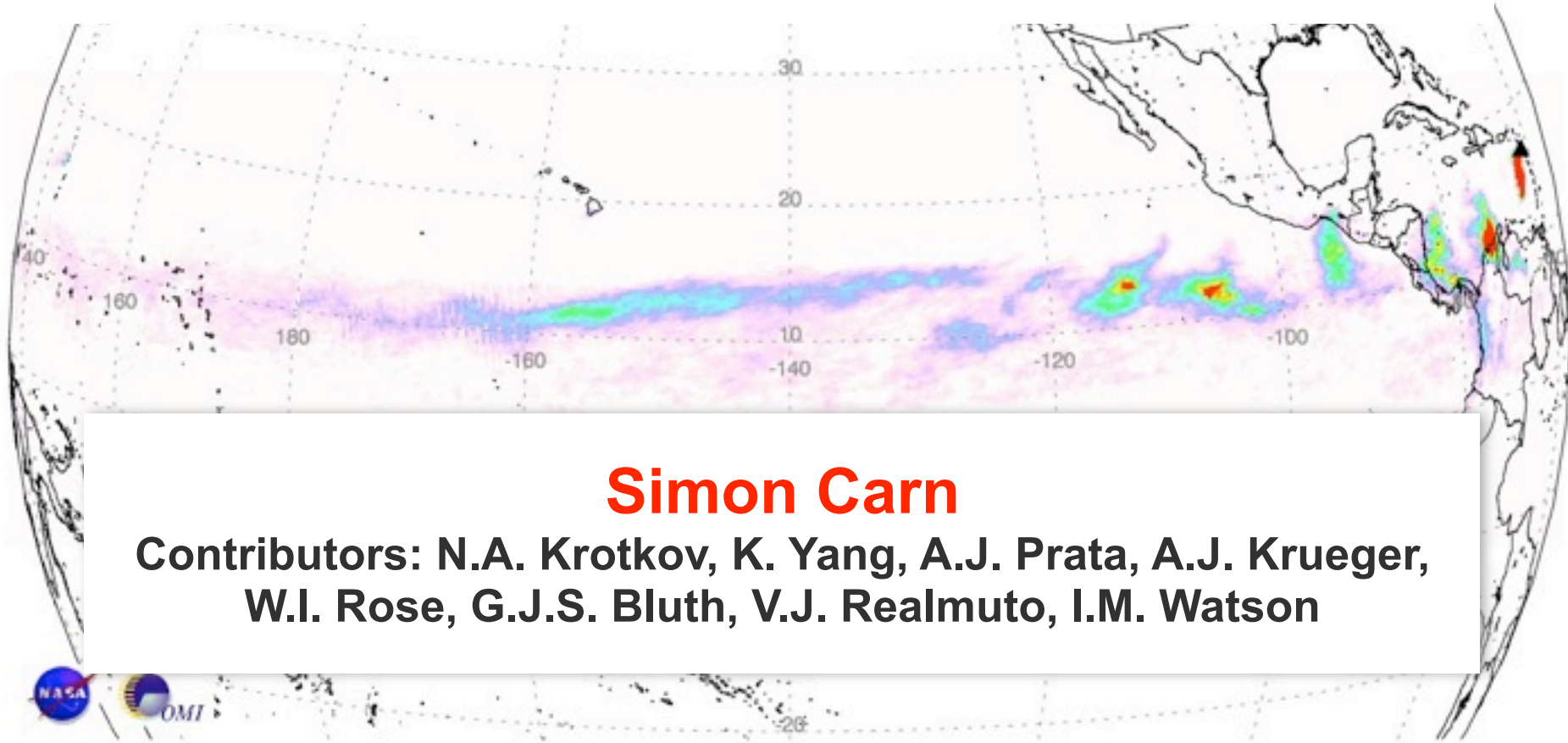


# Remote Sensing of Volcanic Gas Emissions



# Overview

- Motivation for volcanic gas measurements
- Development of satellite remote sensing of SO<sub>2</sub>
- Remote sensing theory (focus on SO<sub>2</sub> measurements)
- Survey of space-based SO<sub>2</sub> sensors
  - UV sensors: OMI, TOMS, GOME-2
  - IR sensors: MODIS, ASTER, TOVS, AIRS, IASI
- Application of Aura/OMI SO<sub>2</sub> data to volcano monitoring
  - SO<sub>2</sub> burden calculations
  - Burdens vs. emission rates
- Satellite sensor synergy: NASA's A-Train
- Web access to near-real time data
- Lab exercise: SO<sub>2</sub> emissions from Latin American volcanoes

# Motivation for volcanic SO<sub>2</sub> measurements

- SO<sub>2</sub> is the most abundant gas in volcanic emissions that can be easily measured by remote sensing techniques
  - Low background concentrations (cf. H<sub>2</sub>O, CO<sub>2</sub>)
  - 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
  - Signature of magmatic eruptions with potential for high altitude eruption columns
  - H<sub>2</sub>S (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)

# Volcanic gas compositions

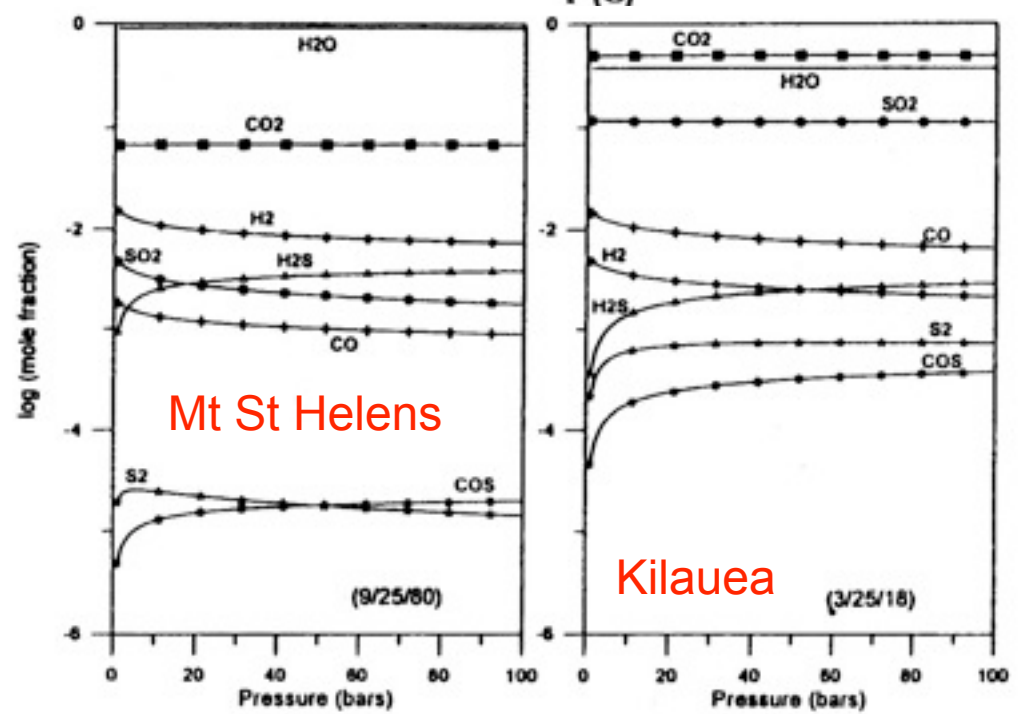
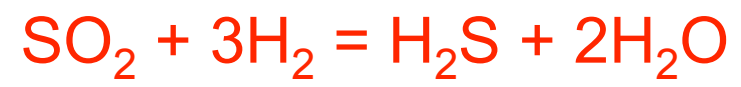
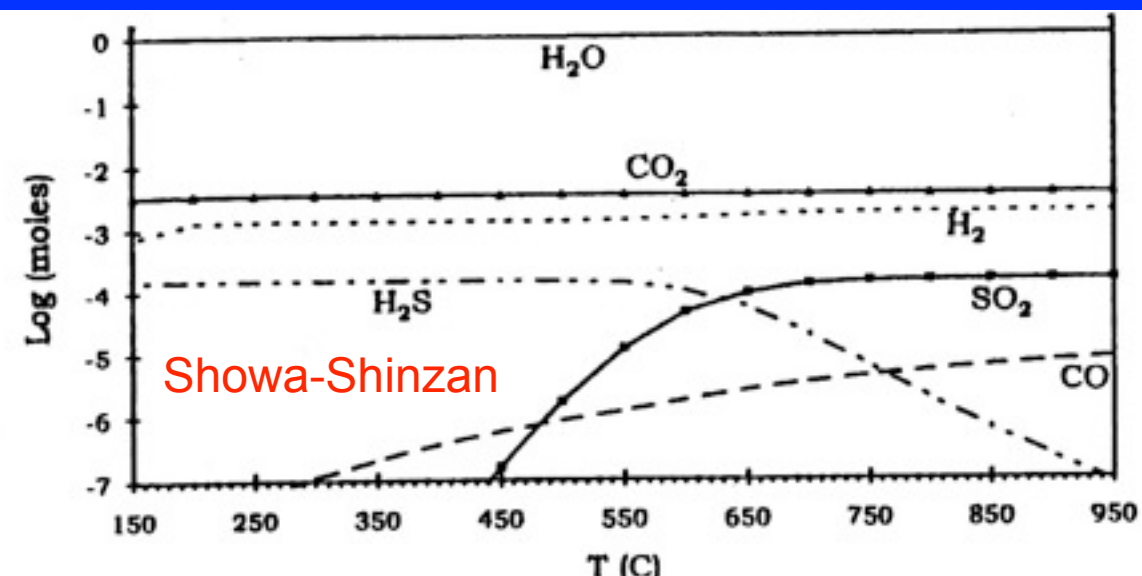
mol%	Nyiragongo (DR Congo) RIFT	Kilauea* (Hawaii) HOTSPOT	Merapi* (Indonesia) SUBDUCTION	Etna* (Sicily) SUBDUCTION
H <sub>2</sub> O	70	37	91	48
CO <sub>2</sub>	24	49	5	20
SO <sub>2</sub>	5	12	1	31
CO	1	2	0.1	0.4
HCl	0.3	0.08	0.6	-
HF	0.1	-	0.04	-

Trace constituents: CH<sub>4</sub>, N<sub>2</sub>, BrO, Zn, Cu, Hg, Au, As, Re, He, Ne, Ar.....

\*Symonds *et al.* [1994]



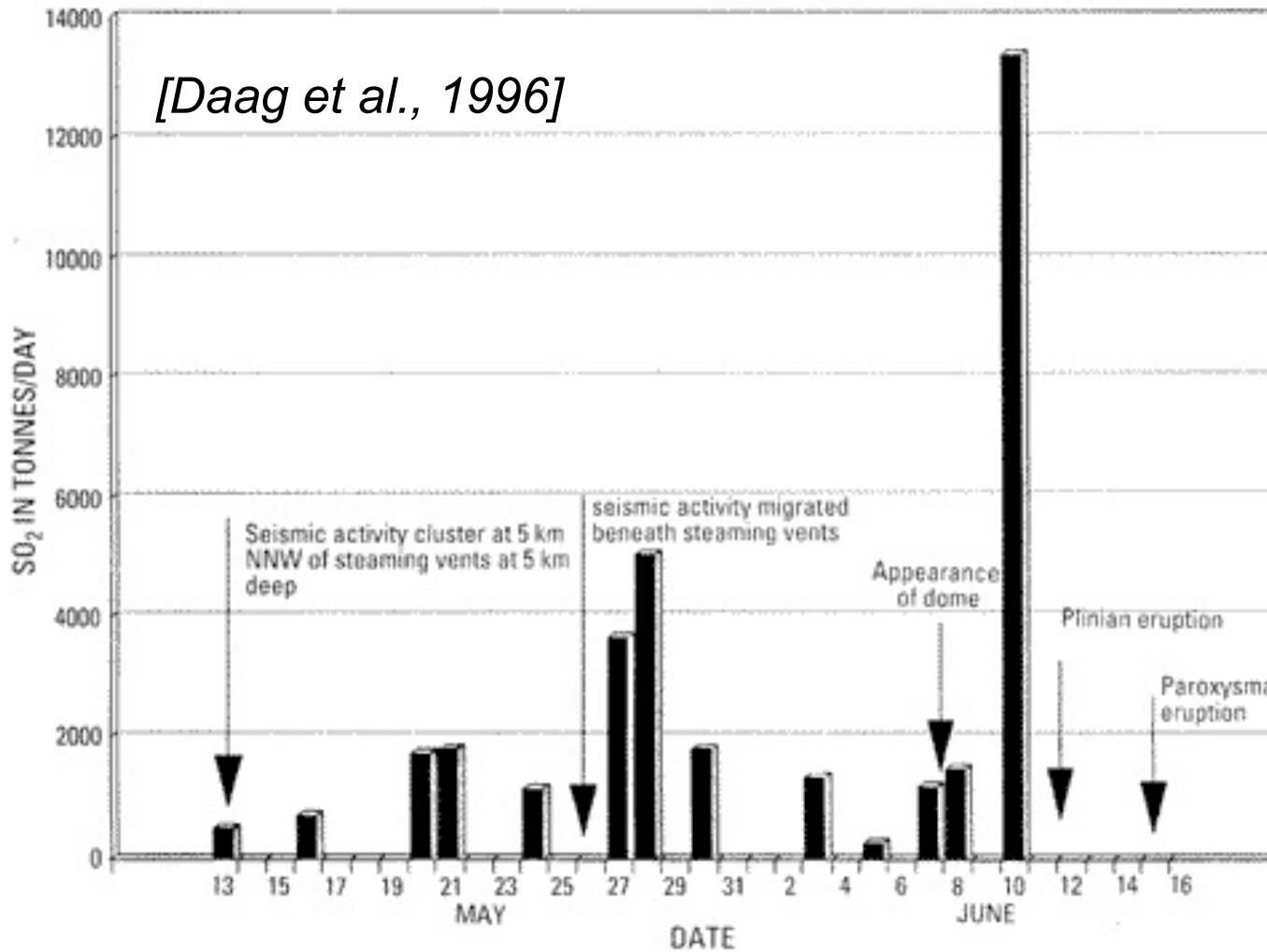
# Temperature and pressure effects on volcanic gas species



$$\log \left( \frac{\text{SO}_2}{\text{H}_2\text{S}} \right) = \log K_T - 3 \log \left( \frac{\text{H}_2}{\text{H}_2\text{O}} \right) - \log P \cdot X_{\text{H}_2\text{O}}$$

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

# Pre-eruptive volcanic degassing



- Increase in SO<sub>2</sub> emissions prior to a major eruption

# SO<sub>2</sub> flux and LP seismicity at Galeras (Colombia)

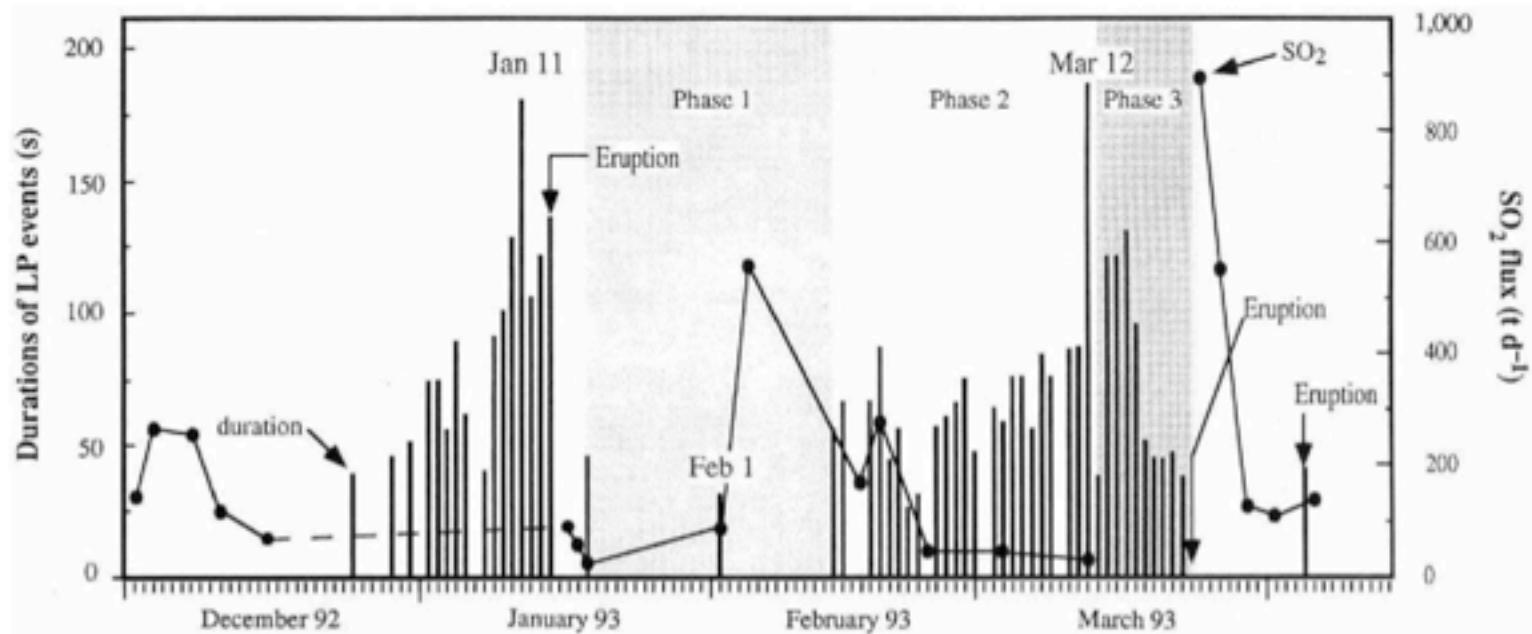
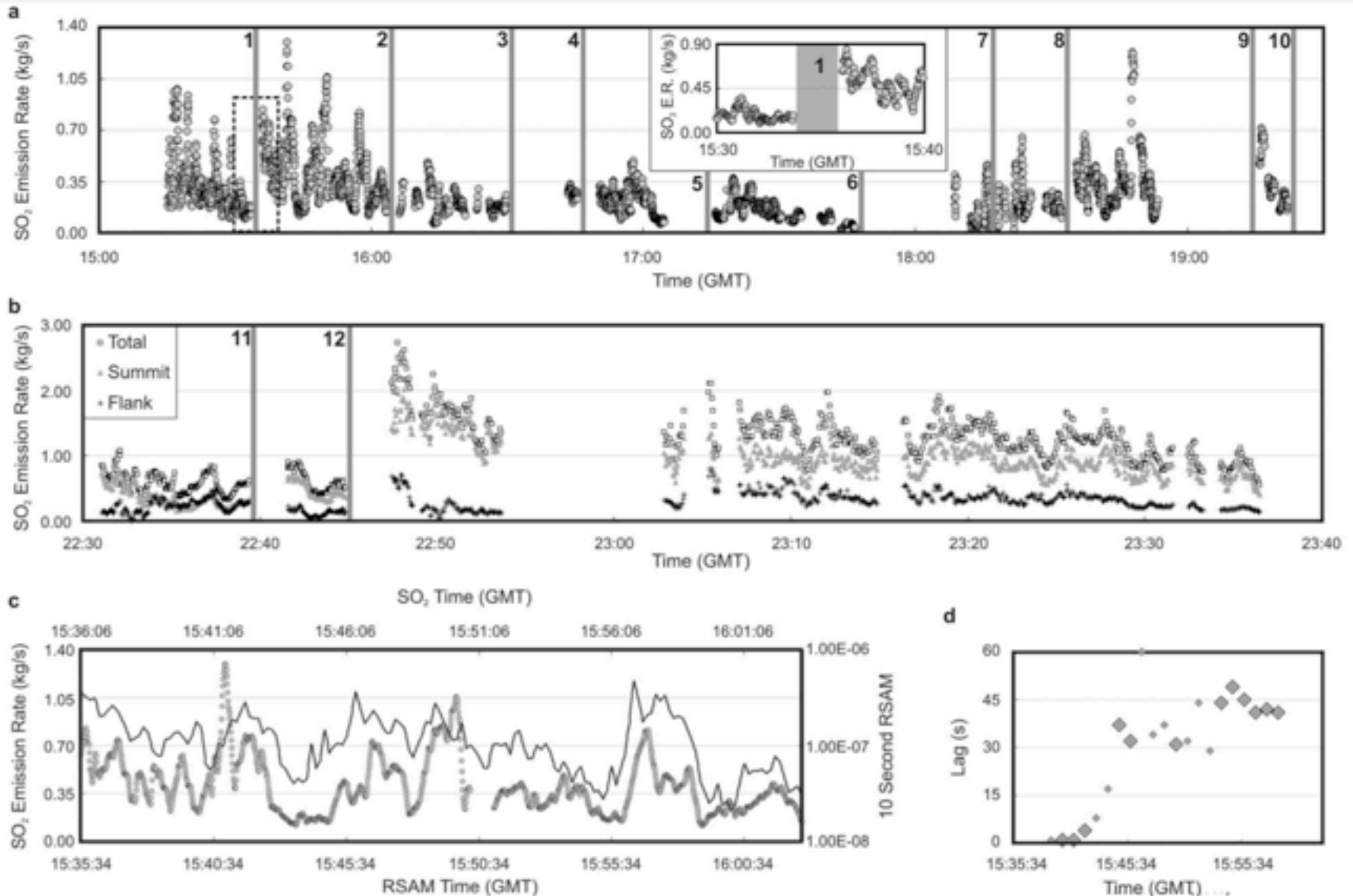


FIG. 2 SO<sub>2</sub> flux in metric tons per day (●) and durations of recorded long-period ( $\geq 22$  s) events (vertical bars) plotted against time, also showing the eruptions during the same time period. The SO<sub>2</sub> flux is measured using correlation spectrometer (COSPEC) methodology<sup>15</sup>. Uncertainty depends mostly on recorded wind speeds. The error at

Galeras is assumed to be  $\pm 20\%$ , in general, and  $\pm 40\%$ , in the worst case. True SO<sub>2</sub> flux is likely to be higher than the calculated value. The three phases reflect changes in fluid dynamics along pathways through which gases flow, as interpreted from seismic and gas flux data.

[Fischer et al., Nature, 1994]

# SO<sub>2</sub> emissions and RSAM at Fuego (Guatemala)



[Nadeau et al., GRL, 2011]



# Aviation hazards from volcanic clouds



- **Immediate hazards**

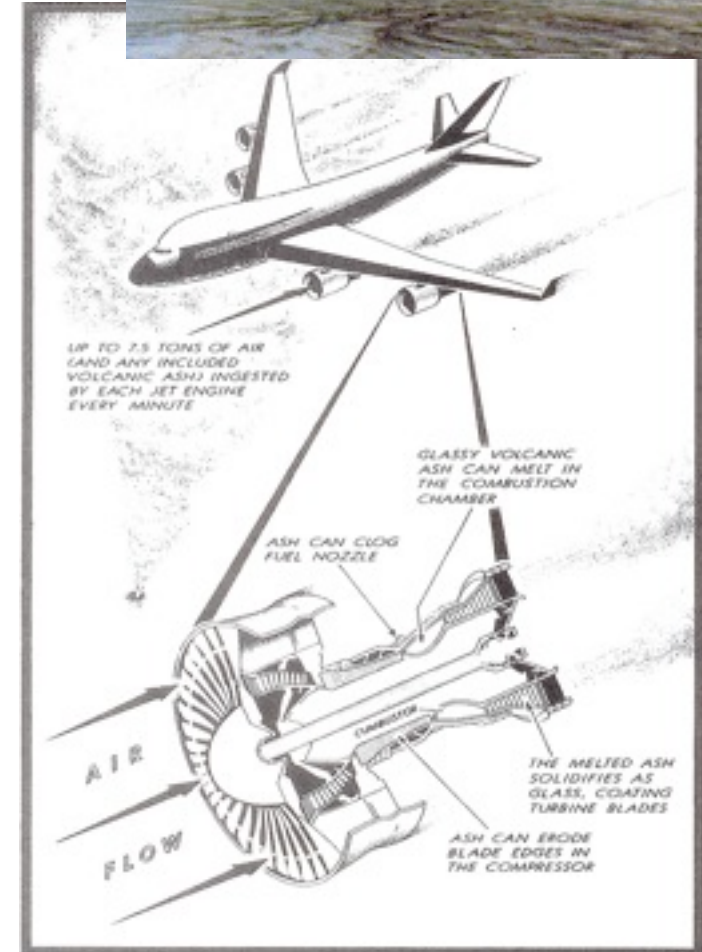
- Engine failure due to melted ash
- Abrasion of windshield

- **Secondary hazards**

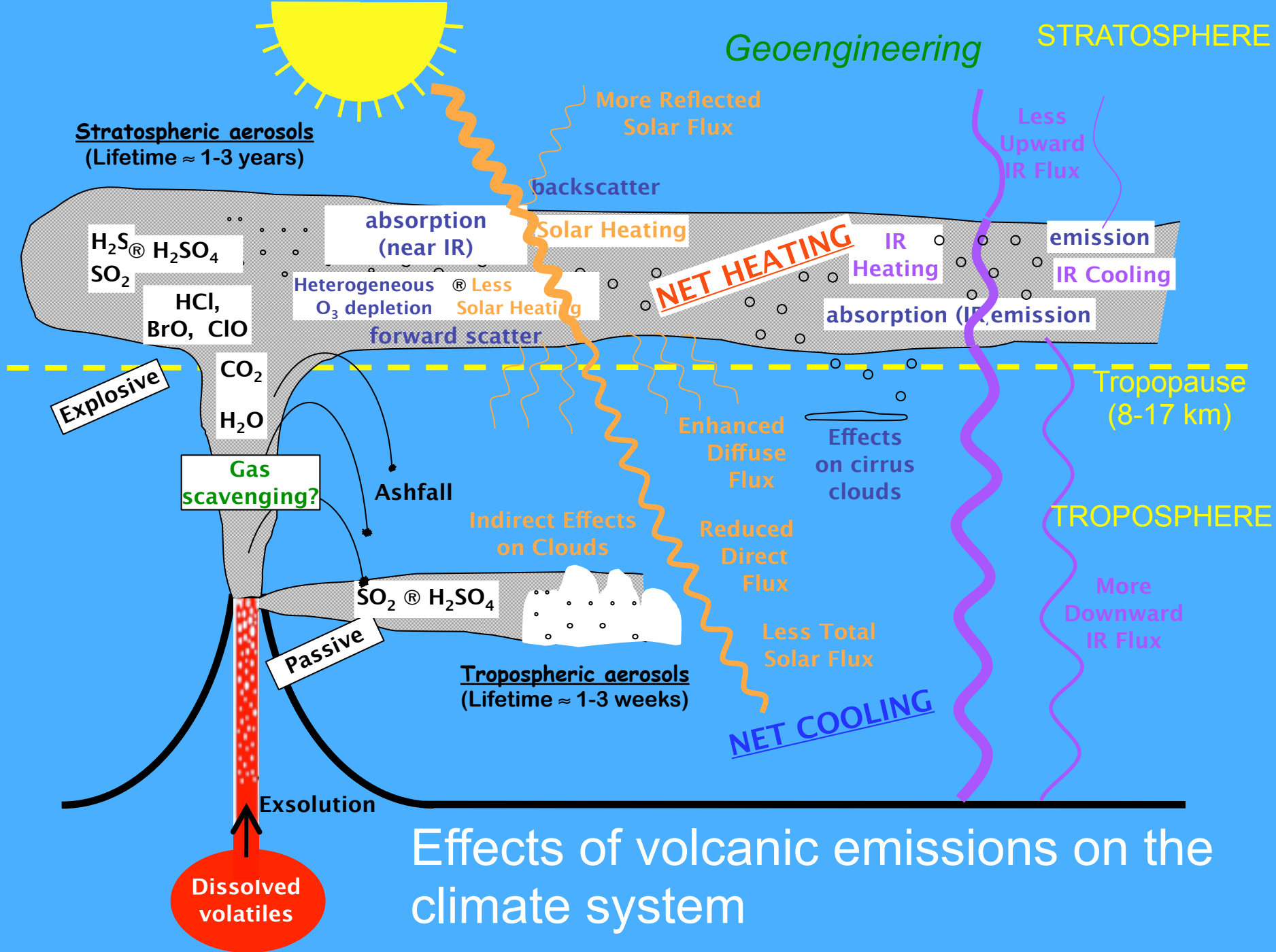
- Corrosion by ash, sulfuric acid

- **Mitigation**

- Immediate detection of fresh volcanic clouds –  $\text{SO}_2$  data valuable
- Tracking/forecast of cloud position and altitude –  $\text{SO}_2$  valuable for cloud tracking



From: *Volcanoes; Crucibles of Change*, Princeton U. Press, Princeton, 1997.





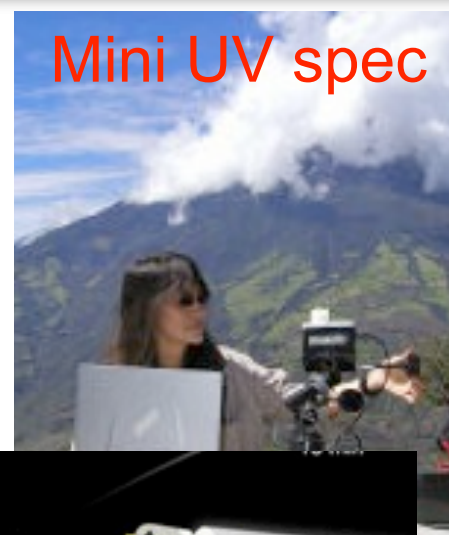
# Volcanic gas monitoring techniques

COSPEC

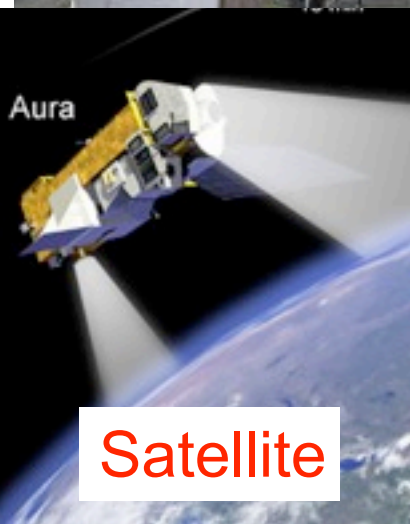
Chemical sensors



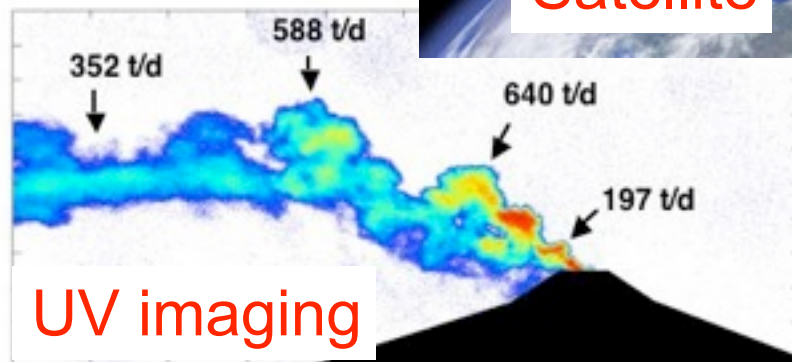
Mini UV spec



FTIR



Satellite

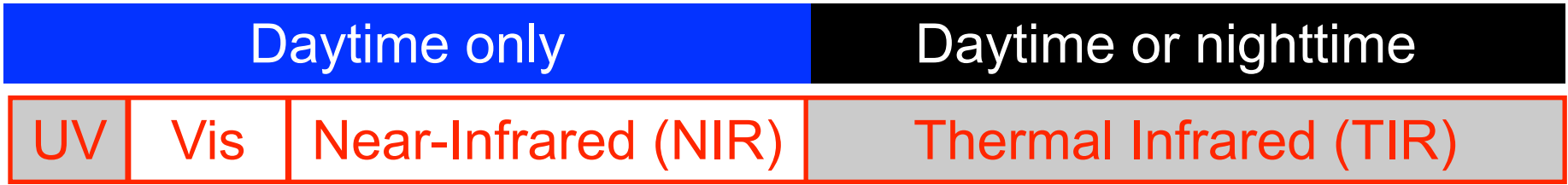


UV imaging



Direct sampling

# Electromagnetic spectrum – SO<sub>2</sub> absorption



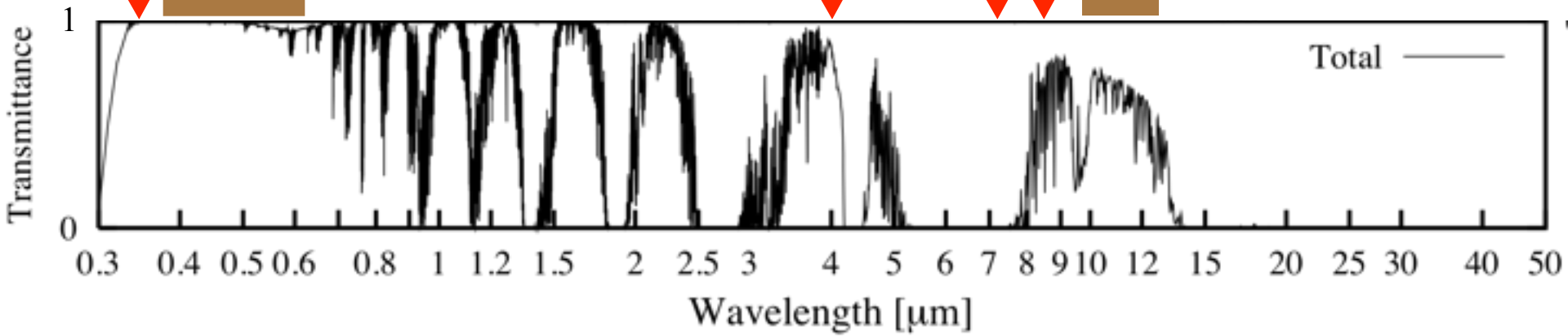
OMI, GOME-2,  
SCIAMACHY

IASI, SEVIRI, MODIS  
AIRS, HIRS, ASTER

MLS  
Microwave  
~1 mm  
→

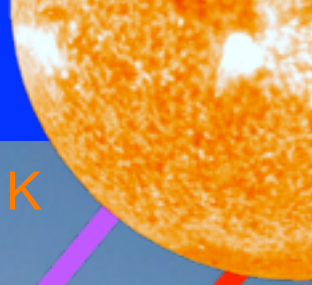
0.3-0.35 μm

4 μm 7.3 8.6 μm





# UV and IR remote sensing



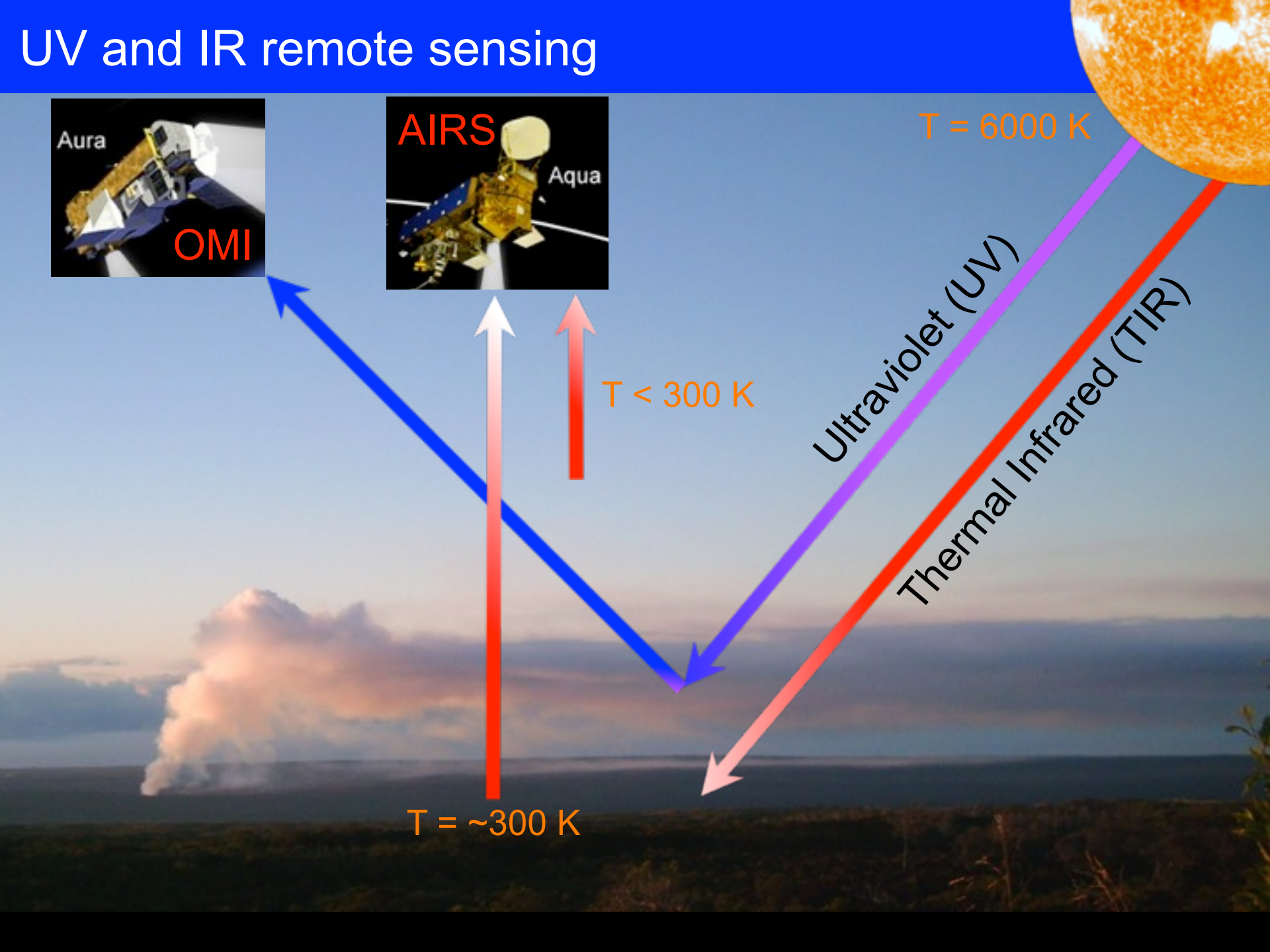
$T = 6000 \text{ K}$

Ultraviolet (UV)

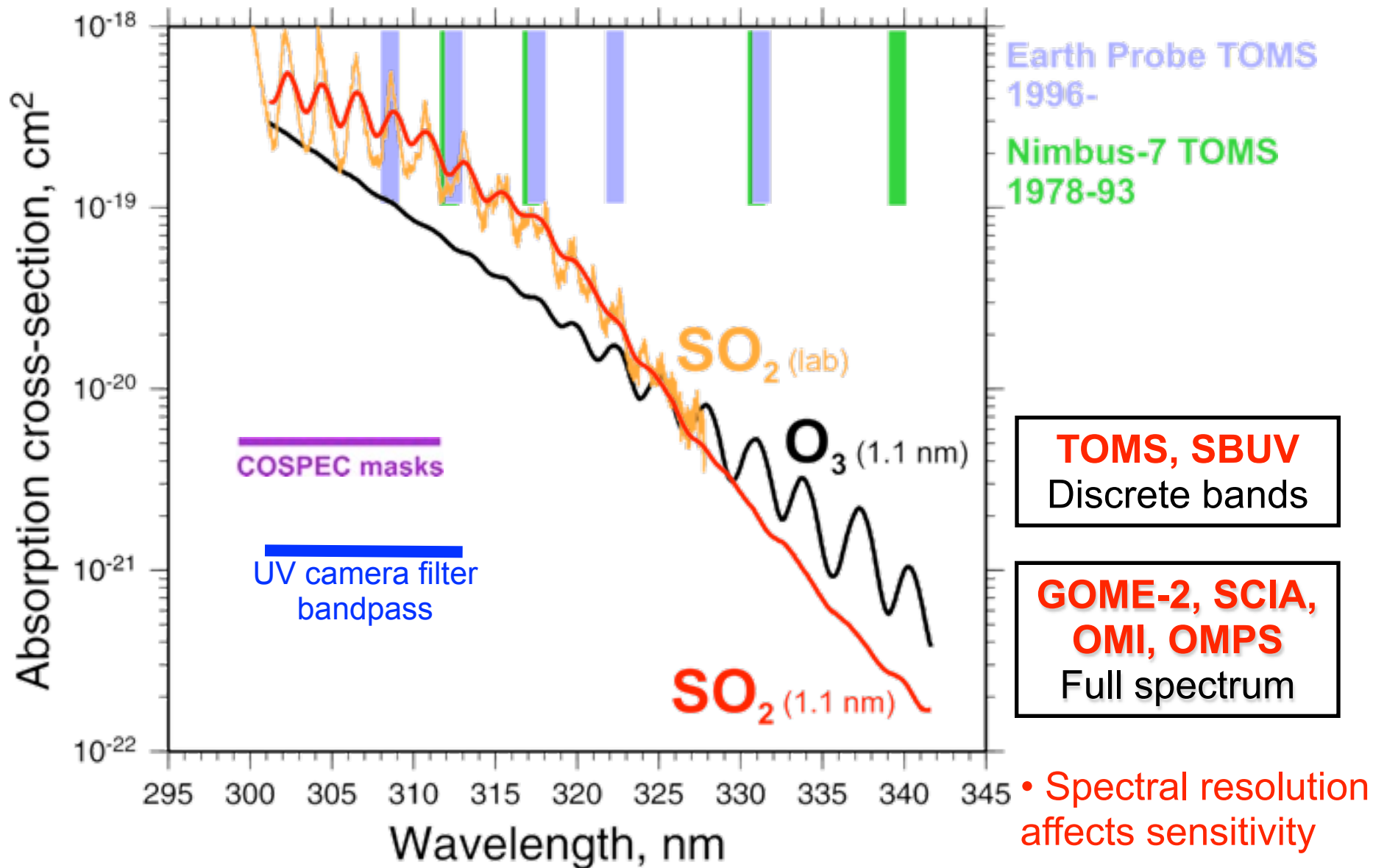
Thermal Infrared (TIR)

$T < 300 \text{ K}$

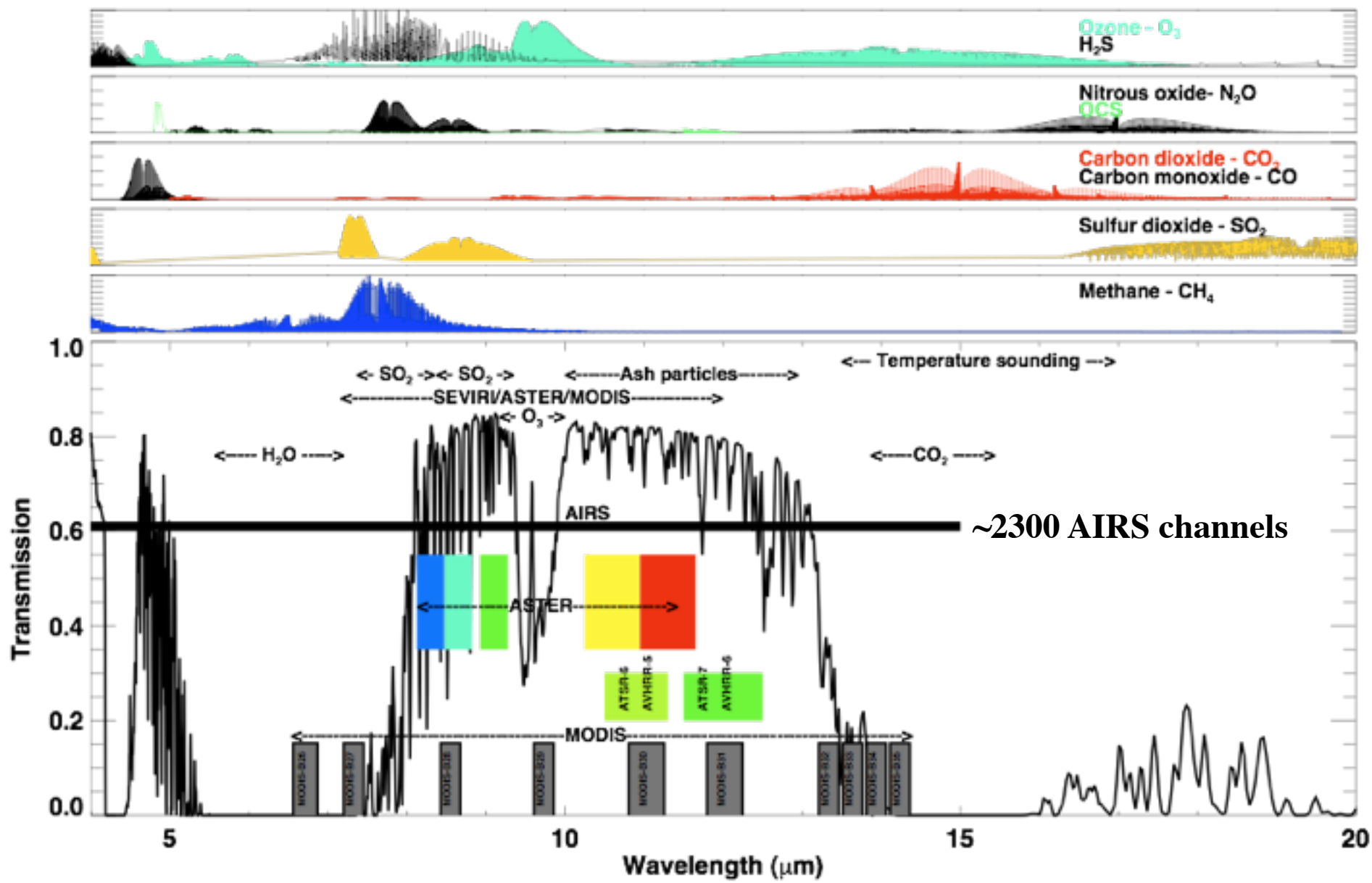
$T = \sim 300 \text{ K}$



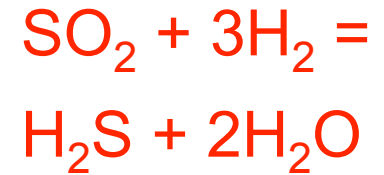
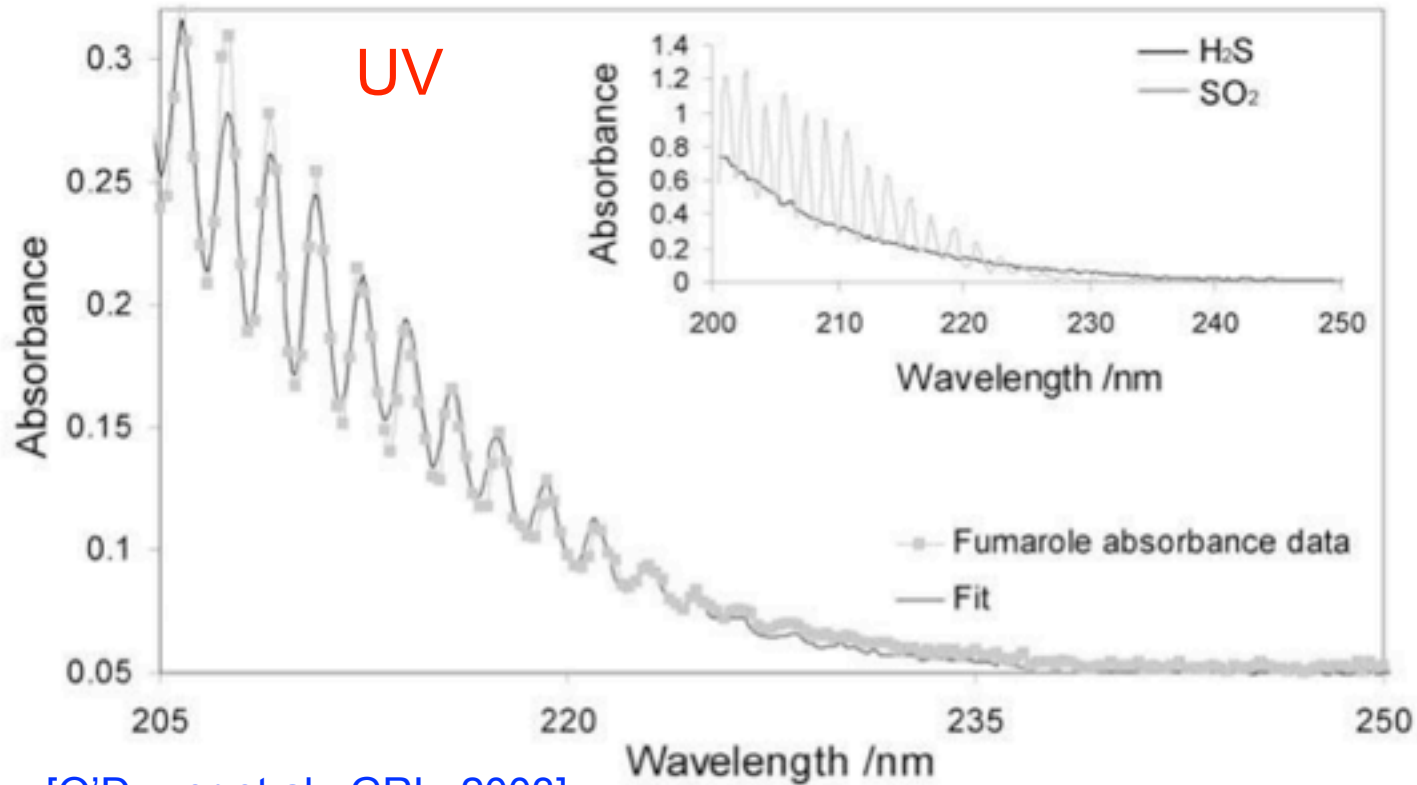
# UV SO<sub>2</sub> and O<sub>3</sub> absorption spectra and instrument bands



# IR-active trace gases and instrument channels

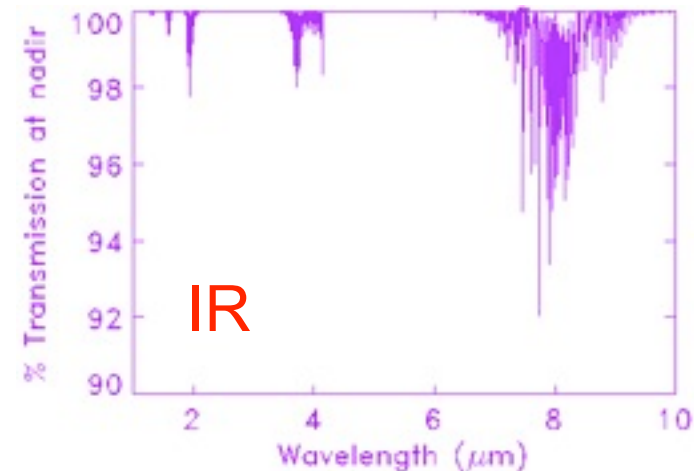


# What about H<sub>2</sub>S?



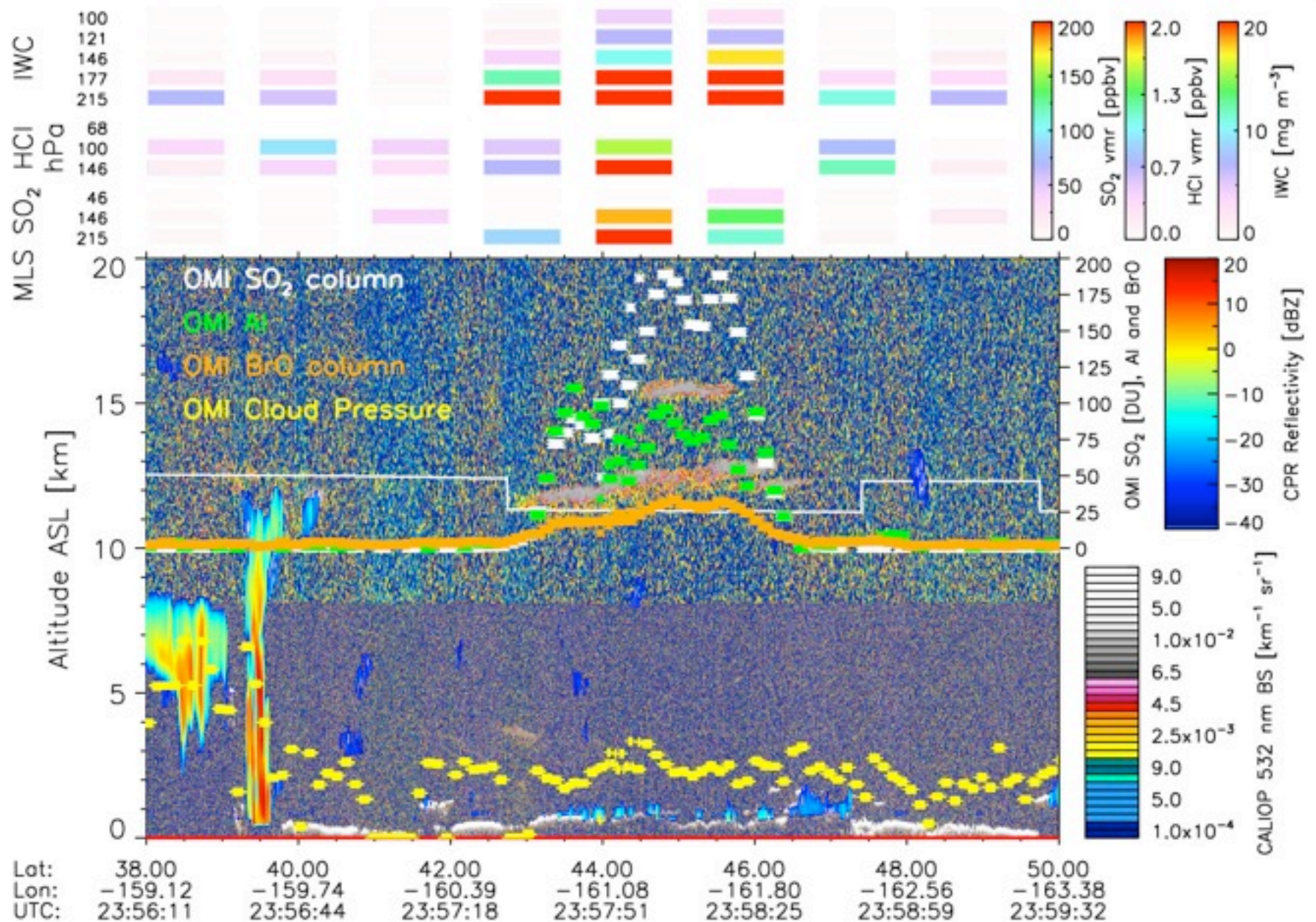
[O'Dwyer et al., GRL, 2003]

- May be a significant component of total S budget at some volcanoes
- Mid-UV absorption bands require active source
- IR absorption bands are very weak





# A-Train observations: Kasatochi, August 9, 2008

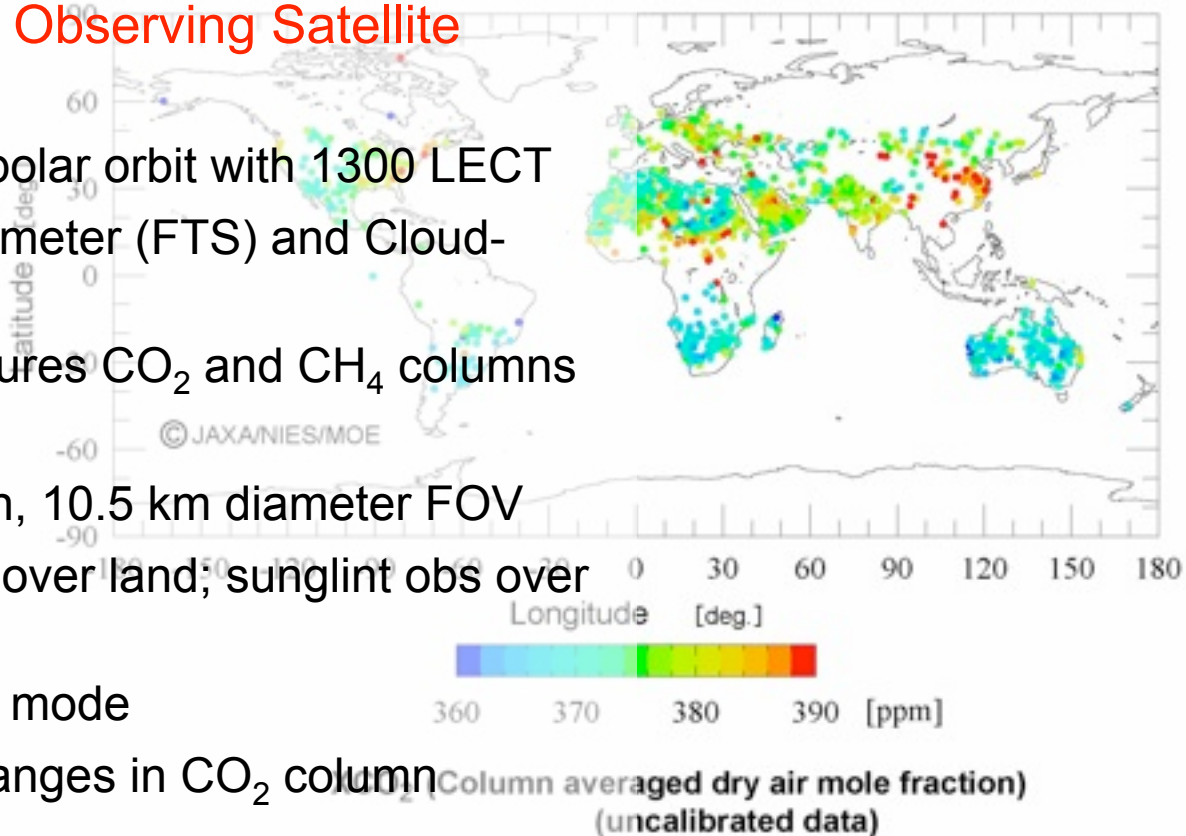


# GOSAT: Measuring CO<sub>2</sub> from space

- NASA Orbiting Carbon Observatory (OCO) – failed at launch

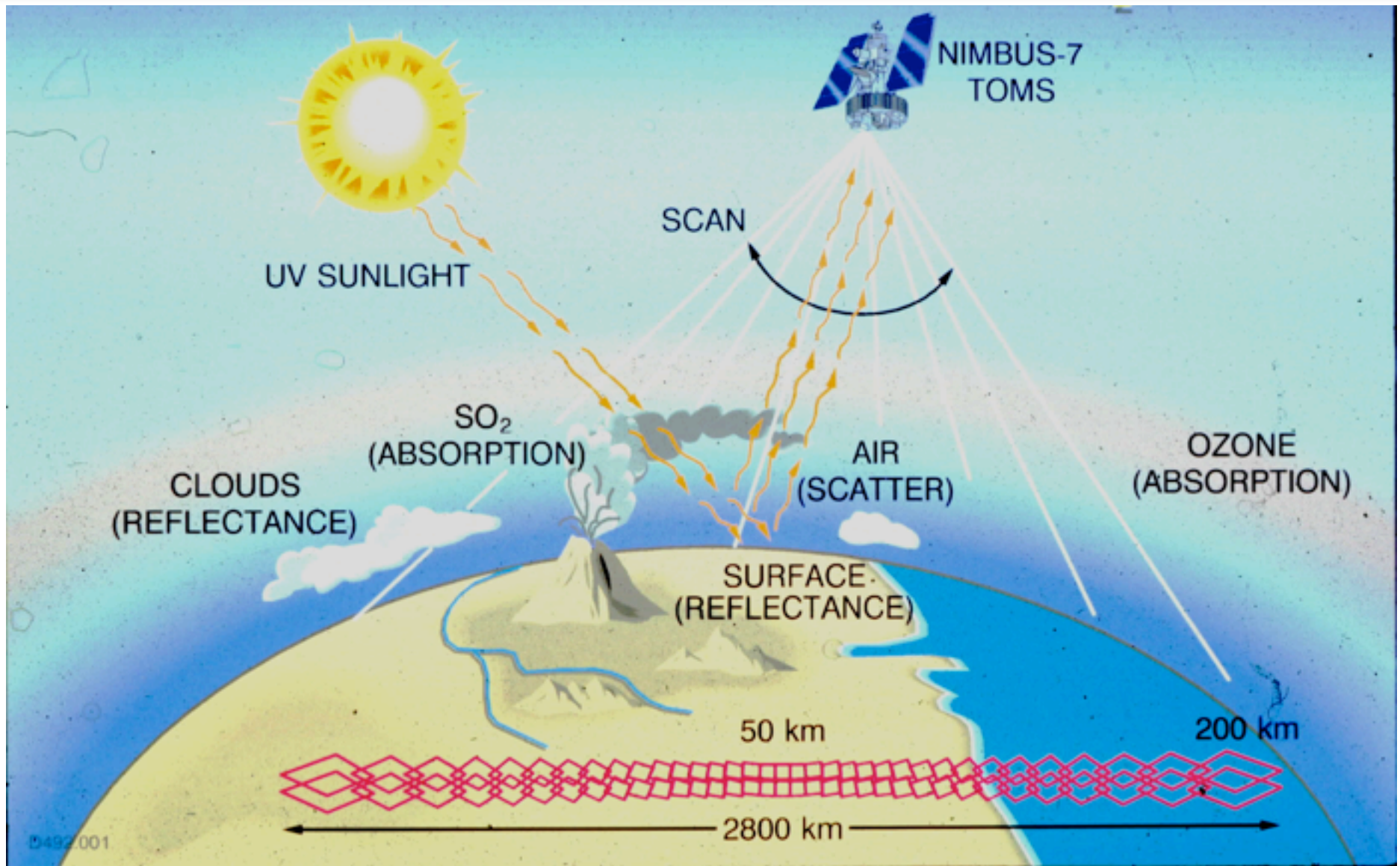
- Japanese Greenhouse Gas Observing Satellite (GOSAT)

- Launched January 2009; polar orbit with 1300 LECT
- Fourier Transform Spectrometer (FTS) and Cloud-Aerosol Imager (CAI)
- TANSO-FTS sensor measures CO<sub>2</sub> and CH<sub>4</sub> columns and profiles in SWIR/TIR
- 0.2 cm<sup>-1</sup> 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<sub>2</sub> column
- Evaluation of GOSAT data for volcanic CO<sub>2</sub> detection underway





# UV Backscatter instrument - basic operation



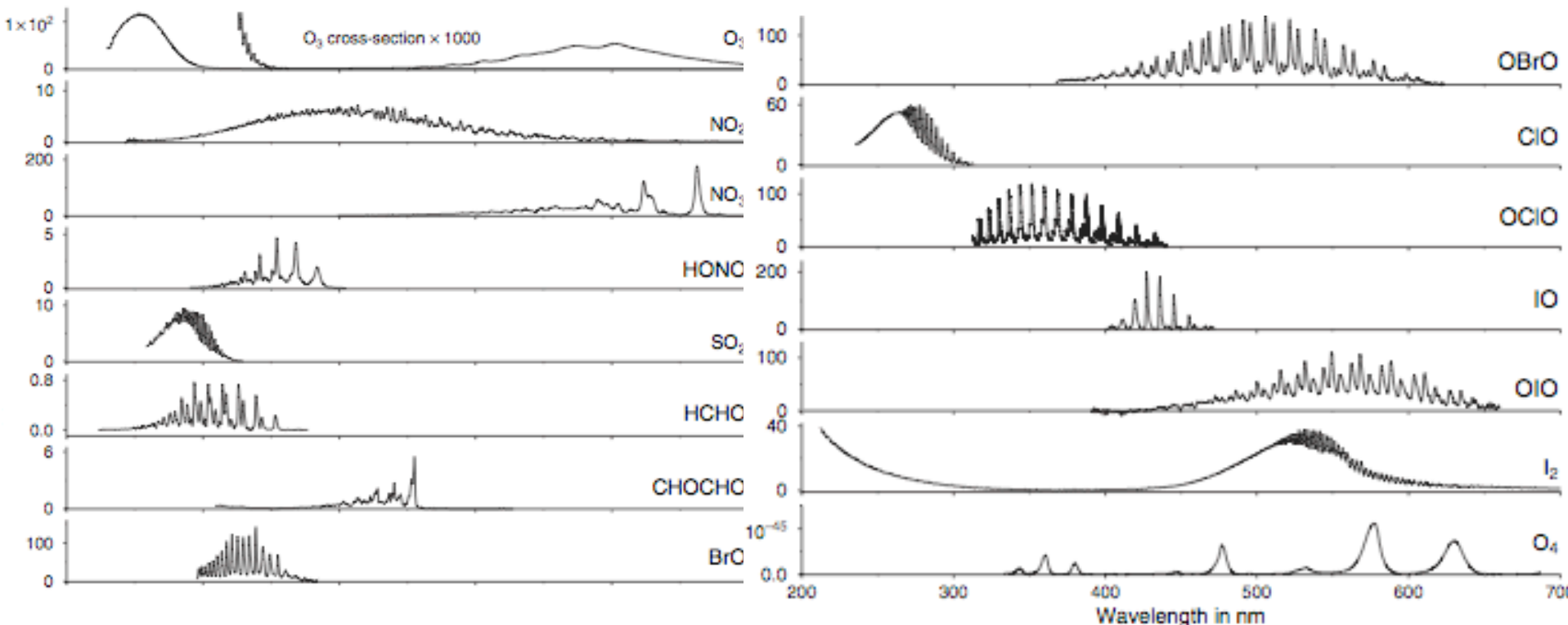
# Forward-model SO<sub>2</sub> retrieval (e.g., TOMS, OMI)

- Simulate at-satellite UV radiances as a function of viewing geometry, latitude, column O<sub>3</sub> and SO<sub>2</sub> amounts, surface pressure and reflecting surface conditions, using a radiative transfer model
- Compare measured normalized radiances with theoretical radiances calculated for the conditions of the measurement
- Derive column O<sub>3</sub> and SO<sub>2</sub> amounts in the scene by finding the values that give a computed radiance equal to the measured radiance
- Errors: highest in the presence of significant ash or sulfate aerosol, and at scan edges



# Differential Optical Absorption Spectroscopy (DOAS)

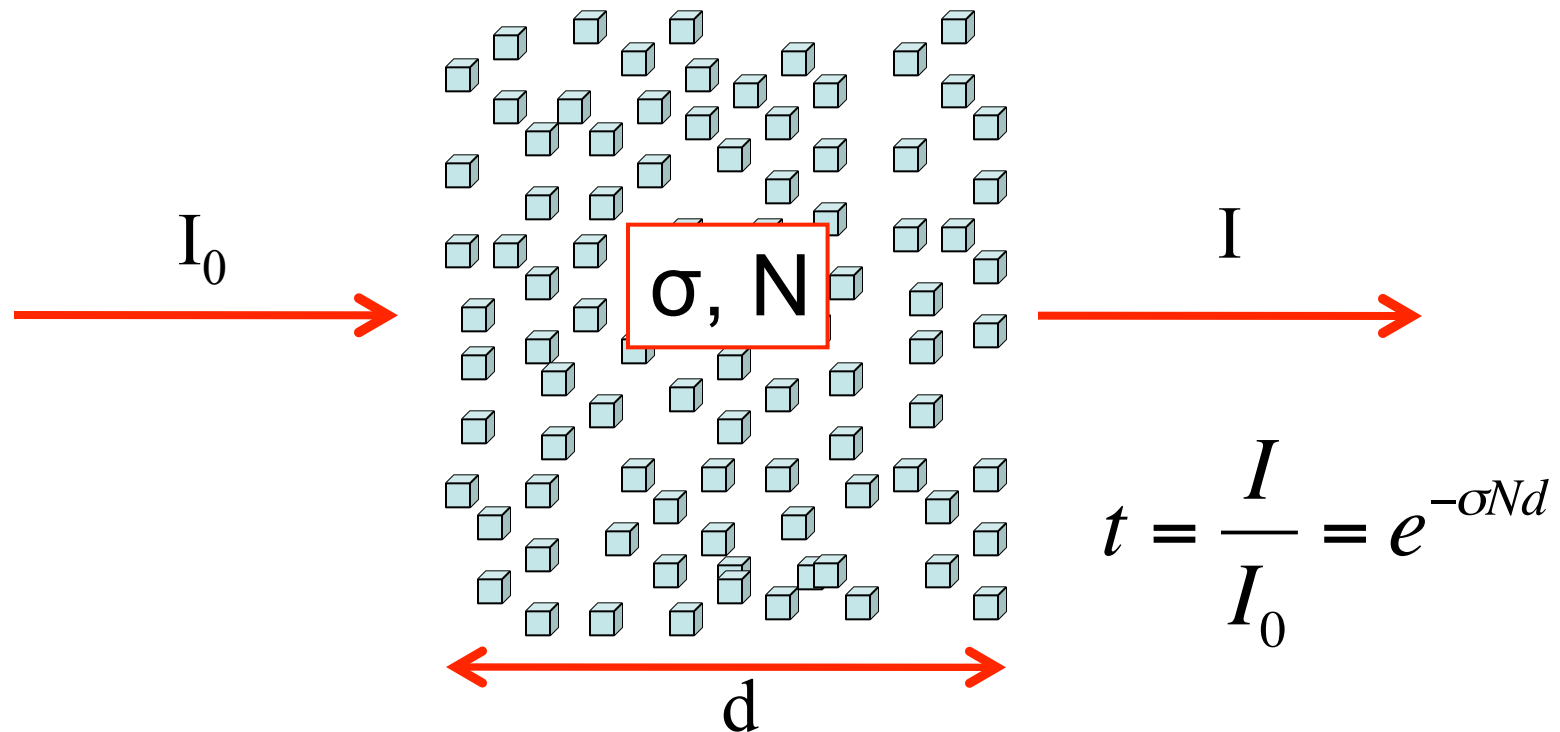
Measured UV-visible spectra contain overlapping structures due to the solar spectrum (Fraunhofer lines), elastic scattering, trace gas absorption, aerosol absorption and the Ring effect (inelastic Raman scattering)



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

# Beer-Bouguer-Lambert (Beer's) Law

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



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

# Motivation for space-based volcanic gas measurements

- During intense activity (safe)
- Cover remote and/or unmonitored volcanoes
- Ground-based or airborne instruments unavailable
- Cloud cover obscures plume from below
- Independent of wind direction
- Aircraft hazards (use  $\text{SO}_2$  as a proxy for ash)

*Carn et al., 2009*



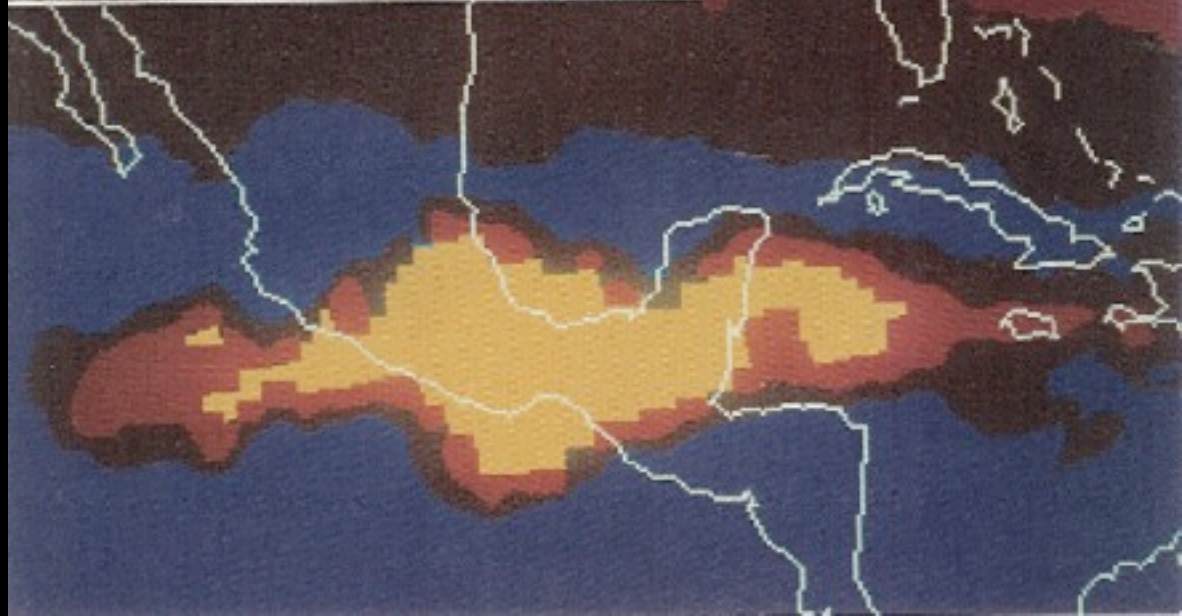
Detection of April 1982  
El Chichon SO<sub>2</sub> cloud  
with the Total Ozone  
Mapping Spectrometer  
(TOMS)

24 JUNE 1983 · VOL. 220 · NO. 4604

\$2.50

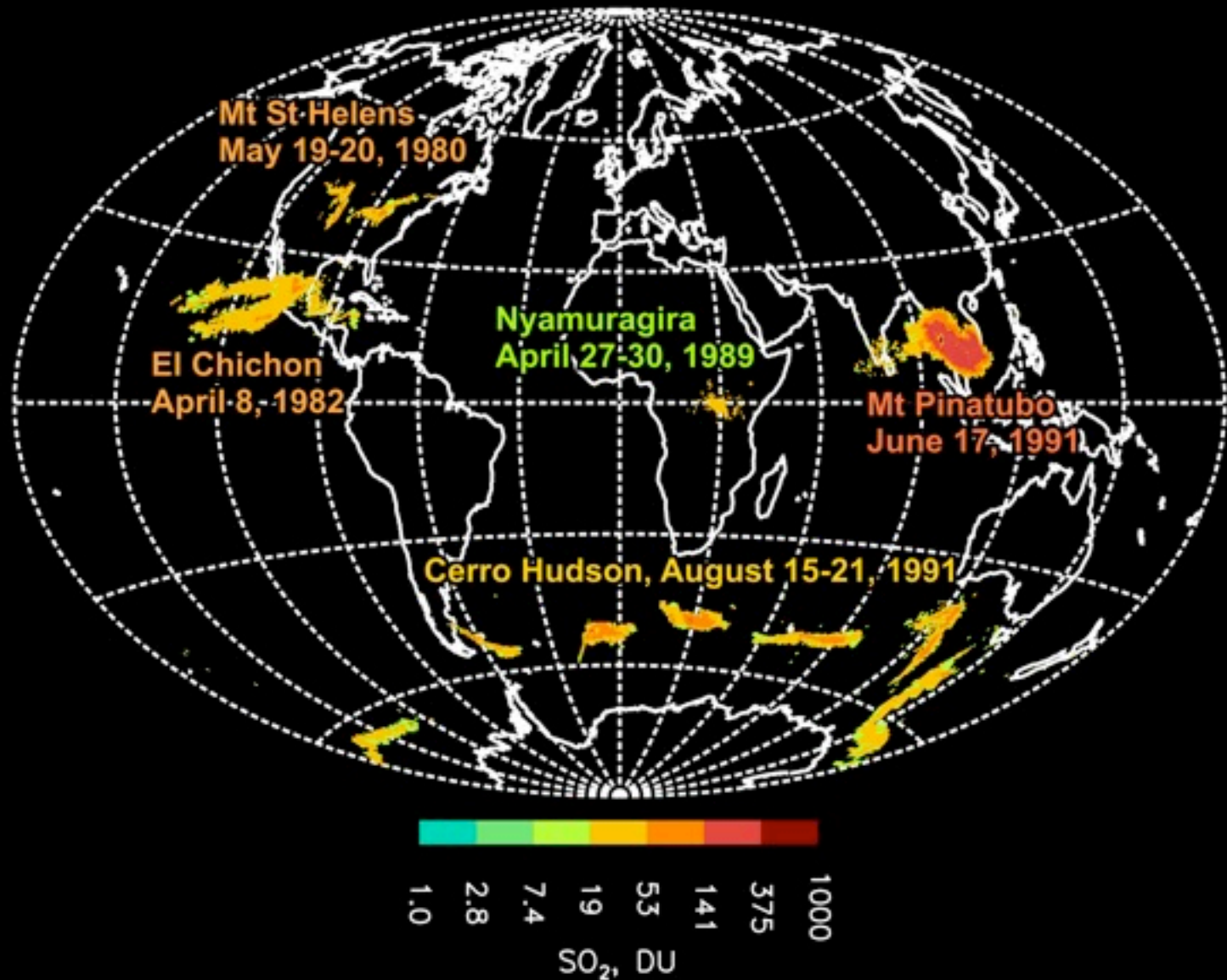
# SCIENCE

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

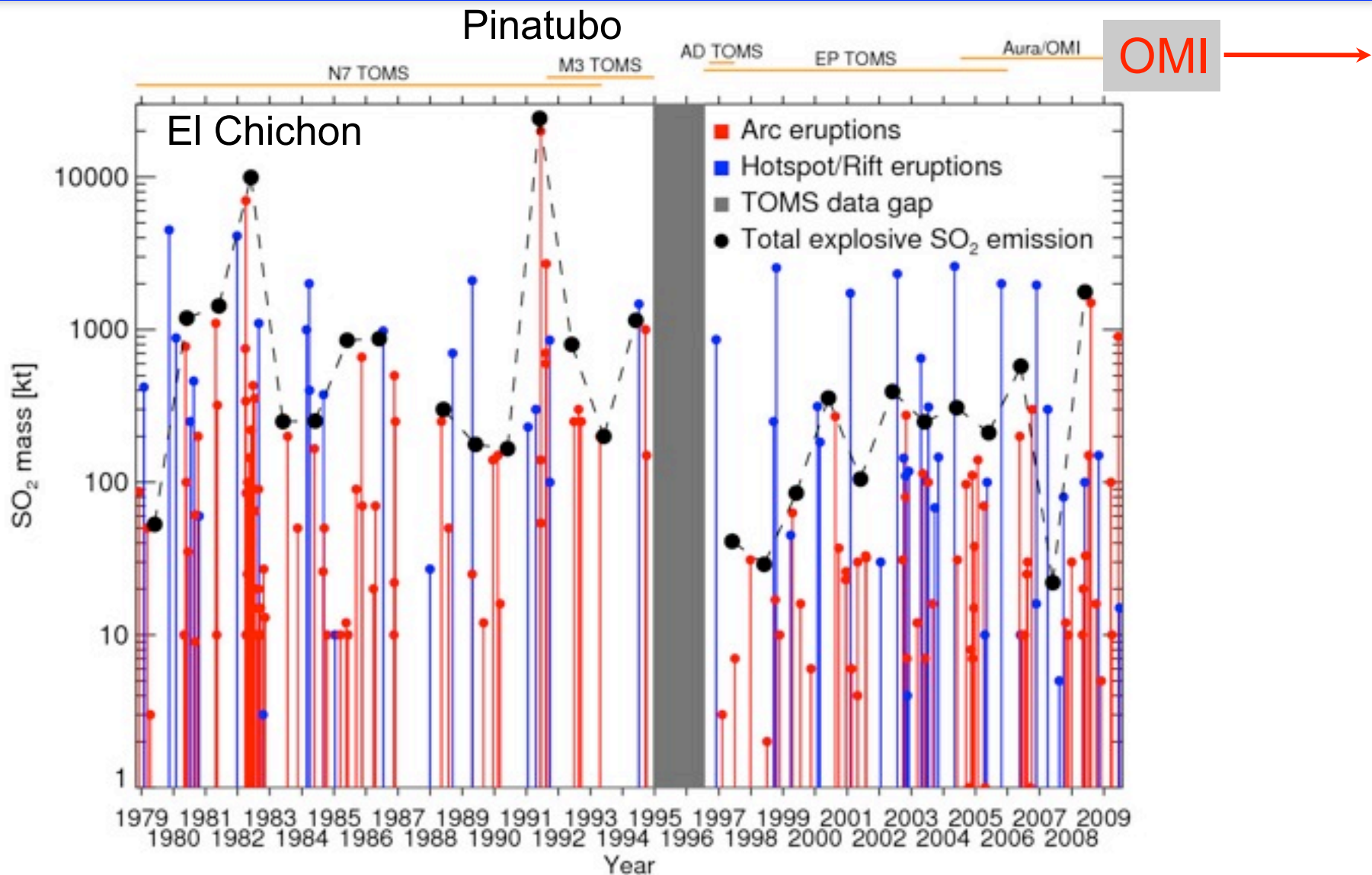


[Krueger, Science, 1983]

# Volcanic SO<sub>2</sub> clouds measured by TOMS



# Volcanic SO<sub>2</sub> Emissions Inventory



[Bluth et al., 1993; Carn et al., 2003]

NSF PASI, San José, Costa Rica, Jan 2011



# Exploiting A-Train synergy for volcanic cloud studies

## Aura

**OMI** -  $\text{SO}_2$ ,  $\text{O}_3$ ,  $\text{NO}_2$ , BrO

**TES** -  $\text{SO}_2$

**MLS** - strat.  $\text{SO}_2$ , HCl,  $\text{O}_3$

## Aqua

**MODIS** -  $\text{SO}_2$ , ash, sulfate

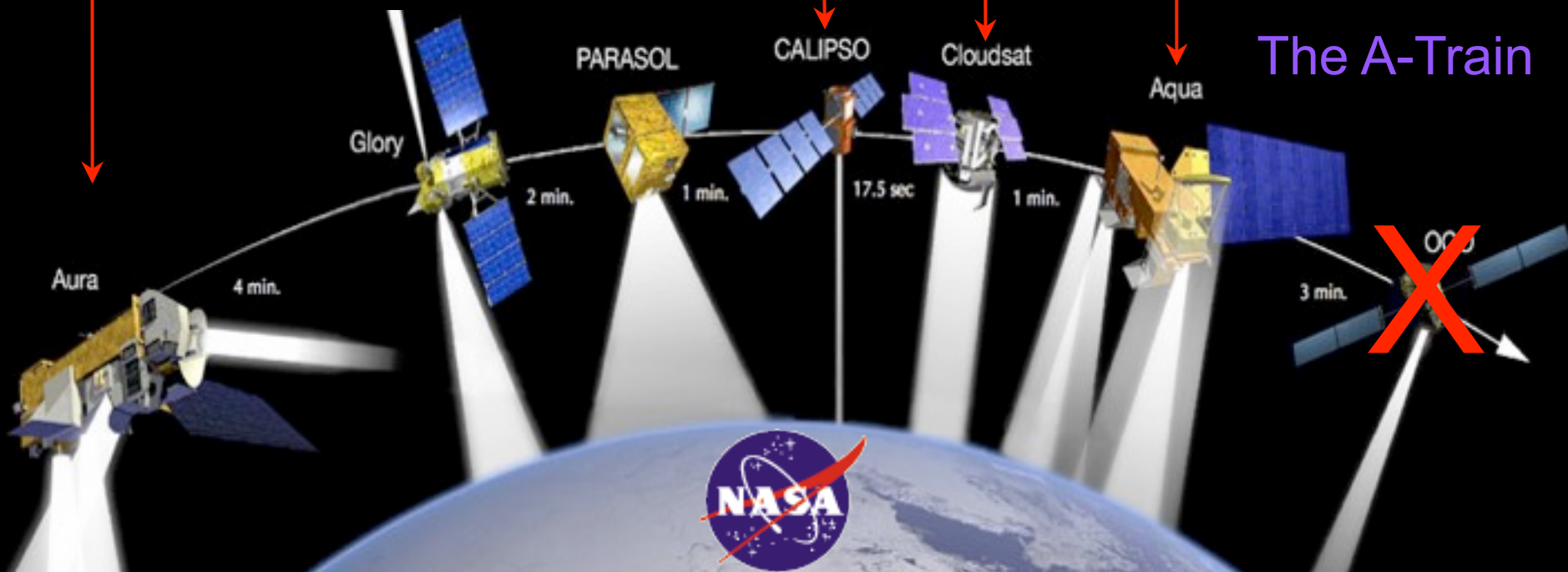
**AIRS** - UTLS  $\text{SO}_2$ , aerosols,  $\text{SO}_2$  profile?

## CloudSat

**CPR** - precipitation, hydrometeors

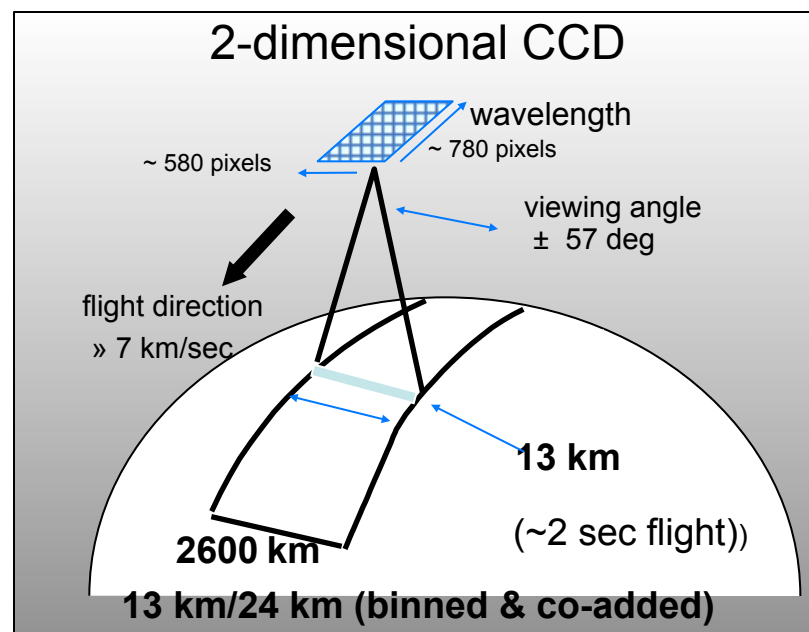
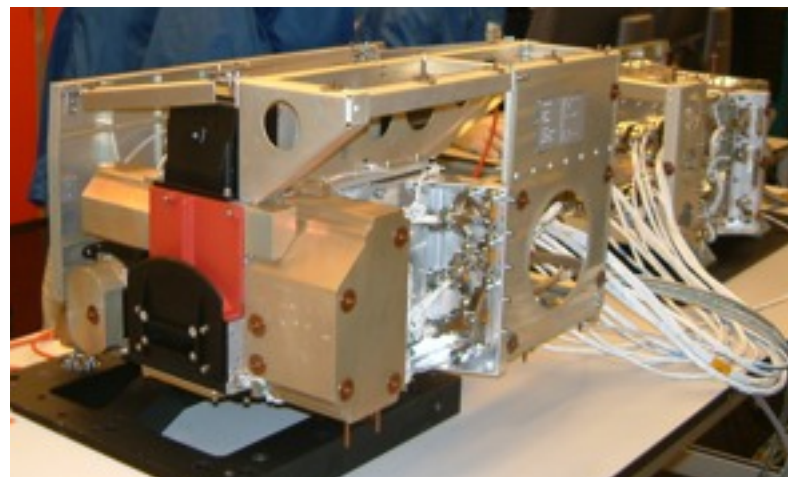
## CALIPSO

**CALIOP** - cloud altitude, aerosol phase/type



# Aura - Ozone Monitoring Instrument (OMI)

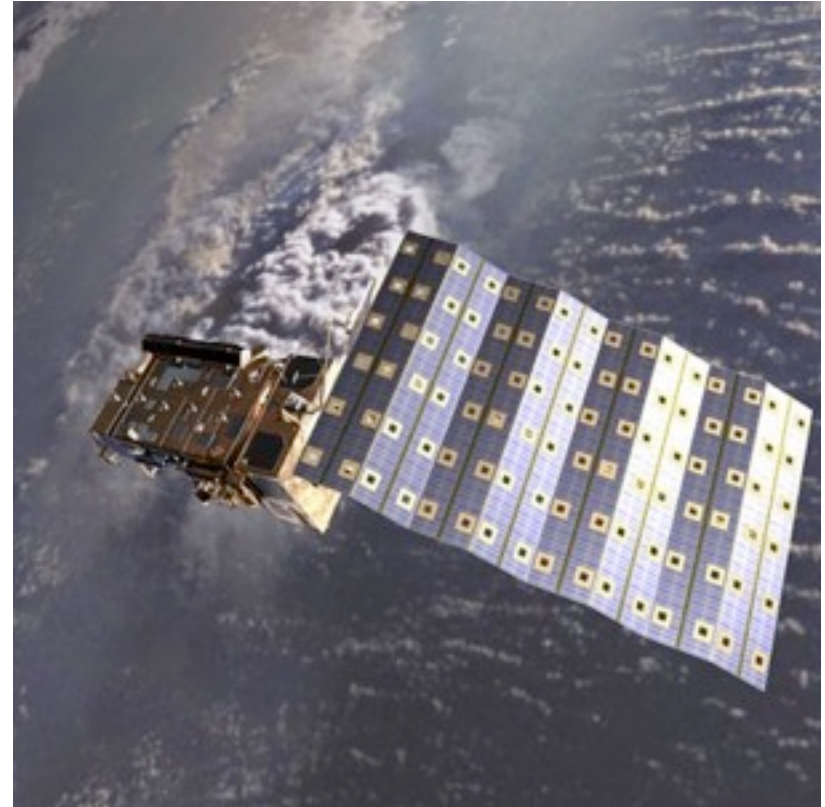
- UV/VIS sensor that succeeded TOMS
- Dutch/Finnish contribution to NASA's EOS/Aura mission (launched July 2004)
- Daily contiguous global coverage
- 13 x 24 km nadir footprint - best ever for UV measurements from space
- Overpass at 1:30-2:00 pm local time
- Data publically available and *free*
- *Row anomaly since August 2008 – some data gaps*
- **The first space-borne sensor to provide daily, global SO<sub>2</sub> measurements with sensitivity to the lower troposphere (i.e., passive degassing)**





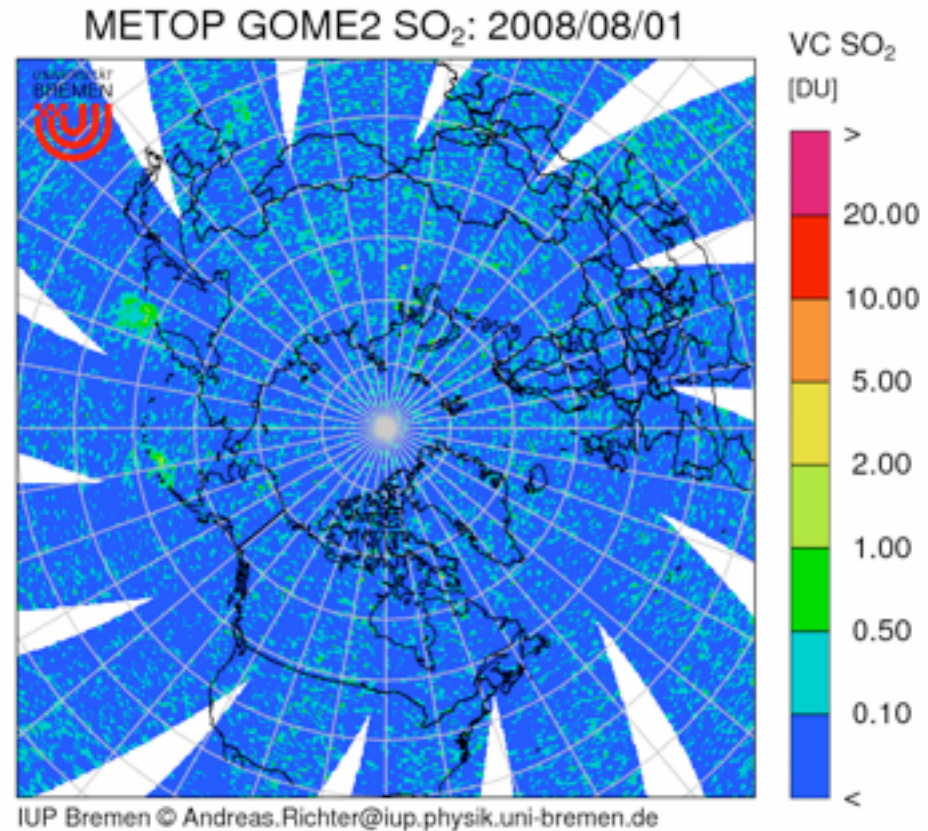
# MetOp-A satellite

- Europe-US collaboration
- First in series of 3 MetOp satellites
- Launched 19 October 2006
- Polar, sun-synchronous orbit
- 9:30 am local time equator crossing
- 11 instruments
- Sensors of volcanological interest:
  - Global Ozone Monitoring Experiment 2 (**GOME-2**) – SO<sub>2</sub>, ash
  - Infrared Atmospheric Sounding Interferometer (**IASI**) – SO<sub>2</sub>, ash
  - High-resolution Infrared Radiation Sounder-4 (**HIRS/4**) – SO<sub>2</sub>, ash
  - Advanced Very High Resolution Radiometer (**AVHRR**) – ash, IR hot spots



# Global Ozone Monitoring Experiment-2 (GOME-2)

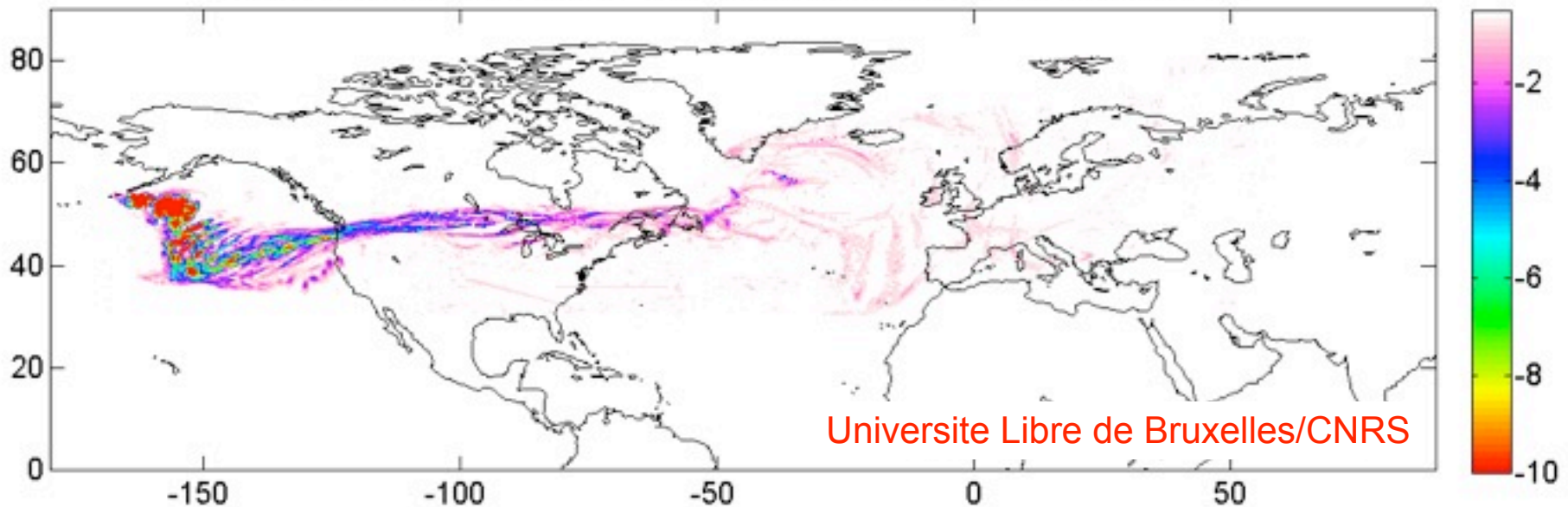
- UV-visible wavelengths
- 1920 km swath width
- 80 x 40 km ground pixel size
- Data gaps at Equator
- 9:30 am local time equator crossing
- High SO<sub>2</sub> sensitivity
- Can detect small eruptions and strong degassing



# Infrared Atmospheric Sounding Interferometer (IASI)

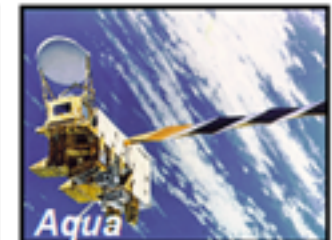
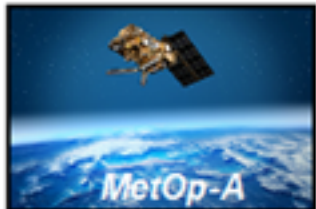
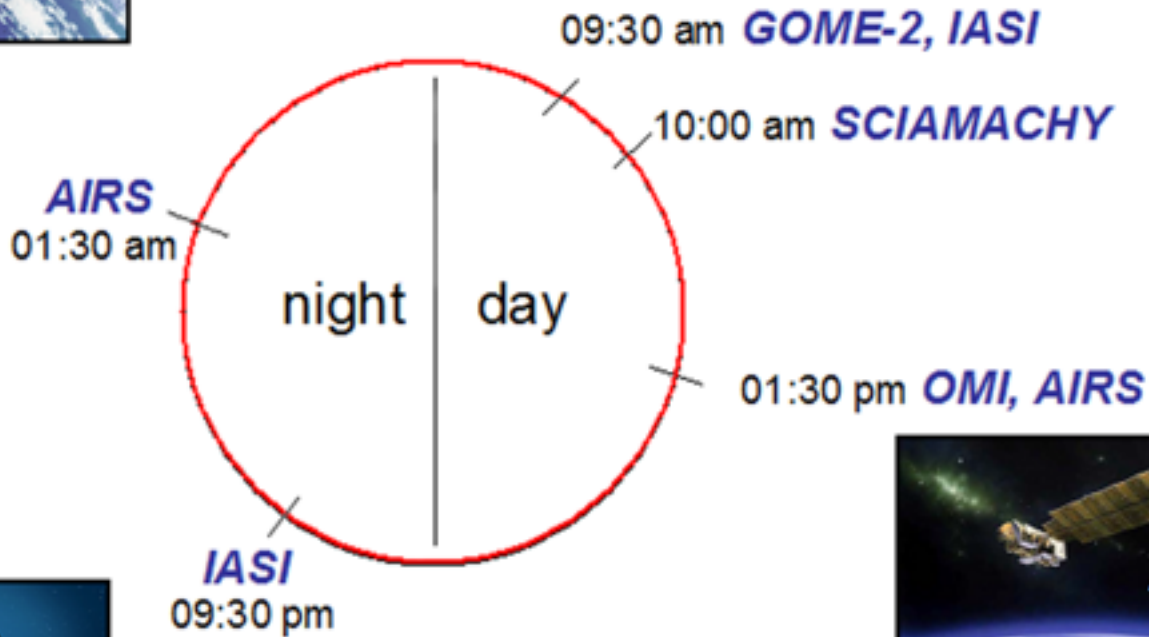
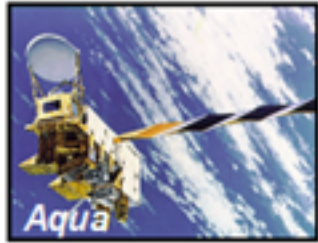
- 3.4 – 15  $\mu\text{m}$  (infrared) wavelengths
- High spectral resolution, Fourier transform interferometer
- Mapping and vertical profiling of  $\text{SO}_2$  possible
- 25 km horizontal resolution, 1 km vertical resolution
- Covers 3  $\text{SO}_2$  absorption bands in the IR
- Measurements at 9:30 am and 9:30 pm local time (IR)
- High sensitivity to eruptions: degassing may be detectable

ULB-SA/CNRS - IASI - BTDSO2(K) - Overview from 20080712 to 20080723



# Up to 7 daily SO<sub>2</sub> measurements from UV/IR sensors

## Satellites equatorial overpass solar local time



<http://sacs.aeronomie.be/nrt/>



# Satellite instruments - UV

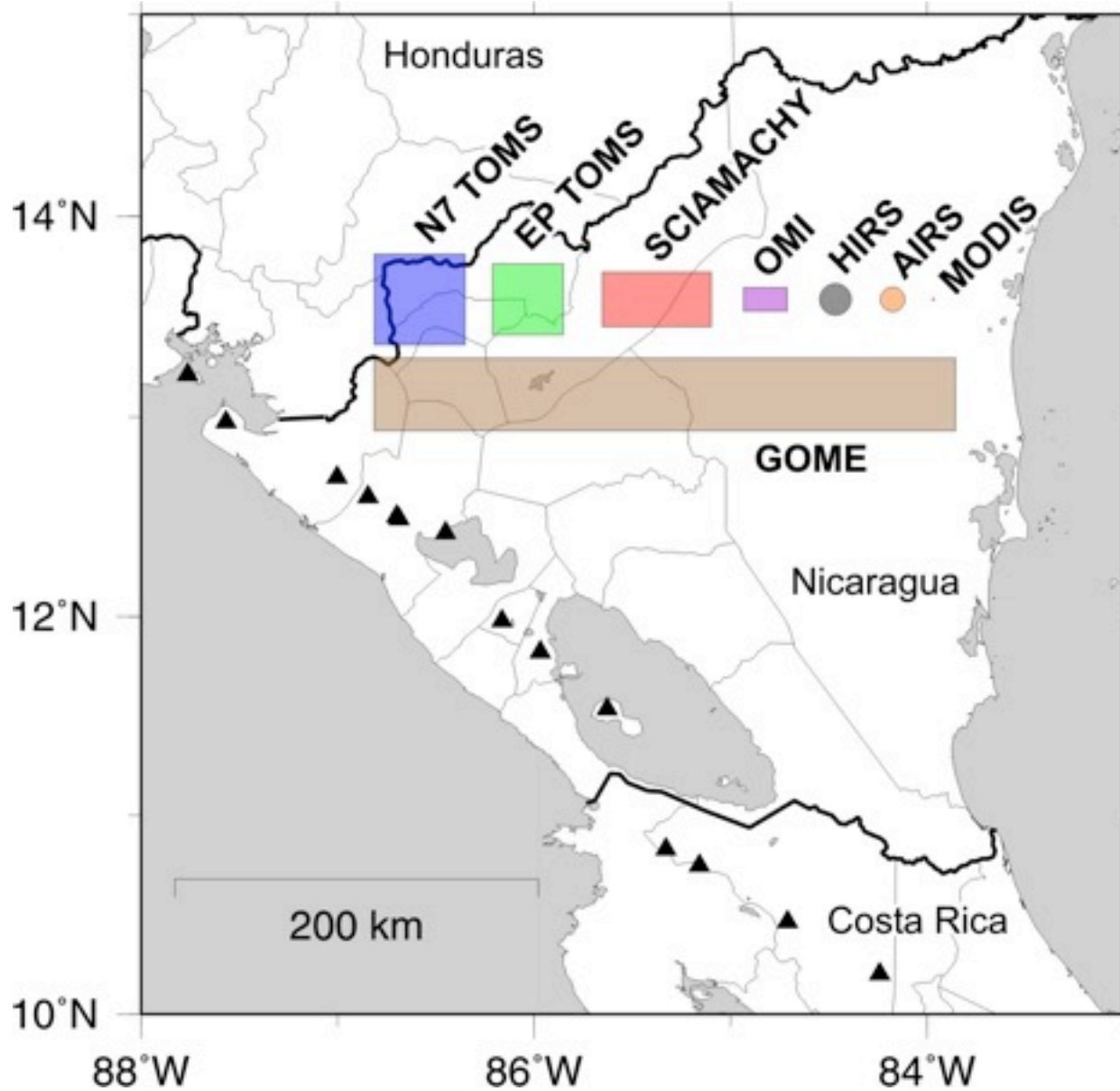
<b>Instrument</b>	<b>Satellite(s)</b>	<b>Data coverage dates</b>	<b>Daily global coverage?</b>
Total Ozone Mapping Spectrometer ( <b>TOMS</b> )	Nimbus-7, Meteor-3, ADEOS, Earth Probe	Nov 78 – Dec 94 Jul 96 – Dec 2005	Yes
Global Ozone Monitoring Experiment ( <b>GOME</b> )	European Remote Sensing Satellite (ERS-2)	July 95 – present	No
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography ( <b>SCIAMACHY</b> )	European Environmental Satellite (Envisat-1)	Sept 03 – present	No
Ozone Monitoring Instrument ( <b>OMI</b> )	NASA EOS Aura	Sept 2004 – present	Yes (until late 2008)
Global Ozone Monitoring Experiment-2 ( <b>GOME-2</b> )	MetOp A, B, C	Oct 2006 - present	No
Ozone Mapping and Profiler Suite ( <b>OMPS</b> )	National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project	2011?	Yes

Operational SO<sub>2</sub> data products

# Satellite instruments – Microwave & IR

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

# Satellite instrument footprints (nadir)



# UV instrument SO<sub>2</sub> sensitivity

Instrument	Footprint area (km <sup>2</sup> )	Sensitivity (DU) 1 $\sigma$		Smallest cloud detection limit (tons) 5 pixels at 5 $\sigma$	
		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 (40×80)	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<sub>2</sub> sensitivity

Instrument	Footprint area (km <sup>2</sup> )	Sensitivity (DU)* 1 $\sigma$		Smallest cloud detection limit (tons) 5 pixels at 5 $\sigma$	
		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)

# Units for SO<sub>2</sub> column amount measurements



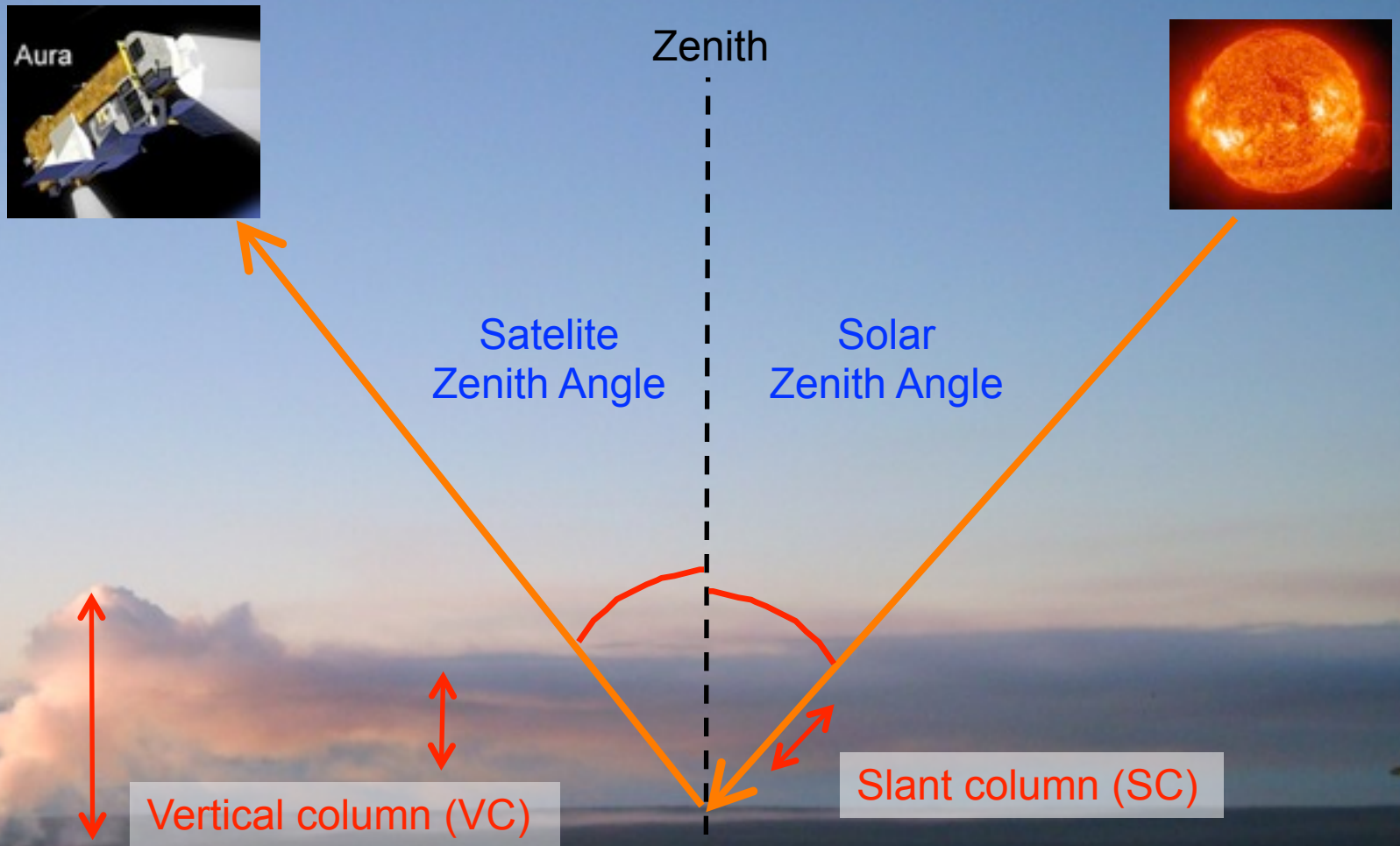
STP = 0°C, 1 atm pressure



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<sub>2</sub>
  - US units: Dobson Unit (DU)
  - 1 DU =  $2.69 \times 10^{16}$  molecules cm<sup>-2</sup> = 0.0285 g m<sup>-2</sup> SO<sub>2</sub>
  - European units: molecules cm<sup>-2</sup>
  - *Milli atm cm* also used (same as DU)
- Typical values in volcanic clouds
  - Fresh eruption cloud: 100s – 1000+ DU
  - Non-eruptive 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

# UV backscatter measurements



$$\text{Air Mass Factor (AMF)} = \text{SC/VC}$$

# UV radiation penetrates clouds

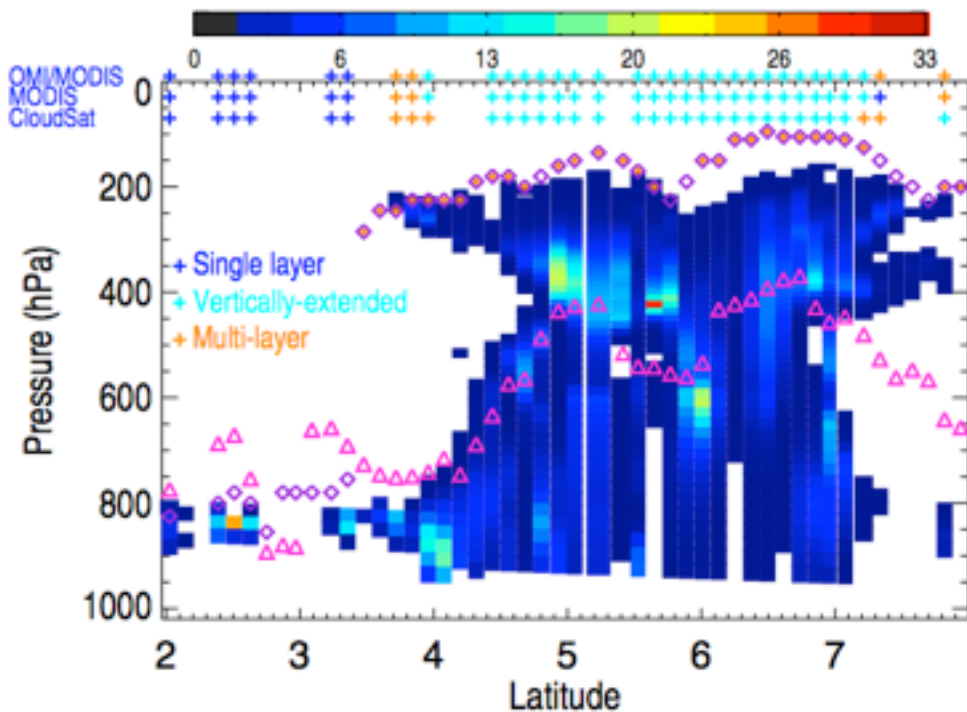


Fig. 7. CloudSat 2B-Tau cross section of cloud extinction ( $\text{km}^{-1}$ ) along OMI orbit 12 402 (western track in tropical Pacific highlighted in Fig. 6); Averaged along-track over OMI pixel ( $\sim 13$  km); Pink triangles: OMI optical centroid cloud pressure; Purple diamonds: MODIS minimum cloud-top pressure within closest passive sensor footprint, orange-filled where MODIS maximum multi-layer flag  $> 2$ .

*(Joiner et al., ATMD, 2009)*

- IR cloud top  $\neq$  UV cloud pressure

## CLOUD SLICING MEASUREMENTS OF OZONE INSIDE THICK CLOUDS

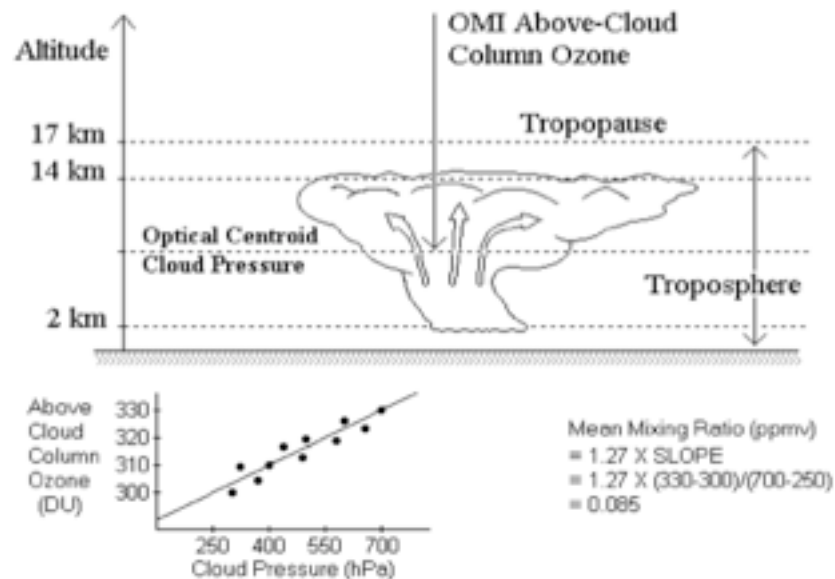
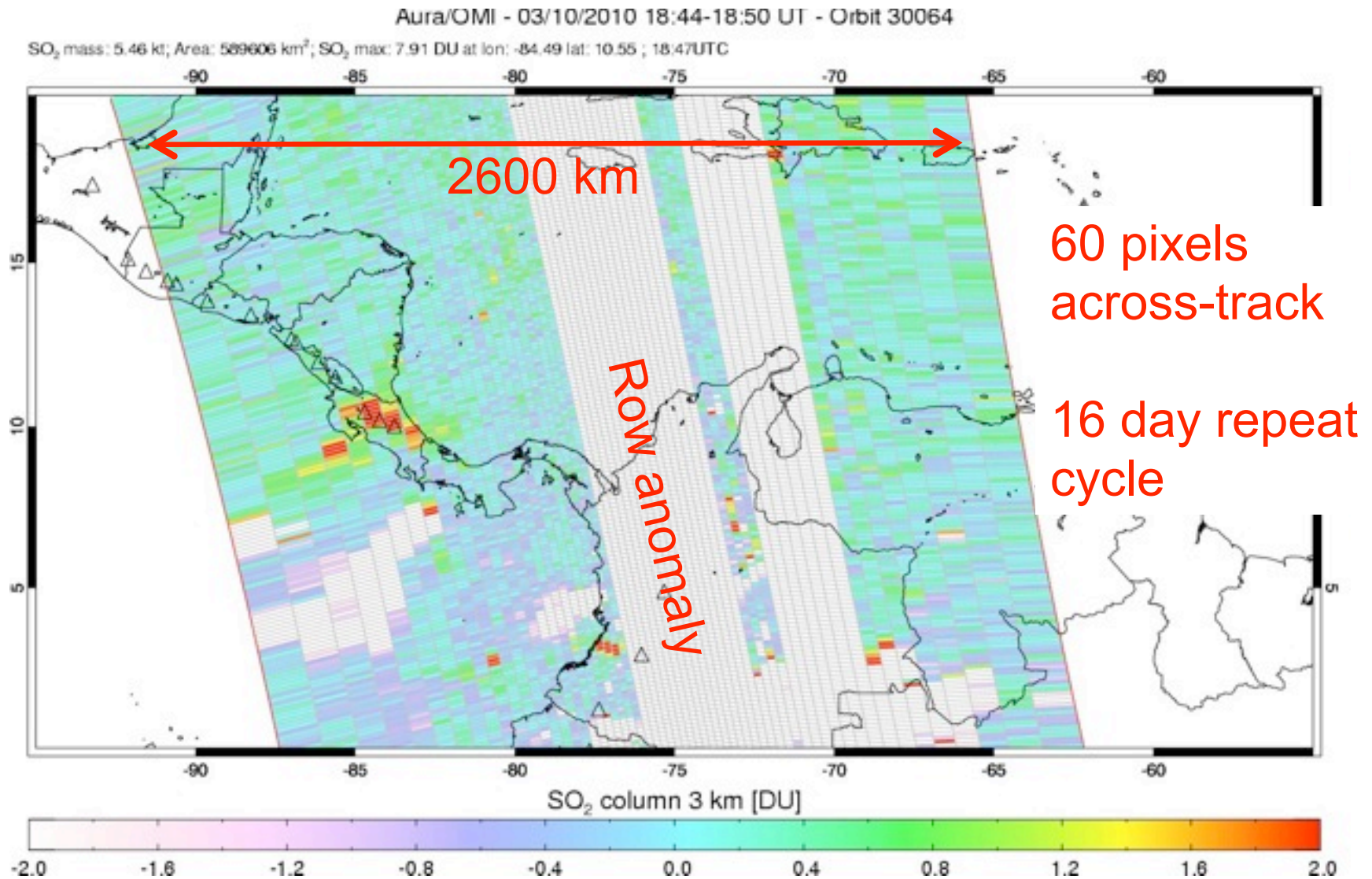


Fig. 4. Schematic diagram illustrating the ensemble cloud-slicing method. The figure shows that a satellite UV instrument is sensitive to the  $\text{O}_3$  column from the top of the atmosphere down to the OCCP altitude which may lie several hundred hPa below geometrical cloud top. The lower half of the figure illustrates that using an ensemble of such measurements over a fixed region, mean volume mixing ratio can be determined from the slope of column  $\text{O}_3$  plotted versus OCCP.

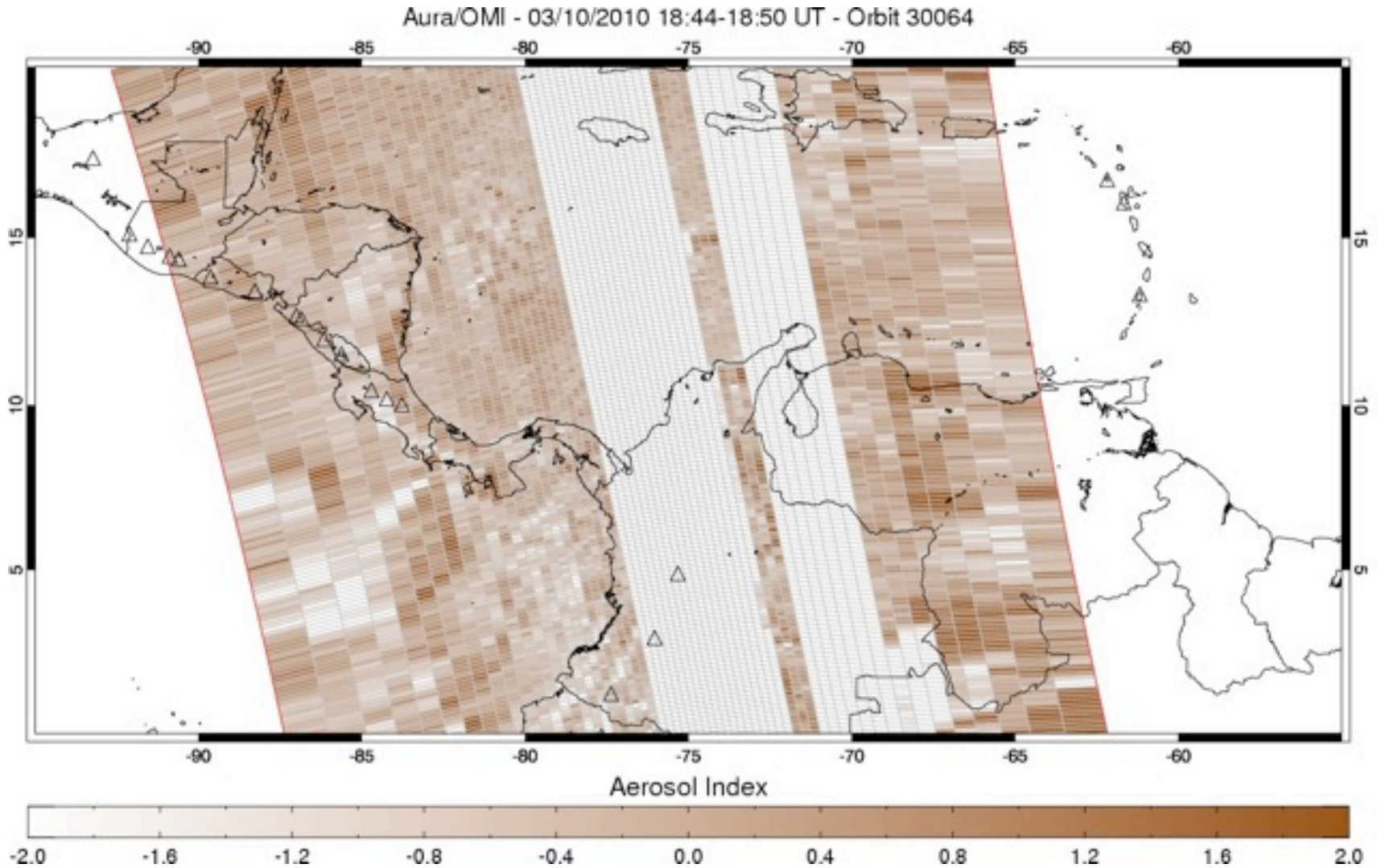
*(Ziemke et al., ACP, 2009)*



# OMI data products – SO<sub>2</sub>

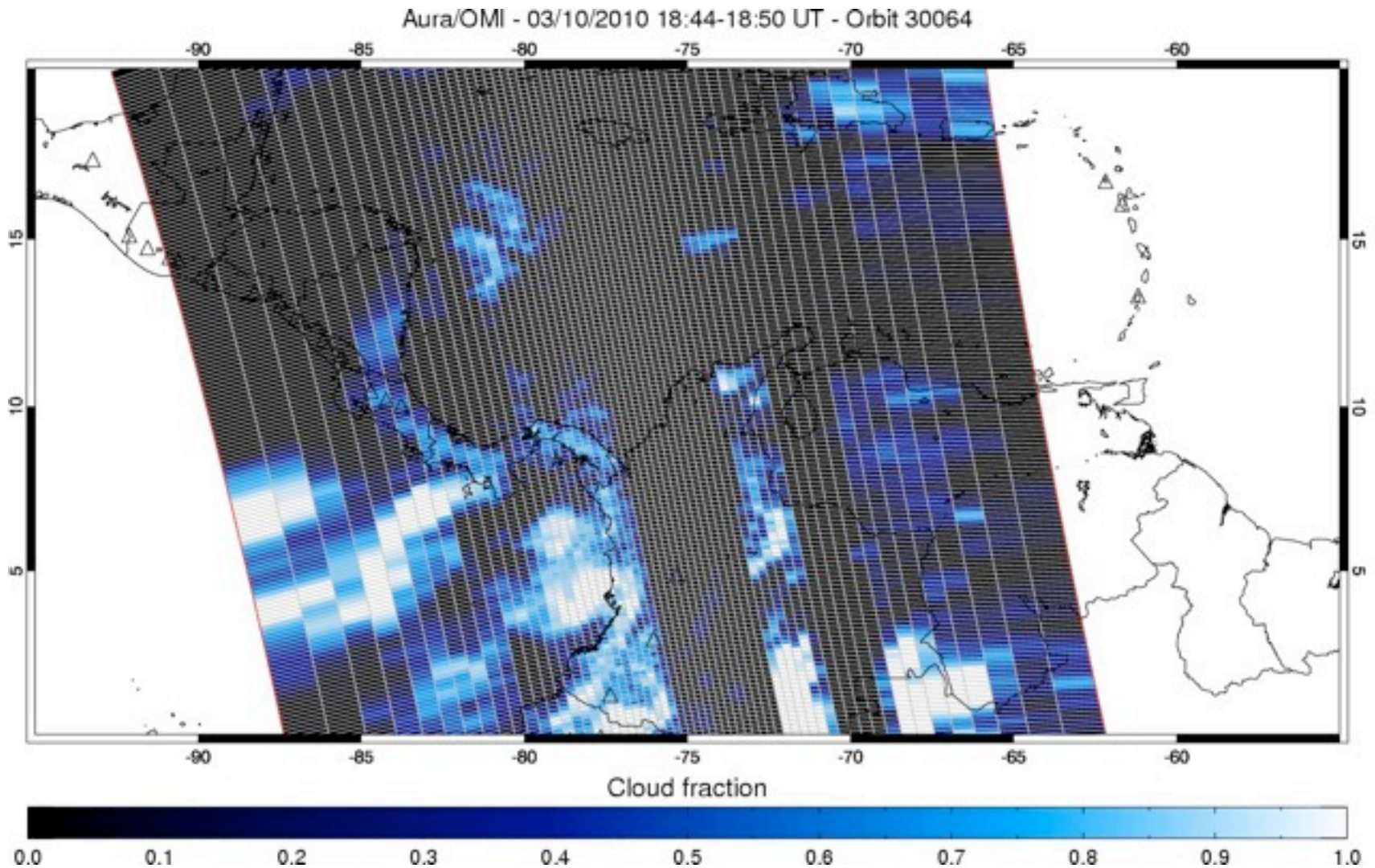


# OMI data products – Aerosol Index

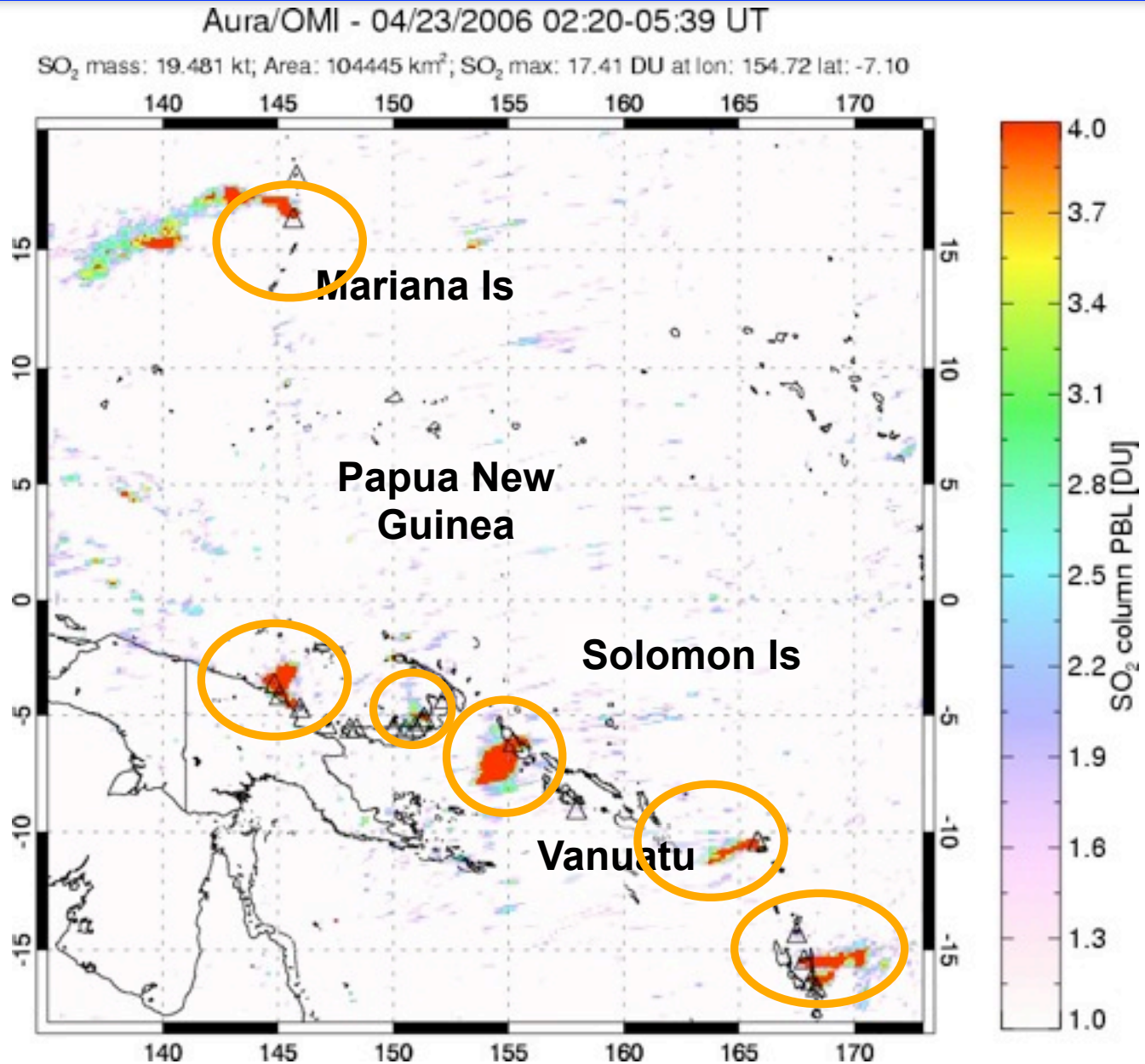




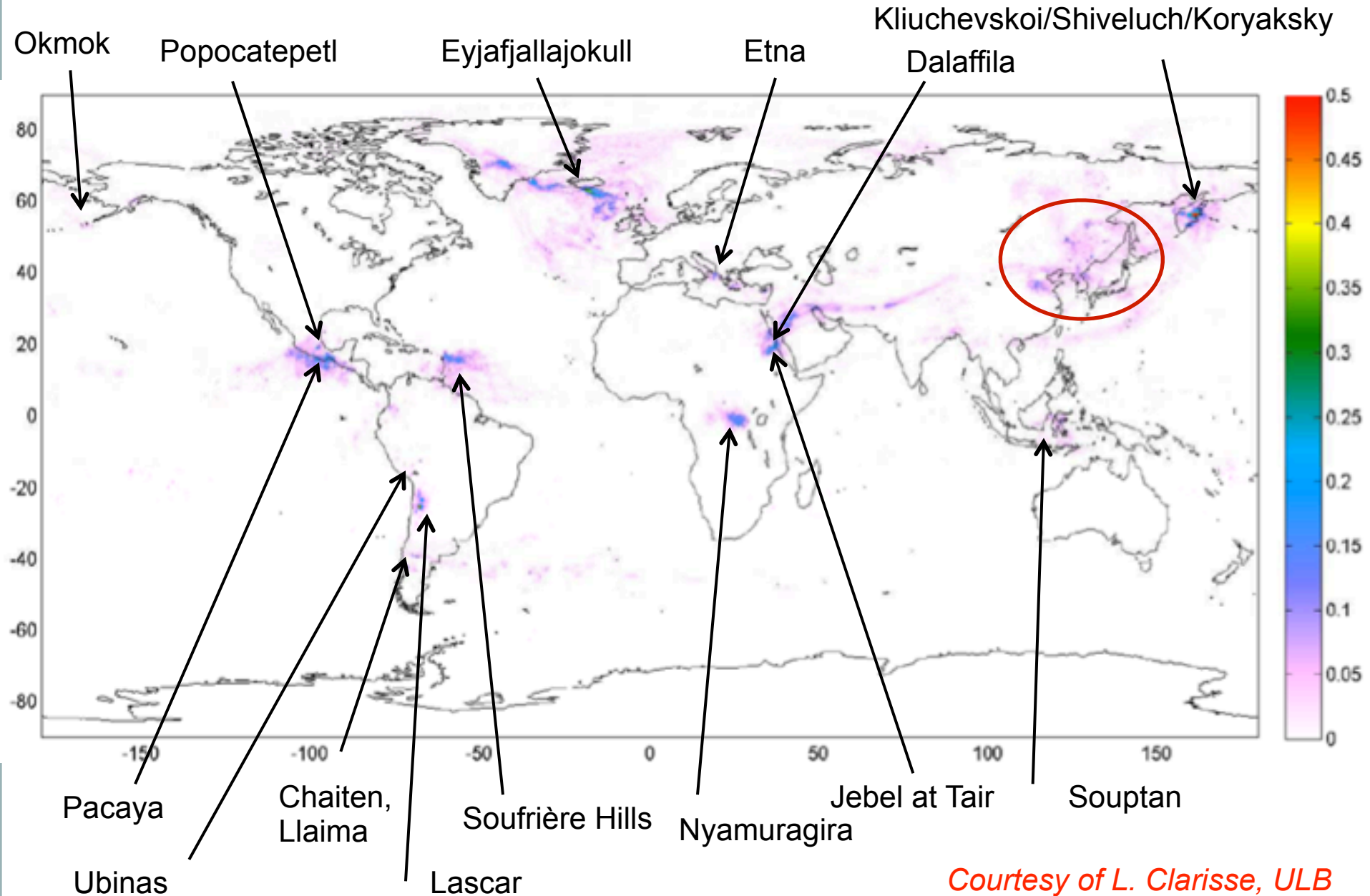
# OMI data products – Cloud fraction



# Detection of passive SO<sub>2</sub> degassing with OMI

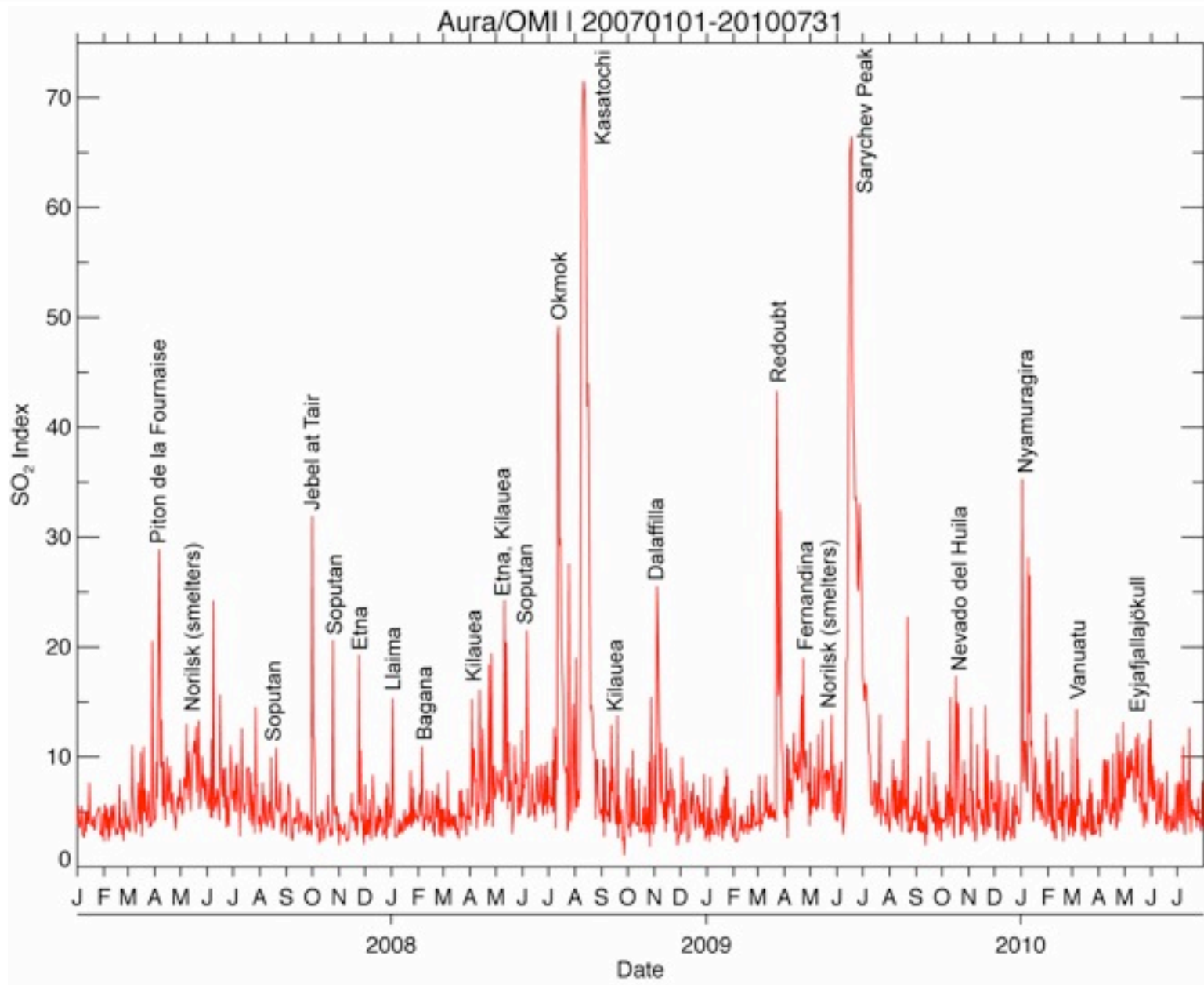


# 3 year global average SO<sub>2</sub> from IASI (without large eruptions)





# Global SO<sub>2</sub> emissions measured by OMI

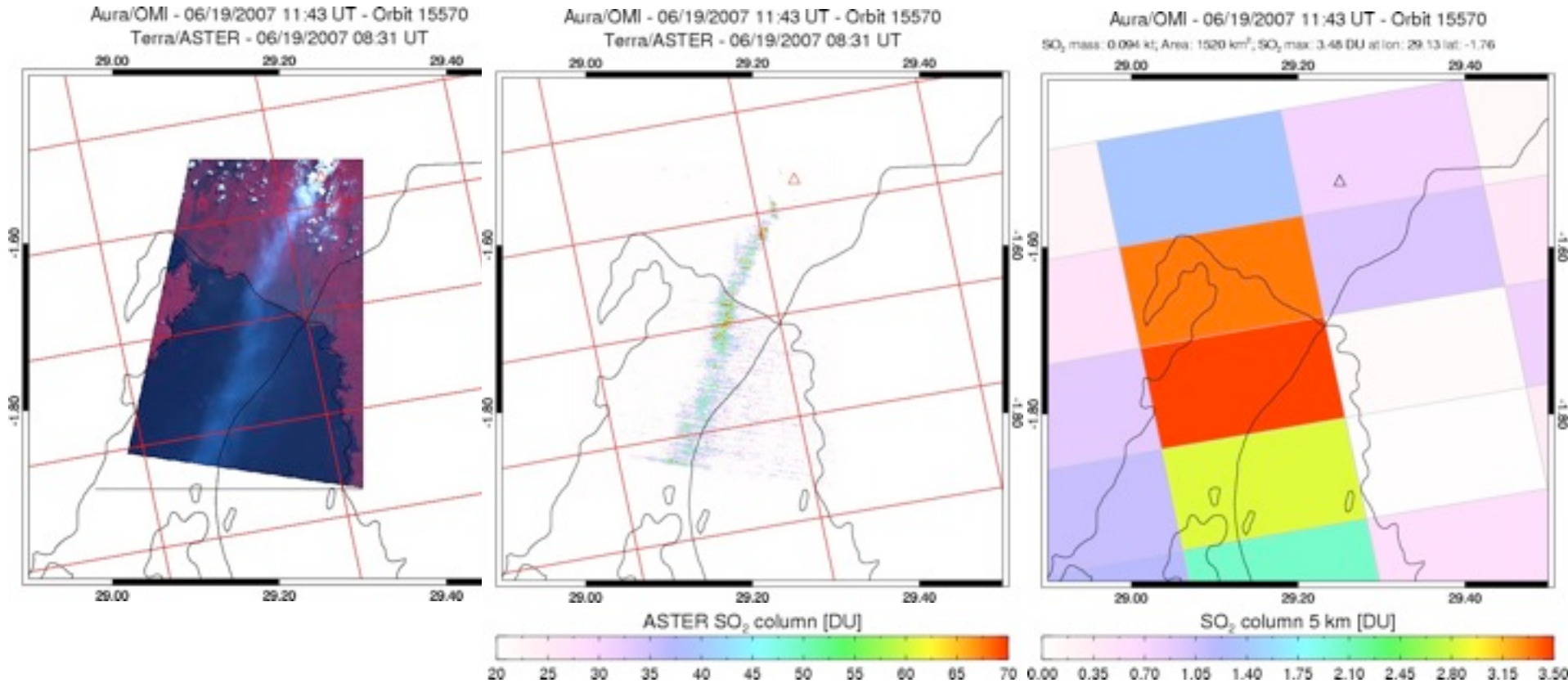




# OMI and ASTER: Nyiragongo (DR Congo), Jun 19, 2007

Terra ASTER (10:30 am)

Aura OMI (1:45 pm)

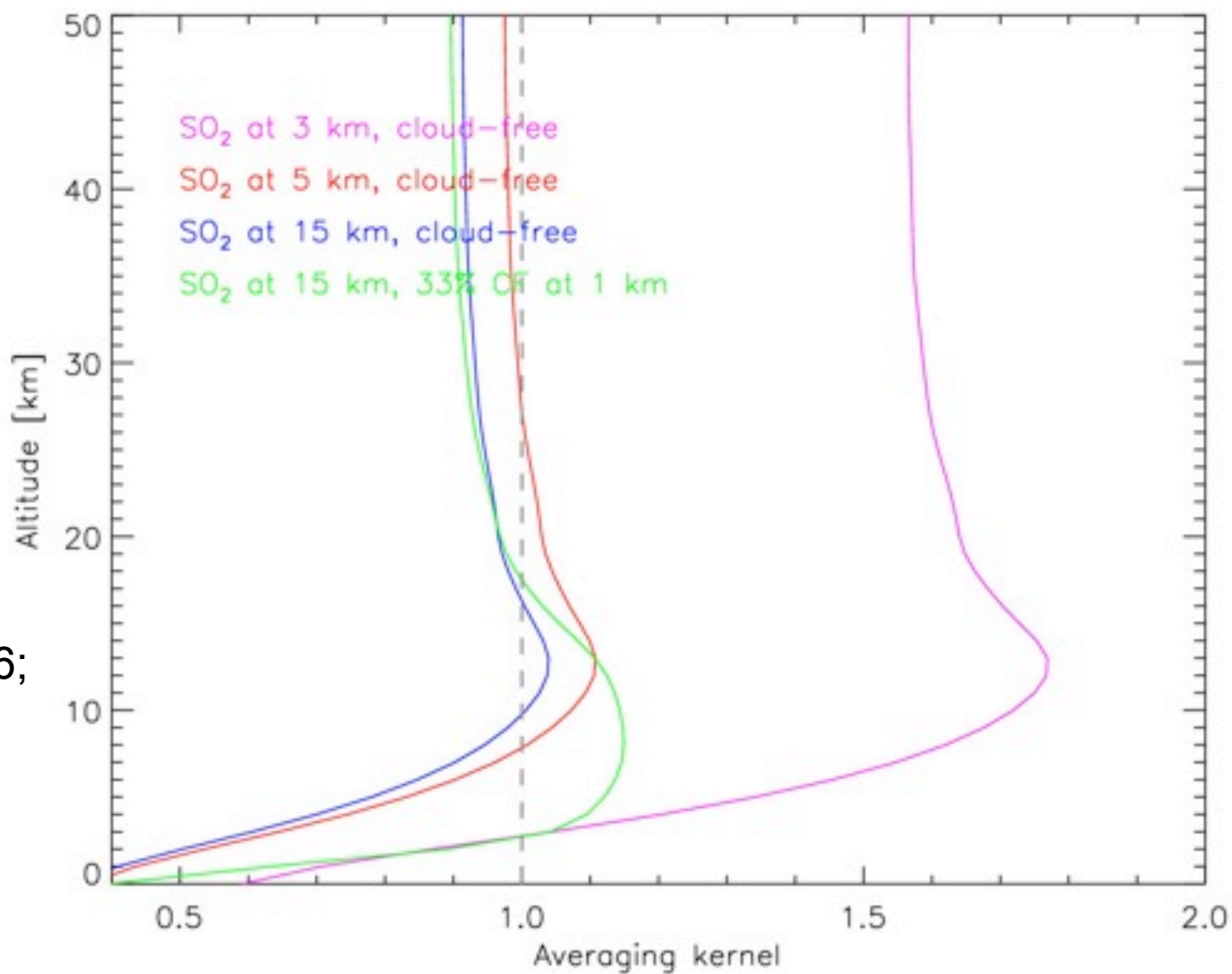


(ASTER 8.6  $\mu\text{m}$  SO<sub>2</sub> retrieval; F. Prata, NILU)

- Plume extent relative to size of satellite FOV constrains detection of degassing plumes from space

# Effect of volcanic plume altitude on SO<sub>2</sub> retrievals

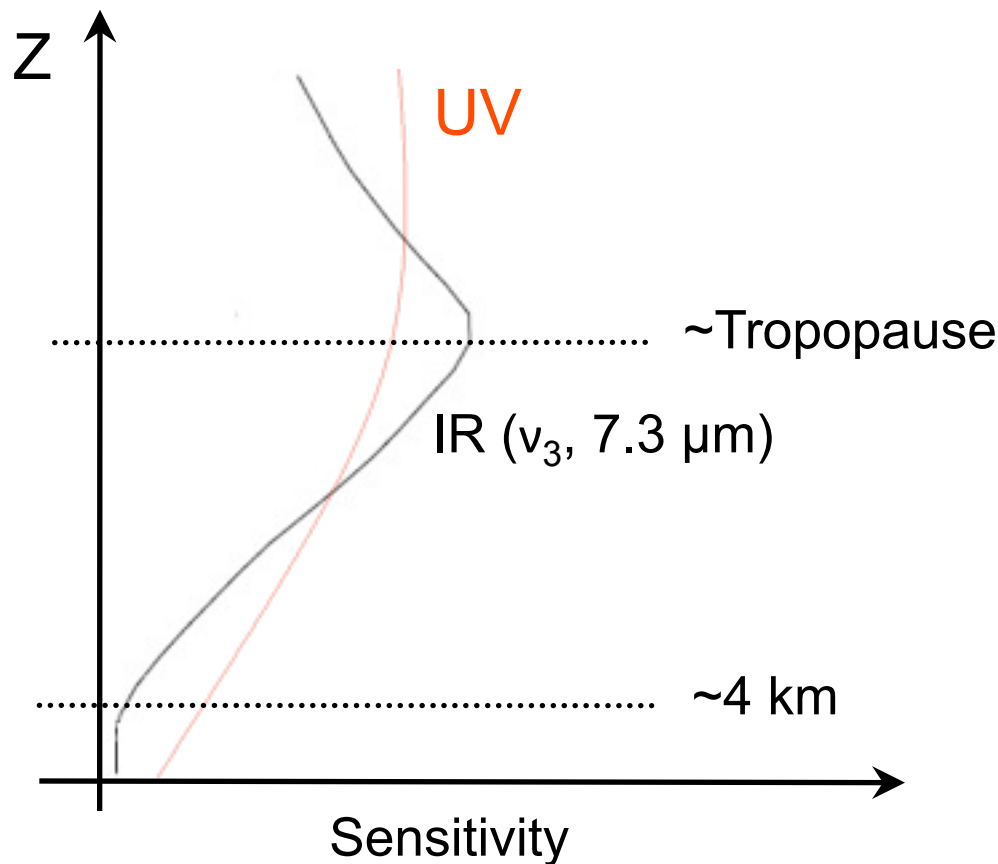
- OMI SO<sub>2</sub> product
- 4 *prescribed* SO<sub>2</sub> profiles:
  - **PBL** (<3 km)
  - **TRL** (0-5 km)
  - **TRM** (5-10 km)
  - **STL** (15-20 km)
  - 2 SO<sub>2</sub> algorithms [Krotkov *et al.*, 2006; Yang *et al.*, 2007]



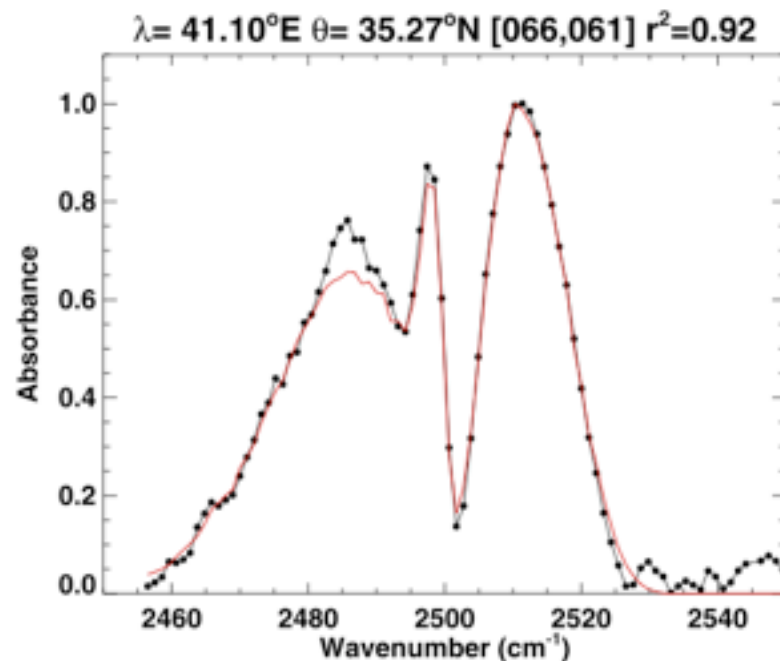
- Knowledge of SO<sub>2</sub> cloud altitude is critical for accurate SO<sub>2</sub> retrieval
- Satellite sensitivity increases with altitude in the troposphere

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

# Relative sensitivity of UV and IR measurements



*Courtesy of L. Clarisse, ULB*

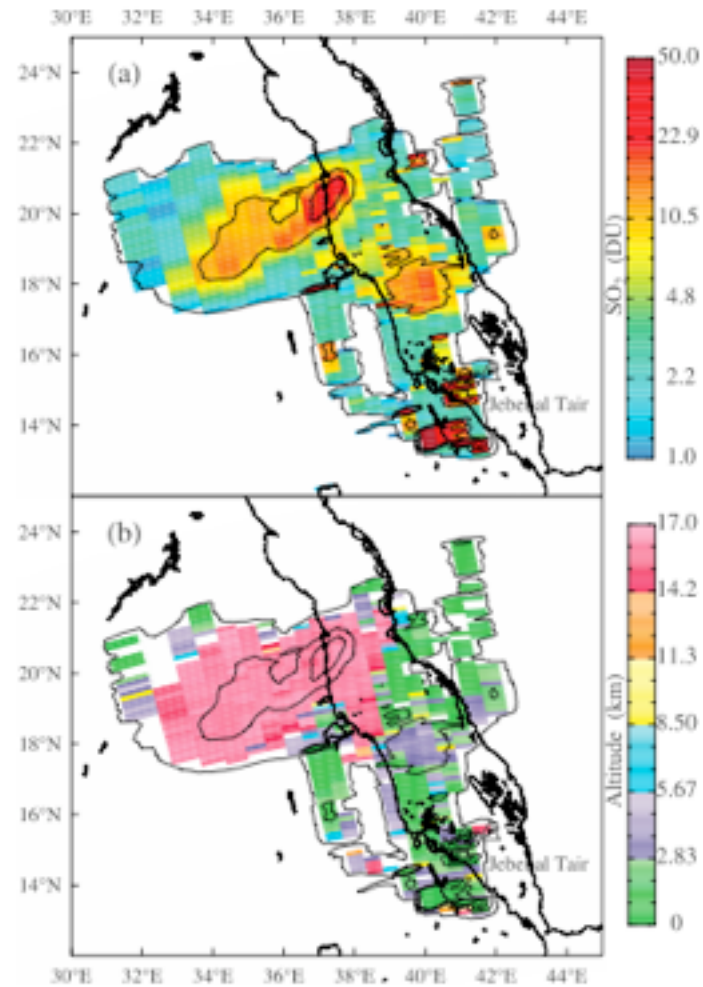
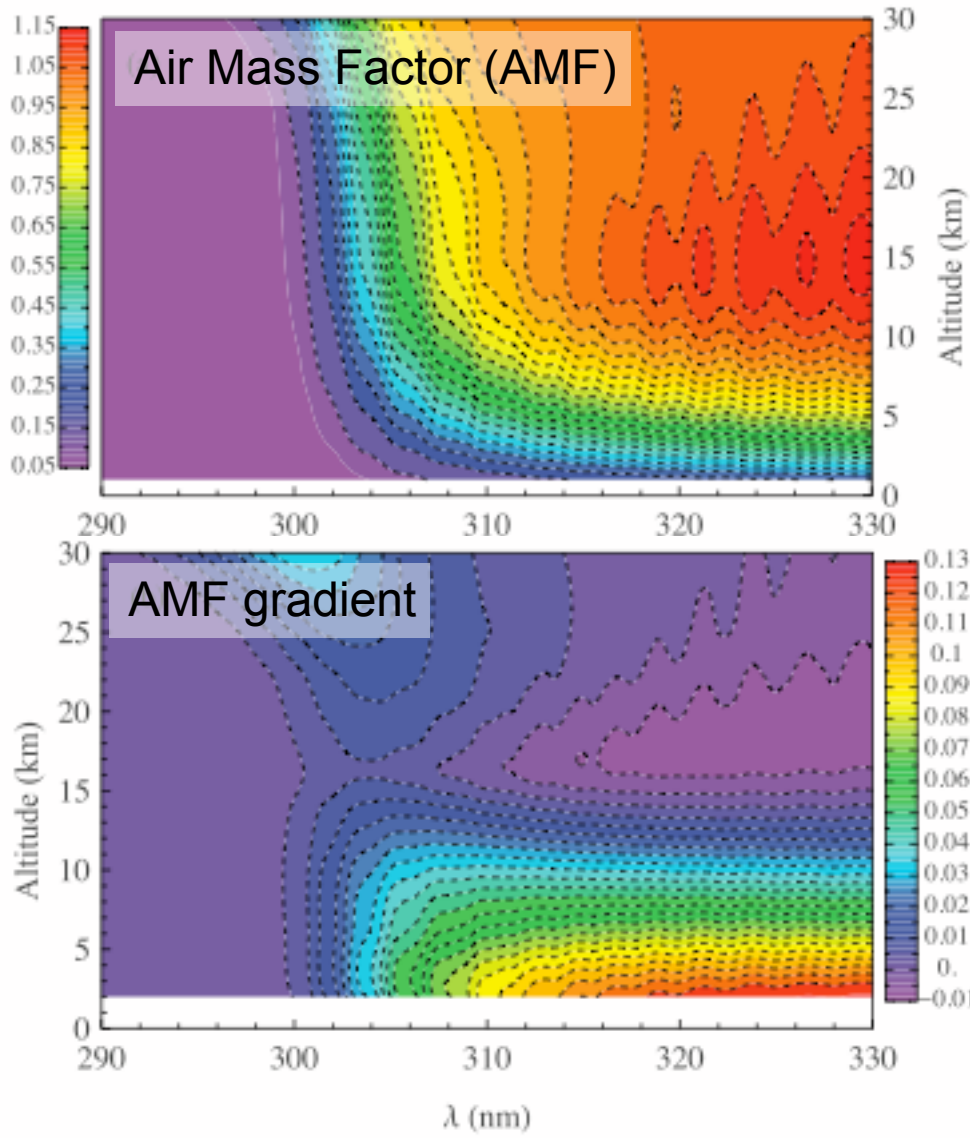


**Figure 15.** Spectral matching plot for the 4  $\mu\text{m}$  band of  $\text{SO}_2$ . The red line shows a synthetic absorbance spectrum and the black line shows AIRS measurements. The data are for an AIRS image of the Al-Mishraq (Iraq)  $\text{SO}_2$  plume on 25 June 2003.

*Prata and Bernardo, 2007*

- IR channels at  $\sim 4 \mu\text{m}$  and  $\sim 8.6 \mu\text{m}$  can detect lower tropospheric  $\text{SO}_2$

# Direct retrieval of SO<sub>2</sub> altitude from UV radiances



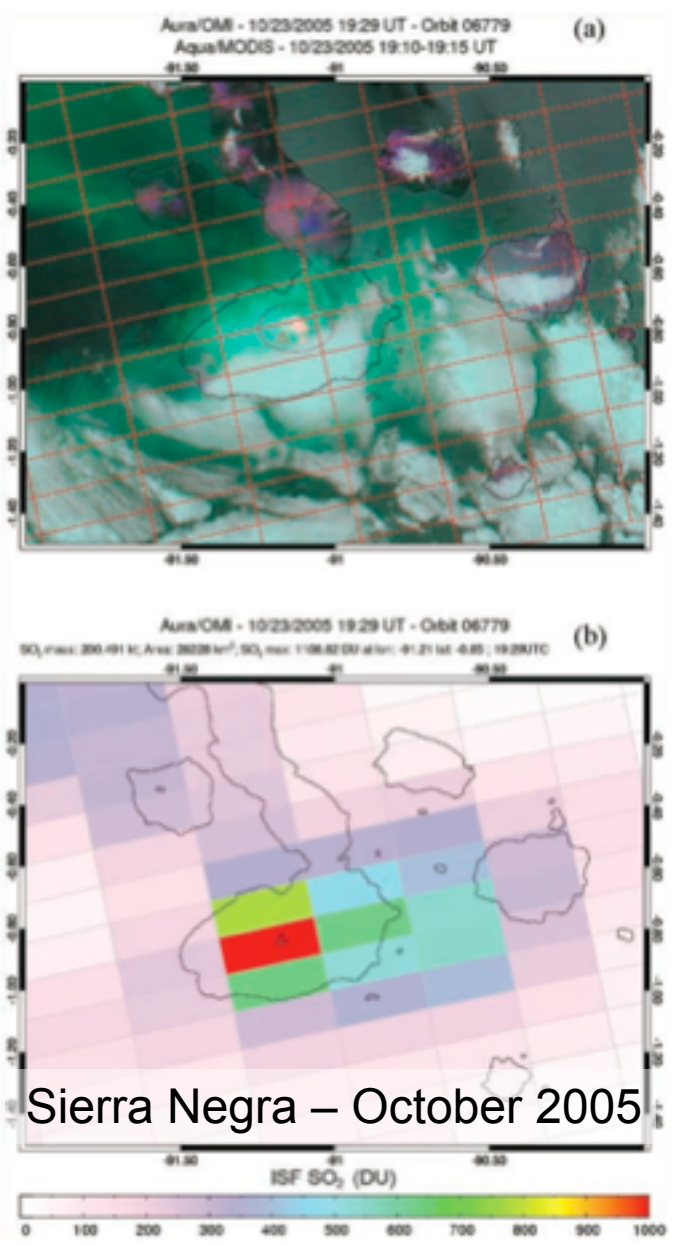
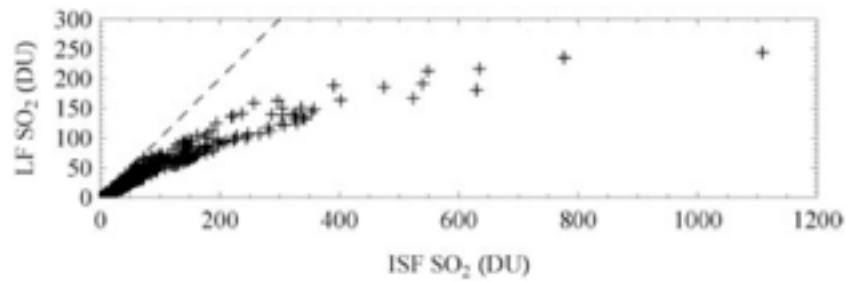
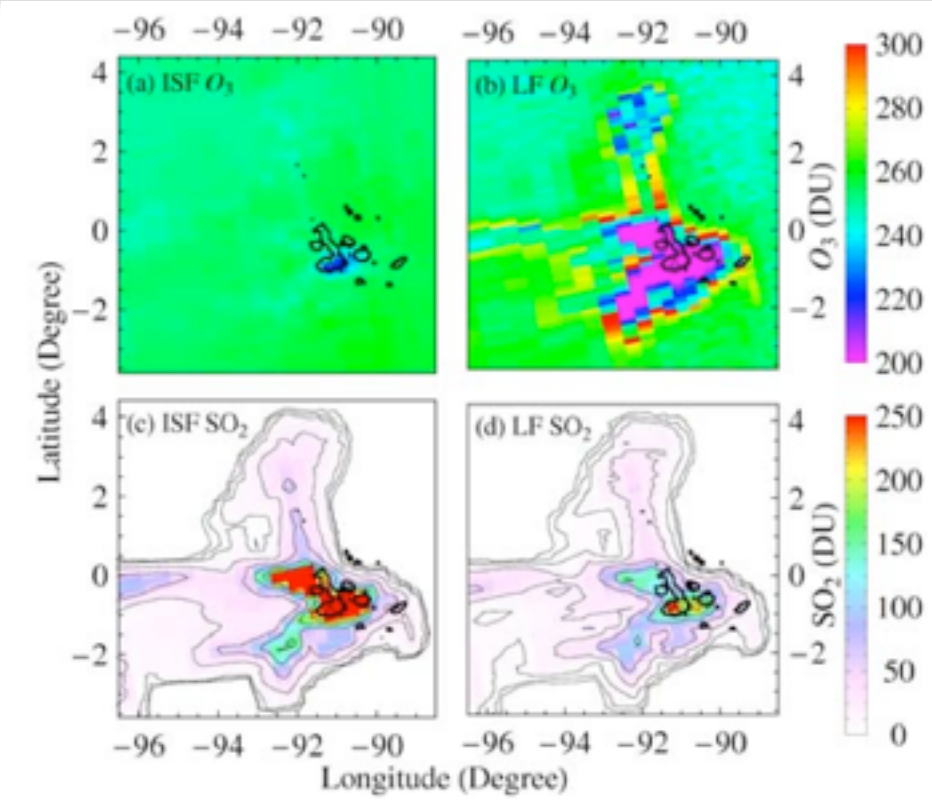
**Figure 3.** (a) SO<sub>2</sub> vertical column and (b) effective altitude maps derived from OMI UV (both UV-1 and UV-2) radiances for the Jebel al Tair volcanic plume at 10:59 UT on October 1, 2007, using the extended ISF algorithm.

• Midlatitude O<sub>3</sub> profile, 325 DU, nadir, clear sky, SZA=45°

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



# Retrieval of large SO<sub>2</sub> columns in volcanic clouds

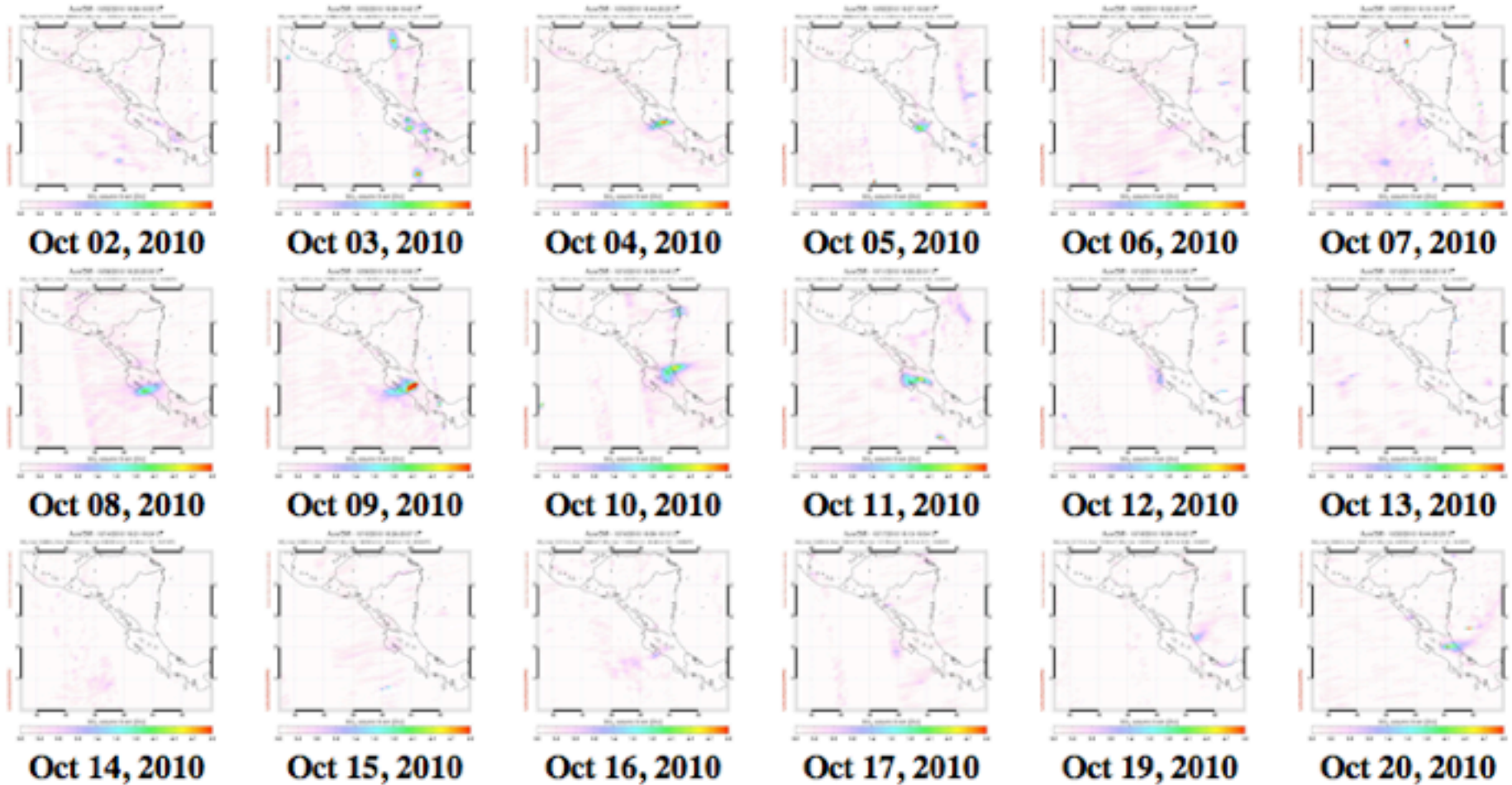


**Figure 3.** Comparison of ISF and LF SO<sub>2</sub> columns in the Sierra Negra eruption cloud on October 23, 2005. The LF retrievals saturate at about 200 DU in this case. [Yang *et al.*, GRL, 2009]

Sierra Negra – October 2005

# Daily OMI SO<sub>2</sub> measurements for Central America

<http://so2.umbc.edu/omi>



- Satellites measure column amounts of gases, NOT emission rates

# Daily OMI SO<sub>2</sub> measurements for Kilauea

<http://so2.umbc.edu/omi>

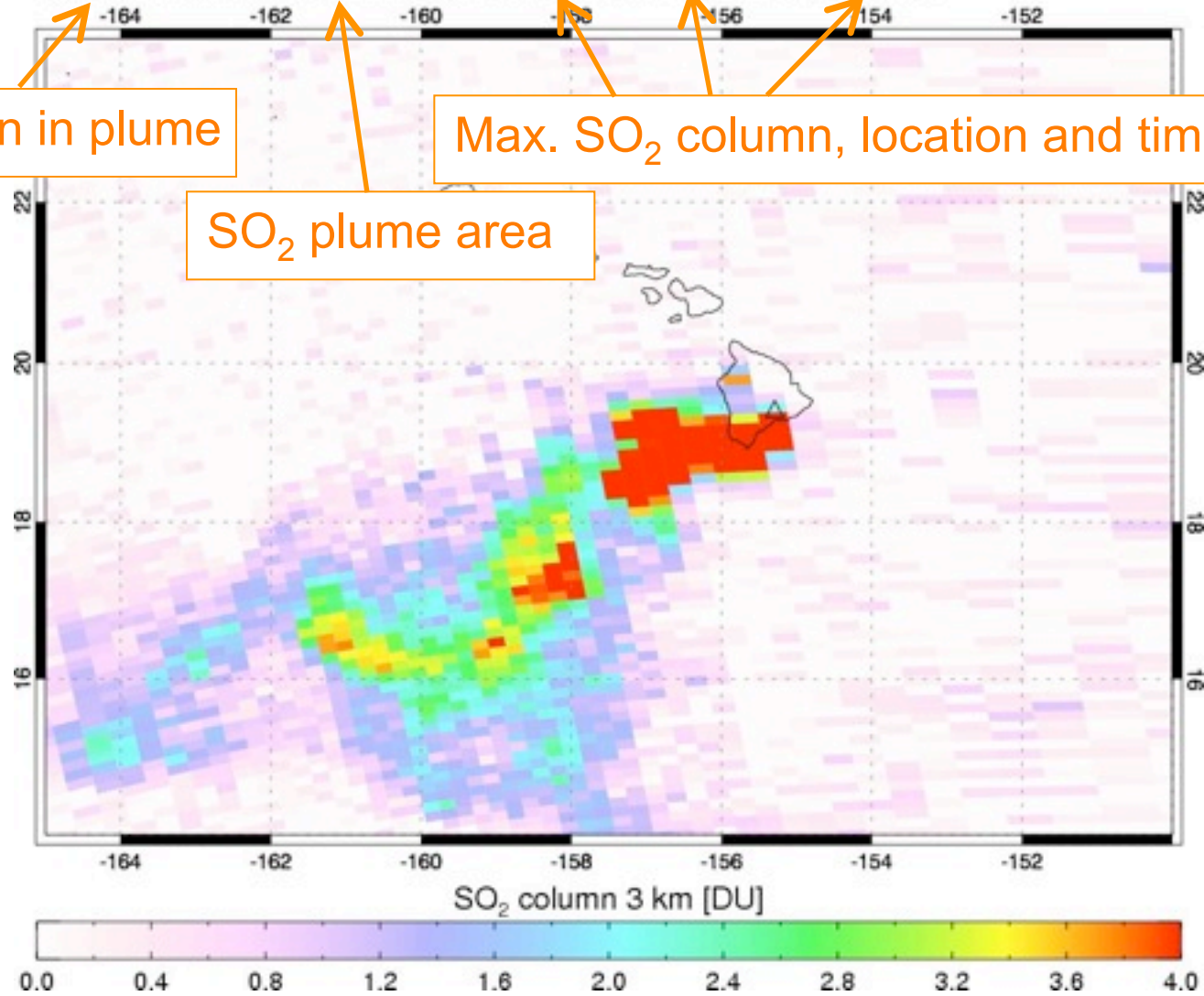
Aura/OMI - 07/13/2008 00:14-00:17 UT - Orbit 21257

SO<sub>2</sub> mass: 19.344 kt; Area: 326084 km<sup>2</sup>; SO<sub>2</sub> max: 31.06 DU at lon: -155.29 lat: 19.21 ; 00:16UTC

SO<sub>2</sub> burden in plume

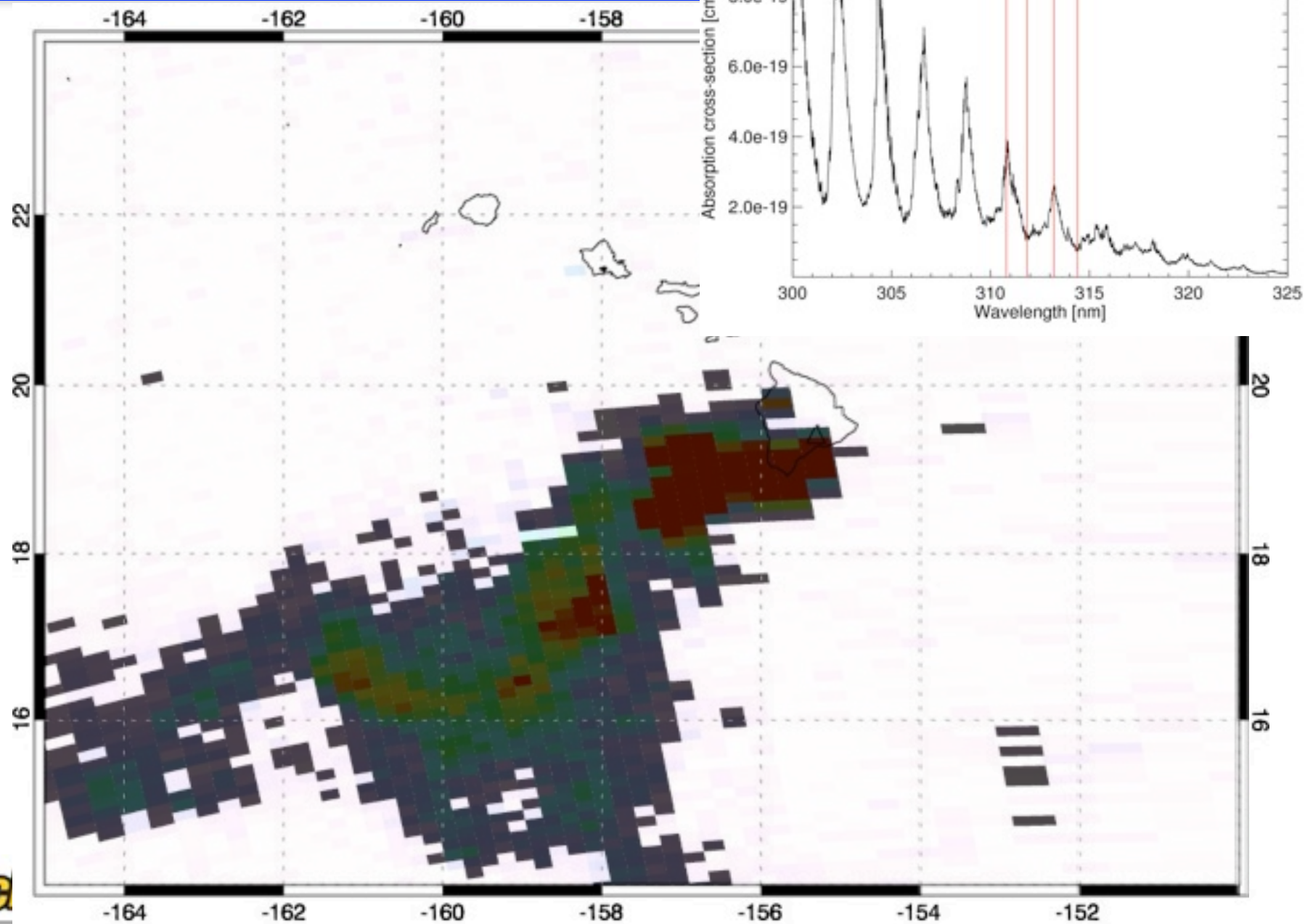
Max. SO<sub>2</sub> column, location and time (UT)

SO<sub>2</sub> plume area



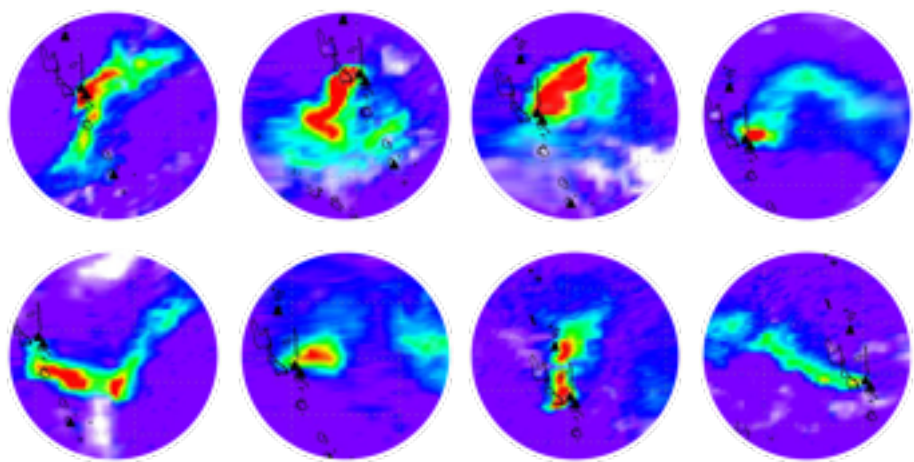


# Hawaii measurement domain





# Construction of SO<sub>2</sub> mass time-series

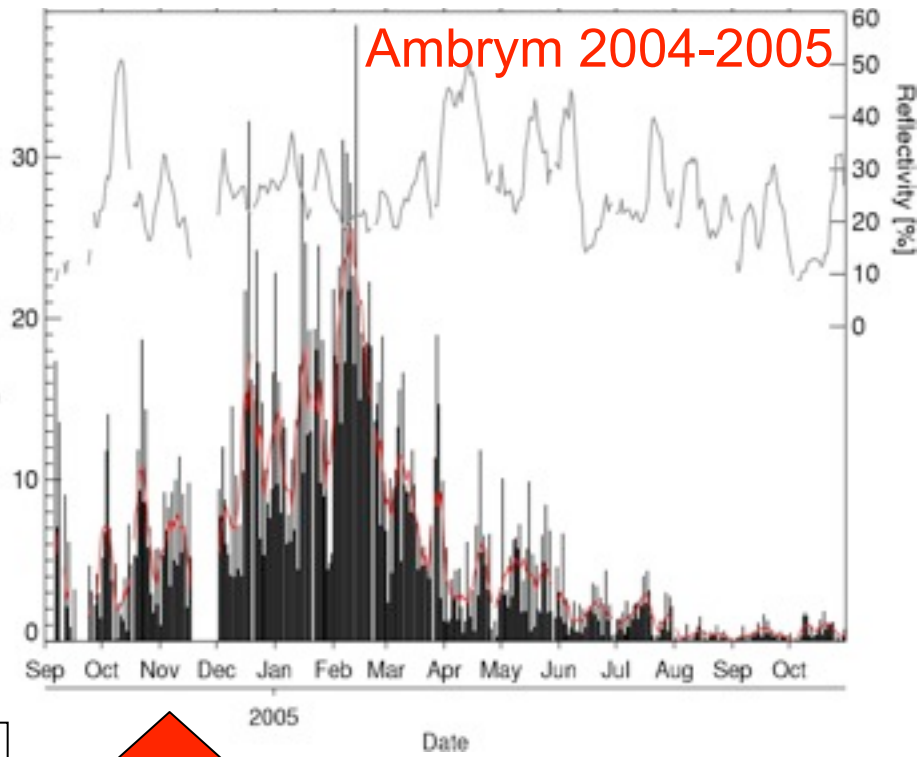


Daily OMI measurements



## Calculate SO<sub>2</sub> burdens

- Threshold (e.g., >0.6 DU = volcanic)
- Background subtraction
- Noise statistics in SO<sub>2</sub>-free region

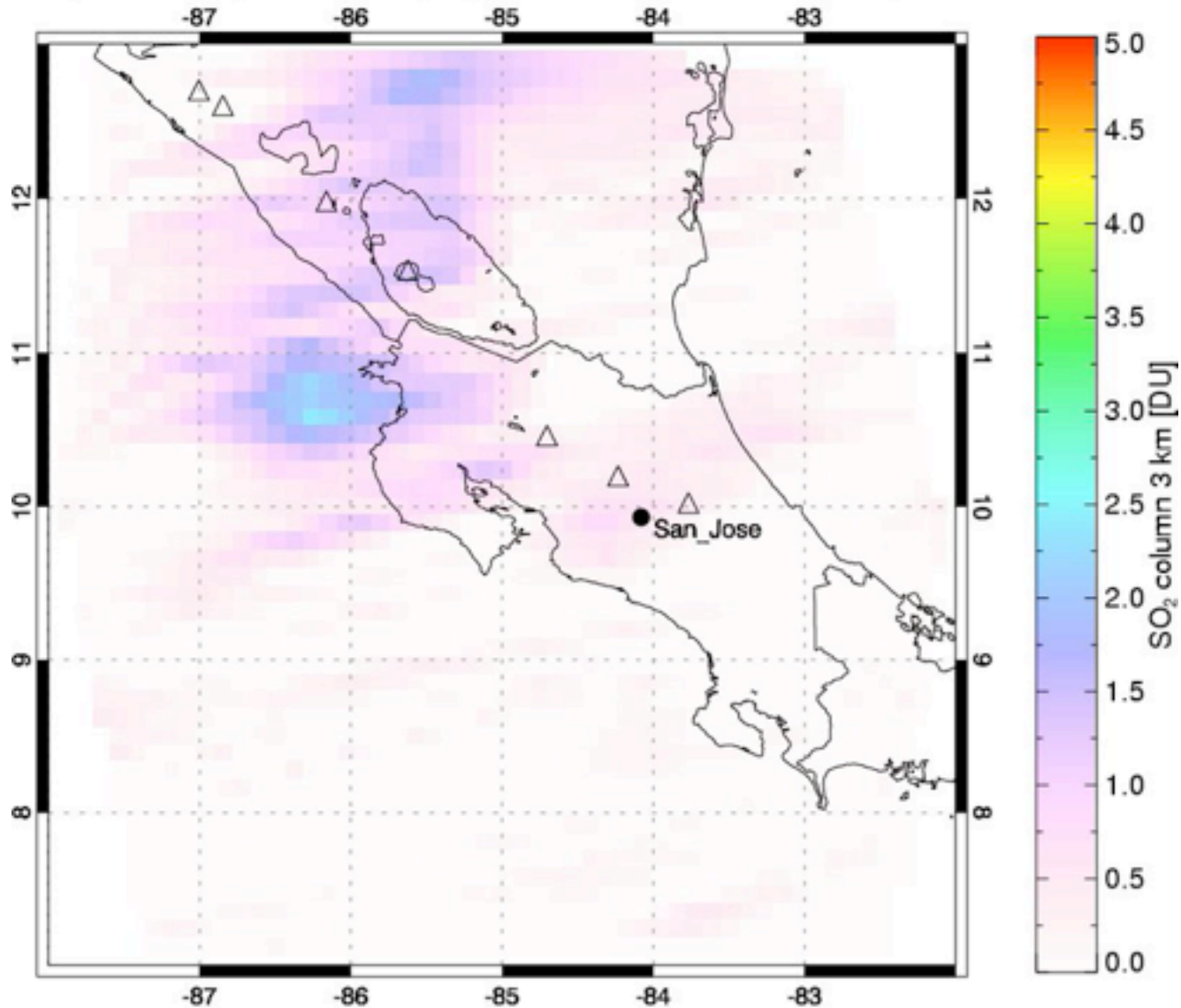


Daily SO<sub>2</sub> burdens (not fluxes)

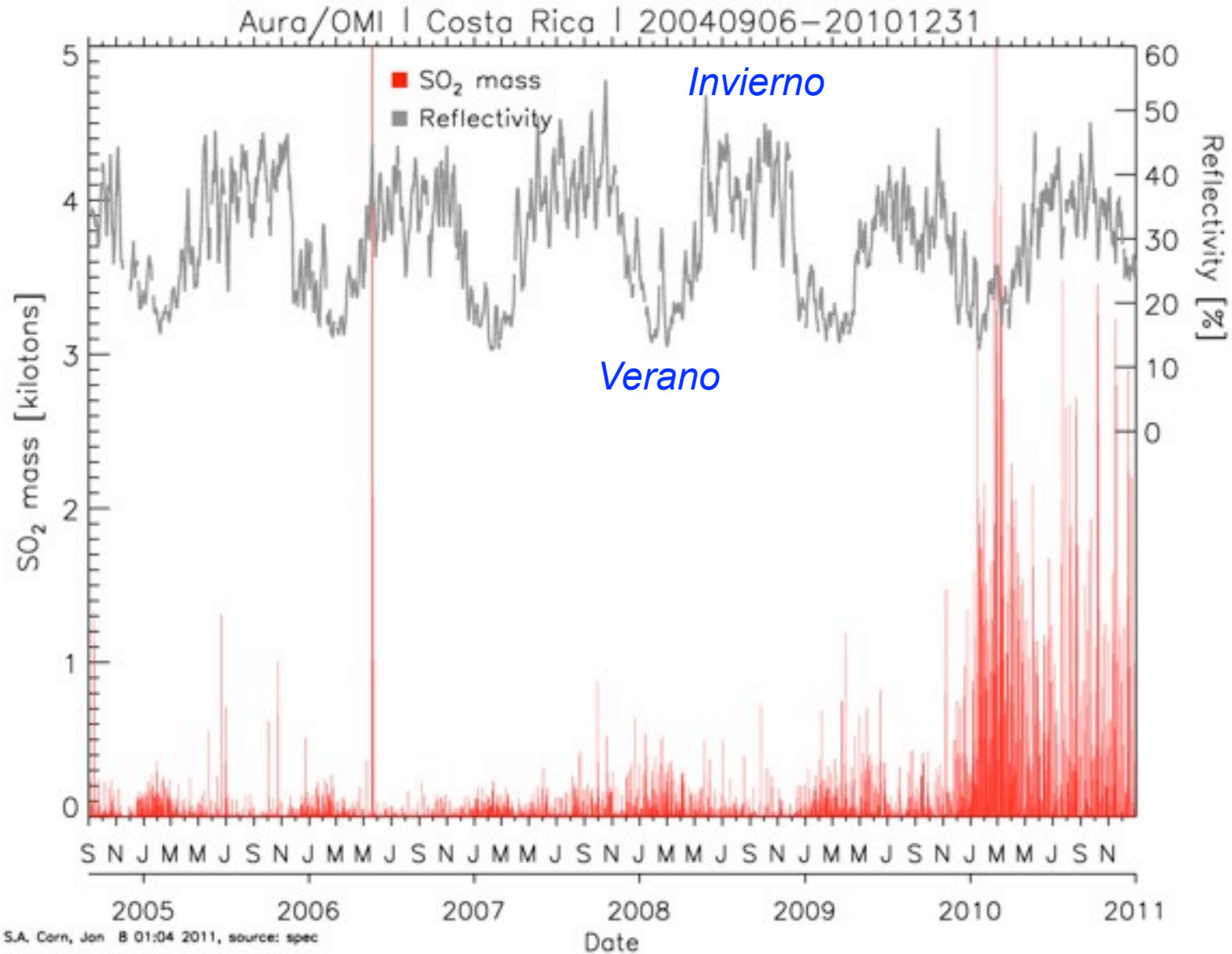
# OMI SO<sub>2</sub> data for Costa Rica

Aura/OMI - 02/01/2010 18:28-20:08 UT

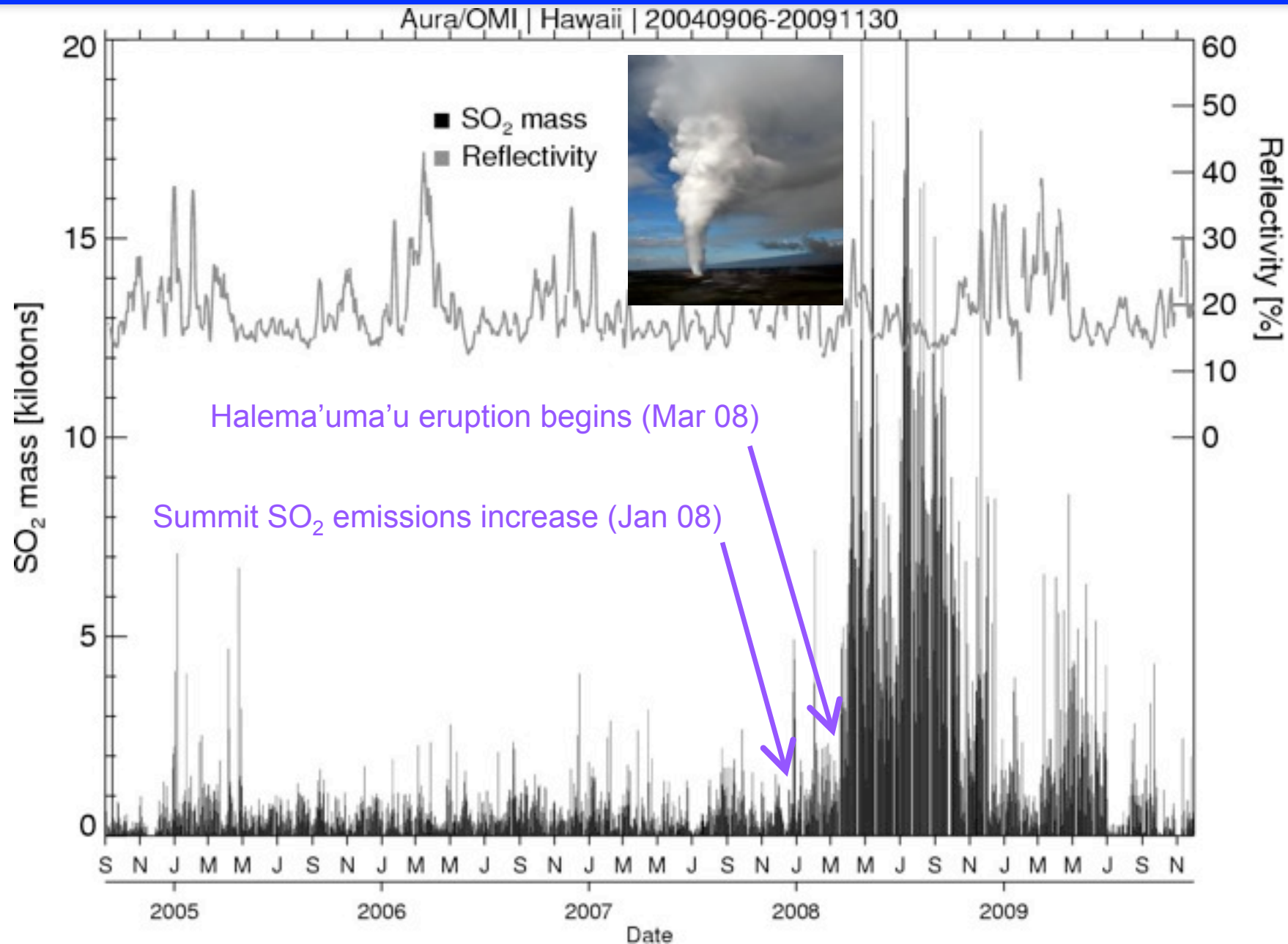
SO<sub>2</sub> mass: 2.16 kt; Area: 91733 km<sup>2</sup>; SO<sub>2</sub> max: 2.43 DU at lon: -86.25 lat: 10.60 ; 20.07UTC



# OMI SO<sub>2</sub> time-series for Costa Rica

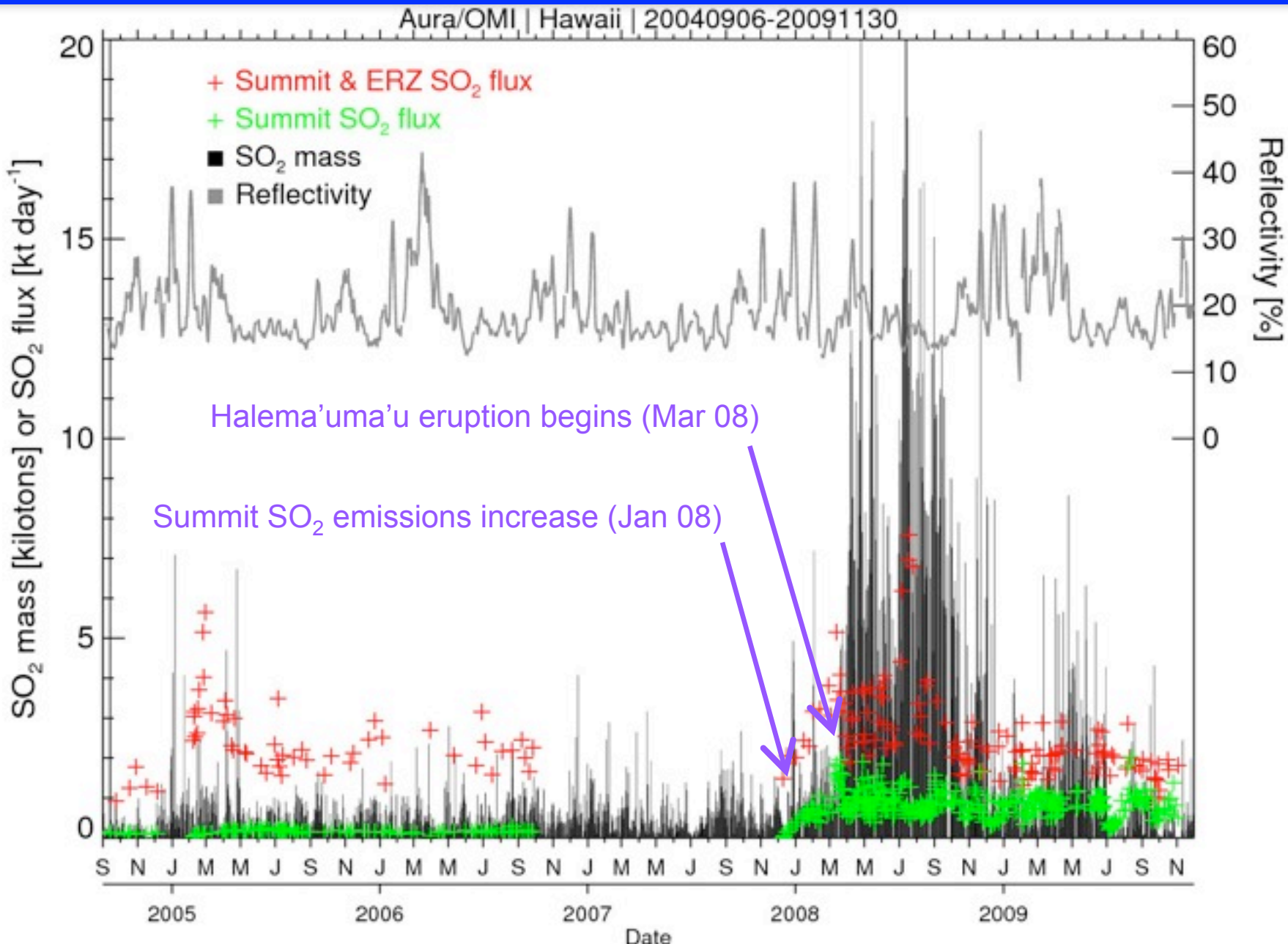


# Kilauea plume SO<sub>2</sub> burdens: 2004-2009

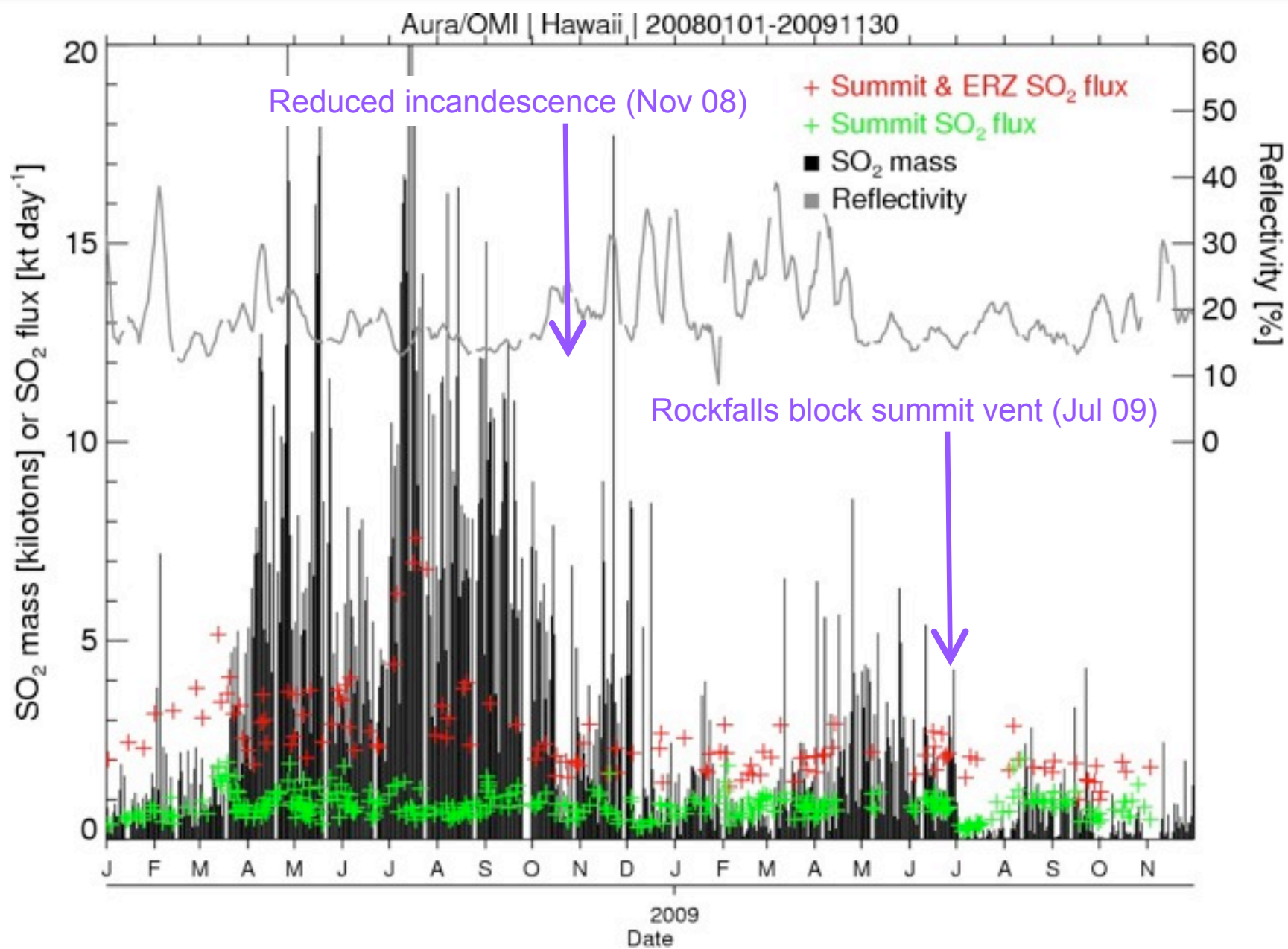




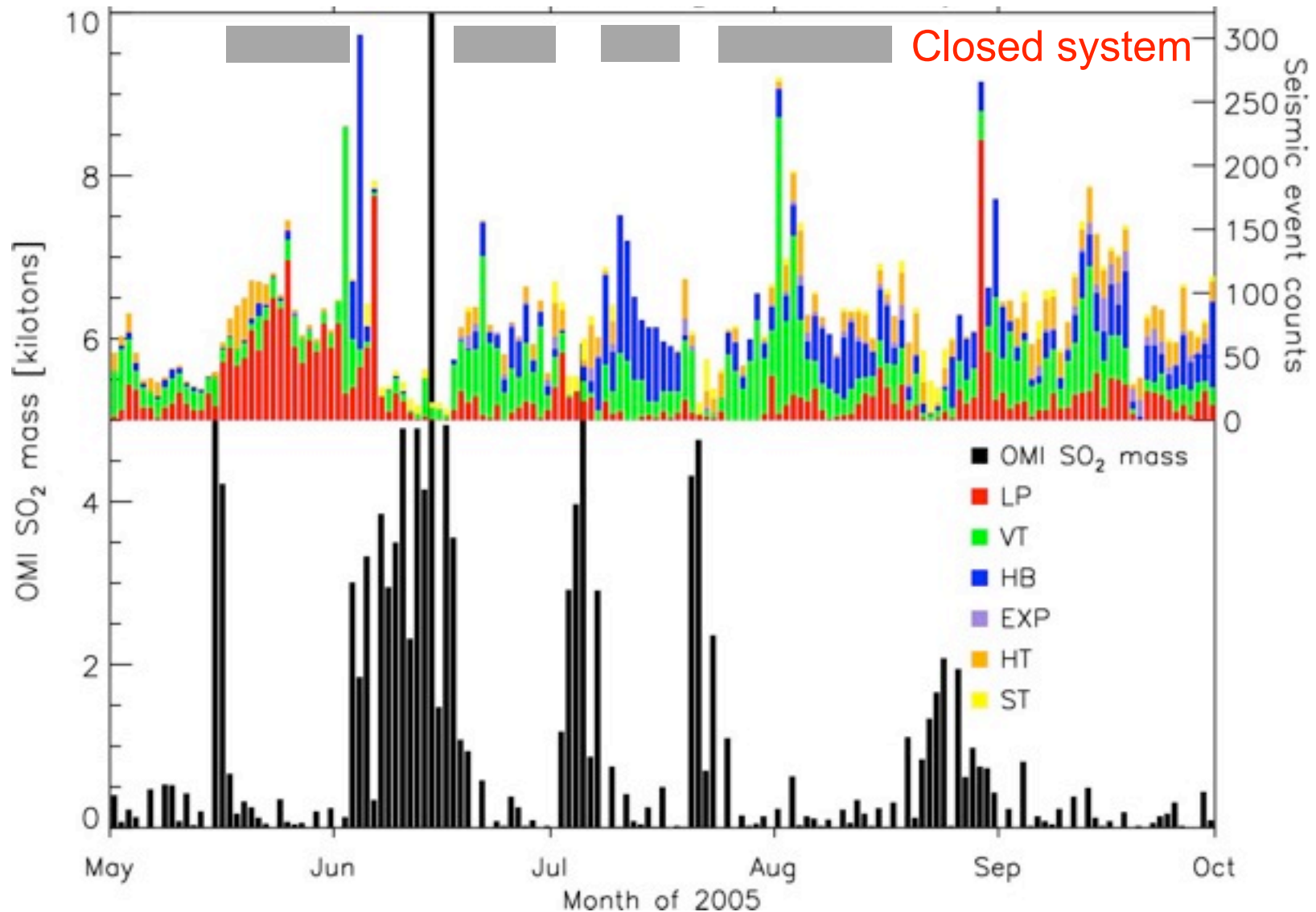
# Kilauea plume SO<sub>2</sub> burdens: 2004-2009



# Kilauea plume SO<sub>2</sub> burdens: 2008-2009



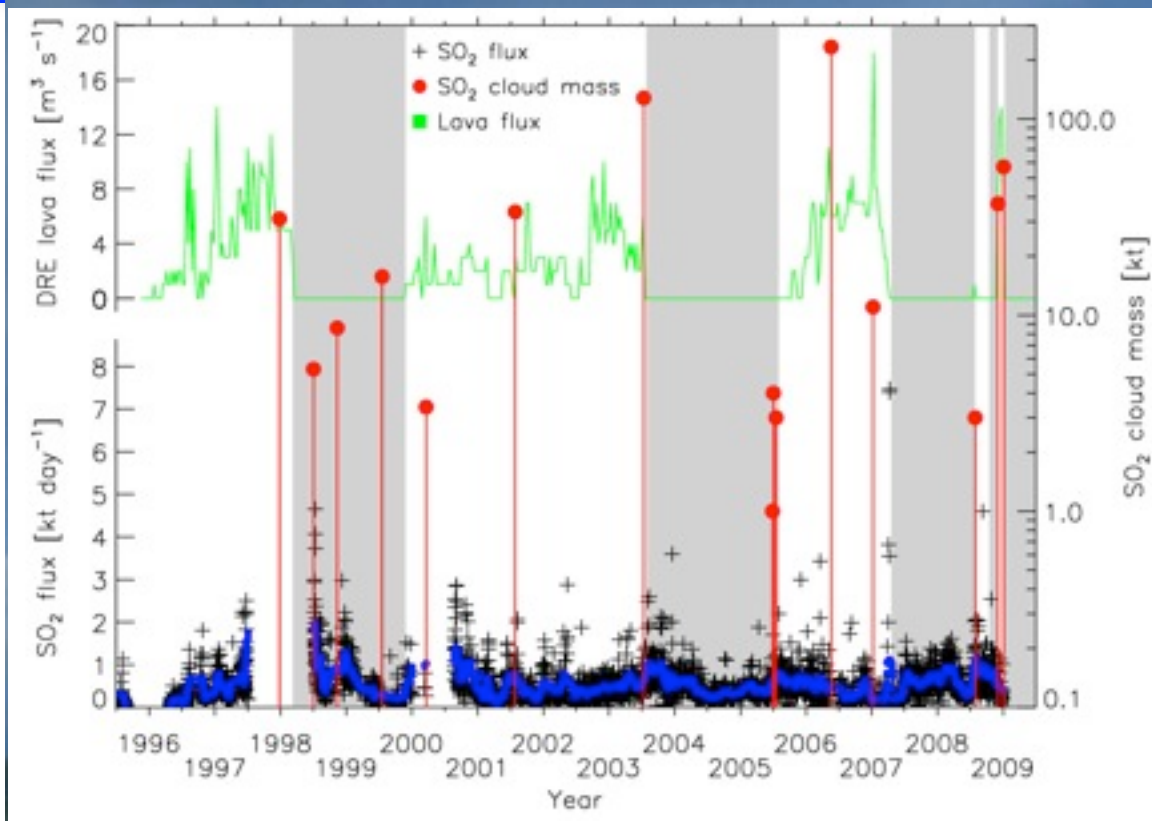
# Reventador (Ecuador) seismicity and OMI SO<sub>2</sub> data





# Soufrière Hills Volcano, Montserrat

[Carn and Prata, GRL, 2010]



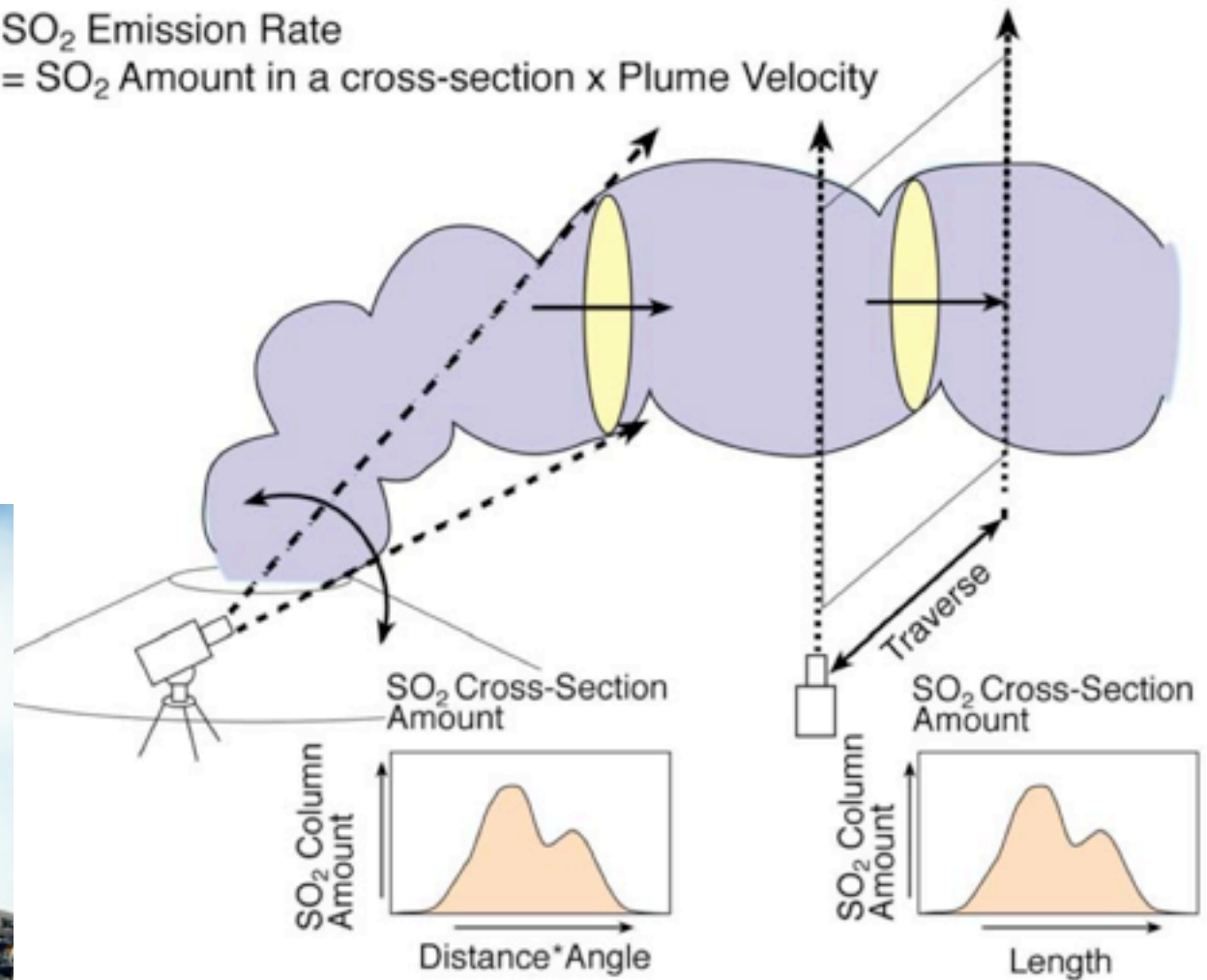
- Combine space-based and ground-based SO<sub>2</sub> measurements to estimate total SO<sub>2</sub> budgets



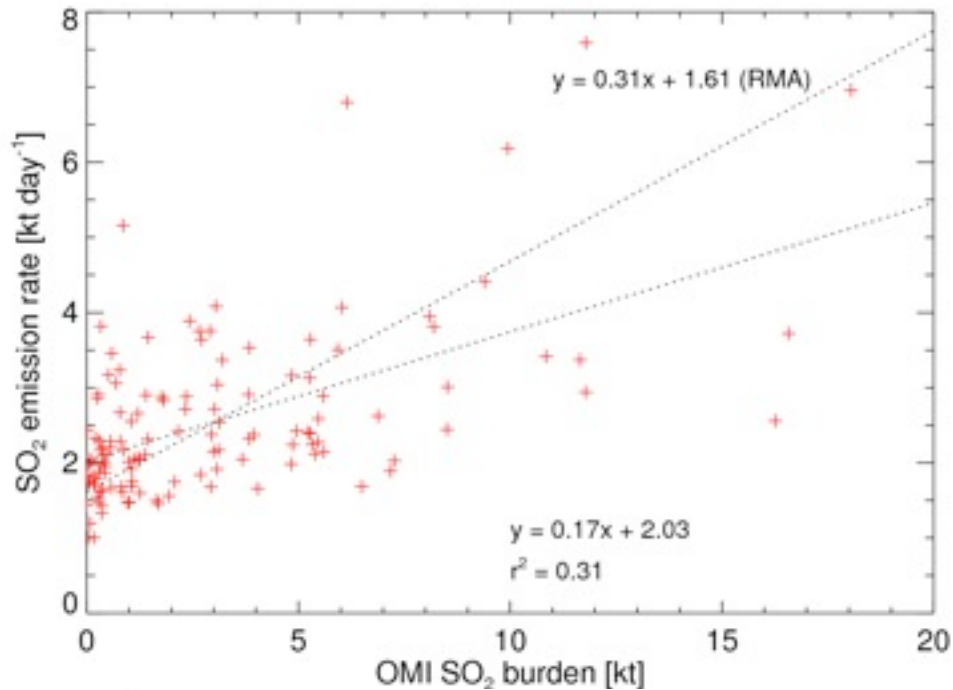
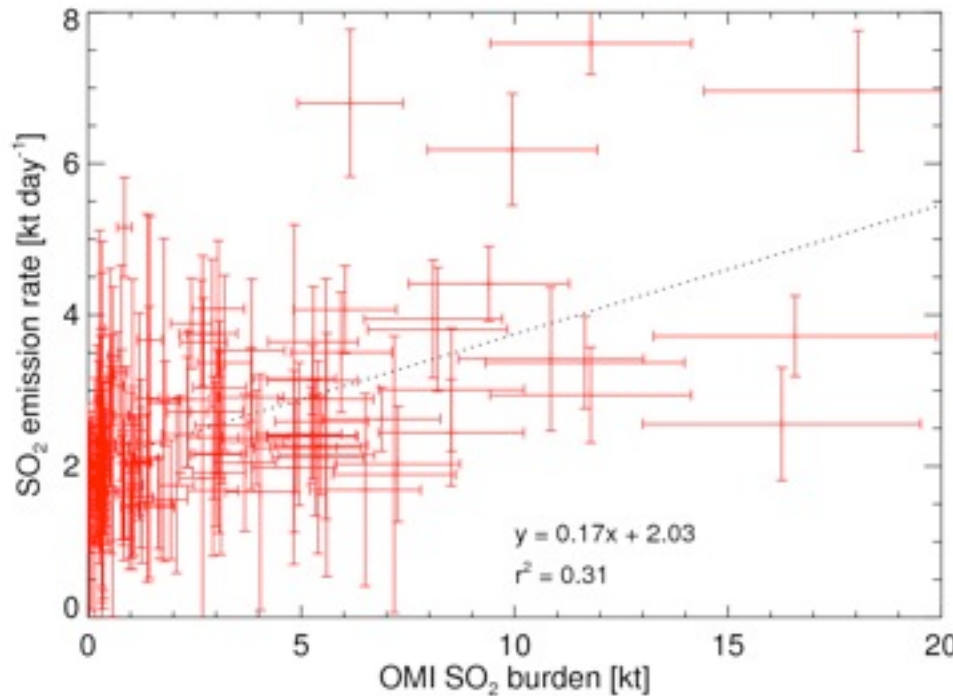
# Volcanic SO<sub>2</sub> flux measurements



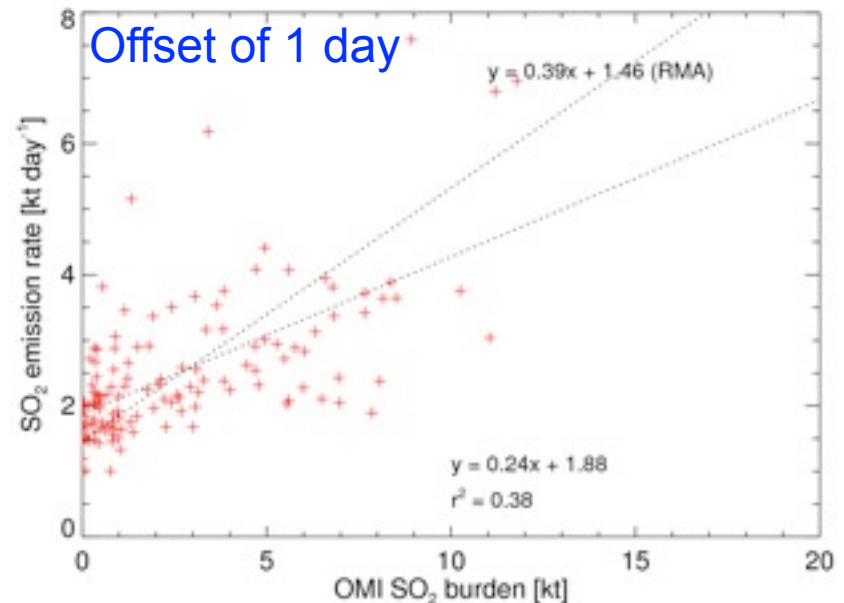
SO<sub>2</sub> Emission Rate  
= SO<sub>2</sub> Amount in a cross-section x Plume Velocity



# Comparing OMI SO<sub>2</sub> burdens with SO<sub>2</sub> emission rates (Kilauea)



- Direct comparison of SO<sub>2</sub> emission rates (summit + ERZ) and OMI SO<sub>2</sub> burdens complicated by variability, meteorology and errors
- Broad positive correlation



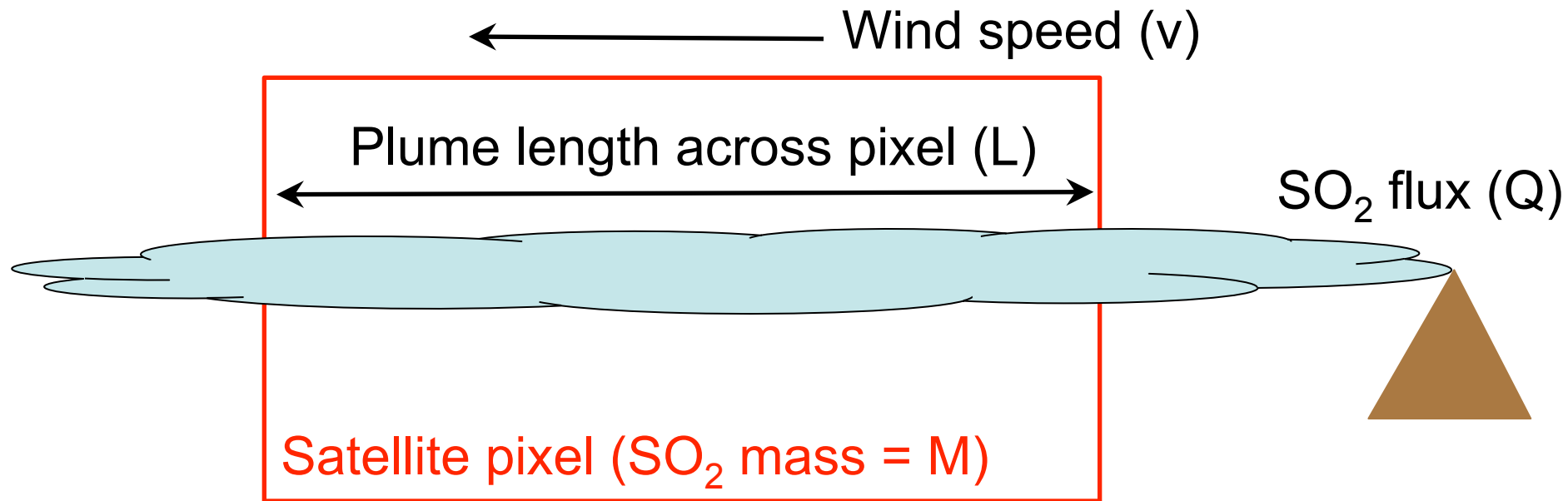
# SO<sub>2</sub> flux estimation from satellite data

- Satellite 'snapshots' measure SO<sub>2</sub> burden, not flux
- To first order, SO<sub>2</sub> emission rates can be inferred using the SO<sub>2</sub> burden and an estimate of the SO<sub>2</sub> lifetime
  - SO<sub>2</sub> lifetime short (hours) at low altitudes and in humid environments
  - May be a few hours in tropical boundary layers

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

- Q = SO<sub>2</sub> emission rate (tons/day), M = SO<sub>2</sub> burden (tons),  $\tau$  = SO<sub>2</sub> lifetime (days)

# SO<sub>2</sub> flux estimation from satellite data

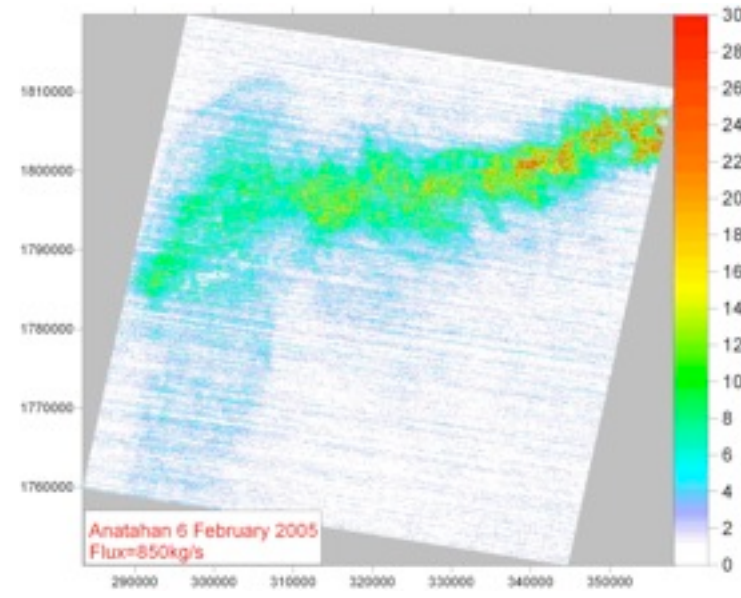
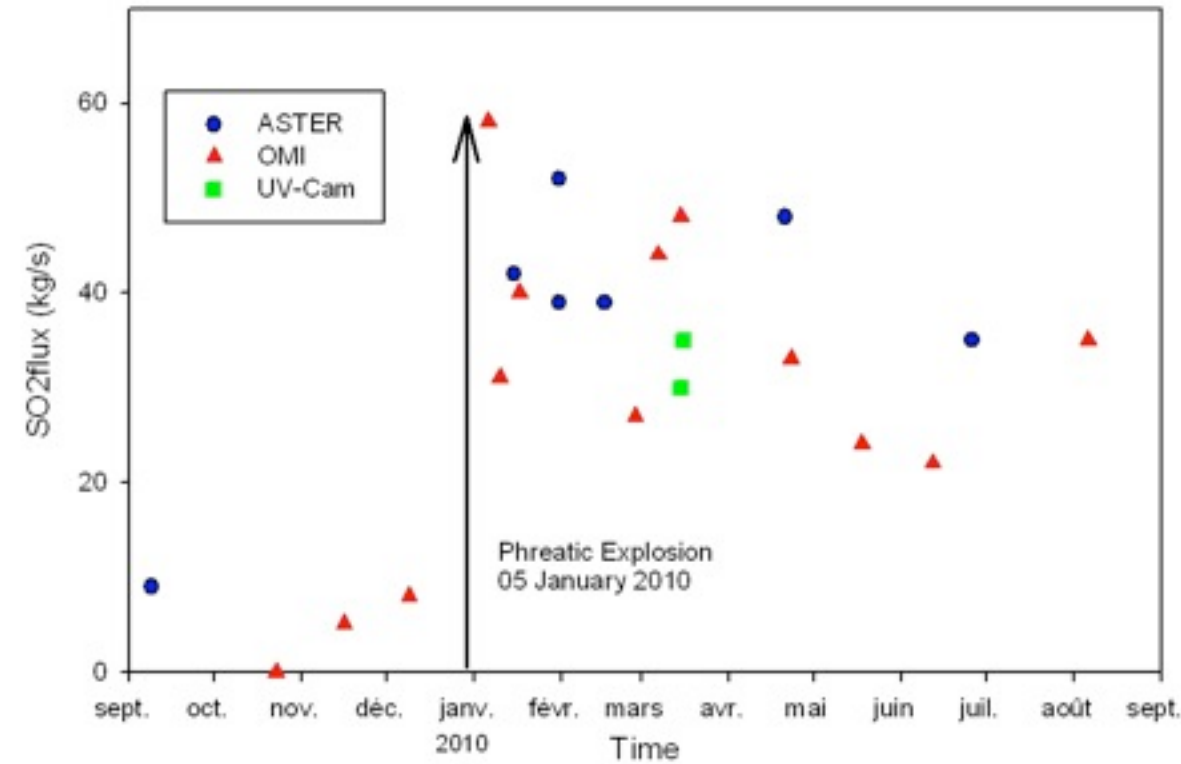


$$Q = \left[ \frac{vM}{L} \right]$$

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



# SO<sub>2</sub> flux estimation from satellite data (Turrialba)



- Comparison between Turrialba SO<sub>2</sub> emission rates derived from ASTER, OMI and UV camera [Campion et al., in prep.]

# OMI sensitivity – passive degassing

Instrument	Minimum detectable SO <sub>2</sub> flux (tons/day)		
	Plume velocity 1 m/s	Plume velocity 5 m/s	Plume velocity 10 m/s
<b>Earth Probe TOMS</b> (1 $\sigma$ = 3.5 DU)	1030	5140	10290
<b>OMI</b> (plume traverses 13 km pixel width)	36	180	360
<b>OMI</b> (plume traverses 24 km pixel length)	19	95	190
COSPEC	10	52	104
Typical volcano	100 - 5000		

Detection limit (3 $\sigma$  above background) of passive SO<sub>2</sub> flux from a 5000m volcano at various plume velocities; 1 $\sigma$  = 0.2 DU assumed for OMI

# OMI SO<sub>2</sub> websites

The screenshot shows a web browser window with the URL <http://so2.umbc.edu/omi/>. The page features the OMI Sulfur Dioxide Group logo and a navigation menu on the left. The main content is a grid of 31 satellite images of SO<sub>2</sub> concentrations over Northern Sulawesi and Halmahera, Indonesia, dated from October 1st to 31st, 2007. Each image includes a color scale at the bottom. A sidebar on the left contains links to various resources such as 'The VDG Blog', 'SO<sub>2</sub> Group Home', 'OMI SO<sub>2</sub>', 'SO<sub>2</sub> Info', 'News', 'Special cases OMI images', 'Daily OMI images', 'OMI Data', 'Documentation', 'Algorithms', 'Publications', 'Personnel', and 'Links'. At the bottom left, there is a 'Webmasters' section listing Dr. Simon Carn, Keith Evans, and Dr. Arin Krueger, along with the date 'Last Modified: August 6, 2008'.

[http://so2.umbc.edu/omi\\_home\\_new2.html/](http://so2.umbc.edu/omi_home_new2.html/)

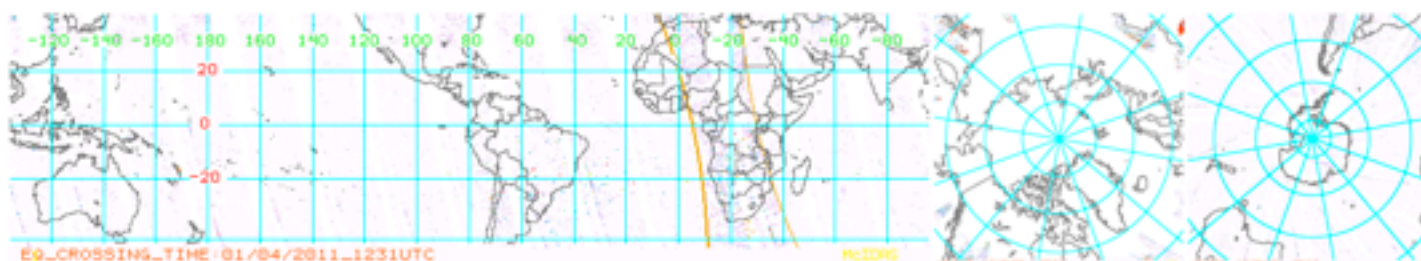
# OMI SO<sub>2</sub> websites - NRT



[>>GOME SO2 Data](#)

## Latest OMI SO<sub>2</sub> Column 5Km - 24-Hour Composite Images

[Important Information for OMI Data Users](#)



Current OMI SO <sub>2</sub> Composites	<a href="#">Tropica</a>	<a href="#">Northern Hemisphere</a>	<a href="#">Southern Hemisphere</a>
Current & Previous Digital Images GeoTIFF, NetCDF, McIDAS, GIF	<a href="#">Tropica</a>	<a href="#">Northern Hemisphere</a>	<a href="#">Southern Hemisphere</a>

## Latest OMI\_SO<sub>2</sub> Column 5Km by Volcano

<a href="#">Alaska, USA</a>	<a href="#">Aleutian Islands, Alaska, USA</a>	<a href="#">Anatahan, Mariana Islands</a>	<a href="#">Cascade</a>
<a href="#">Central America</a>	<a href="#">Comoro Islands</a>	<a href="#">Eastern China</a>	<a href="#">Ecuador</a>
<a href="#">Etna, Sicily, Italy</a>	<a href="#">Galapagos Islands, Ecuador</a>	<a href="#">Hawaii, USA</a>	<a href="#">Iceland</a>
<a href="#">Japan</a>	<a href="#">Java, Indonesia</a>	<a href="#">Kamchatka, Russia</a>	<a href="#">Mexico</a>
<a href="#">Montserrat, West Indies</a>	<a href="#">New Zealand</a>	<a href="#">North Western Europe</a>	<a href="#">Northern Atlantic</a>
<a href="#">Northern Chile</a>	<a href="#">Nyirasongo, DR Congo</a>	<a href="#">Peru</a>	<a href="#">Philippines</a>
<a href="#">Papua New Guinea</a>	<a href="#">Red Sea</a>	<a href="#">Reunion Island</a>	<a href="#">Southern Chile</a>
<a href="#">Sulawesi Sangeha, Indonesia</a>	<a href="#">Sumatra, Indonesia</a>	<a href="#">Tanzania</a>	<a href="#">Vanuatu, South Pacific</a>

**DISCLAIM:** This page is experimental and for testing purpose only

For AIRS SO<sub>2</sub> products check the [AIRS SO<sub>2</sub> Alert Site](#)

Near real-time: <http://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/index.html>



# Operational OMI SO<sub>2</sub> data from NASA Mirador

**NASA** National Aeronautics and Space Administration  
Goddard Earth Sciences Data and Information Services Center

**AURA**

You are here: [GES DISC Home](#) → [Aura](#) → [Data Holdings](#) → [Aura OMI Data products](#) → [Aura OMI Sulphur Dioxide Data Product-OMSO2](#)

### Aura OMI Sulphur Dioxide Data Product-OMSO2

**NEWS:** Please read the important information related to OMI Anomaly (see current OMI Anomaly Exclusion Rules for OMSO2 Product)

**Data Access**

[Mirador - fast search & download](#)

SO2 Plume from Nyamunaga Volcano  
(OMI SO2 Amount: avg Nov 28- Dec 4, 2006)

**Platform:** EOS-Aura  
**Instrument:** OMI

**Product:** Level-2 OMI Sulphur Dioxide (SO2) Data Product

**Data Set Short Name:** OMSO2

**Data Set Long Name:** OMI/Aura Sulphur Dioxide Total Column 1-orbit L2 Swath 13x24 km

**OMI Data Documents**

- Short Data Guide from GES DISC
- [ReadMe, Data Quality Information and Known Issues \(from Algorithm Lead\)](#)
- [File Format Specification](#)
- Data Read Software & Tools
- Giovanni: Data Exploration Interface
- OMI Data User's Guide

**OMI Algorithm Documents**

- OMI Algorithm Theoretical Basis Documents

**Other Related Documents:**

- OMSO2 Document for Global Change Master Directory
- HDF-EOS Aura File Format Guidelines

**Other Links:**

- EOS-Aura OMI Page
- OMI Home Page (KNAW-Netherlands)
- OMI/TOMS Home Page (GSFC-NASA)

**Additional Features**

- Documentation
- Tools
- Links
- FAQ
- News

**Data Version and Data Holdings**

Processing	Version	Begin Date	End Date
Forward	003	001, 2004	Current

Production Frequency: 14 files/day  
Granule (File) Coverage: one orbit  
File Size (Approx): 21 MB

[http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2\\_v003.shtml](http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml)

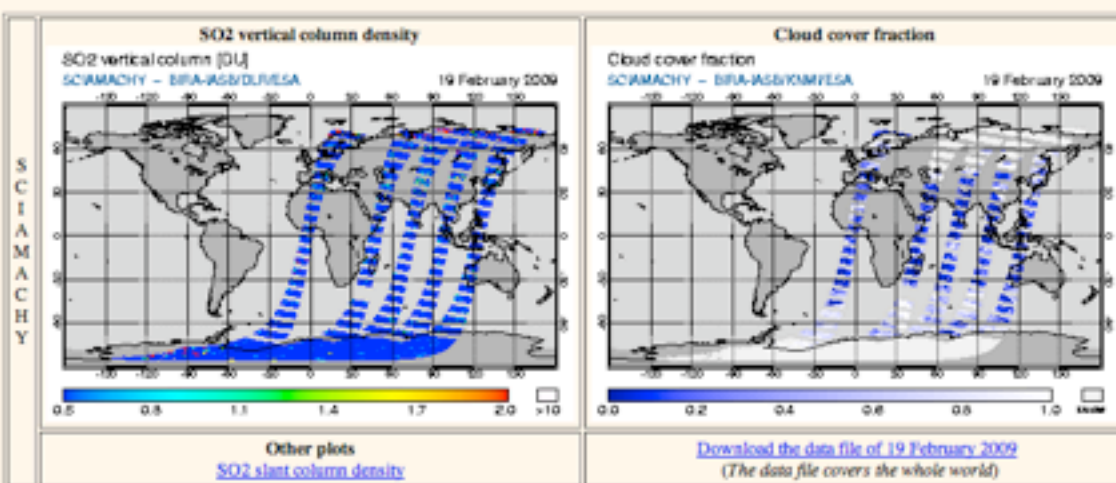
# Near real-time OMI SO<sub>2</sub> data from NASA LANCE

The screenshot shows the NASA LANCE website interface. The main navigation bar includes 'Home', 'Data Producers', 'NRT Data Products', 'Help', and 'News'. Below this, there are sub-navigators for 'AMSR-E SIPS', 'GES DISC', 'MODAPS', and 'OMI SIPS'. The left sidebar contains sections for 'About', 'Products', 'Image Browser', 'Support', and 'News'. The main content area is titled 'OMI SIPS Products' and includes a 'Quick Links' box with buttons for 'MODAPS Products >>', 'GES DISC Products >>', and 'AMSR-E Products >>'. Below the text is a table of OMI SIPS Products.

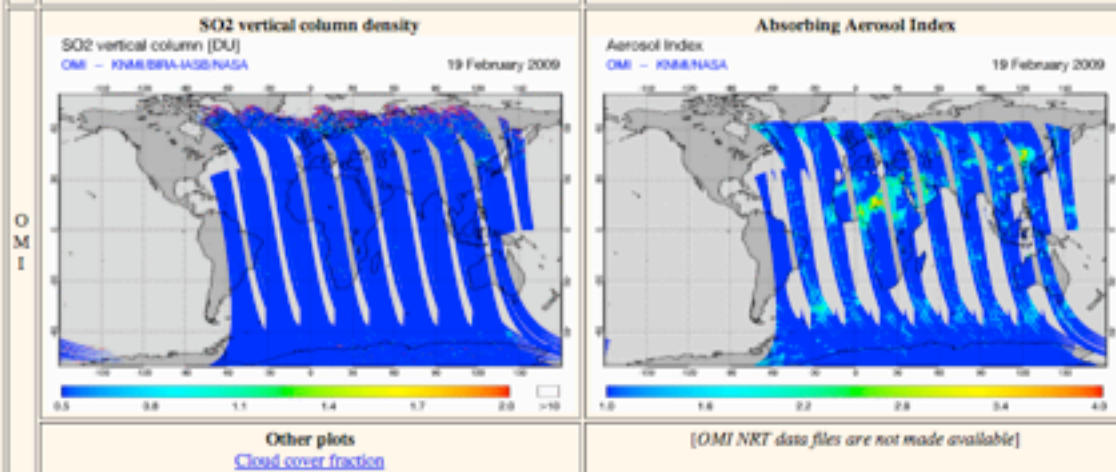
Product	PCE	Volume (GB/day)	FTP	Browse	Known Issues
Orbital	OMCLDRR	N/A	<a href="#">OMCLDRR</a>	N/A	N/A
Daily	OMT03e	N/A	<a href="#">OMT03e</a>	<a href="#">Browse</a>	N/A
Orbital	OMT03	N/A	<a href="#">OMT03</a>	<a href="#">Browse</a>	N/A
Orbital	OMAERUV	N/A	<a href="#">OMAERUV</a>	N/A	N/A
Orbital	OMS02NRTb	N/A	<a href="#">OMS02NRTb</a>	N/A	N/A

<http://lance.nasa.gov/data-producers/omi-sips/omi-sips-products/>  
(Registration required)

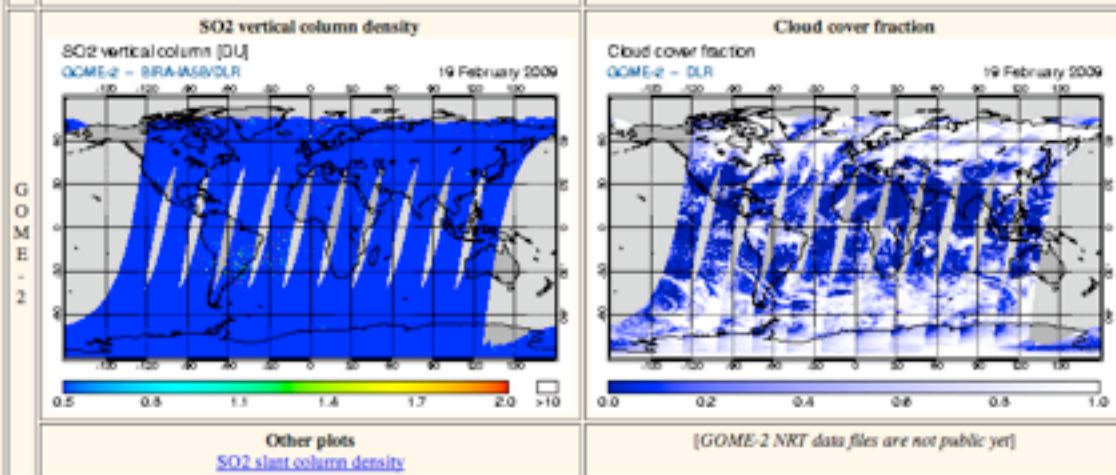
## SCIAMACHY



## OMI



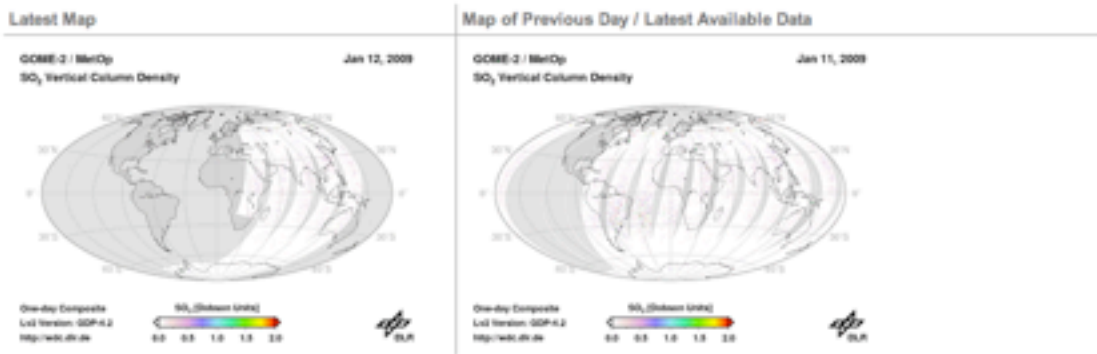
## GOME-2



## GOME-2 Near-Real-Time Service


GOME-2 level 3 products on SO<sub>2</sub> are generated at DLR in near-real-time in the framework of the projects ESA/PROMOTE, EUMETSAT/AGORA and BMBF/EXUPERY.

GOME-2 NRT Products (level 3)



Archive: Images (GIF, PS)

SO<sub>2</sub> Navigation Tool

Select Region from List	Select Region from Map
<ul style="list-style-type: none"><li>Hawaii</li><li>Iceland</li><li>Indonesia East</li><li>Indonesia West</li><li>Italy / Greece</li><li>Japan</li><li>Kamchatka</li><li>Southern Indian Ocean</li><li>Western Indian Ocean</li><li>Marion Islands</li><li>Mexico</li><li>New Zealand</li></ul>	 <p>Map Satellite Hybrid Terrain</p> <p>Select</p>
From	To optional
Year : 2009 February 19	Year : 2009 February 19 SO <sub>2</sub> > DU
<p>Search Archive Clear Form</p>	

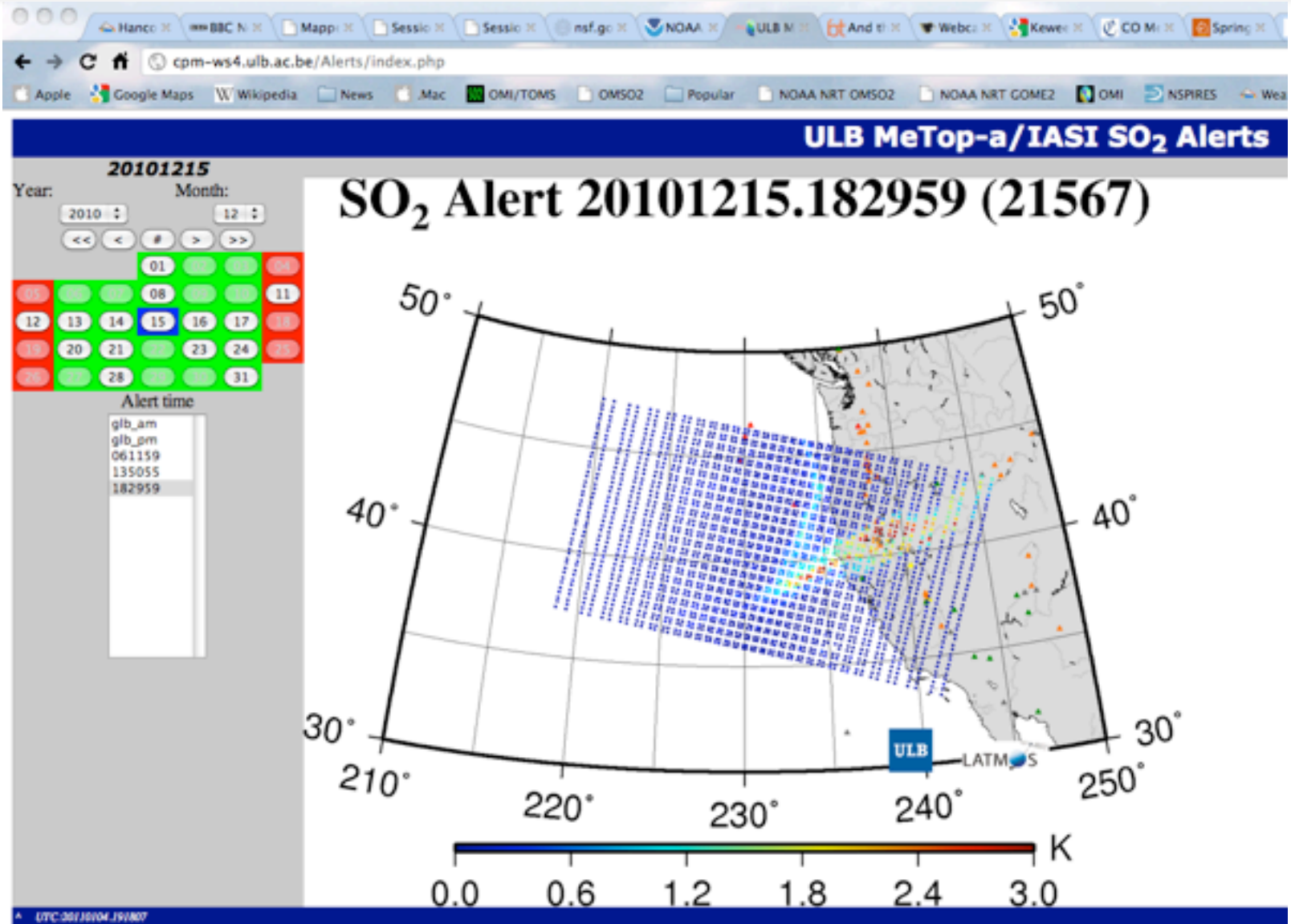


# AIRS NRT SO<sub>2</sub> website

Date,Granule	Image 1	Image 2	AIRS L1B ( <a href="#">to get hdf data, email us</a> )
2007.11.24.118			AIRS_2007.11.24.118.L1B.AIRS_Rad.v4.0.9.0.N07328092701.hdf
2007.11.24.007			AIRS_2007.11.24.007.L1B.AIRS_Rad.v4.0.9.0.N07327220006.hdf
2007.10.15.163			AIRS_2007.10.15.163.L1B.AIRS_Rad.v4.0.9.0.N07288144427.hdf
2007.10.15.147			AIRS_2007.10.15.147.L1B.AIRS_Rad.v4.0.9.0.N07288130040.hdf
2007.10.04.217			AIRS_2007.10.04.217.L1B.AIRS_Rad.v4.0.9.0.N07277195643.hdf
2007.10.04.096			AIRS_2007.10.04.096.L1B.AIRS_Rad.v4.0.9.0.N07277063327.hdf
2007.10.04.080			AIRS_2007.10.04.080.L1B.AIRS_Rad.v4.0.9.0.N07277062356.hdf
2007.10.03.226			AIRS_2007.10.03.226.L1B.AIRS_Rad.v4.0.9.0.N07276203956.hdf
2007.10.03.105			AIRS_2007.10.03.105.L1B.AIRS_Rad.v4.0.9.0.N07276072757.hdf
2007.10.03.089			AIRS_2007.10.03.089.L1B.AIRS_Rad.v4.0.9.0.N07276071649.hdf
2007.10.02.236			AIRS_2007.10.02.236.L1B.AIRS_Rad.v4.0.9.0.N07275214657.hdf
2007.10.02.235			AIRS_2007.10.02.235.L1B.AIRS_Rad.v4.0.9.0.N07275214658.hdf

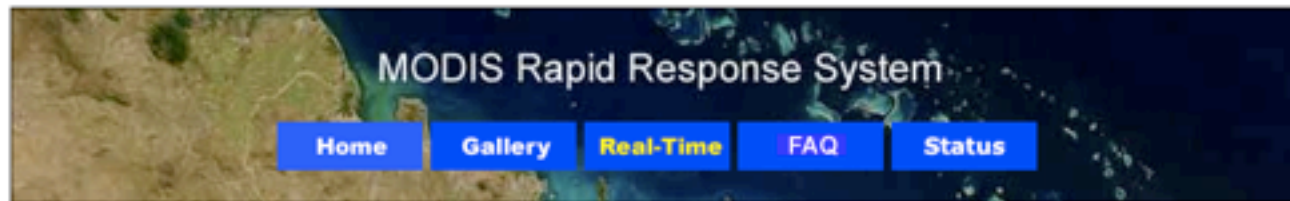
<http://www.star.nesdis.noaa.gov/smcd/spb/iosspdt/iosspdt.php?so2=1#1>

# IASI NRT SO<sub>2</sub> alerts



<http://cpm-ws4.ulb.ac.be/Alerts/index.php>

# MODIS Rapid Response website

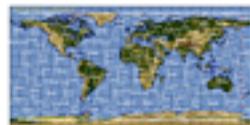


## Near-Real-Time Level-2 Browse

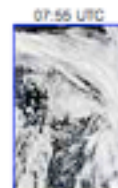
All 250-meter, near-real-time swath images acquired before August 6, 2007, were removed from the system on January 11, 2008.

Date: 2009/055 - 02/24/09

← prev

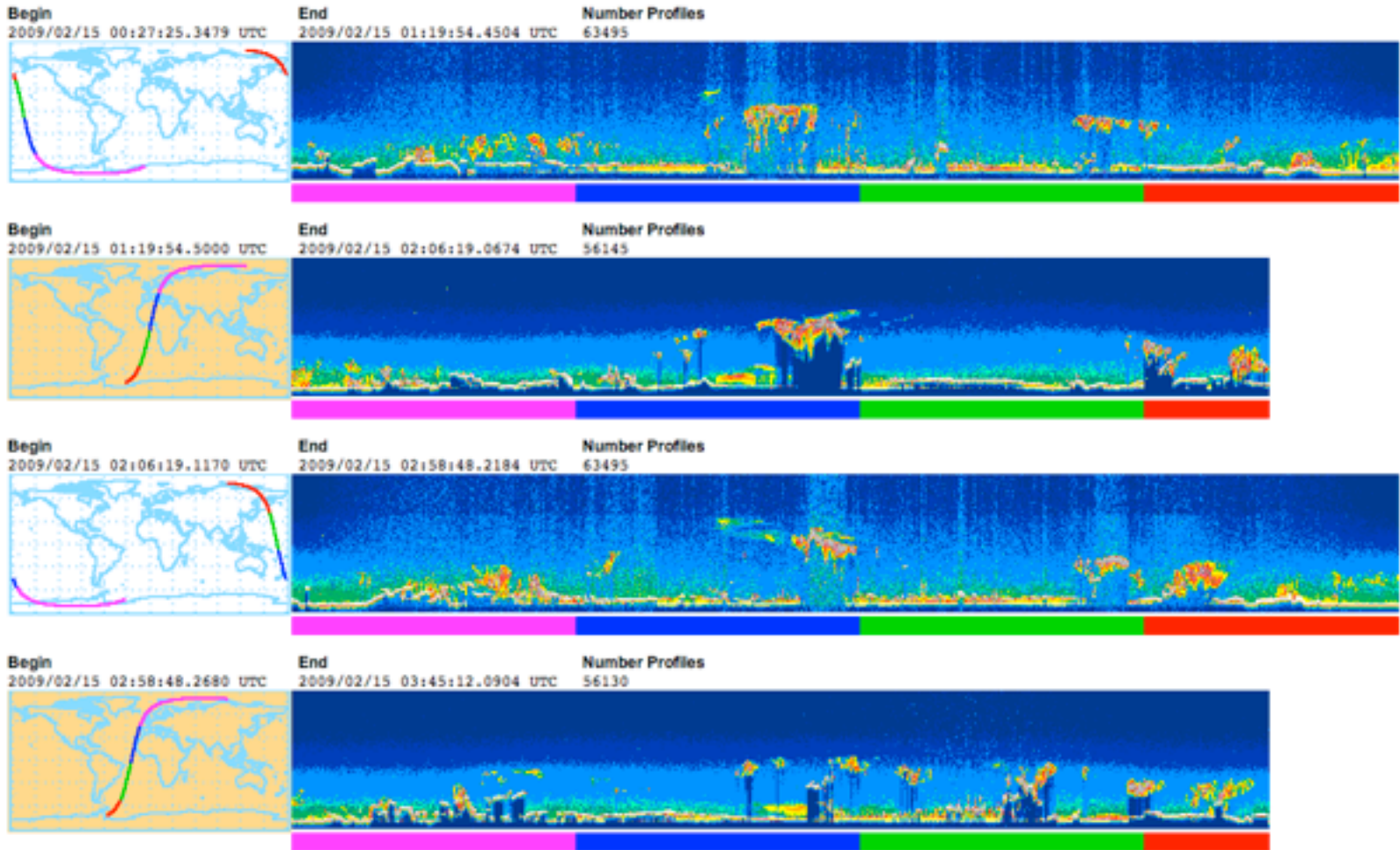


### Terra/MODIS



<http://rapidfire.sci.gsfc.nasa.gov/realtime/>

# CALIPSO website



[http://www-calipso.larc.nasa.gov/products/lidar/browse\\_images/show\\_calendar.php](http://www-calipso.larc.nasa.gov/products/lidar/browse_images/show_calendar.php)



# The fate of sulfur gases in the atmosphere

- $\text{SO}_2$  ( $\text{S}^{+4}$ ) oxidizes to sulfuric acid (sulfate) aerosol ( $\text{H}_2\text{SO}_4$ )
  - Rapid in aqueous phase (hours) – clouds, fog
  - Slower in gas phase (days-weeks) – stratosphere
  - Sulfuric acid ( $\text{S}^{+6}$ ) highly soluble in water – rapid removal in precipitation
  - $\text{SO}_2$  also scrubbed by  $\text{H}_2\text{O}$  before emission
- $\text{H}_2\text{S}$  ( $\text{S}^{-2}$ ) oxidizes to  $\text{SO}_2$  (and sulfate) by reaction with OH, ozone ( $\text{O}_3$ )
  - Less water-soluble than  $\text{SO}_2$  (lower oxidation state)
  - Less susceptible to scrubbing
  - Not easily detected using remote sensing techniques

# Diurnal evolution of planetary boundary layer

OMI @ 1:30-1:45 pm

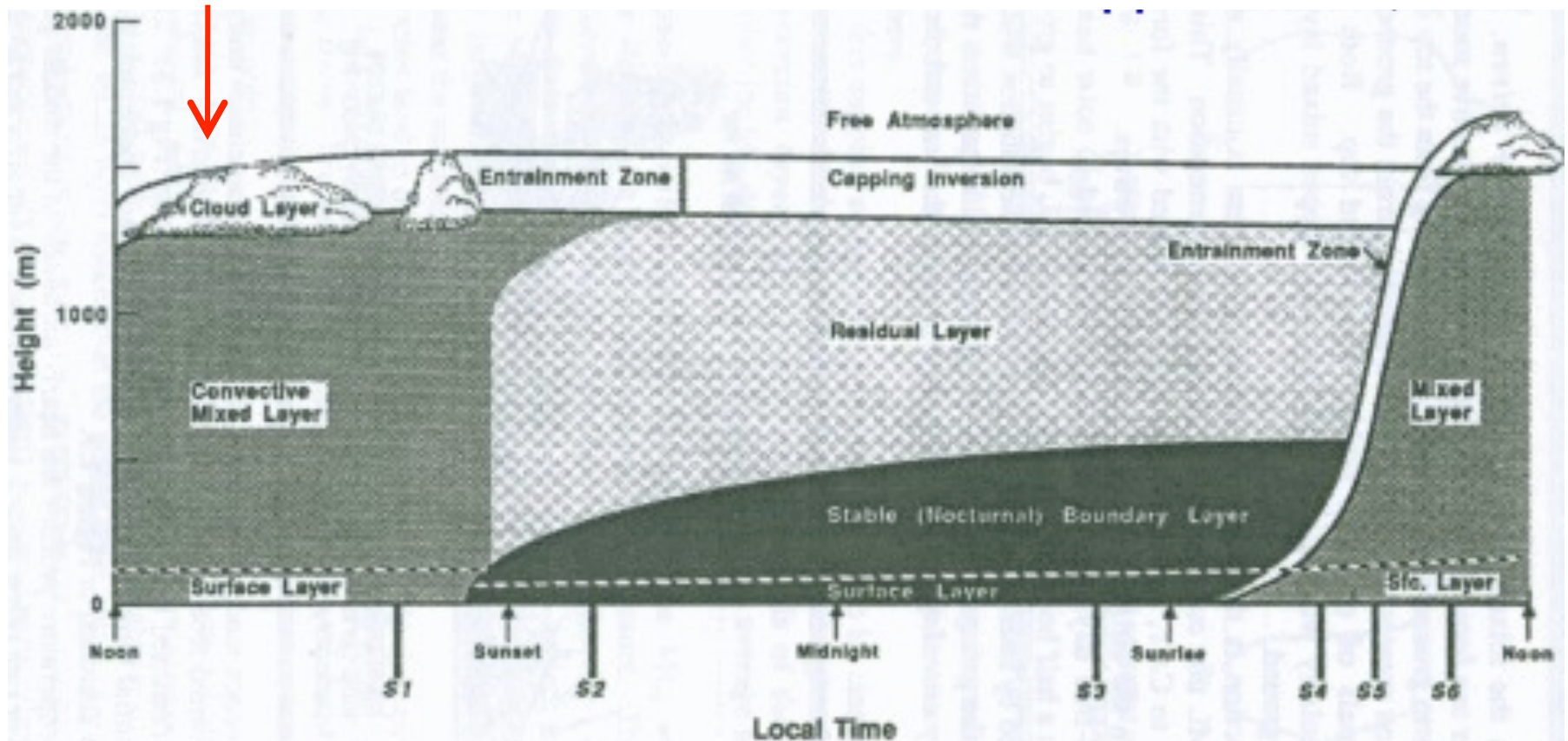
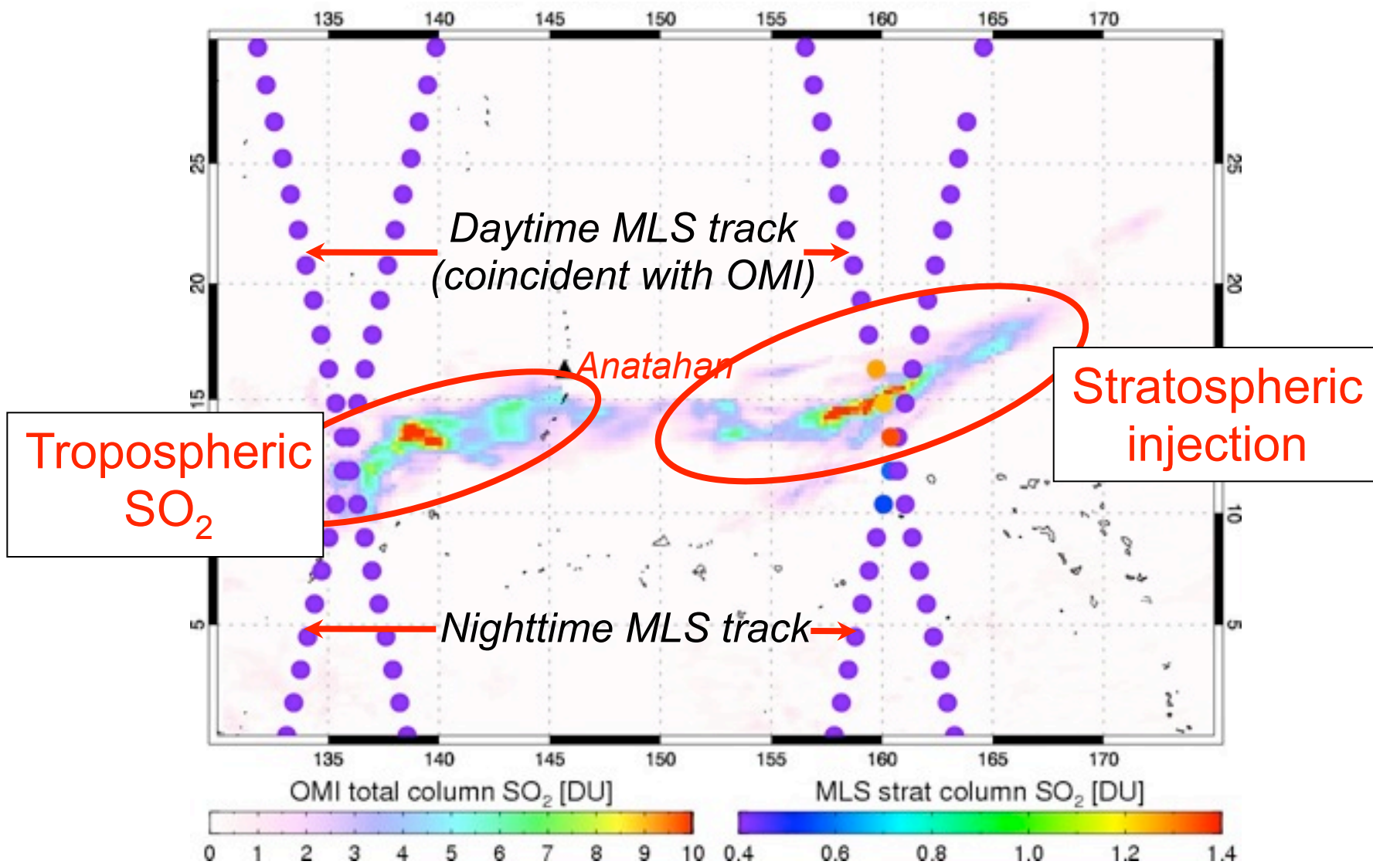


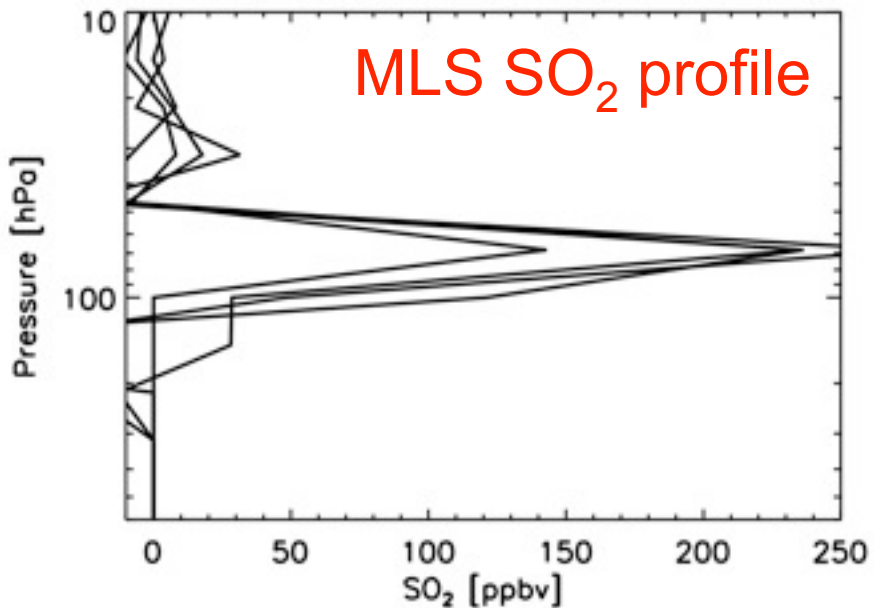
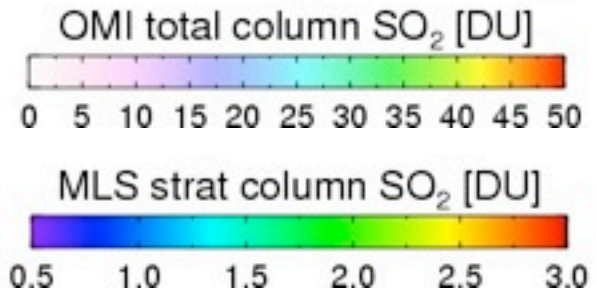
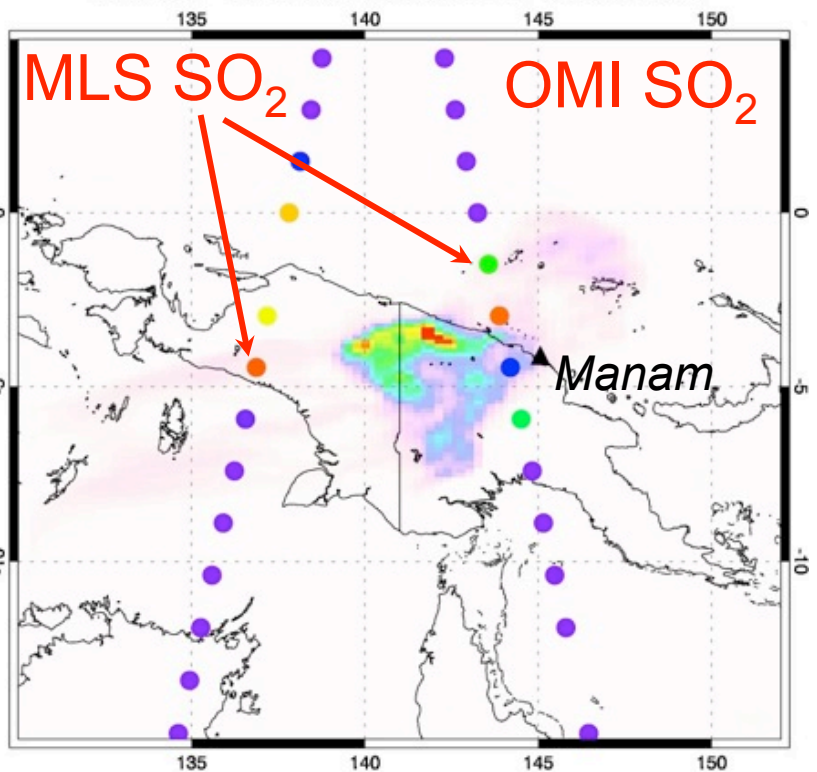
Fig. 1.7

The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

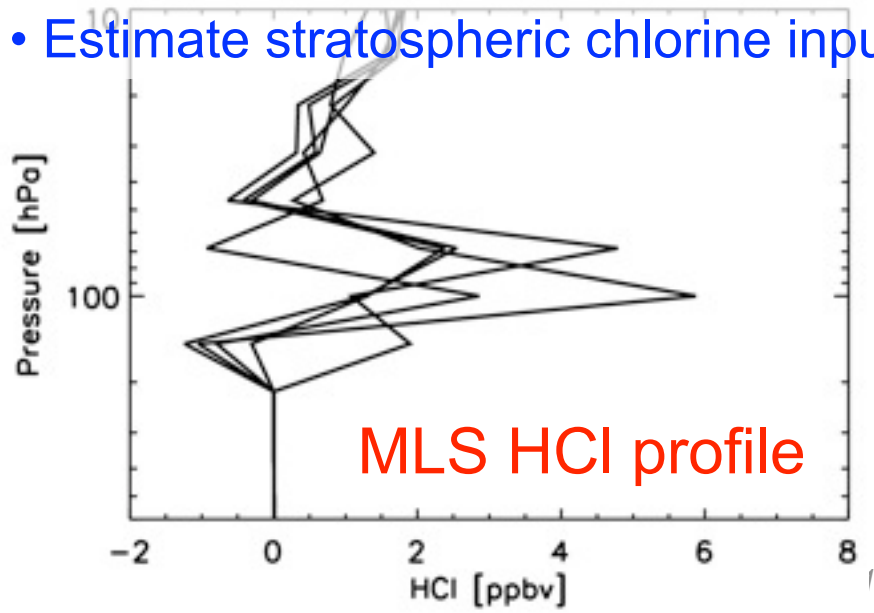
# Aura/OMI - Aura/MLS: Anatahan (CNMI), April 7, 2005



# Aura/OMI – Aura/MLS: Manam (PNG), Jan 2005

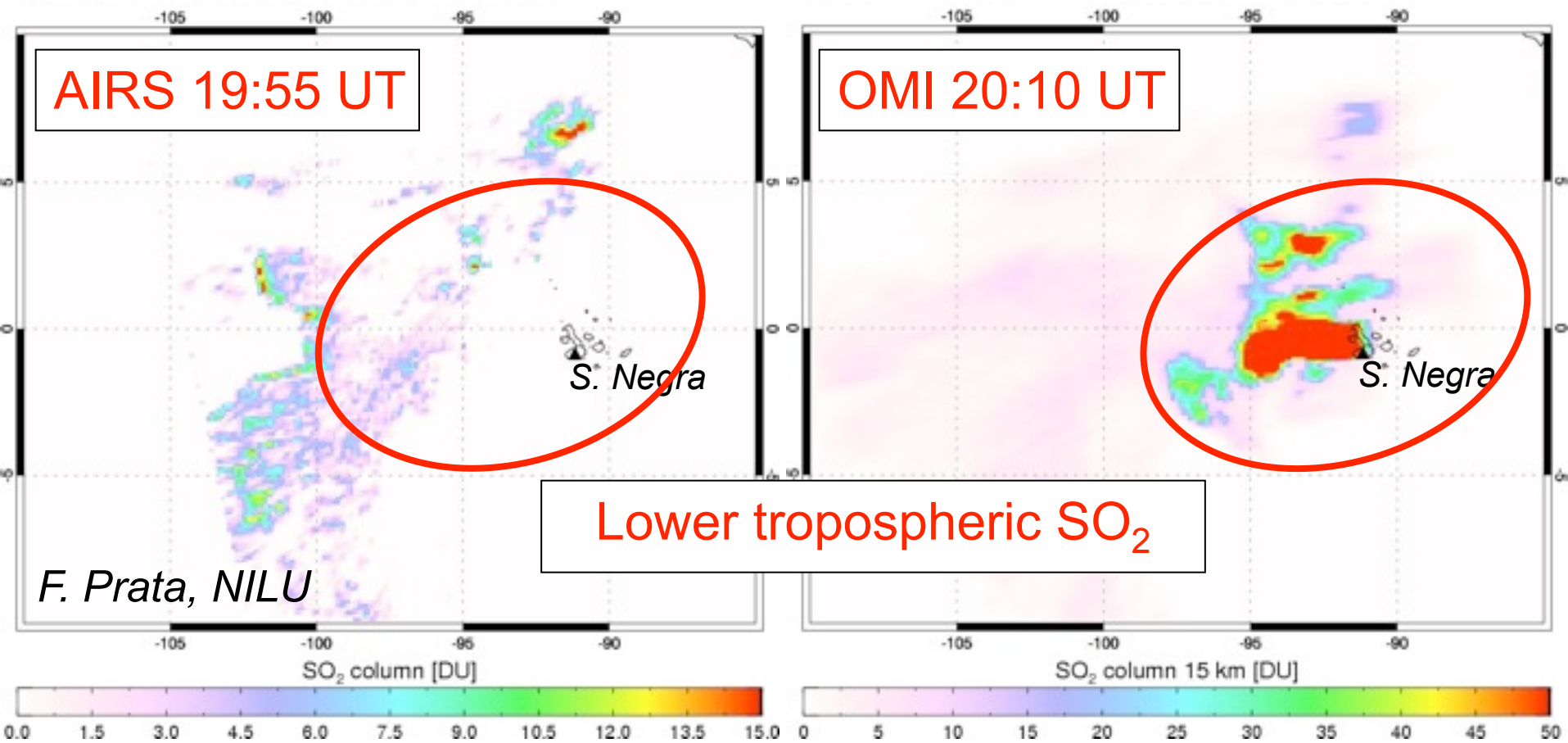


• Estimate stratospheric chlorine input





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



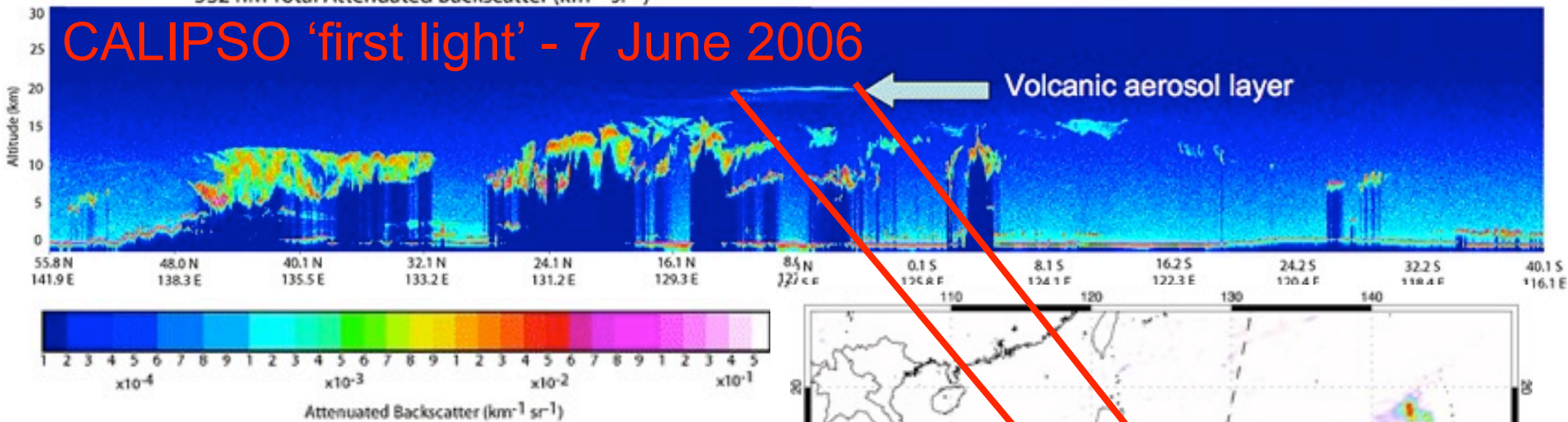
- Sierra Negra (Galapagos) eruption, October 24, 2005
- OMI-AIRS synergy indicates SO<sub>2</sub> concentrated in the lower troposphere

# Aura/OMI - CALIPSO lidar: Soufriere Hills, May 2006

532 nm Total Attenuated Backscatter ( $\text{km}^{-1} \text{sr}^{-1}$ )

CALIPSO 'first light' - 7 June 2006

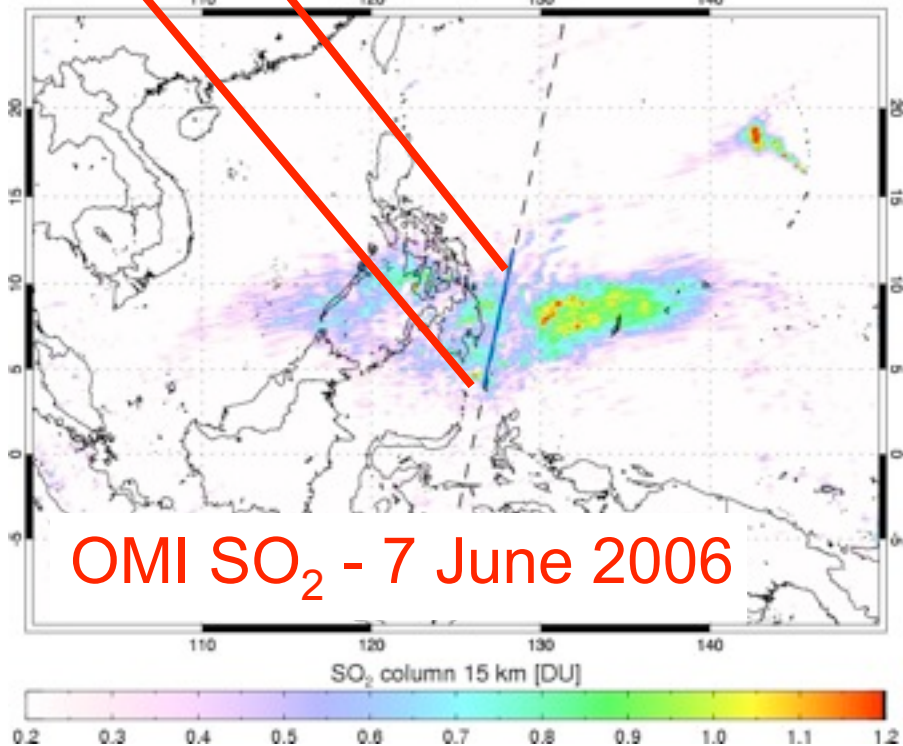
Volcanic aerosol layer



[Credit: CALIPSO Team, NASA Langley]

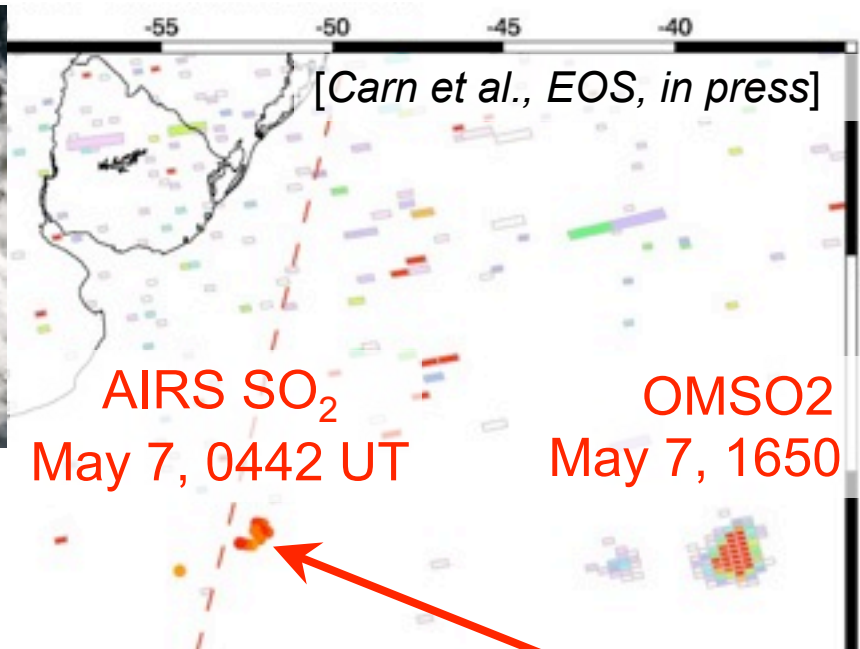
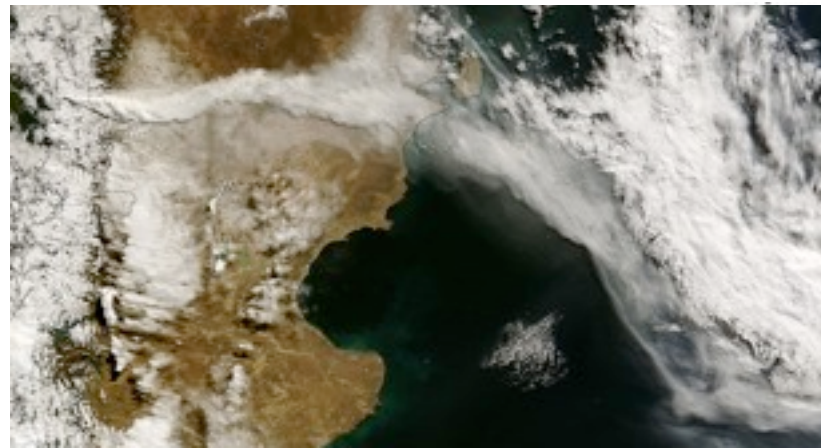
- May 20 eruption on Montserrat
- SO<sub>2</sub> tracked for 3 weeks
- Cloud altitude ~20 km
- Aerosol layer non-depolarizing
- Sulfate dominant, not ash

[Carn et al., ACPD, 2007]

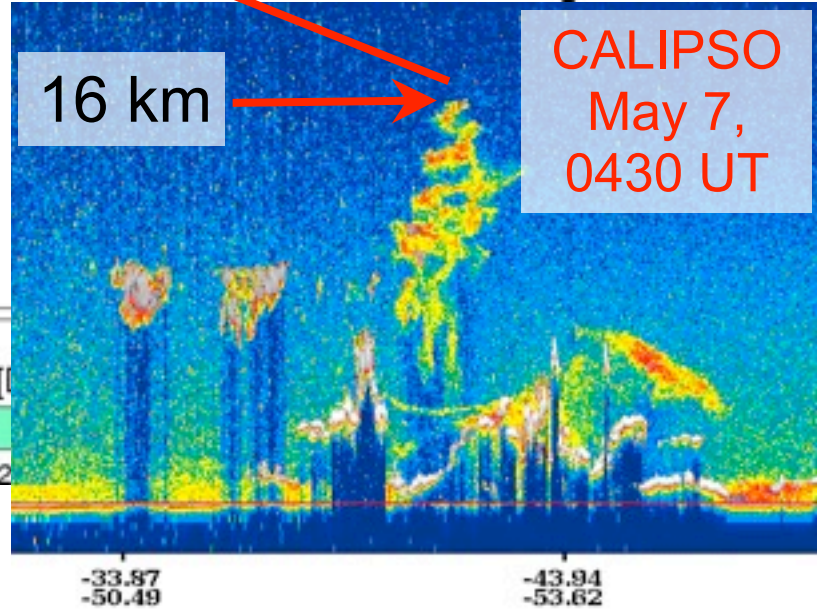
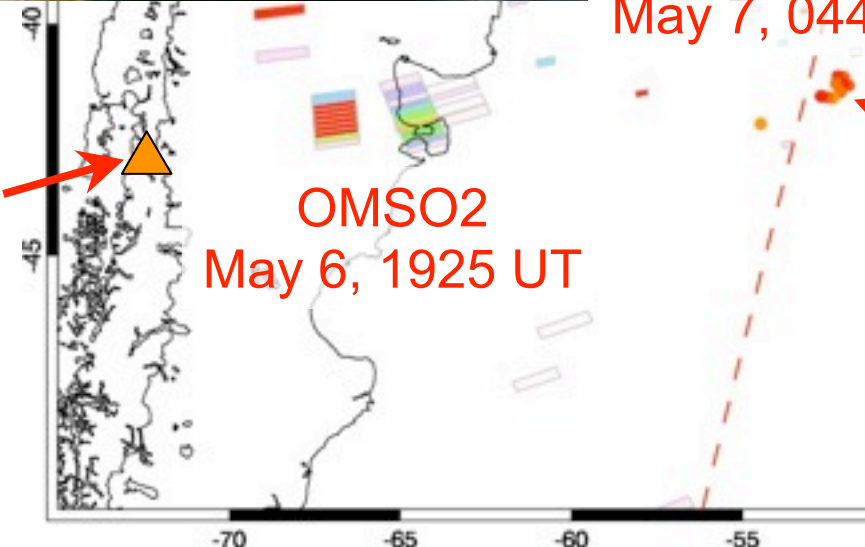


OMI SO<sub>2</sub> - 7 June 2006

# OMI - Aqua/AIRS - CALIPSO: Chaitén (Chile), May 2008

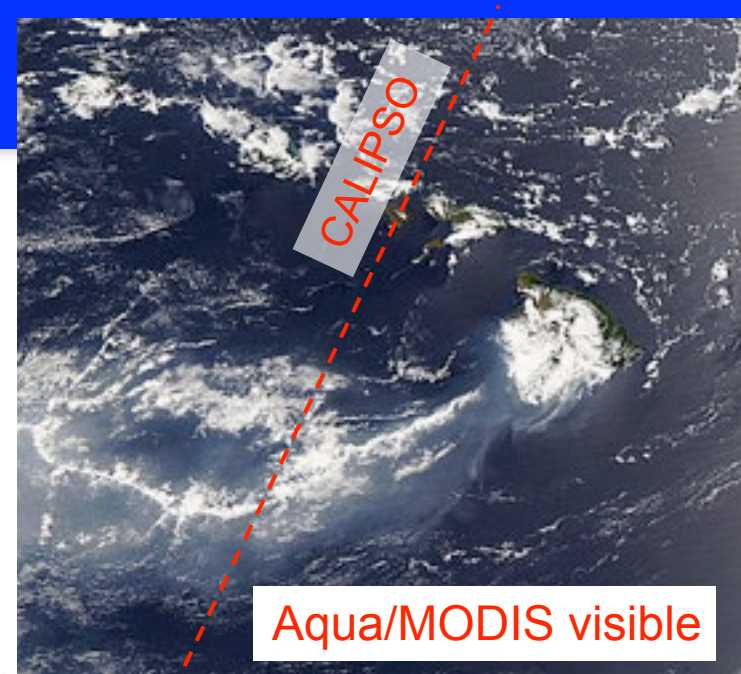
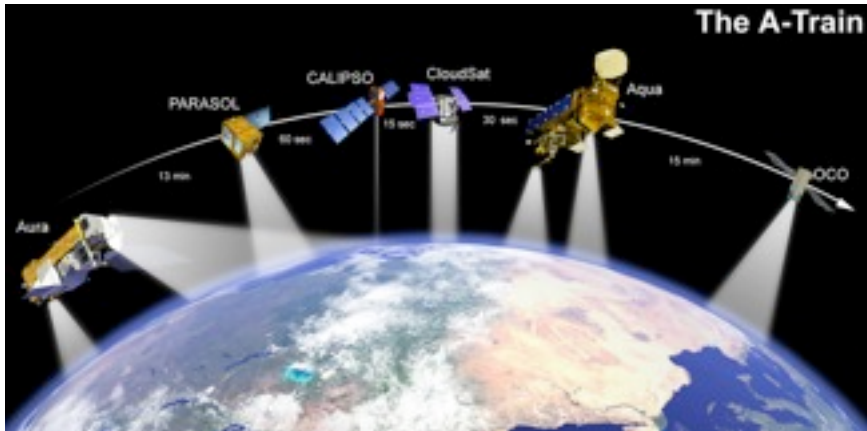


Chaitén

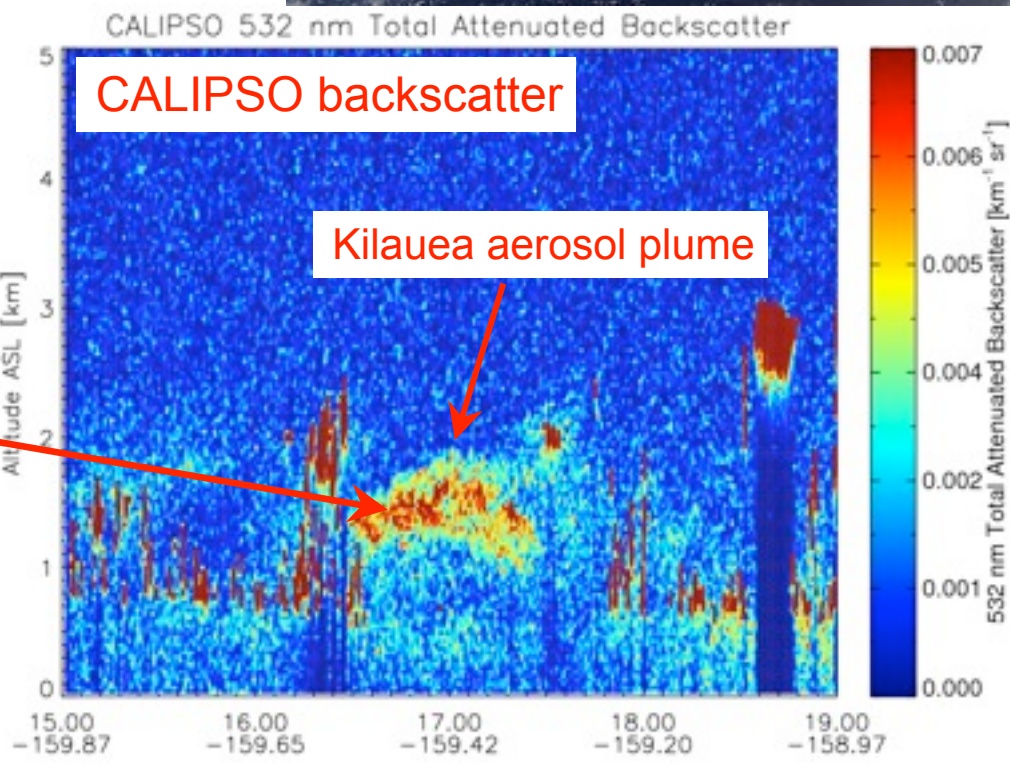
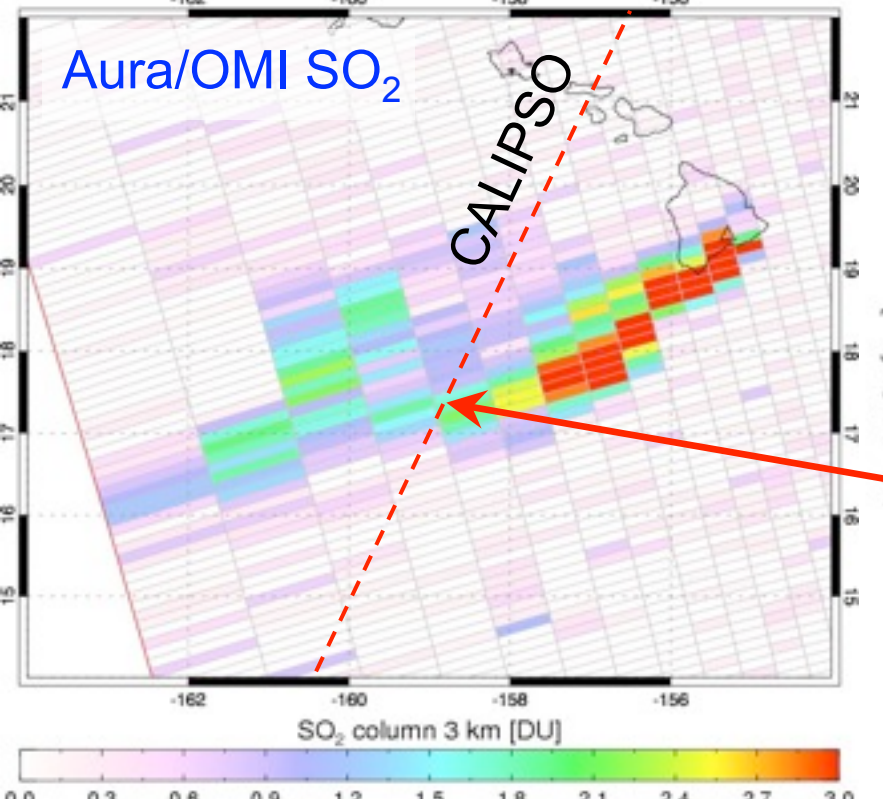




# Kilauea degassing – April 7, 2008

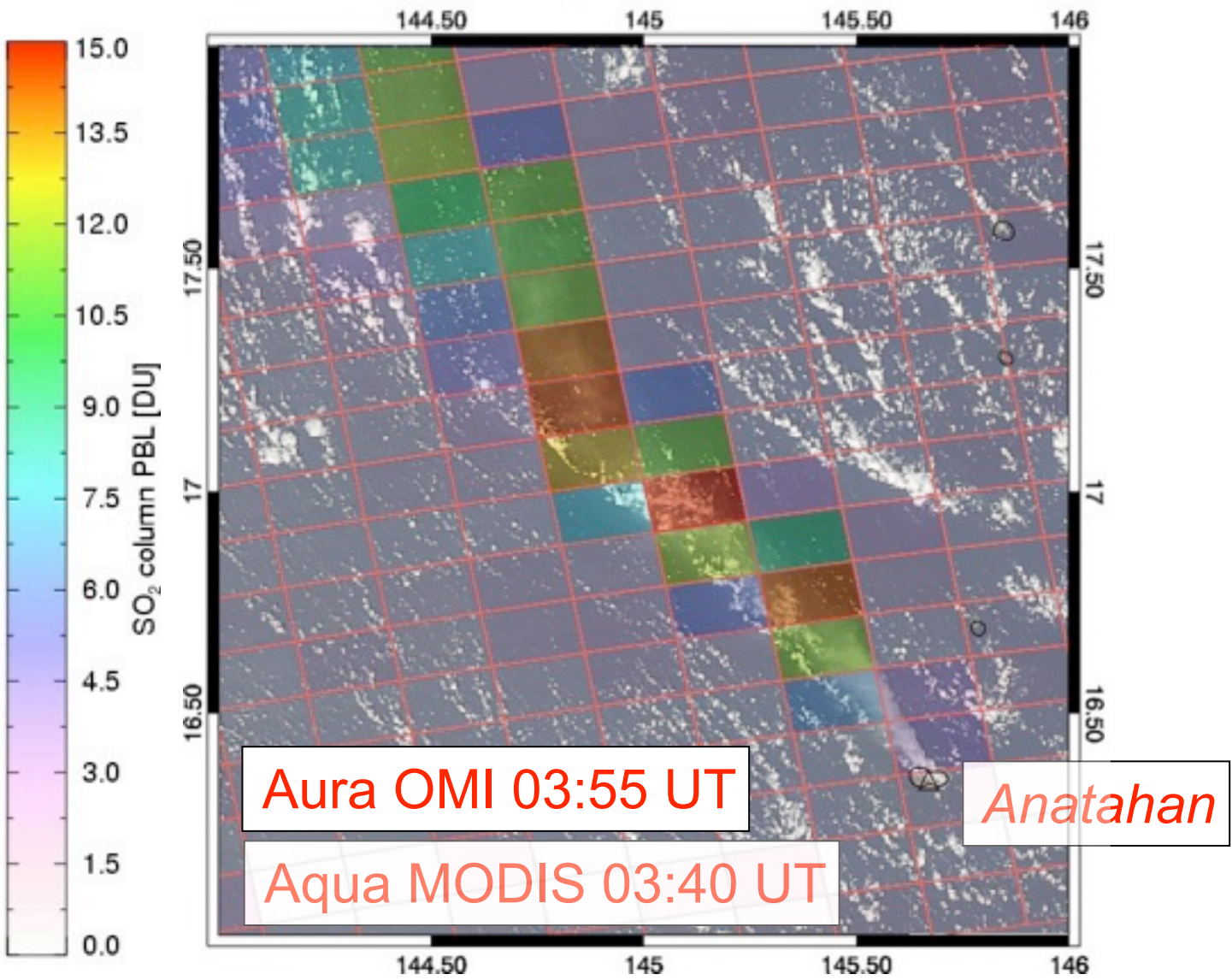


Aqua/MODIS visible



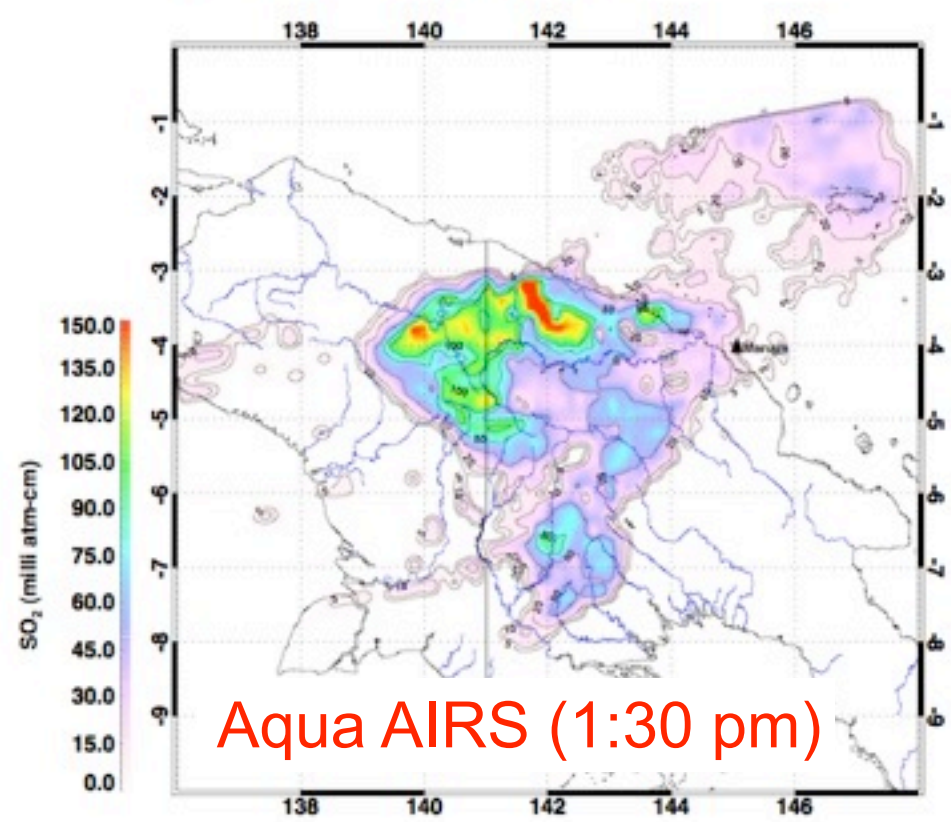
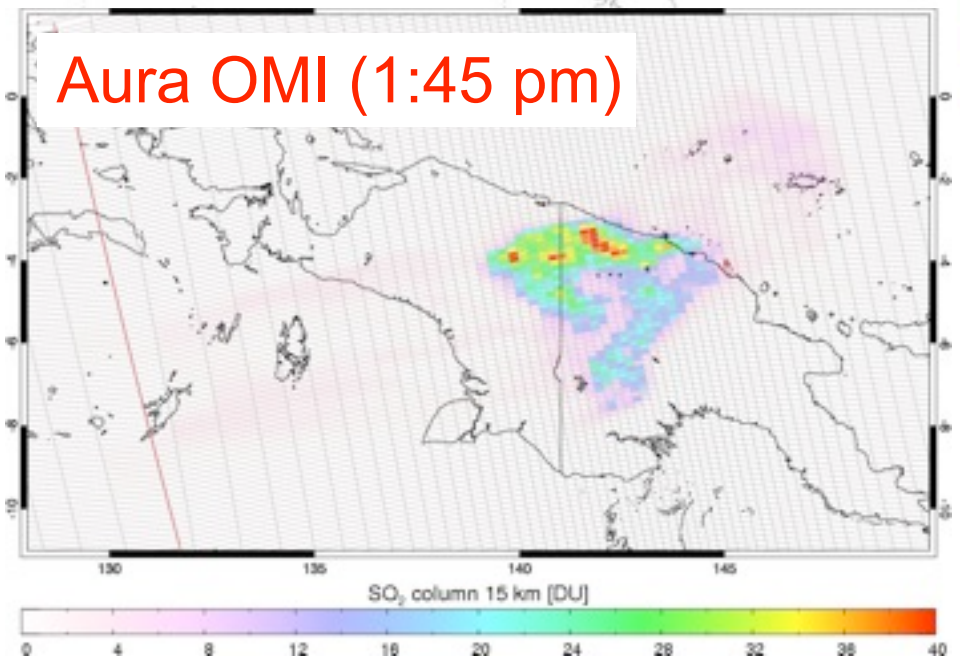
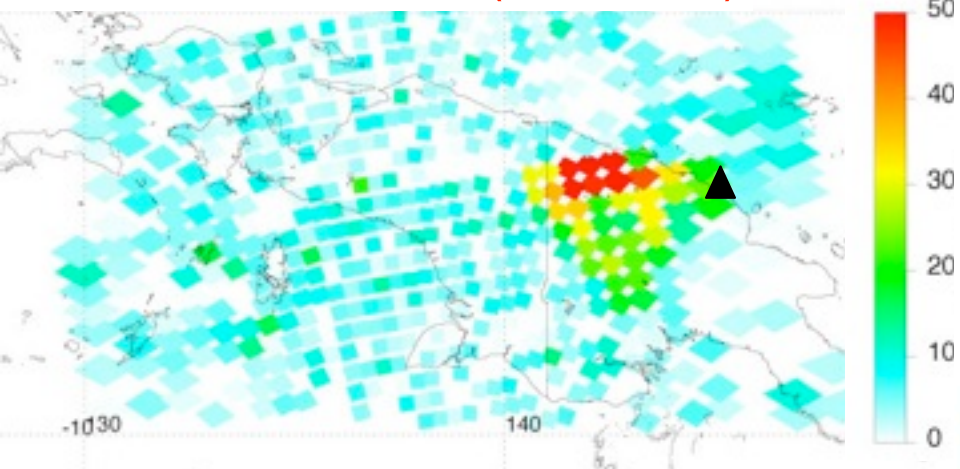


# Aura/OMI - Aqua/MODIS - Anatahan (CNMI), Feb 10, 2008



# OMI, TOMS and AIRS: Manam (PNG), Jan 28, 2005

Earth Probe TOMS (11:00 am)



- Independent SO<sub>2</sub> retrievals from 3 instruments (UV/IR)
- Volcanic cloud SO<sub>2</sub> burdens agree to within 20%

# Strengths and weaknesses of SO<sub>2</sub> data

- **Strengths**

- Unique marker of magmatic volcanic eruptions
- Virtually no interference from other sources in most volcanic regions (apart from other volcanoes...)
- Current UV/IR satellite sensors sensitive to low SO<sub>2</sub> amounts
- UV sensors can detect SO<sub>2</sub> degassing prior to eruptions
- Can map volcanic clouds when ash is encased in ice
- UV sensors can detect SO<sub>2</sub> in opaque volcanic clouds
- SO<sub>2</sub> measurements have been validated (but more is needed)
- Could SO<sub>2</sub> be used to assess cumulative aircraft exposure to volcanic clouds?

- **Weaknesses**

- Poor proxy for dense ash when SO<sub>2</sub> and ash clouds separate
- No geostationary SO<sub>2</sub> data in NOPAC region (yet → GOES-R ABI)
- UV techniques restricted during winter months

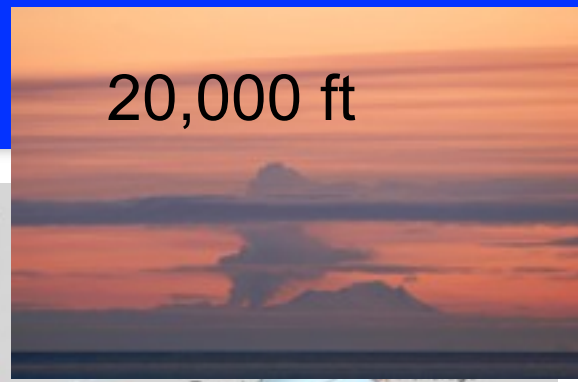
# Summary

- Numerous satellite sensors now provide SO<sub>2</sub> measurements
- Some have standard SO<sub>2</sub> products, others require application of retrieval algorithms to yield quantitative SO<sub>2</sub> data
- Aura/OMI is an economical and effective tool for monitoring volcanic SO<sub>2</sub> degassing on a regional or local (single volcano) scale
- OMI's high SO<sub>2</sub> 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<sub>2</sub> plumes by OMI depends on several factors, hence the lower detection limit in terms of SO<sub>2</sub> flux is variable (with latitude, vent altitude etc.)
- Altitude sensitivity must be considered when evaluation satellite SO<sub>2</sub> data
- New satellite constellations (A-Train) provide opportunities for sensor synergy and '3D' analysis of volcanic clouds

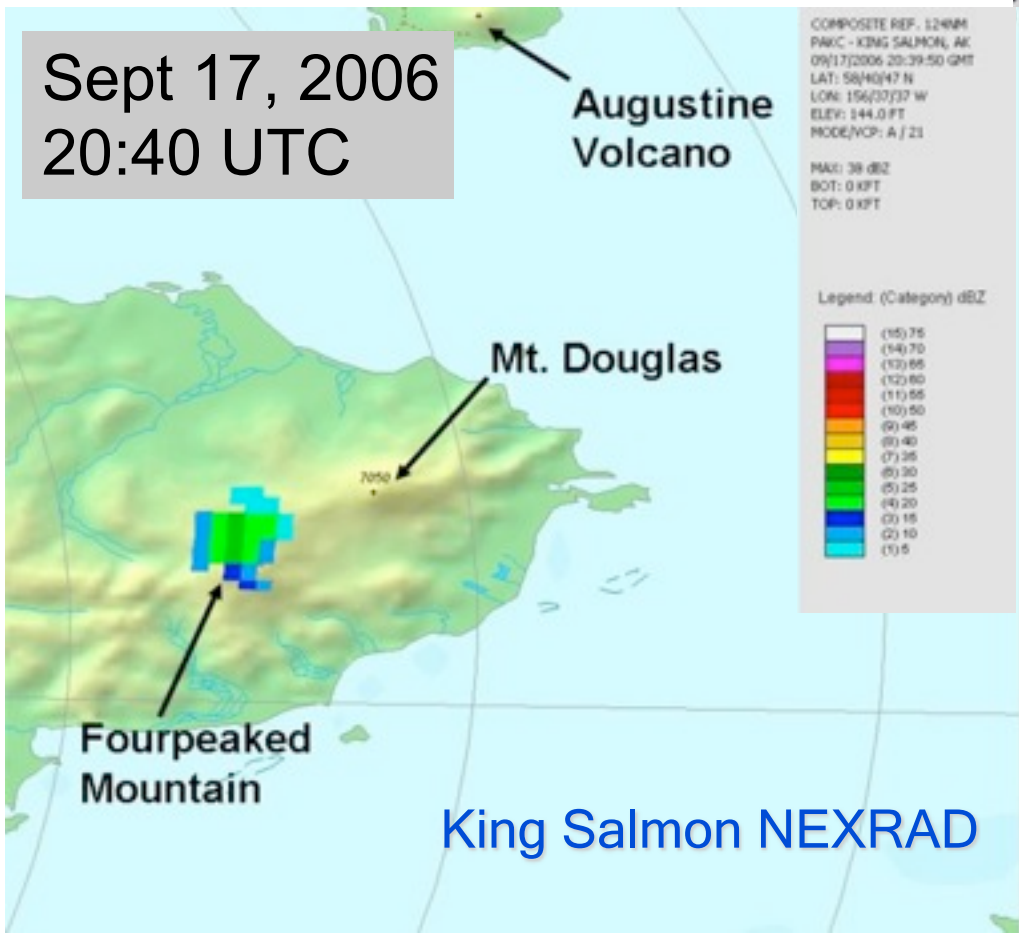


# Eruption detection: Fourpeaked (AK)

20,000 ft



Sept 17, 2006  
20:40 UTC



## Fourpeaked Volcano, AK:

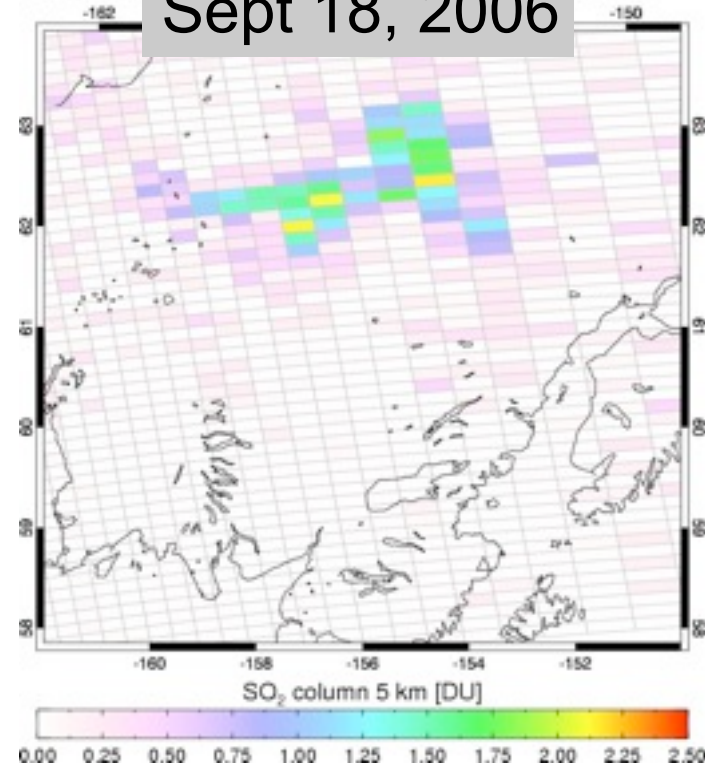
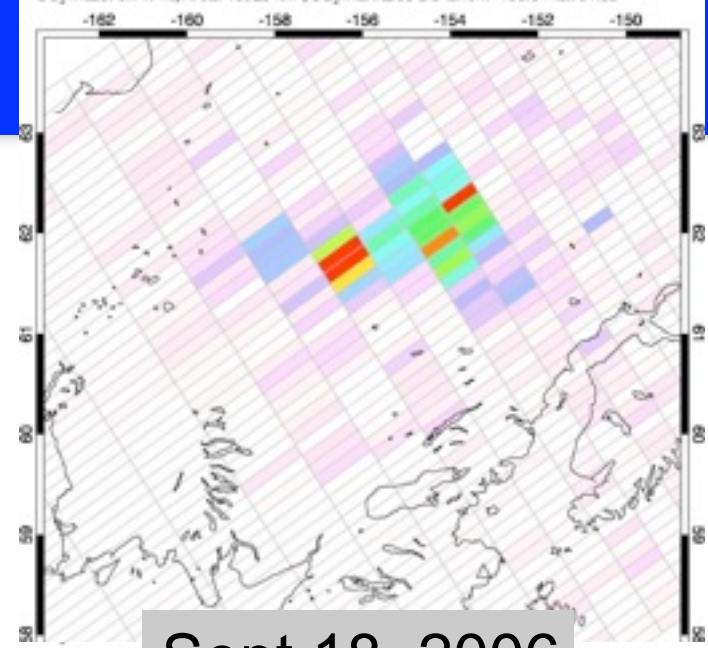
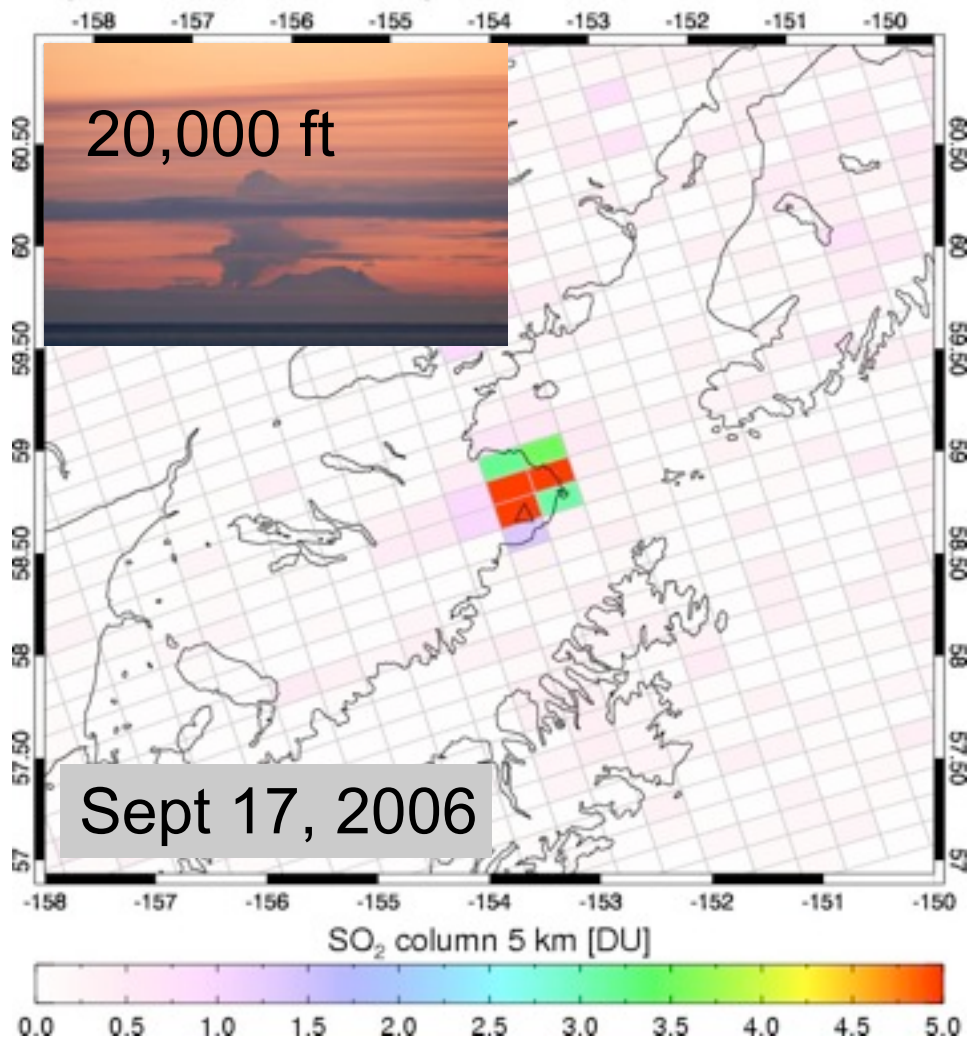
A long dormant volcano - last volcanic activity was prior to glaciation (>10,000 years ago). No known fumarolic areas around the volcano.

[NEXRAD data courtesy AVO]

# Fourpeaked (AK) – Sept 2006

Aura/OMI - 09/17/2006 23:01-23:02 UT - Orbit 11572

SO<sub>2</sub> mass: 0.290 kt; Area: 3223 km<sup>2</sup>; SO<sub>2</sub> max: 7.25 DU at lon: -153.41 lat: 58.95



- Small magmatic intrusion at shallow depth?



# Garbuna (PNG) – October 2005

Aura/OMI - 10/17/2005 03:35-03:36 UT - Orbit 06682

SO<sub>2</sub> mass: 0.112 kt; Area: 2692 km<sup>2</sup>; SO<sub>2</sub> max: 2.11 DU at lon: 149.91 lat: -5.41

148

149

150

151

-4.50

-5

-5.50

-6

-6.50

Garbuna

Oct 17, 2005

SO<sub>2</sub> column 5 km [DU]

0.0

0.2

0.4

0.6

0.8

1.0

1.2

1.4

1.6

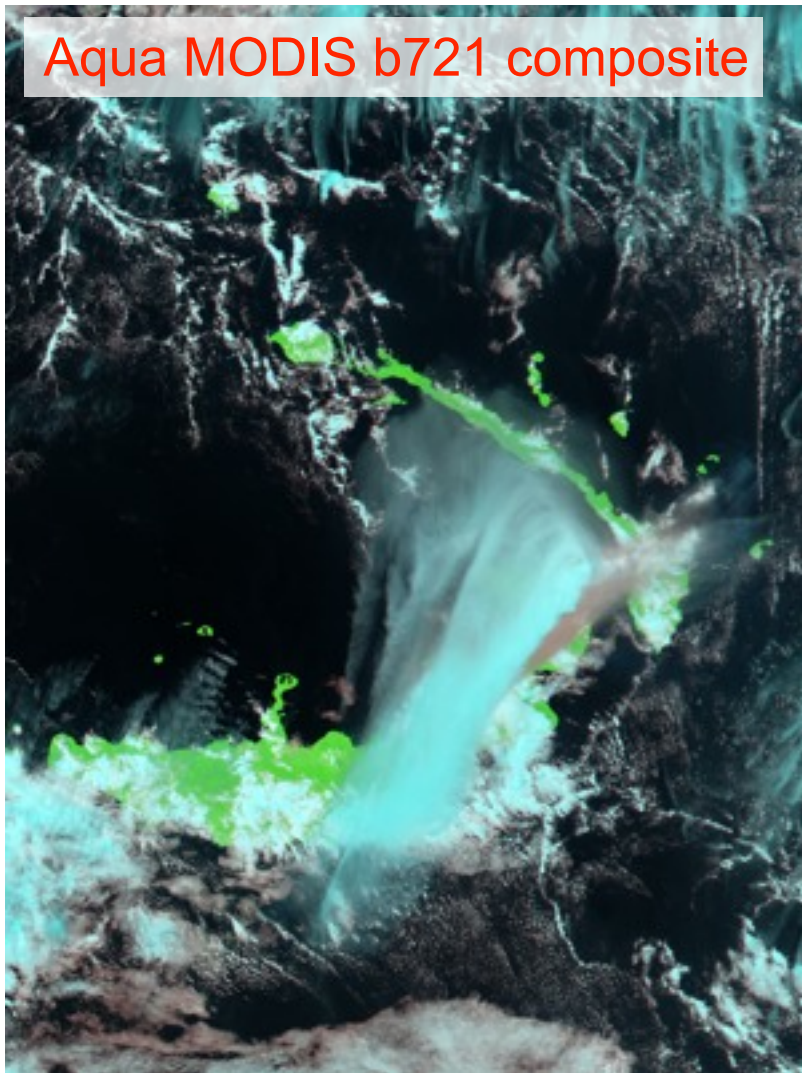
1.8

2.0

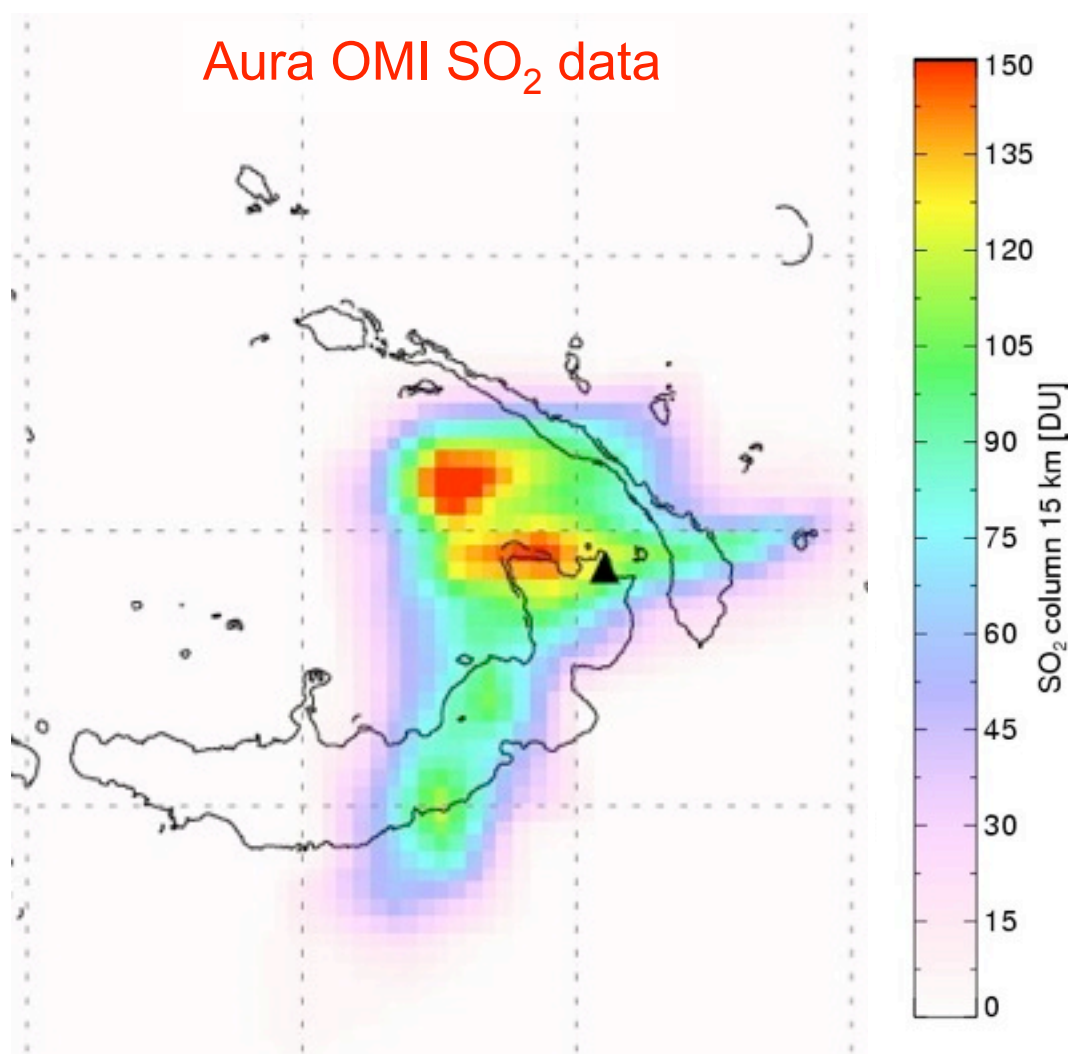
- As of June 2007, seismic activity continued and a boiling lake occupied the crater

# Detection of ice-rich volcanic clouds

Aqua MODIS b721 composite



Aura OMI SO<sub>2</sub> data



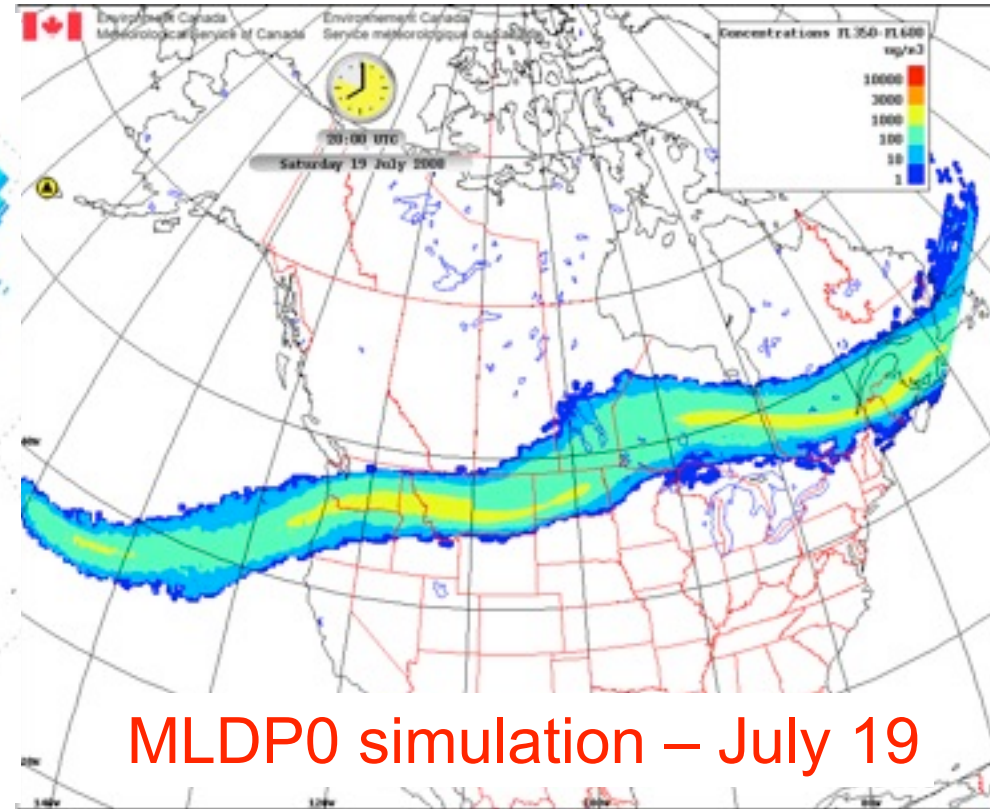
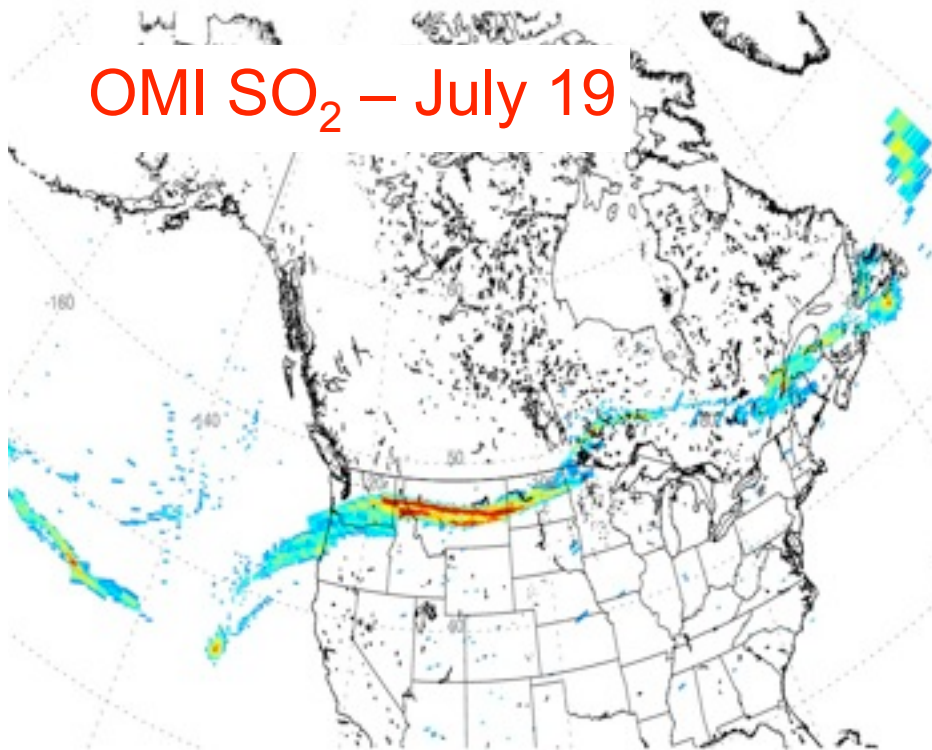
Rabaul (PNG) eruption, 7 Oct 2006



# Validation of trajectory/dispersion models

[http://eer.cmc.ec.gc.ca/people/Alain/eeer/exercises/okmok/exp\\_05/sig2v\\_0.5/FL350-FL600/anim.html](http://eer.cmc.ec.gc.ca/people/Alain/eeer/exercises/okmok/exp_05/sig2v_0.5/FL350-FL600/anim.html)

OMI SO<sub>2</sub> – July 19



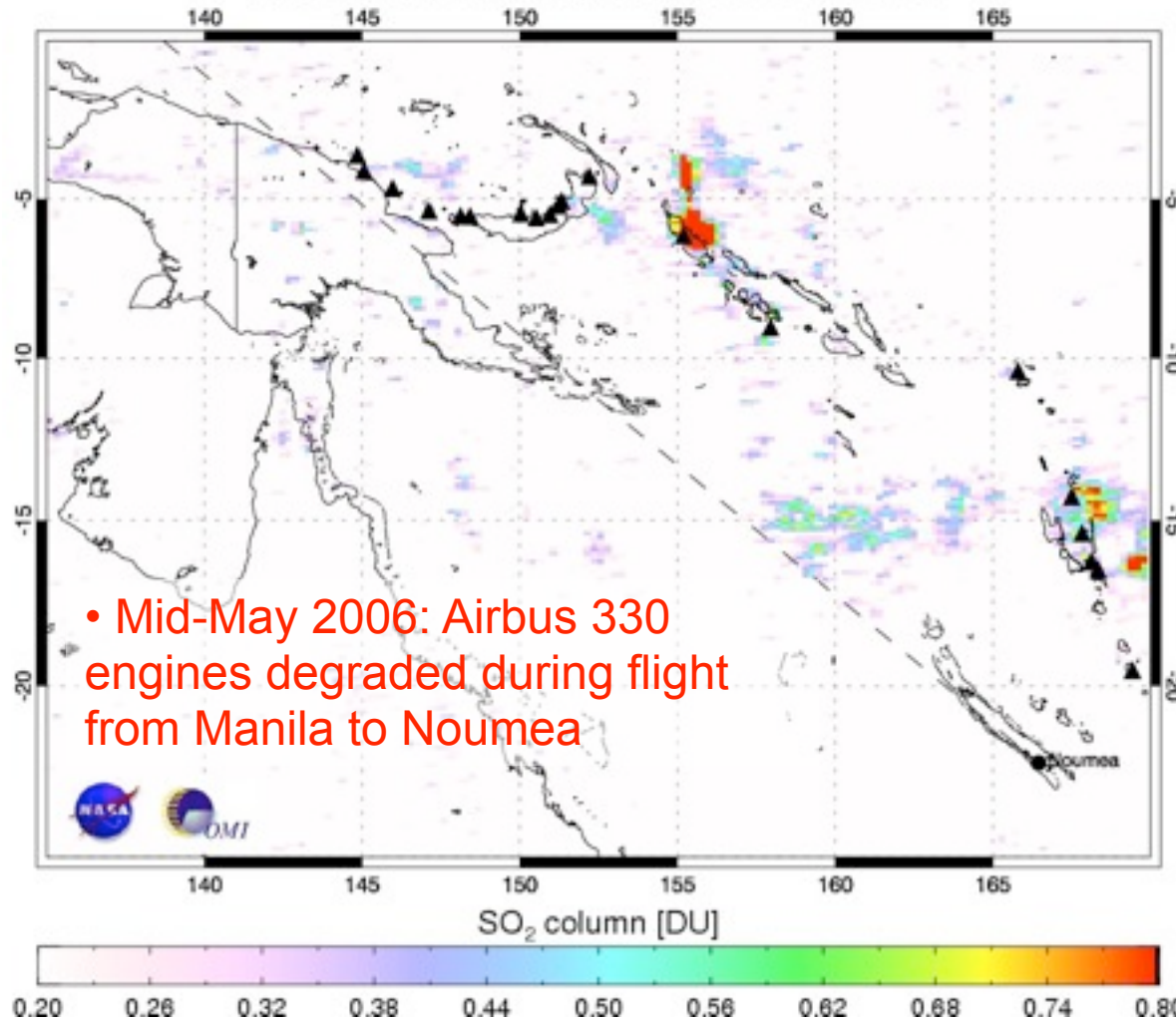
MLDP0 simulation – July 19

*MLDP0 data courtesy of René Servranckx and Alain Malo, Montreal VAAC*

- Accurate dispersion models are essential for volcanic ash forecasting
- SO<sub>2</sub> better suited for model validation due to its much longer atmospheric residence time

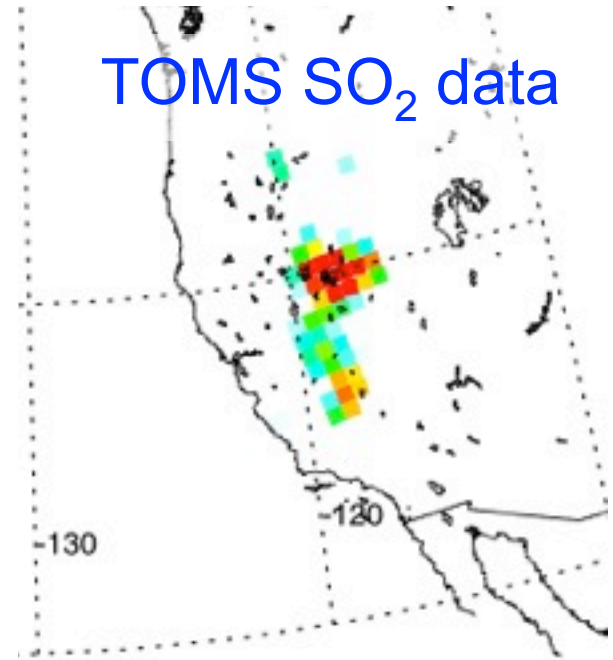
# Aviation encounters with dilute volcanic clouds

Aura/OMI - Average column for 20060512-20060513



- Mid-May 2006: Airbus 330 engines degraded during flight from Manila to Noumea

TOMS SO<sub>2</sub> data



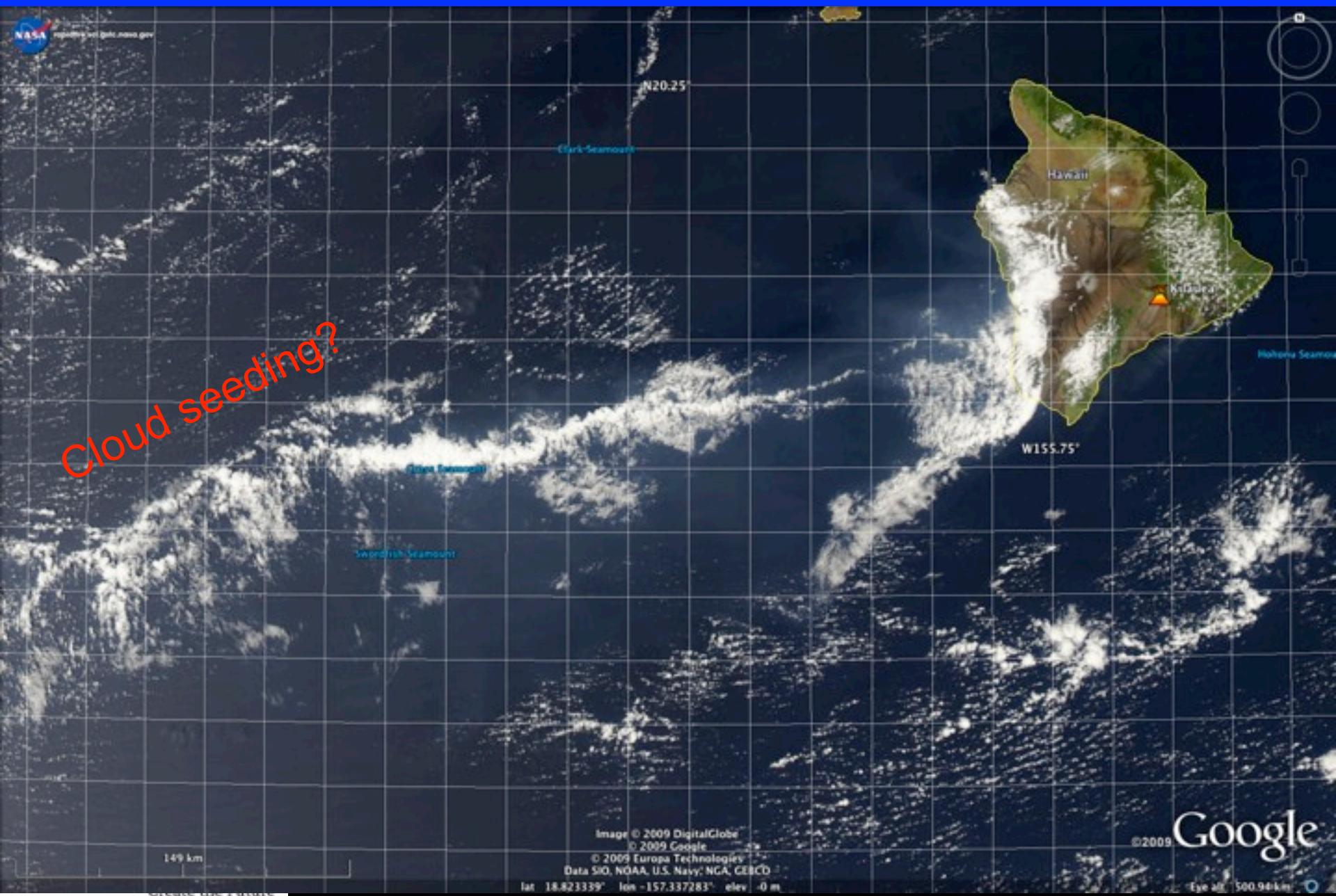
- Redoubt eruption cloud over CA and NV on 16 Dec 1989

[Carn et al., 2009]

- Encounters over Micronesia, Nov 2002 and March 2003 [Tupper et al., 2006]
- 'Gulfstream incident': twin-engined flameout over PNG, July 2006 [Tupper et al., 2007]
- NASA DC8 encounter with Hekla volcanic cloud, Feb 2000



# Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)

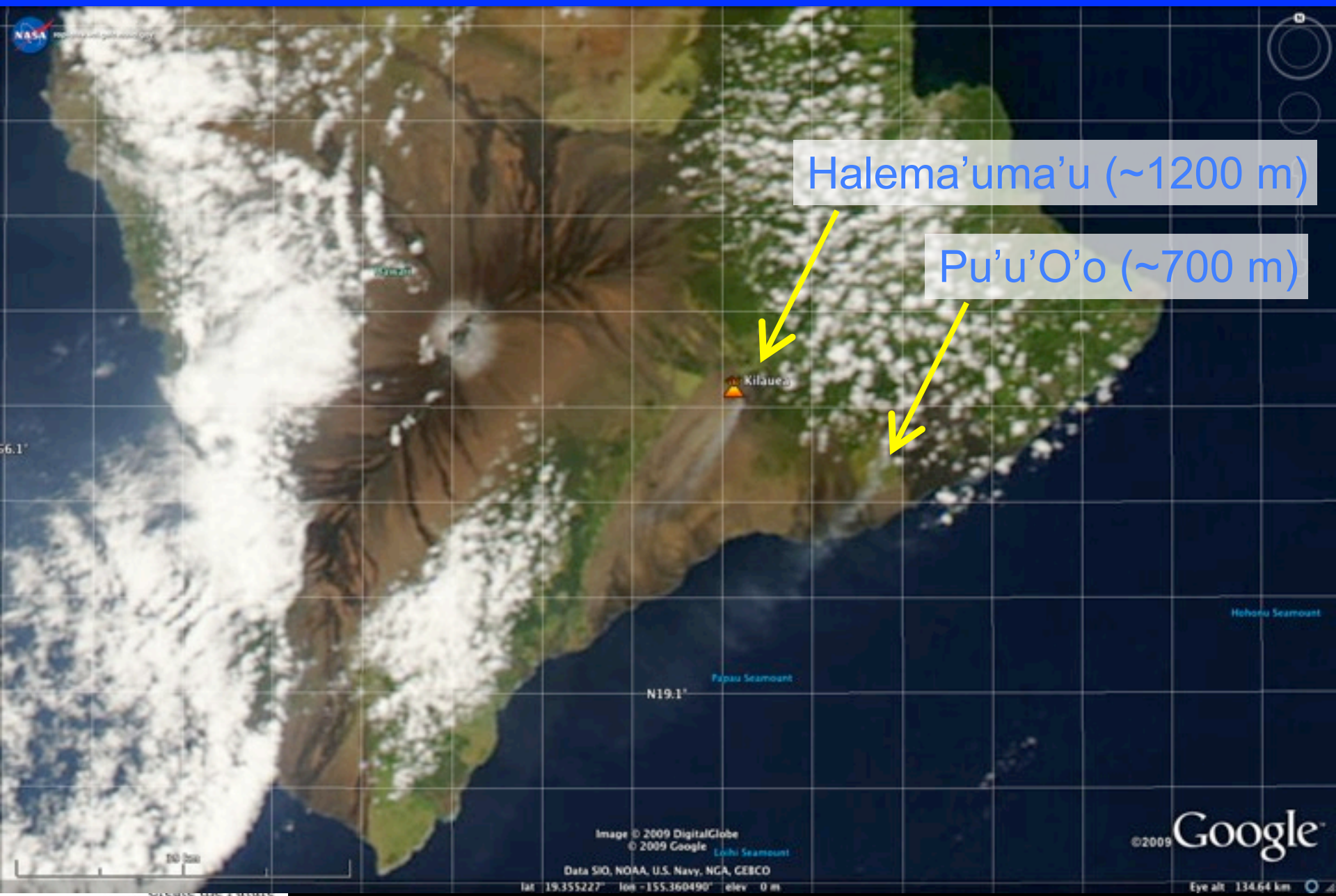




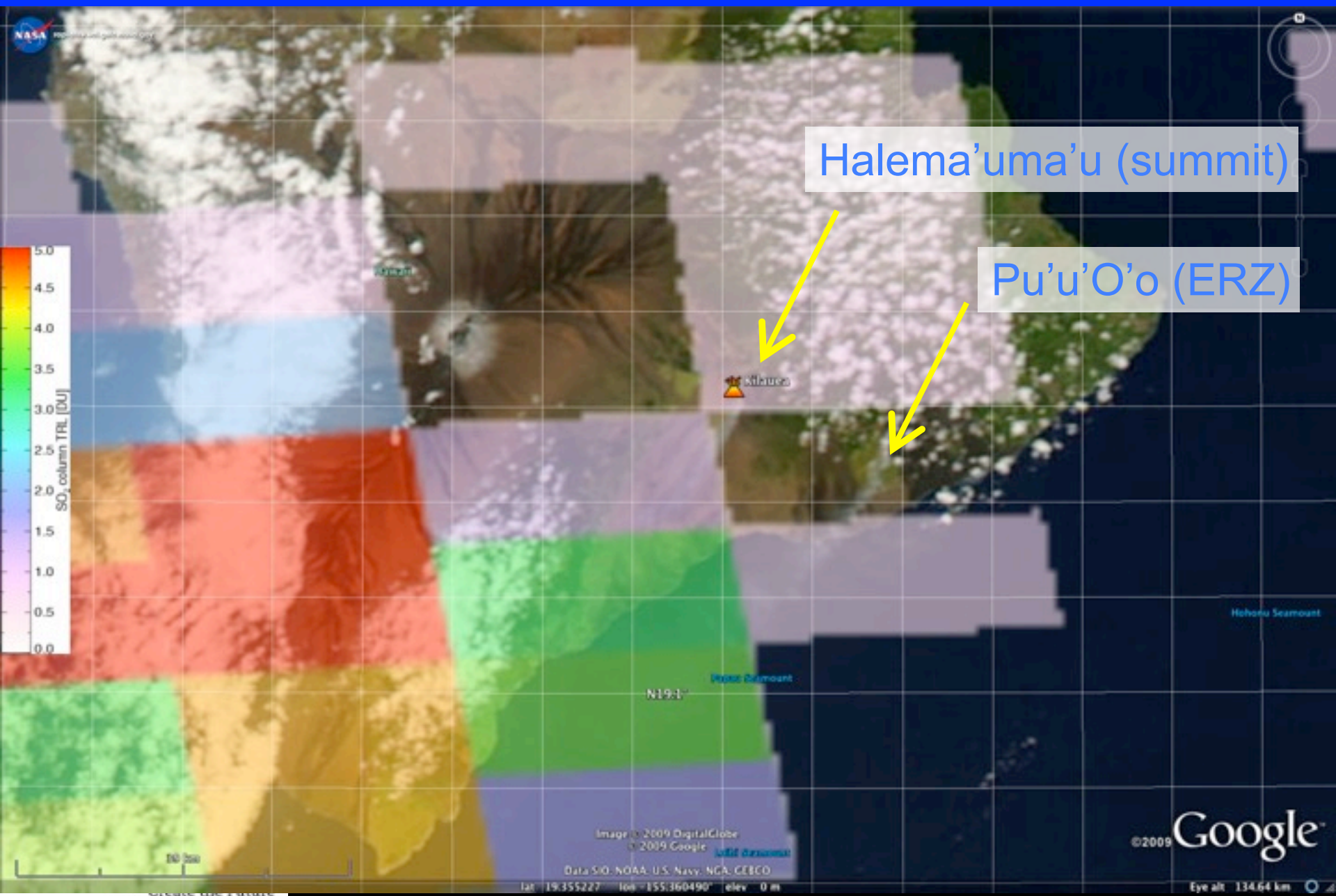




# Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)

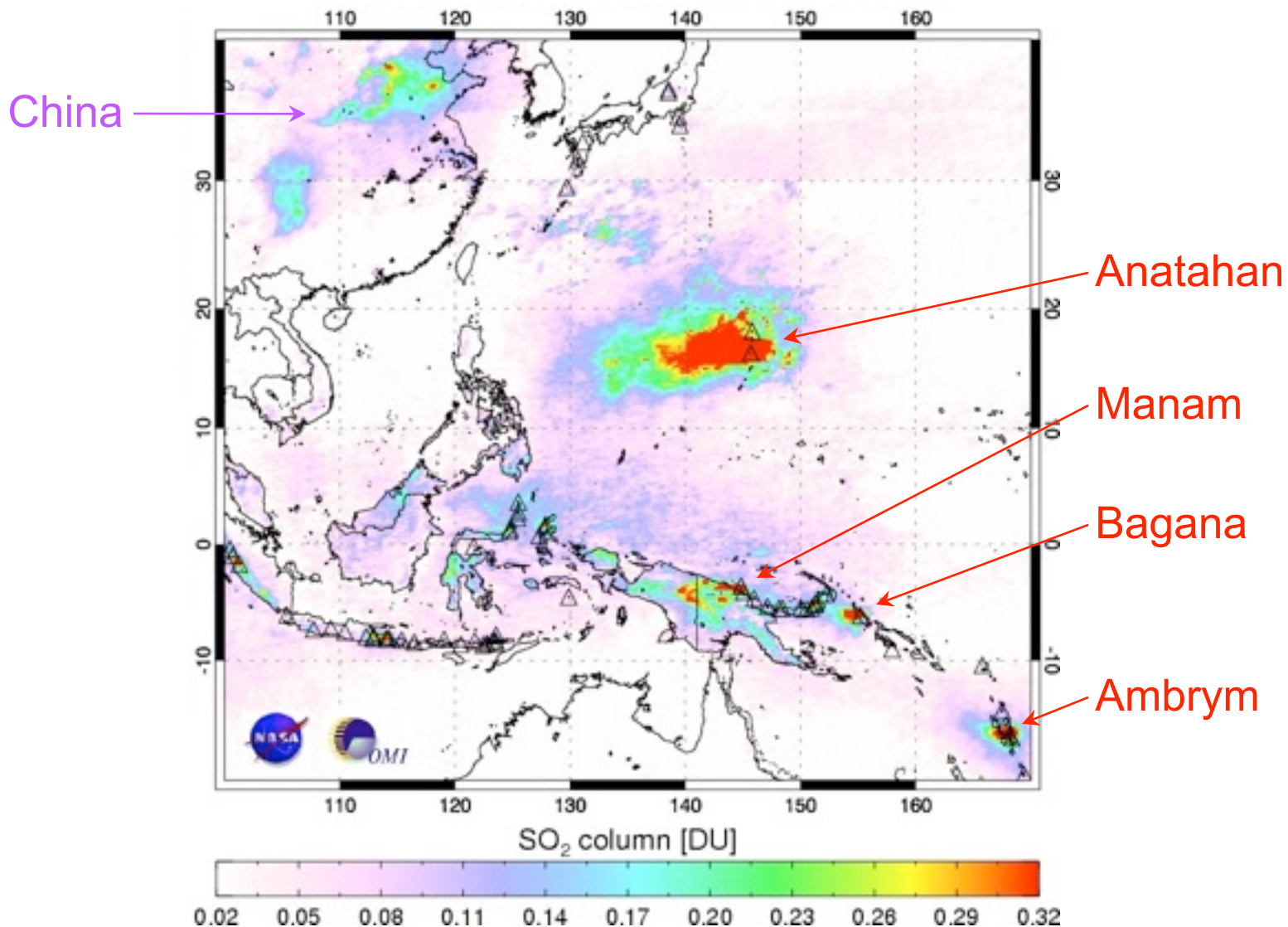


# Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)





# OMI annual average SO<sub>2</sub> in 2005: W. Pacific/S.E. Asia



# OMI annual average SO<sub>2</sub> in 2006: W. Pacific/S.E. Asia

