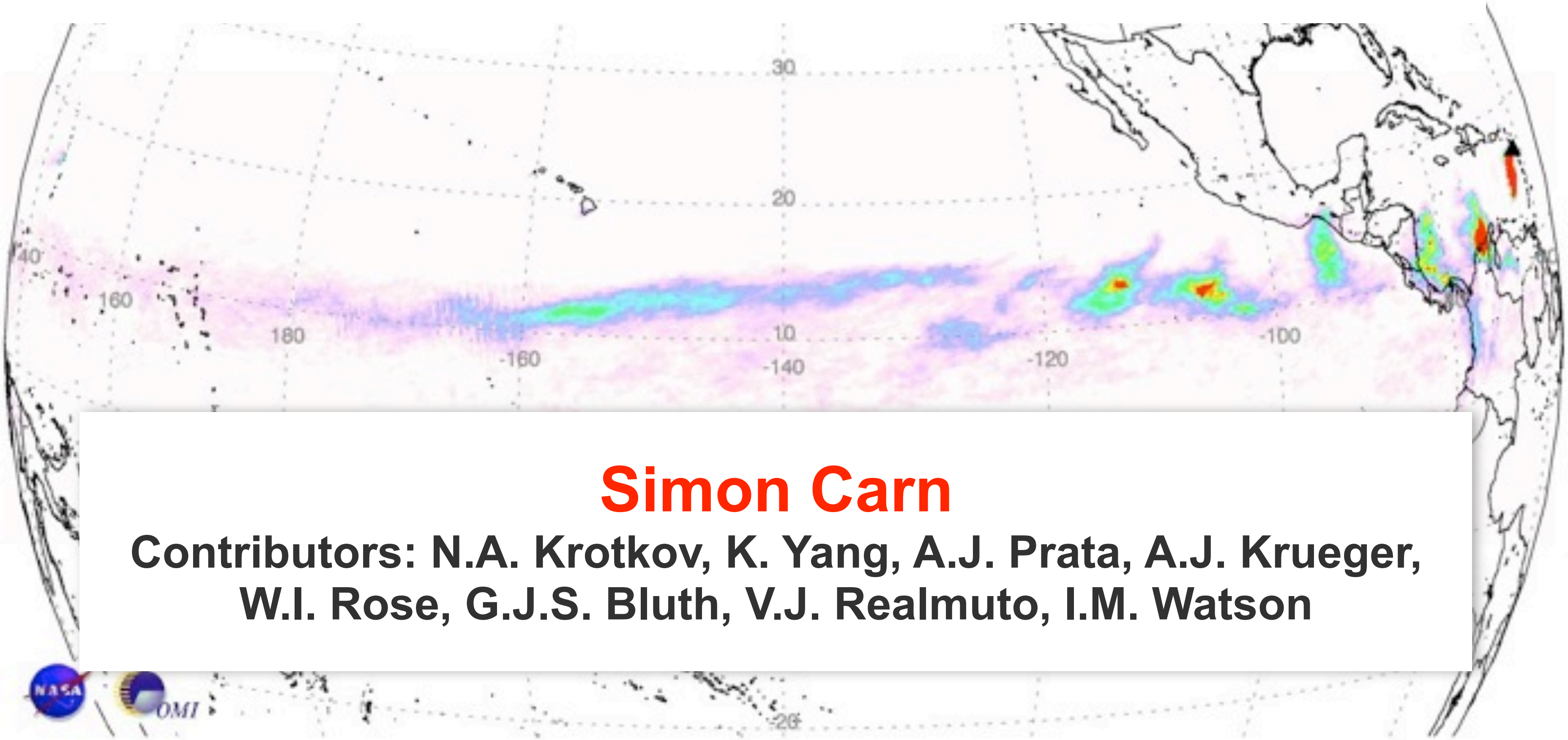
Remote Sensing of Volcanic Gas Emissions



Simon Carn

Contributors: N.A. Krotkov, K. Yang, A.J. Prata, A.J. Krueger, W.I. Rose, G.J.S. Bluth, V.J. Realmuto, I.M. Watson

NSF PASI, San José, Costa Rica, Jan 2011

Overview

- Motivation for volcanic gas measurements
- Development of satellite remote sensing of SO_2
- Remote sensing theory (focus on SO_2 measurements)
- Survey of space-based SO_2 sensors
    - UV sensors: OMI, TOMS, GOME-2
    - IR sensors: MODIS, ASTER, TOVS, AIRS, IASI
- Application of Aura/OMI SO_2 data to volcano monitoring
    - SO_2 burden calculations
    - Burdens vs. emission rates
- Satellite sensor synergy: NASA's A-Train
- Web access to near-real time data
- Lab exercise: SO_2 emissions from Latin American volcanoes

Motivation for volcanic SO_2 measurements

- SO_2 is the most abundant gas in volcanic emissions that can be easily measured by 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
  - 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)

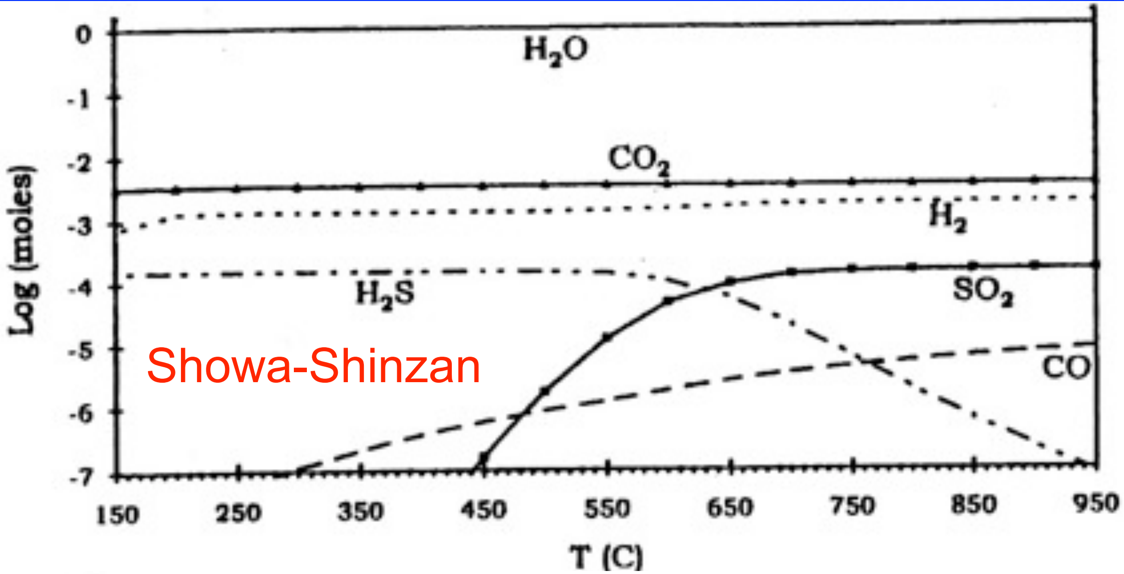
Volcanic gas compositions

mol%	Nyiragongo (DR Congo) RIFT	Kilauea* (Hawaii) HOTSPOT	Merapi* (Indonesia) SUBDUCTION	Etna* (Sicily) SUBDUCTIO N
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	-

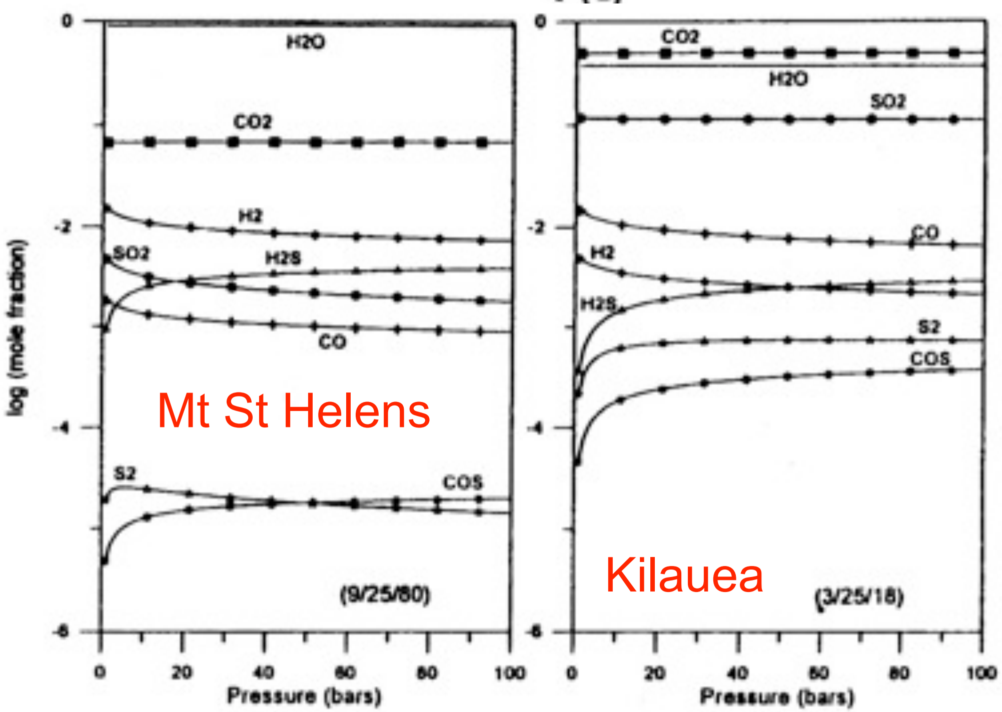
Trace constituents: CH_4, N_2, BrO, Zn, Cu, Hg, Au, As, Re, He, Ne, Ar…..

*Symonds *et al.* [1994]

Temperature and pressure effects on volcanic gas species



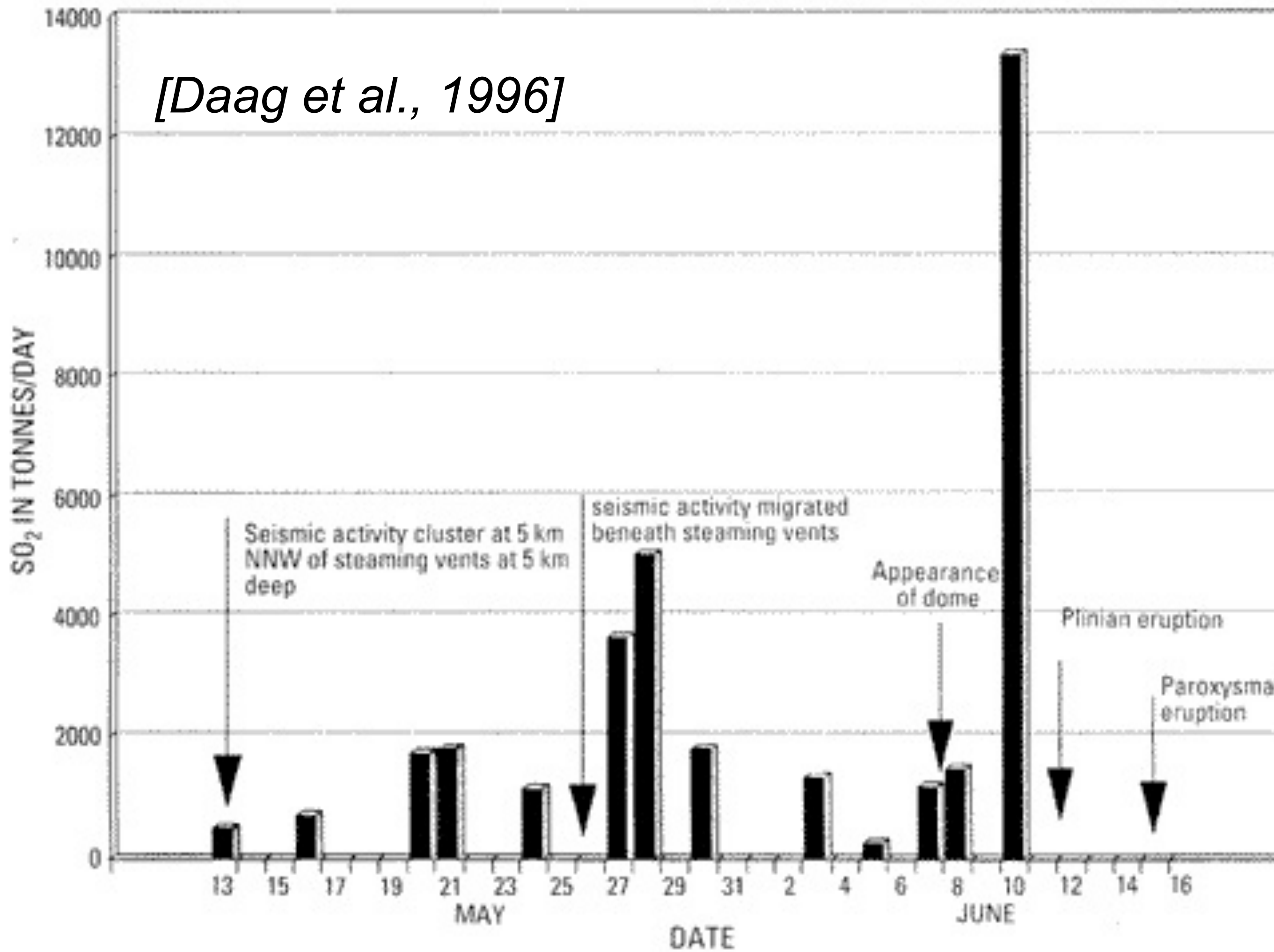
$$SO_2 + 3H_2 = H_2S + 2H_2O$$



$$\log (SO_2/H_2S) = \log K_T - 3 \log (H_2/H_2O) - \log P \cdot X_{H2O}$$

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

Pre-eruptive volcanic degassing



- Increase in SO_2 emissions prior to a major eruption

SO_2 flux and LP seismicity at Galeras (Colombia)

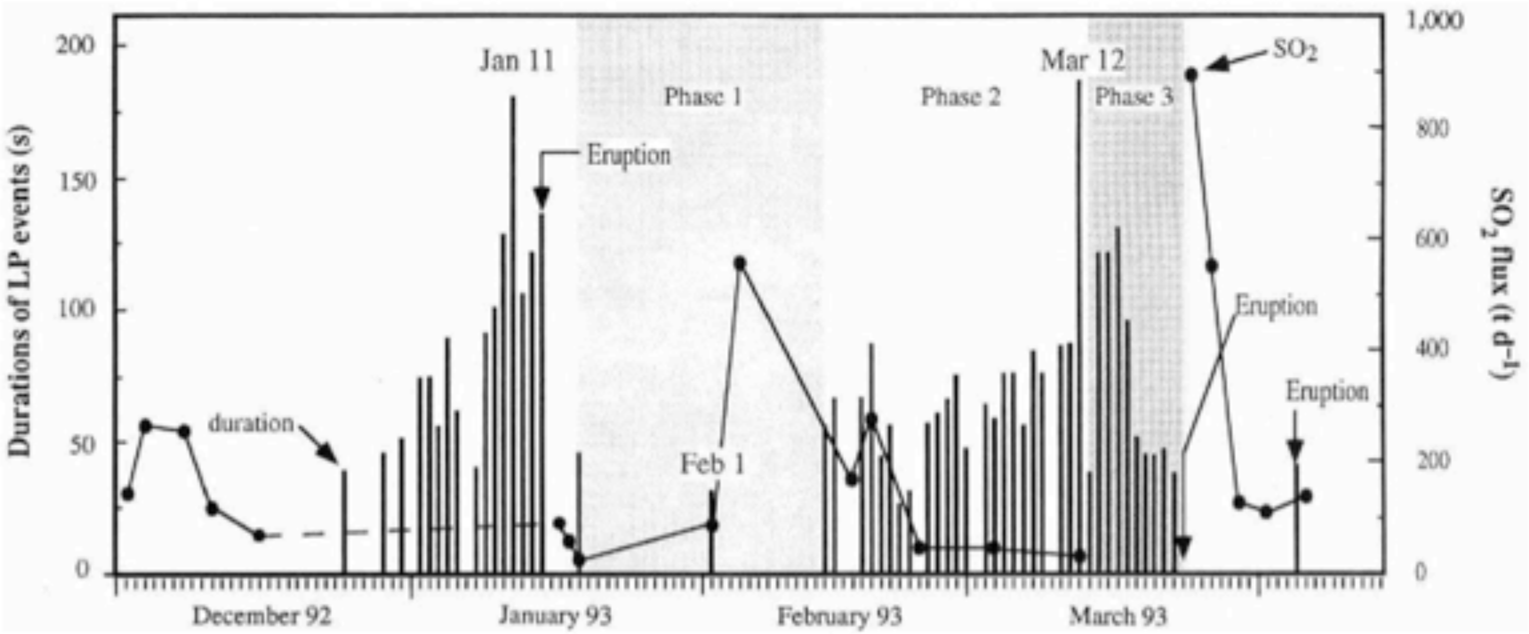
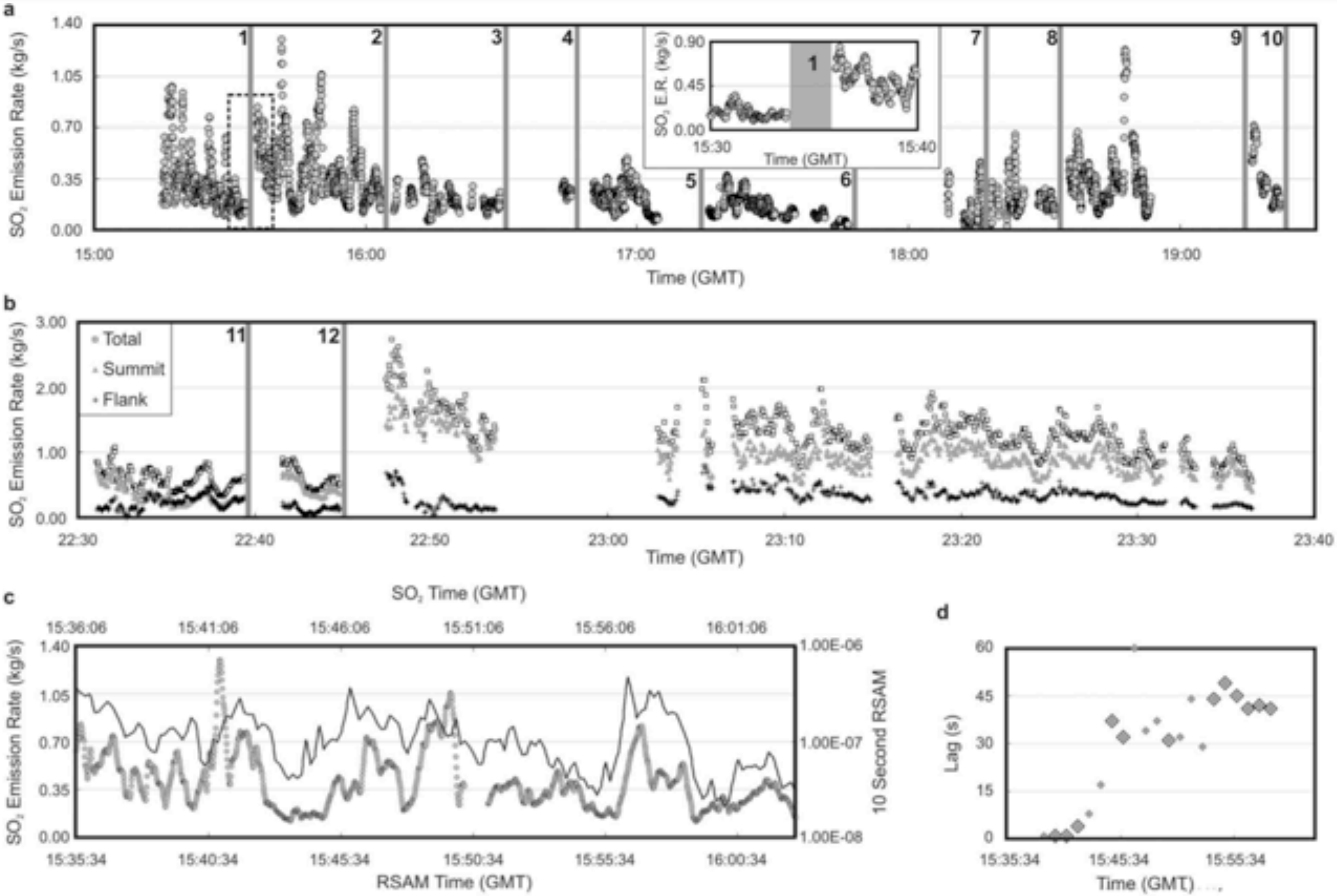


FIG. 2 SO_2 flux in metric tons per day (●) and durations of recorded long-period (≥22 s) events (vertical bars) plotted against time, also showing the eruptions during the same time period. The SO_2 flux is measured using correlation spectrometer (COSPEC) methodology[15]. Uncertainty depends mostly on recorded wind speeds. The error at Galeras is assumed to be ±20%, in general, and ±40%, in the worst case. True SO_2 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_2 emissions and RSAM at Fuego (Guatemala)

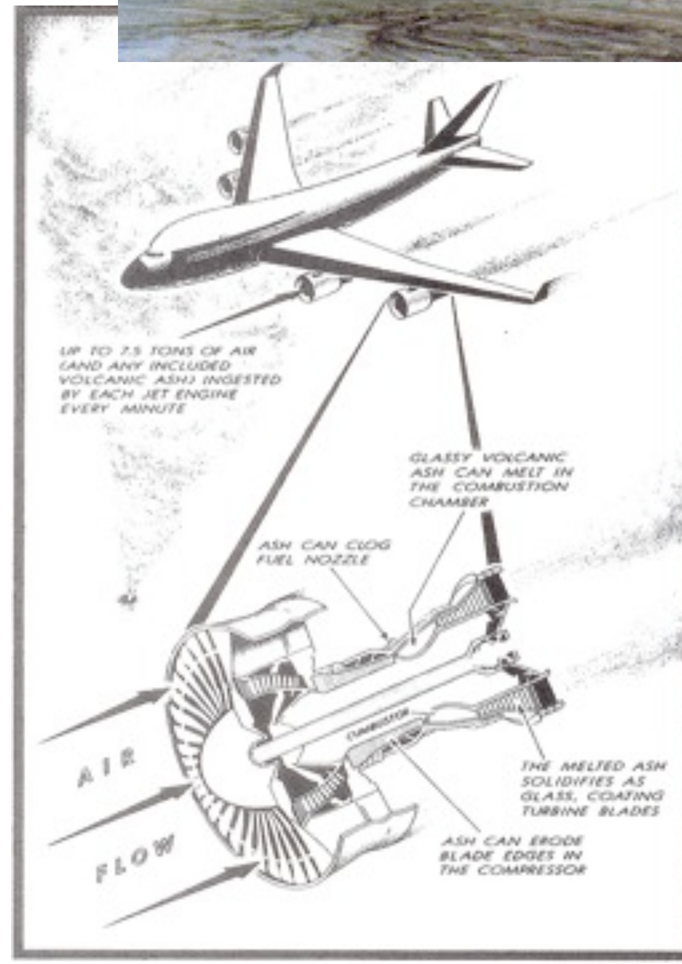


[Nadeau et al., GRL, 2011]

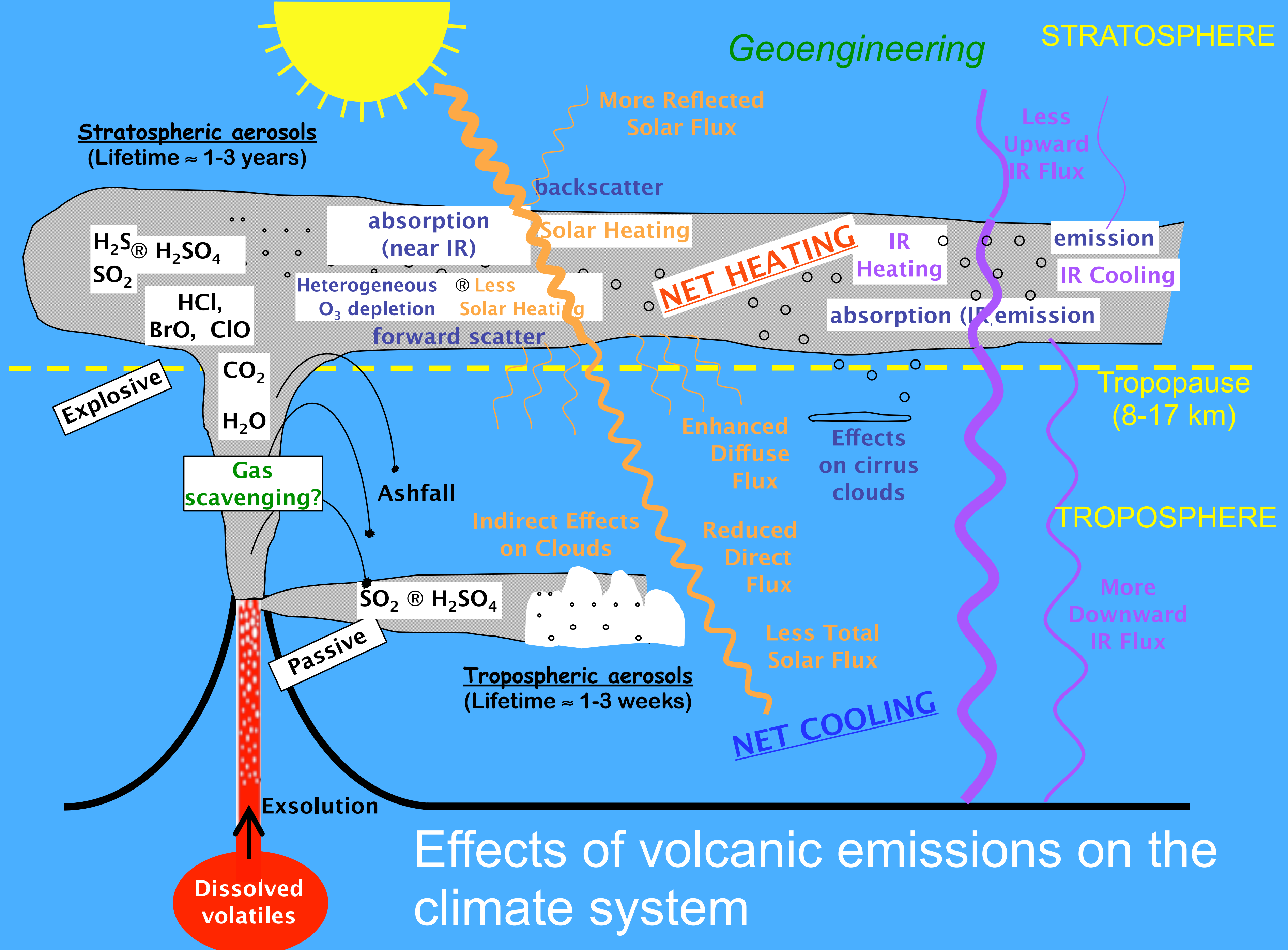
Michigan Tech
Create the Future

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 – SO_2 data valuable
  - Tracking/forecast of cloud position and altitude – SO_2 valuable for cloud tracking

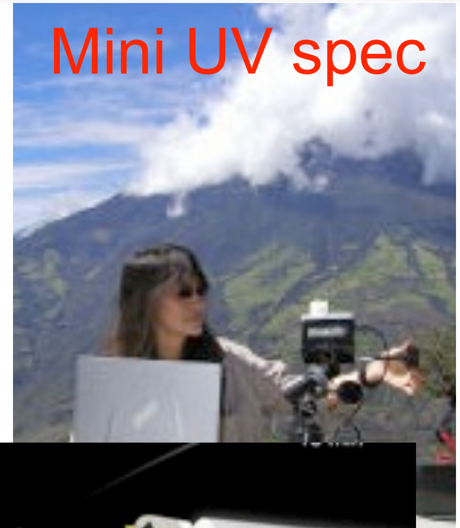


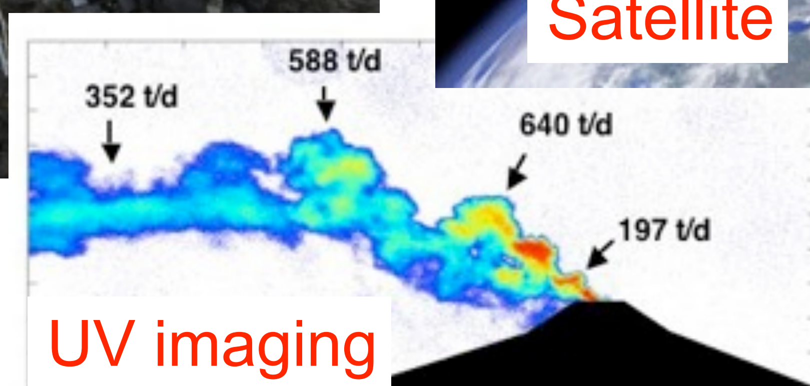
From: Volcanoes; Crucibles of Change, Princeton U. Press, Princeton, 1997.



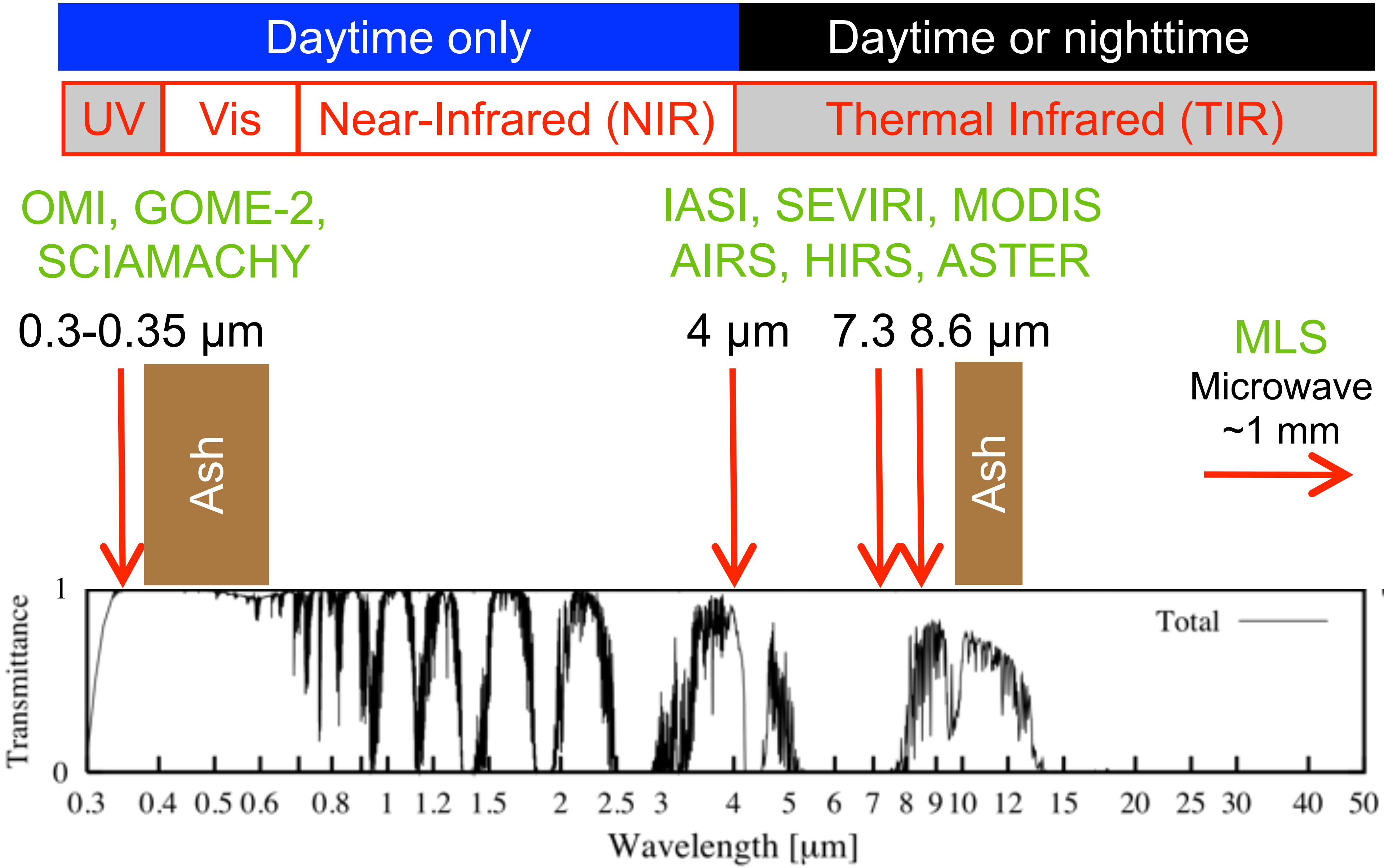
Effects of volcanic emissions on the climate system

Volcanic gas monitoring techniques

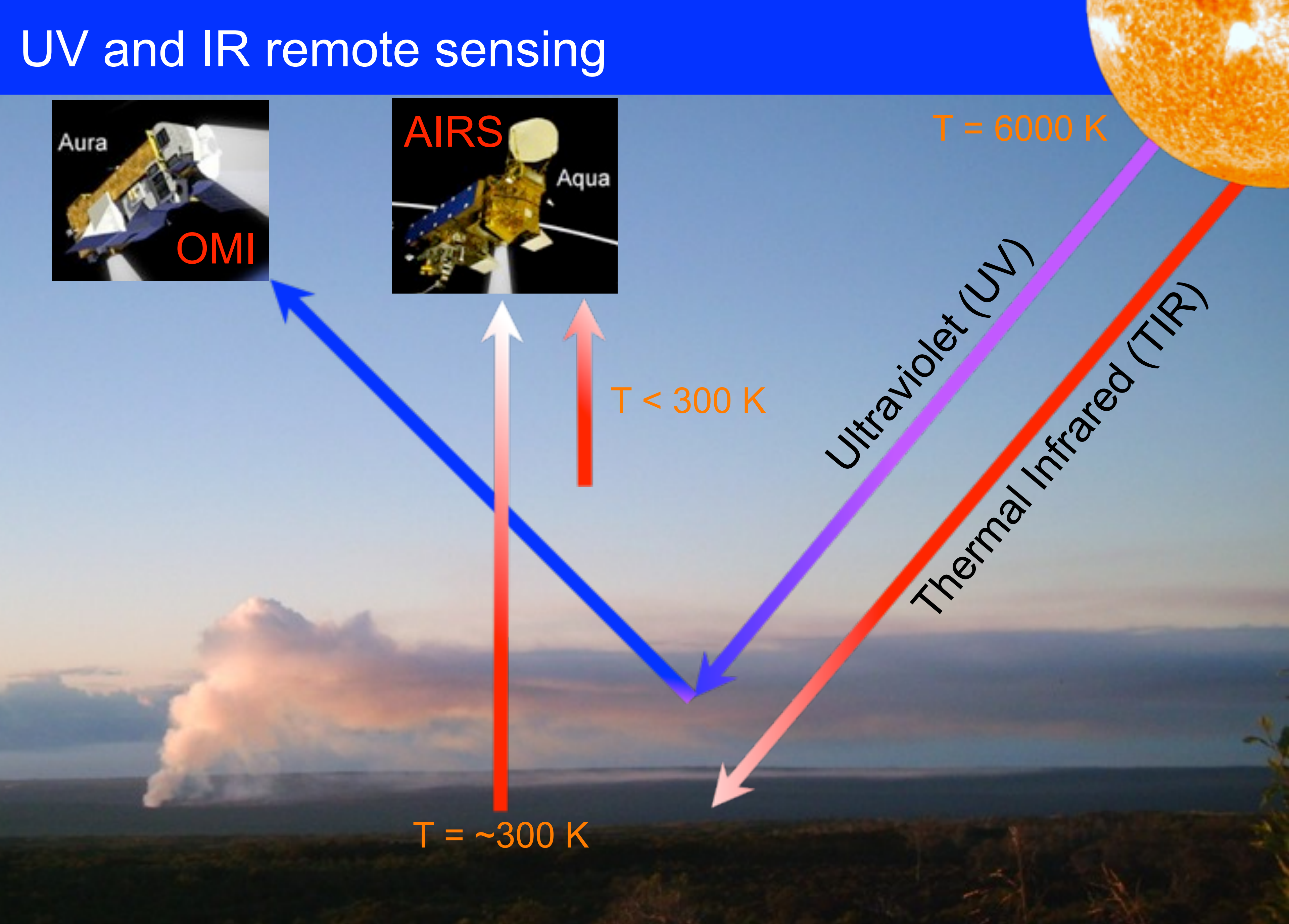




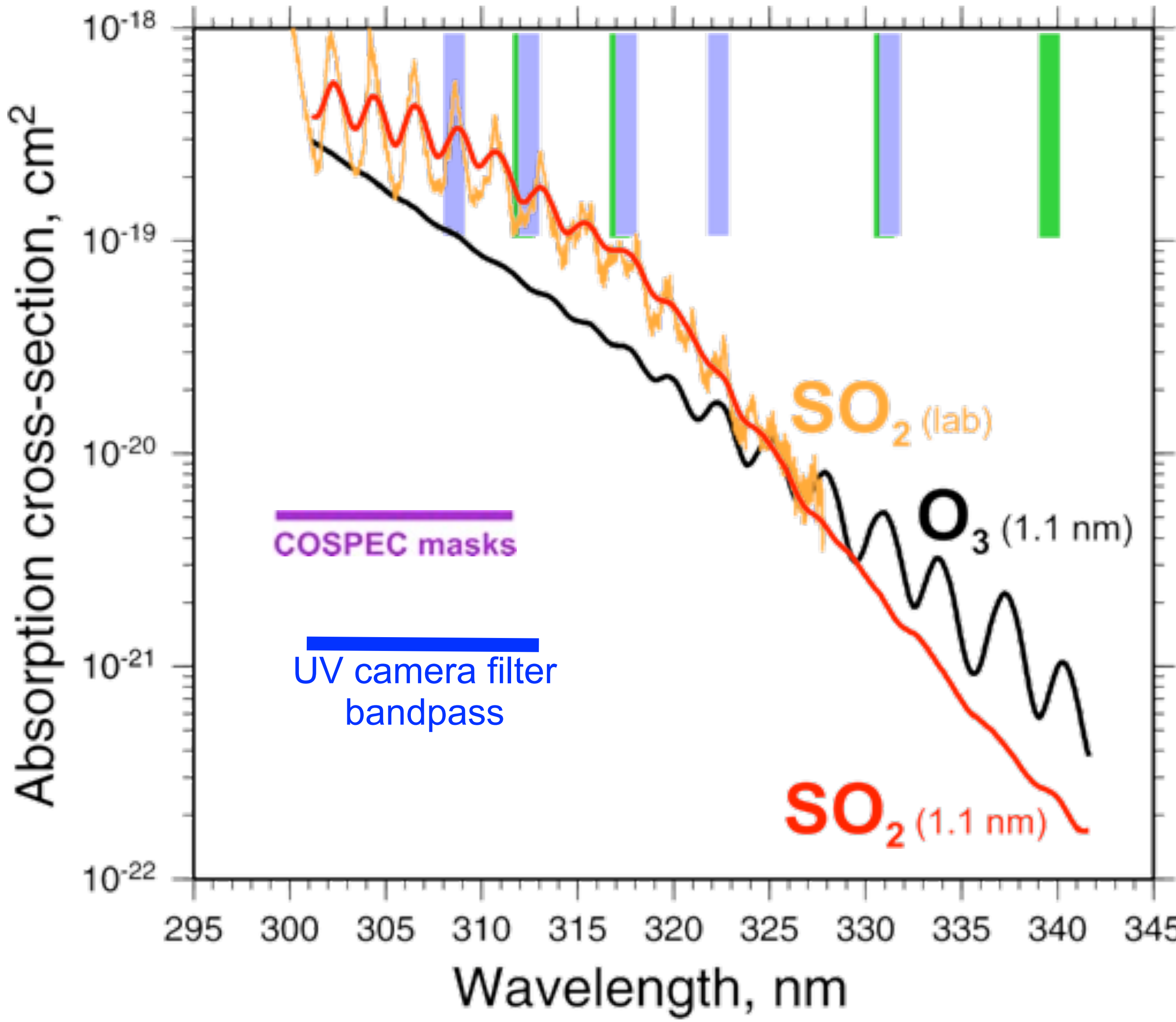
Electromagnetic spectrum – SO_2 absorption



UV and IR remote sensing



UV SO_2 and O_3 absorption spectra and instrument bands

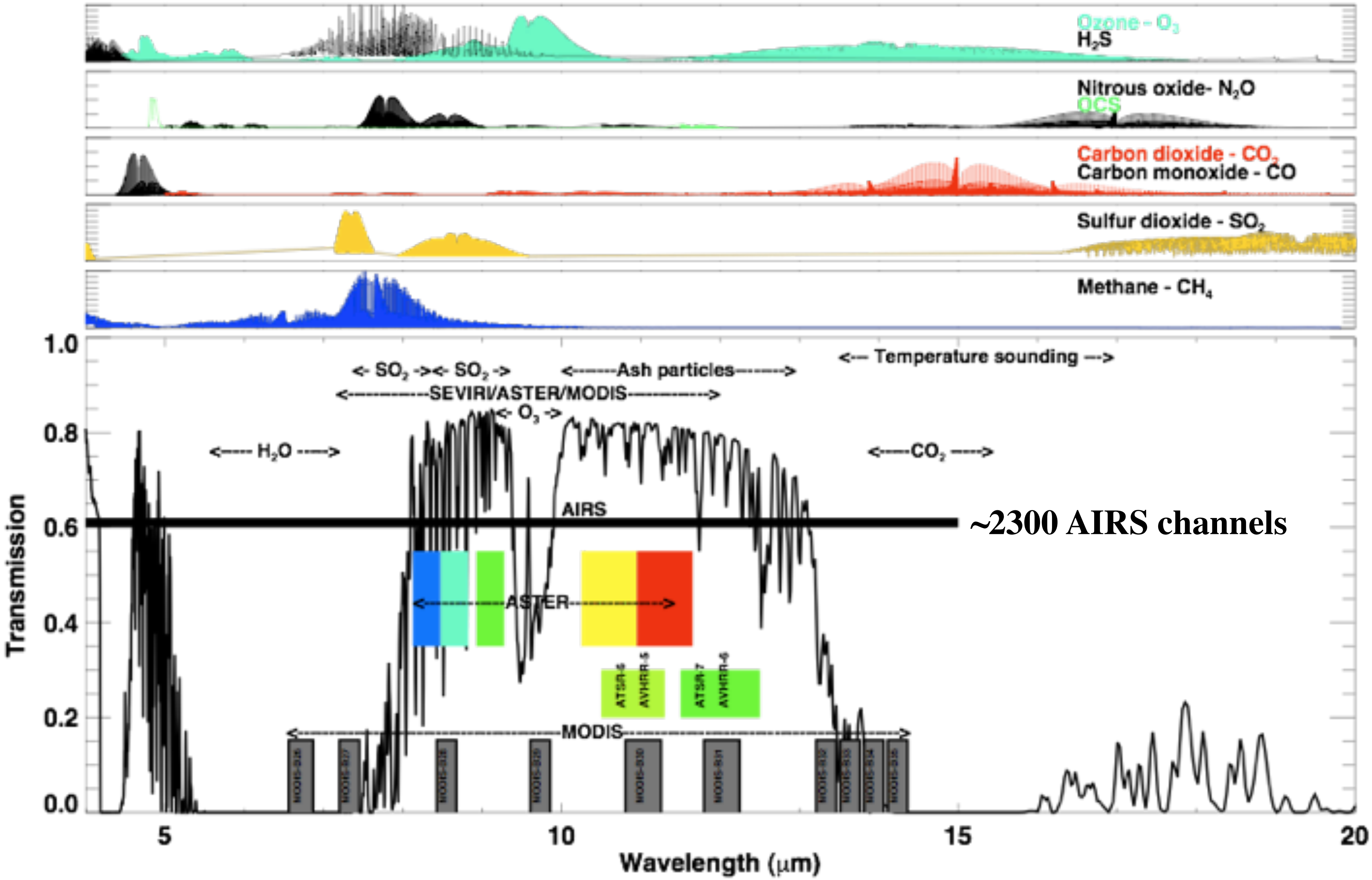


TOMS, SBUV
Discrete bands

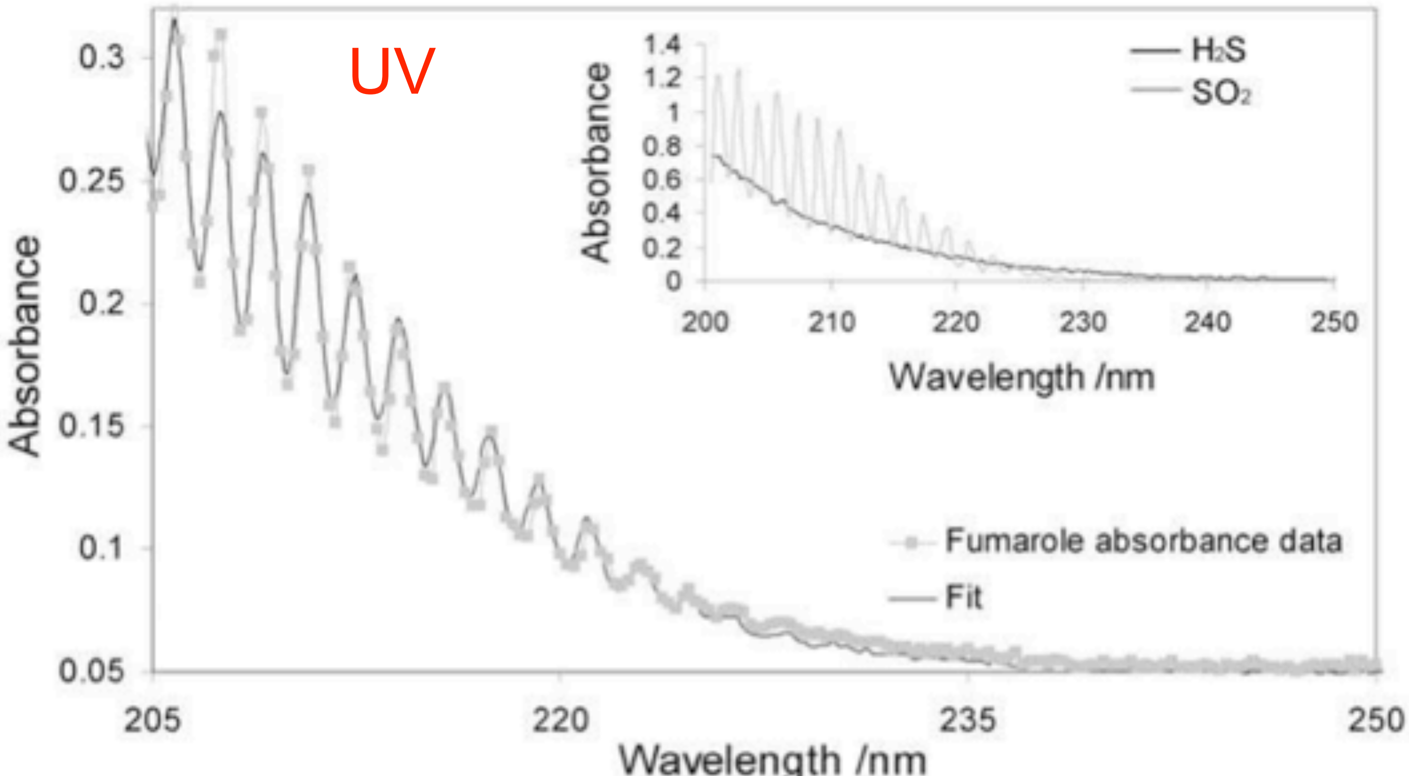
GOME-2, SCIA, OMI, OMPS
Full spectrum

- Spectral resolution affects sensitivity

IR-active trace gases and instrument channels



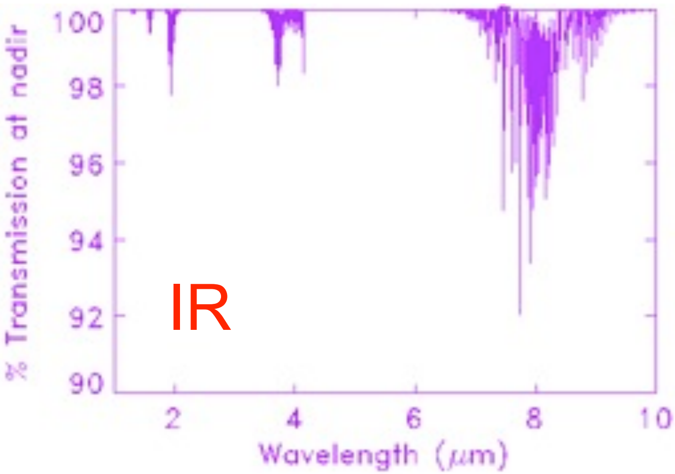
What about H_2S?



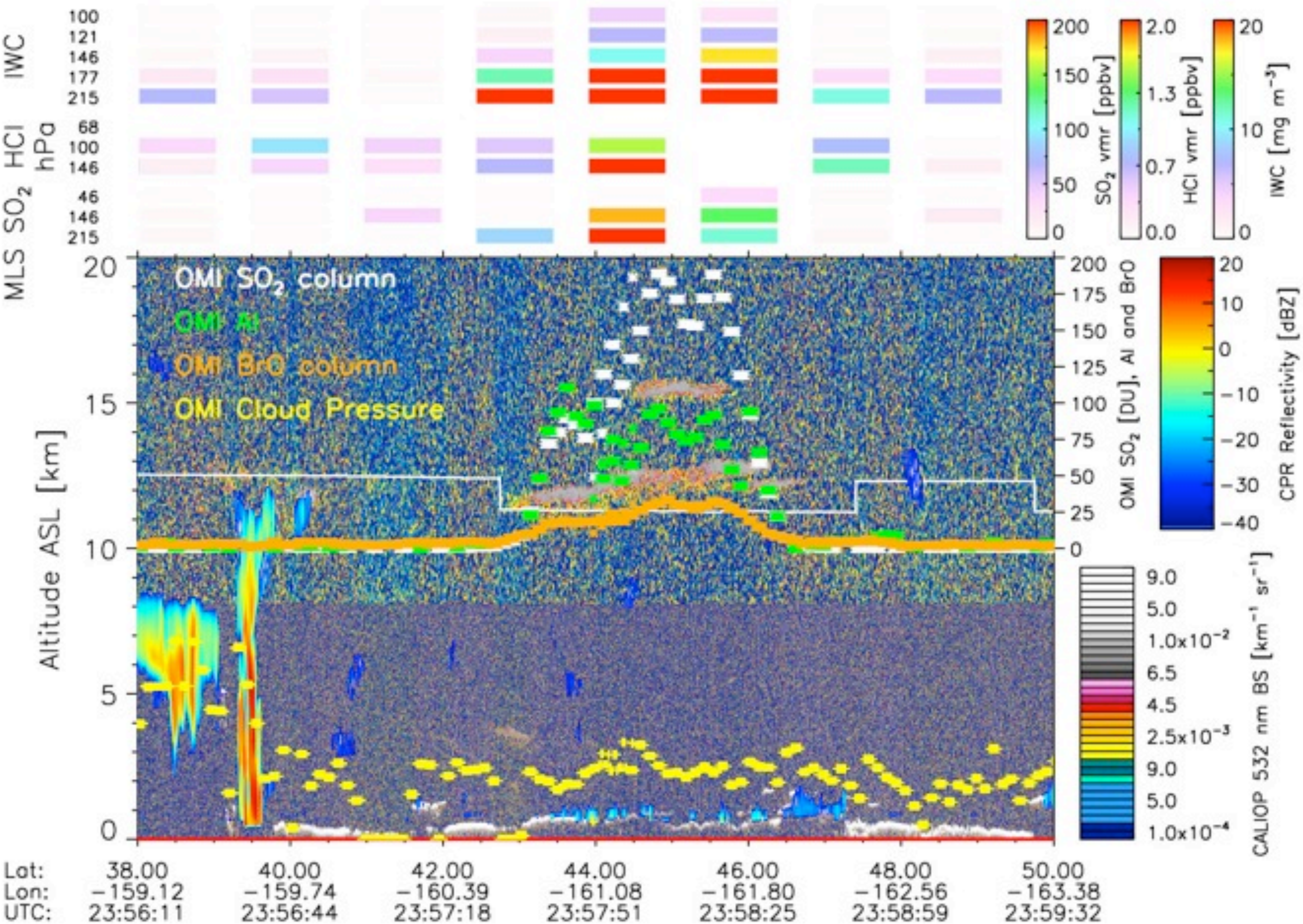
$SO_2 + 3H_2 =$
$H_2S + 2H_2O$

[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

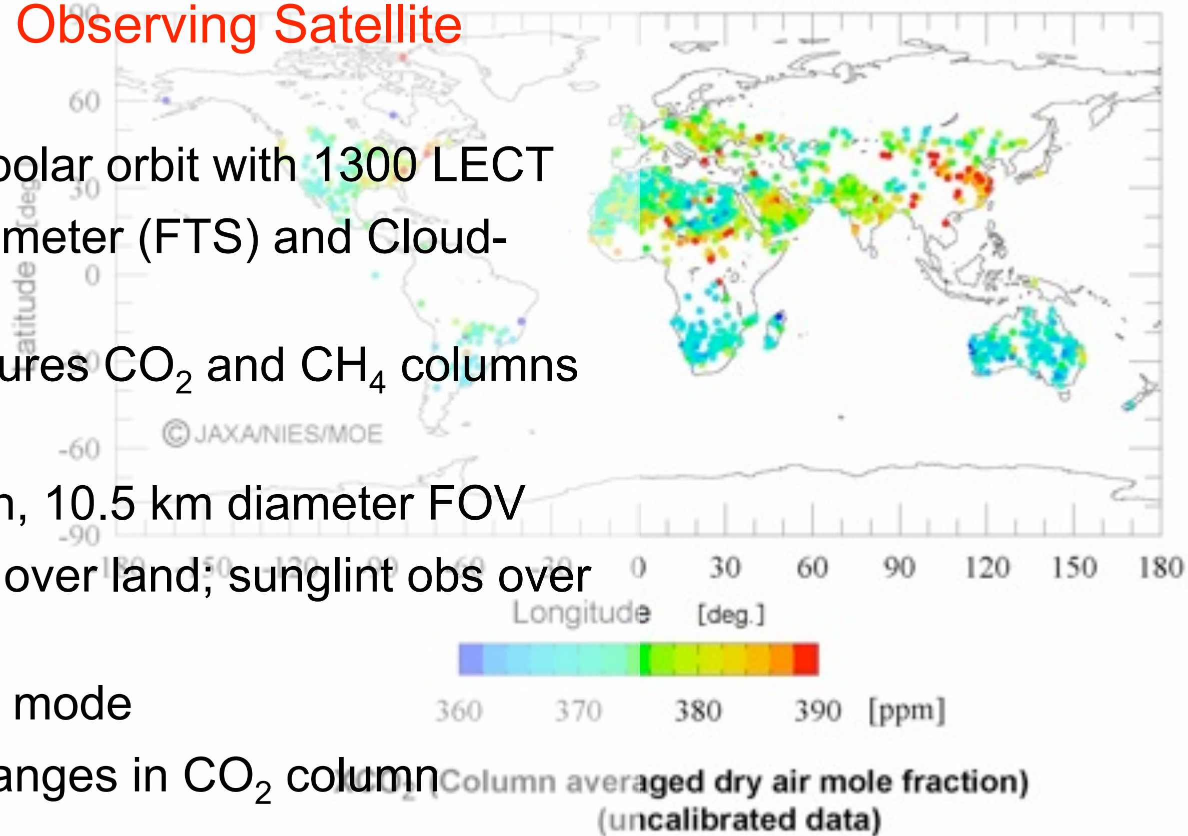


A-Train observations: Kasatochi, August 9, 2008

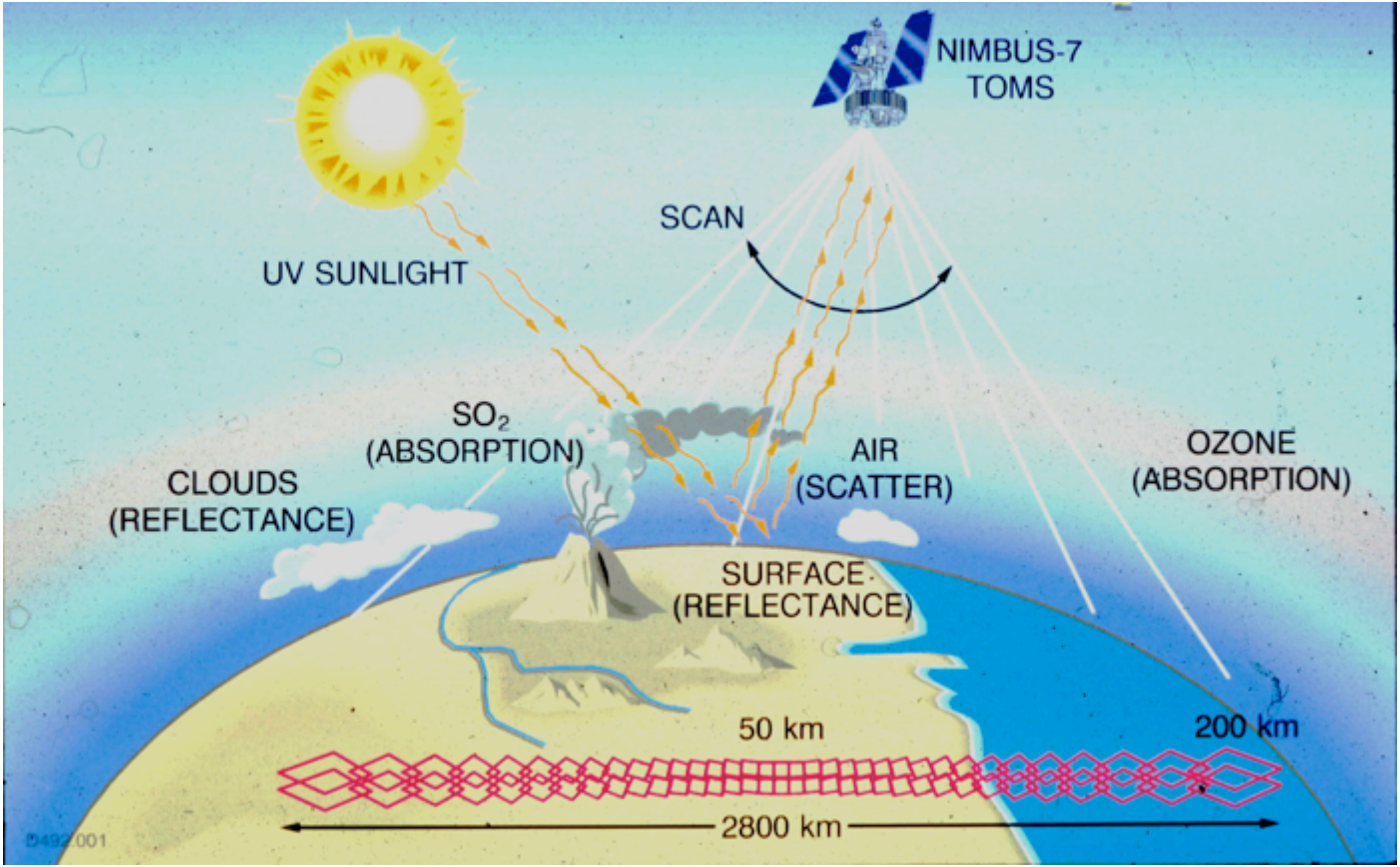


GOSAT: Measuring CO_2 from space

- 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_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



UV Backscatter instrument - basic operation



Forward-model SO_2 retrieval (e.g., TOMS, OMI)

- Simulate at-satellite UV radiances as a function of viewing geometry, latitude, column O_3 and SO_2 amounts, surface pressure and reflecting surface conditions, using a radiative transfer model

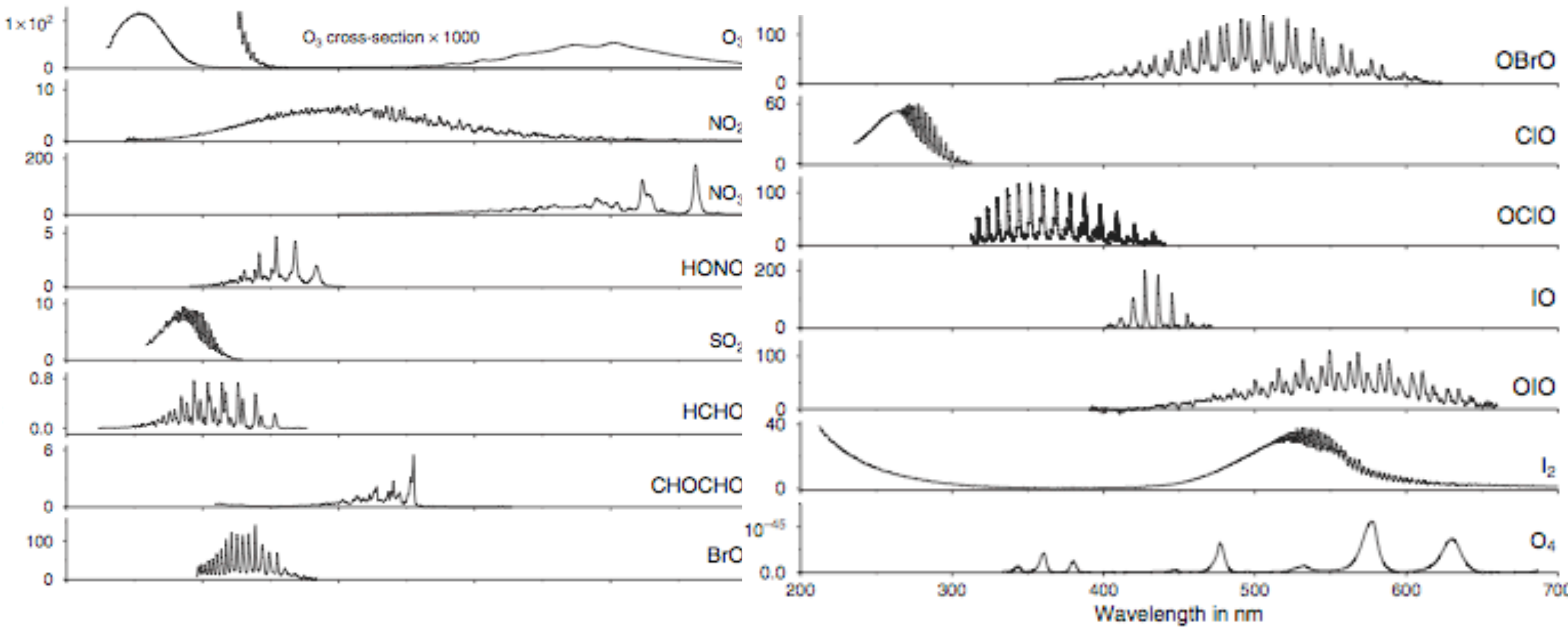
- Compare measured normalized radiances with theoretical radiances calculated for the conditions of the measurement

- Derive column O_3 and SO_2 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)

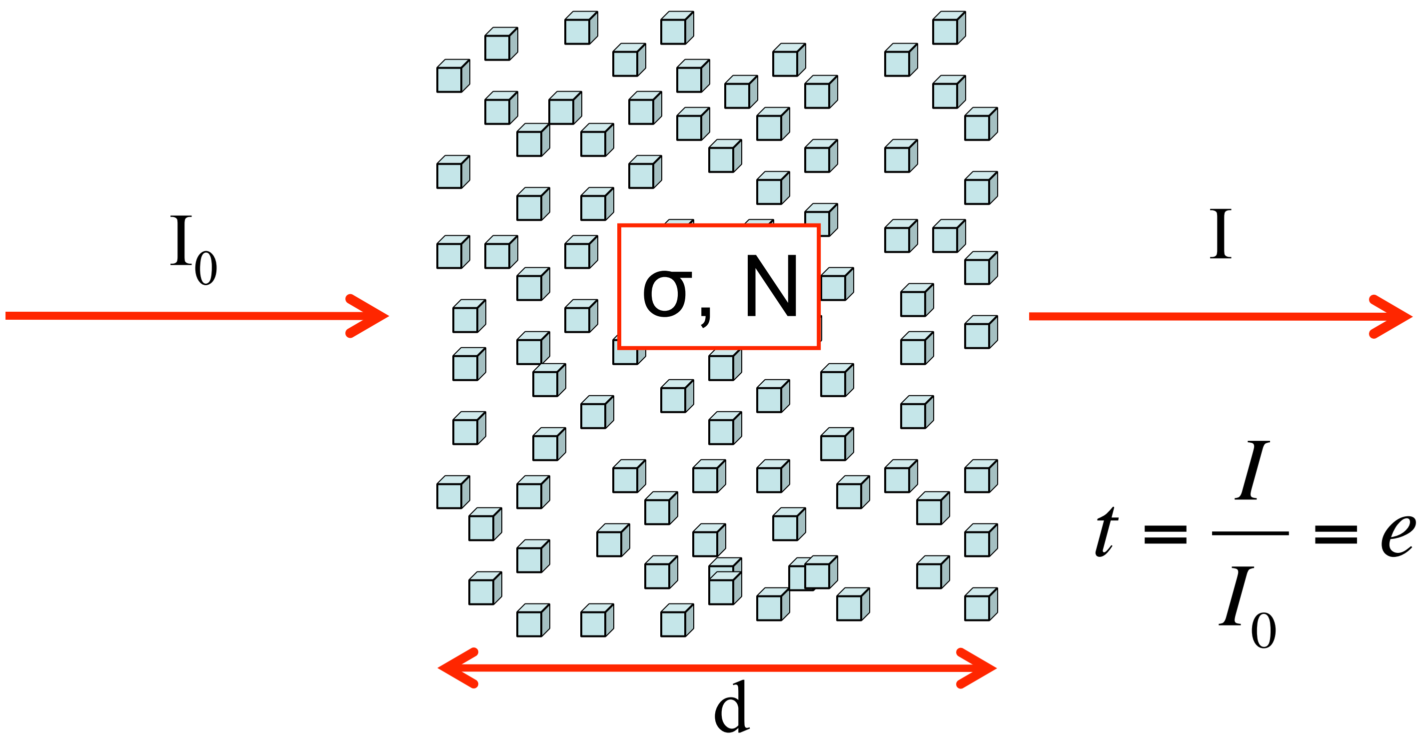


Absorption cross-sections of trace gases in the 200-700 nm wavelength range

Michigan Tech
Create the Future

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}):



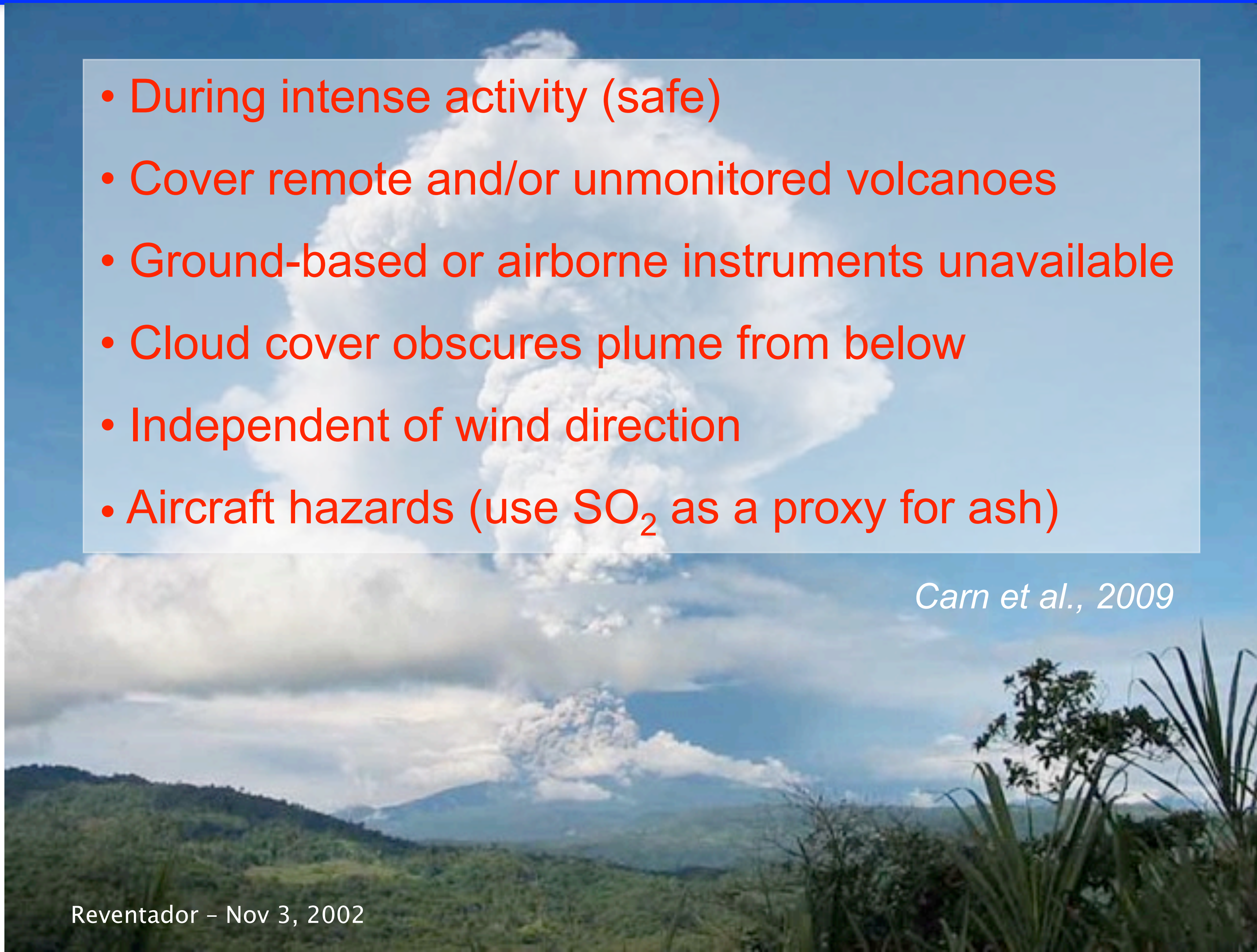
$$t = \frac{I}{I_0} = e^{-\sigma N d}$$

- 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 SO_2 as a proxy for ash)

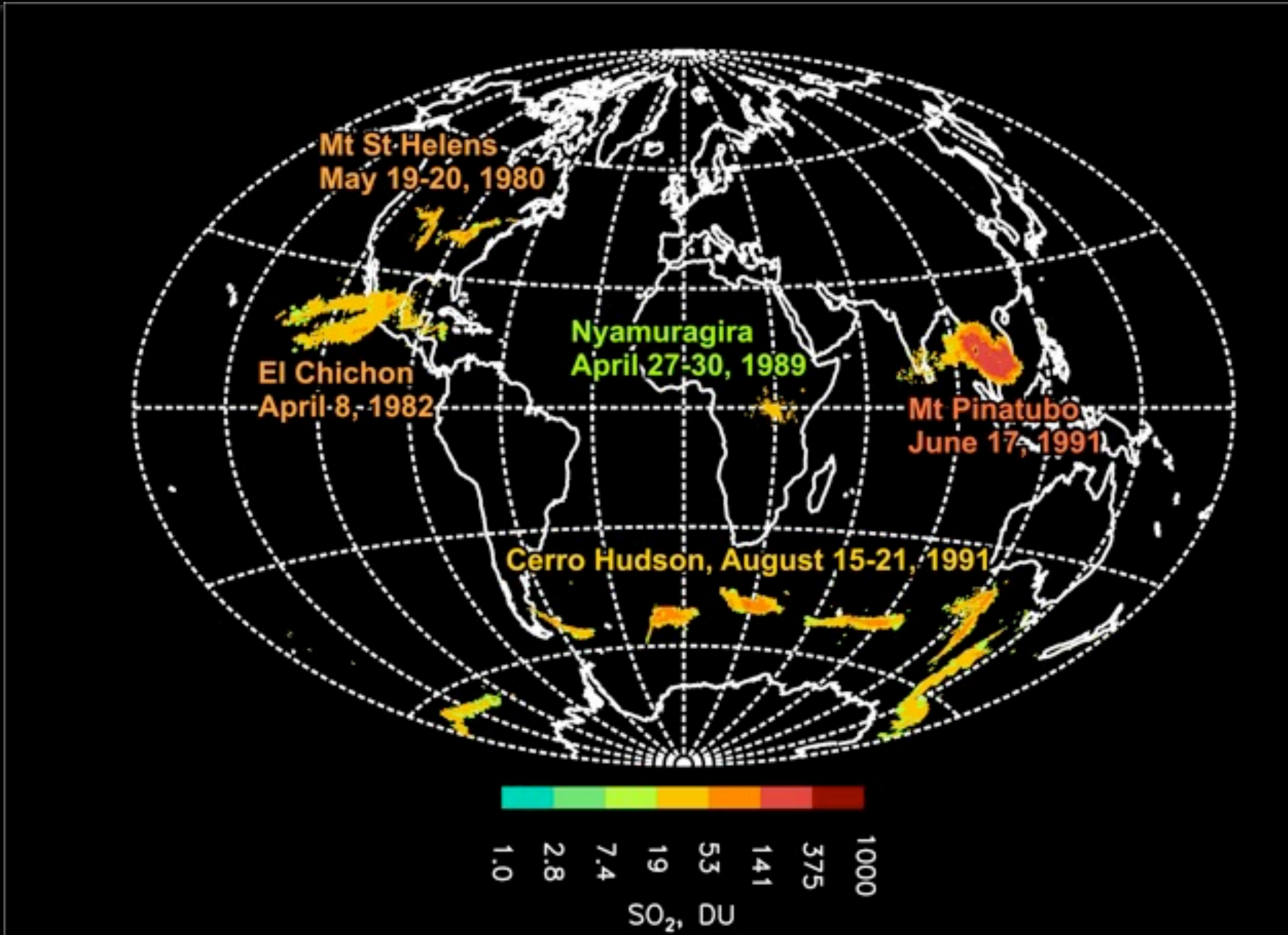
Carn et al., 2009



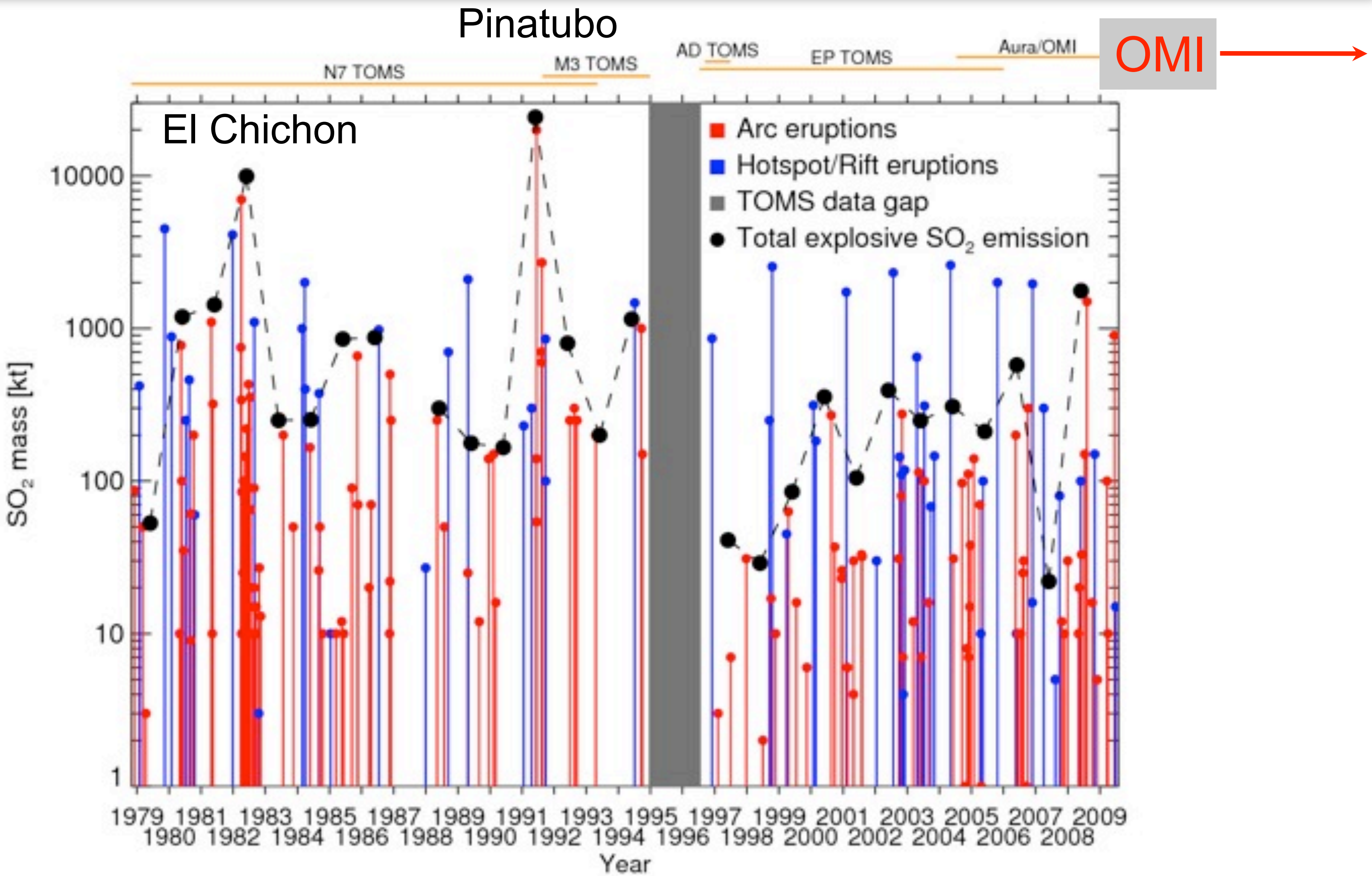
Detection of April 1982 El Chichon SO_2 cloud with the Total Ozone Mapping Spectrometer (TOMS)

[*Krueger, Science, 1983*]

Volcanic SO_2 clouds measured by TOMS



Volcanic SO_2 Emissions Inventory



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

Exploiting A-Train synergy for volcanic cloud studies

Aura

OMI - SO_2, O_3, NO_2, BrO

TES - SO_2

MLS - strat. SO_2, HCl, O_3

Aqua

MODIS - SO_2, ash, sulfate

AIRS - UTLS SO_2, aerosols, SO_2 profile?

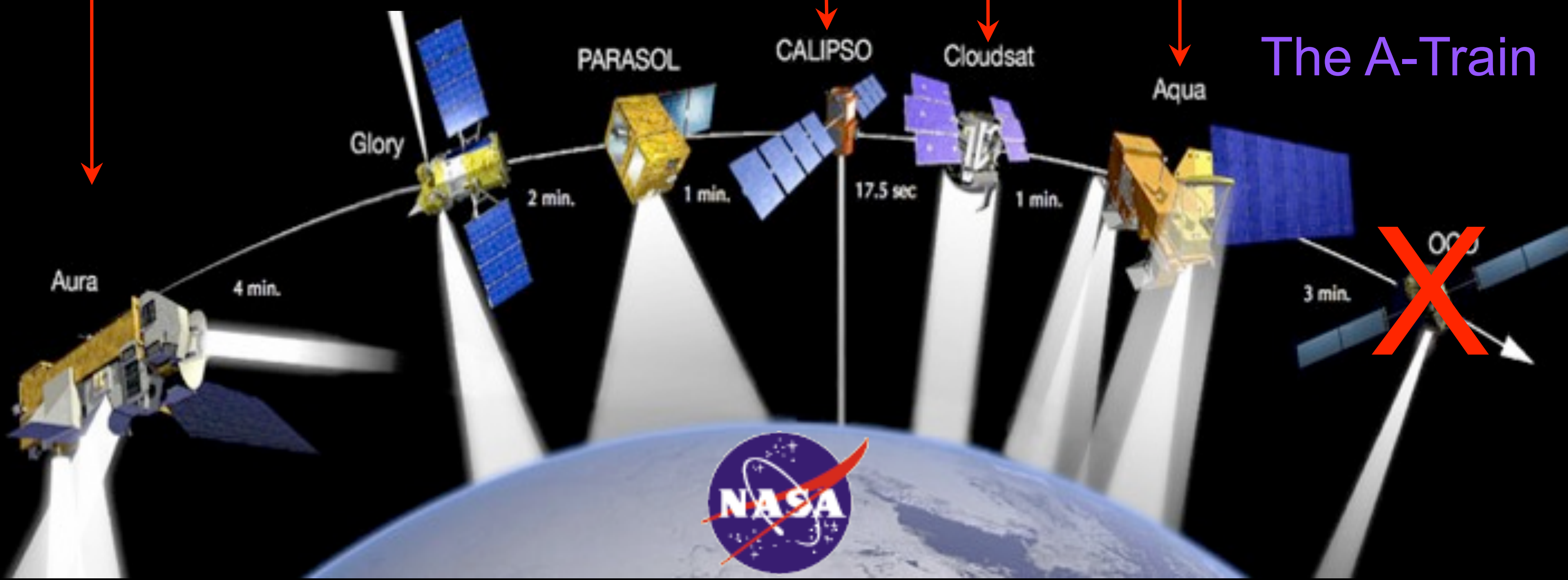
CloudSat

CPR – precipitation, hydrometeors

CALIPSO

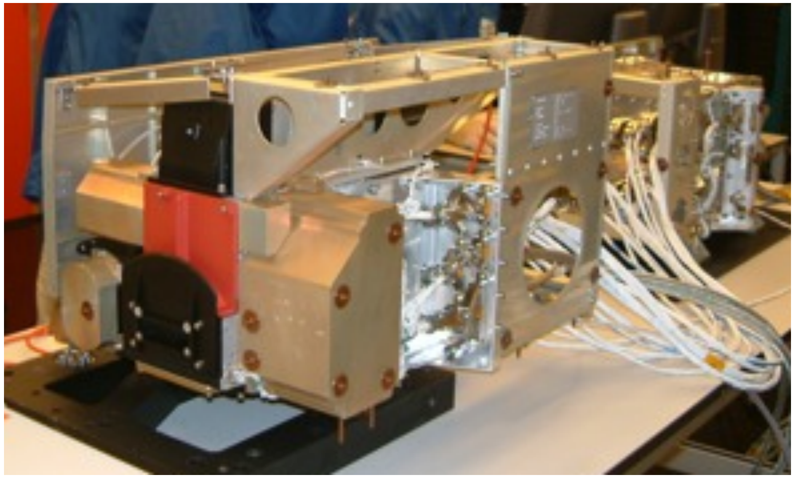
CALIOP - cloud altitude, aerosol phase/type

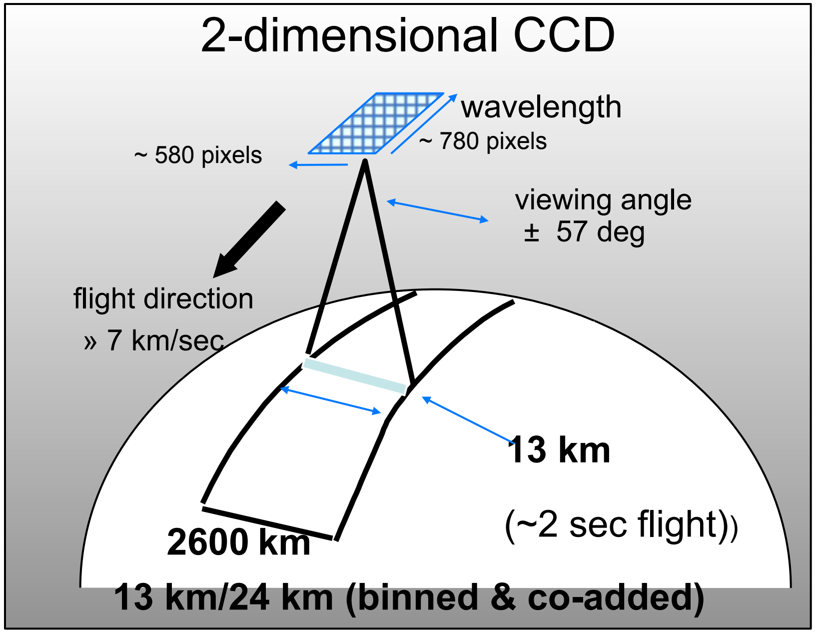
The A-Train



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_2 measurements with sensitivity to the lower troposphere (i.e., passive degassing)





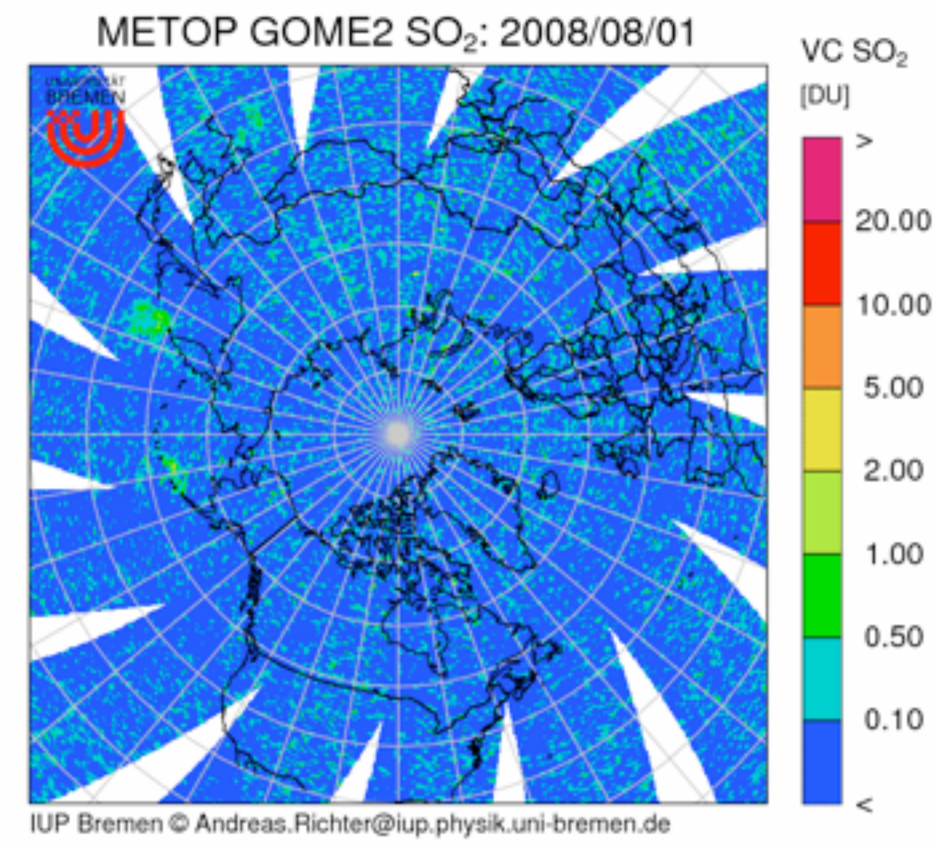
Michigan Tech Create the Future

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_2, ash
  - Infrared Atmospheric Sounding Interferometer (IASI) – SO_2, ash
  - High-resolution Infrared Radiation Sounder-4 (HIRS/4) – SO_2, ash
  - Advanced Very High Resolution Radiometer (AVHRR) – ash, IR hot spots

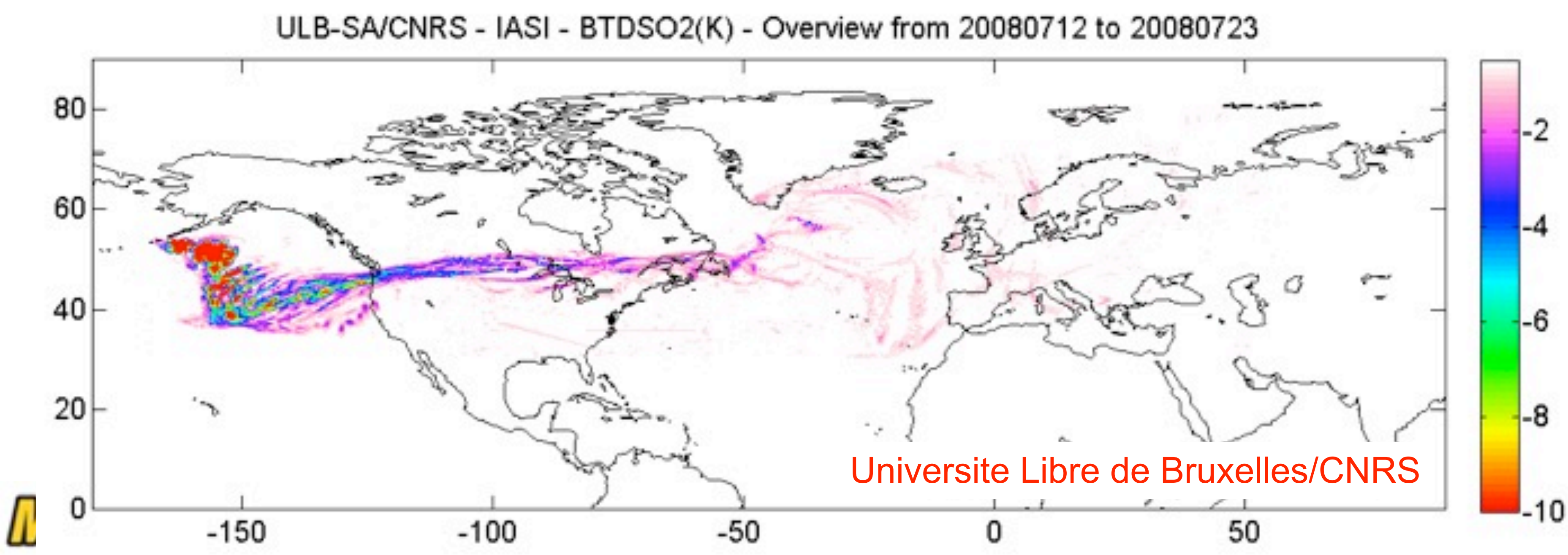
Global Ozone Monitoring Experiment-2 (GOME-2)

- 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_2 sensitivity
- Can detect small eruptions and strong degassing



Infrared Atmospheric Sounding Interferometer (IASI)

- 3.4 – 15 µm (infrared) wavelengths
- High spectral resolution, Fourier transform interferometer
- Mapping and vertical profiling of SO_2 possible
- 25 km horizontal resolution, 1 km vertical resolution
- Covers 3 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



Up to 7 daily SO_2 measurements from UV/IR sensors

Satellites equatorial overpass solar local time

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

Michigan Tech
Create the Future

Satellite instruments - UV

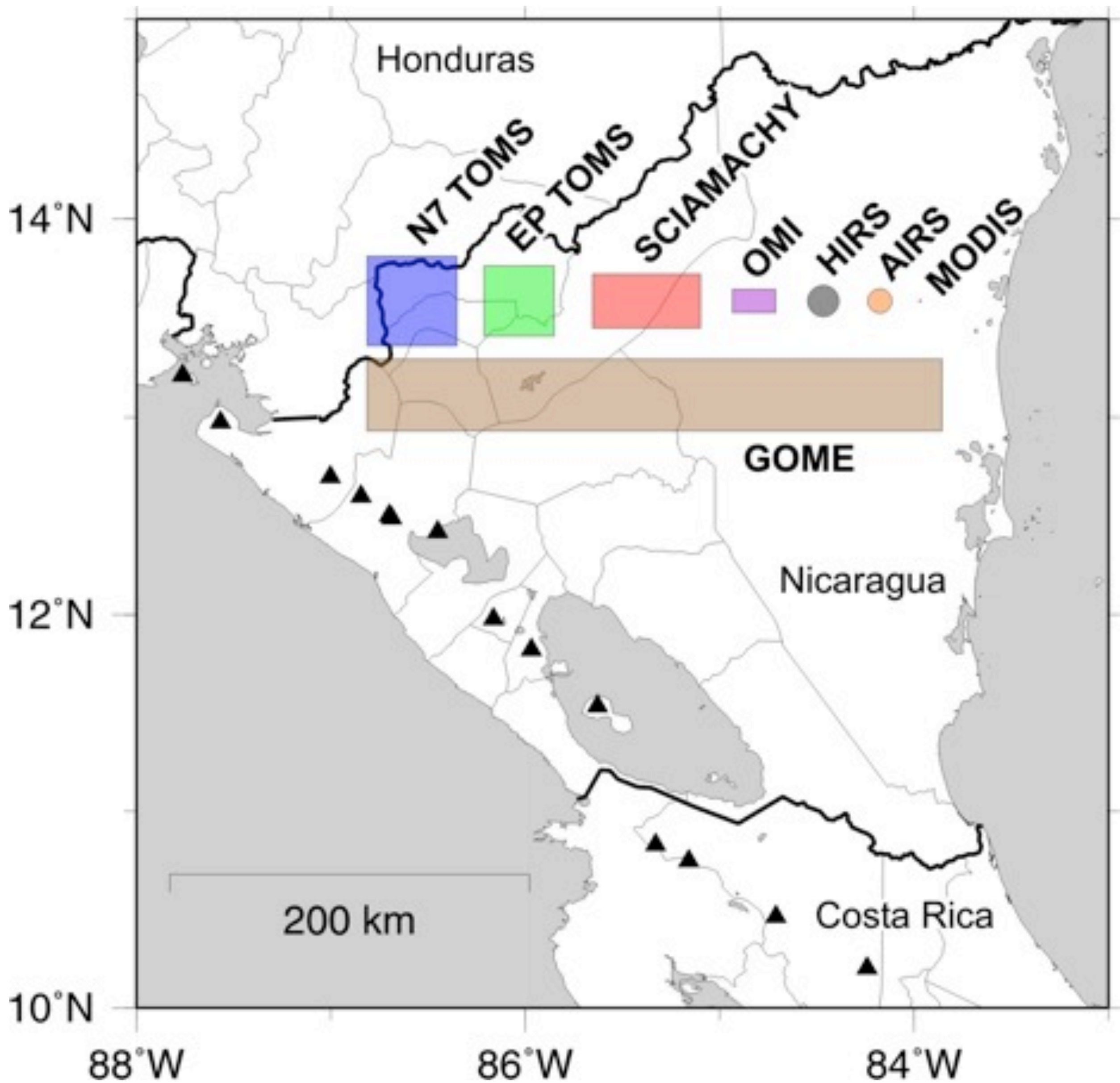
Instrument	Satellite(s)	Data coverage dates	Daily global coverage?
Total Ozone Mapping Spectrometer (**TOMS**)	Nimbus-7, Meteor-3, ADEOS, Earth Probe	Nov 78 – Dec 94 Jul 96 – Dec 2005	Yes
Global Ozone Monitoring Experiment (**GOME**)	European Remote Sensing Satellite (ERS-2)	July 95 – present	No
Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (**SCIAMACHY**)	European Environmental Satellite (Envisat-1)	Sept 03 – present	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)	2011?	Yes

Operational SO_2 data products

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

Satellite instrument footprints (nadir)



UV instrument SO_2 sensitivity

Instrument	Footprint area (km^2)	Sensitivity (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

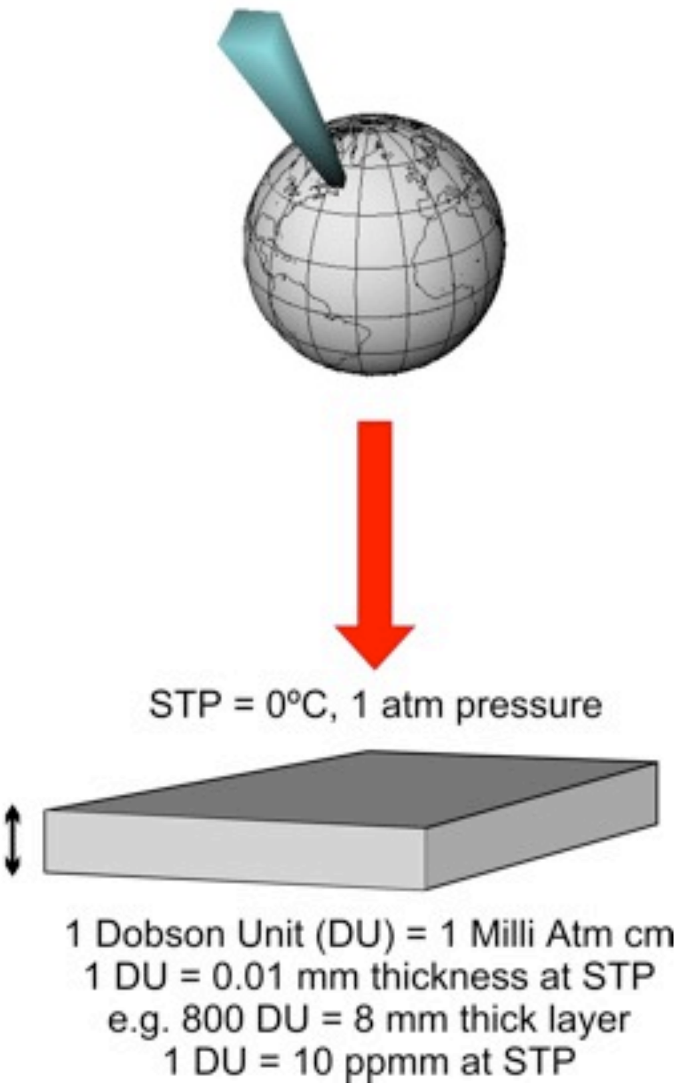
Michigan Tech
Create the Future

IR instrument SO_2 sensitivity

Instrument	Footprint area (km^2)	Sensitivity (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)

Units for SO_2 column amount measurements



- 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
  - 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

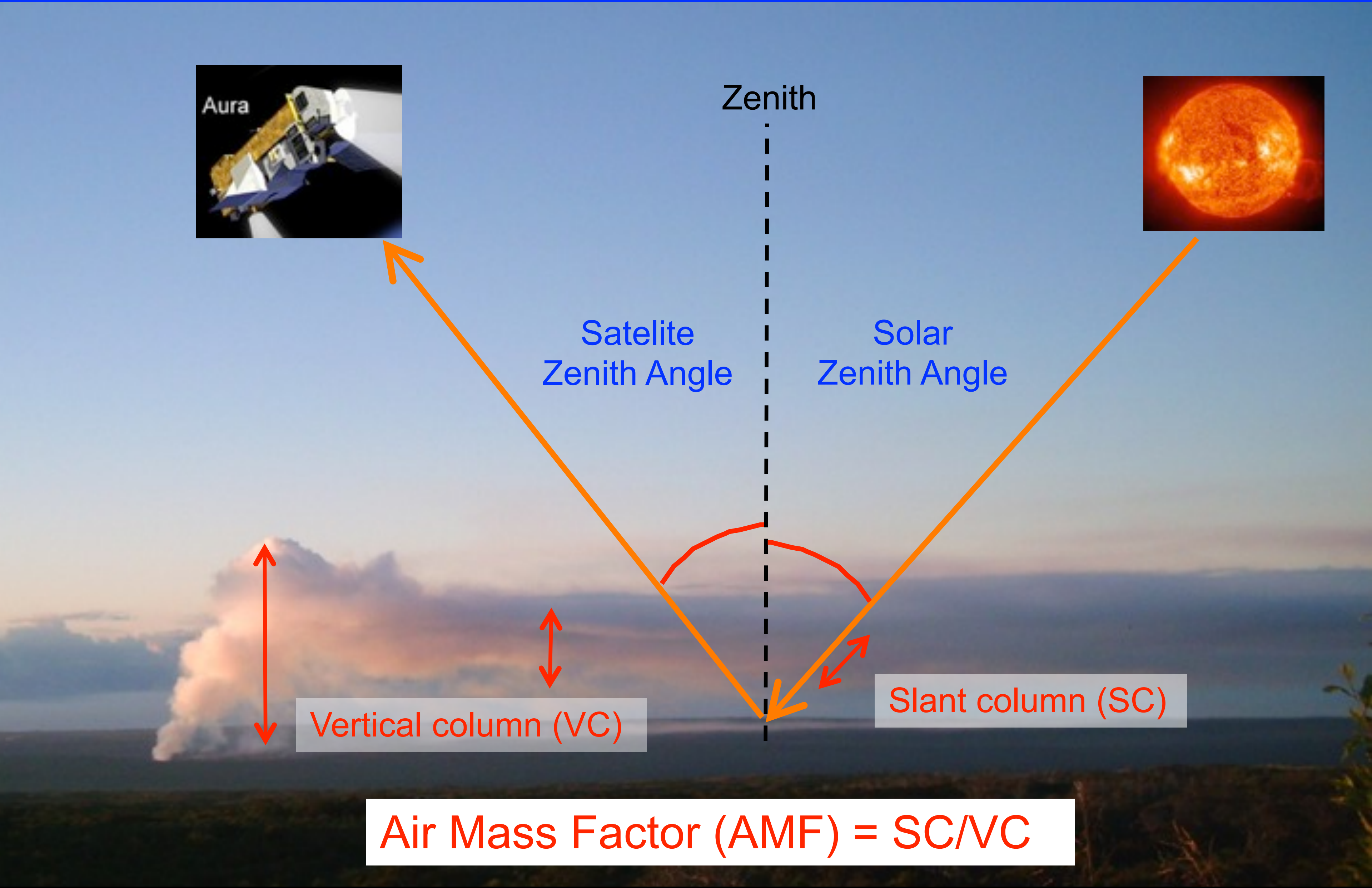


Image courtesy Matt Patrick (HVO)

UV radiation penetrates clouds

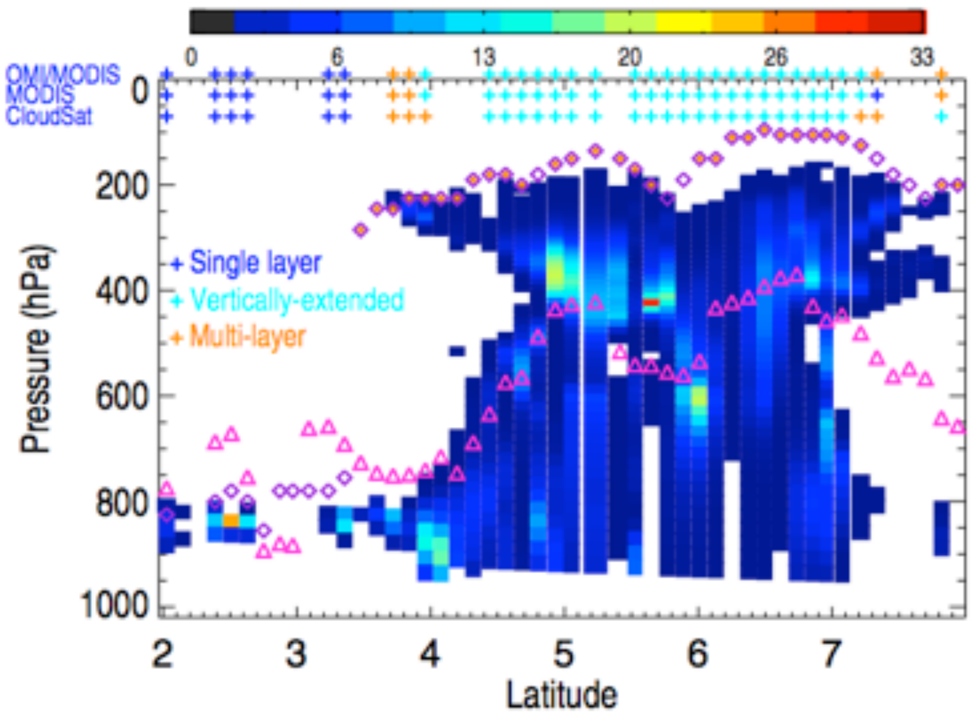


Fig. 7. CloudSat 2B-Tau cross section of cloud extinction (km^{-1}) along OMI orbit 12 402 (western track in tropical Pacific highlighted in Fig. 6); Averaged along-track over OMI pixel (~13 km); Pink triangles: OMI optical centroid cloud pressure; Purple diamonds: MODIS minimum cloud-top pressure within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

(Joiner et al., ATMD, 2009)

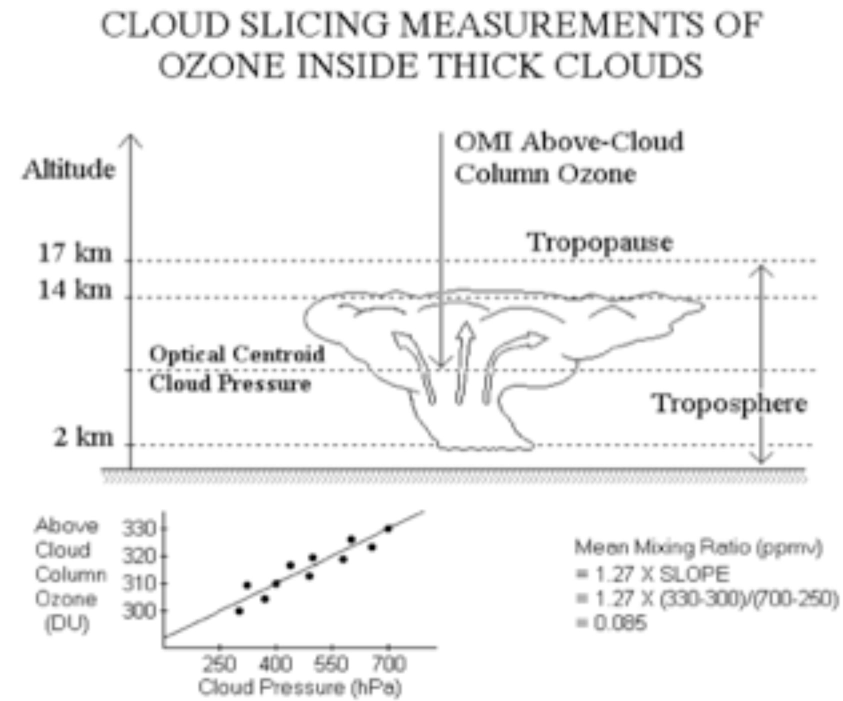


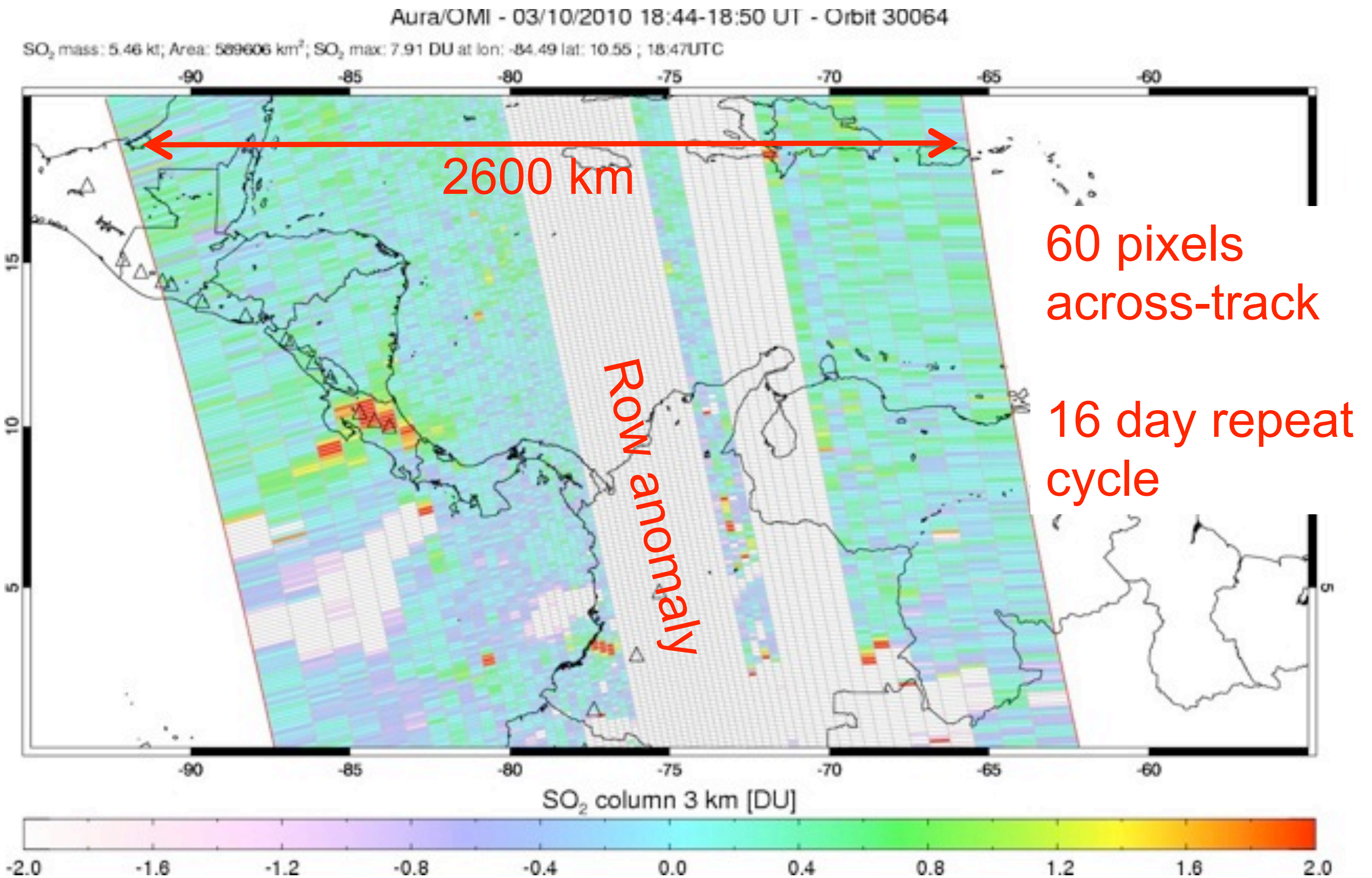
Fig. 4. Schematic diagram illustrating the ensemble cloud-slicing method. The figure shows that a satellite UV instrument is sensitive to the O_3 column from the top of the atmosphere down to the OCCP altitude which may lie several hundred hPa below geometrical cloud top. The lower half of the figure illustrates that using an ensemble of such measurements over a fixed region, mean volume mixing ratio can be determined from the slope of column O_3 plotted versus OCCP.

(Ziemke et al., ACP, 2009)

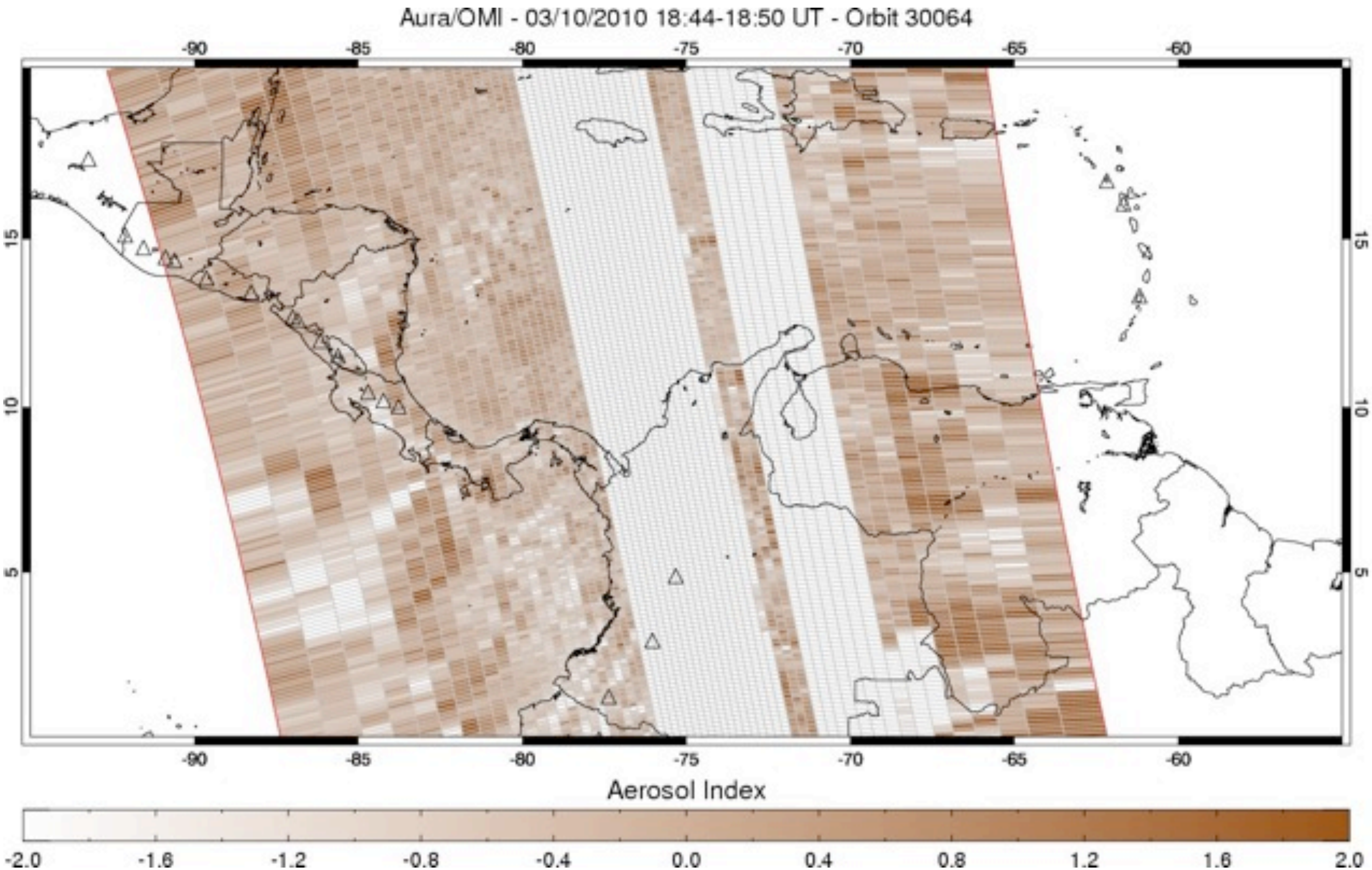
- IR cloud top ≠ UV cloud pressure

Michigan Tech
Create the Future

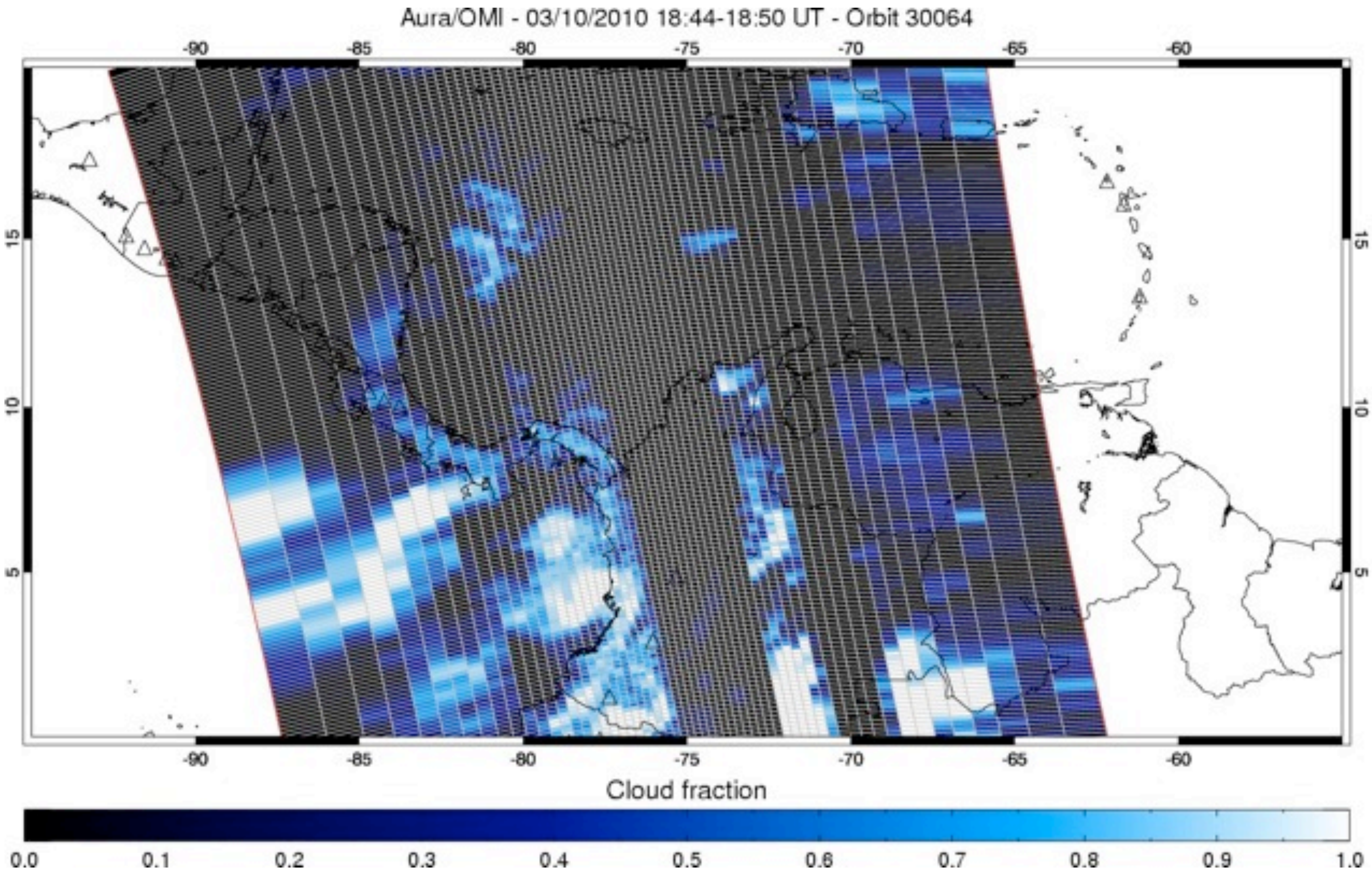
OMI data products – SO_2



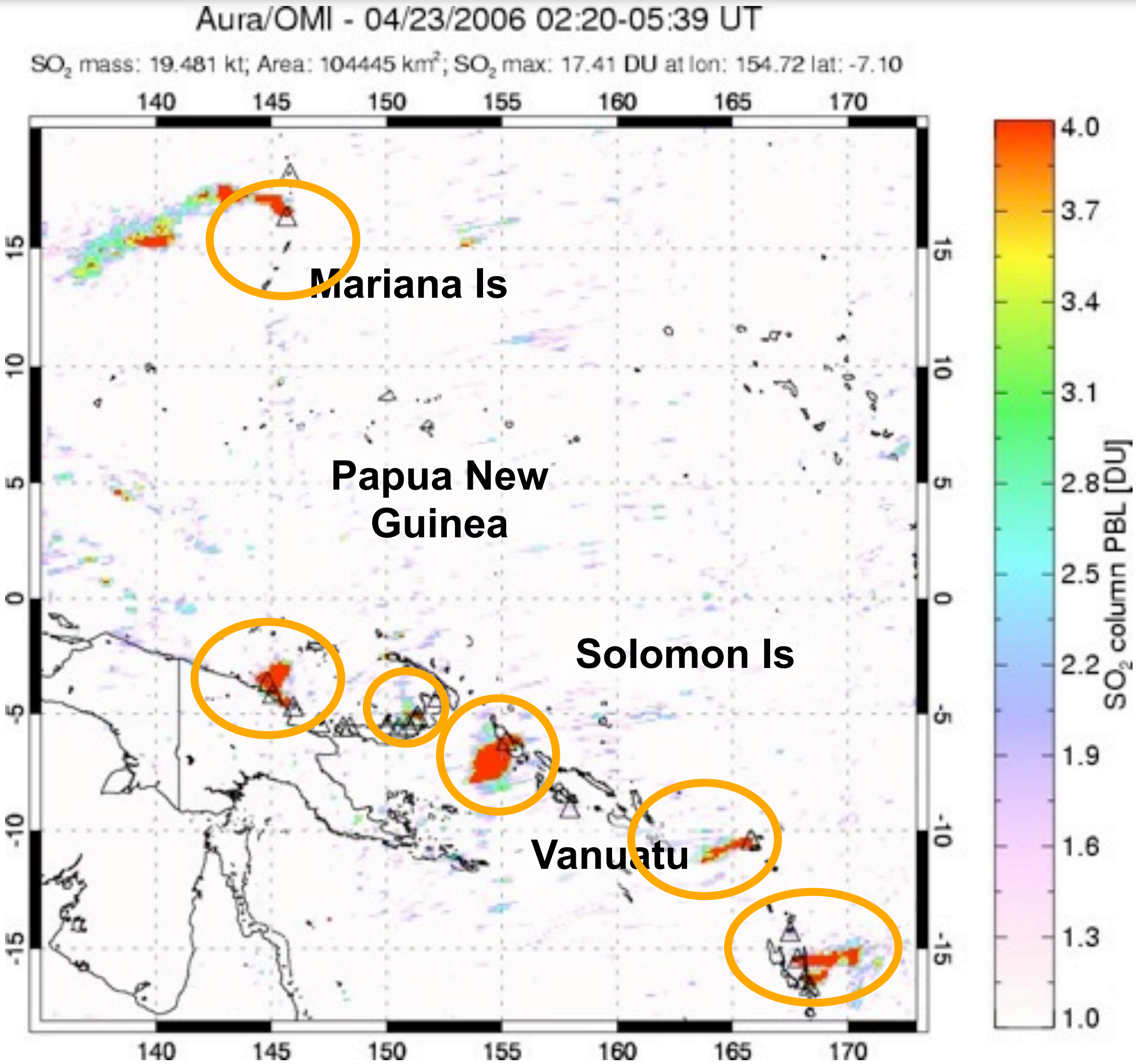
OMI data products – Aerosol Index



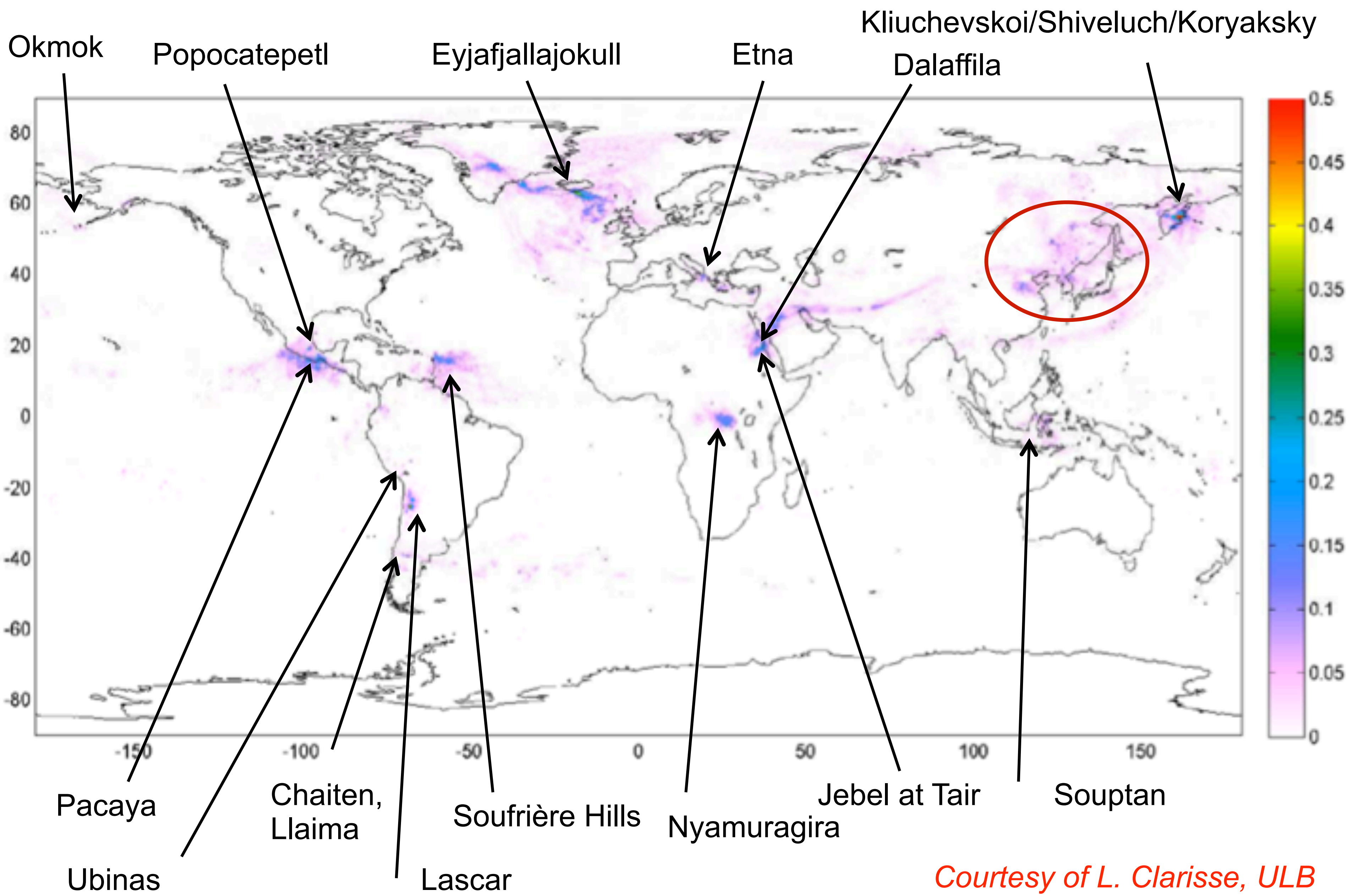
OMI data products – Cloud fraction



Detection of passive SO_2 degassing with OMI

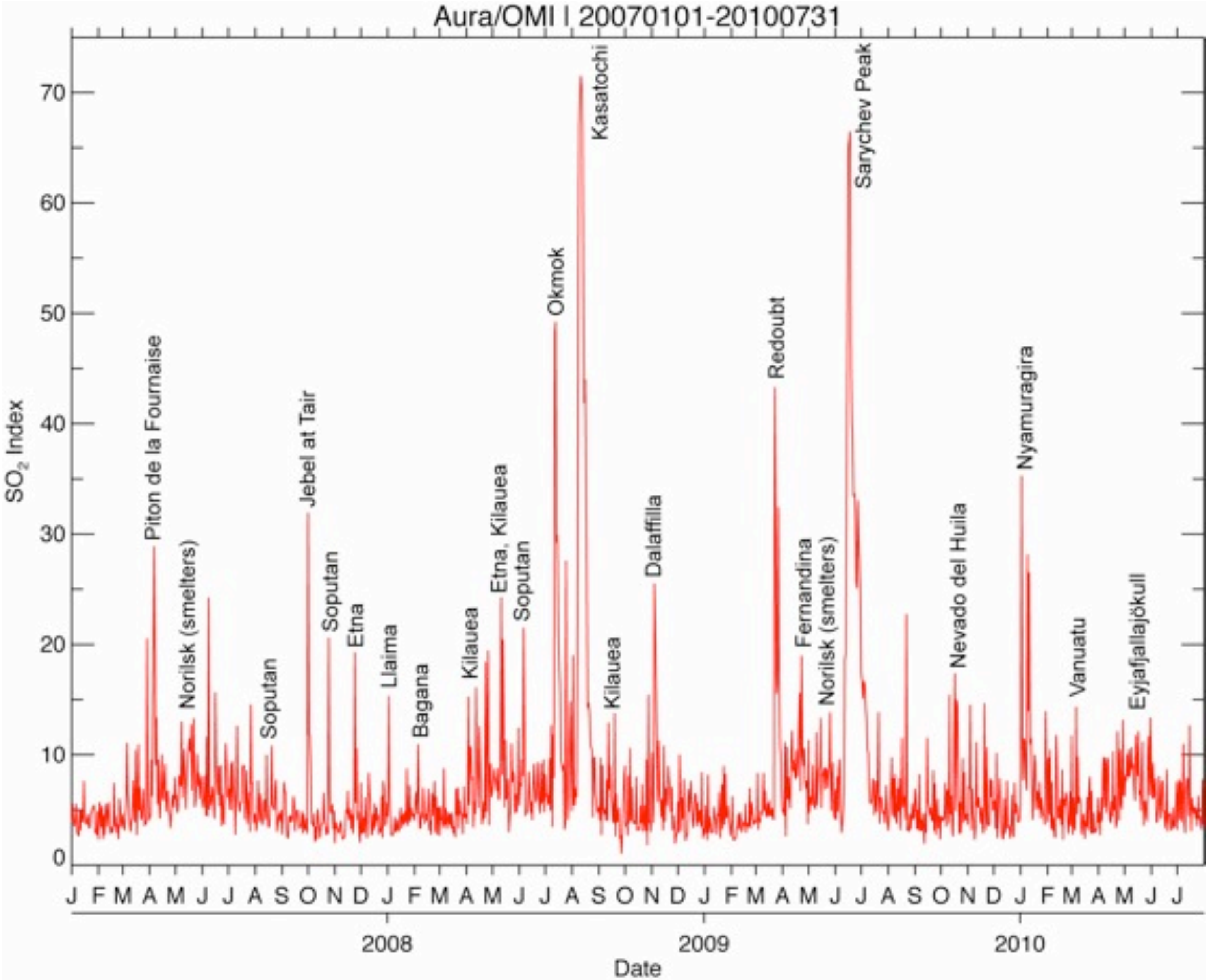


3 year global average SO_2 from IASI (without large eruptions)

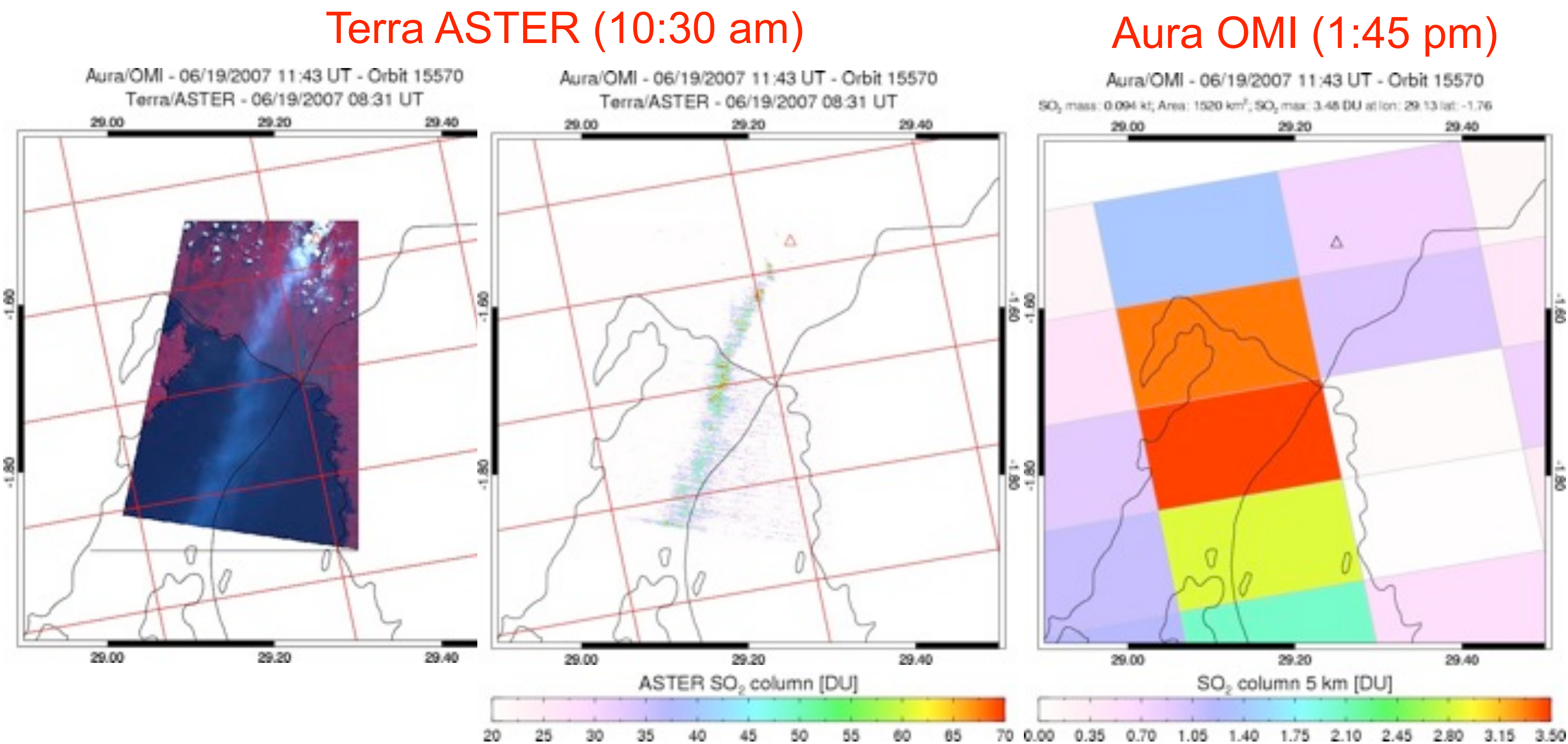


Courtesy of L. Clarisse, ULB

Global SO_2 emissions measured by OMI



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

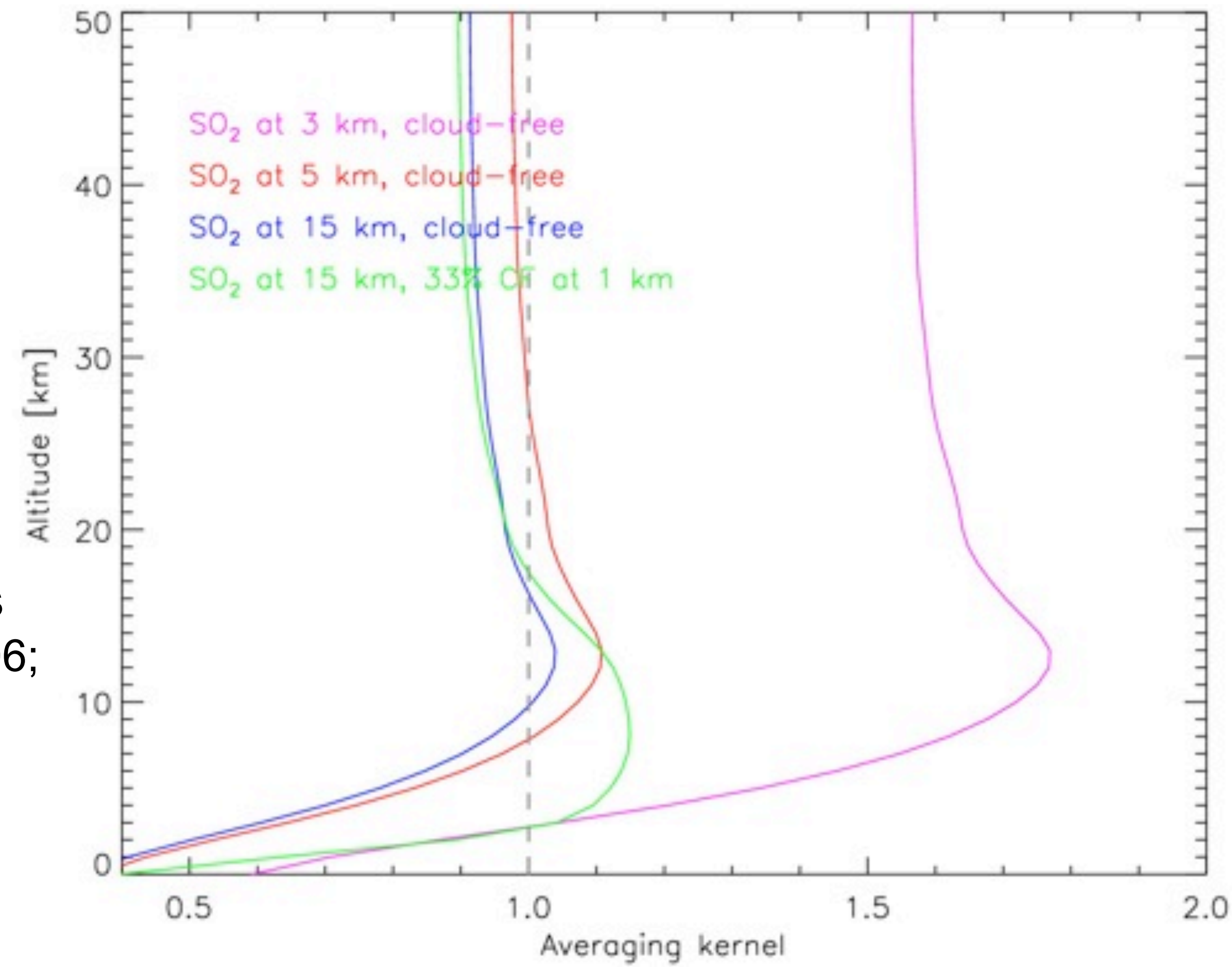


(ASTER 8.6 μm SO_2 retrieval; F. Prata, NILU)

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

Effect of volcanic plume altitude on SO_2 retrievals

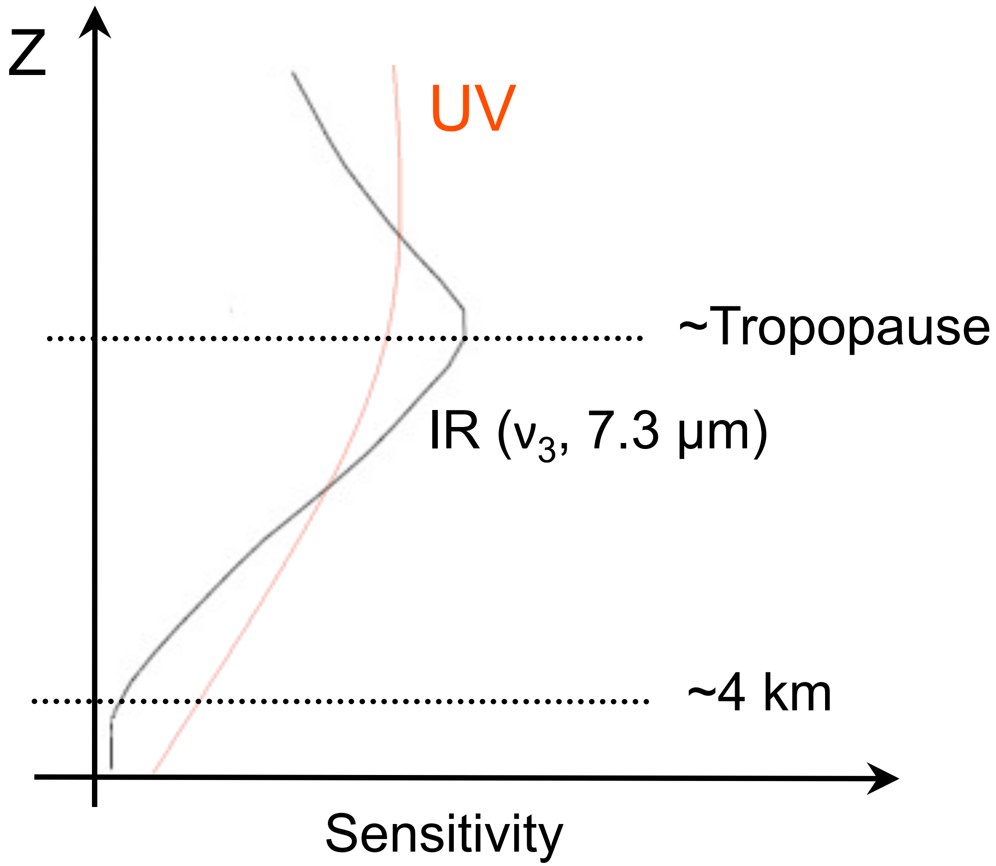
- OMI SO_2 product
- 4 *prescribed* SO_2 profiles:
  - PBL (<3 km)
  - TRL (0-5 km)
  - TRM (5-10 km)
  - STL (15-20 km)
  - 2 SO_2 algorithms [Krotkov *et al.*, 2006; Yang *et al.*, 2007]



- 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

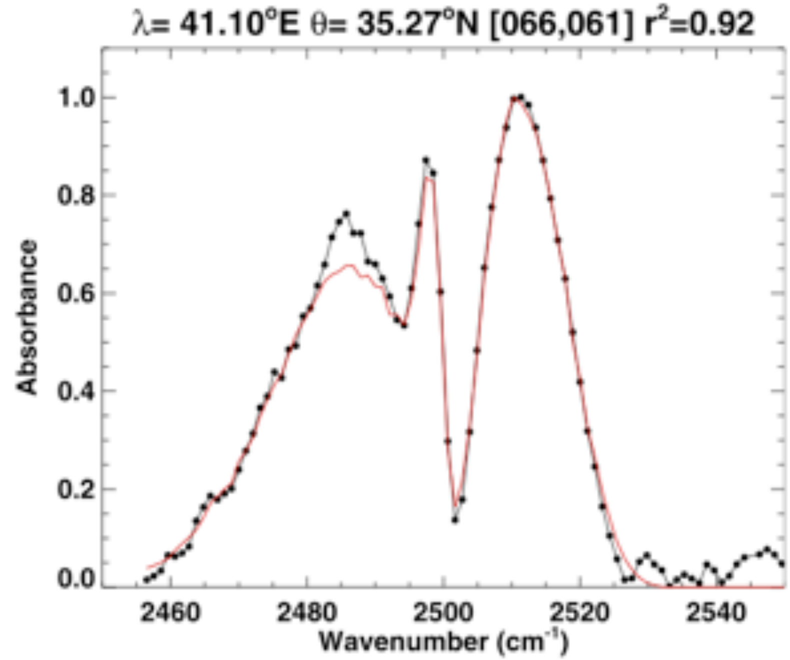
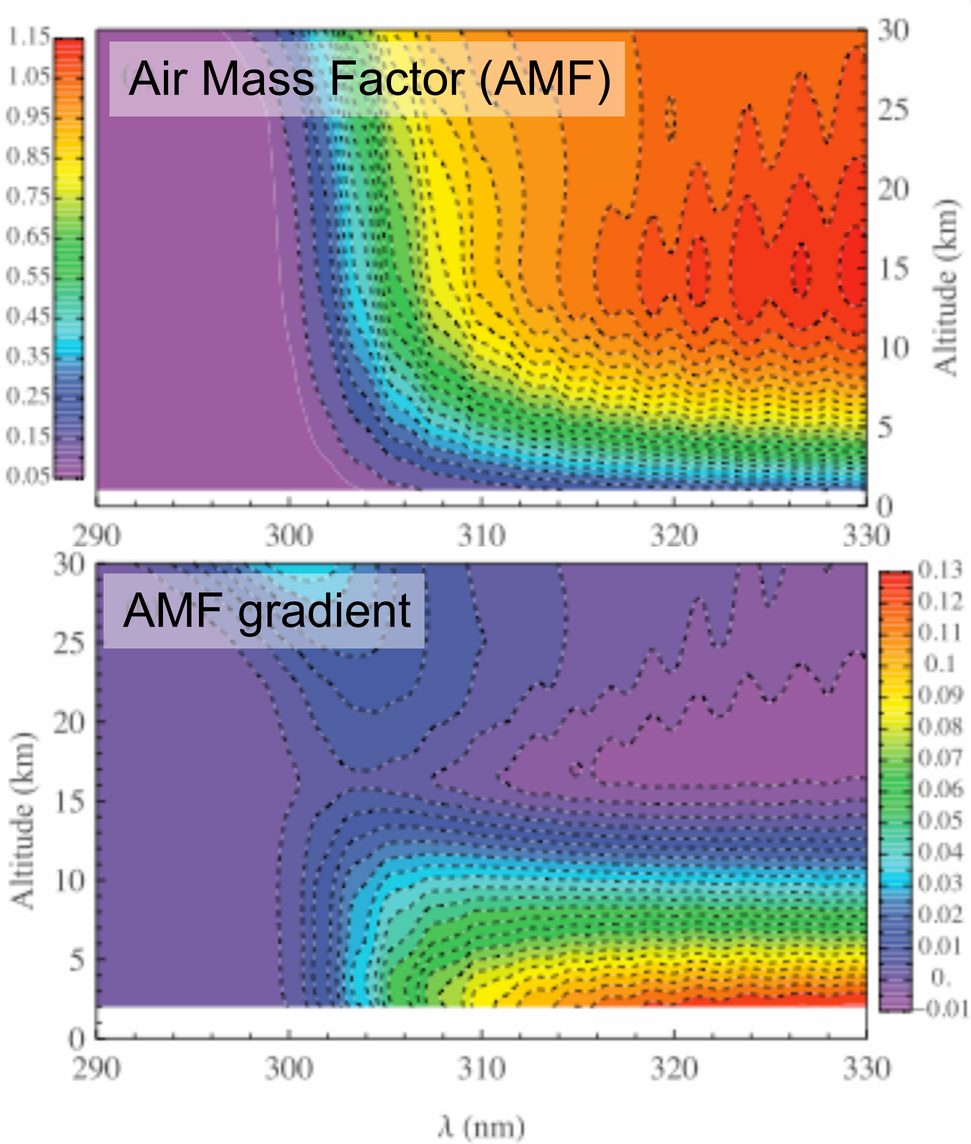


Figure 15. Spectral matching plot for the 4 μm band of SO_2. The red line shows a synthetic absorbance spectrum and the black line shows AIRS measurements. The data are for an AIRS image of the Al-Mishraq (Iraq) SO_2 plume on 25 June 2003.

Prata and Bernardo, 2007

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

Direct retrieval of SO_2 altitude from UV radiances



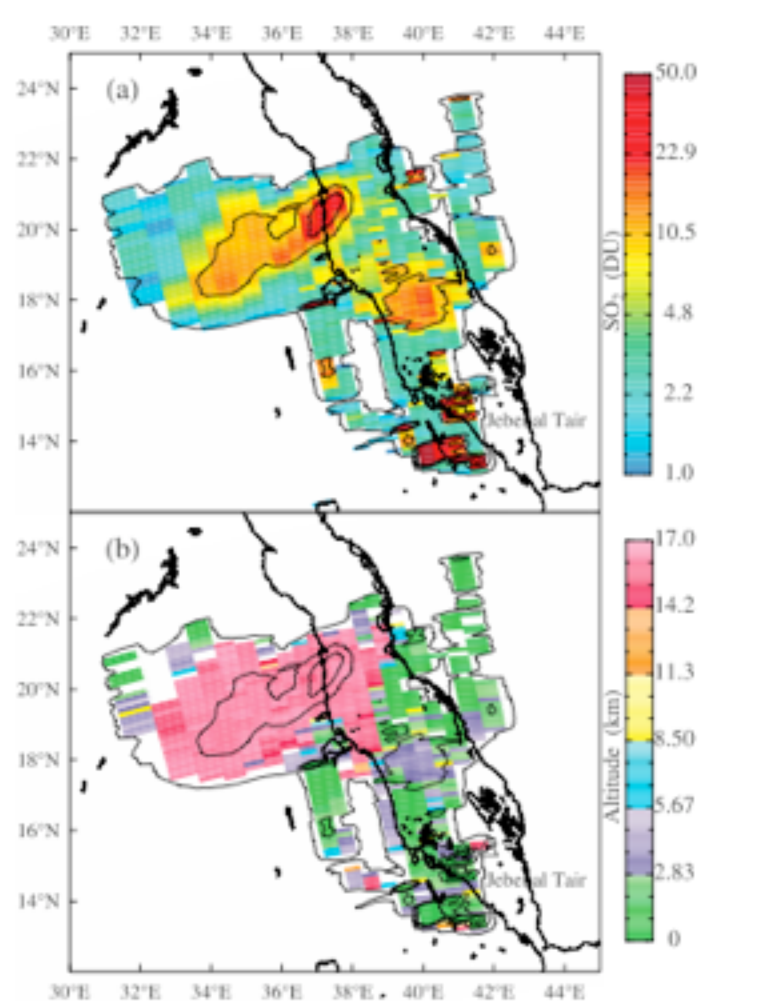


Figure 3. (a) SO_2 vertical column and (b) effective altitude maps derived from OMI UV (both UV-1 and UV-2) radiances for the Jebel al Tair volcanic plume at 10:59 UT on October 1, 2007, using the extended ISF algorithm.

- Midlatitude O_3 profile, 325 DU, nadir, clear sky, SZA=45°

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

Retrieval of large SO_2 columns in volcanic clouds

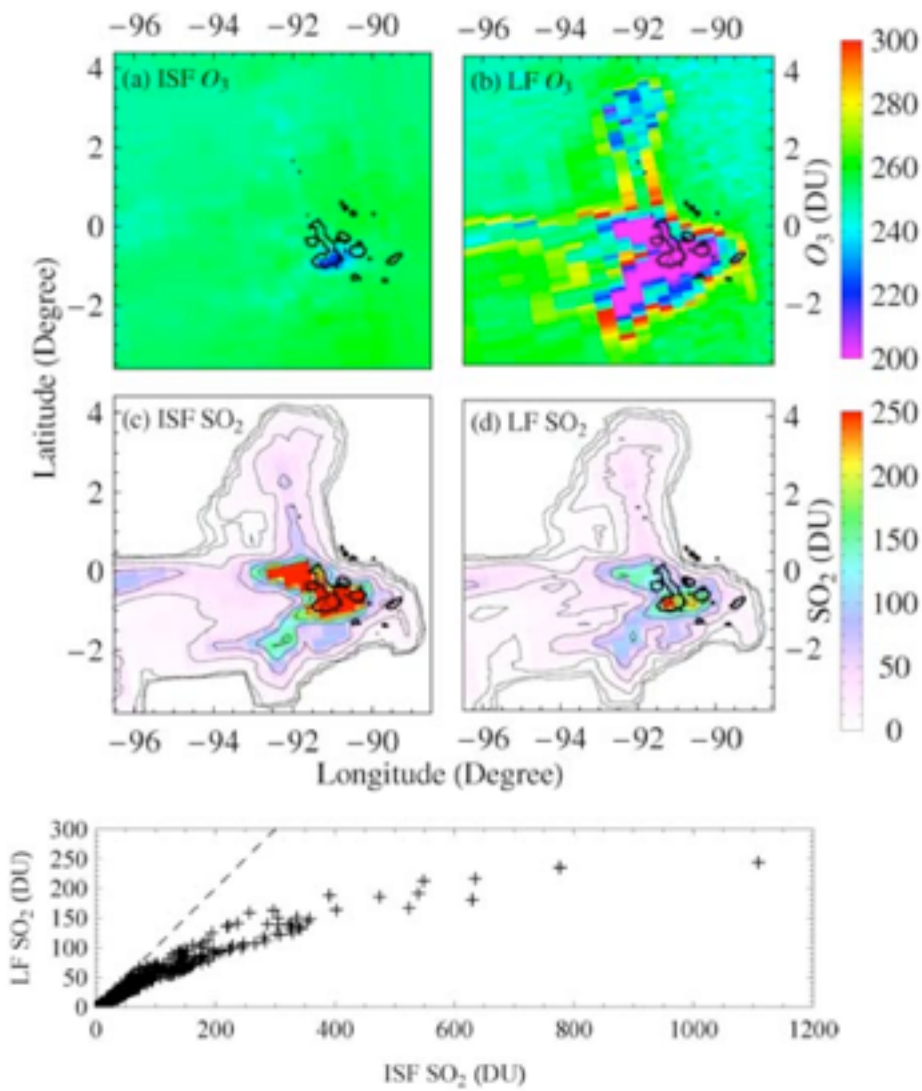
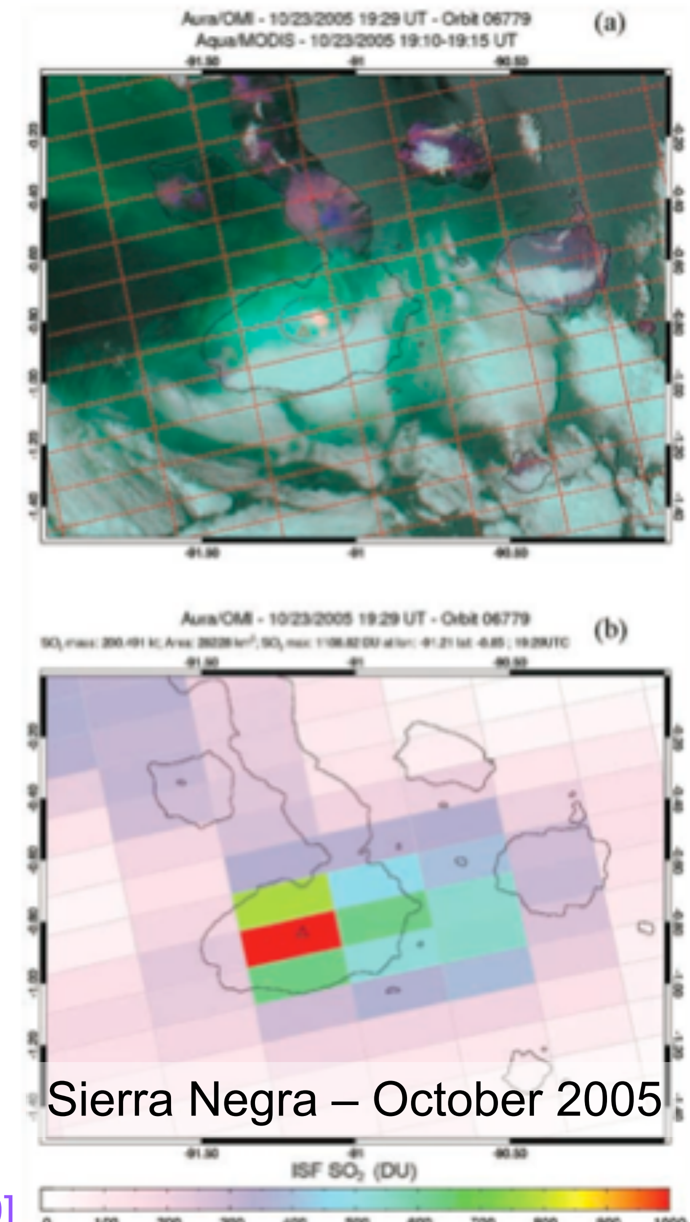


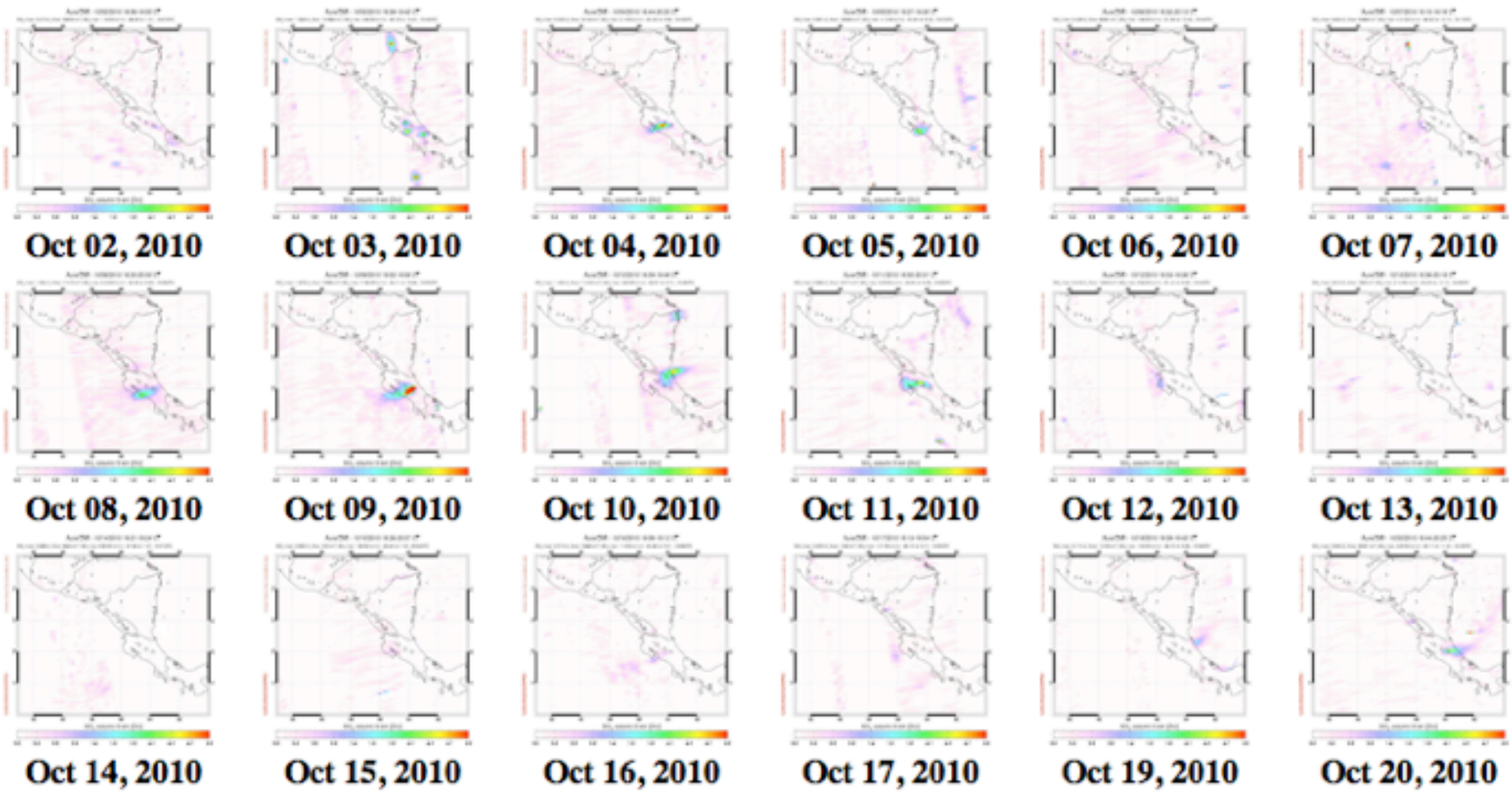
Figure 3. Comparison of ISF and LF SO_2 columns in the Sierra Negra eruption cloud on October 23, 2005. The LF retrievals saturate at about 200 DU in this case.

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



Daily OMI SO_2 measurements for Central America

http://so2.umbc.edu/omi

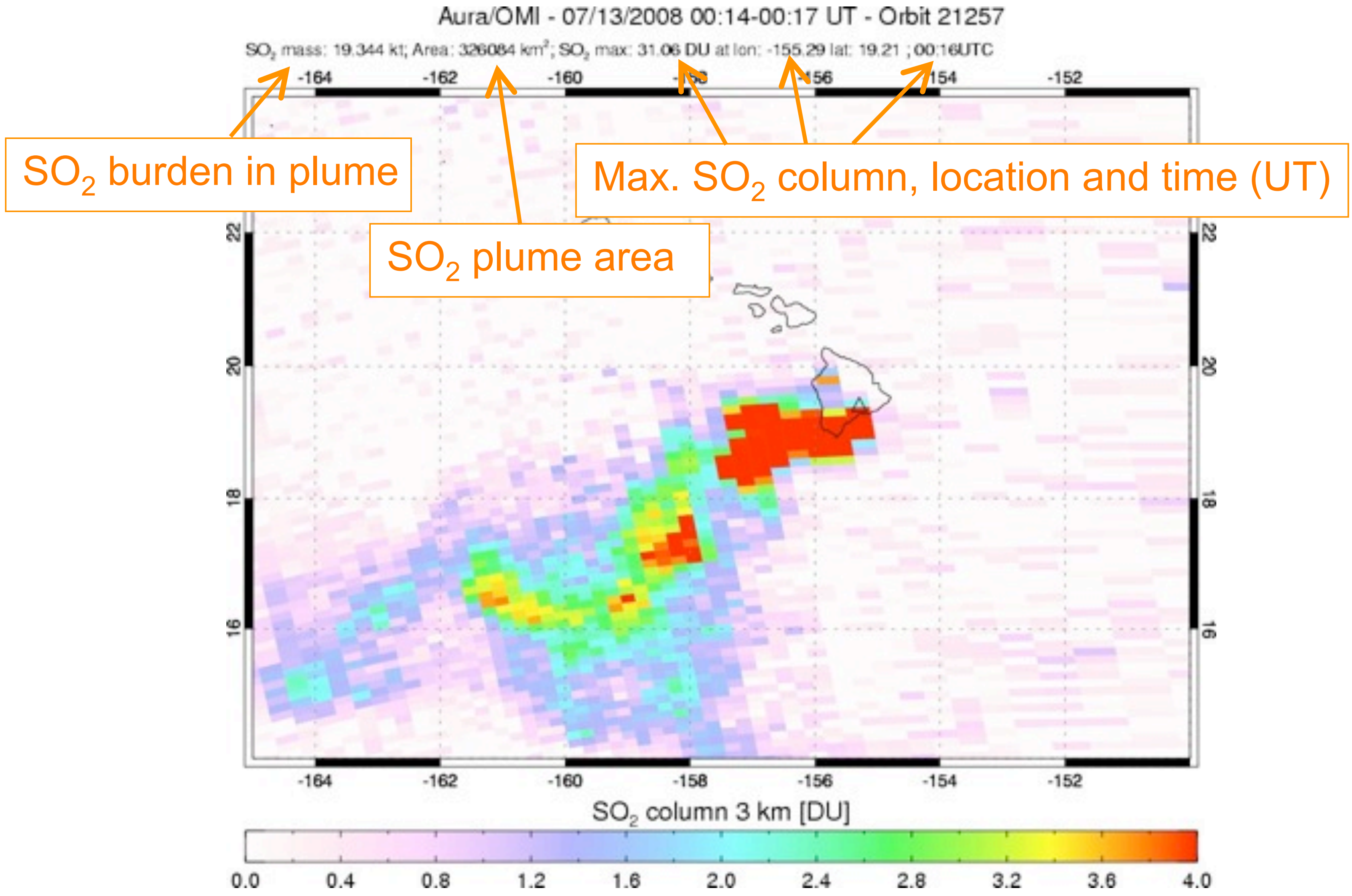


- Satellites measure column amounts of gases, NOT emission rates

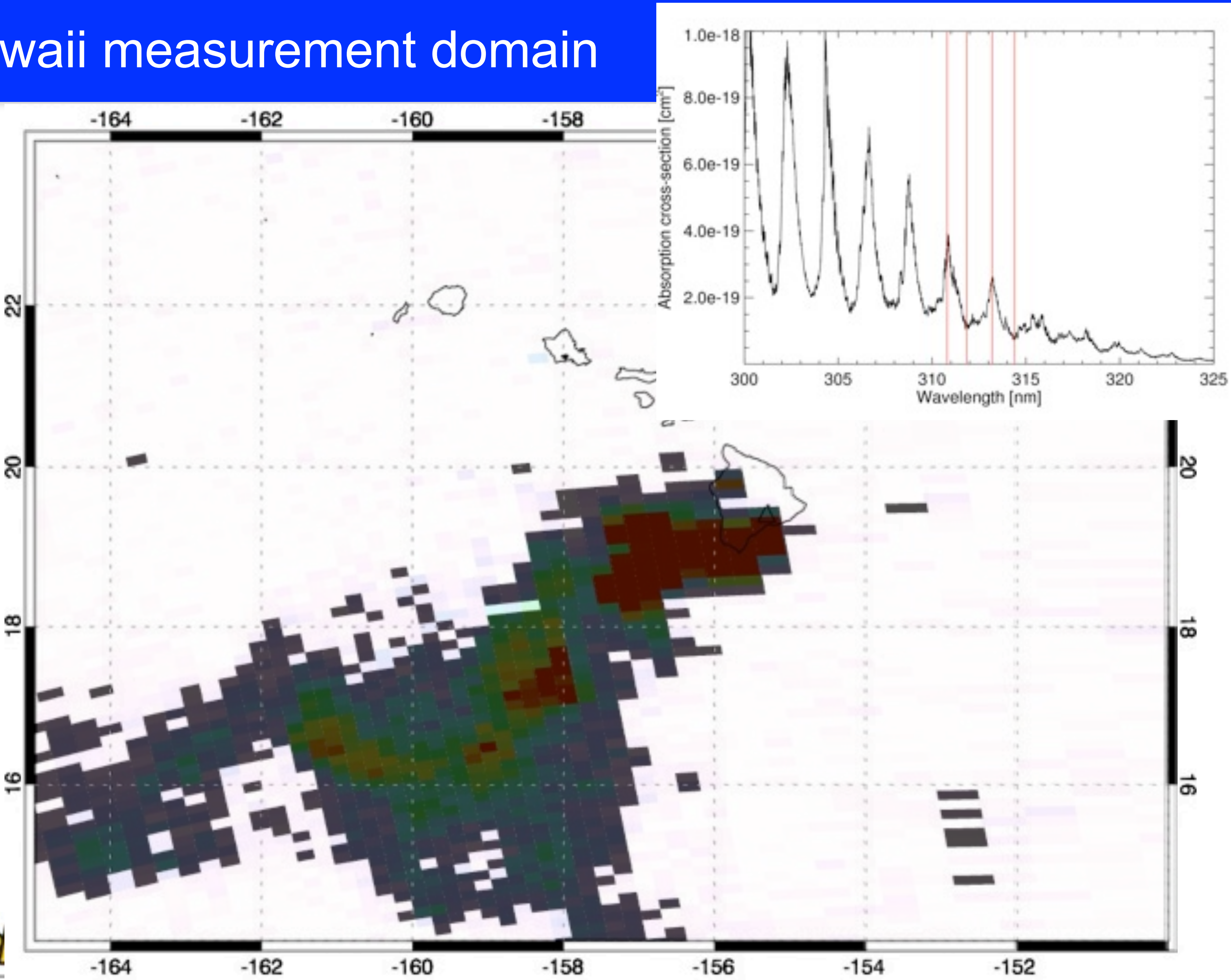
Michigan Tech
Create the Future

Daily OMI SO_2 measurements for Kilauea

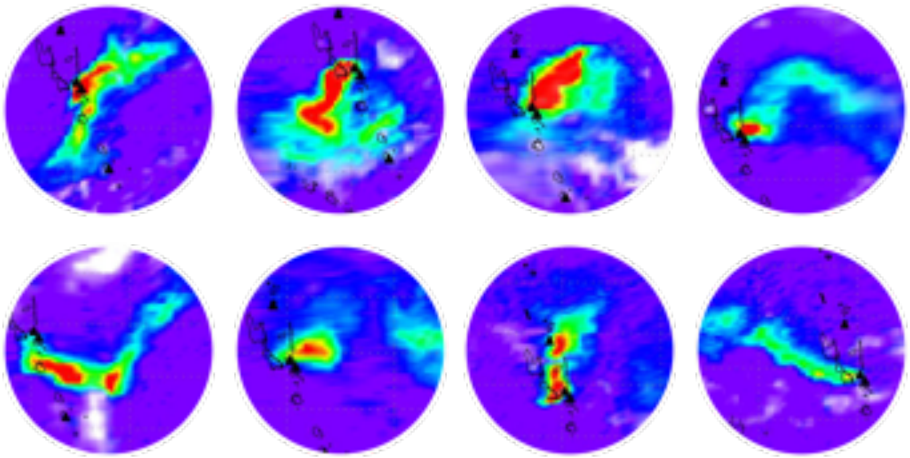
http://so2.umbc.edu/omi



Hawaii measurement domain



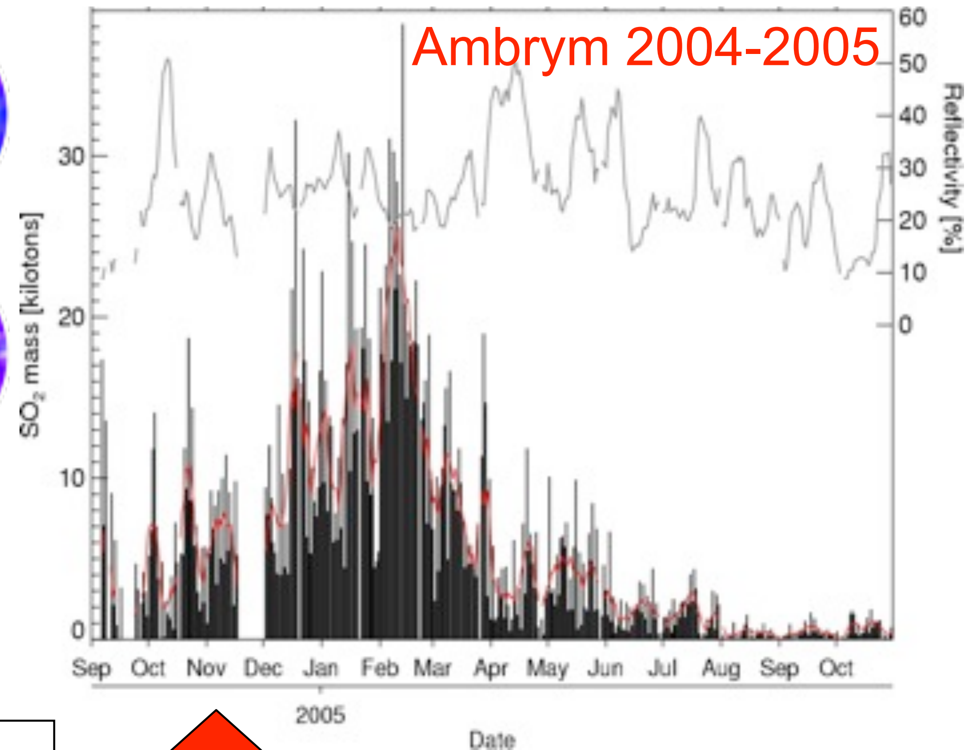
Construction of SO_2 mass time-series



Daily OMI measurements

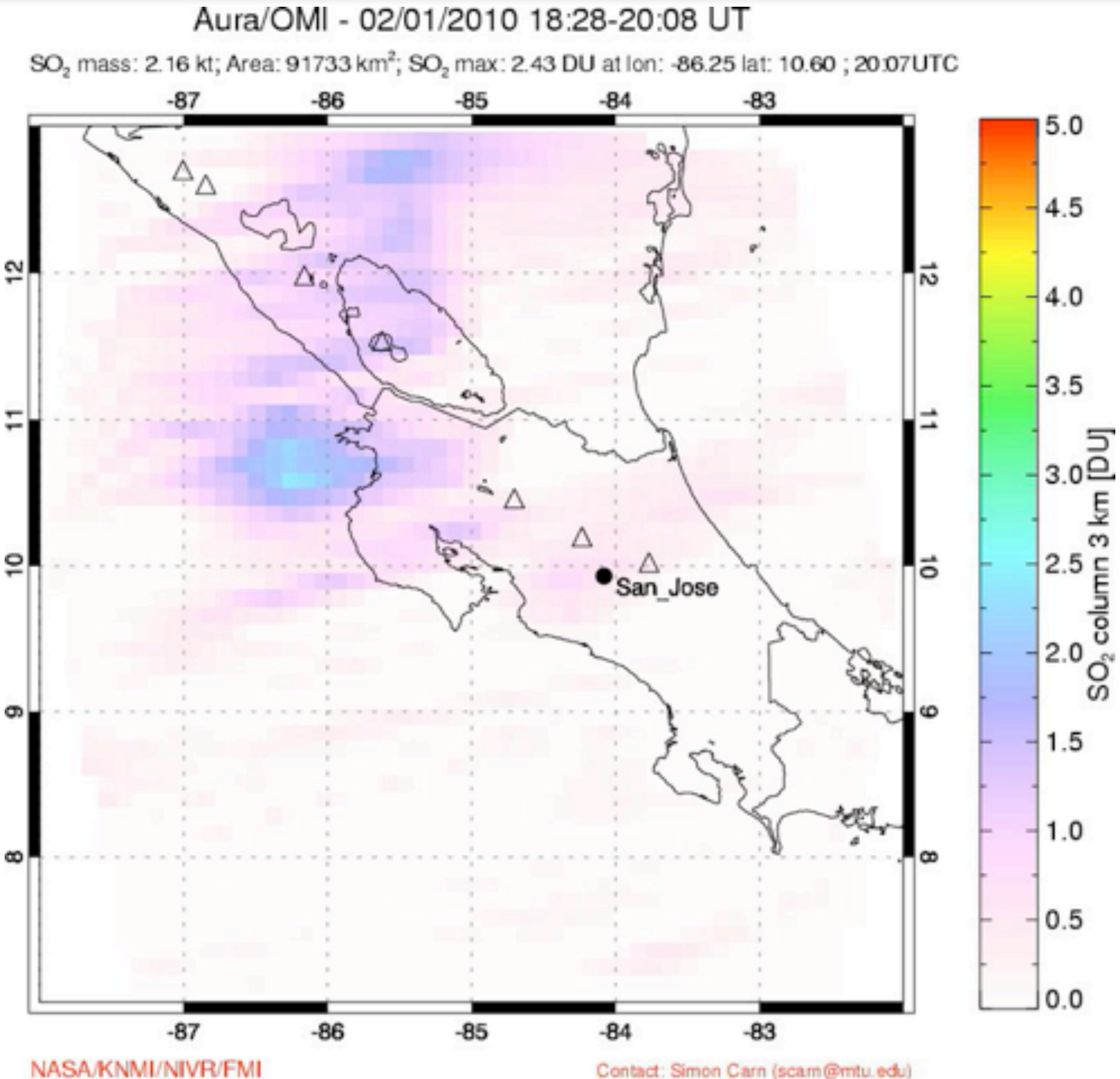
Calculate SO_2 burdens

- Threshold (e.g., >0.6 DU = volcanic)
- Background subtraction
- Noise statistics in SO_2-free region

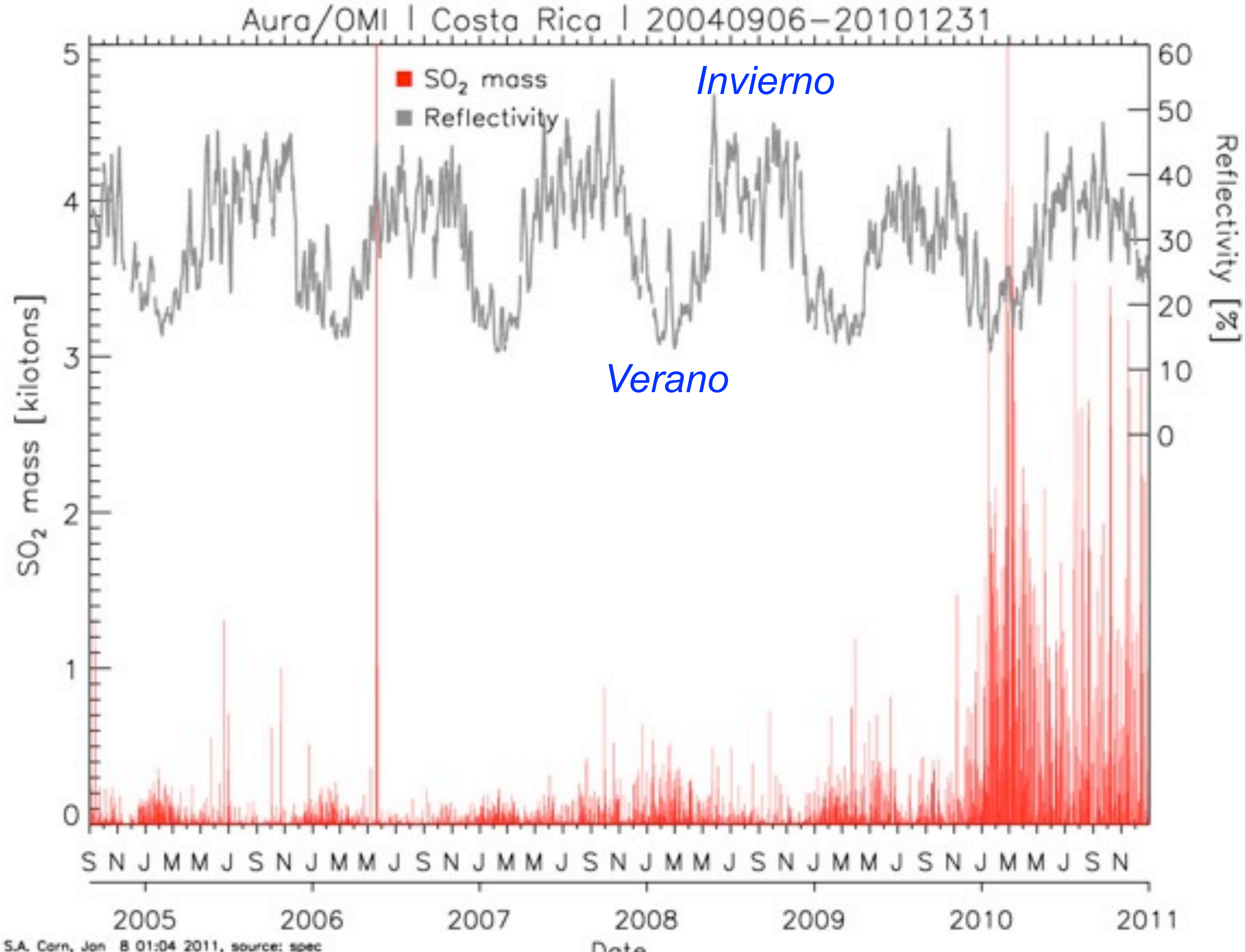


Daily SO_2 burdens (not fluxes)

OMI SO_2 data for Costa Rica

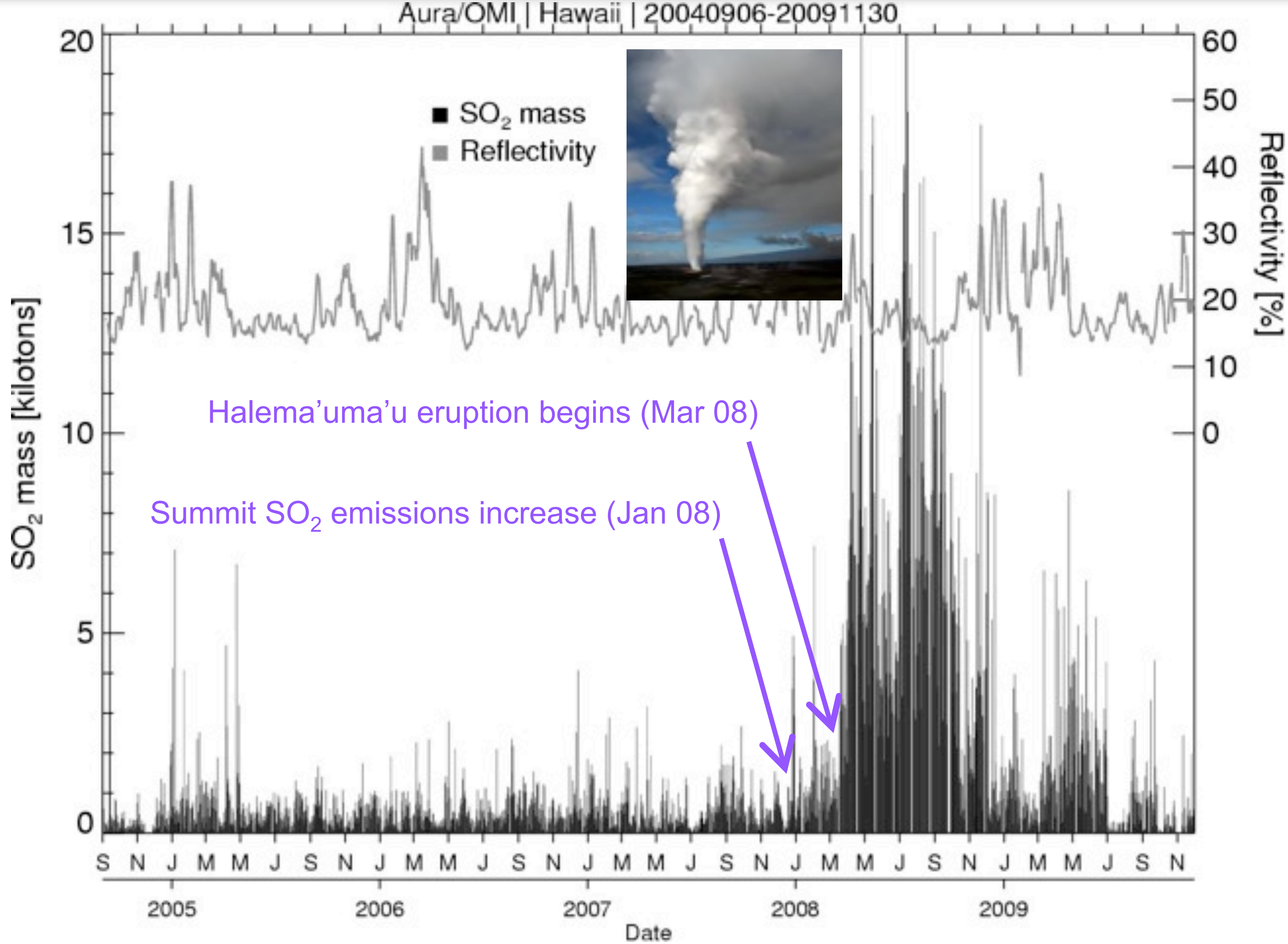


OMI SO_2 time-series for Costa Rica

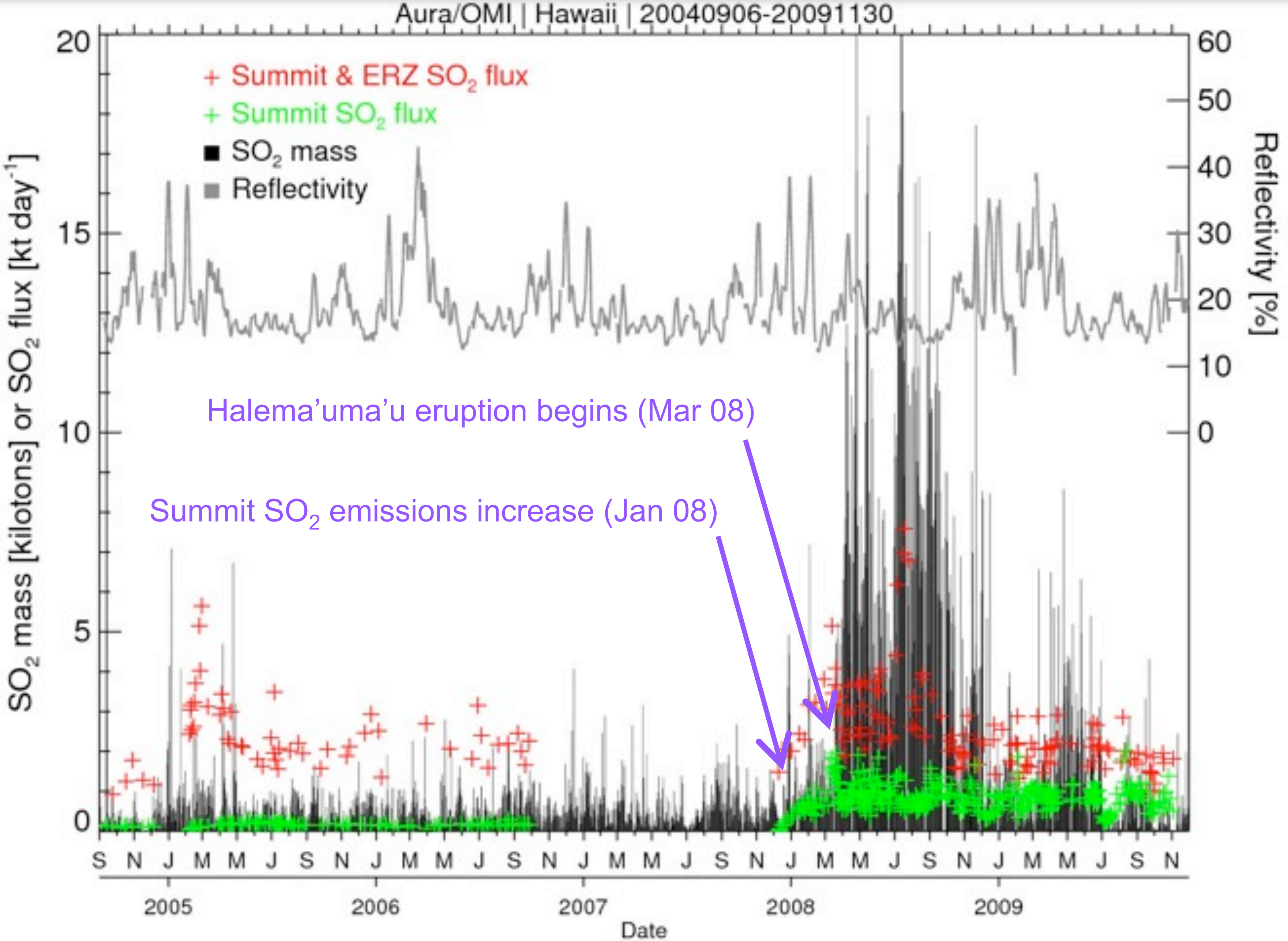


Michigan Tech
Create the Future

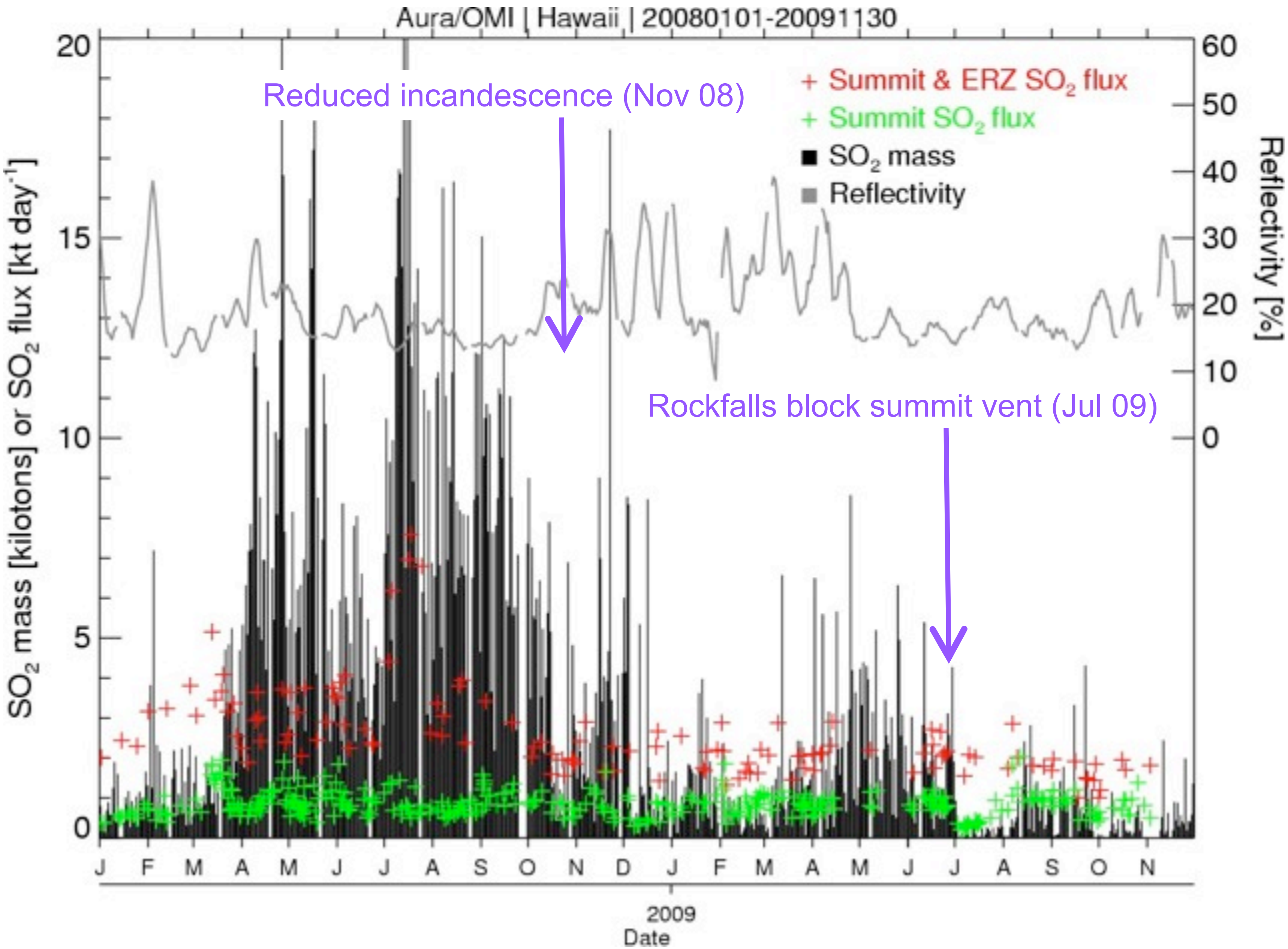
Kilauea plume SO_2 burdens: 2004-2009



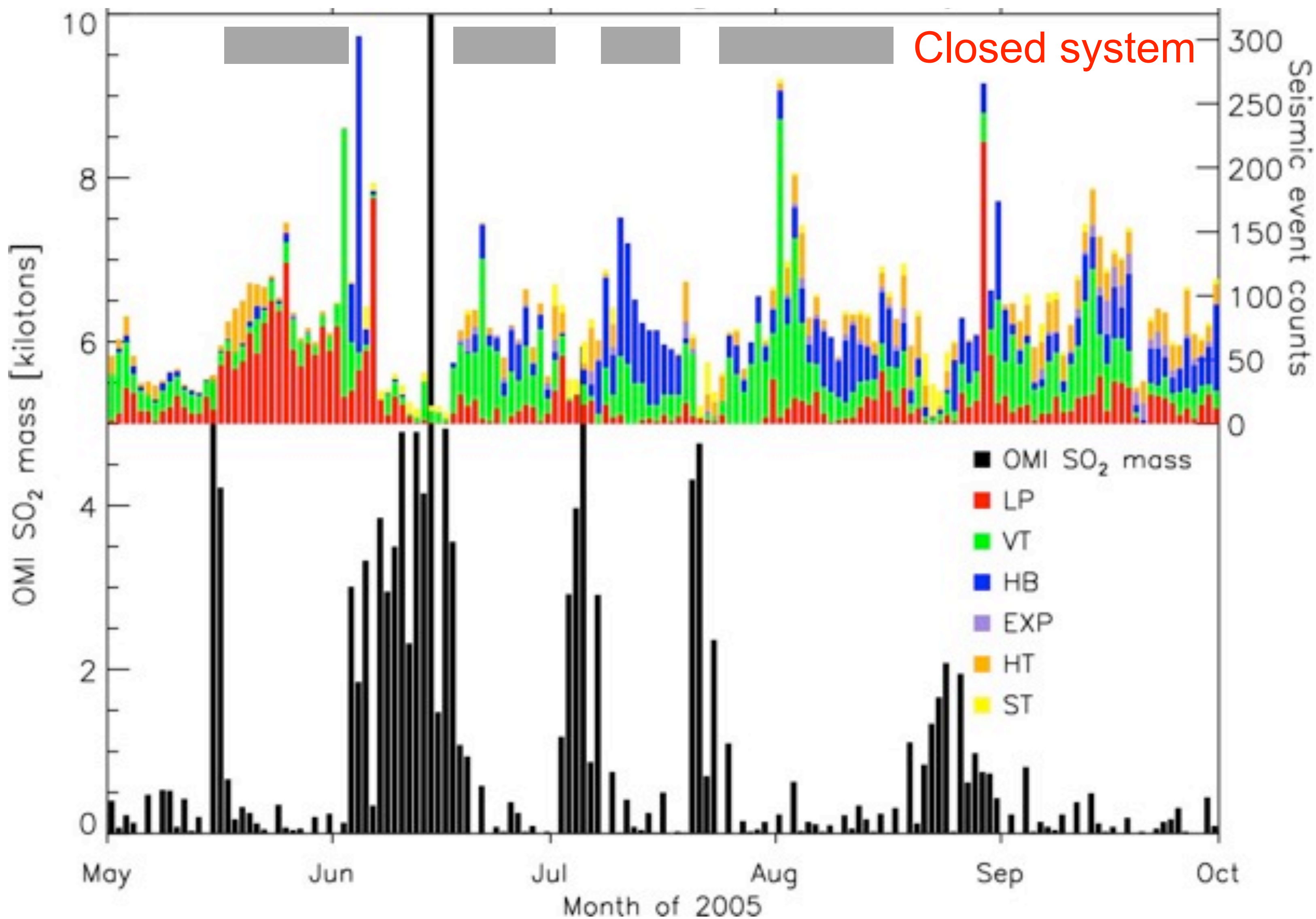
Kilauea plume SO_2 burdens: 2004-2009



Kilauea plume SO_2 burdens: 2008-2009



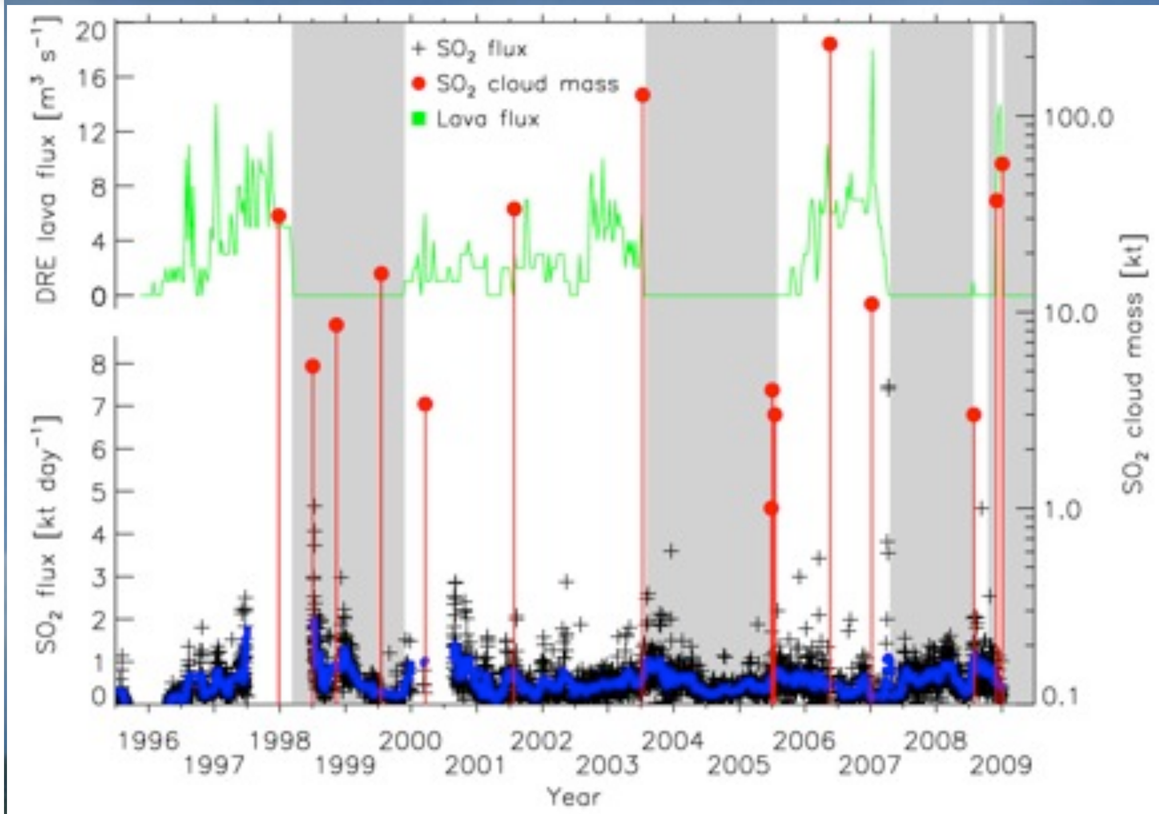
Reventador (Ecuador) seismicity and OMI SO_2 data



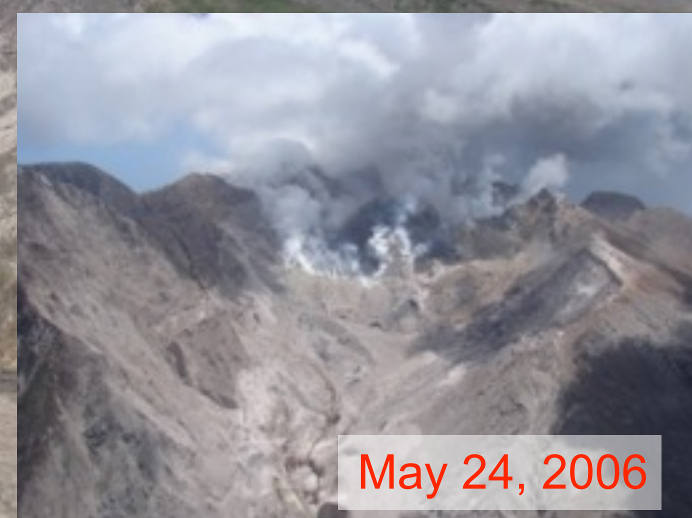
[Carn et al., JVGR, 2008]

Soufrière Hills Volcano, Montserrat

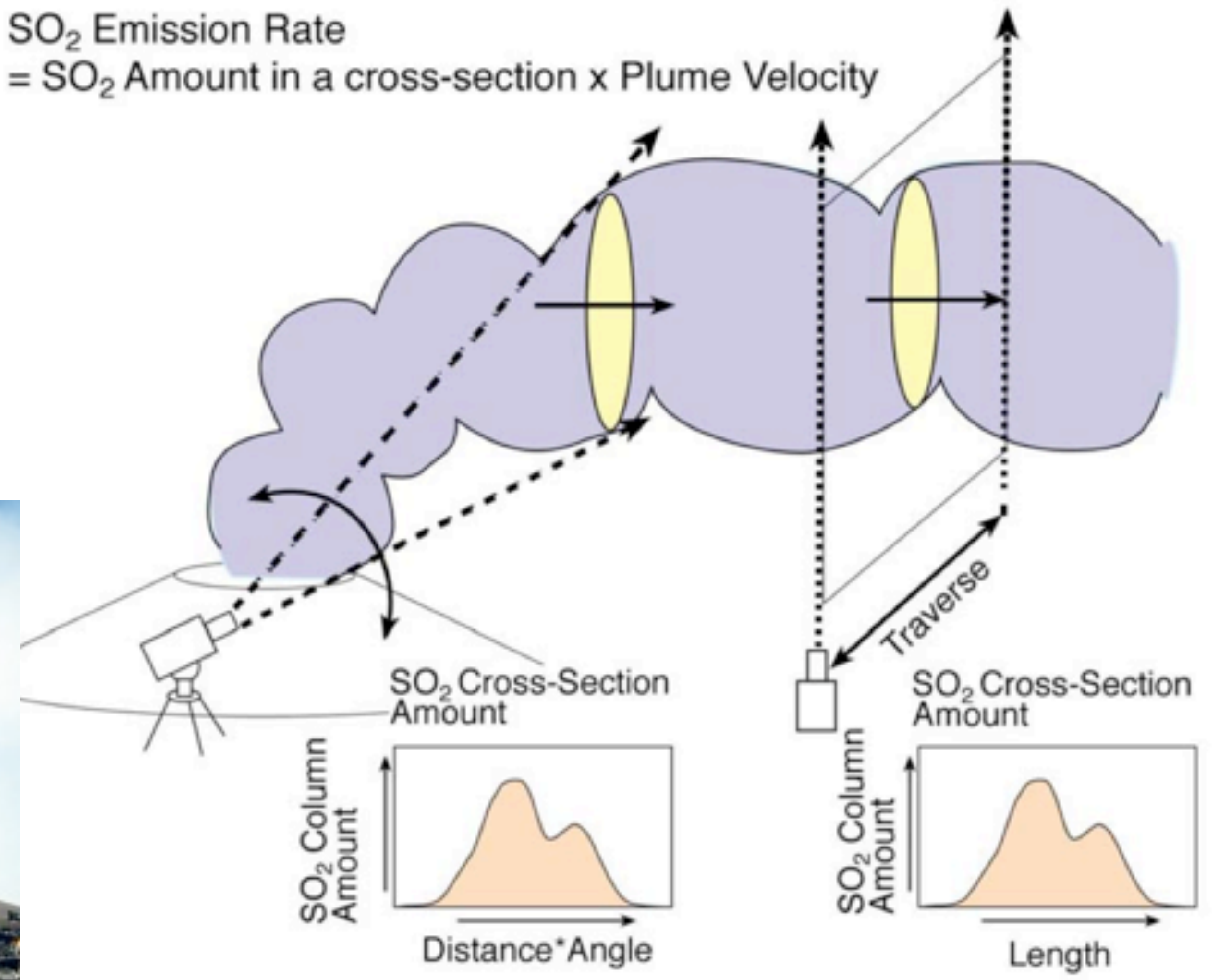
[Carn and Prata, GRL, 2010]



- Combine space-based and ground-based SO_2 measurements to estimate total SO_2 budgets

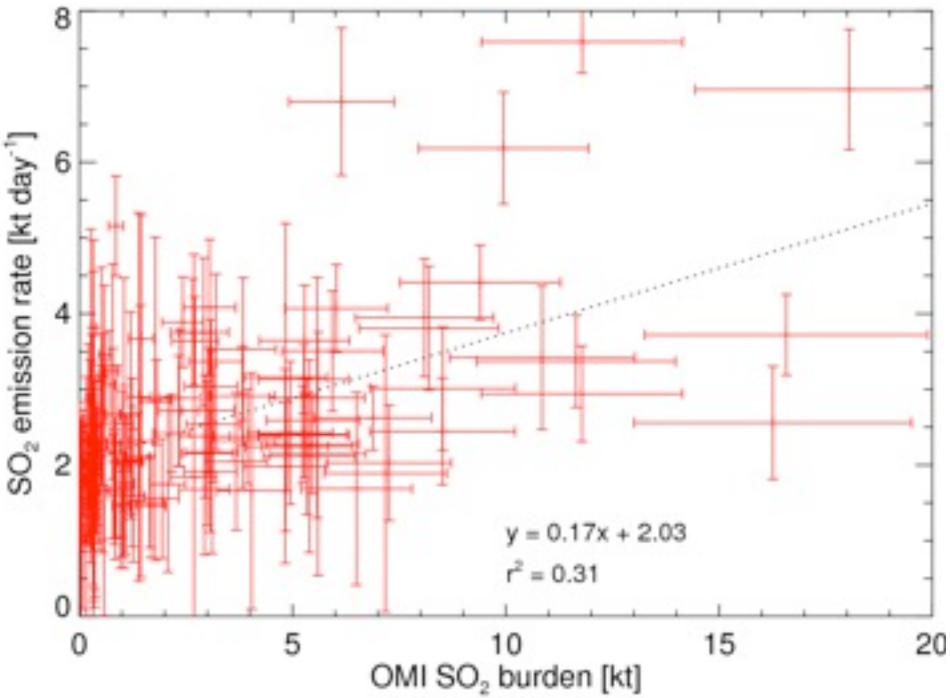


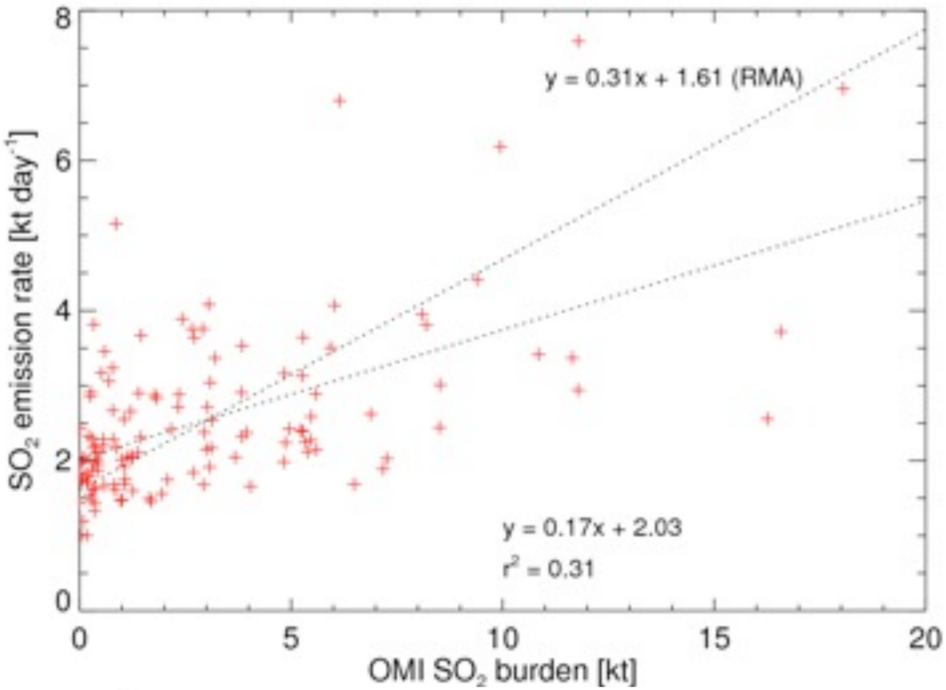
Volcanic SO_2 flux measurements



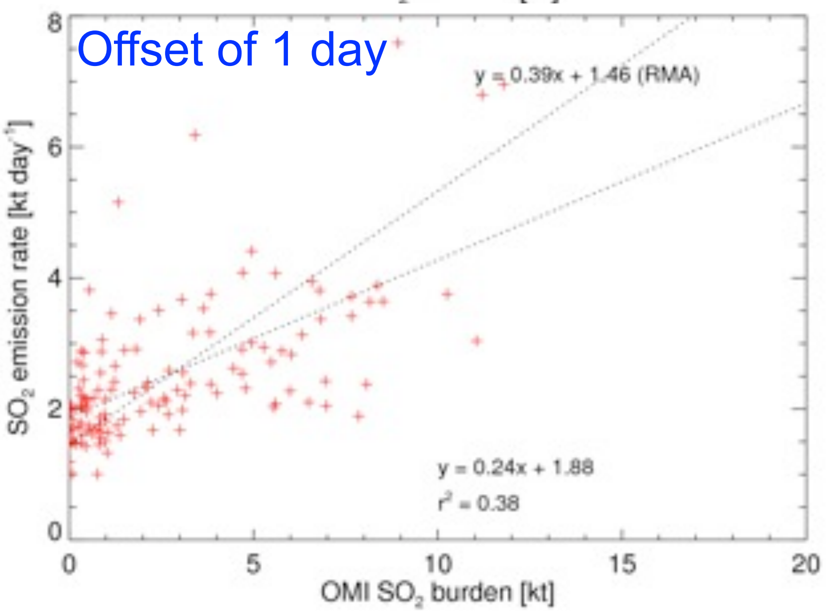
Michigan Tech
Create the Future

Comparing OMI SO_2 burdens with SO_2 emission rates (Kilauea)





- Direct comparison of SO_2 emission rates (summit + ERZ) and OMI SO_2 burdens complicated by variability, meteorology and errors
- Broad positive correlation



Michigan Tech
Create the Future

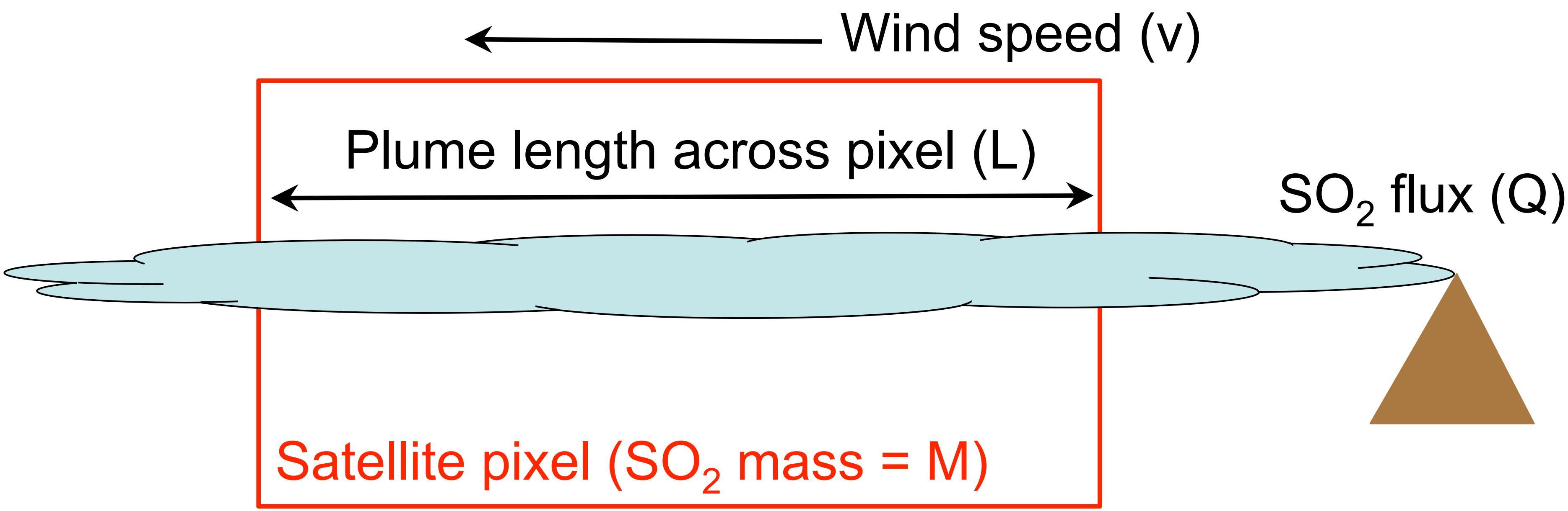
SO_2 flux estimation from satellite data

- 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
    - May be a 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)

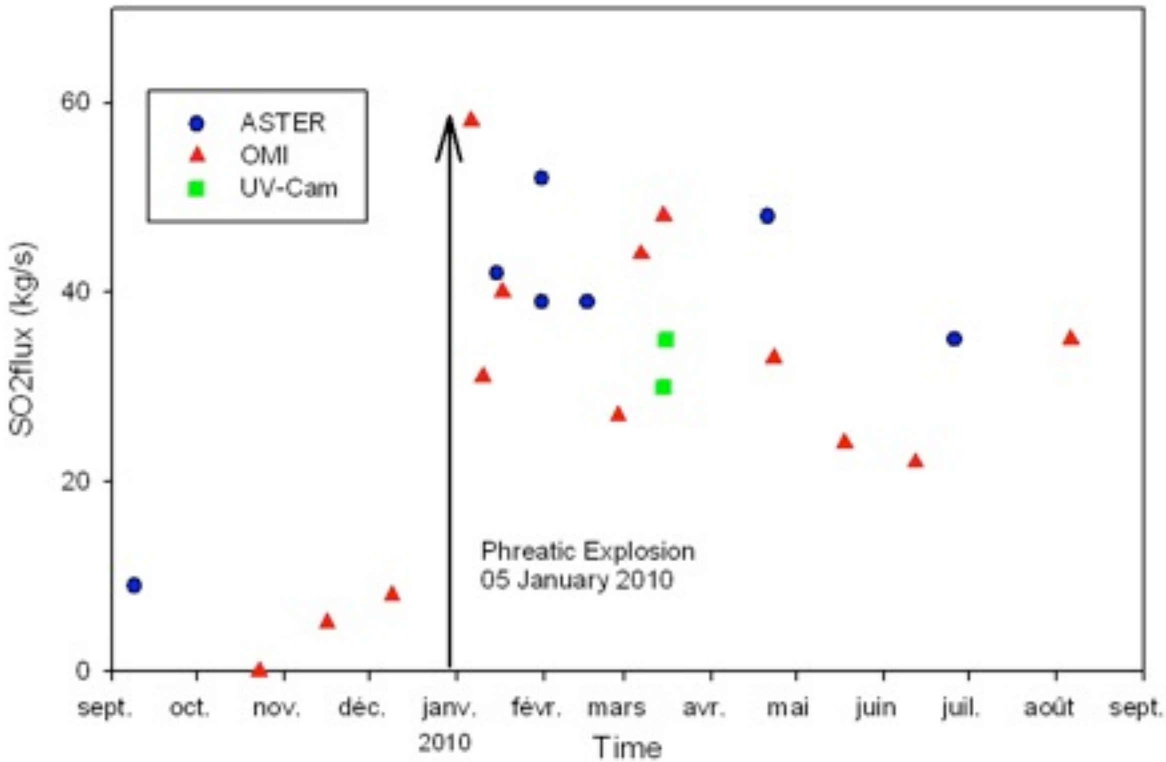
SO_2 flux estimation from satellite data

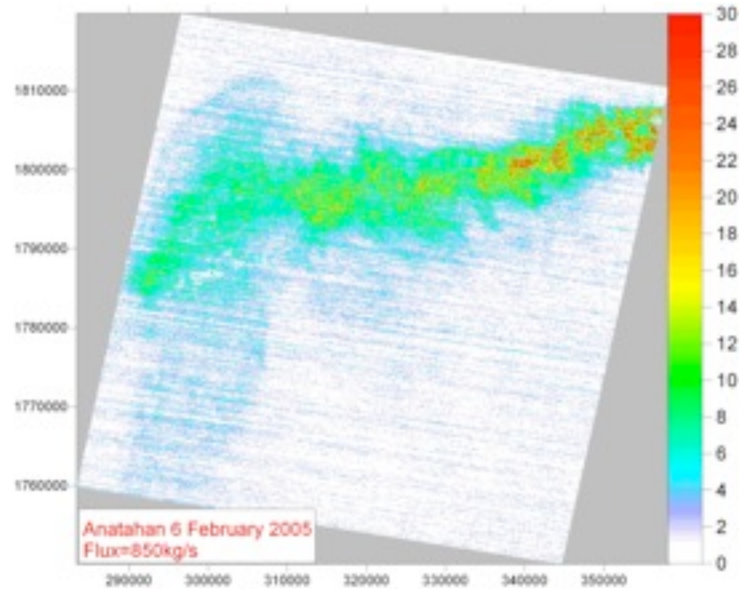


$$Q = \left[\frac{vM}{L} \right]$$

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

SO_2 flux estimation from satellite data (Turrialba)





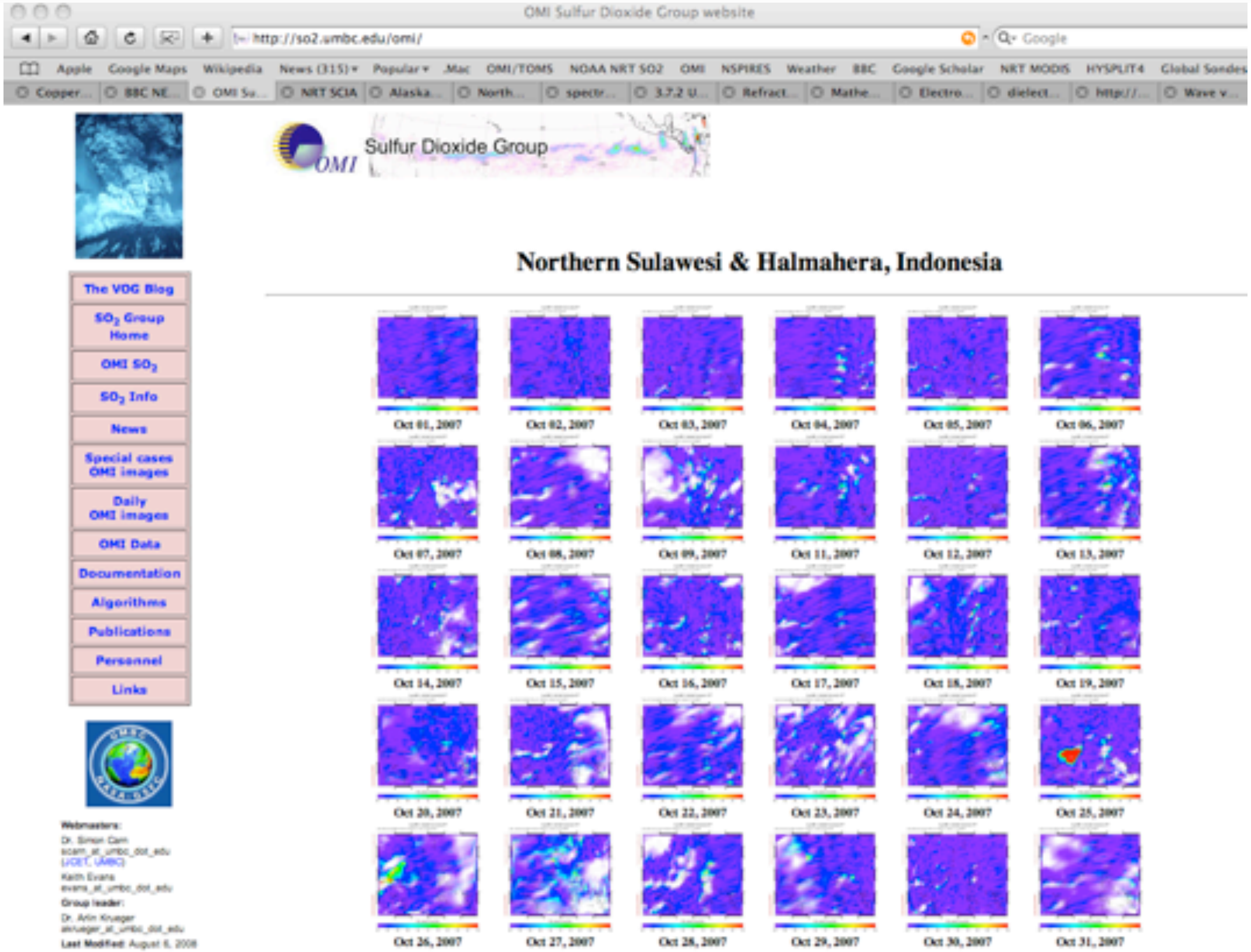
• Comparison between Turrialba SO_2 emission rates derived from ASTER, OMI and UV camera [*Campion et al.*, in prep.]

OMI sensitivity – passive degassing

Instrument	Minimum detectable SO_2 flux (tons/day)		
	Plume velocity 1 m/s	Plume velocity 5 m/s	Plume velocity 10 m/s
Earth Probe TOMS (1σ = 3.5 DU)	1030	5140	10290
OMI (plume traverses 13 km pixel width)	36	180	360
OMI (plume traverses 24 km pixel length)	19	95	190
COSPEC	10	52	104
Typical volcano	100 - 5000		

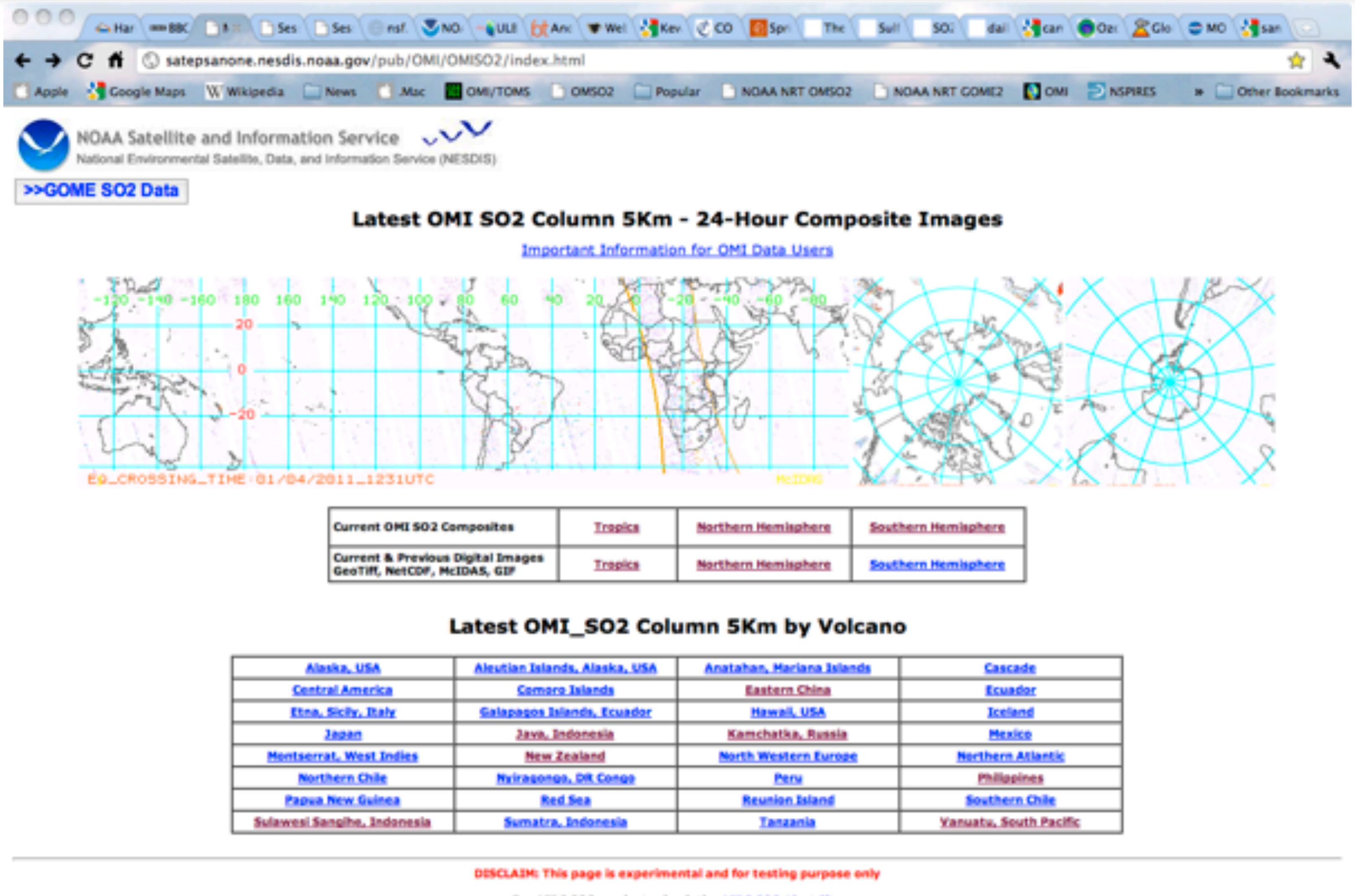
Detection limit (3σ above background) of passive SO_2 flux from a 5000m volcano at various plume velocities; 1σ = 0.2 DU assumed for OMI

OMI SO_2 websites



http://so2.umbc.edu/omi_home_new2.html/

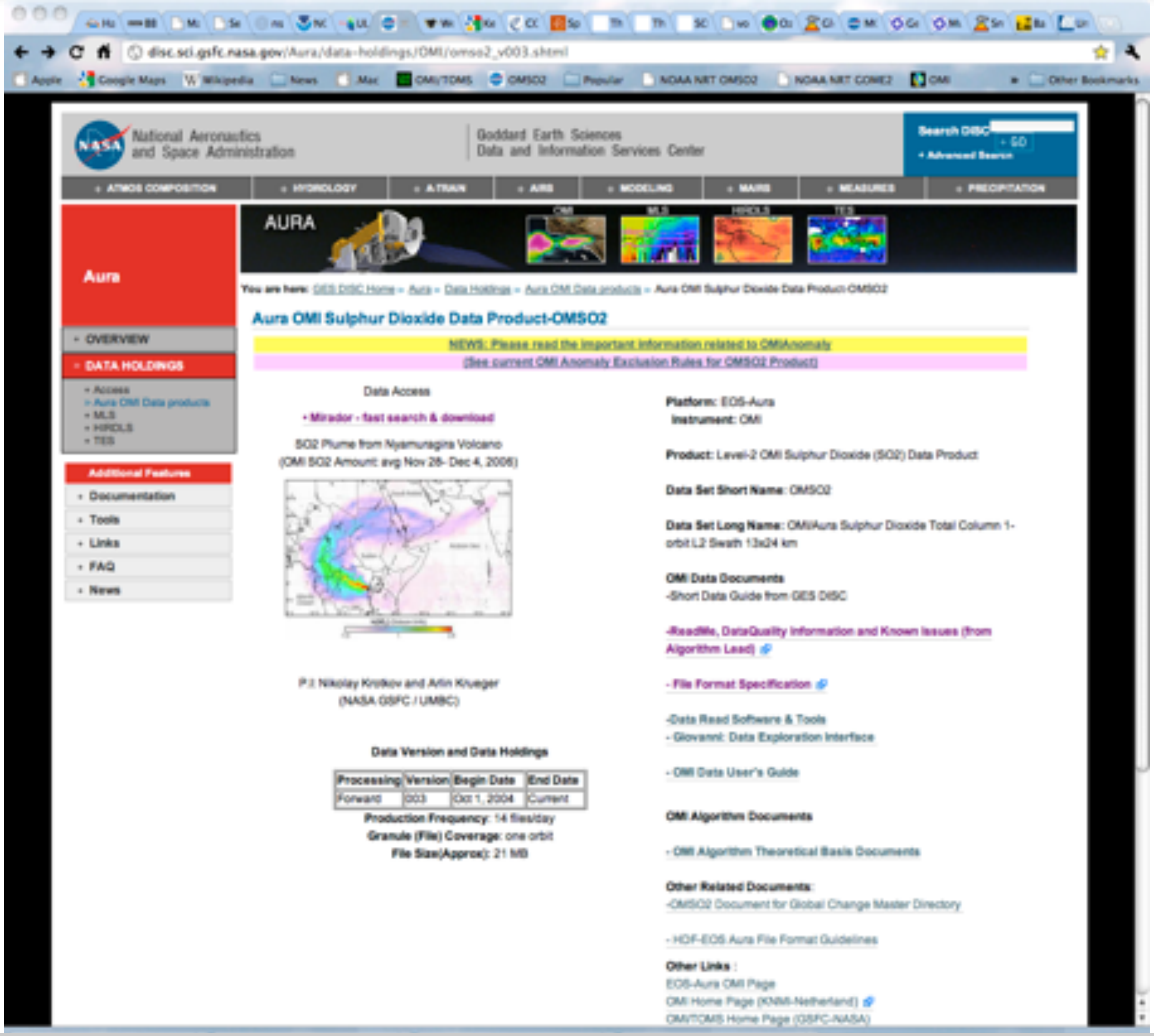
OMI SO_2 websites - NRT



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

Michigan Tech
Create the Future

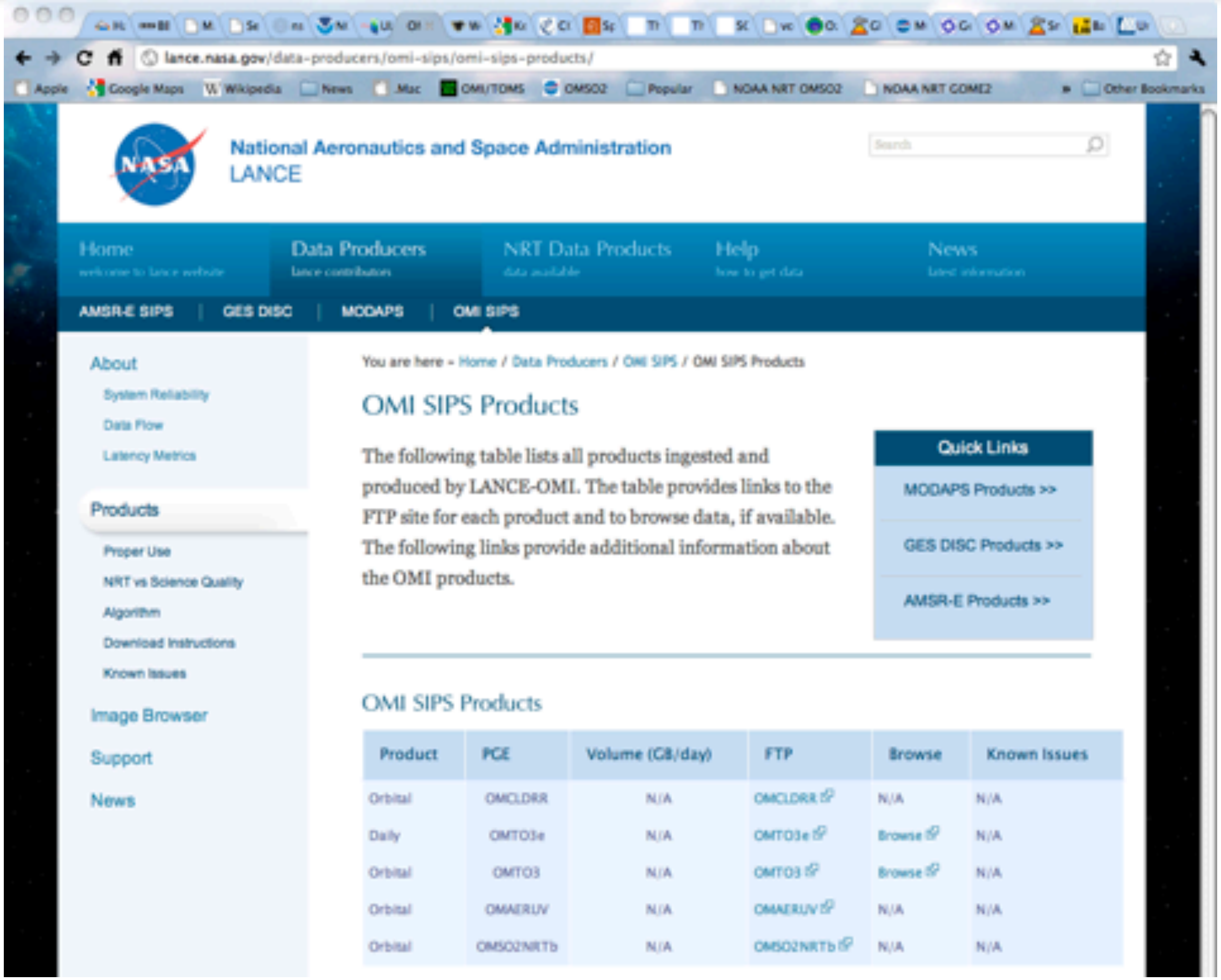
Operational OMI SO_2 data from NASA Mirador



http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI/omso2_v003.shtml

Michigan Tech
Create the Future

Near real-time OMI SO_2 data from NASA LANCE



http://lance.nasa.gov/data-producers/omi-sips/omi-sips-products/

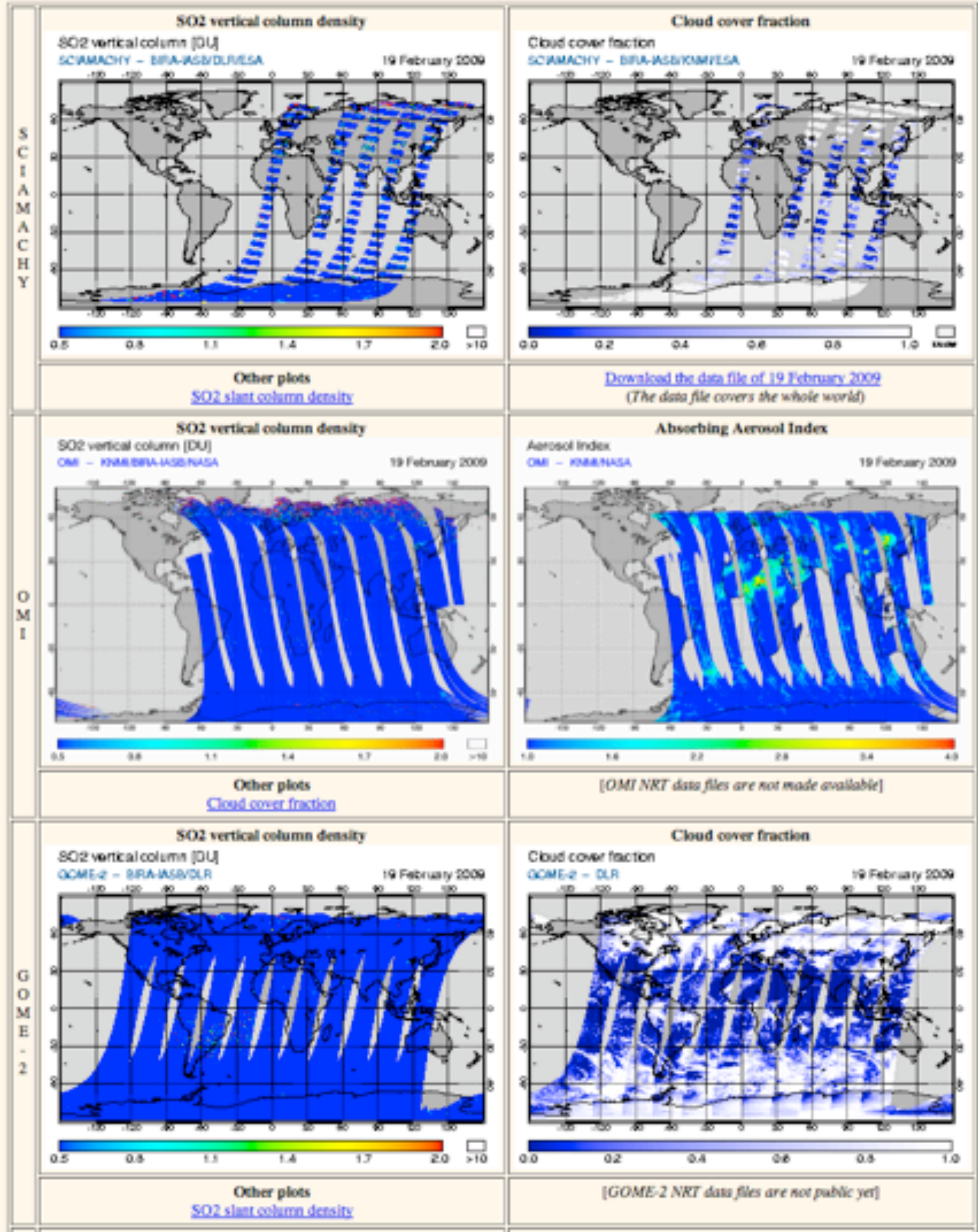
(Registration required)

BIRA website

SCIAMACHY

OMI

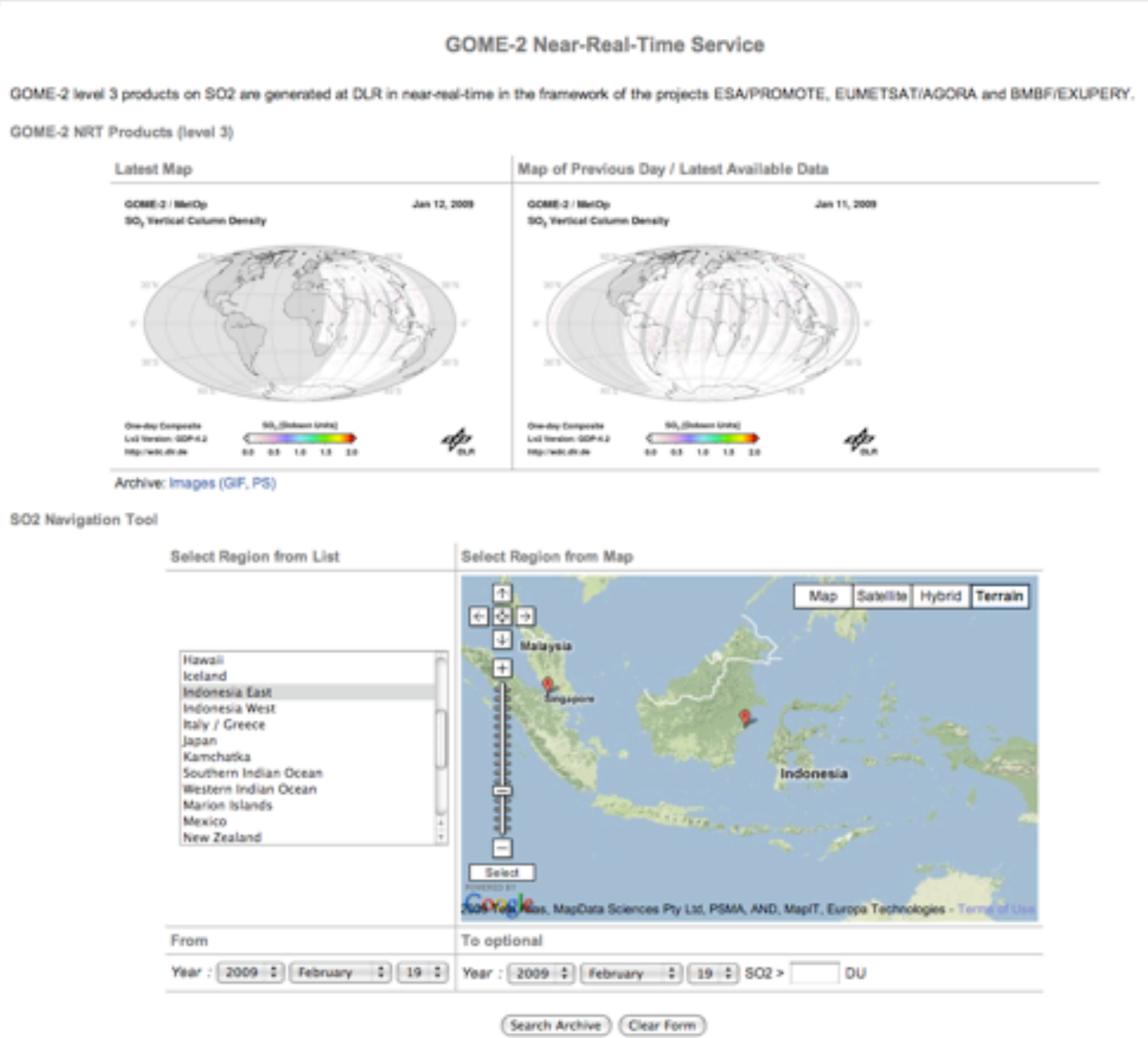
GOME-2



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

DLR GOME-2 website

German Aerospace Center



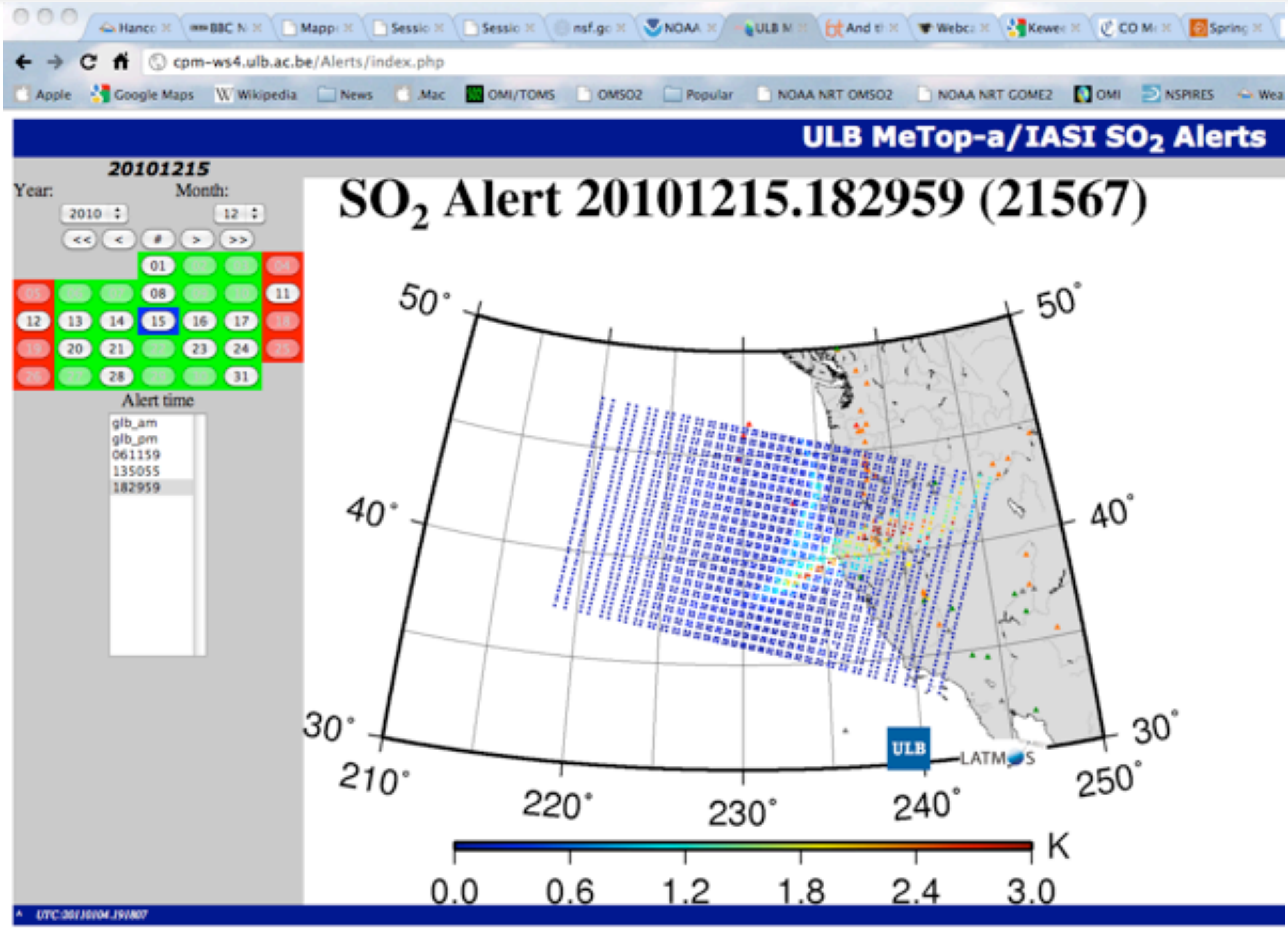
http://wdc.dlr.de/data_products/SERVICES/GOME2NRT/so2.php

AIRS NRT SO_2 website

Date.Granule	Image 1	Image 2	AIRS L1B (to get hdf data, email us)
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

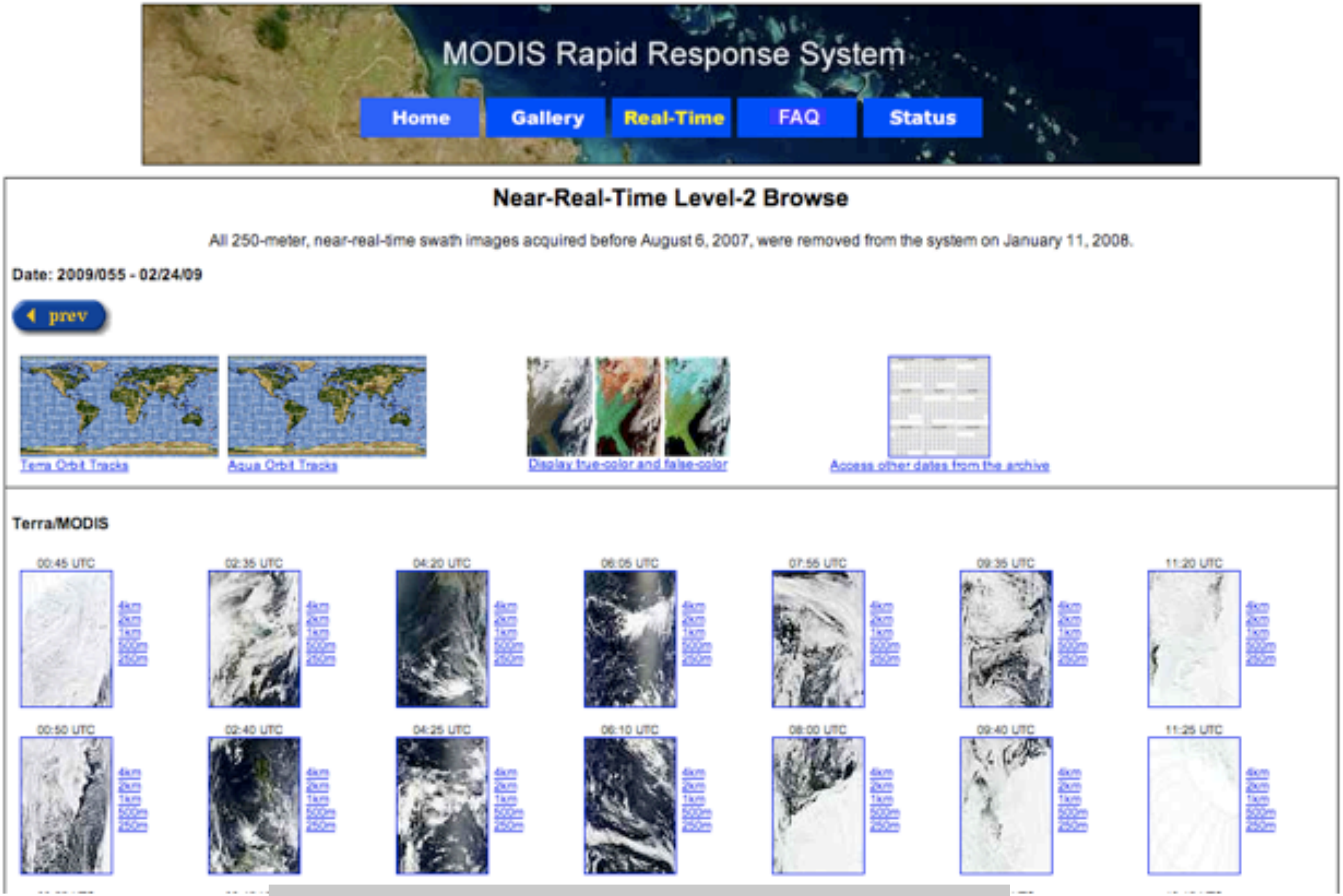
http://www.star.nesdis.noaa.gov/smcd/spb/iosspdt/iosspdt.php?so2=1#1

IASI NRT SO_2 alerts



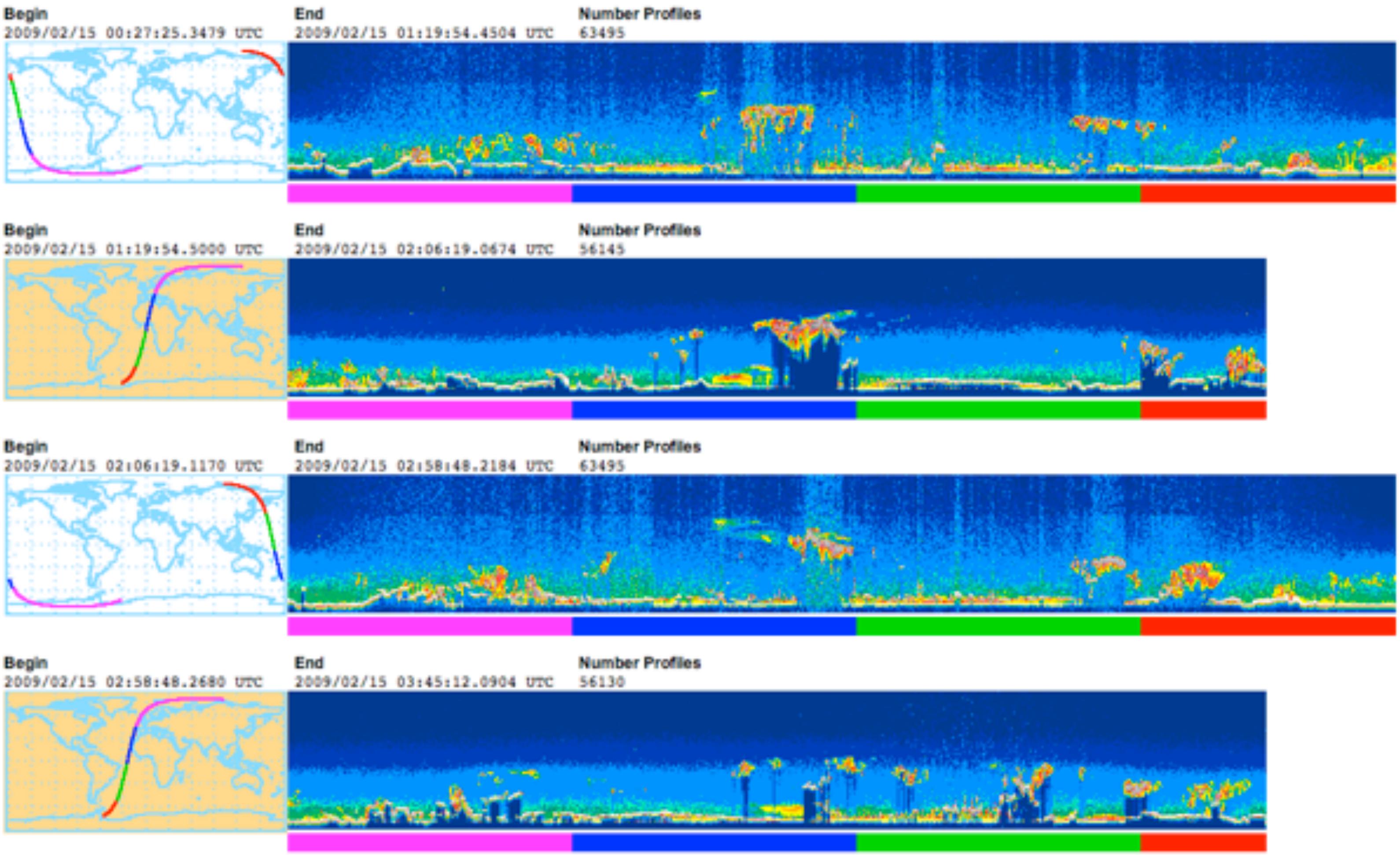
http://cpm-ws4.ulb.ac.be/Alerts/index.php

MODIS Rapid Response website



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

CALIPSO website



http://www-calipso.larc.nasa.gov/products/lidar/browse_images/show_calendar.php

The fate of sulfur gases in the atmosphere

- SO_2 (S^{+4}) oxidizes to sulfuric acid (sulfate) aerosol (H_2SO_4)
  - Rapid in aqueous phase (hours) – clouds, fog
  - Slower in gas phase (days-weeks) – stratosphere
  - Sulfuric acid (S^{+6}) highly soluble in water – rapid removal in precipitation
  - SO_2 also scrubbed by H_2O before emission
- H_2S (S^{-2}) oxidizes to SO_2 (and sulfate) by reaction with OH, ozone (O_3)
  - Less water-soluble than 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

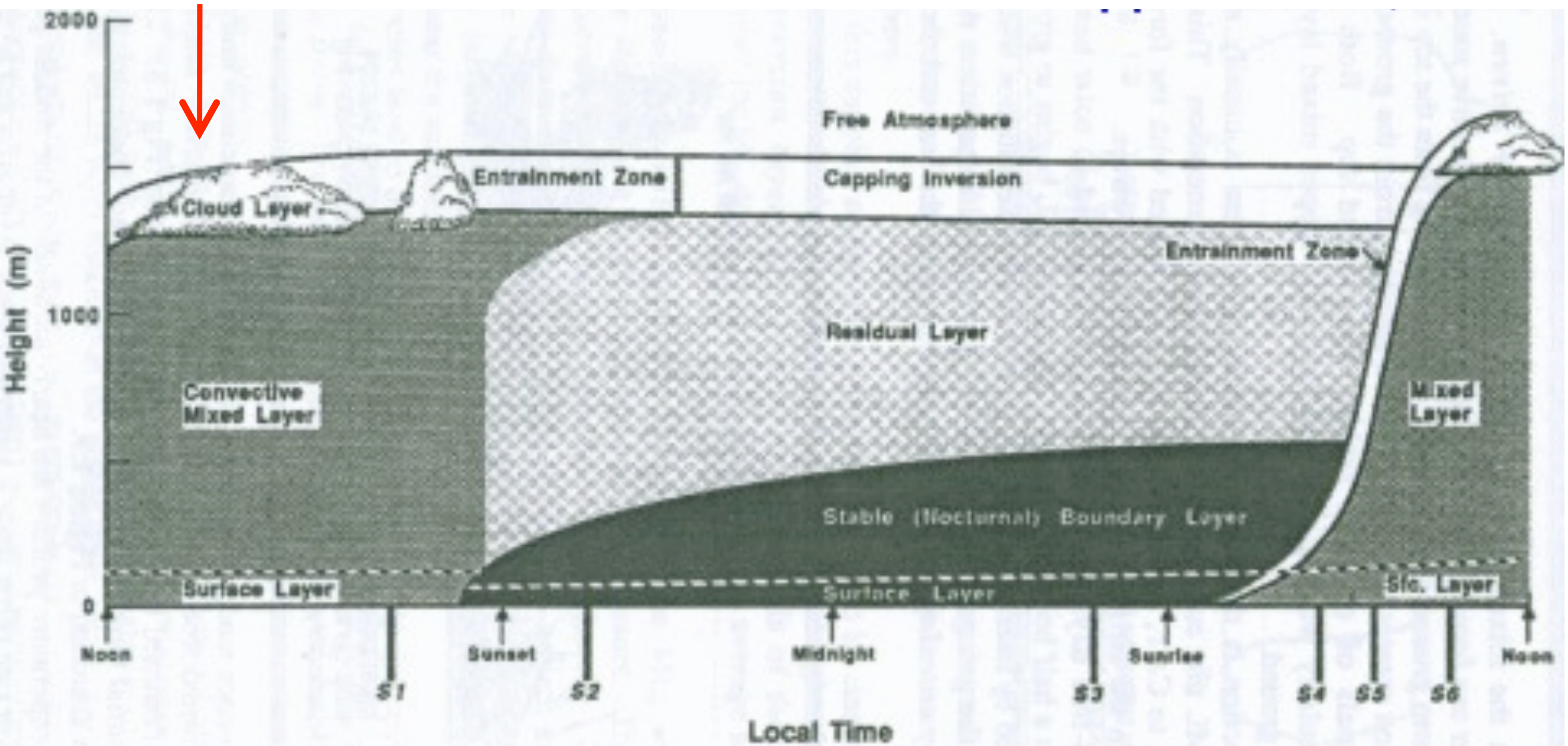
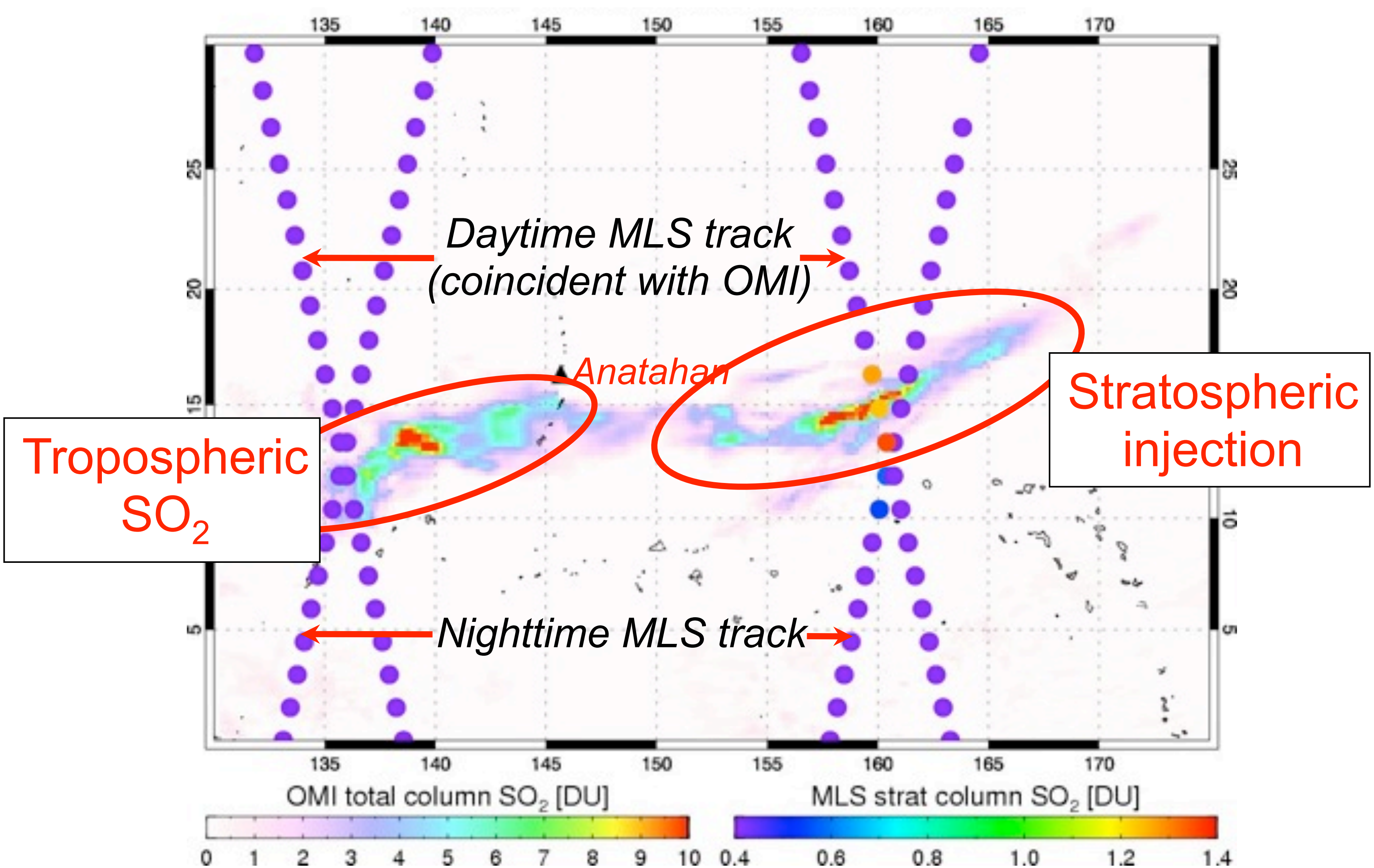


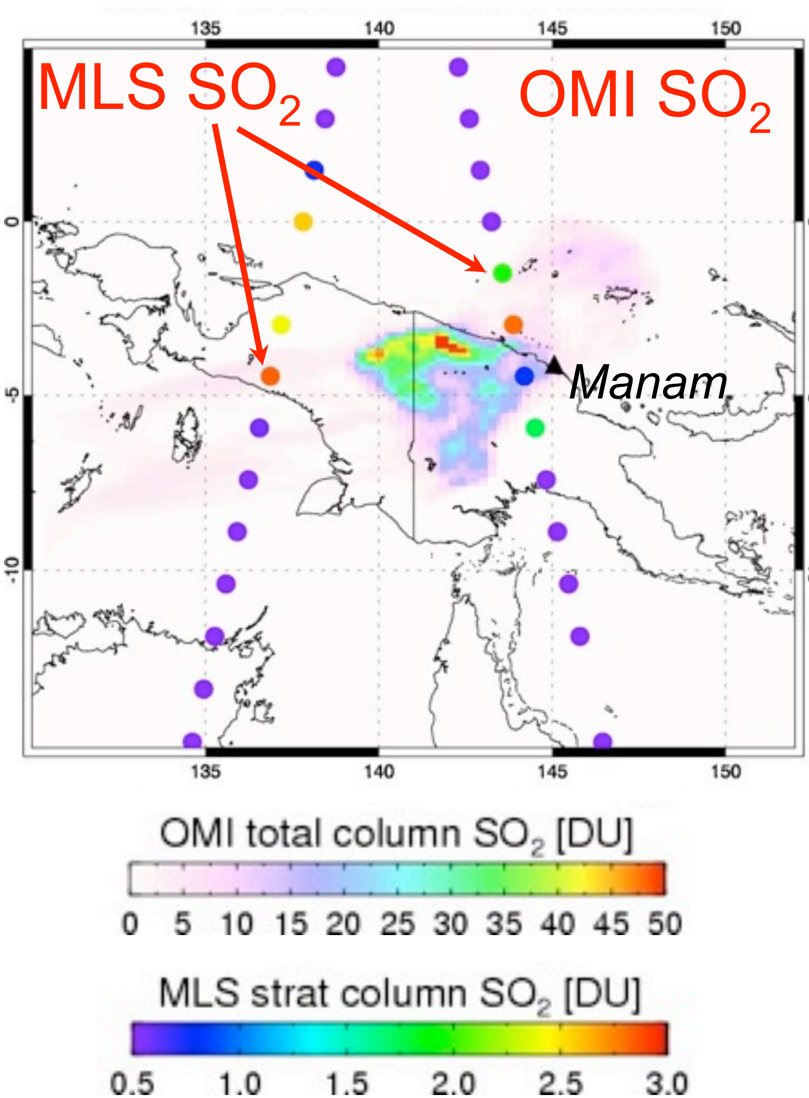
Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

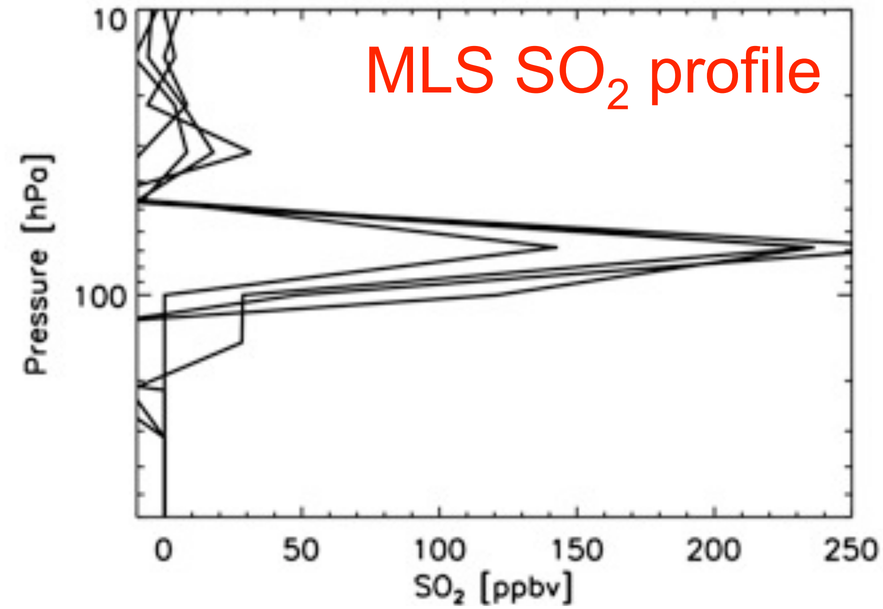
Aura/OMI - Aura/MLS: Anatahan (CNMI), April 7, 2005



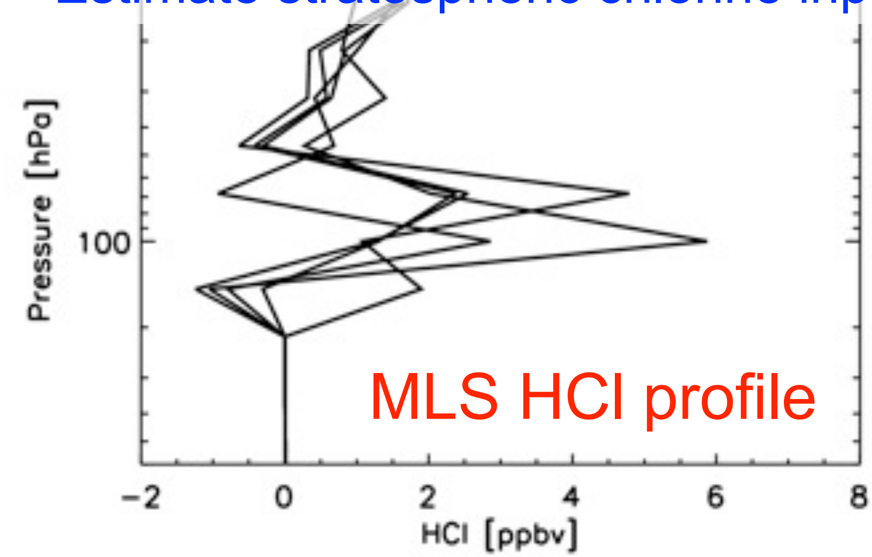
Michigan Tech
Create the Future

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



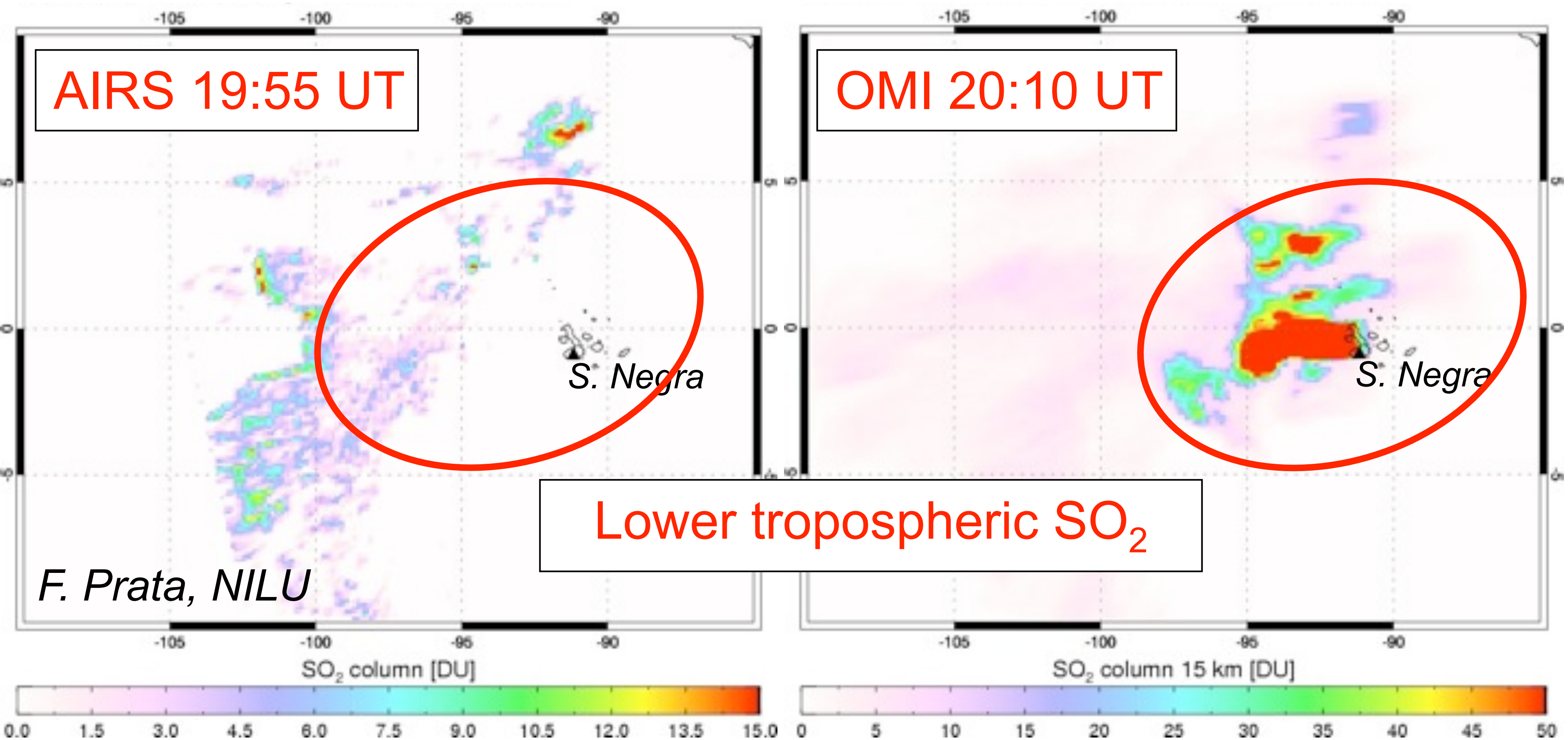


- Estimate stratospheric chlorine input



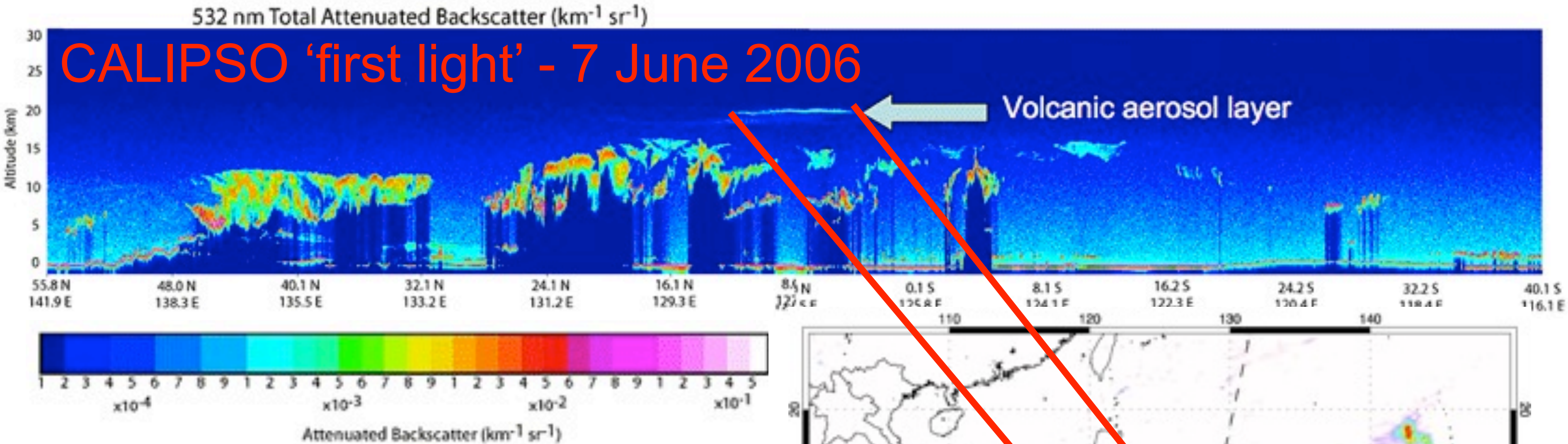
Michigan Tech
Create the Future

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

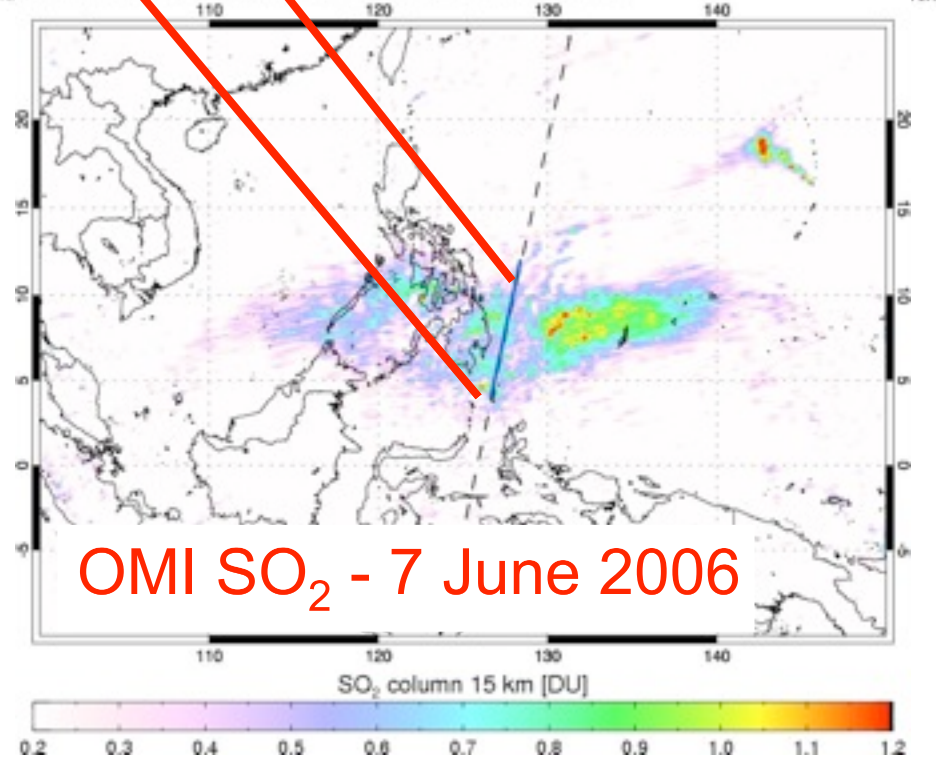


- Sierra Negra (Galapagos) eruption, October 24, 2005
- OMI-AIRS synergy indicates SO_2 concentrated in the lower troposphere

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



[Credit: *CALIPSO Team, NASA Langley*]

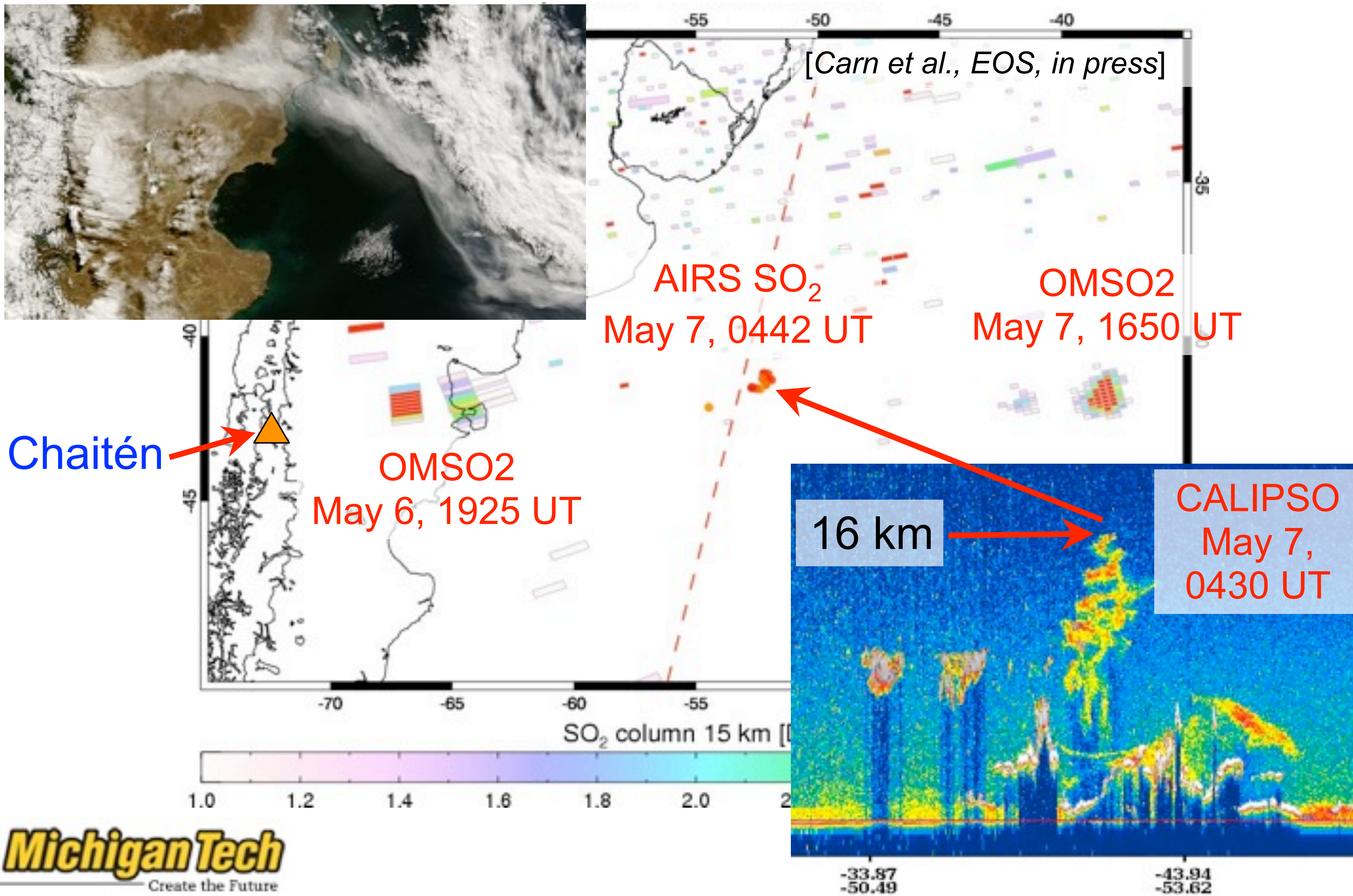


- May 20 eruption on Montserrat
- SO_2 tracked for 3 weeks
- Cloud altitude ~20 km
- Aerosol layer non-depolarizing
- Sulfate dominant, not ash

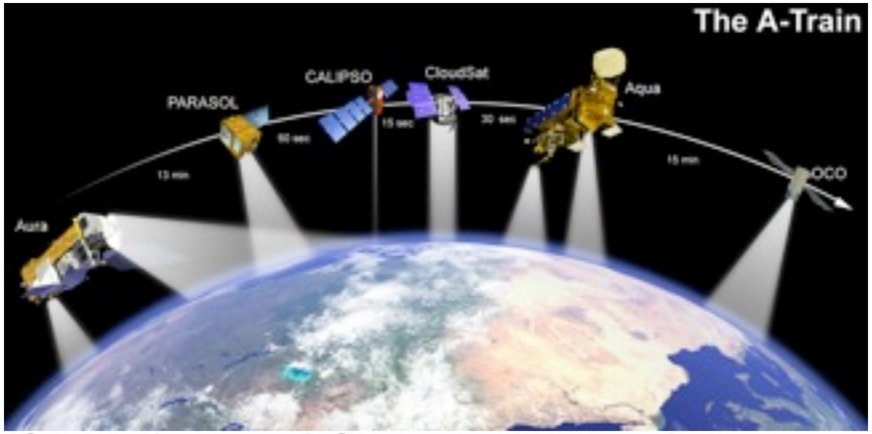
[*Carn et al., ACPD, 2007*]

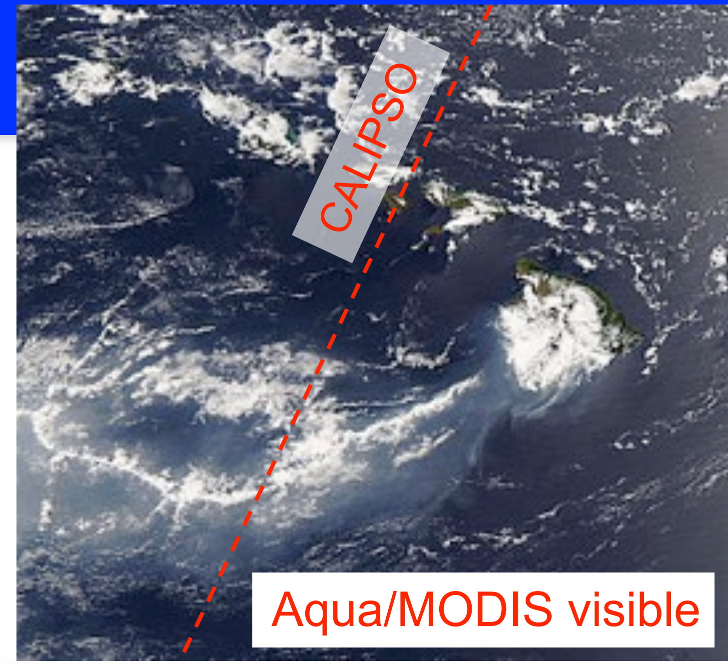
Michigan Tech
Create the Future

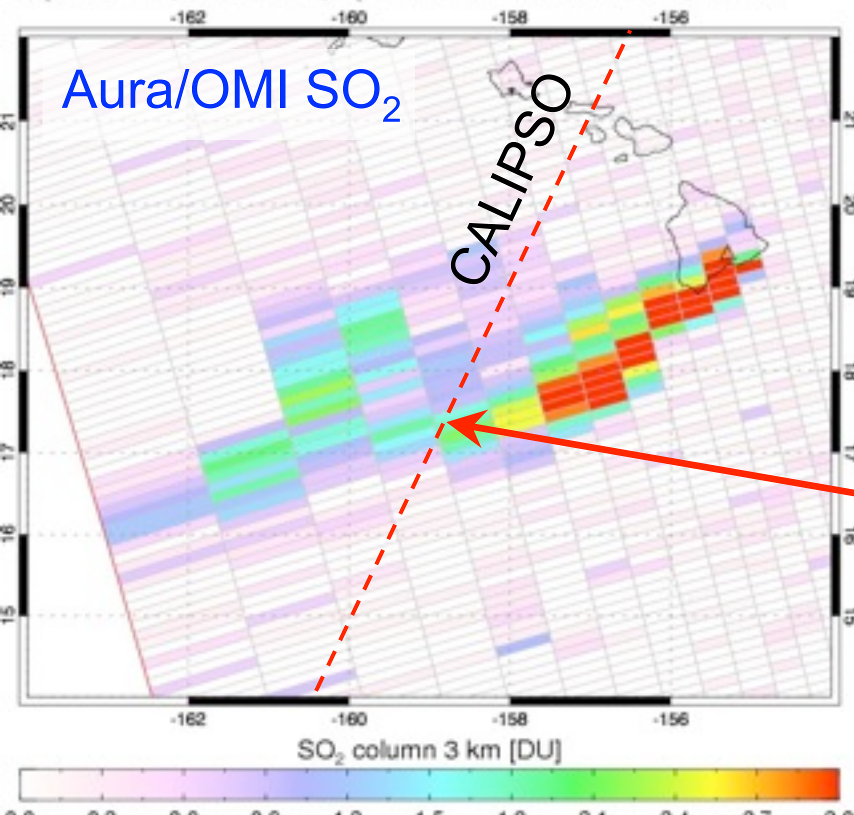
OMI - Aqua/AIRS - CALIPSO: Chaitén (Chile), May 2008

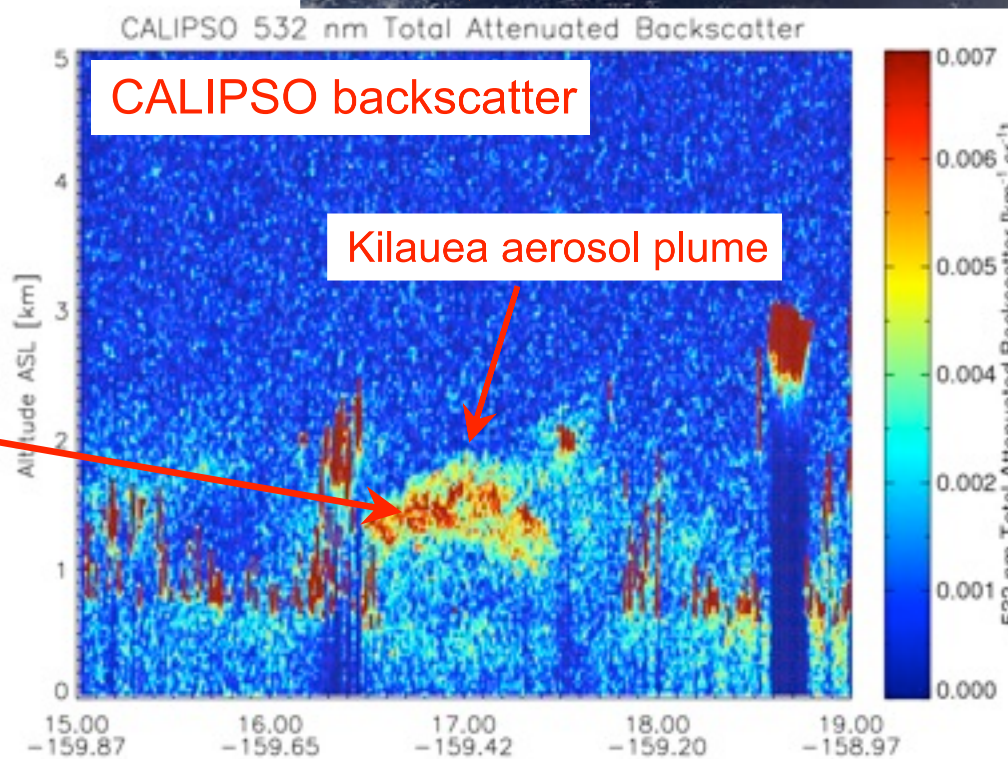


Kilauea degassing – April 7, 2008

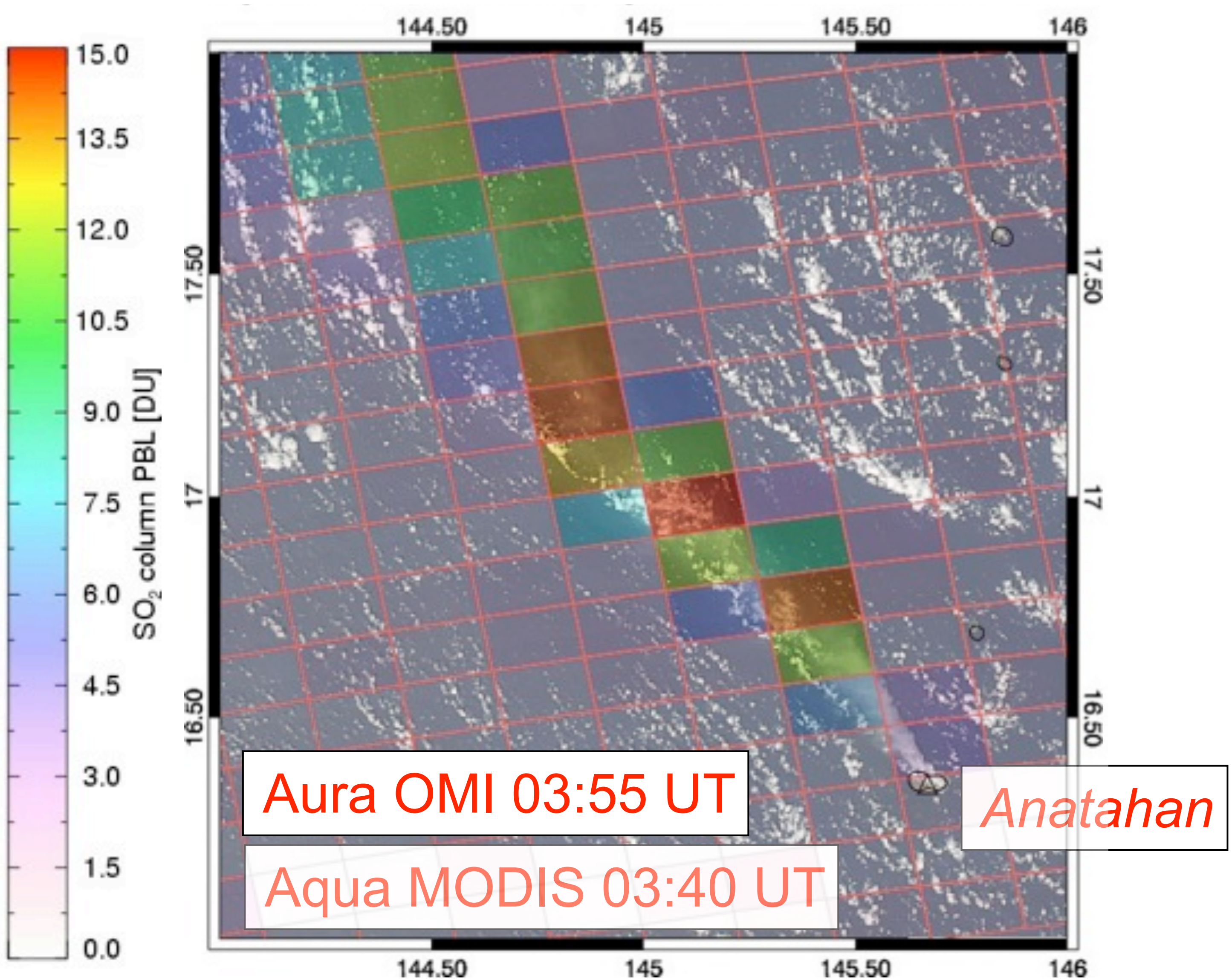






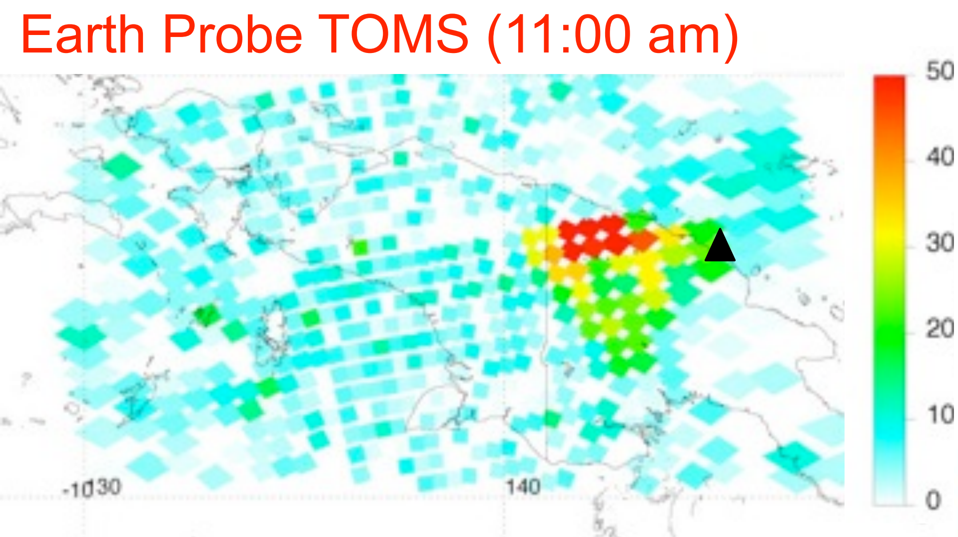


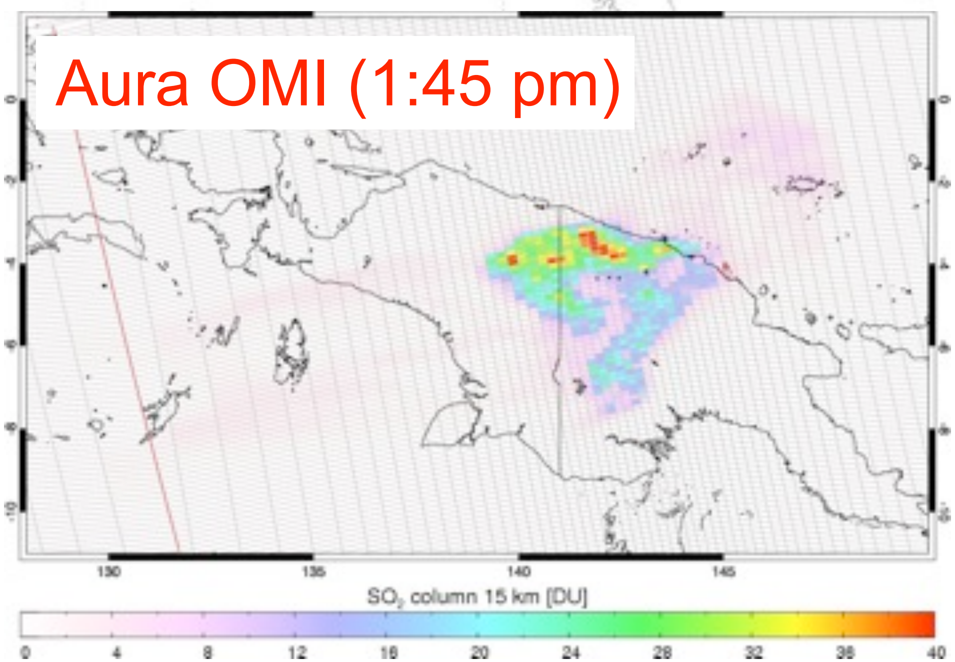
Aura/OMI - Aqua/MODIS - Anatahan (CNMI), Feb 10, 2008

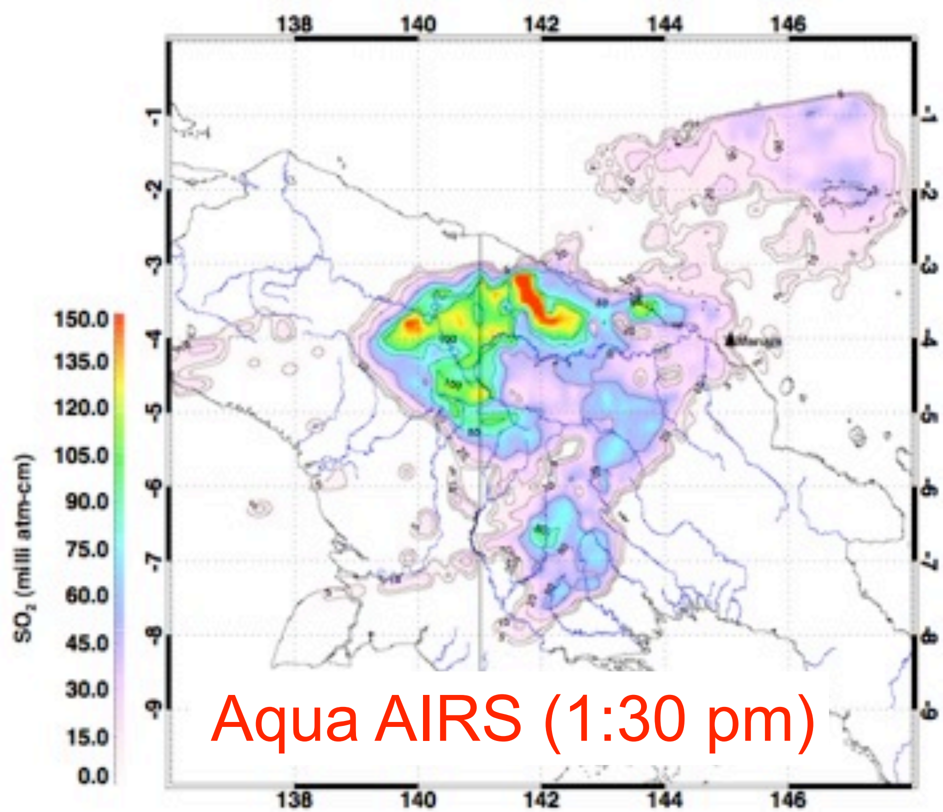


Michigan Tech
Create the Future

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







- Independent SO_2 retrievals from 3 instruments (UV/IR)
- Volcanic cloud SO_2 burdens agree to within 20%

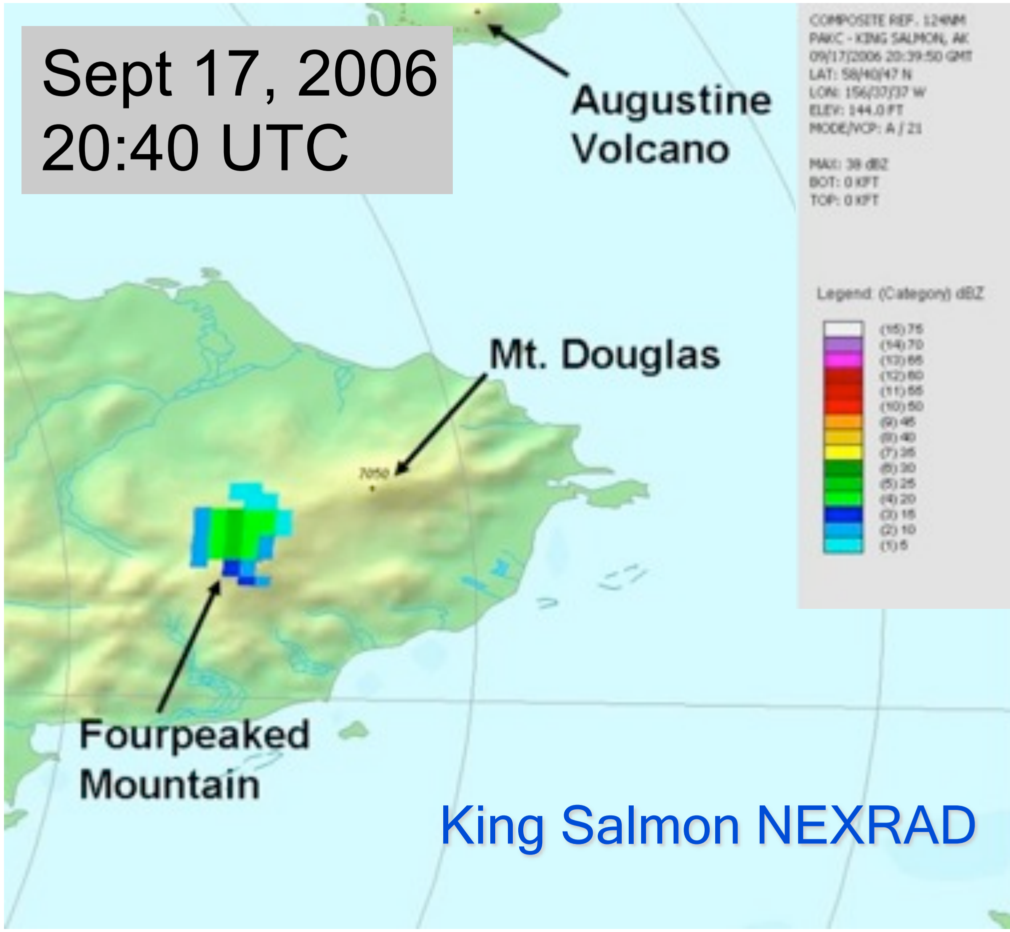
Strengths and weaknesses of SO_2 data

- 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_2 amounts
  - UV sensors can detect SO_2 degassing prior to eruptions
  - Can map volcanic clouds when ash is encased in ice
  - UV sensors can detect SO_2 in opaque volcanic clouds
  - SO_2 measurements have been validated (but more is needed)
  - Could SO_2 be used to assess cumulative aircraft exposure to volcanic clouds?
- Weaknesses
  - Poor proxy for dense ash when SO_2 and ash clouds separate
  - No geostationary SO_2 data in NOPAC region (yet –> GOES-R ABI)
  - UV techniques restricted during winter months

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 evaluation satellite SO_2 data
- New satellite constellations (A-Train) provide opportunities for sensor synergy and '3D' analysis of volcanic clouds

Eruption detection: Fourpeaked (AK)

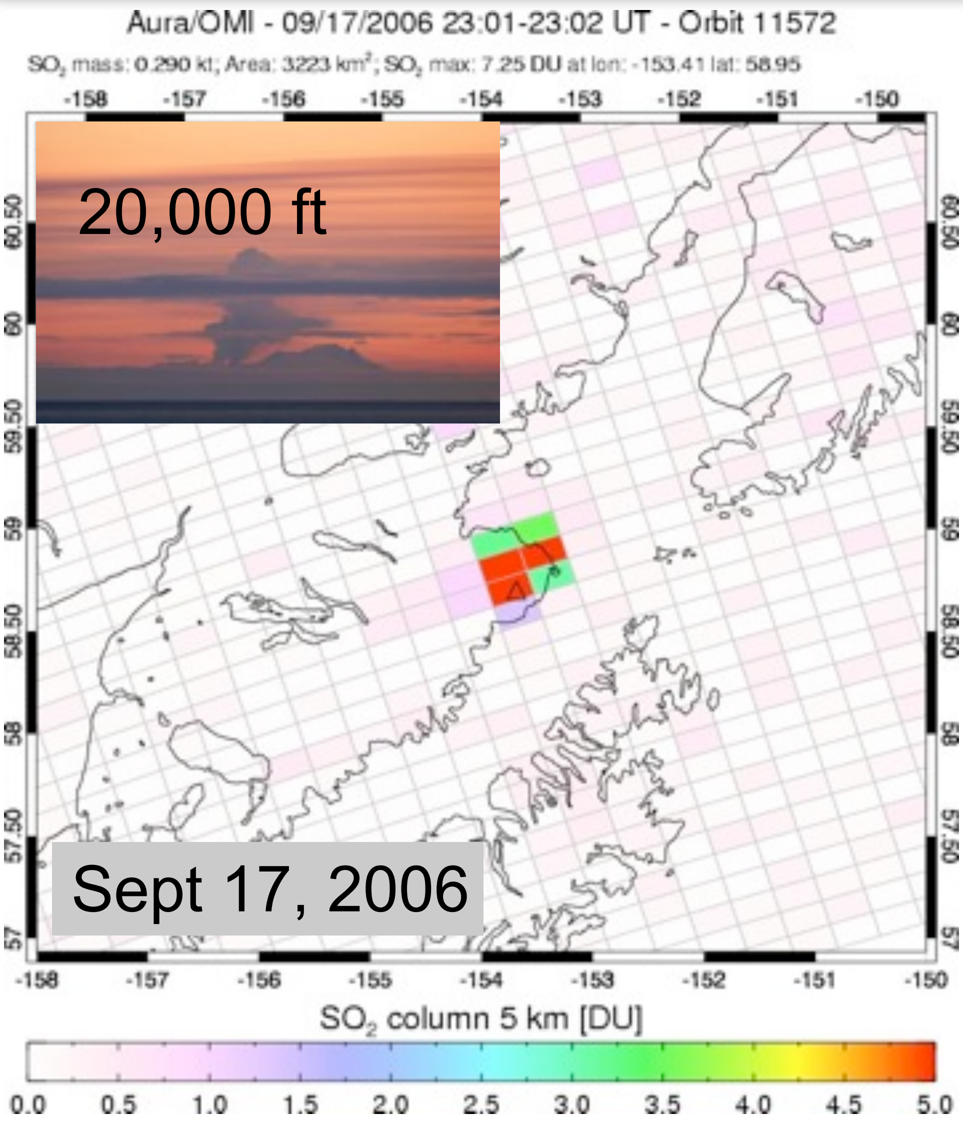


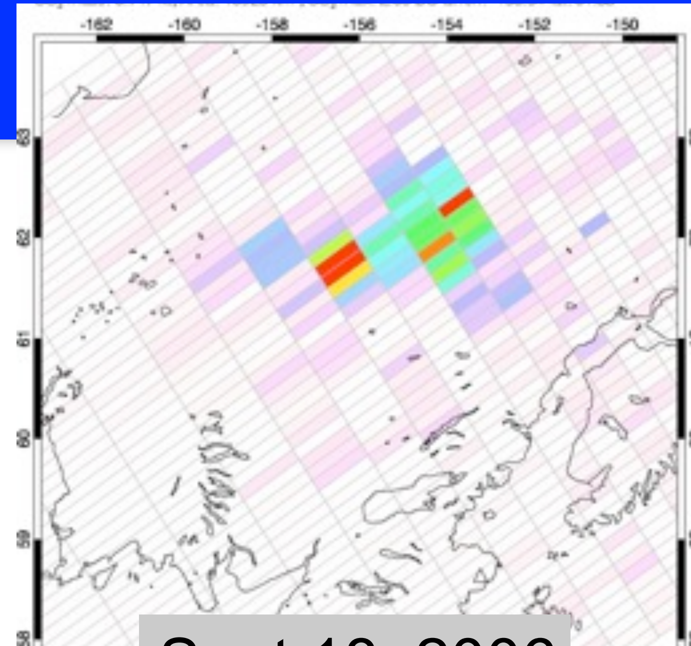
[NEXRAD data courtesy AVO]

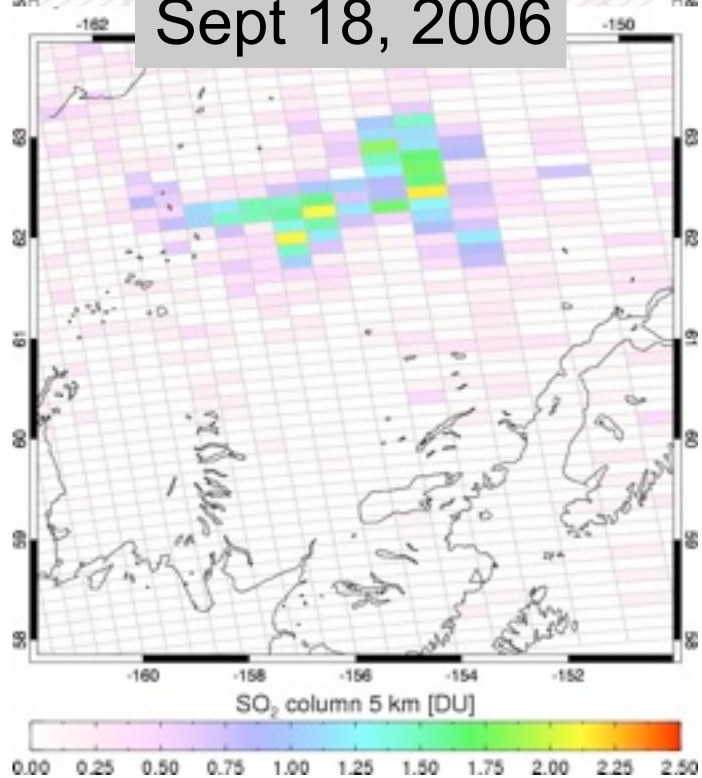
Fourpeaked Volcano, AK:
A long dormant volcano - last volcanic activity was prior to glaciation (>10,000 years ago). No known fumarolic areas around the volcano.

Fourpeaked (AK) eruption, Sept 2006

Fourpeaked (AK) – Sept 2006

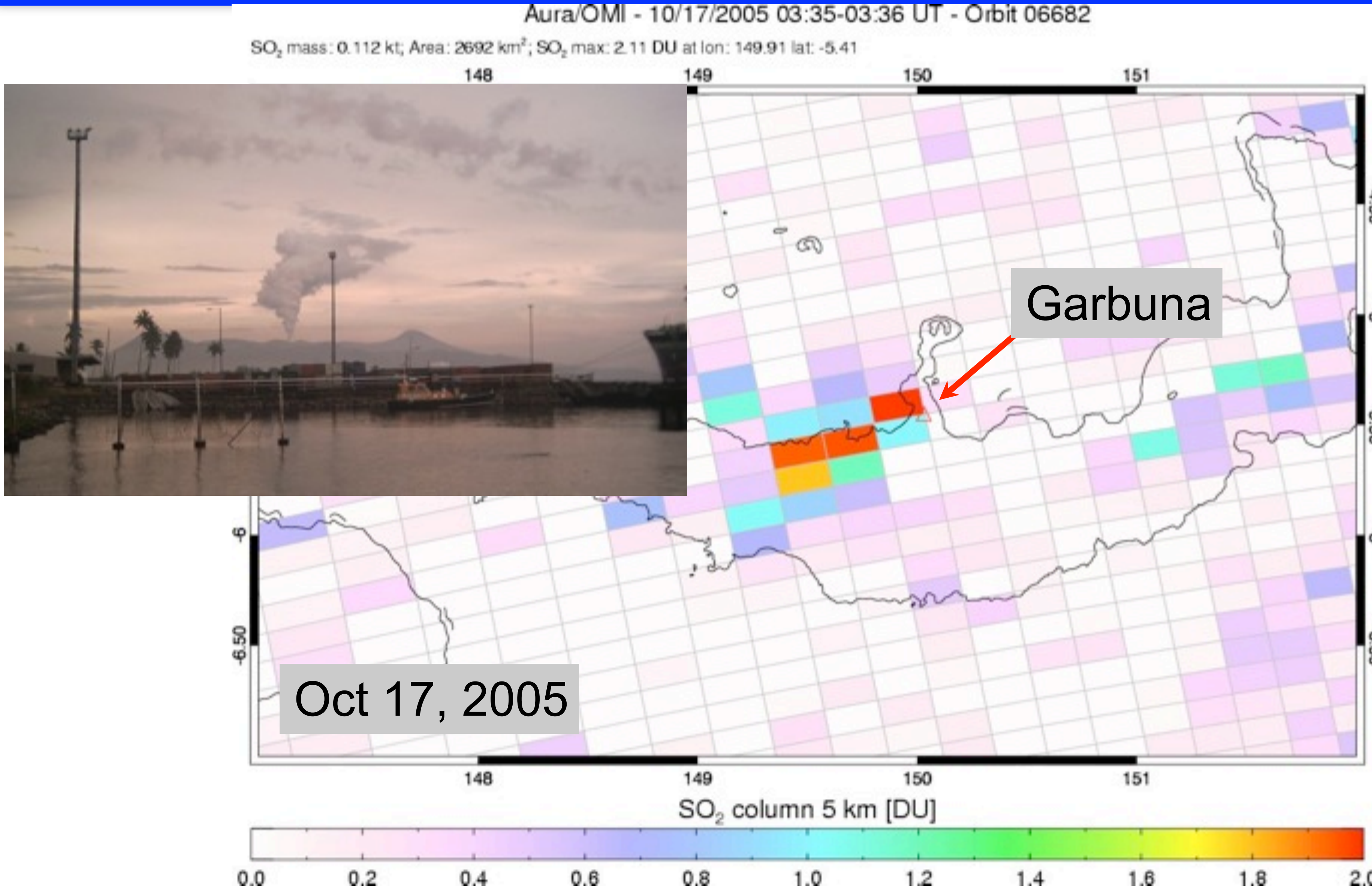






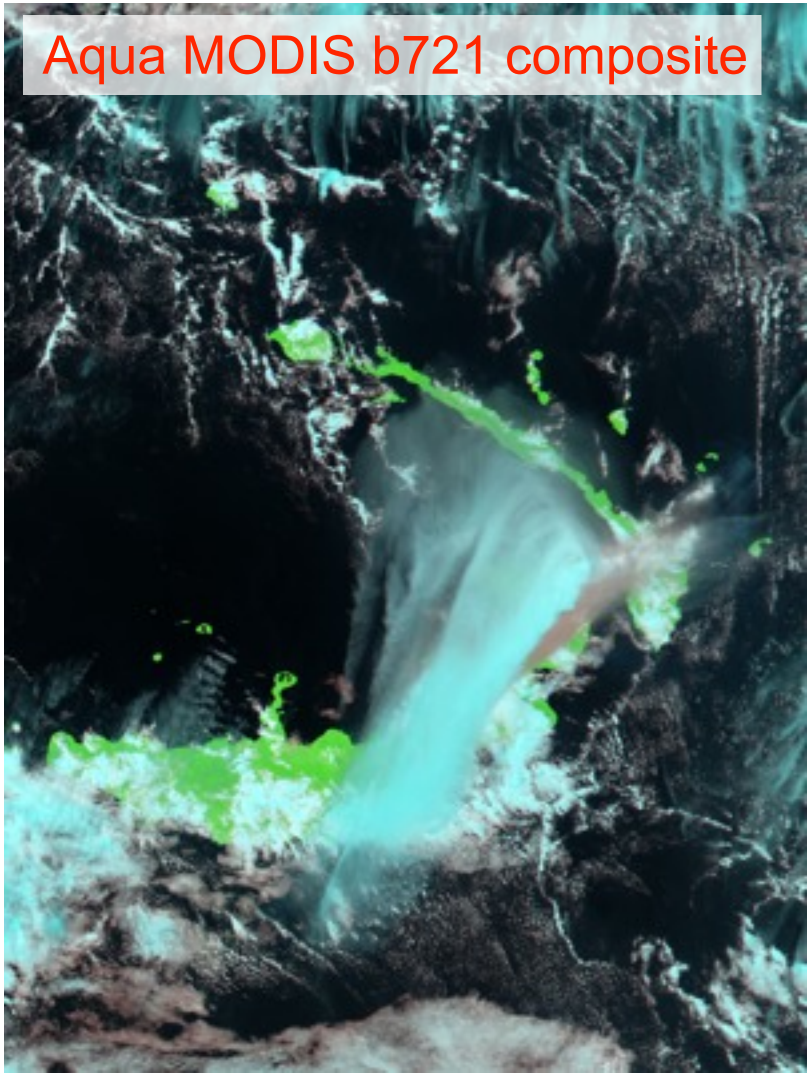
- Small magmatic intrusion at shallow depth?

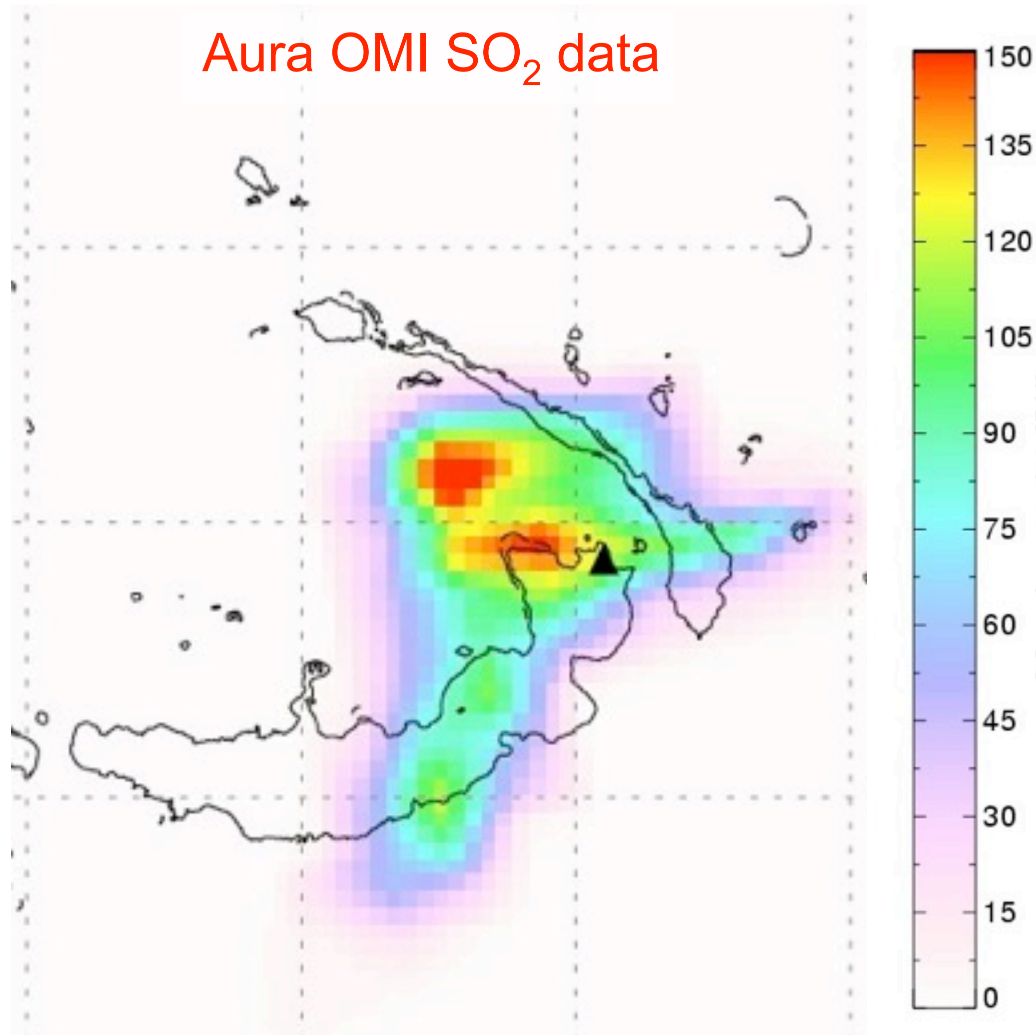
Garbuna (PNG) – October 2005



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

Detection of ice-rich volcanic clouds

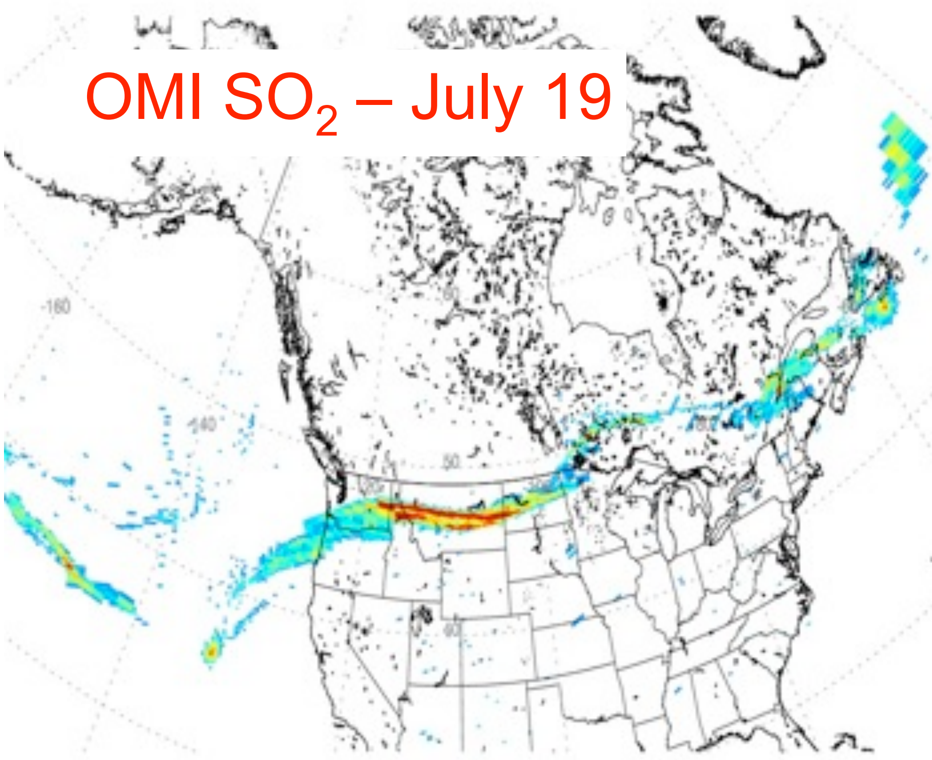


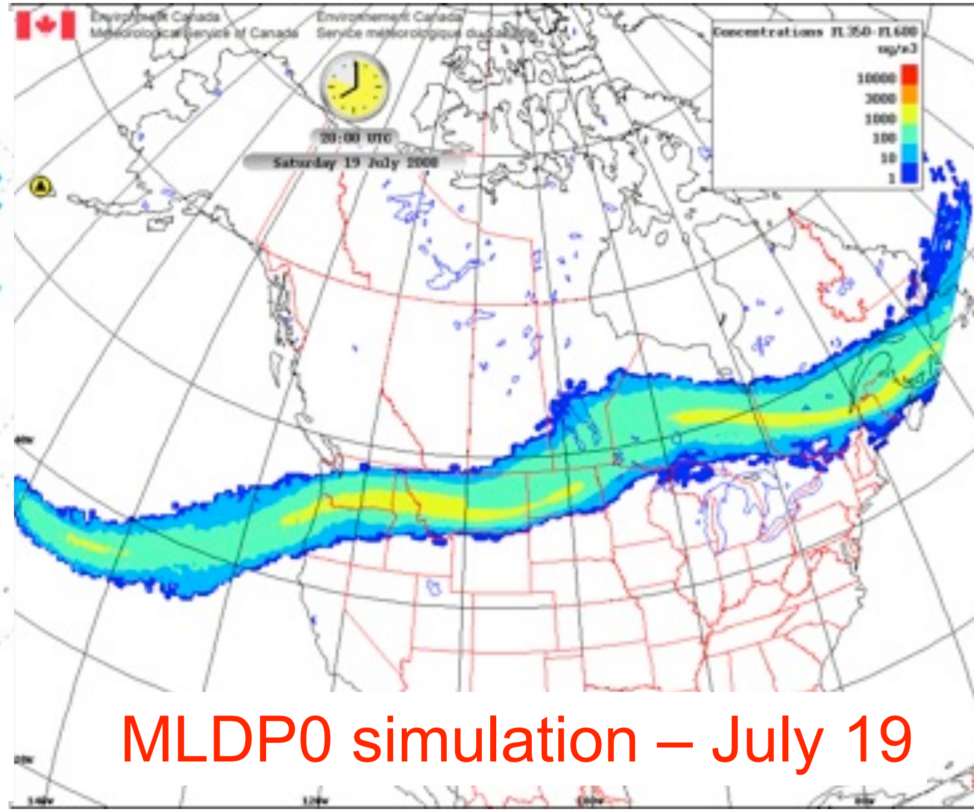


Rabaul (PNG) eruption, 7 Oct 2006

Validation of trajectory/dispersion models

http://eer.cmc.ec.gc.ca/people/Alain/eer/exercises/okmok/exp_05/sig2v_0.5/FL350-FL600/anim.html

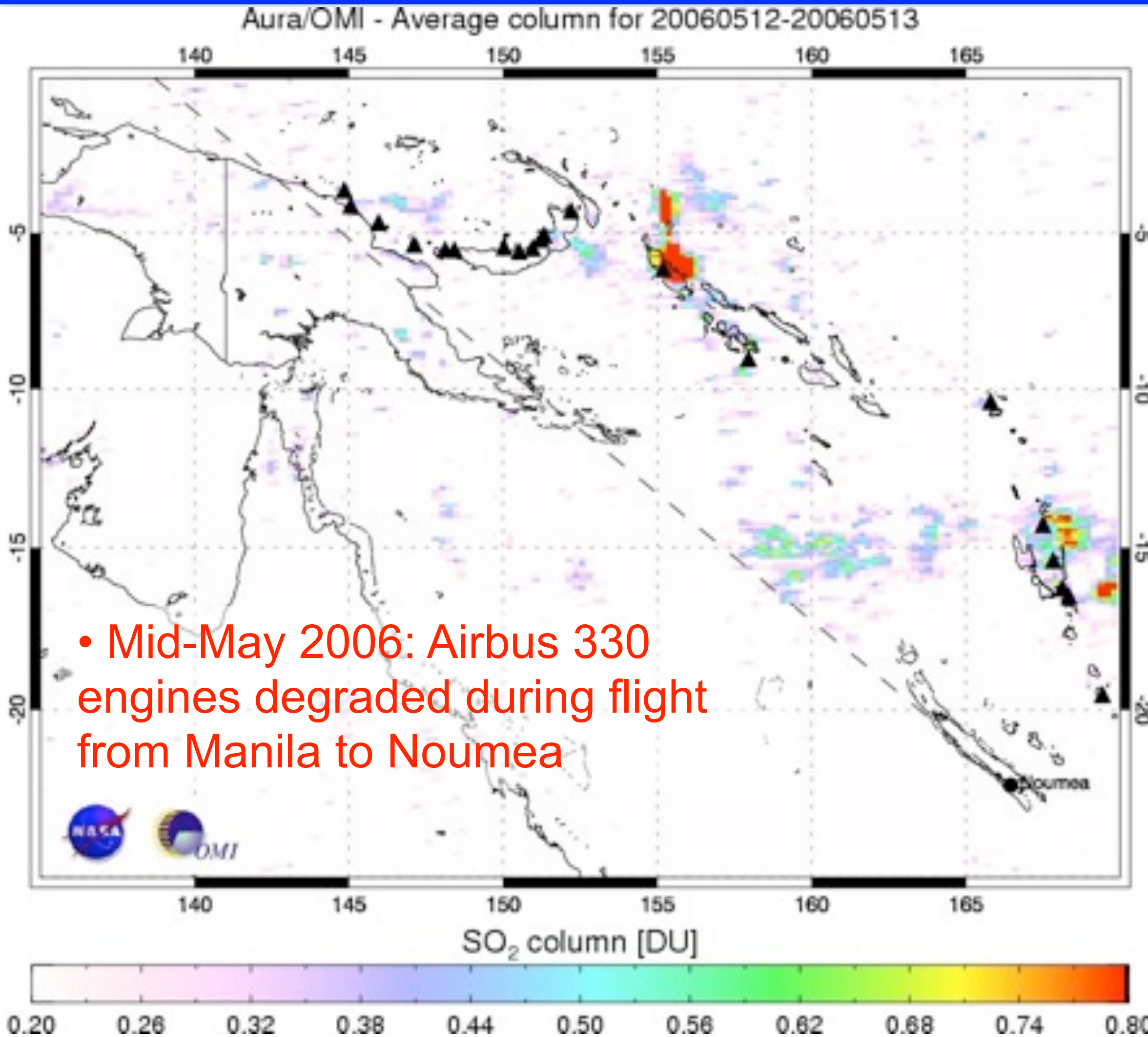




MLDP0 data courtesy of René Servranckx and Alain Malo, Montreal VAAC

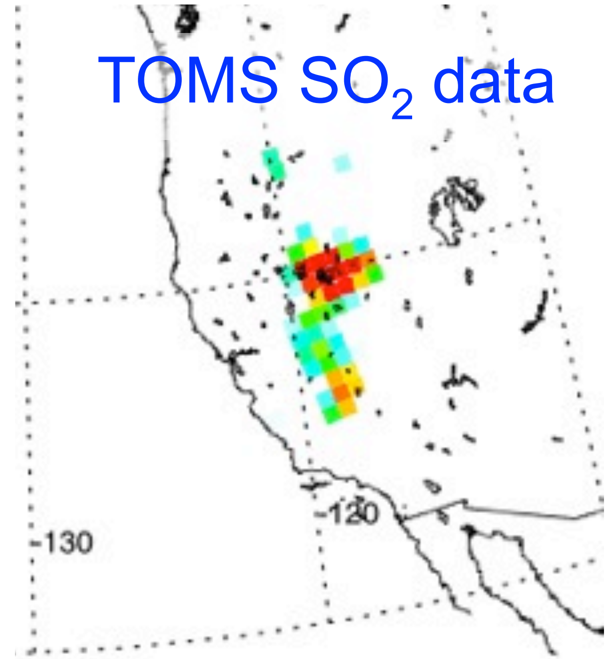
- Accurate dispersion models are essential for volcanic ash forecasting
- SO_2 better suited for model validation due to its much longer atmospheric residence time

Aviation encounters with dilute volcanic clouds



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

TOMS SO_2 data



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

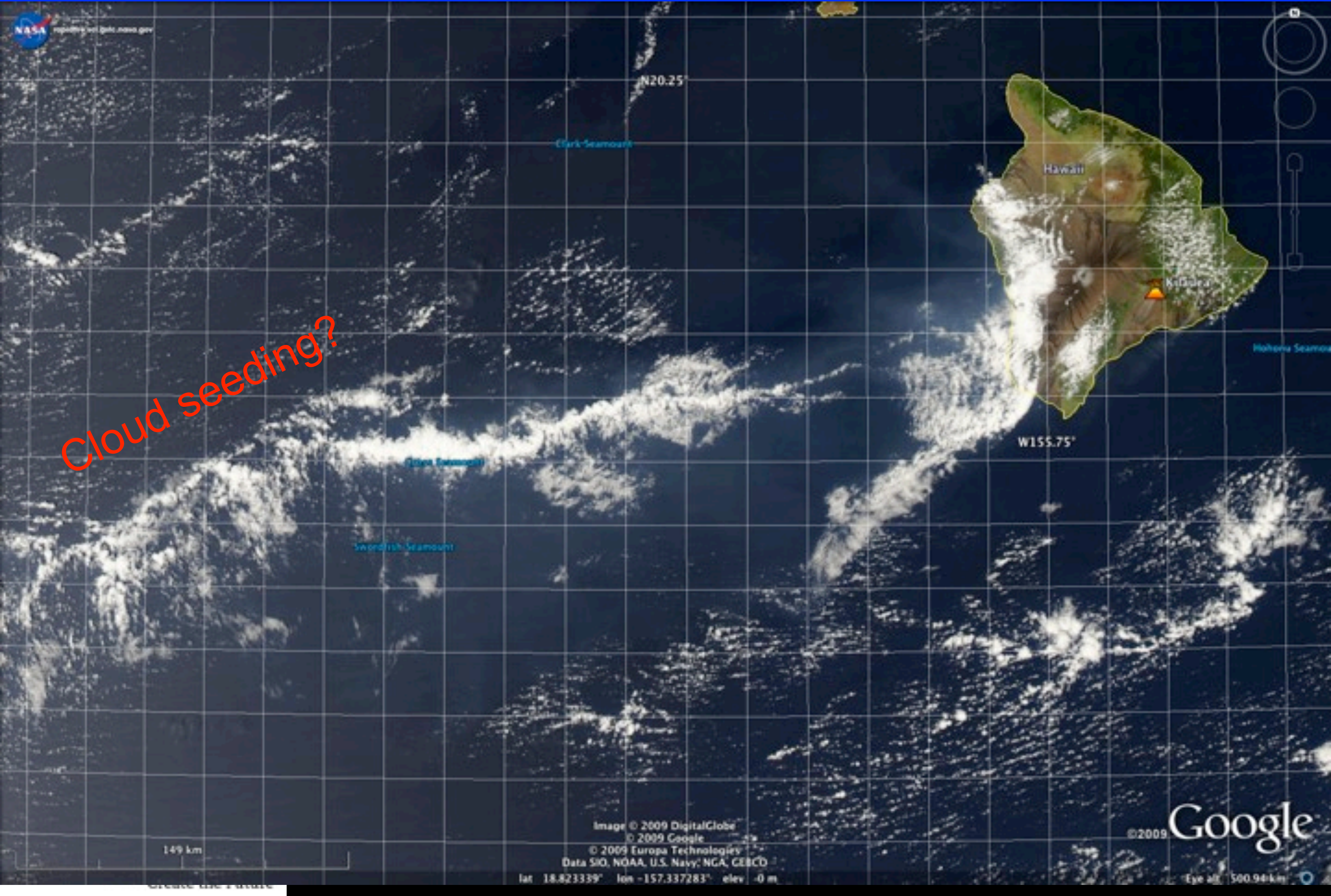
[*Carn et al.*, 2009]

• Encounters over Micronesia, Nov 2002 and March 2003 [*Tupper et al.*, 2006]

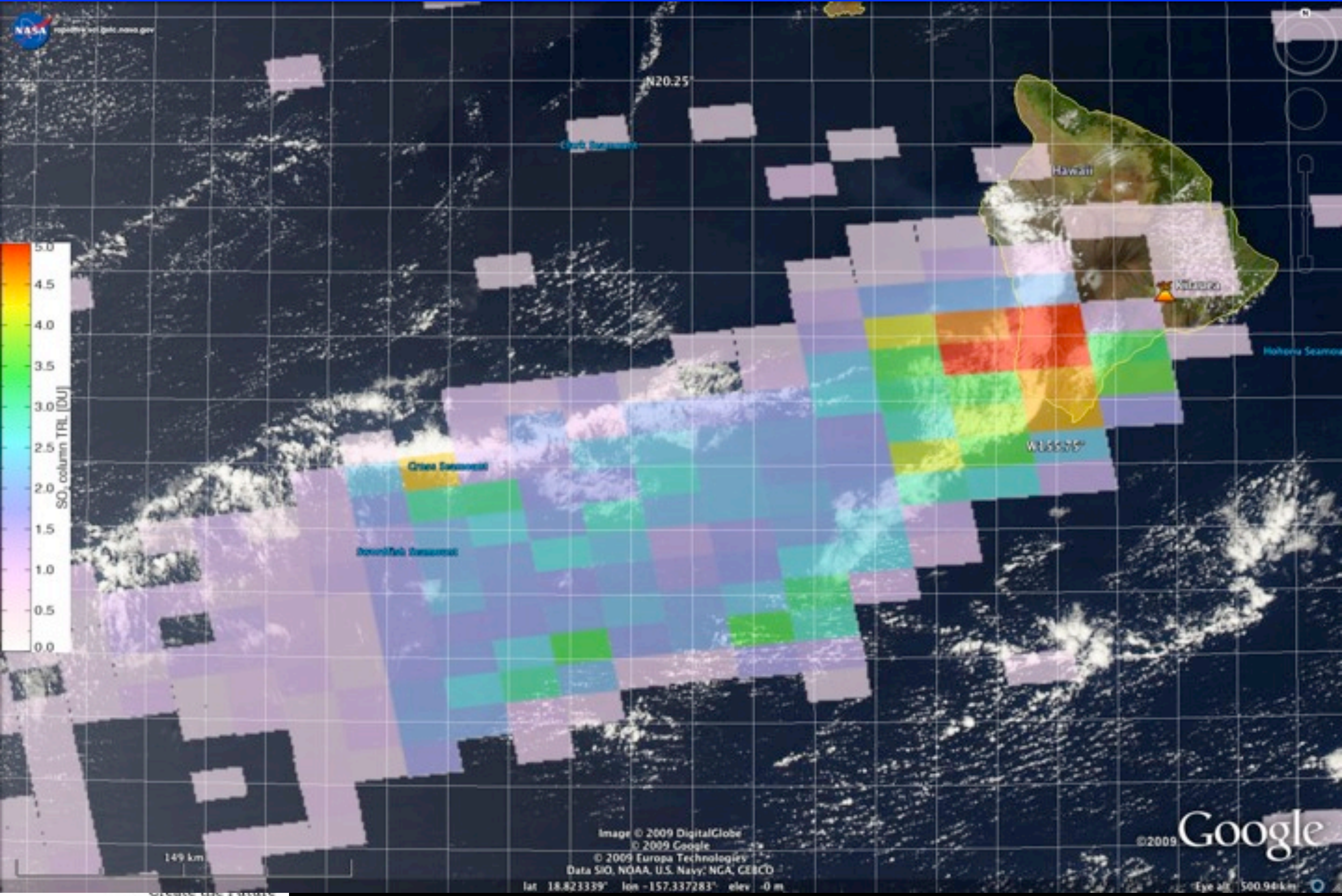
• 'Gulfstream incident': twin-engined flameout over PNG, July 2006 [*Tupper et al.*, 2007]

• NASA DC8 encounter with Hekla volcanic cloud, Feb 2000

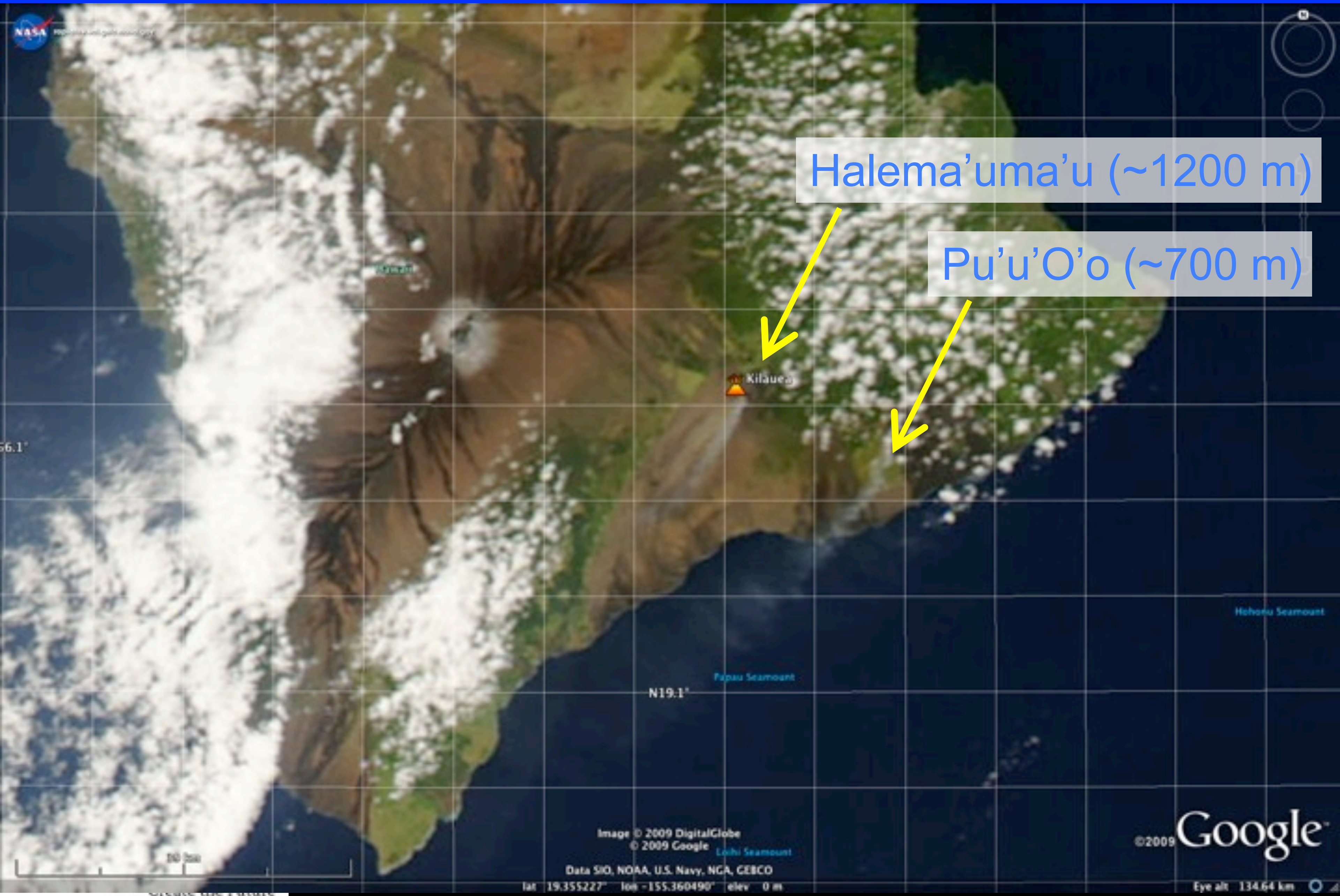
Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)



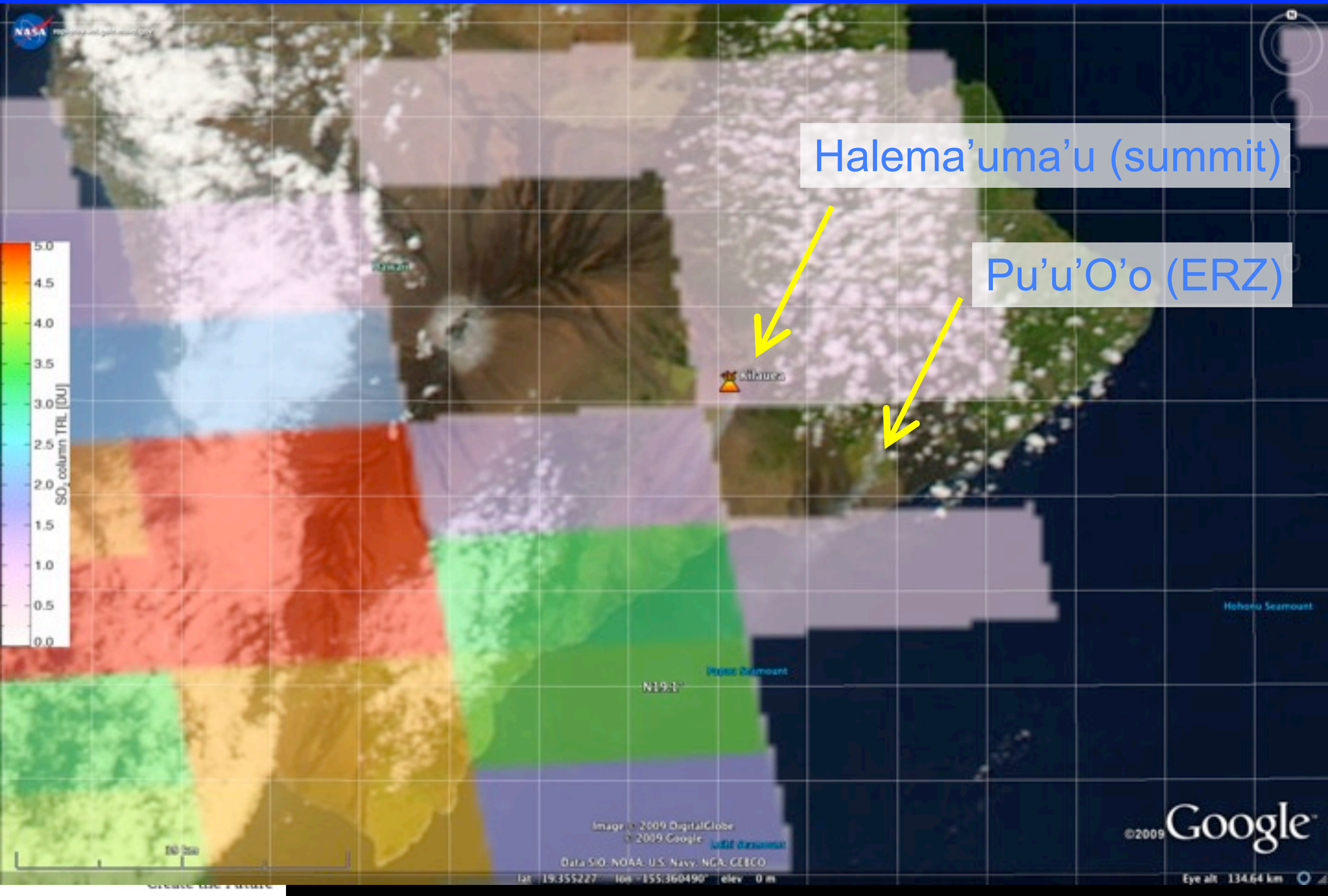
Kilauea plume (April 1, 2008) – Aura OMI SO_2 (1410 LT)



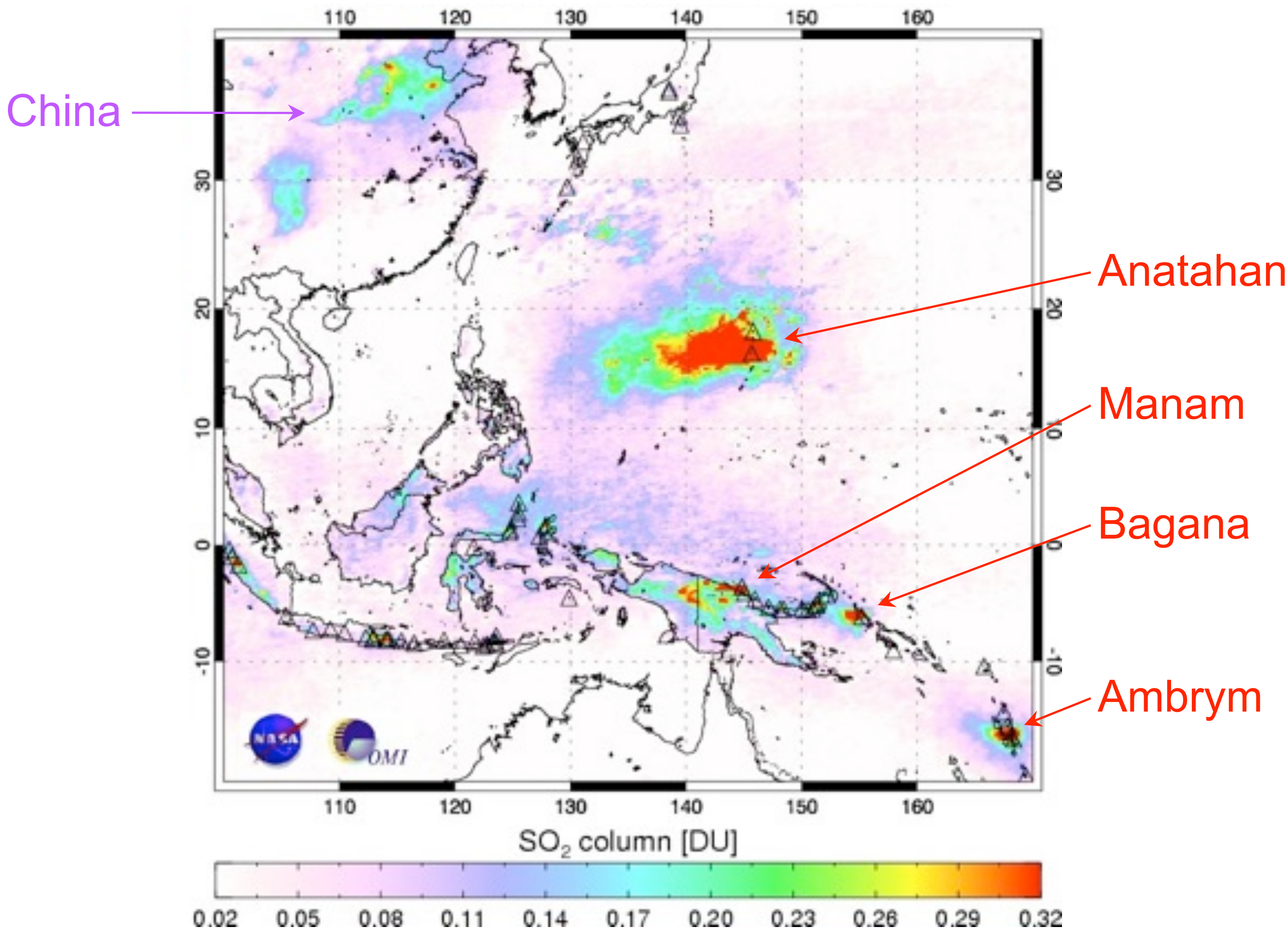
Kilauea plume (April 1, 2008) – Aqua MODIS (1400 LT)



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

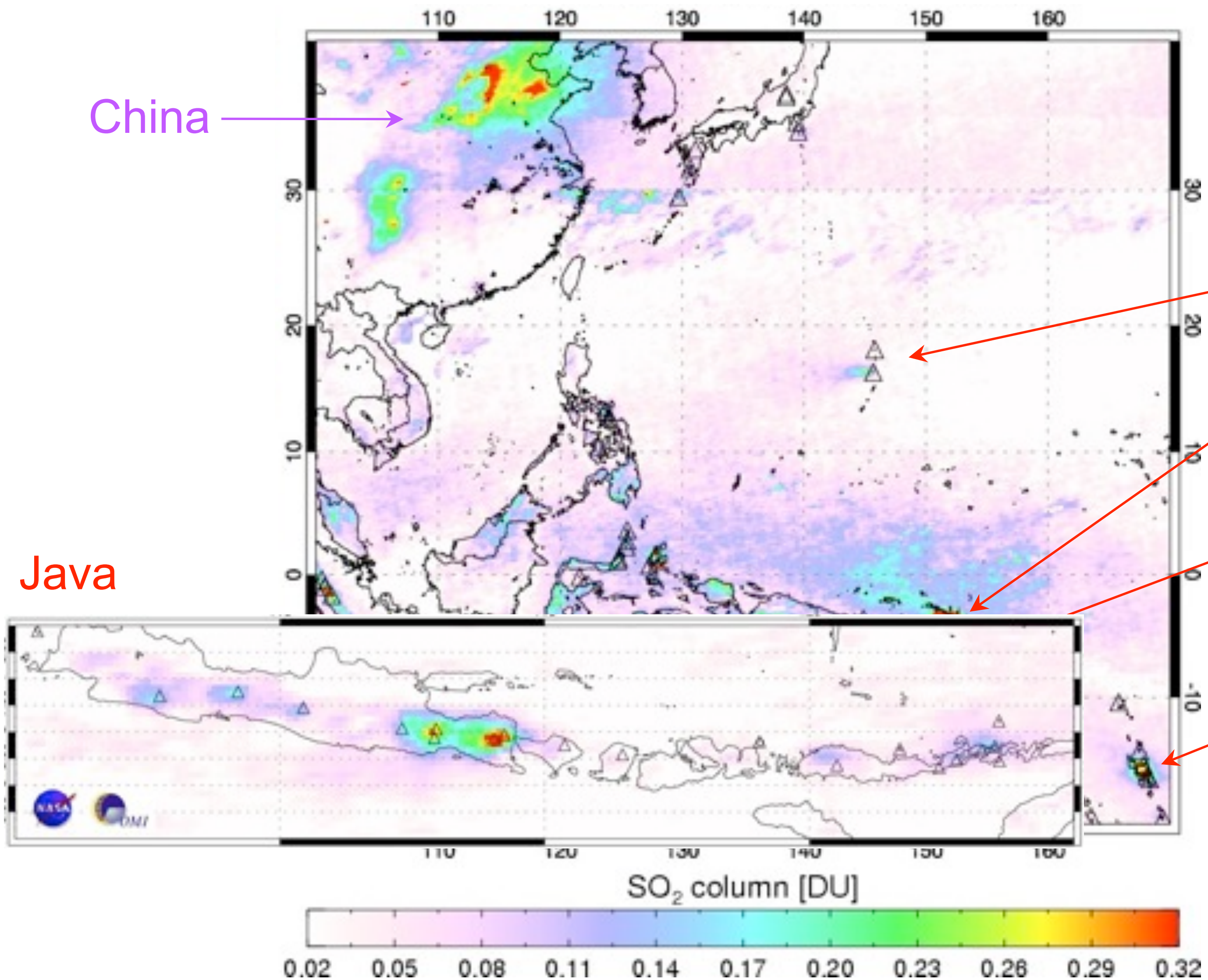


OMI annual average SO_2 in 2005: W. Pacific/S.E. Asia



Michigan Tech
Create the Future

OMI annual average SO_2 in 2006: W. Pacific/S.E. Asia



Michigan Tech
Create the Future