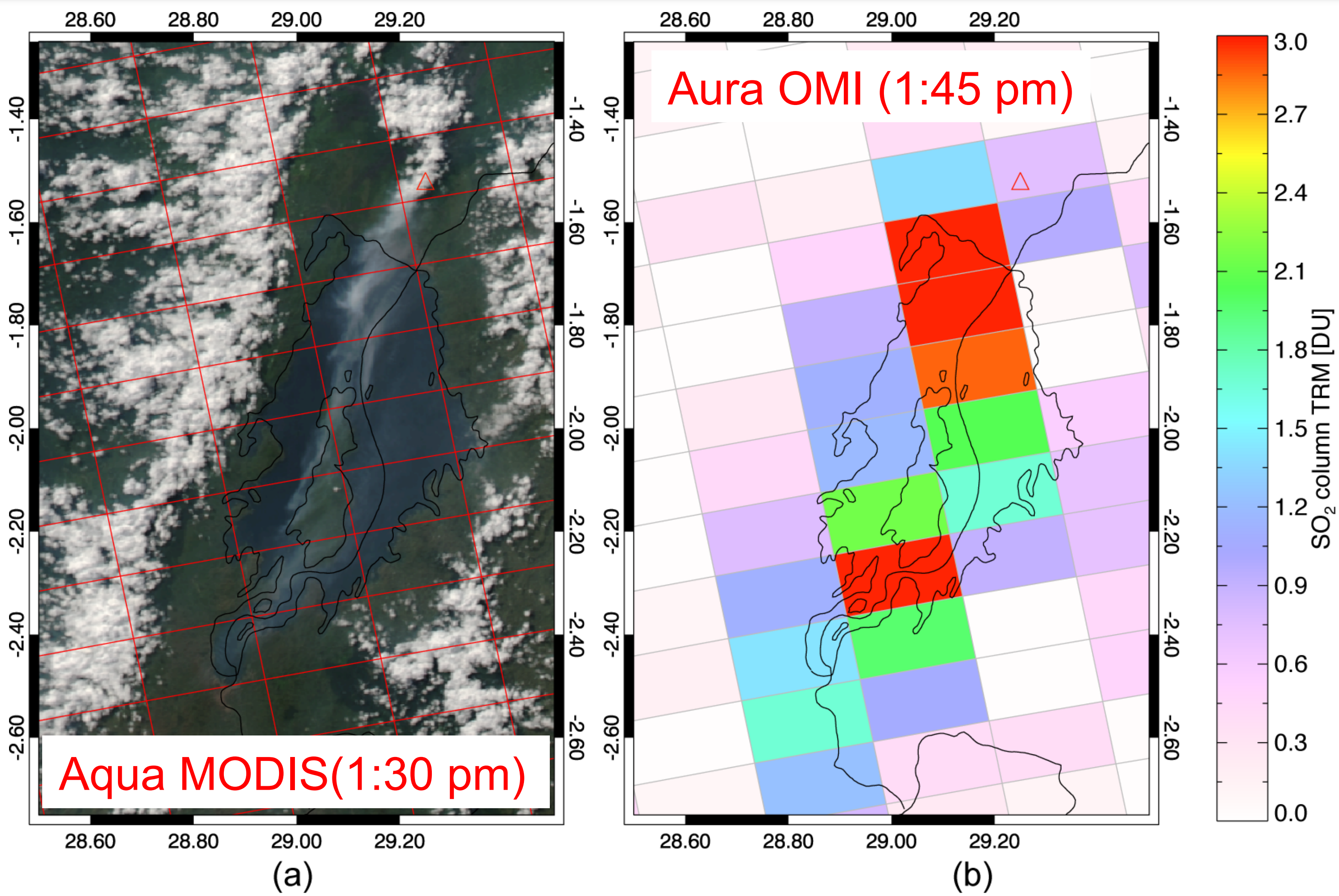
Instrument	Footprint area (km^2)	Noise (DU) 1σ		Smallest cloud detection limit (tons) 5 pixels at 5σ	
		Stratosphere 20 km	Troposphere <5 km	Stratosphere 20 km	Troposphere <5 km
EP TOMS	1521 (39×39)	3.5	7	3900	7800
GOME	12800 (40×320)	0.2	0.4	3600	7100
SCIAMACHY	1800 (30×60)	0.2	0.4	125	251
GOME-2	3200 (40x80)	0.2	0.4	460	914
OMI	312 (13×24)	0.2	0.4	43	87
OMPS	2500 (50×50)	0.2	0.4	350	700

IR instrument SO_2 sensitivity

Instrument	Footprint area (km^2)	Noise (DU)* 1σ		Smallest cloud detection limit (tons) 5 pixels at 5σ	
		Stratosphere 20 km	Troposphere <5 km	Stratosphere 20 km	Troposphere <5 km
MODIS	1 (1×1)	9	250	6	174
ASTER	0.008 (0.09×0.09)	9	250	0.05	1.4
AIRS	143 (d = 13.5 km)	1	30	100	2986
SEVIRI	23 (4.8×4.8)	9	250	144	4009

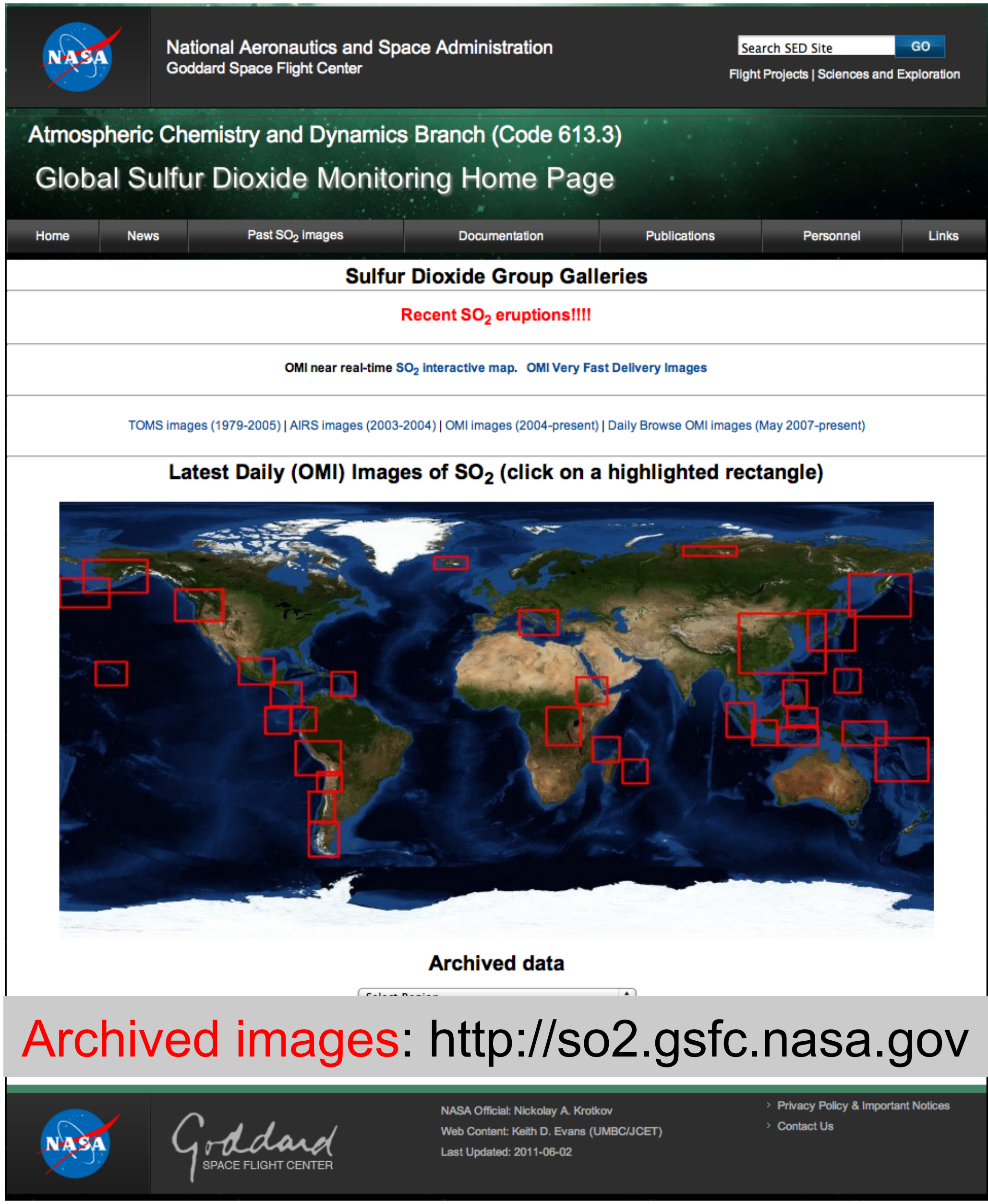
*Based on *Realmuto* [1999], AGU Geophysical Monograph 116, p101-115 (except AIRS)

The 'sub-pixel' plume problem



- Fraction of satellite IFOV covered by volcanic plume constrains detection of tropospheric SO_2 degassing plumes from space

Global SO_2 monitoring website



Archived images: http://so2.gsfc.nasa.gov

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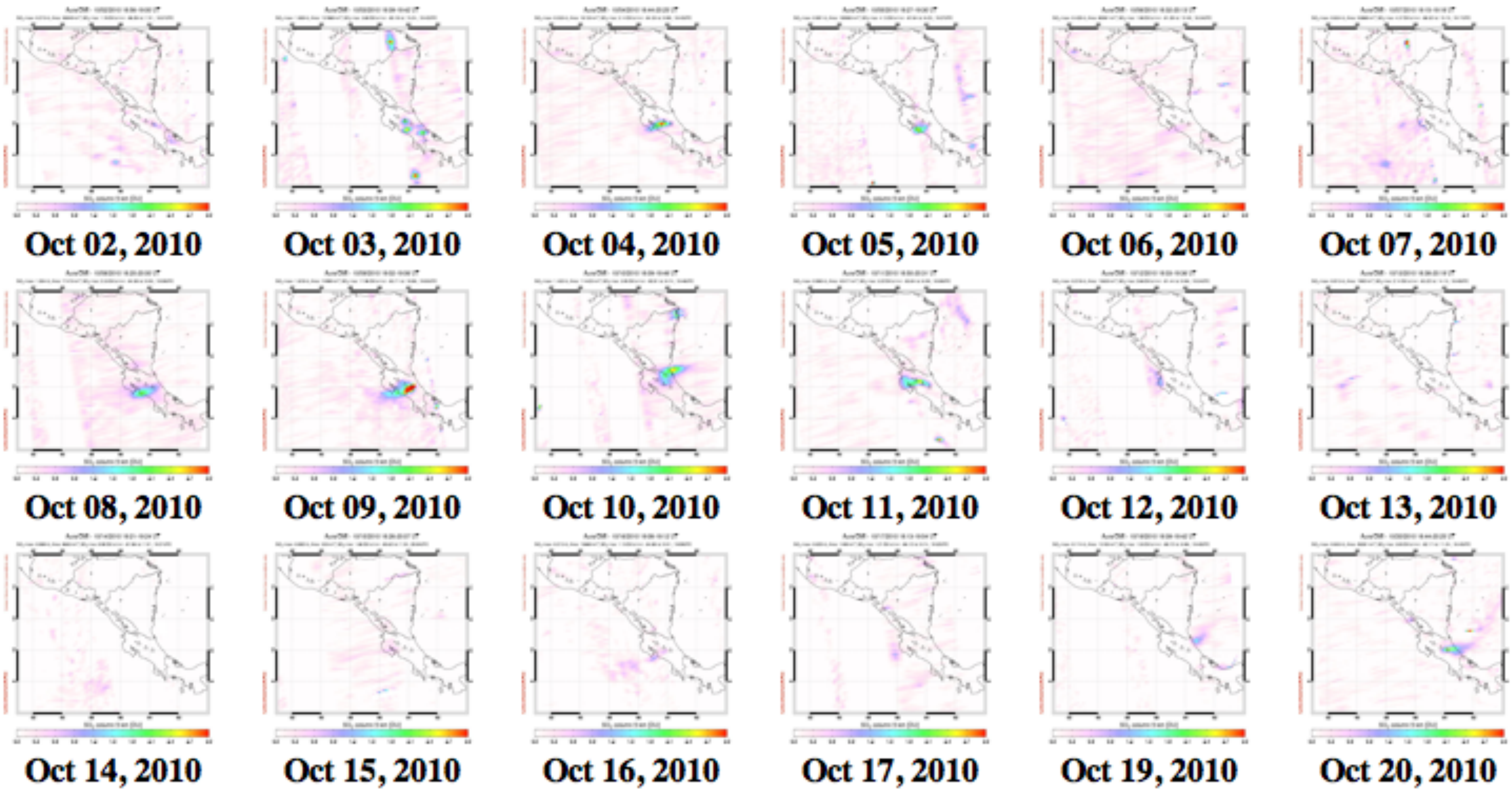
Daily OMI SO_2 measurements

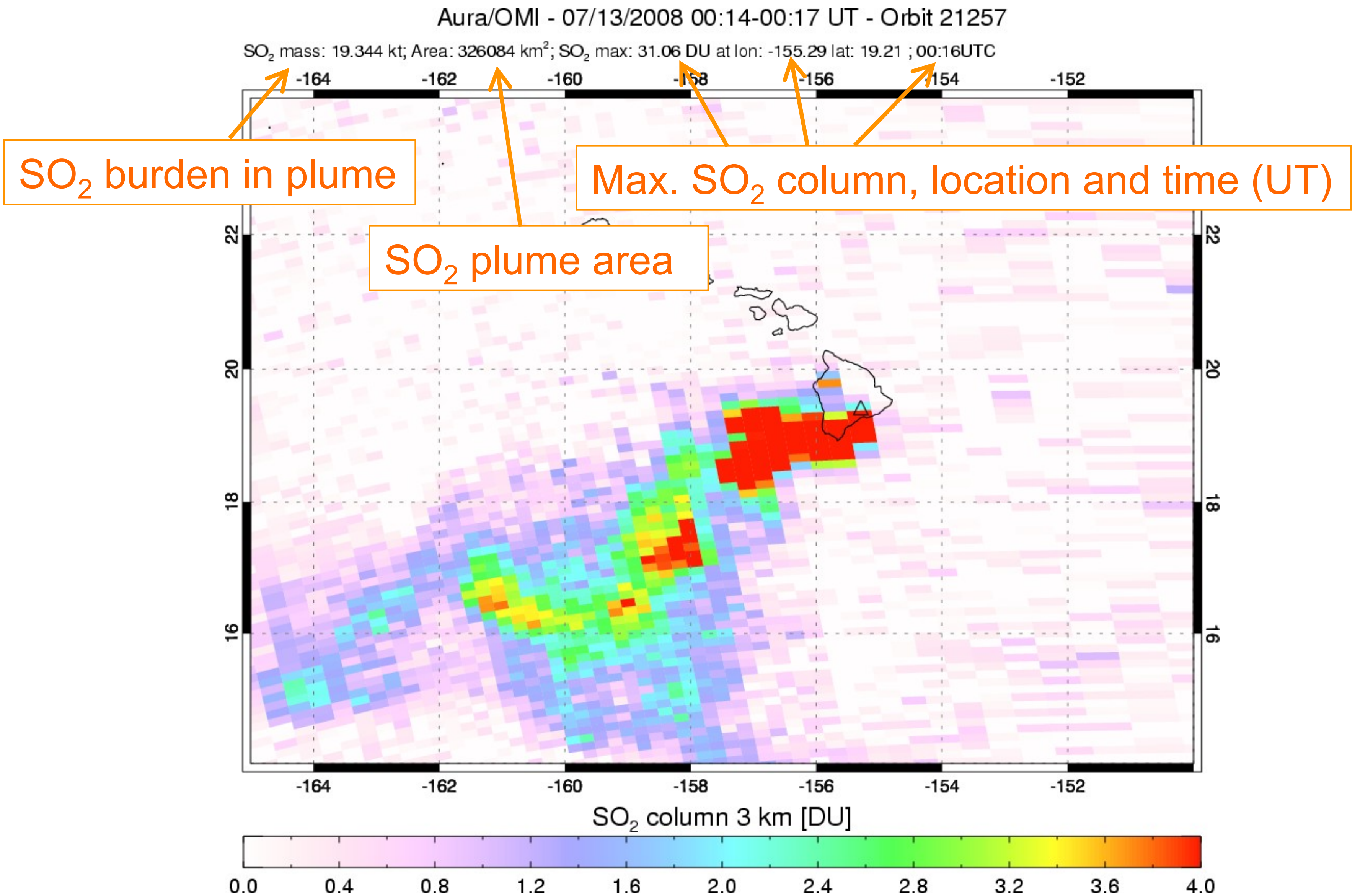
http://so2.gsfc.nasa.gov



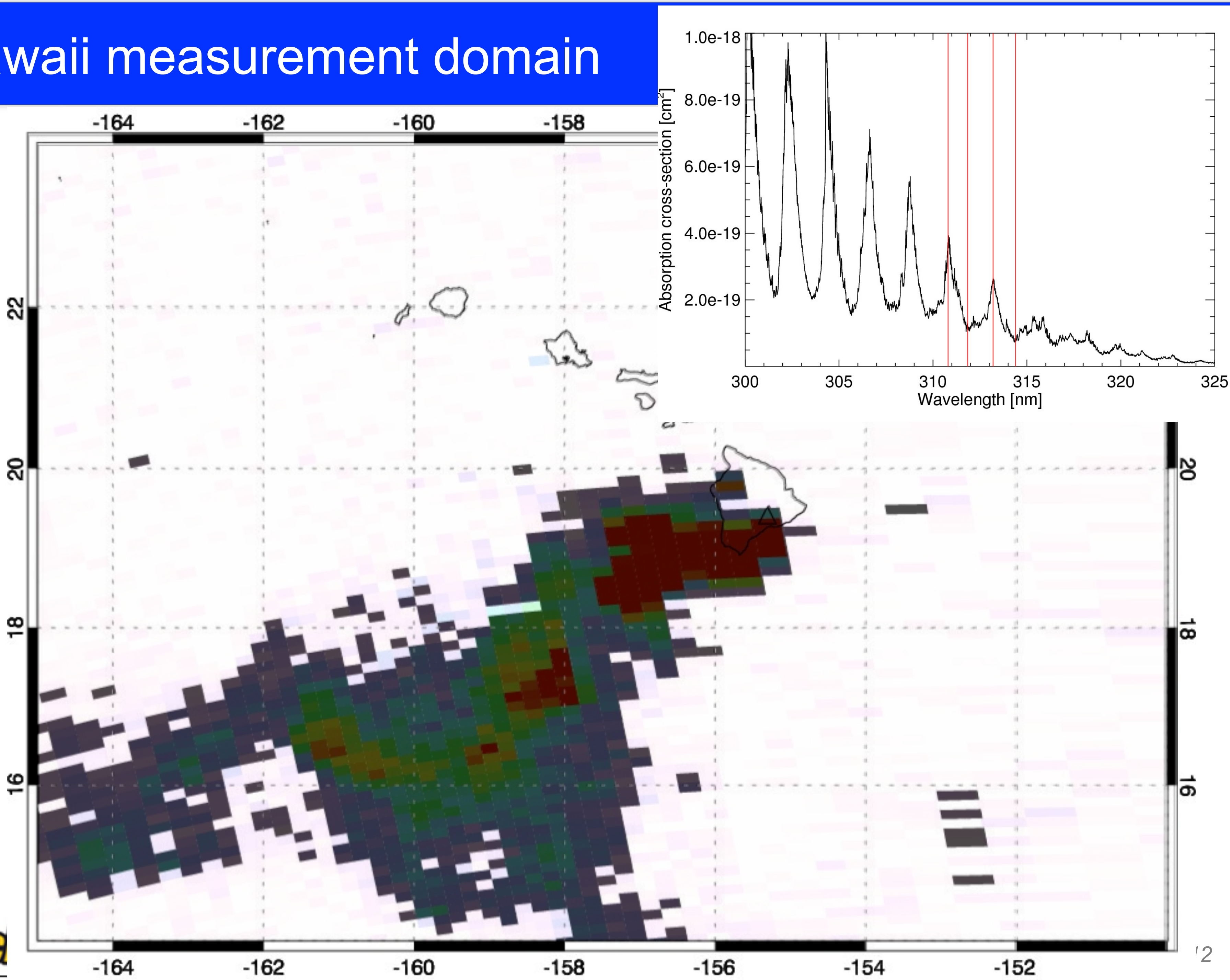
- Satellites measure column amounts of gases, NOT emission rates

Daily OMI SO_2 measurements for Kilauea

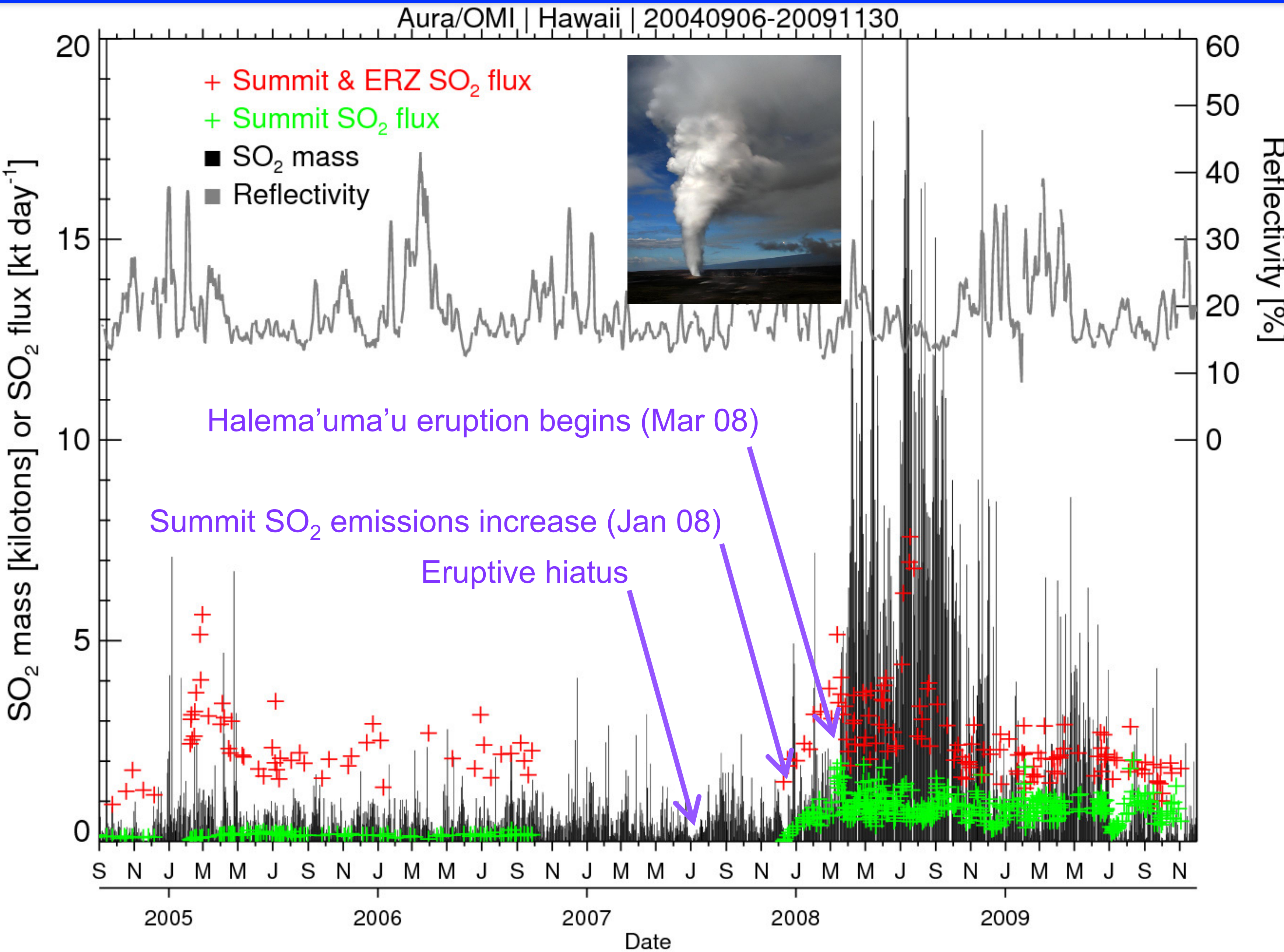
http://so2.gsfc.nasa.gov



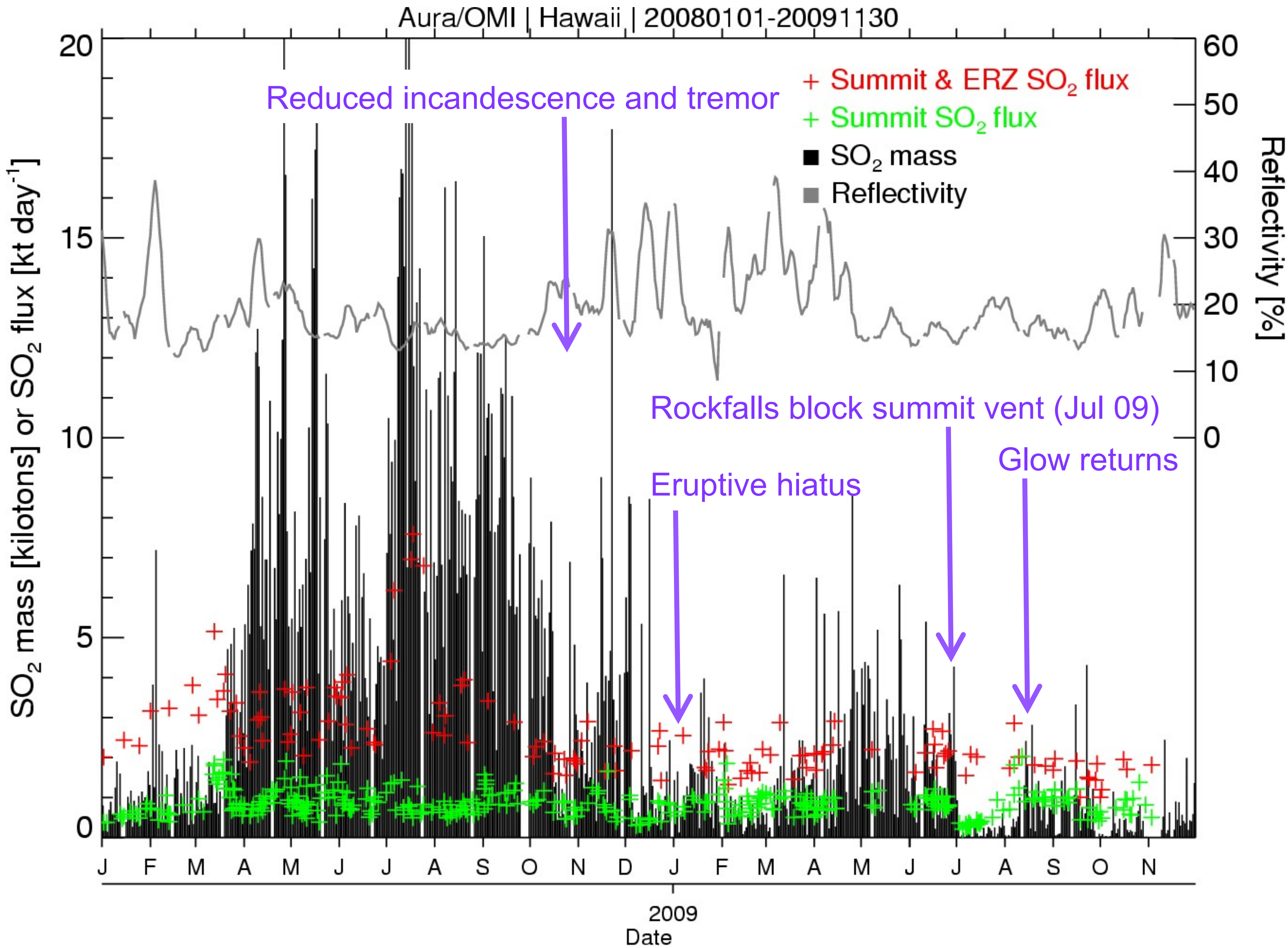
Hawaii measurement domain



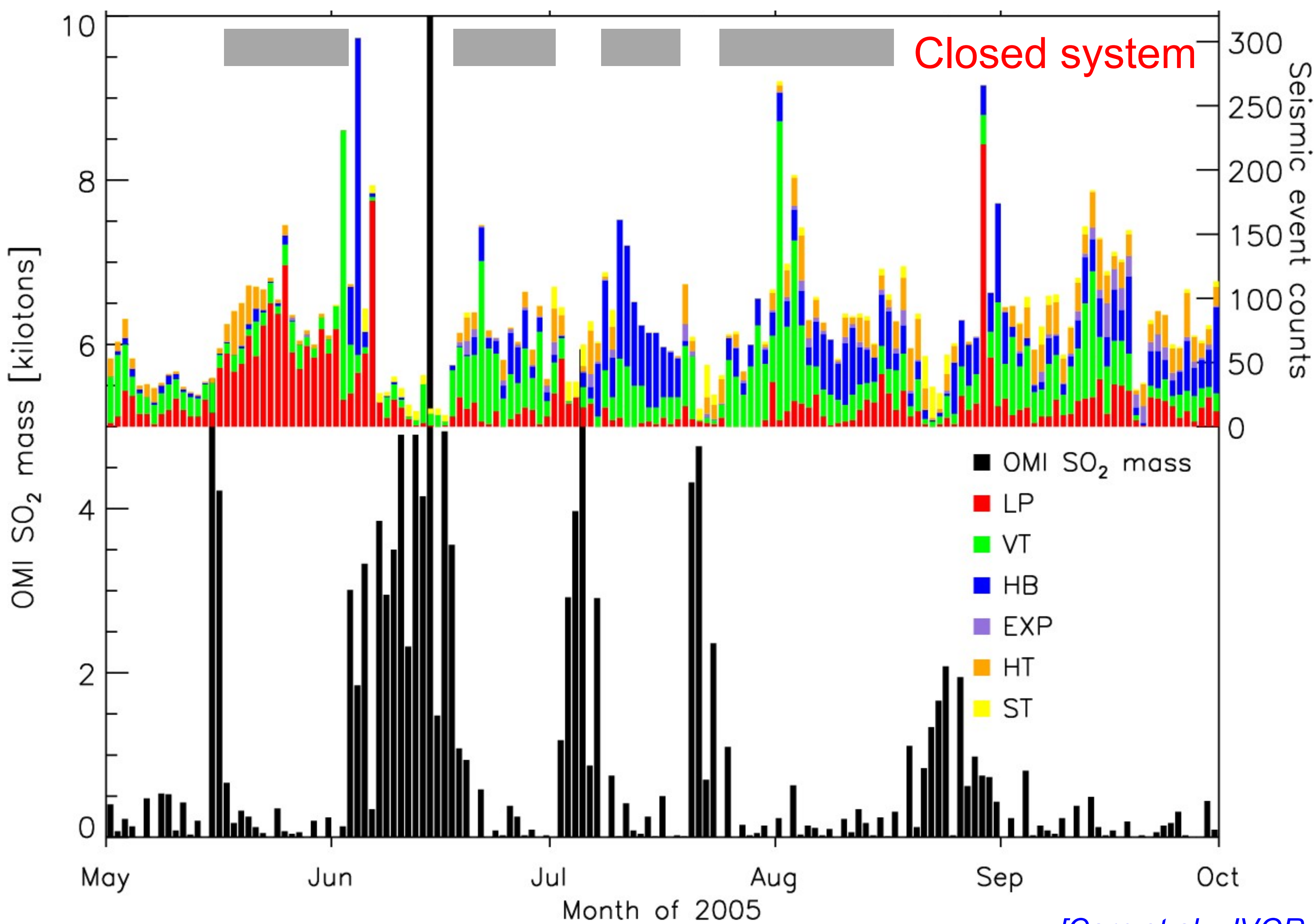
Kilauea plume SO_2 burdens: 2004-2009



Kilauea plume SO_2 burdens: 2008-2009

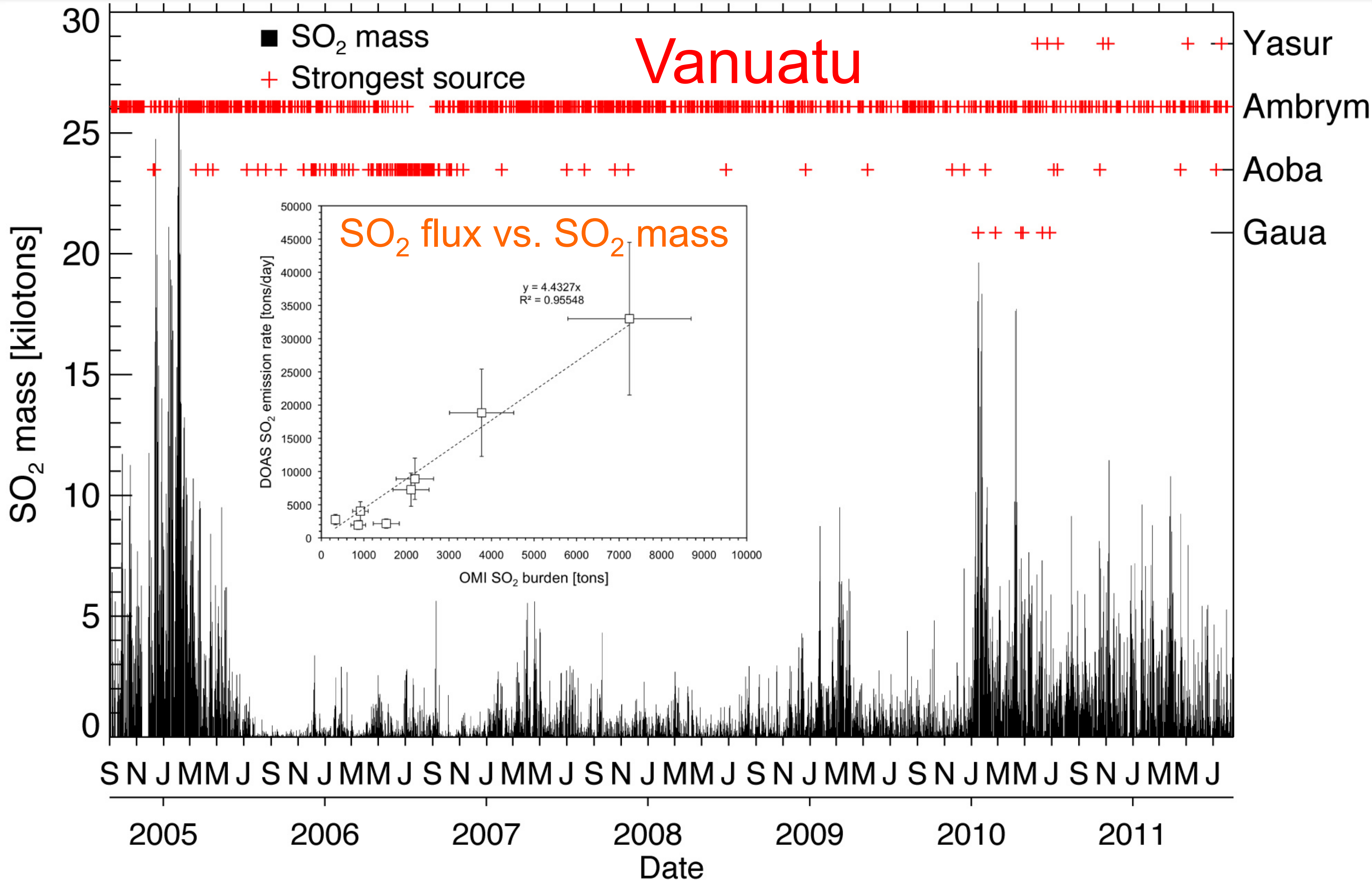


Reventador (Ecuador) seismicity and OMI SO_2 data



[Carn et al., JVGR, 2008]

Detailed analyses of SO_2 emissions from volcanic arcs



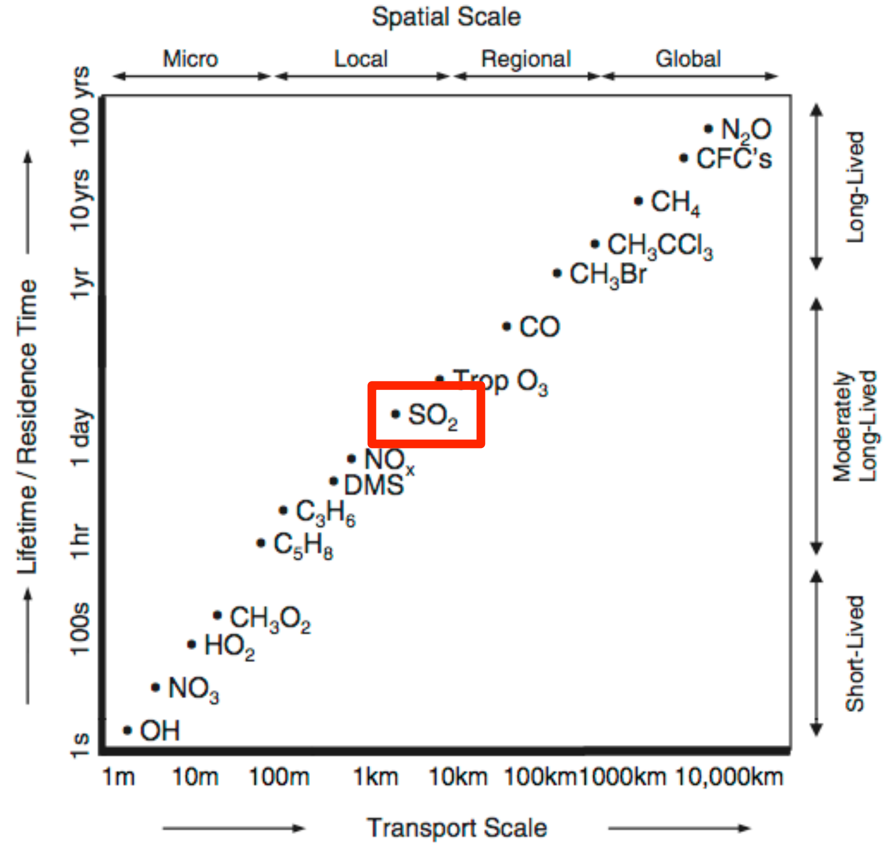
Carn et al., JVGR, 2008 (Ecuador); *Bani et al., JVGR,* 2011 (Vanuatu); McCormick et al., G^3, 2012 (PNG)

SO_2 flux estimation from satellite data - lifetime

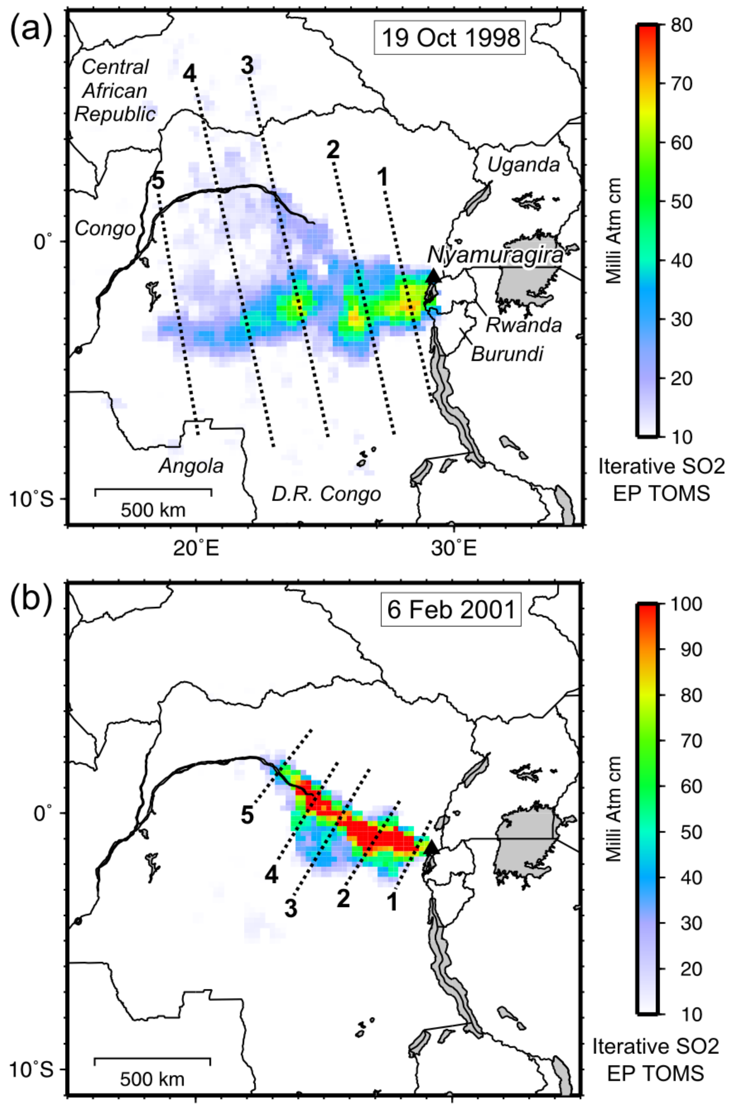
- Satellite 'snapshots' measure SO_2 burden, not flux
- To first order, SO_2 emission rates can be inferred using the SO_2 burden and an estimate of the SO_2 lifetime
- SO_2 lifetime short (hours) at low altitudes and in humid environments
- Few hours in tropical boundary layers

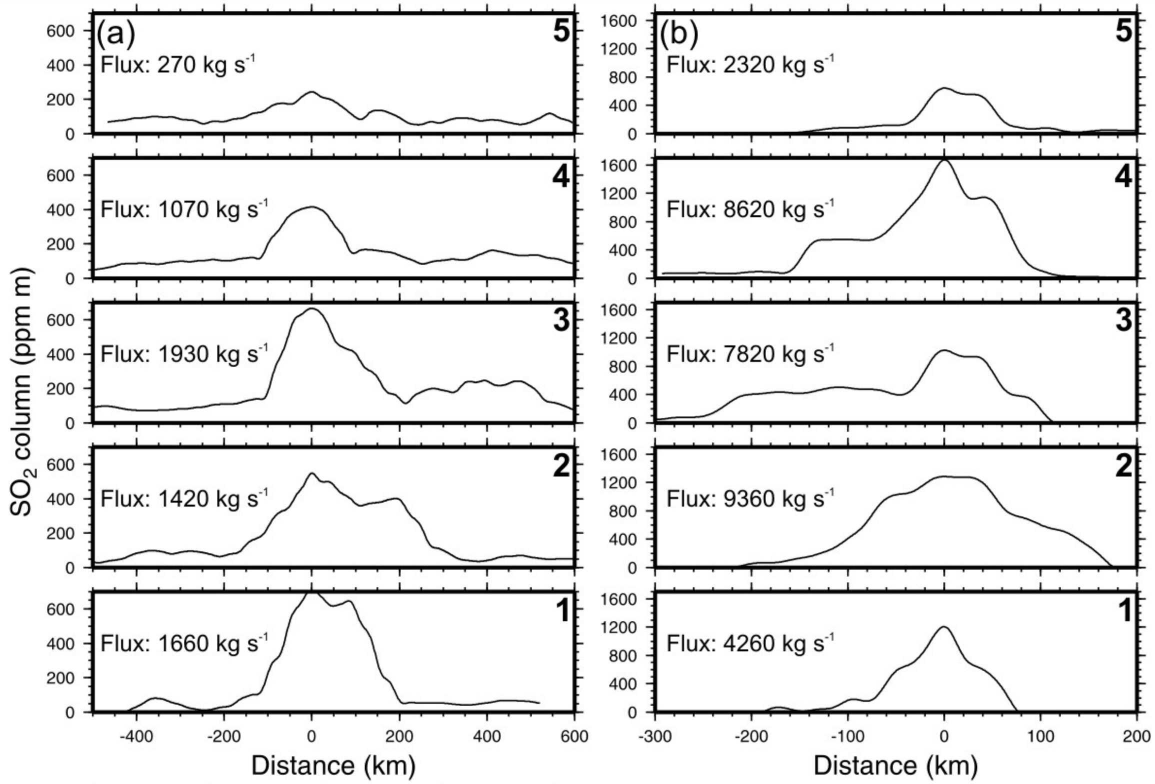
$$Q = \frac{M}{\tau}$$

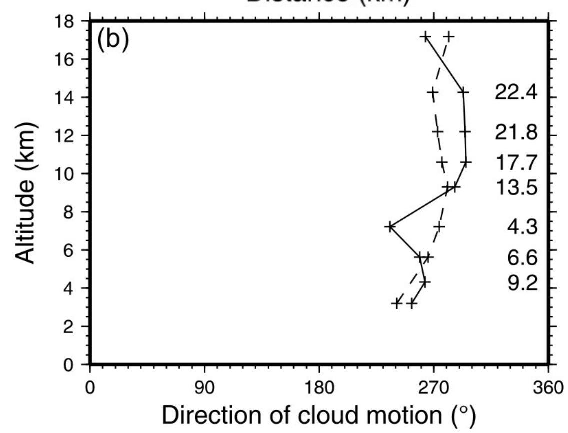
- Q = SO_2 emission rate (tons/day)
- M = SO_2 burden (tons)
- τ = SO_2 lifetime (days)



SO_2 flux estimation from satellite data - transects







- Plume transect method
- Wind profile required (e.g., radiosonde, model)

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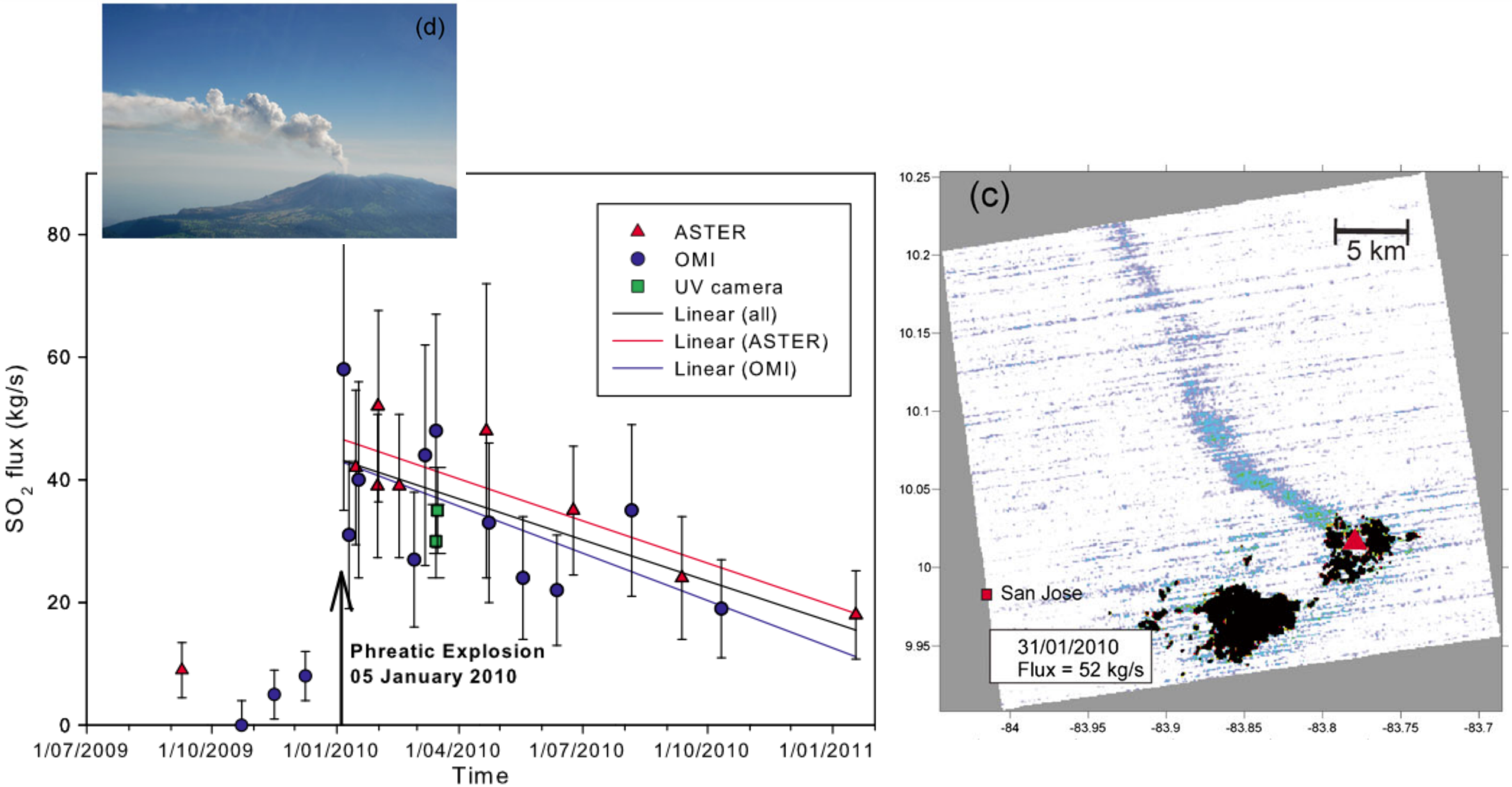
[*Carn & Bluth, 2003*]

SO_2 flux estimation from satellite data (Turrialba)



- Comparison between Turrialba (Costa Rica) SO_2 emission rates derived from ASTER, OMI and ground-based UV camera [*Campion et al.*, Bull Volc., 2012]

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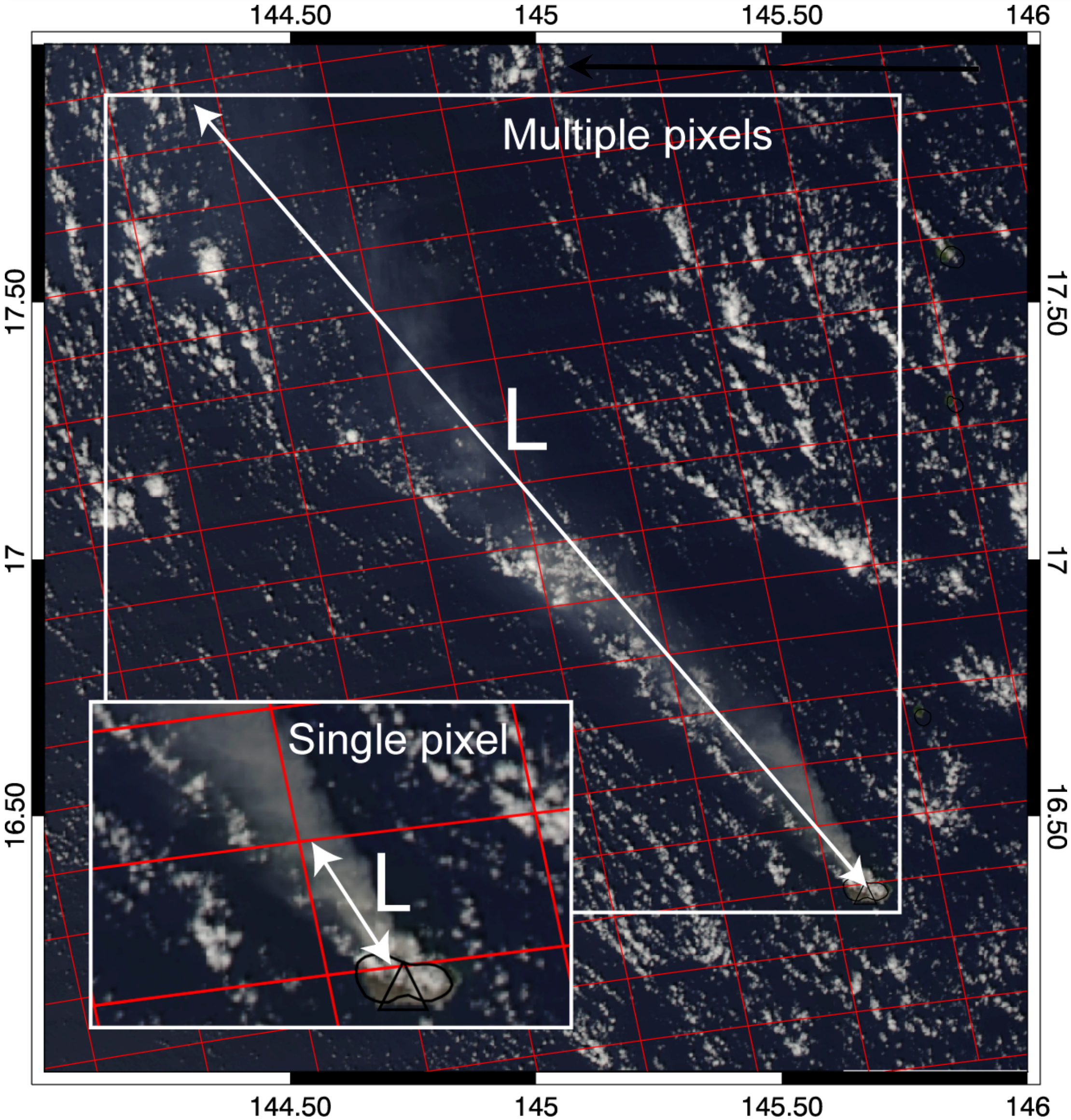
SO_2 flux estimation from satellite data – single pixel



$$Q = \left[\frac{vM}{L}\right]$$

M = SO_2 mass in pixel (kg)
v = wind speed (m s^{-1})
L = length of plume (m)
Q = SO_2 flux (kg s^{-1})

- Similar approach used to estimate smoke emissions from fires [*Ichoku and Kaufman*, 2005]
- Note that asymmetry of OMI pixel affects plume detection

[*Carn et al.*, in press]

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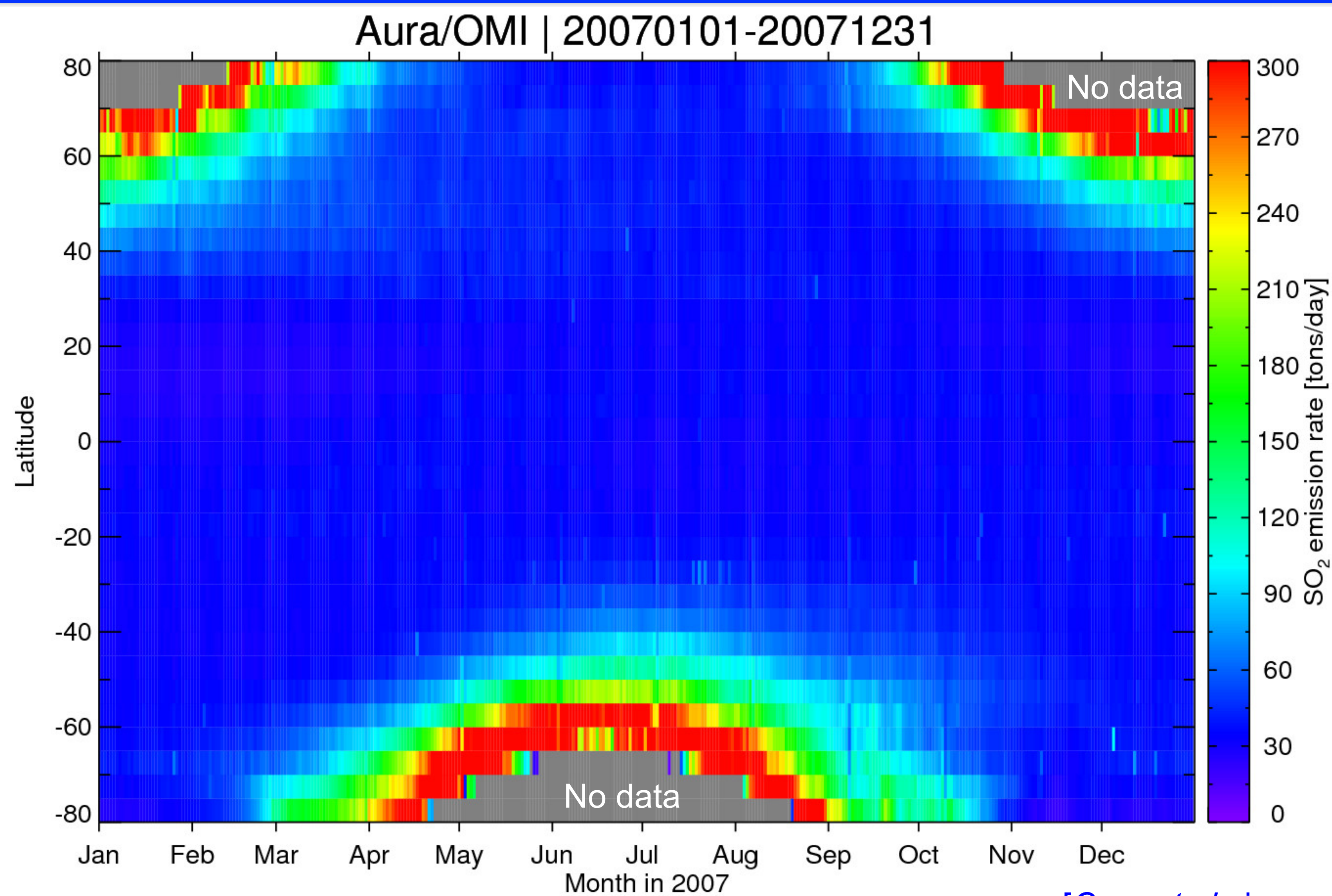
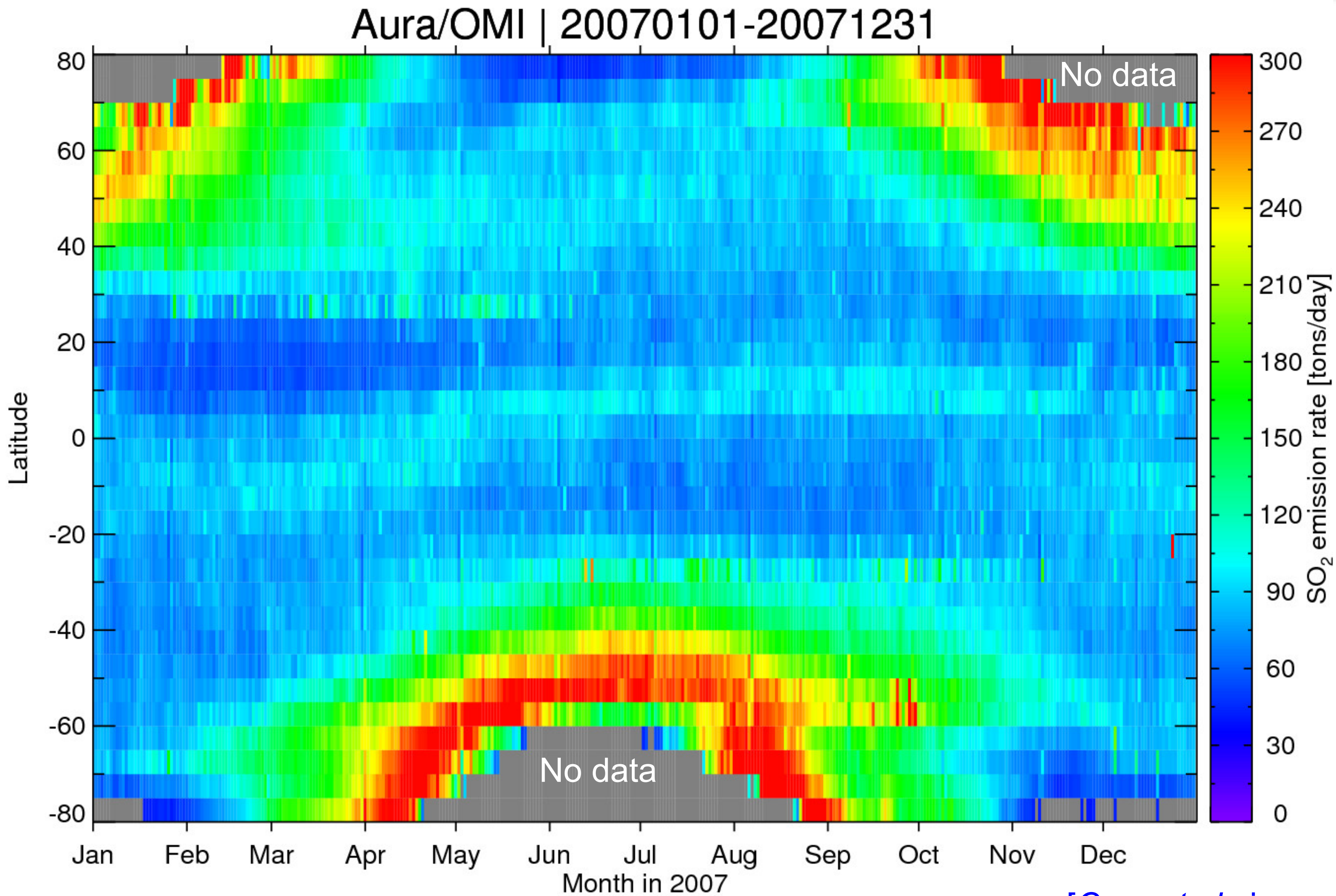
SO_2 flux detection limits – zonal means (TRM)



[*Carn et al.*, in press]

- 5σ noise; 1 m s^{-1} wind speed; plume parallel to long-axis of pixel

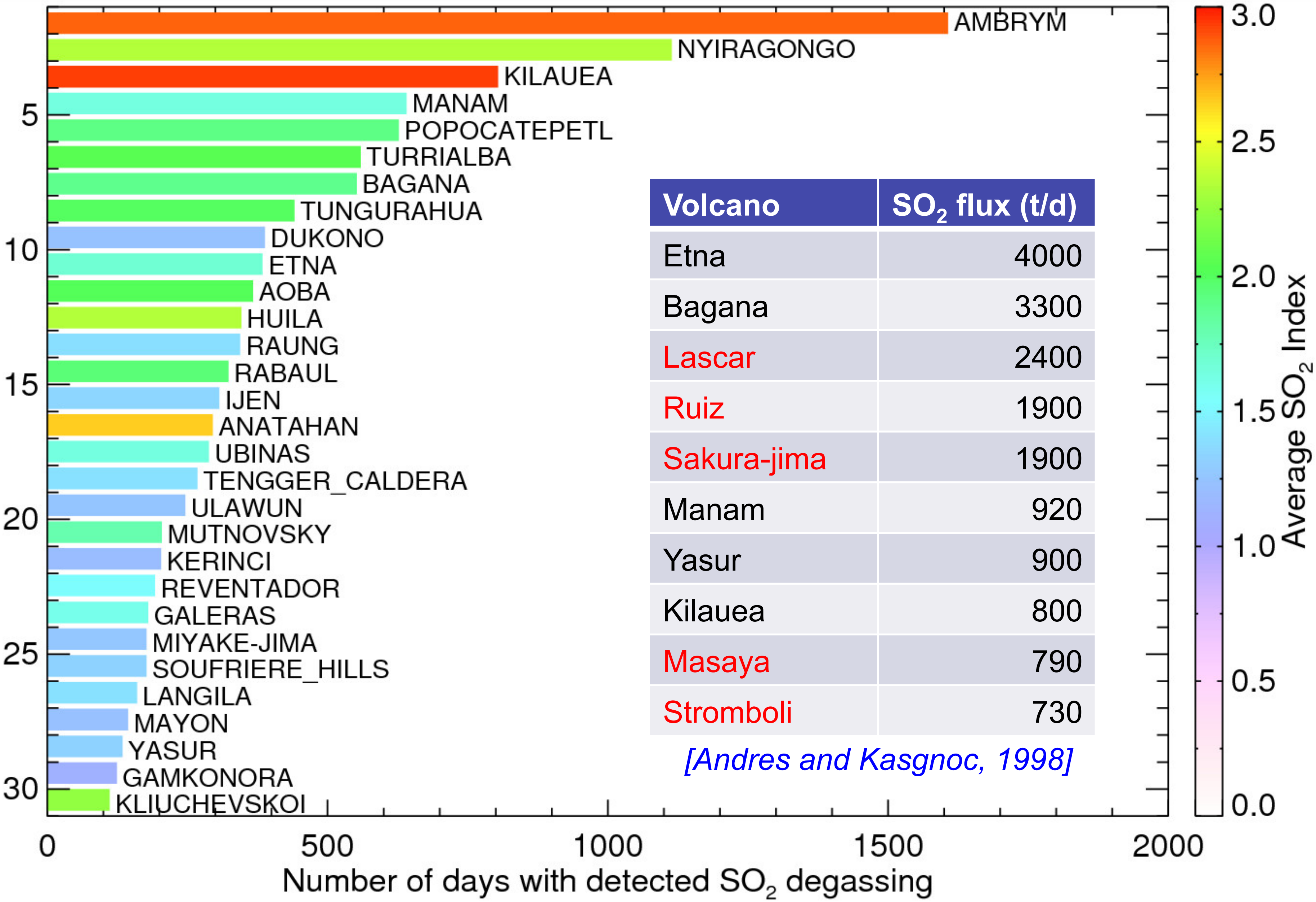
SO_2 flux detection limits – zonal means (TRL)



[*Carn et al.*, in press]

- 5σ noise; 1 m s^{-1} wind speed; plume parallel to long-axis of pixel

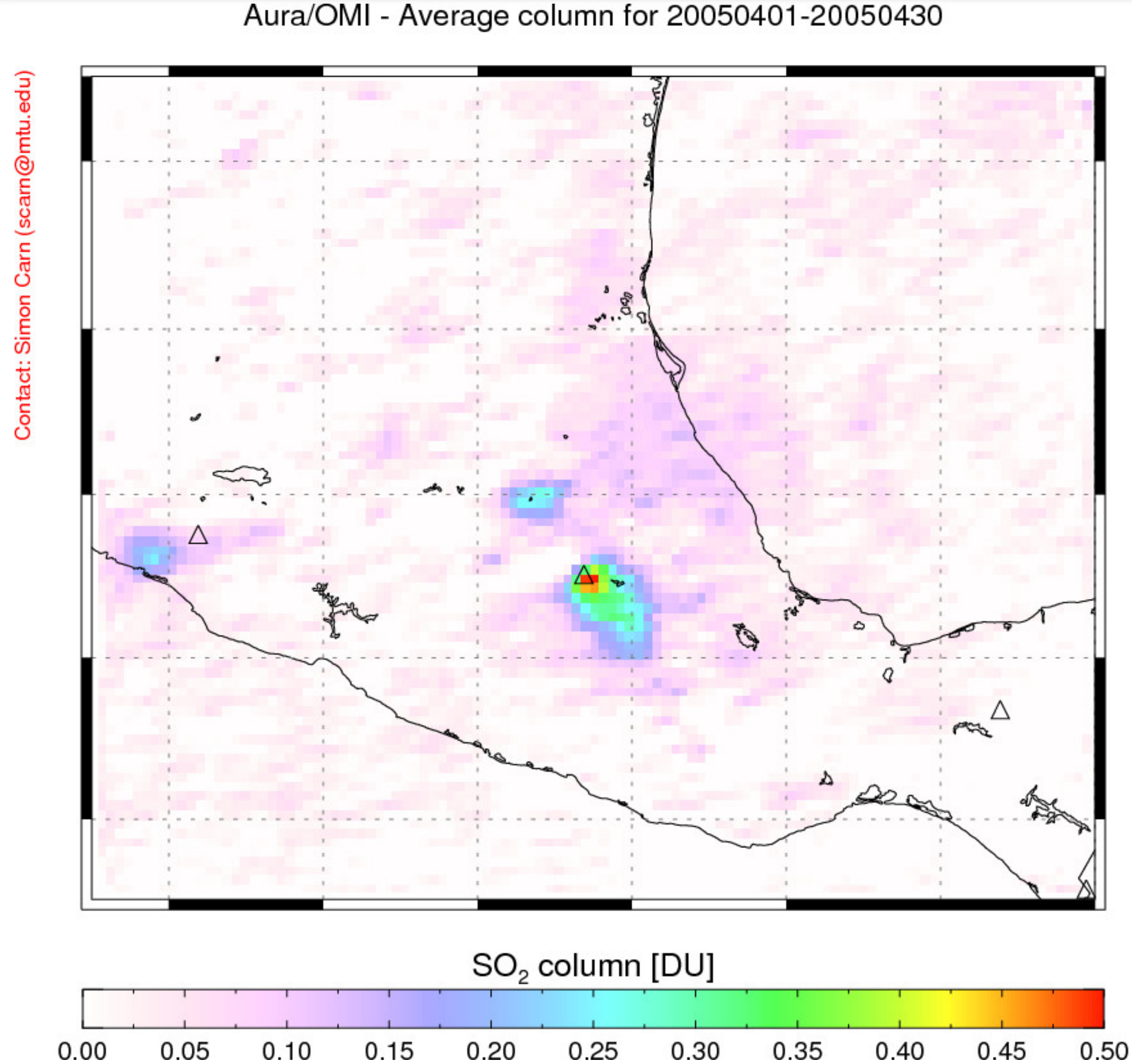
Most persistent volcanic SO_2 sources (2004-2011; ~2500 days)



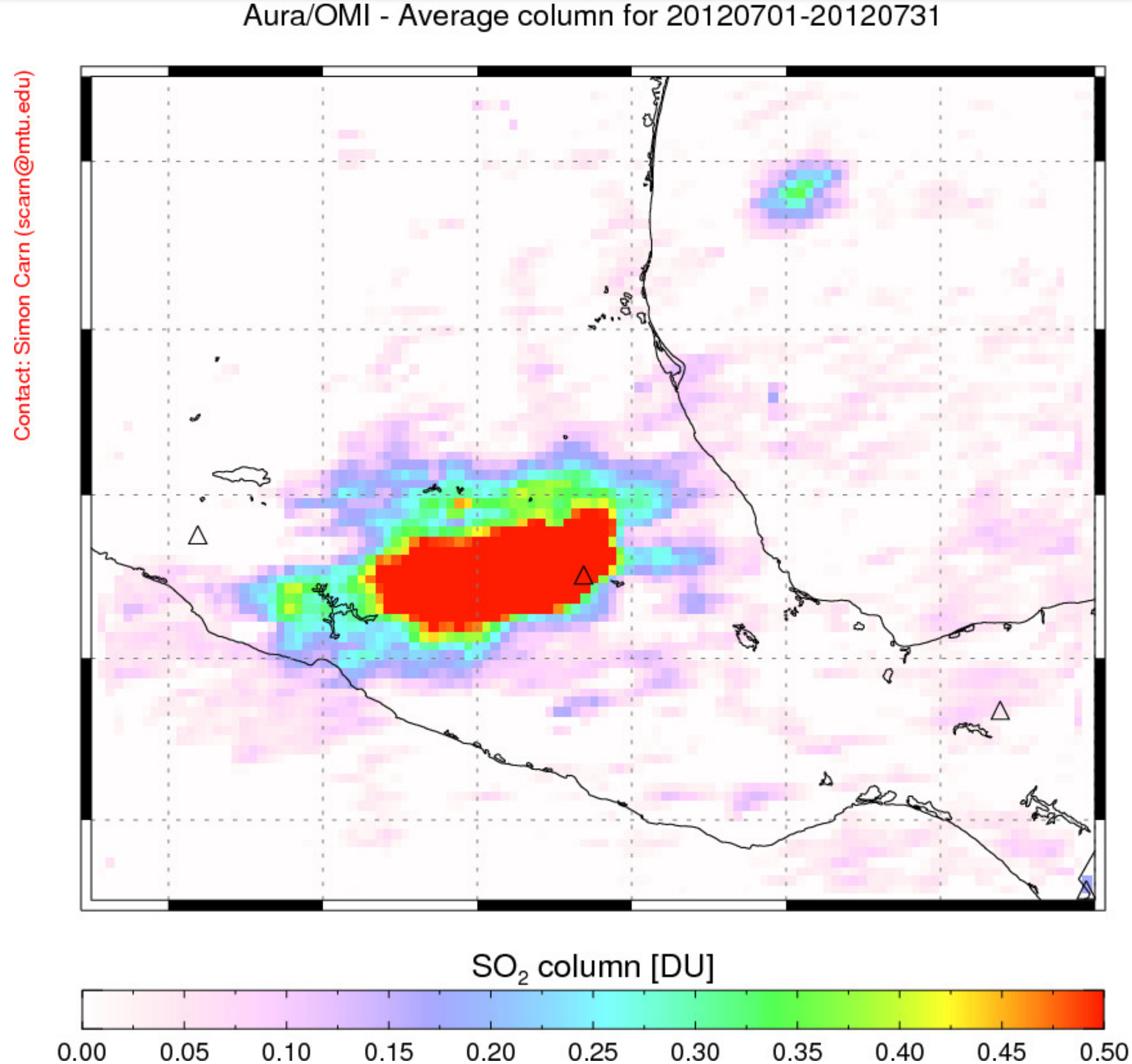
Volcano	SO_2 flux (t/d)
Etna	4000
Bagana	3300
Lascar	2400
Ruiz	1900
Sakura-jima	1900
Manam	920
Yasur	900
Kilauea	800
Masaya	790
Stromboli	730

[Andres and Kasgnoc, 1998]

Monthly average SO_2 – Mexico (April 2005)



Monthly average SO_2 – Mexico (July 2012)



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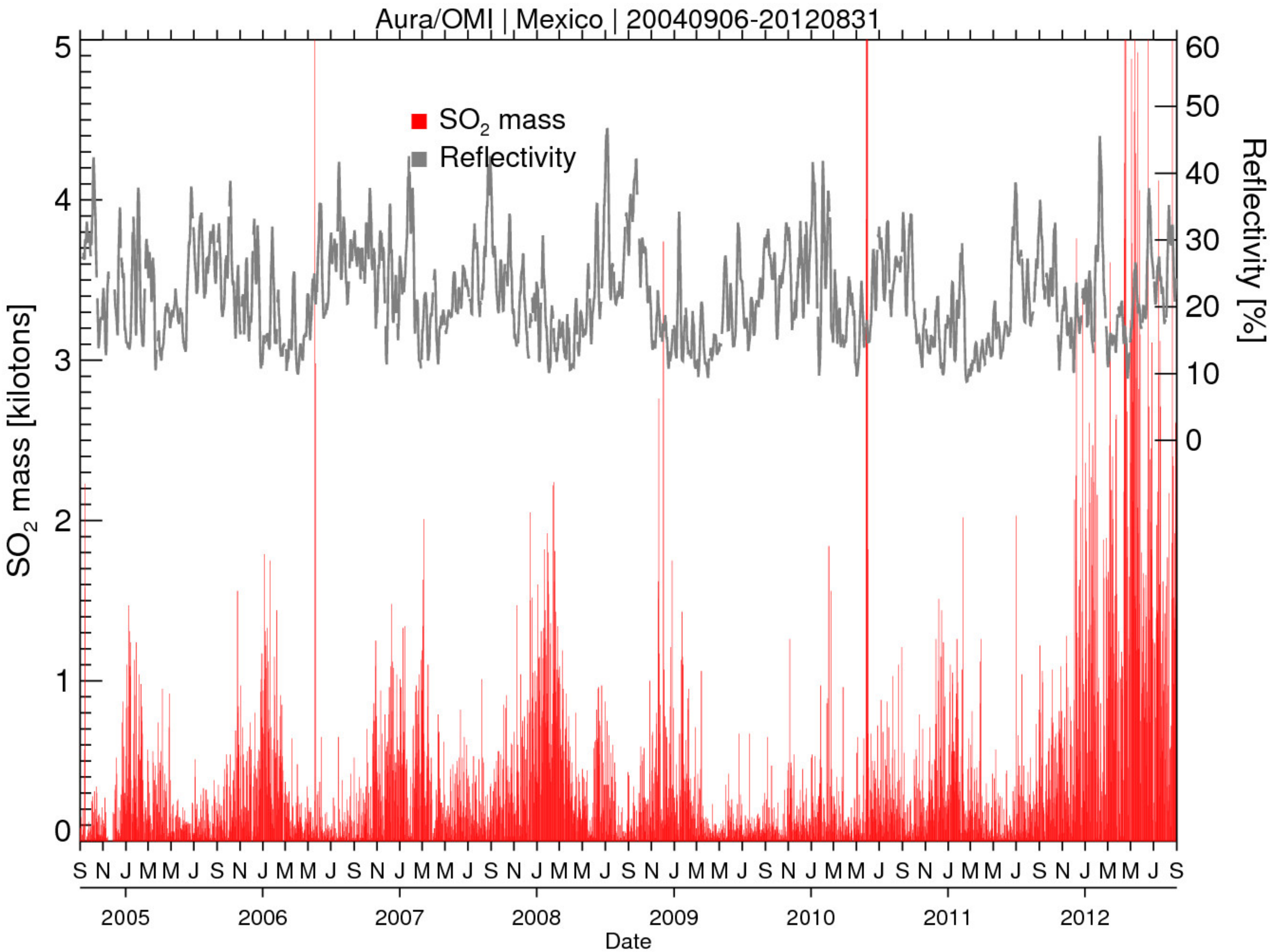
Daily SO_2 burdens – Mexico (2004-2012)



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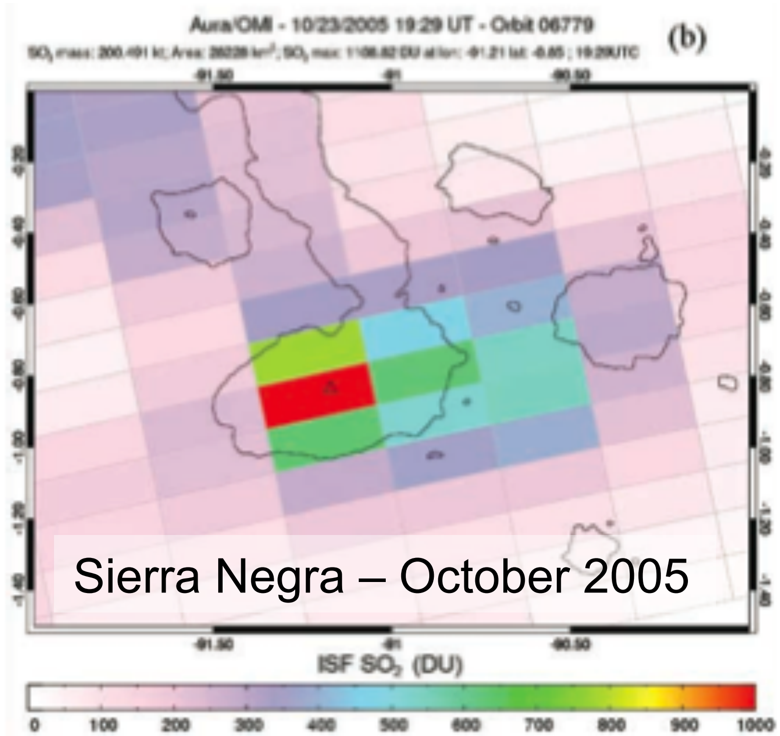
Volcano Monitoring Techniques workshop, COV7, Colima, Nov 2012

Advanced OMI SO_2 algorithms

- Large SO_2 columns (>200 DU)



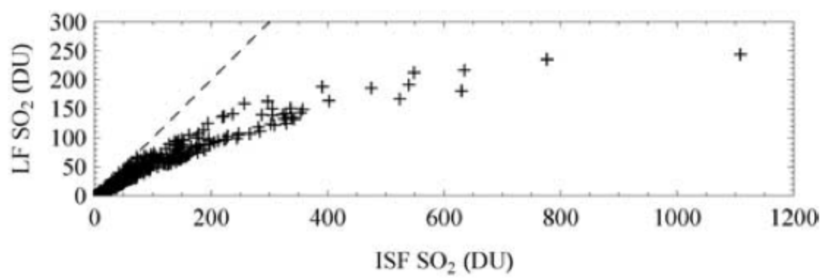


Figure 3. Comparison of ISF and LF SO_2 columns in the Sierra Negra eruption cloud on October 23, 2005. The LF retrievals saturate at about 200 DU in this case.

- SO_2 altitude

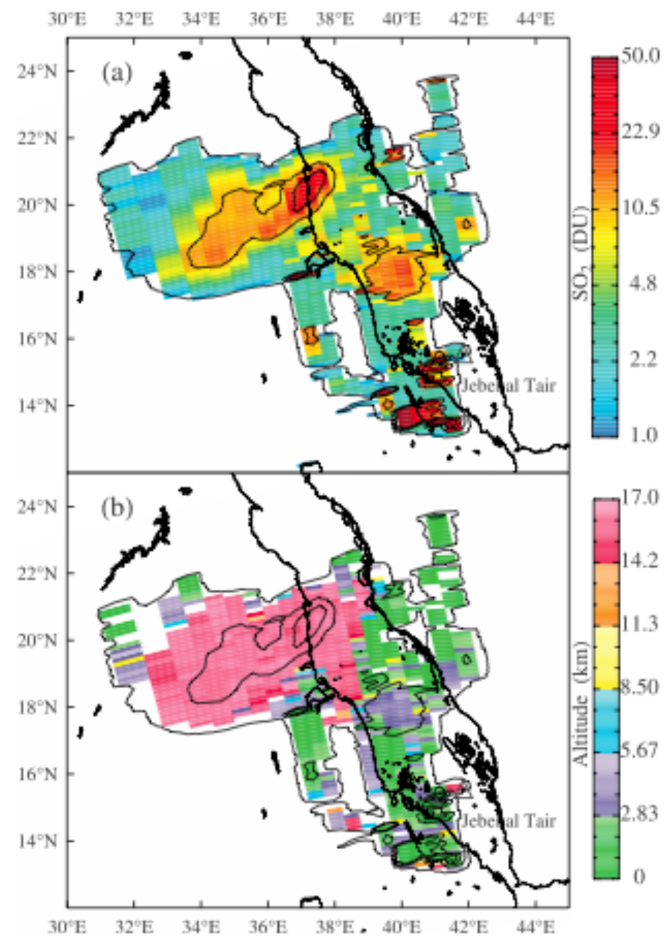
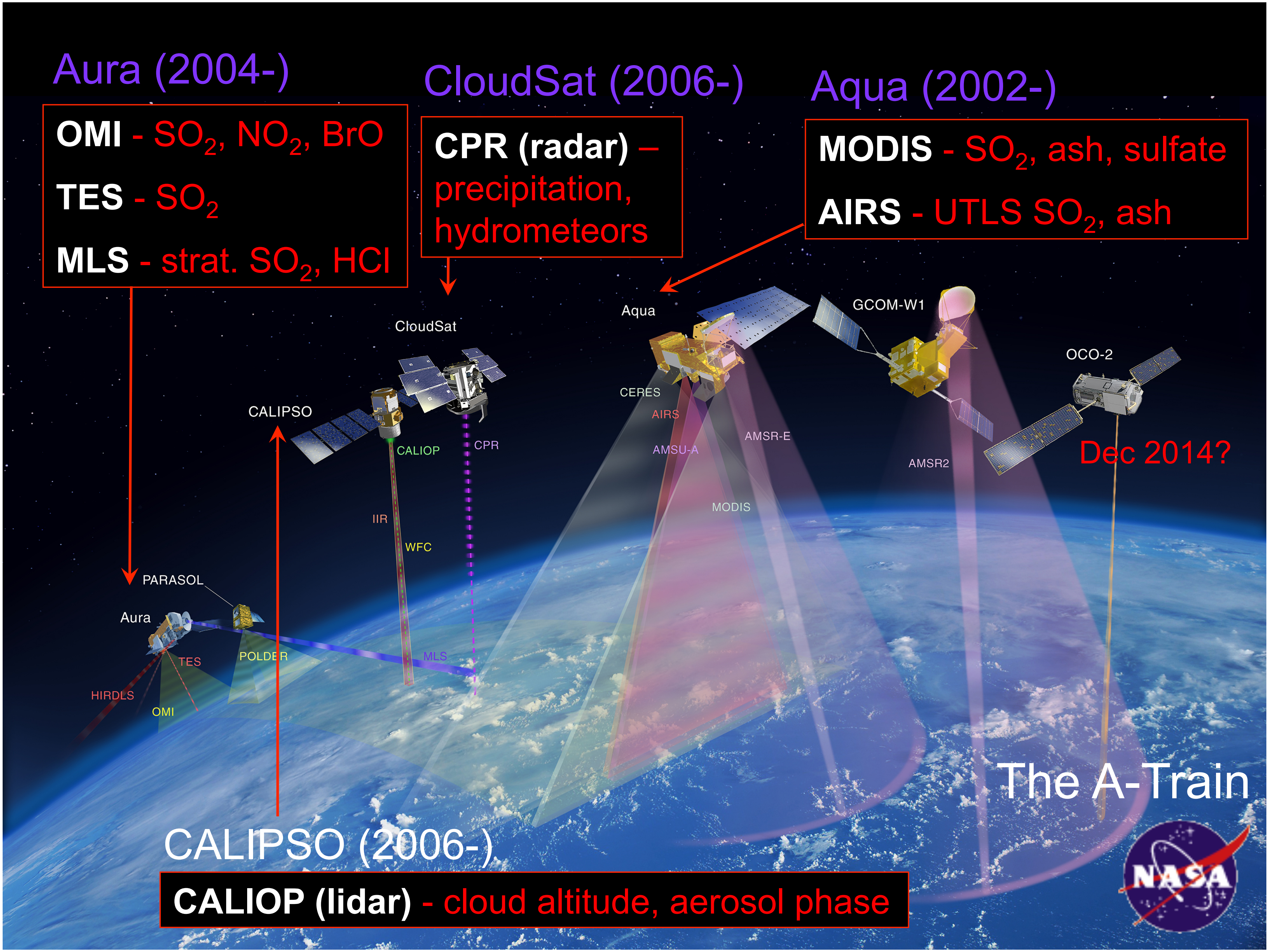
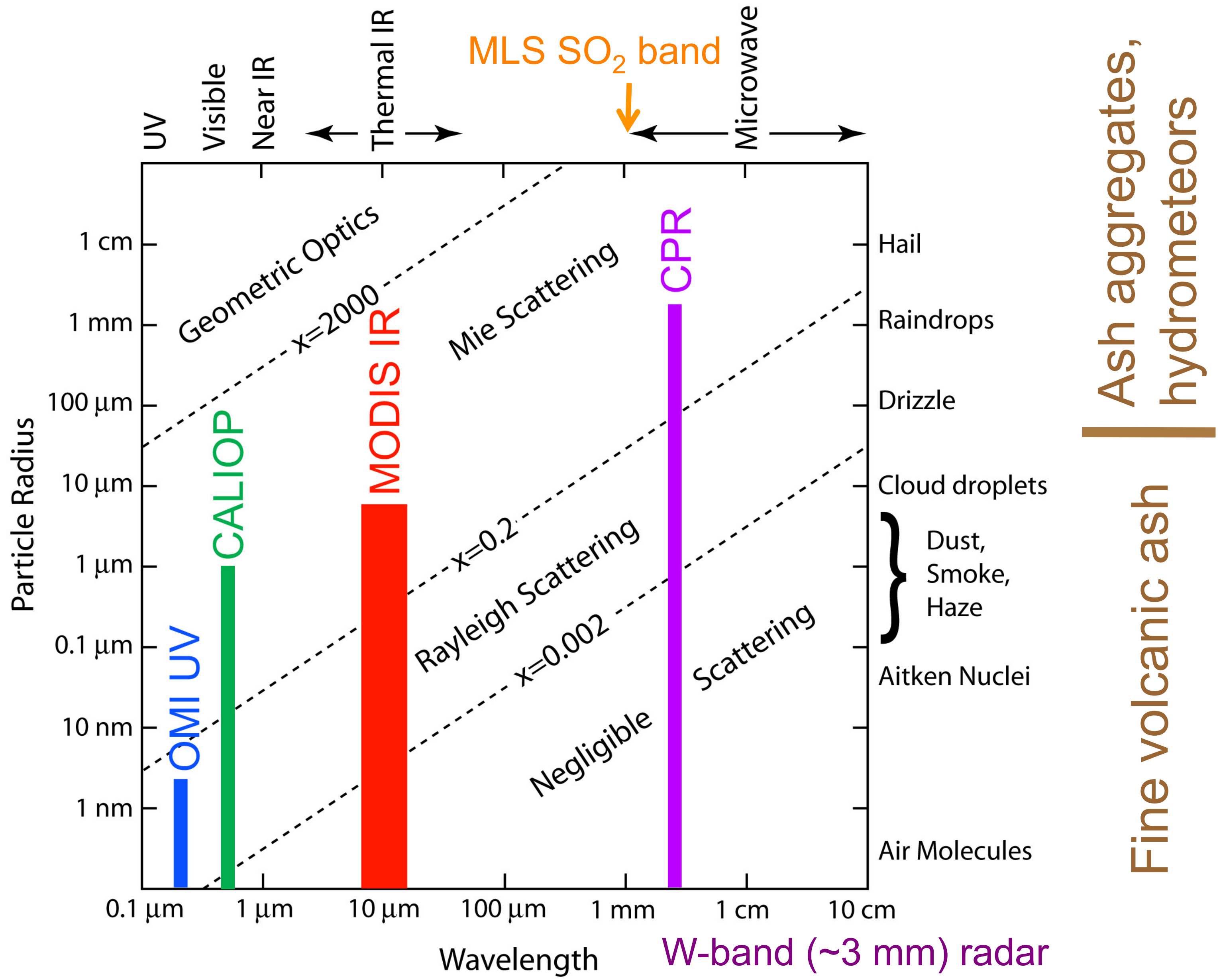


Figure 3. (a) SO_2 vertical column and (b) effective altitude maps derived from OMI UV (both UV-1 and UV-2) radiances for the Jebel al Tair volcanic plume at 10:59 UT on October 1, 2007, using the extended ISF algorithm.

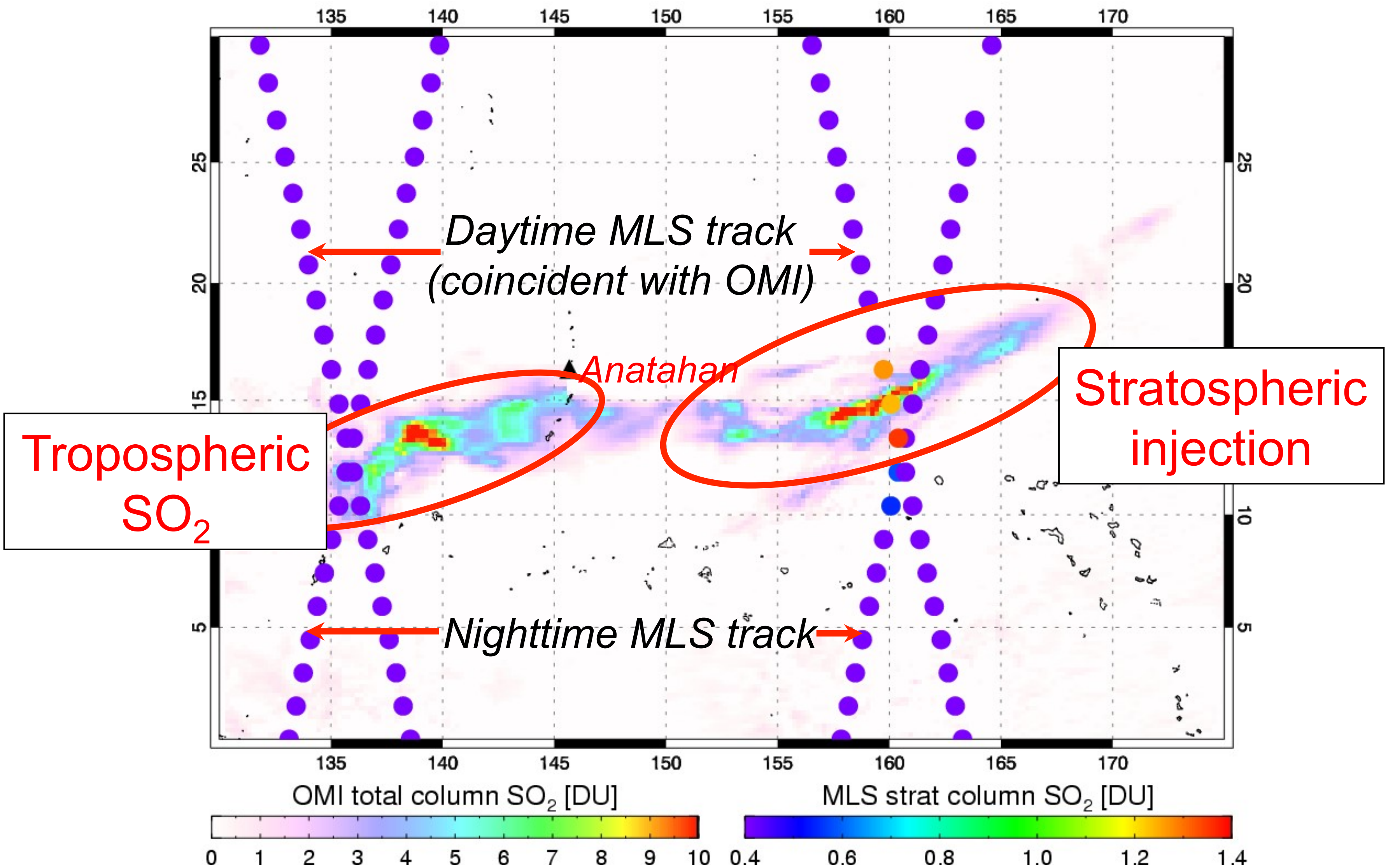
[Yang *et al.*, GRL, 2009a, 2009b]


Aura (2004-)
OMI - SO_2, NO_2, BrO
TES - SO_2
MLS - strat. SO_2, HCl
CloudSat (2006-)
CPR (radar) – precipitation, hydrometeors
Aqua (2002-)
MODIS - SO_2, ash, sulfate
AIRS - UTLS SO_2, ash
CloudSat
Aqua
GCOM-W1
OCO-2
CALIPSO
CERES
AIRS
AMSR-E
AMSU-A
AMSR2
CALIOP
CPR
Dec 2014?
MODIS
IIR
WFC
PARASOL
Aura
TES
POLDER
MLS
HIRDLS
OMI
The A-Train
CALIPSO (2006-)
CALIOP (lidar) - cloud altitude, aerosol phase
NASA

A-Train sensor synergy



Aura/OMI - Aura/MLS: Anatahan (CNMI), April 7, 2005



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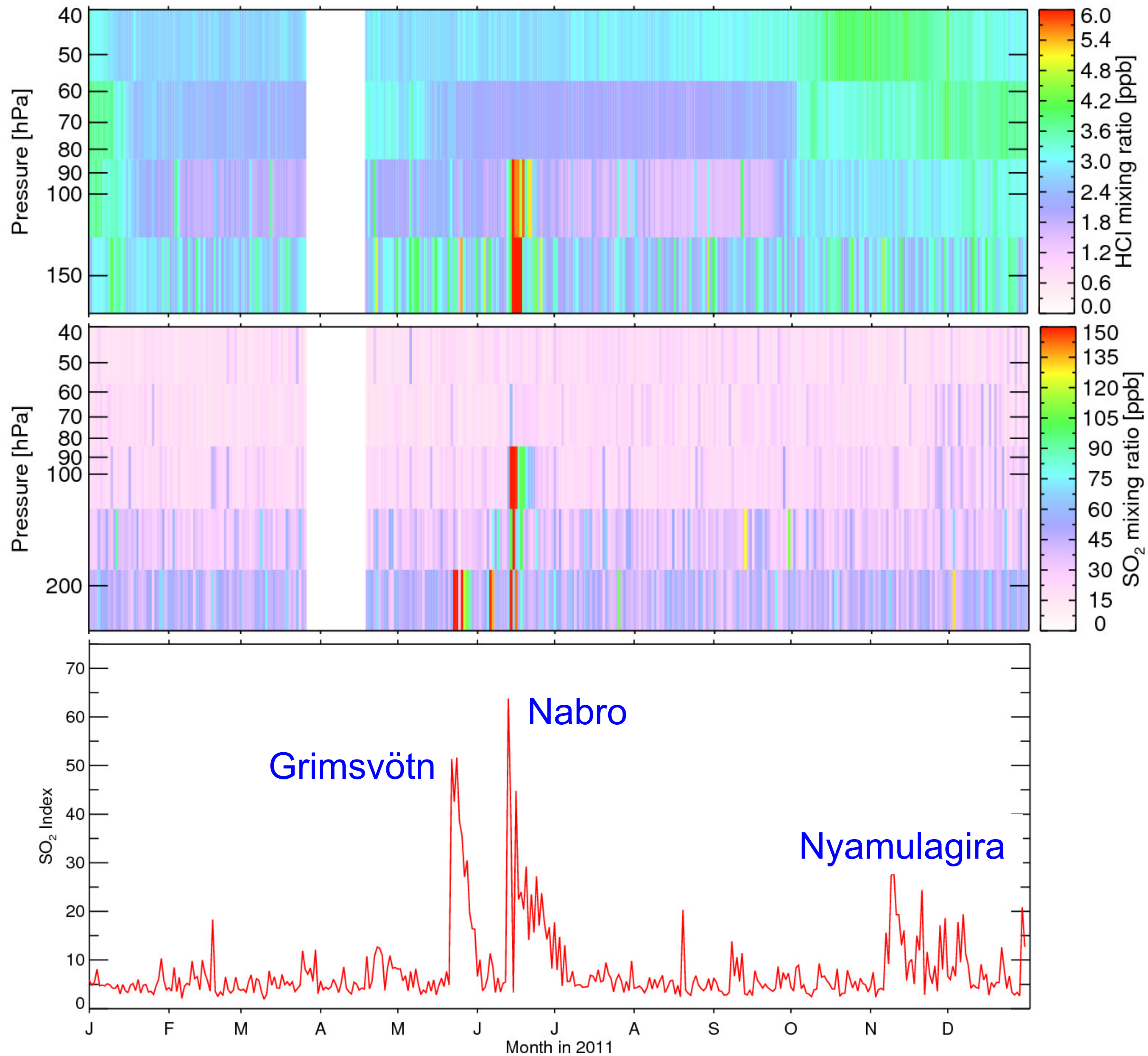
2011

MLS
HCl

MLS
SO_2

OMI
SO_2

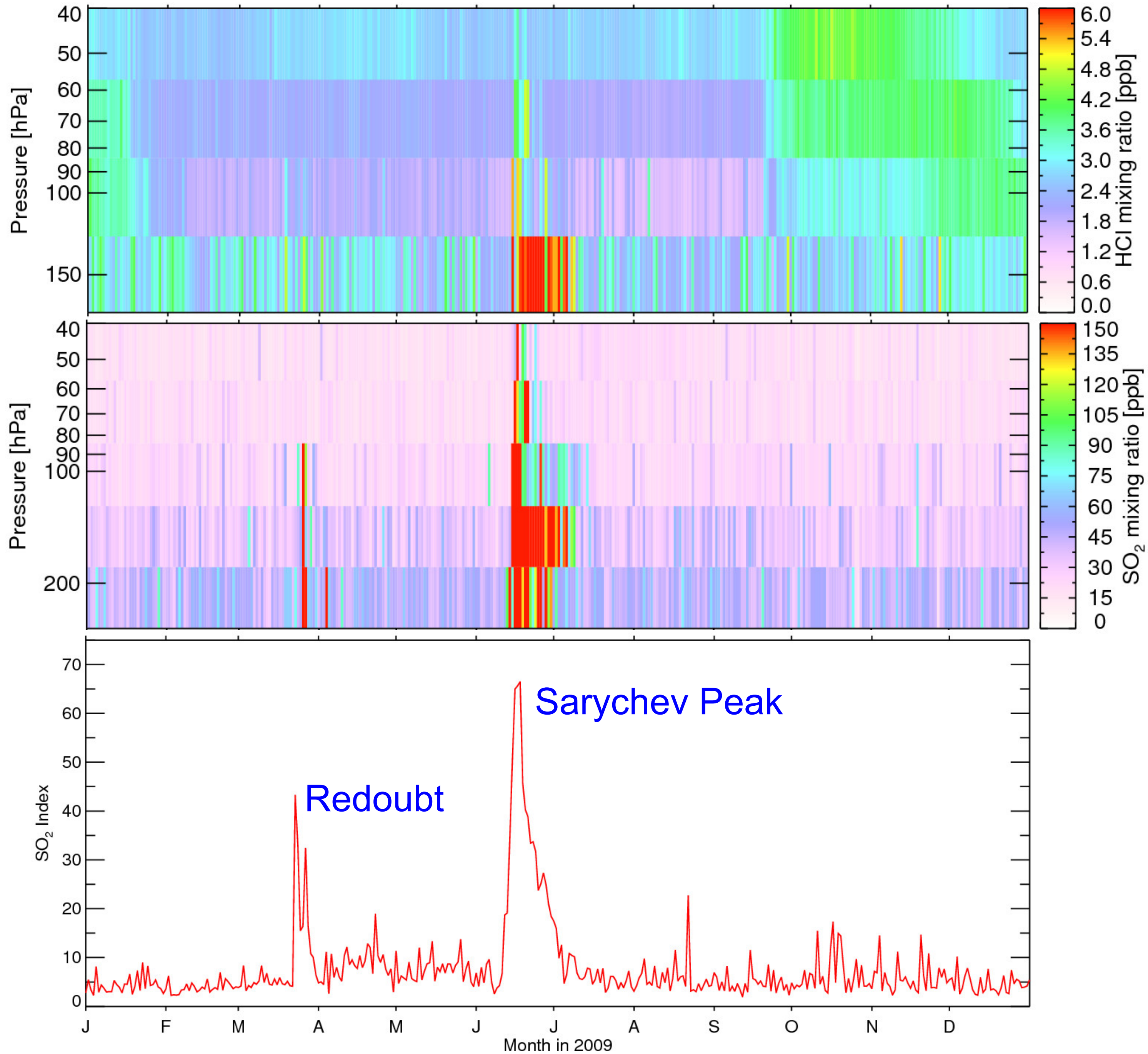


2009

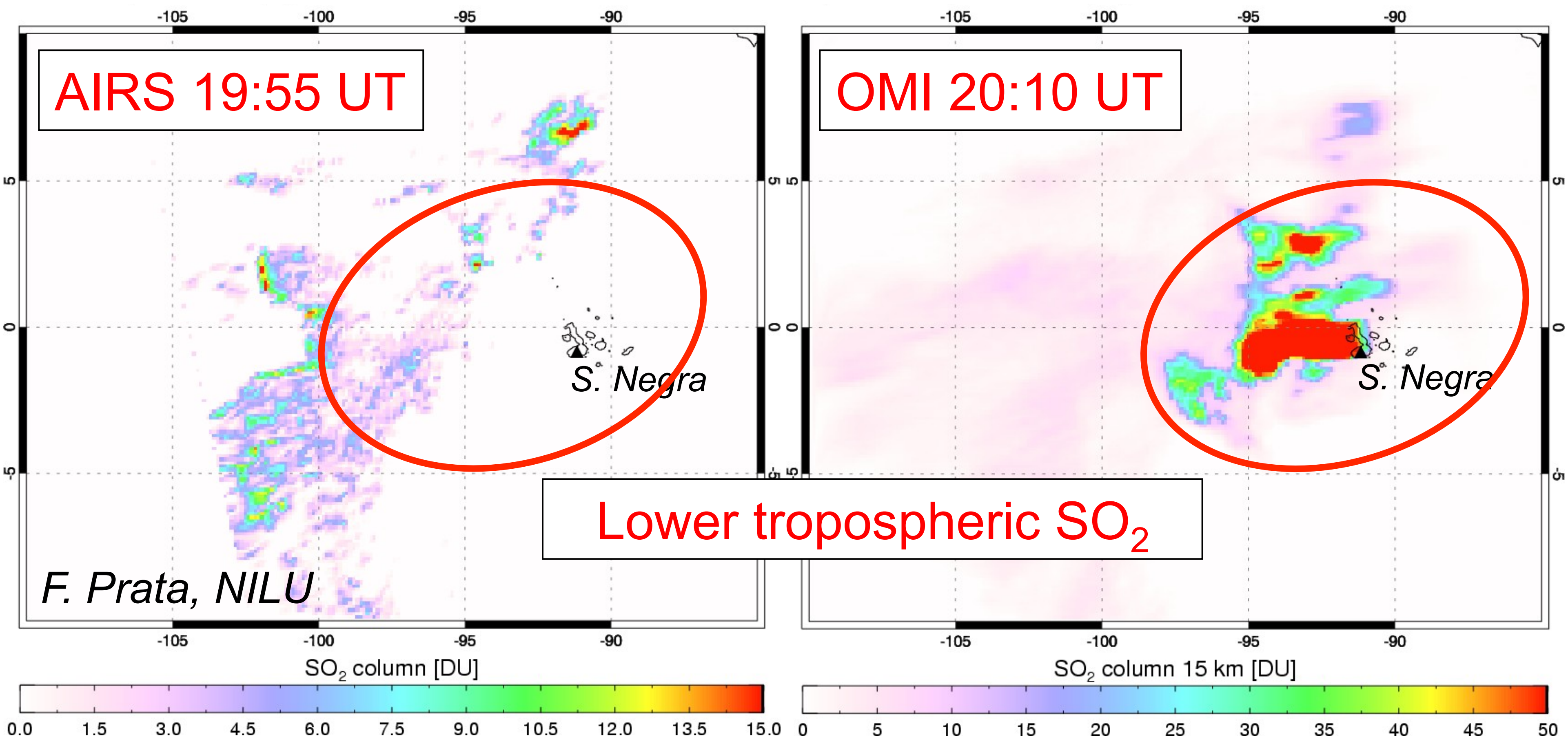
MLS HCl

MLS SO_2

OMI SO_2



Aura/OMI - Aqua/AIRS: Sierra Negra (Galapagos) 2005



- Sierra Negra (Galapagos) eruption, October 24, 2005
- OMI-AIRS synergy indicates SO_2 concentrated in the lower troposphere

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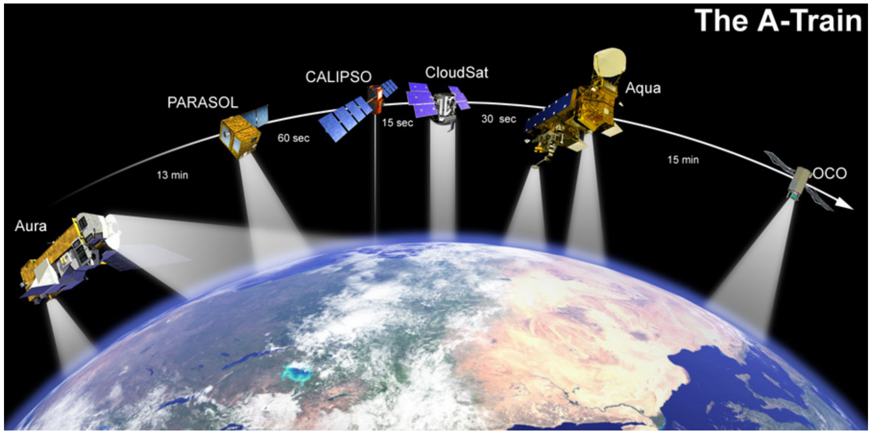
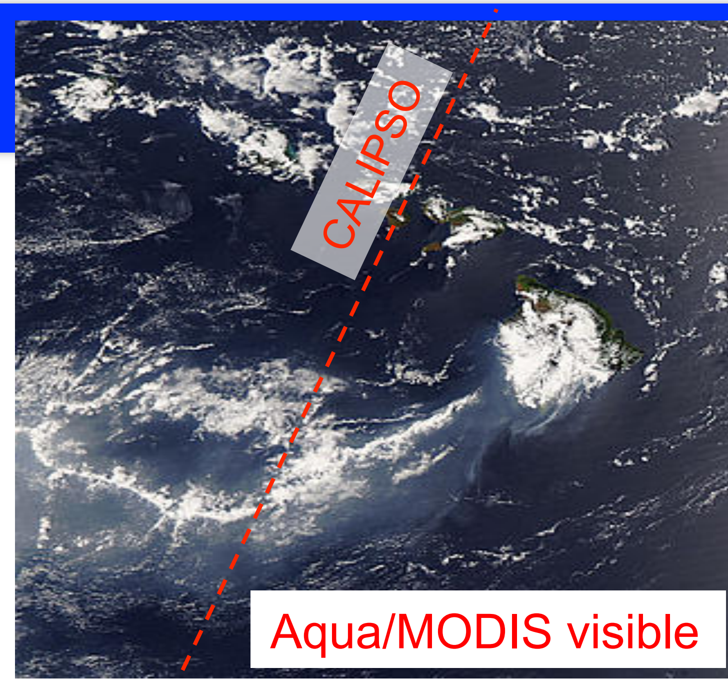
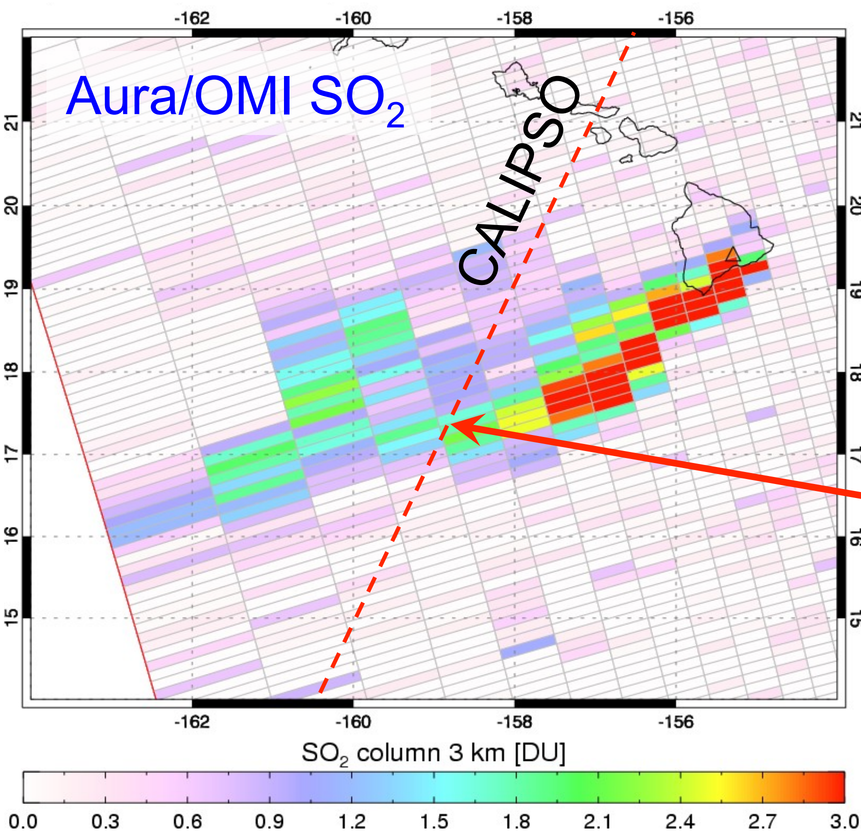
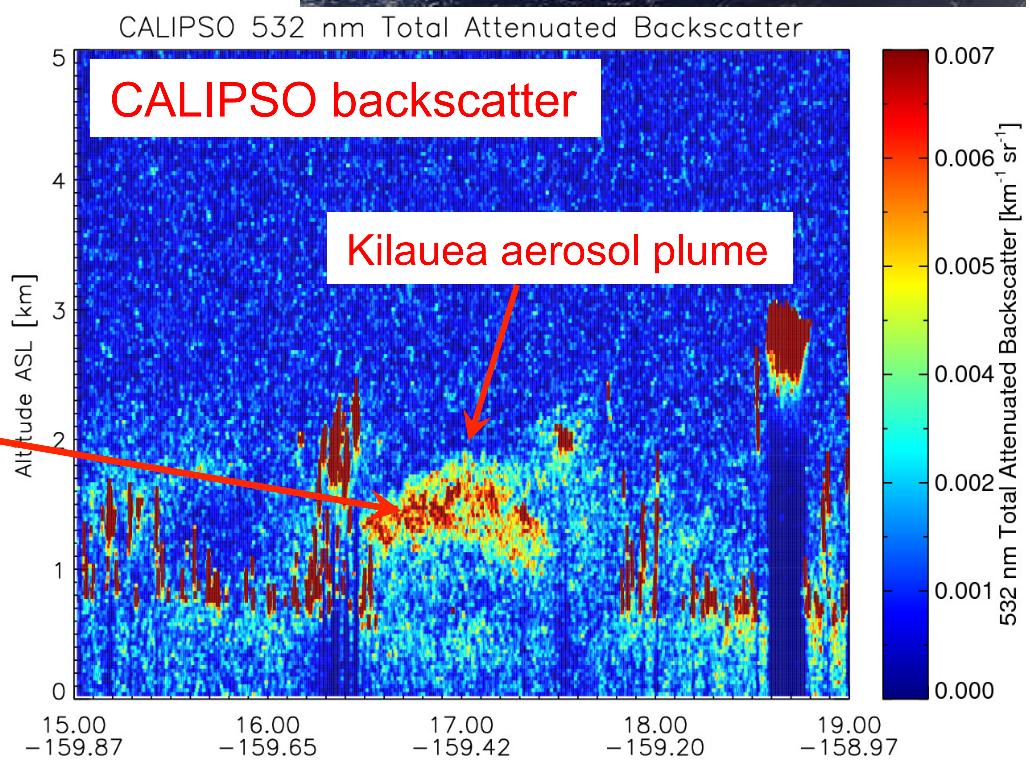
Kilauea degassing – April 7, 2008

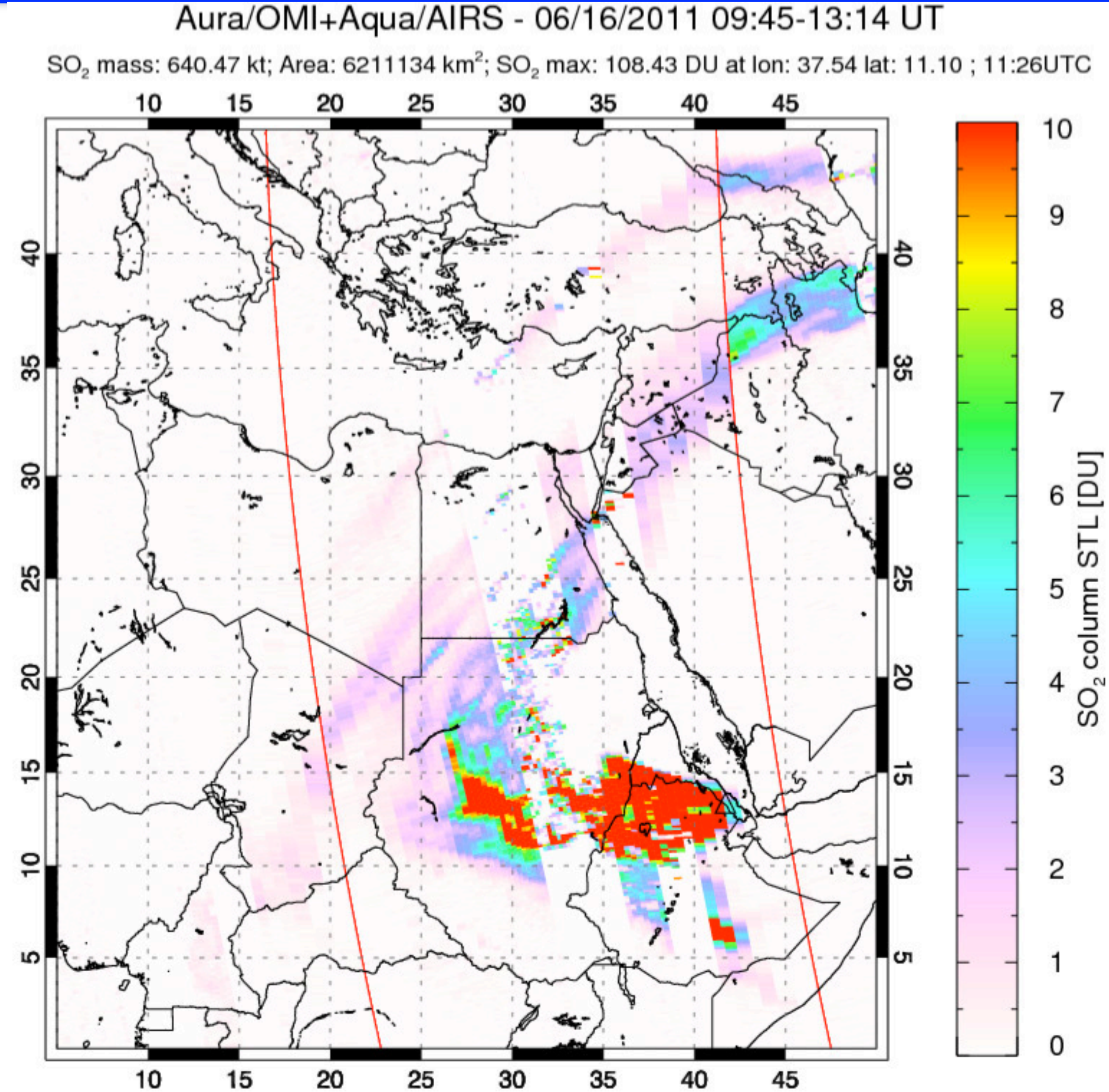




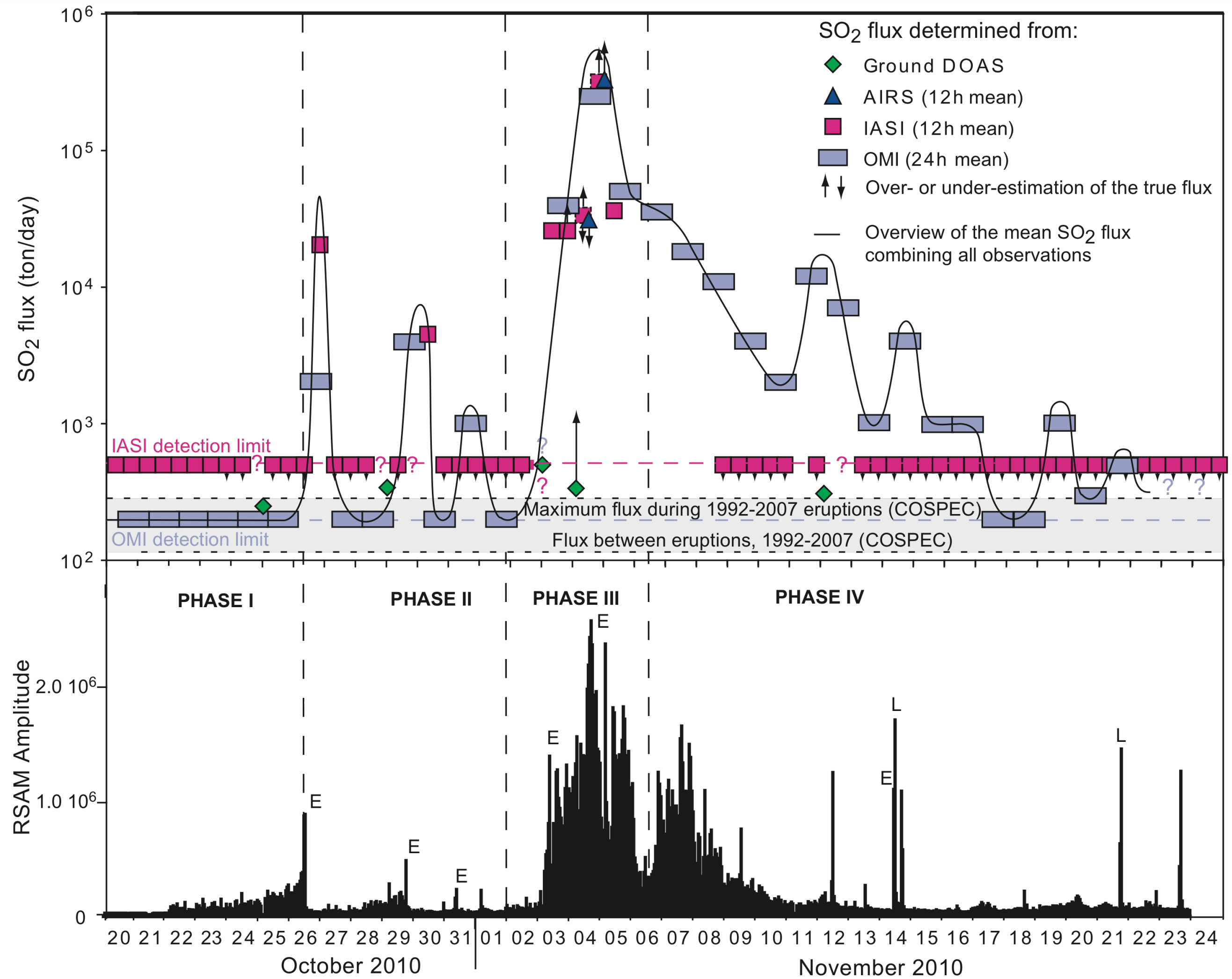


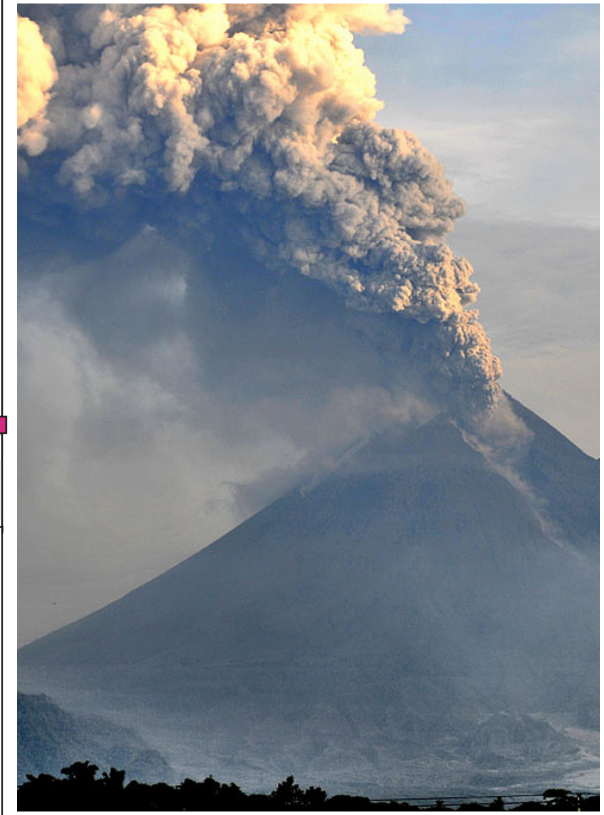


OMI + AIRS SO_2 : Nabro (June 16, 2011)



2010 Merapi eruption – evolution of SO_2 emissions

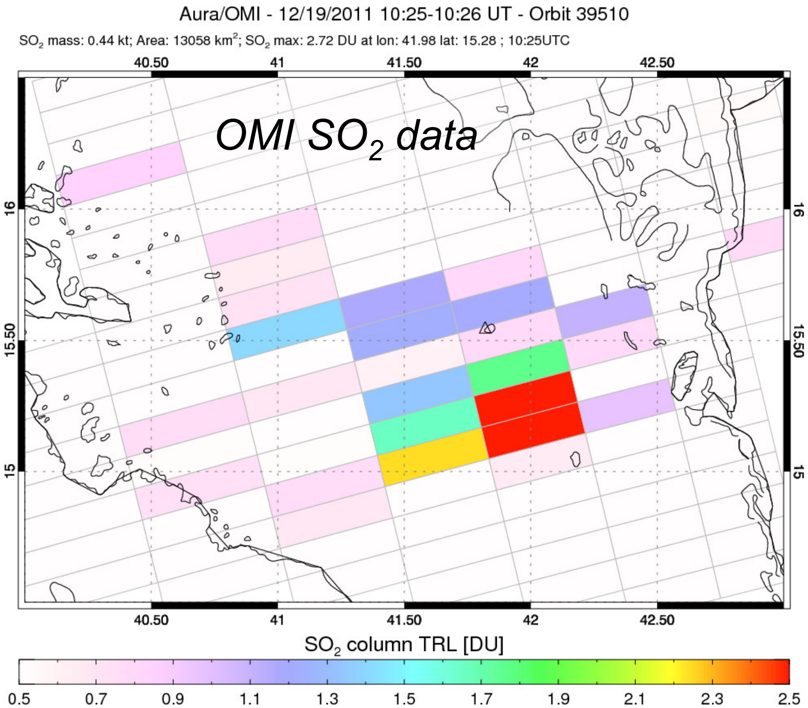


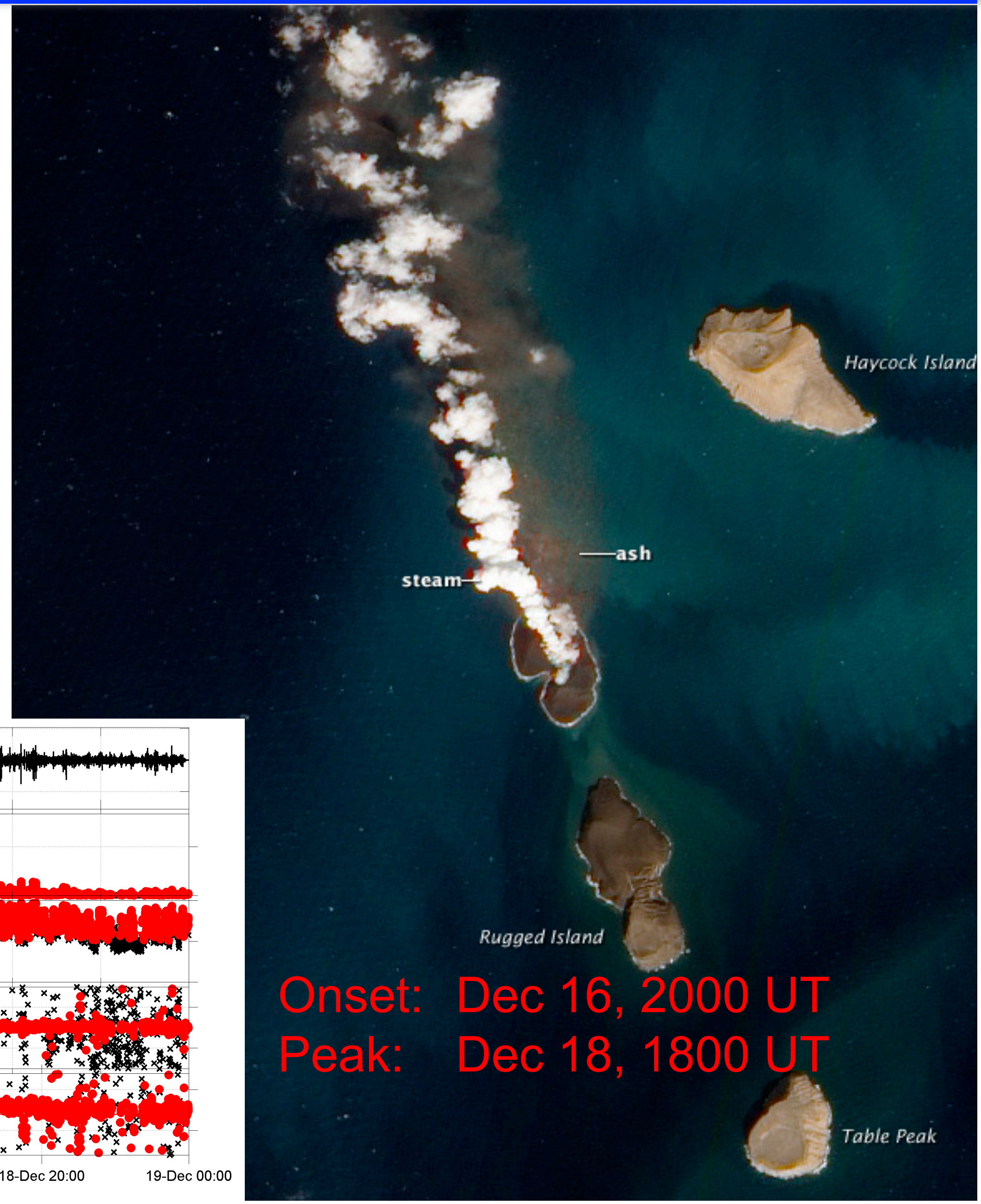


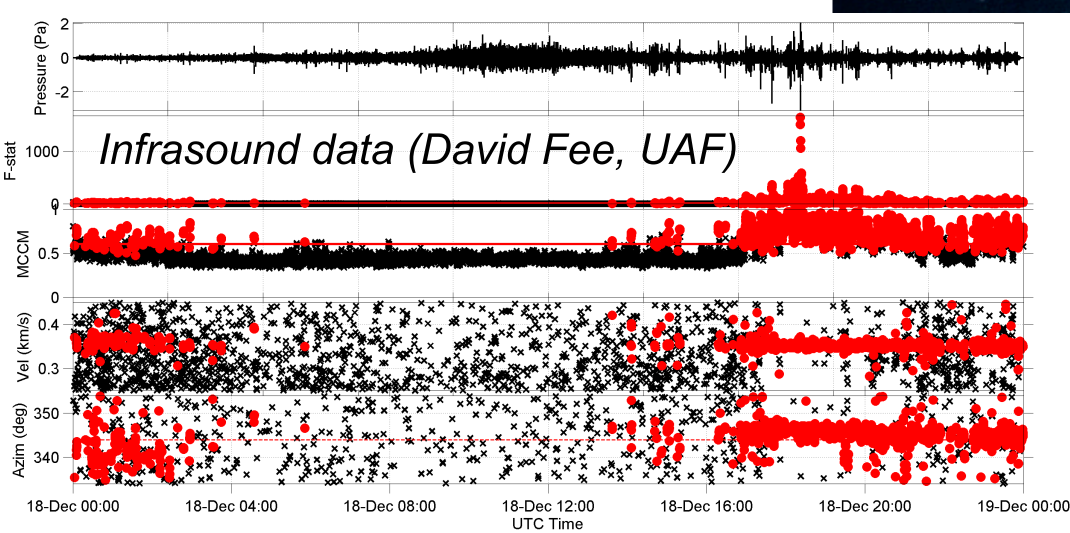
Surono et al., JVGR, 2012

- Total SO_2 emission of 0.2-0.3 Tg
- Satellite sensors (OMI, IASI, AIRS) provided key SO_2 observations

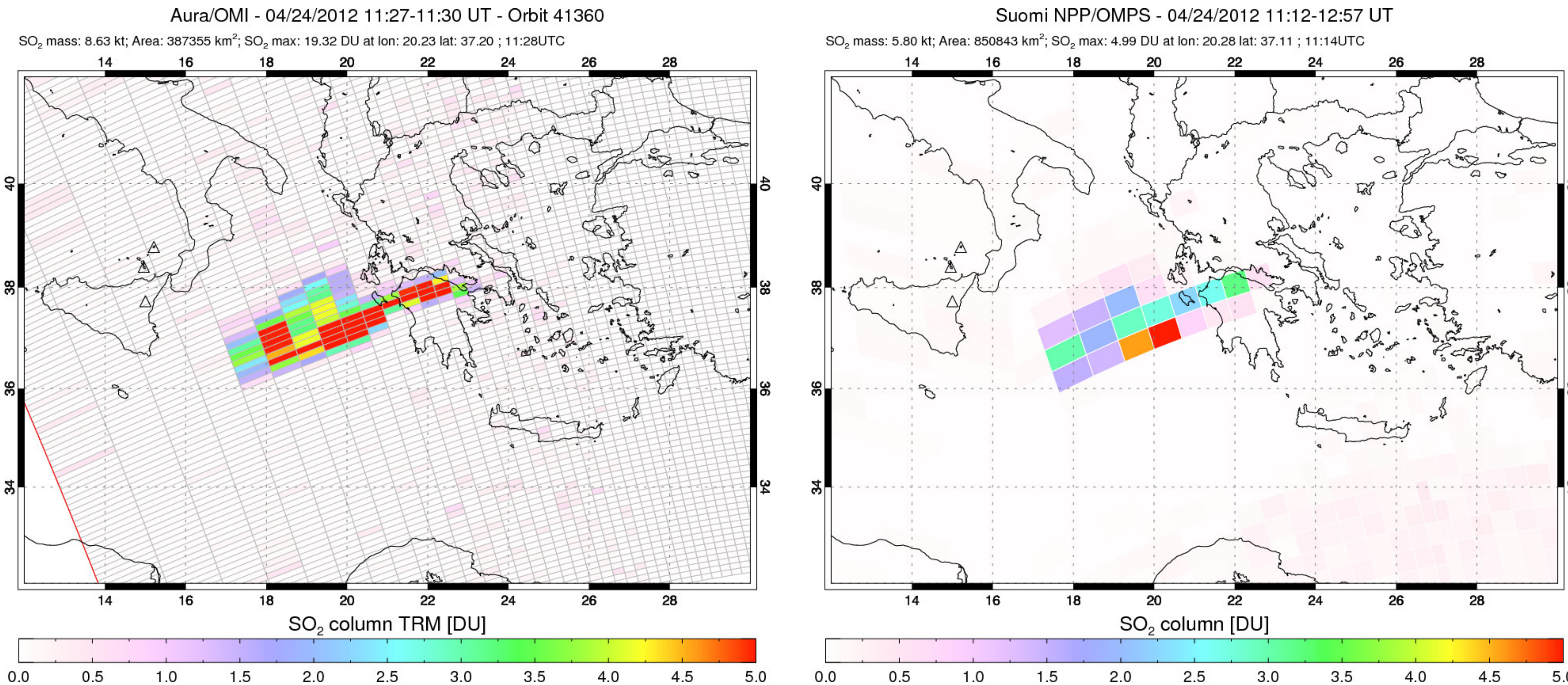
Eruption in Zubair archipelago, Yemen – Dec 2011







Ozone Mapper Profiler Suite (OMPS) SO_2 data



OMI Etna eruption, April 2012 OMPS

- OMPS launched on Suomi NPP satellite in October 2011
- OMPS spatial resolution currently 50×50 km – up to 10×10 km possible
- Impacts measurements of volcanic degassing

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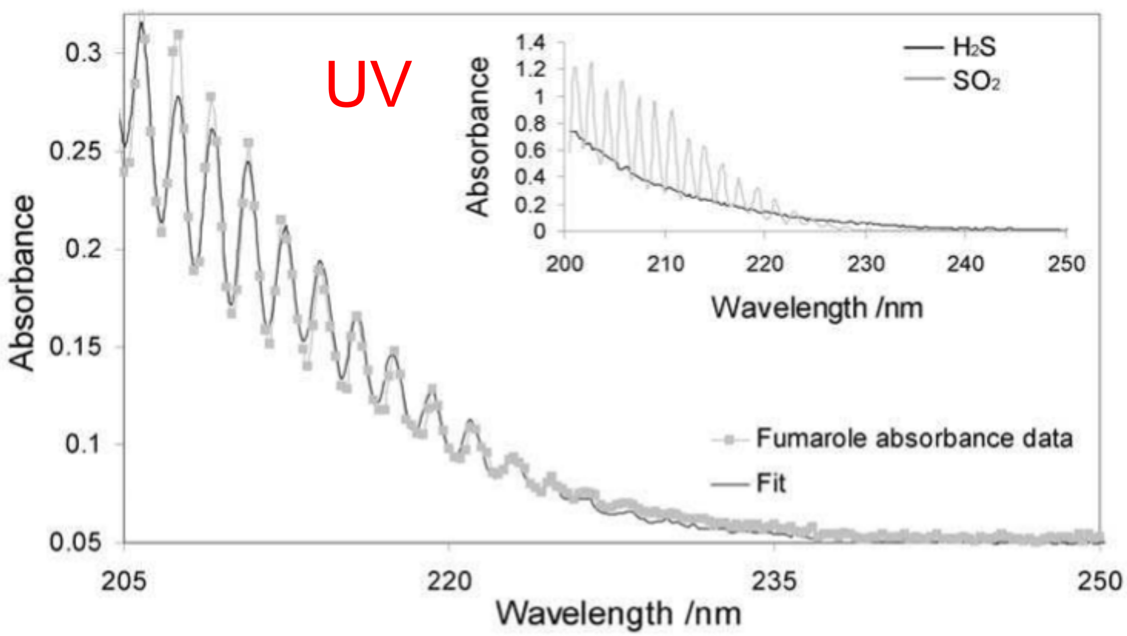
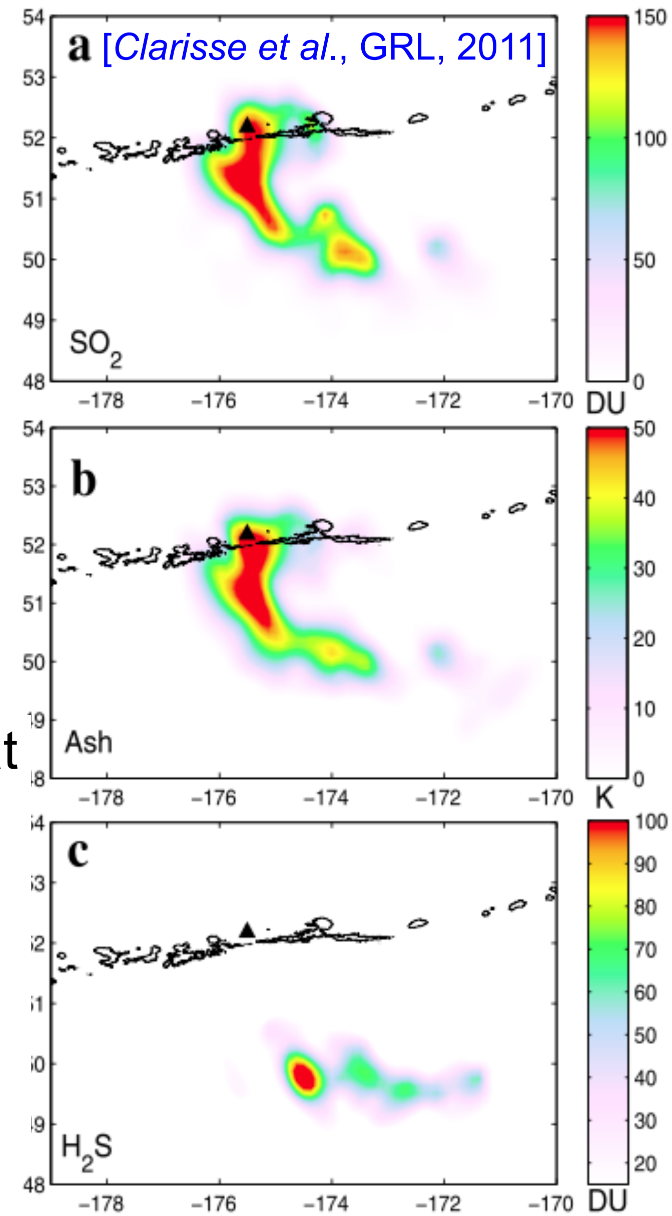
Remote sensing of H_2S emissions



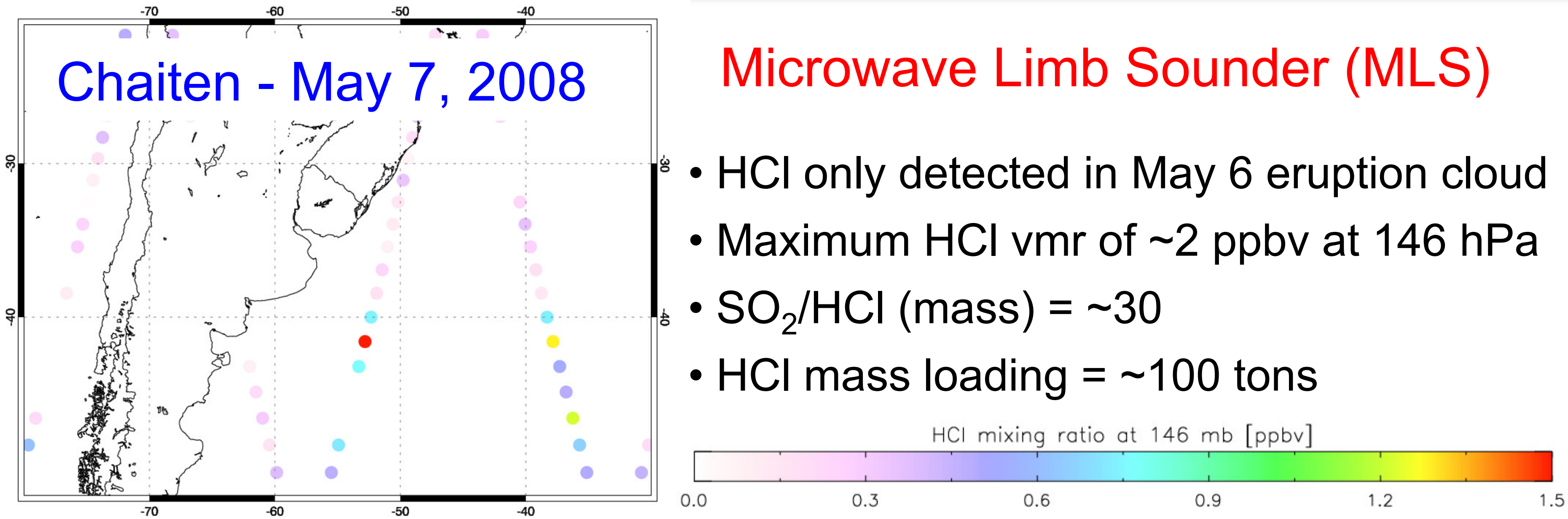
[*O'Dwyer et al.*, GRL, 2003]

2008 Kasatochi eruption



- May be a significant component of total S budget at some volcanoes [*Aiuppa et al.*, 2005]
- Mid-UV absorption bands require active source
- IR absorption bands are very weak, but can be detected from space [IASI; *Clarisse et al.*, 2011]
- USGS airborne in-situ volcanic plume surveys (H_2S, CO_2)

Detection of HCl in volcanic clouds from space

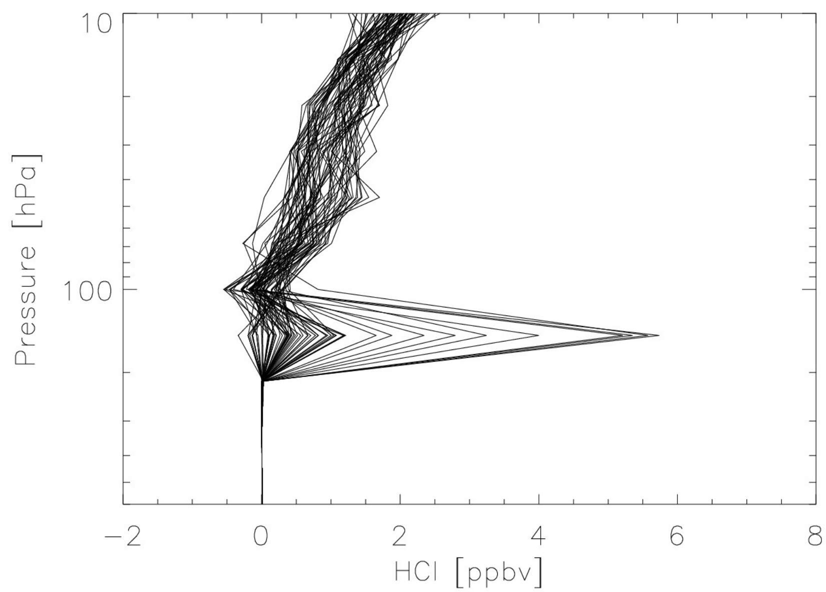


Microwave Limb Sounder (MLS)

- HCl only detected in May 6 eruption cloud
- Maximum HCl vmr of ~2 ppbv at 146 hPa
- SO_2/HCl (mass) = ~30
- HCl mass loading = ~100 tons

MLS volcanic HCl (ppbv)

Manam 2005:	4-6
Anatahan 2005:	8
Okmok 2008:	5
Kasatochi 2008:	5
Redoubt 2009:	4-5
Sarychev 2009:	7
Merapi 2010:	6



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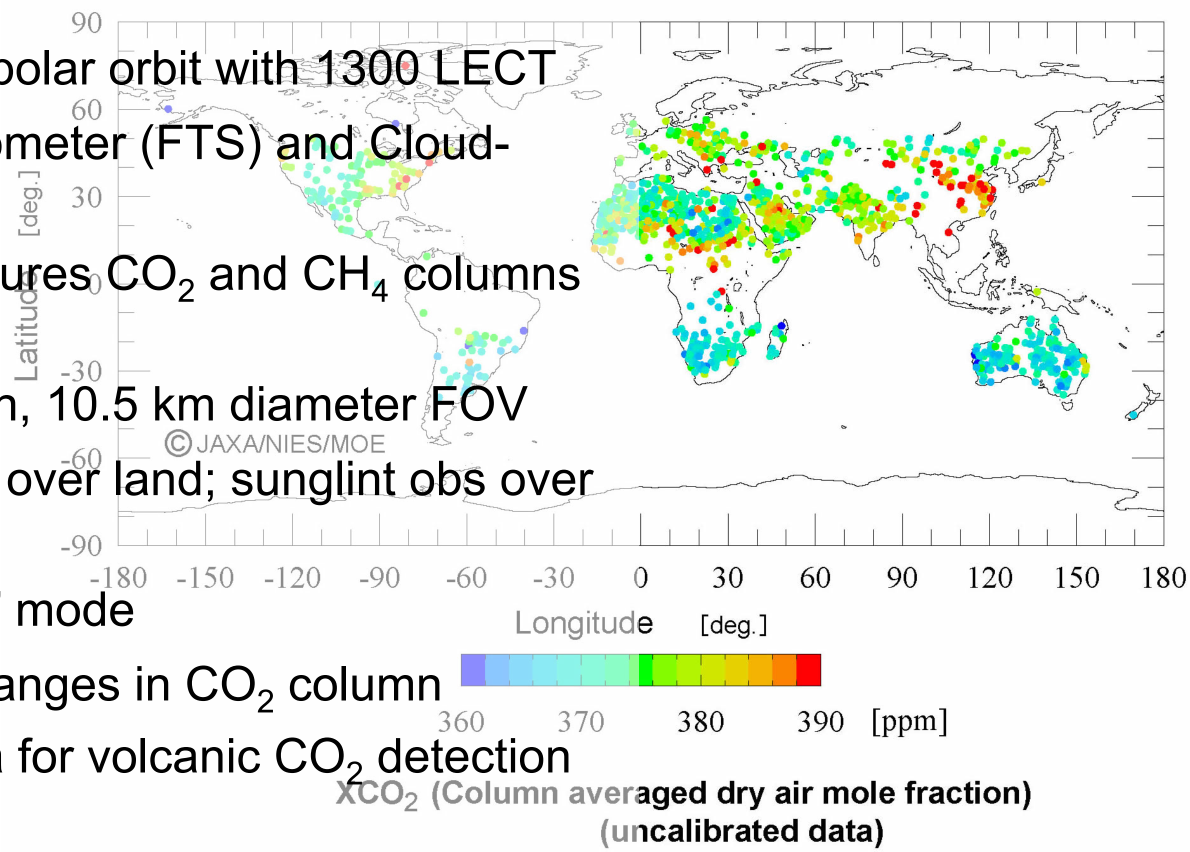
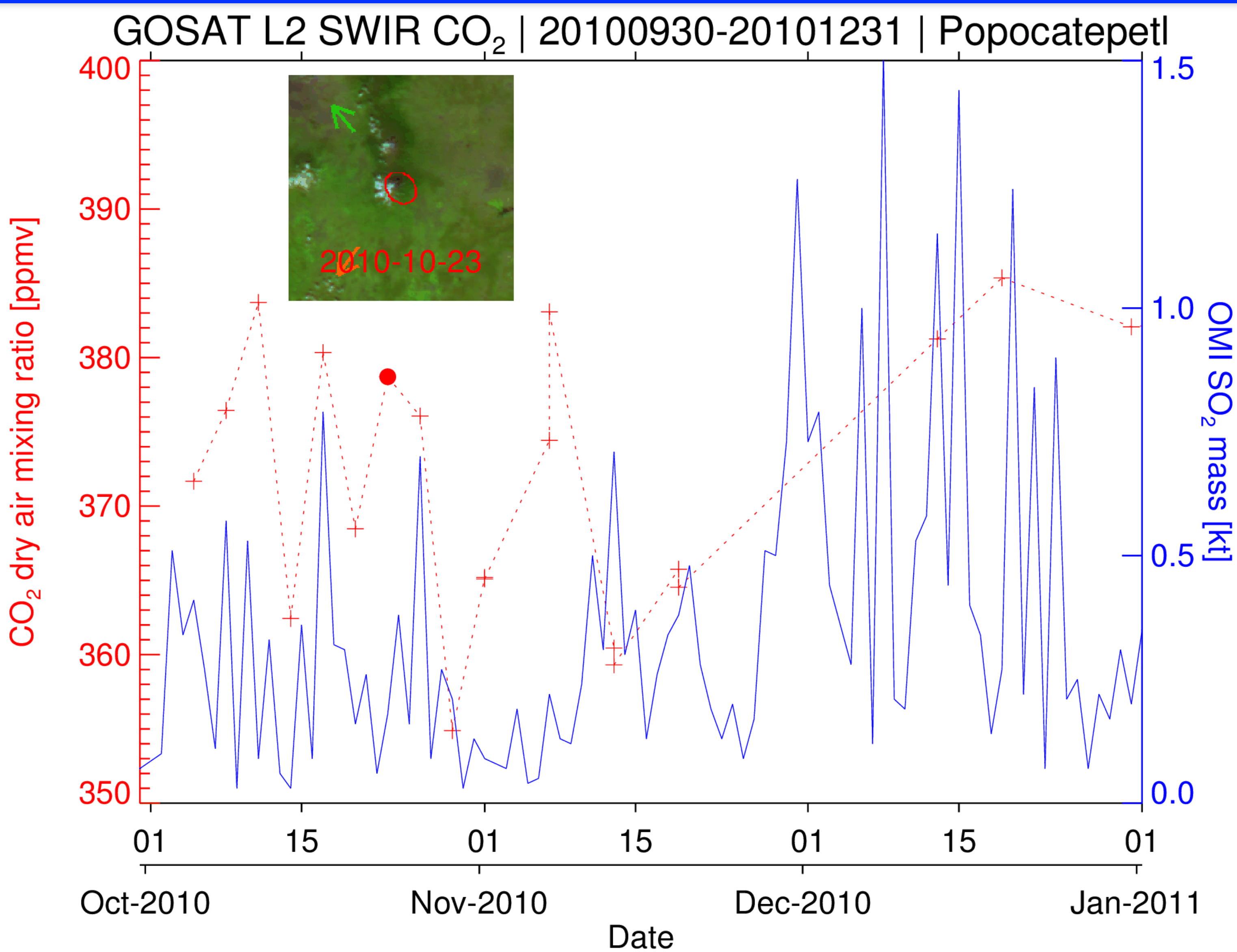
GOSAT: Measuring CO_2 from space

- Japanese Greenhouse Gas Observing Satellite (GOSAT)
  - Launched January 2009; polar orbit with 1300 LECT
  - Fourier Transform Spectrometer (FTS) and Cloud-Aerosol Imager (CAI)
  - TANSO-FTS sensor measures CO_2 and CH_4 columns and profiles in SWIR/TIR
  - 0.2 cm^{-1} spectral resolution, 10.5 km diameter FOV
  - 56,000 observation points over land; sunglint obs over oceans
  - Special observation ‘stare’ mode
  - ppm-level sensitivity to changes in CO_2 column
  - Evaluation of GOSAT data for volcanic CO_2 detection underway
  - Special observations made over volcanic vents



GOSAT CO_2 special observations – Popocatepetl (Mexico)



• Space-based volcanic CO_2 observations will improve with the Orbiting Carbon Observatory 2 (OCO-2) after launch in 2014 (?)

Summary

- Numerous satellite sensors now provide SO_2 measurements
- Some have standard SO_2 products, others require application of retrieval algorithms to yield quantitative SO_2 data
- Aura/OMI is an economical and effective tool for monitoring volcanic SO_2 degassing on a regional or local (single volcano) scale
- OMI's high SO_2 sensitivity and global coverage allows detection of nearly all significant volcanic eruption clouds, assisting aviation hazard mitigation and improving our understanding of the atmospheric impacts of volcanism
- Detection of tropospheric SO_2 plumes by OMI depends on several factors, hence the lower detection limit in terms of SO_2 flux is variable (with latitude, vent altitude etc.)
- Altitude sensitivity must be considered when evaluating satellite SO_2 data
- New satellite constellations (A-Train) provide opportunities for sensor synergy and '3D' analysis of volcanic clouds
- Many datasets are now available online in near-real time