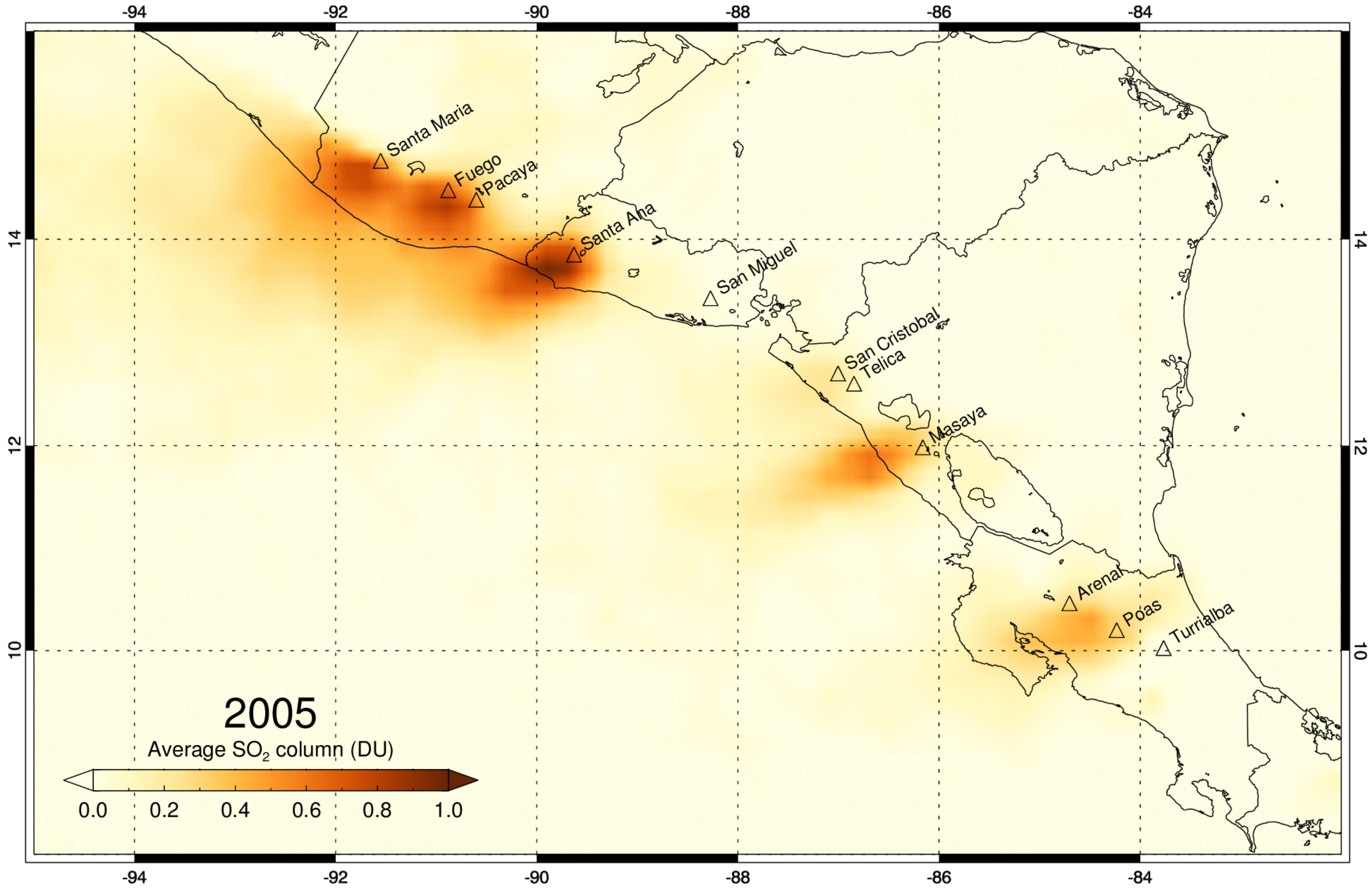
Satellite Monitoring of Volcanic Degassing



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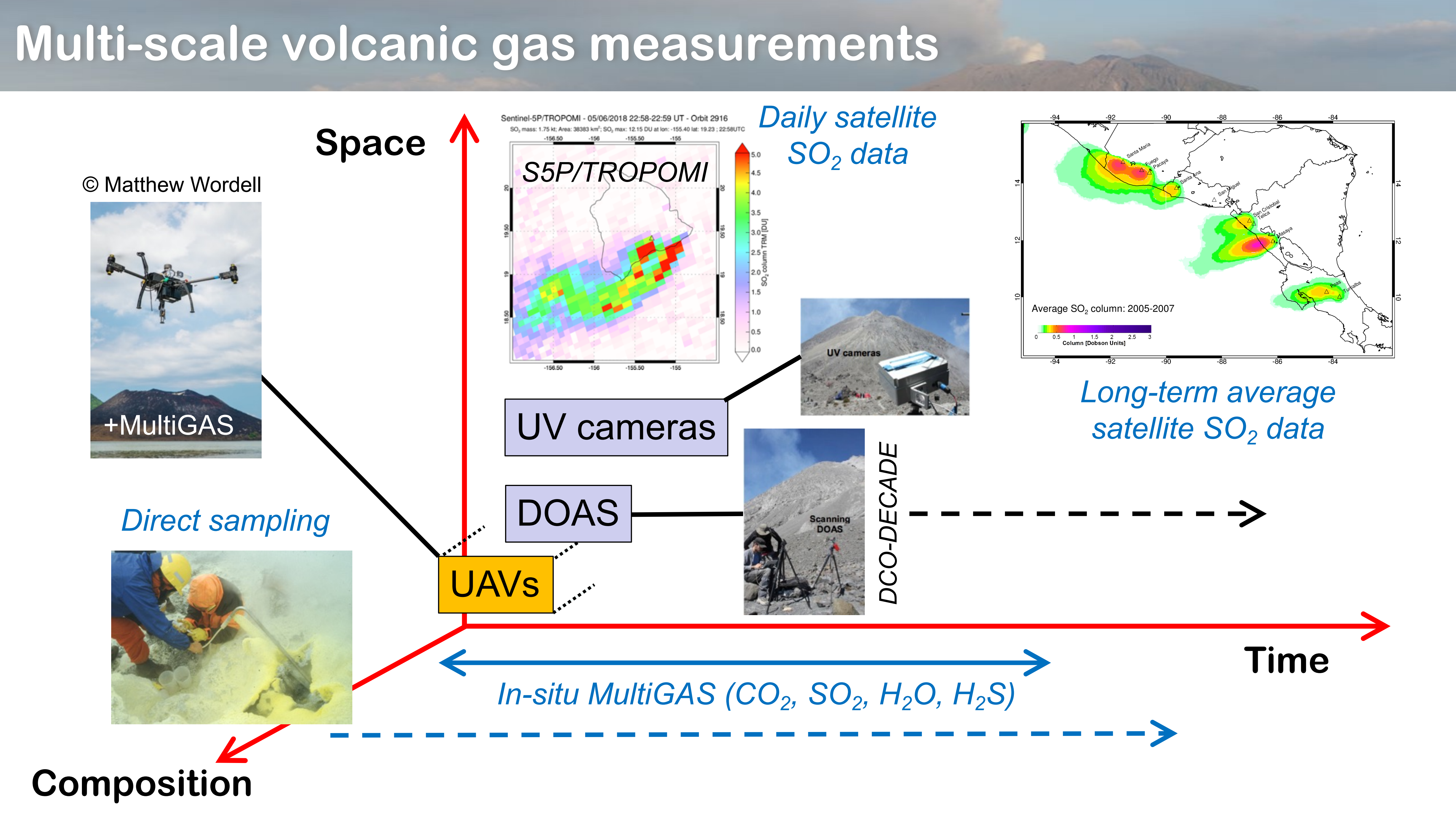
Goddard Space Flight Center

Satellite data tutorial

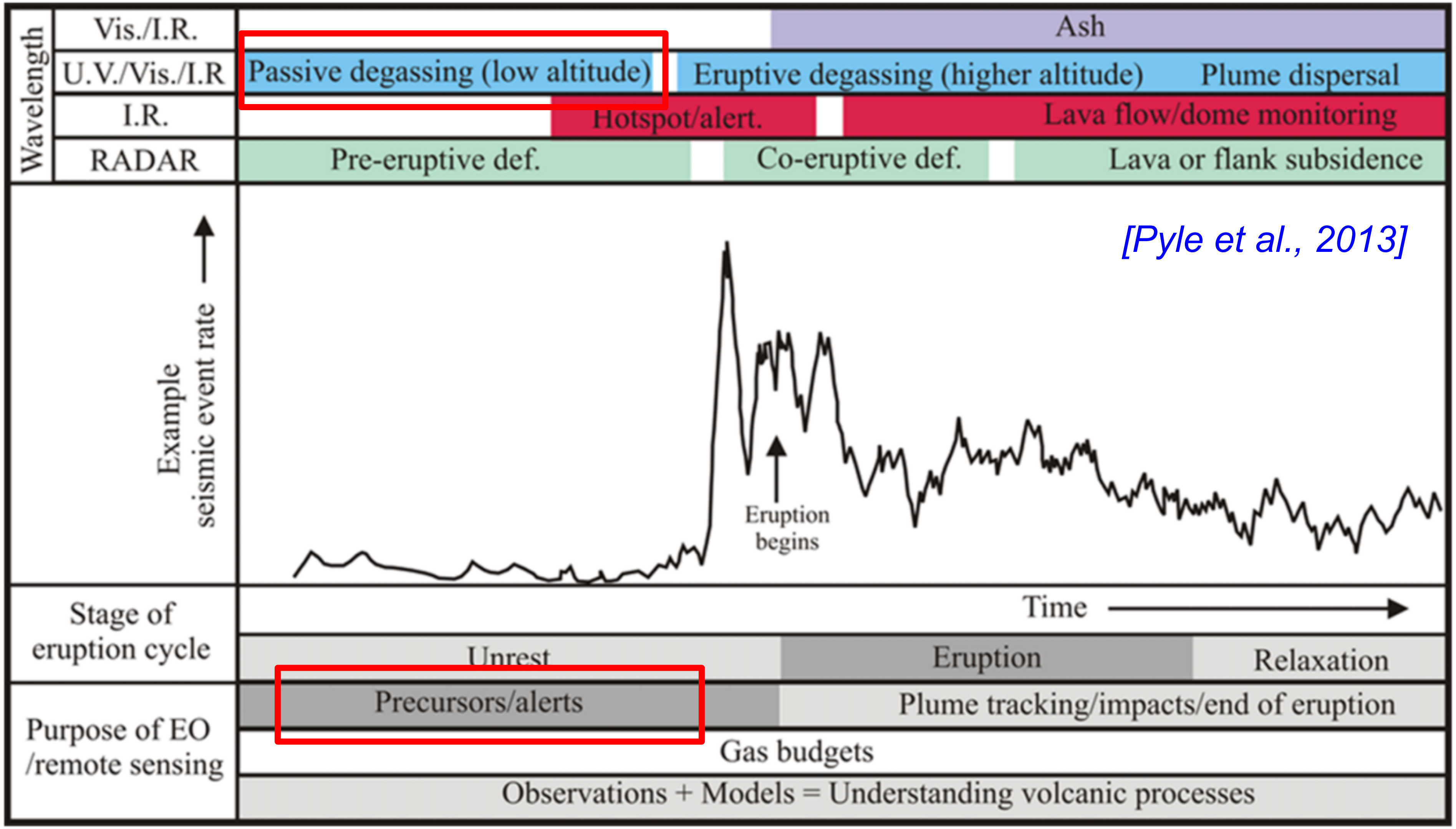
- Satellite data tutorial materials: https://drive.google.com/drive/folders/1aE_0q9diEKJGXX5pJjg0ZvuvOHFqHnyn?usp=sharing

- Instructions: carn_SatelliteDataTutorial.pdf

- Includes:
  - Web-based satellite data visualization with NASA Worldview
  - Satellite data visualization/extraction with NASA Panoply
  - Online satellite data analysis using NASA Giovanni

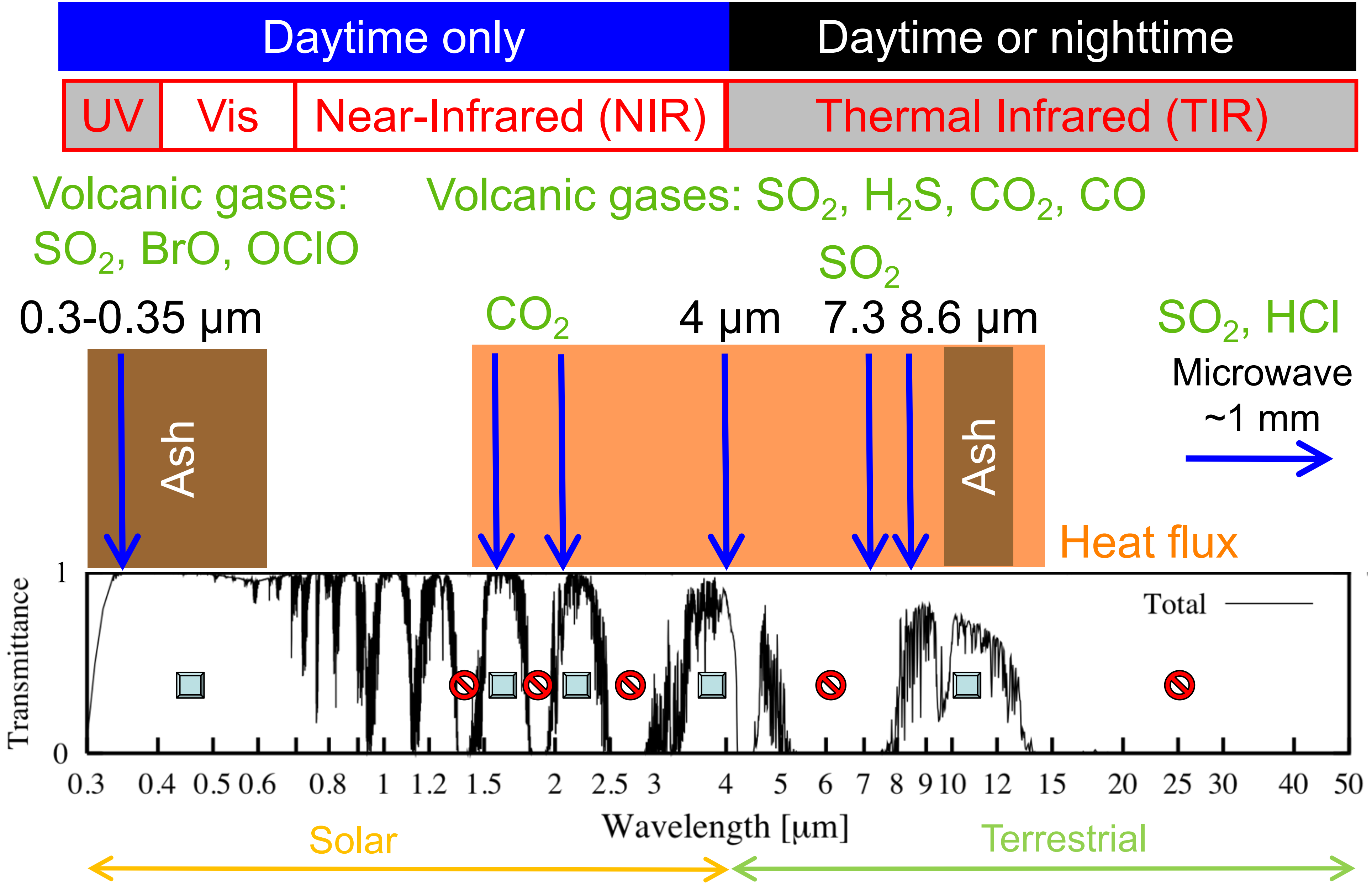

Multi-scale volcanic gas measurements
Space
© Matthew Wordell
+MultiGAS
Sentinel-5P/TROPOMI - 05/06/2018 22:58-22:59 UT - Orbit 2916
S5P/TROPOMI
Daily satellite SO_2 data
Average SO_2 column: 2005-2007
Column [Dobson Units]
Long-term average satellite SO_2 data
UV cameras
UV cameras
DOAS
Scanning DOAS
DCO-DECADE
UAVs
Direct sampling
Time
In-situ MultiGAS (CO_2, SO_2, H_2O, H_2S)
Composition

Application of remote sensing during eruption cycles



- UV/IR measurements of eruptive degassing and plume dispersal are mature
- When does passive degassing become ‘pre-eruptive’ degassing? Need ‘baseline’ or climatology.

Remote sensing of volcanic emissions



Volcanic gases detected from space (to date)

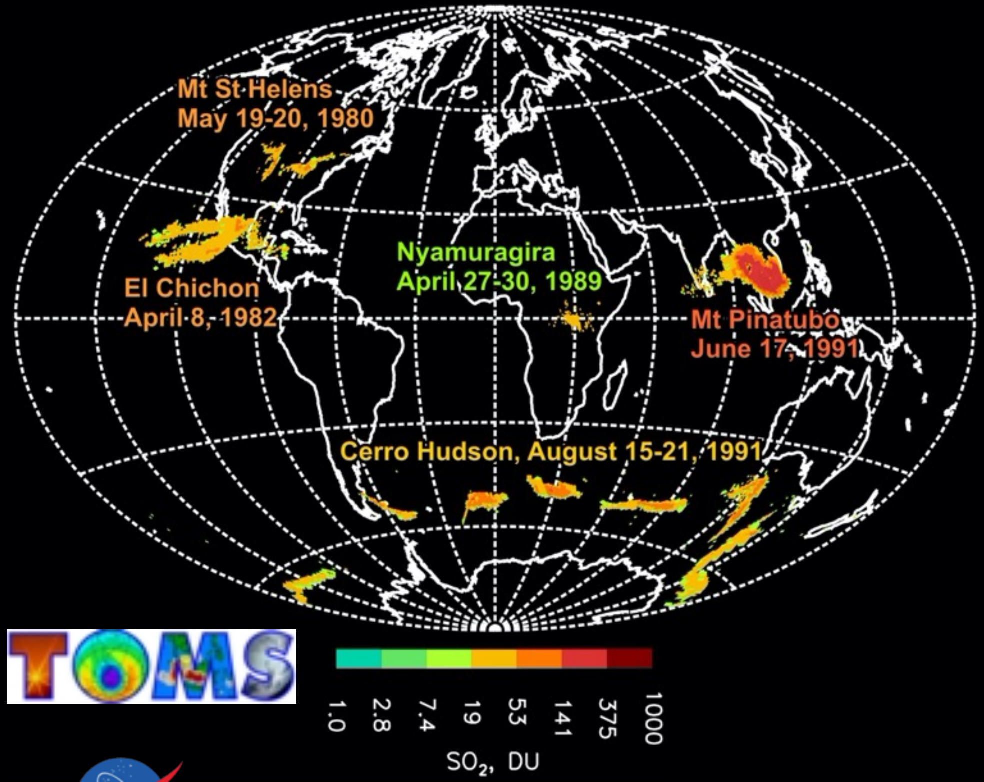
UV/IR Sensor[a]	Volatile species											Timespan
	H_2O	CO_2	CO	SO_2	H_2S	NO_2	HCl	BrO	OClO	IO	CH_3Cl	
TOMS*				■								1978-2005
SBUV* (P)				■								1978-present ★
HIRS*				■								1978-present ★
GOME	▒			■		▒		▒	▒			1995-2003
MODIS*	▒			■								1999-present ★
ASTER				■								1999-present ★
MOPITT			■									1999-present ★
SCIAMACHY (L)	▒	▒	▒	■		▒		■	■	■		2002-2012
MIPAS (L)				■								2002-2012
AIRS	▒	▒	▒	■								2002-present ★
ACE (L)	■	▒	▒	■			▒				▒	2003-present ★
SEVIRI				■								2004-present ★
OMI				■		■		■	■	■		2004-present ★
MLS* (L)	■		▒	■			■	▒	▒		■	1991-2001; 2004-present ★
TES (P)				■								2004-present
GOME-2*	▒			■		▒		■	■	■		2006-present ★
IASI*	▒	▒	■	■	■		■					2006-present ★
GOSAT (P)		▒		▒								2009-present ★
OMPS*				■		▒		▒	▒	▒		2011-present ★
VIIRS				■								2011-present ★
CrIS				■								2011-present ★
OCO-2		■										2014-present ★
AHI				■								2015-present ★
EPIC				■								2015-present ★
TROPOMI			▒	■		▒		■	▒	▒		2017-present ★
OCO-3		▒										2019-present ★

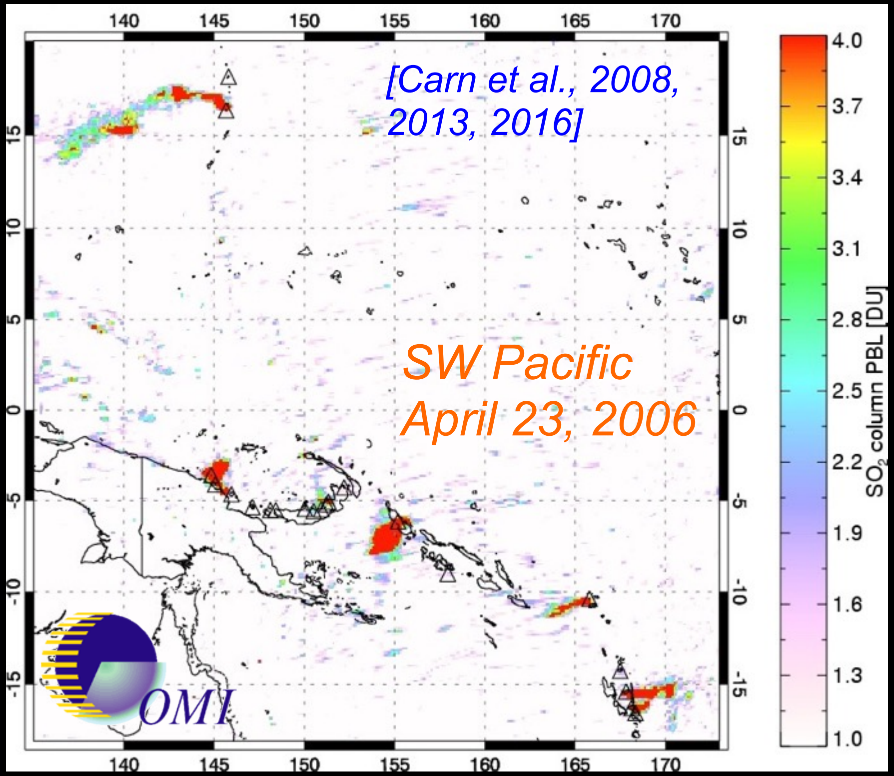
* = Multiple sat.
P = Profiler
L = Limb
■ = Confirmed
▒ = Possible?
★ = Currently operational

- Measurements heavily biased towards SO_2, *especially for passive degassing*
- >20 daily polar-orbiting SO_2 sensor overpasses
- Daily satellite *monitoring* mostly restricted to SO_2

Carn et al. (2016) + updates

NASA and ESA UV satellite remote sensing of volcanic SO_2





1978-2005
Total Ozone Mapping Spectrometer (TOMS)

esa 1995-2003
Global Ozone Monitoring Experiment (GOME)

2004-
Ozone Monitoring Instrument (OMI)

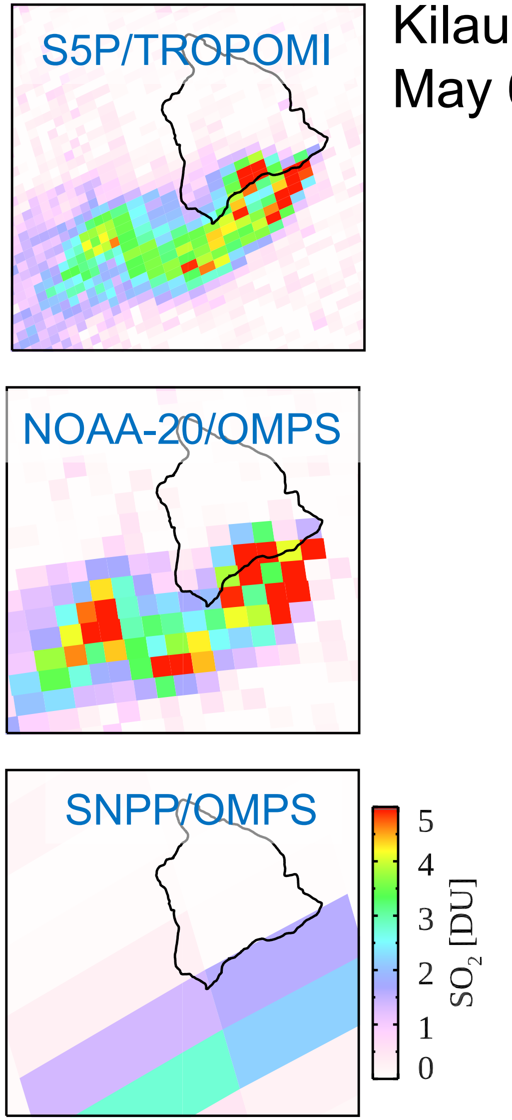
esa 2006-
GOME-2

2012- & 2017-
Ozone Mapping and Profiler Suite (OMPS)

2015-
DSCOVR/ EPIC

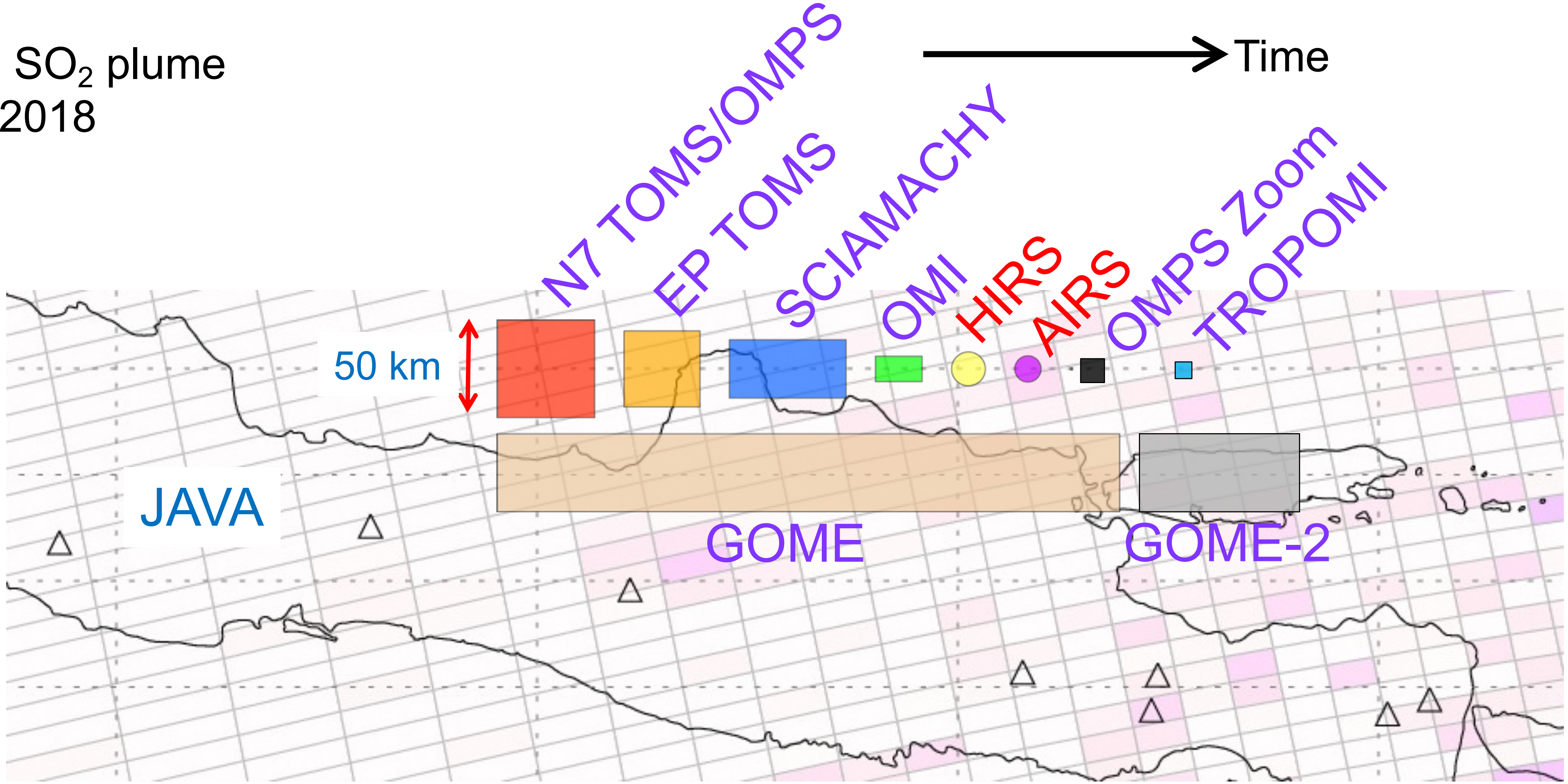
2017-
Sentinel 5P TROPOMI

Satellite instrument spatial resolution



Can Li (NASA/GSFC)

Kilauea SO_2 plume
May 6, 2018

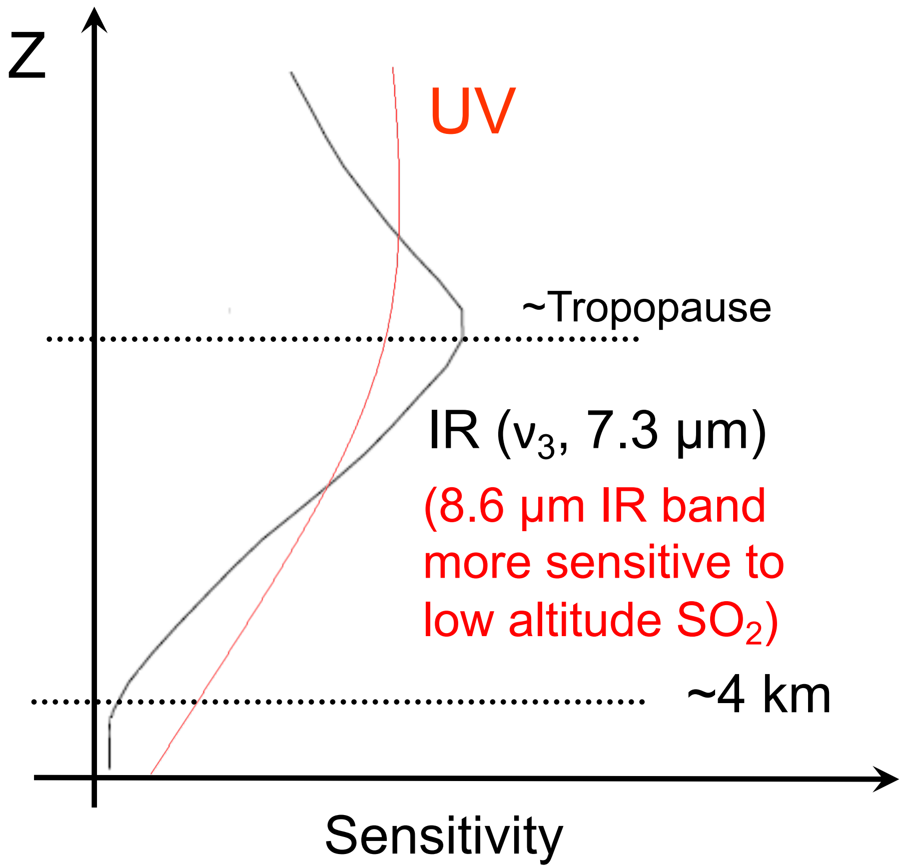


- Detection requires that a volcanic plume cover a large fraction of the sensor pixel or instantaneous field of view (IFOV)
- For most instruments, IFOV size also varies across the swath
- For large volcanic clouds (>IFOV), footprint size is less important

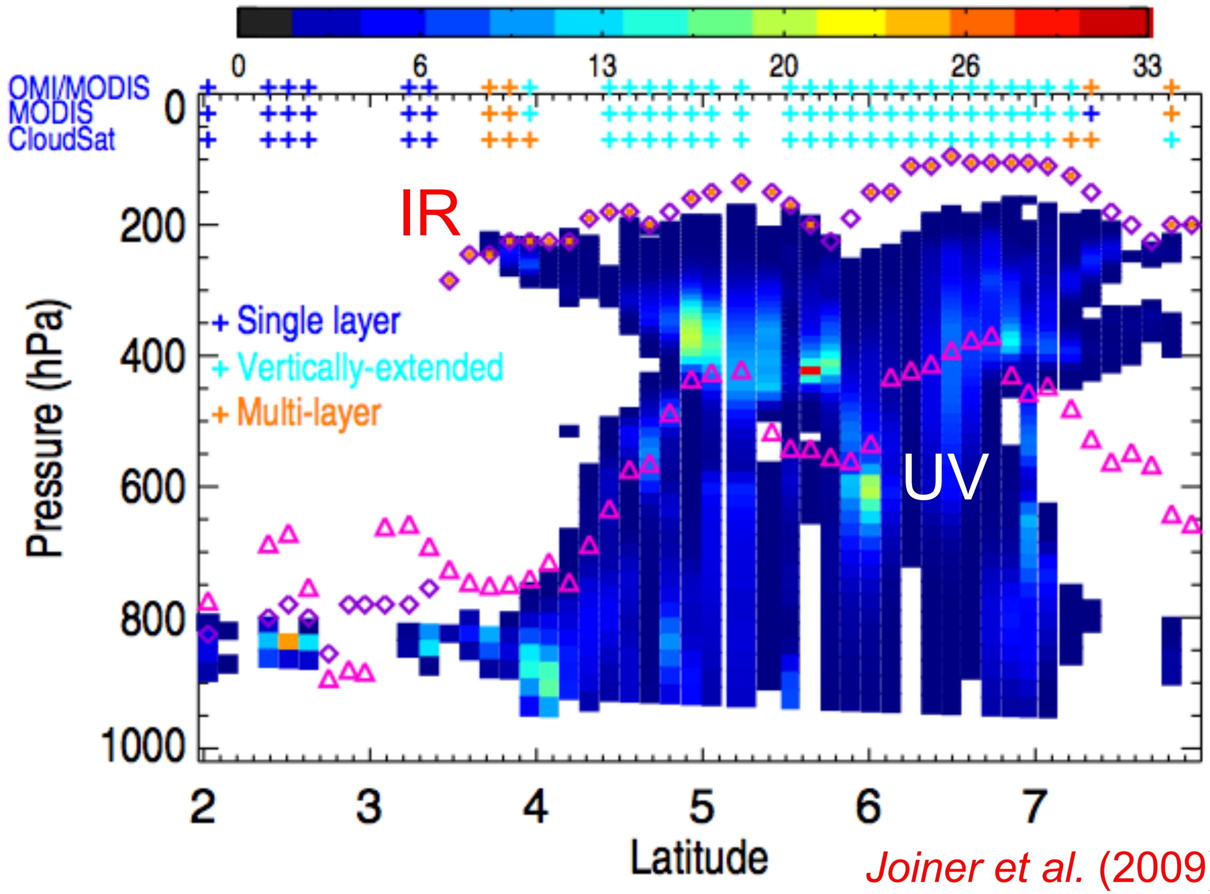
UV instrument SO_2 sensitivity

Instrument	Footprint area (km^2)	Noise (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-2 (ESA/MetOp)	3200 (40x80)	0.2	0.4	460	914
OMI (NASA/Aura)	312 (13 × 24)	0.1	0.3	22	67
OMPS (NASA-NOAA/SNPP)	2500 (50 × 50)	0.1	0.3	178	535
OMPS (NOAA-20)	100 (10 × 10)	0.5	1	36	71
TROPOMI (Sentinel 5P)	20 (5.6 × 3.5)	0.2	0.4	3	6

Relative sensitivity of UV and IR measurements



Courtesy of L. Clarisse, ULB



Joiner et al. (2009)

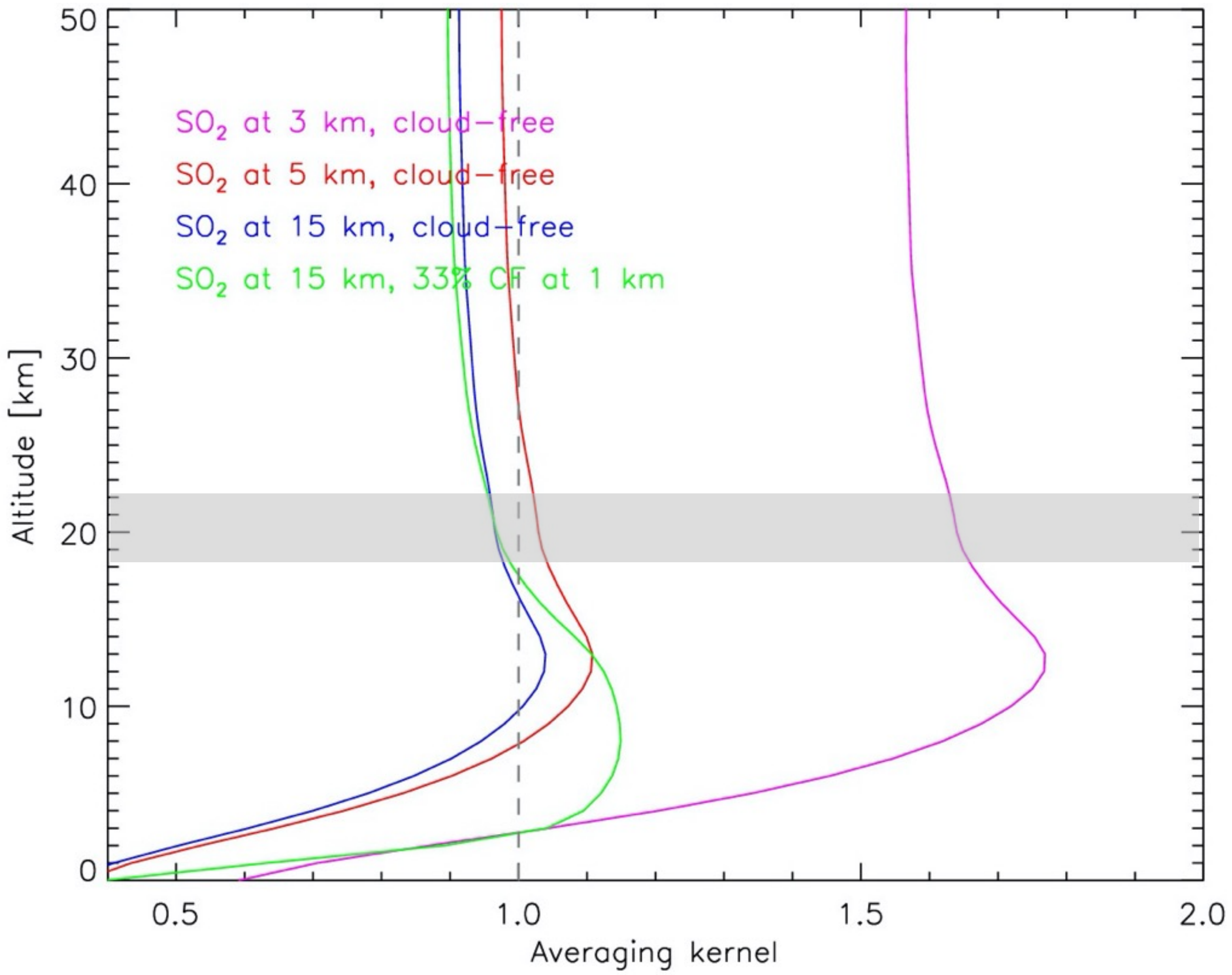
- IR cloud top ≠ UV cloud pressure

- Satellite sensitivity increases with altitude in the troposphere
- UV measurements more sensitive to passive degassing (low altitude)

Effect of volcanic plume altitude on UV SO_2 retrievals

- OMI, OMPS and TROPOMI SO_2 products
- SO_2 columns provided for 3-5 *prescribed* SO_2 profiles:
  - Planetary Boundary Layer (PBL): <3 km
  - Lower Troposphere (TRL): ~3 km
  - Mid-Troposphere (TRM): ~8 km
  - Upper Troposphere (TRU): ~10 km
  - Lower Stratosphere (STL): ~18 km
- User must select most appropriate value

[*Krotkov et al.*, 2006; *Yang et al.*, JGR, 2007; *Li et al.*, 2017]



- Knowledge of SO_2 cloud altitude is critical for accurate SO_2 retrieval
- SO_2 altitude can now be directly retrieved from UV and IR measurements (more accurate SO_2 mass)

Satellite SO_2 sensor 'constellation'

+ DSCOVR/EPIC, TOVS/HIRS,
MSG/SEVIRI, GOES/ABI, Himawari-8/AHI

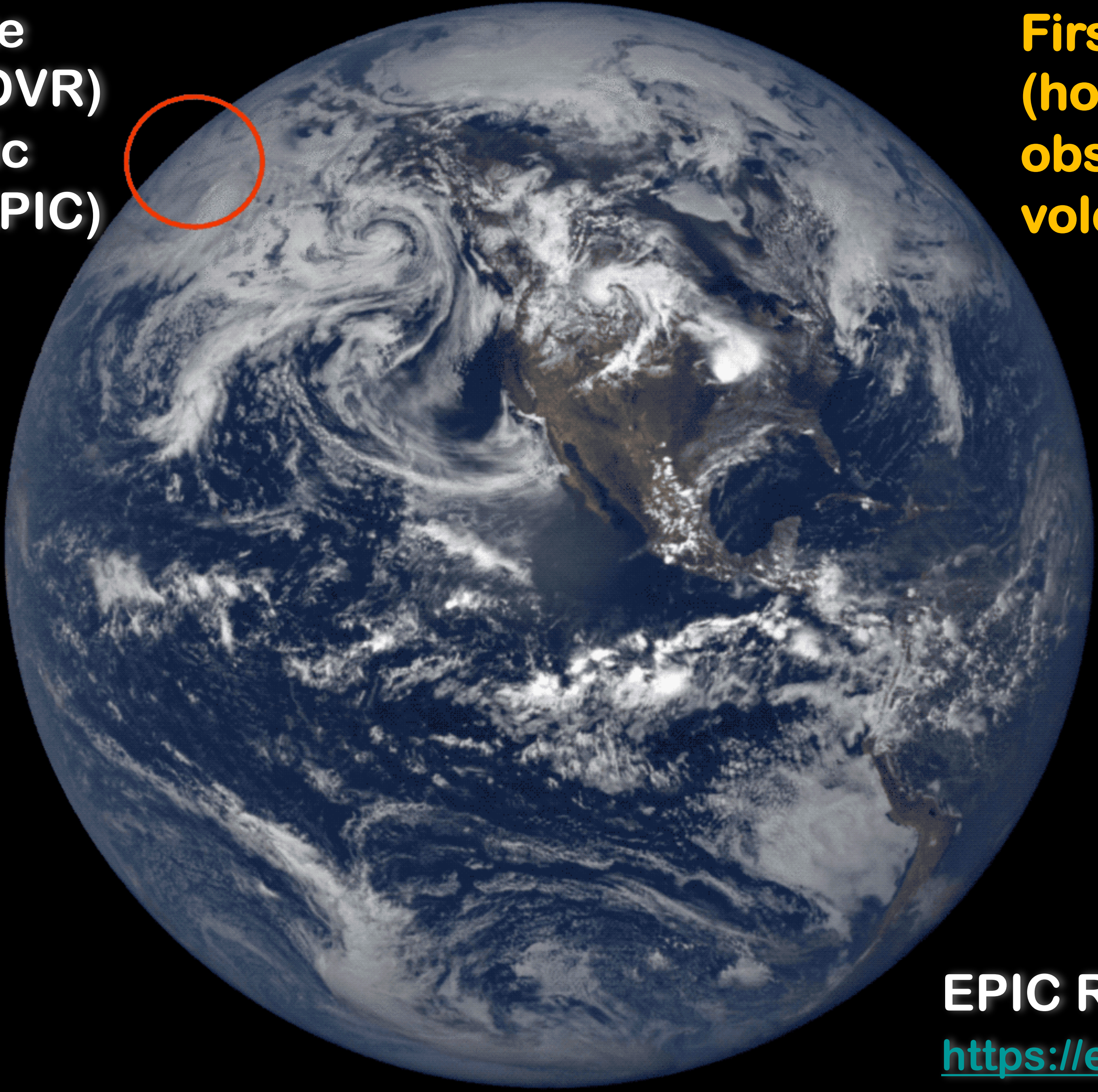
Adapted from *Brenot et al. (2014)*

Deep Space Climate Observatory (DSCOVR) Earth Polychromatic Imaging Camera (EPIC)

L_1 Earth-Sun Lagrange Point

(1,000,000 miles from Earth)

Raikoke eruption (Kuril Islands, Russia) – June 21, 2019



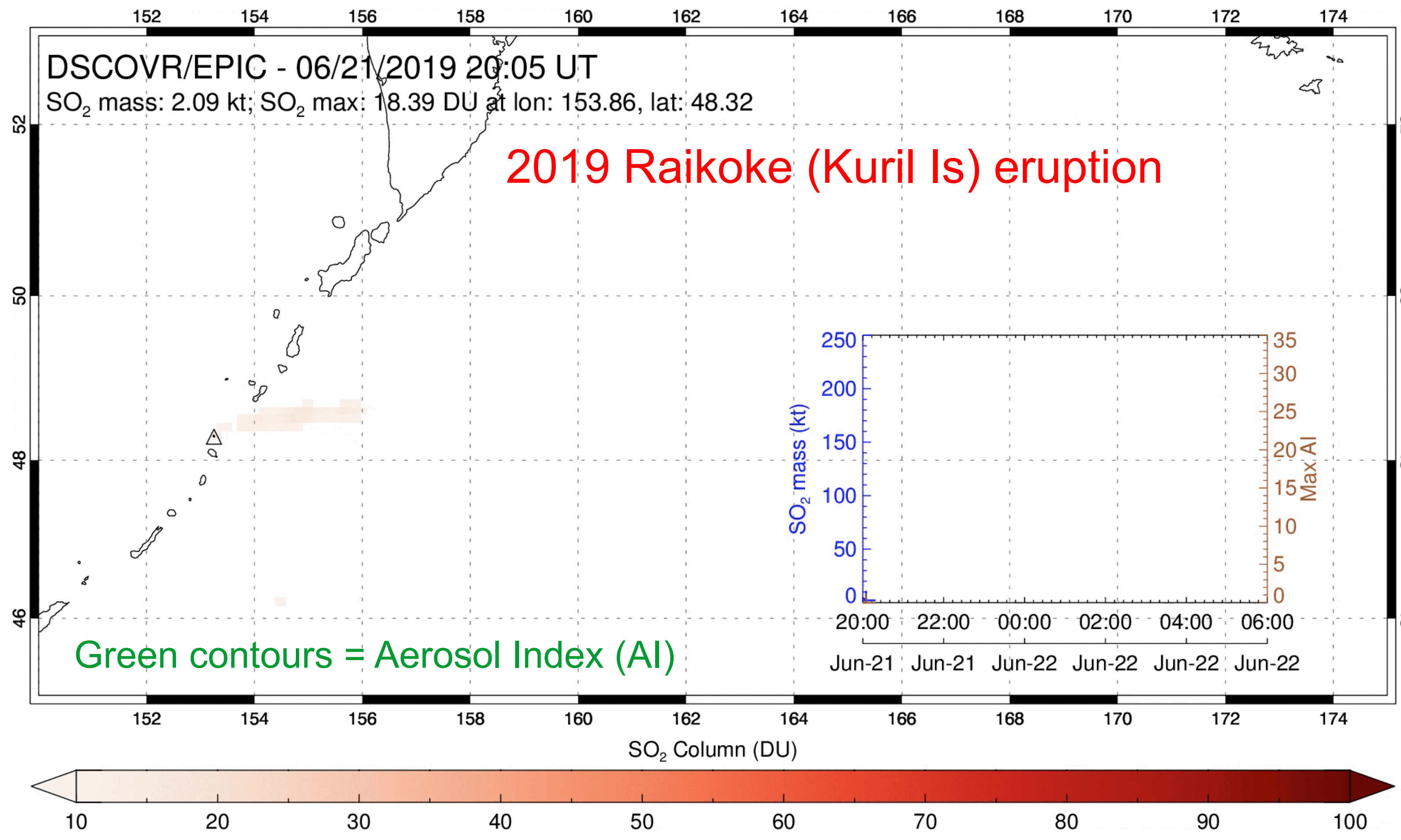
First high-cadence (hourly) UV observations of volcanic eruptions

International Space Station

EPIC RGB images

https://epic.gsfc.nasa.gov/

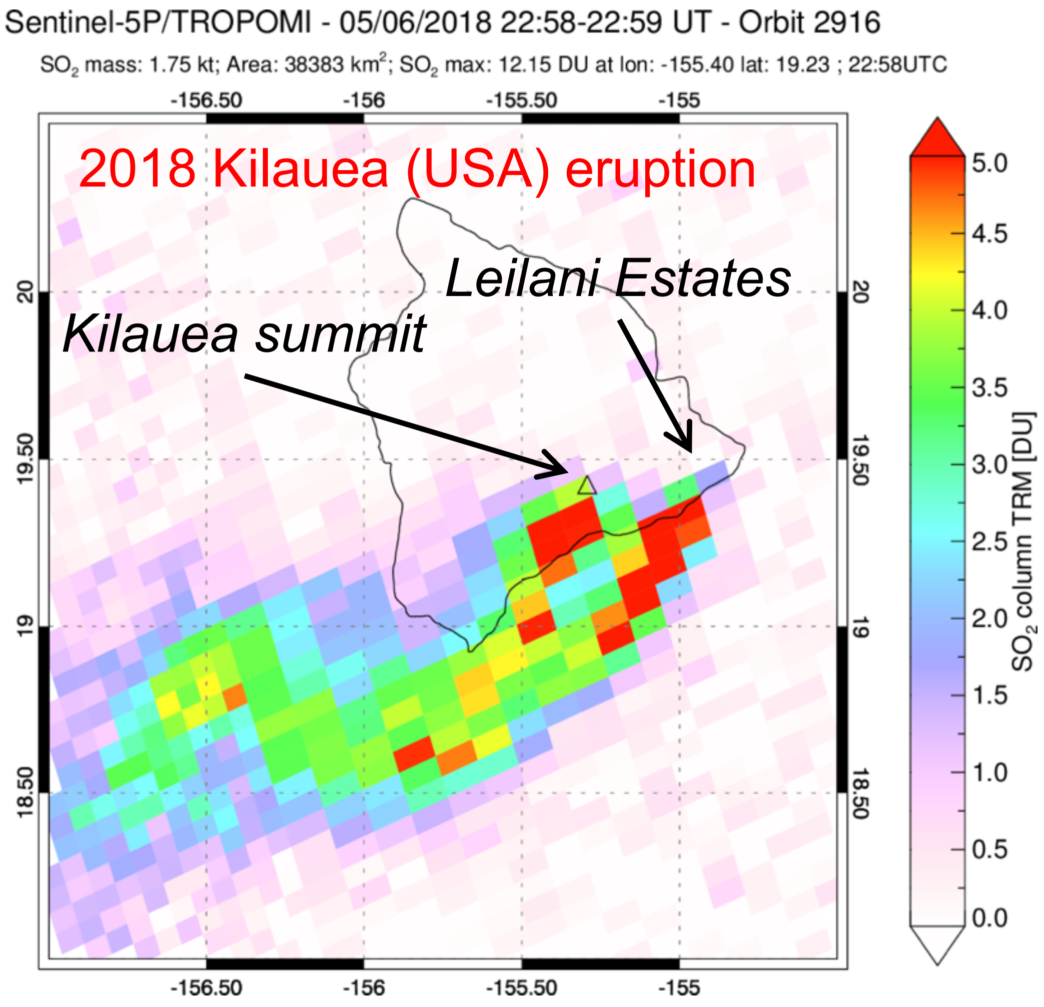
Recent advances in UV satellite measurements

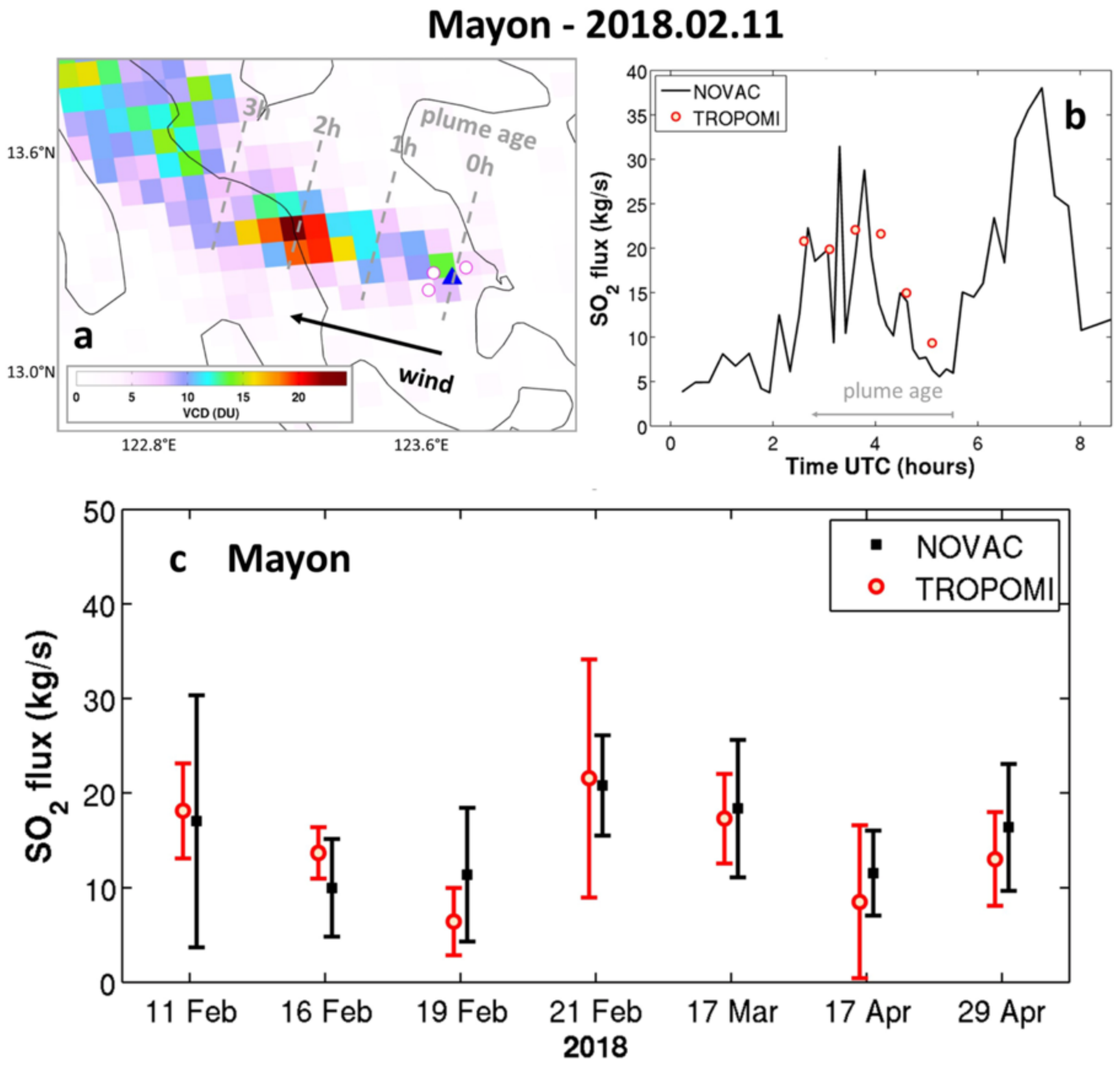


- NASA Deep Space Climate Observatory (DSCOVR) Earth Polychromatic Imaging Camera (EPIC)
- Hourly UV measurements of volcanic SO_2 and ash for large eruptions since mid-2015
- New insight into eruption processes (e.g., gas accumulation, SO_2 emission rates)
- NASA EPIC SO_2 product available (currently processed for large eruptions only)

Carn et al., 2018

Recent advances in UV satellite measurements





- ESA Sentinel-5P UV TROPOMI (Oct 2017 - present)
- Improved volcanic plume resolution with 5.6 x 3.5 km pixel size – aids SO_2 source identification and SO_2 plume analysis (e.g., SO_2 fluxes)

Theys et al., 2019; Queisser et al., 2019

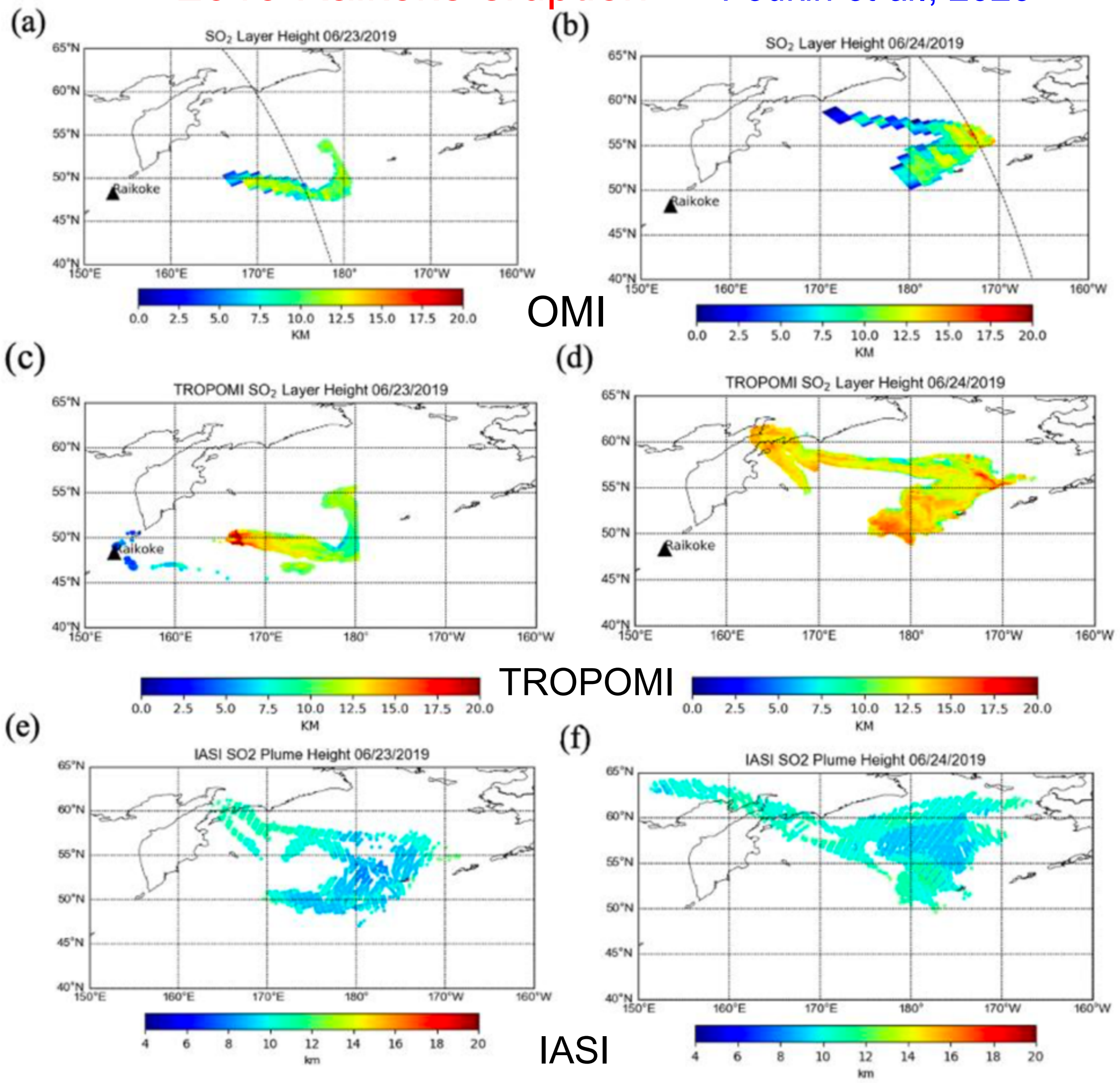
Volcanic SO_2 layer height retrievals

- Volcanic SO_2 layer height retrieval is possible using UV and IR satellite measurements.
- Previously limited (for operational or NRT applications) by computational expense.
- New machine learning algorithms now permit fast volcanic SO_2 layer height retrievals (e.g., OMI, TROPOMI).
- Limited to relatively large SO_2 columns (>20-40 DU), typically found in eruption clouds (not passive degassing).
- Also produces more accurate SO_2 columns (and hence SO_2 mass).

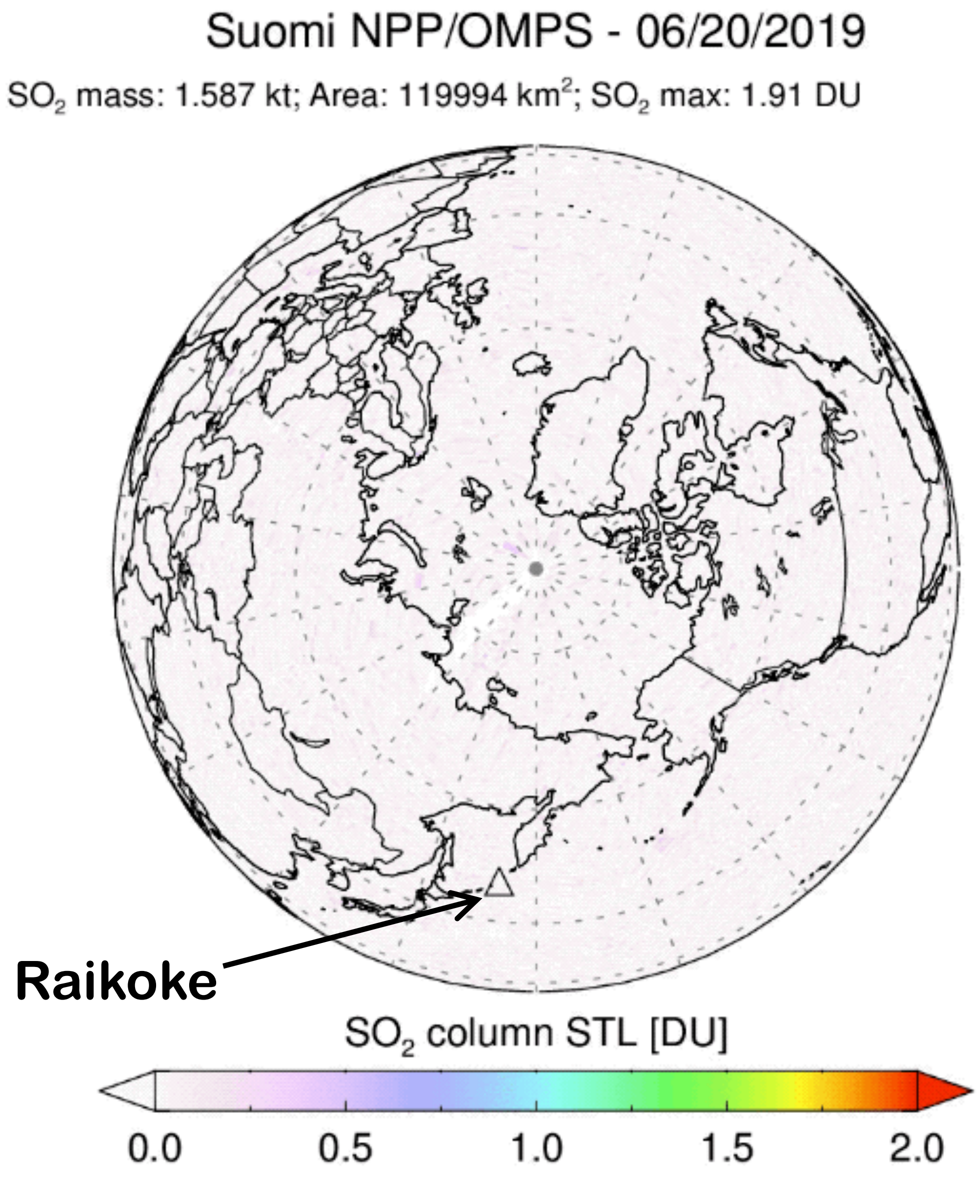
[*Yang et al.*, 2009, 2010; *Nowlan et al.*, 2011; *Clarisse et al.*, 2014; *Carboni et al.*, 2016; *Efremenko et al.*, 2017; *Hedelt et al.*, 2019; *Fedkin et al.*, 2020]

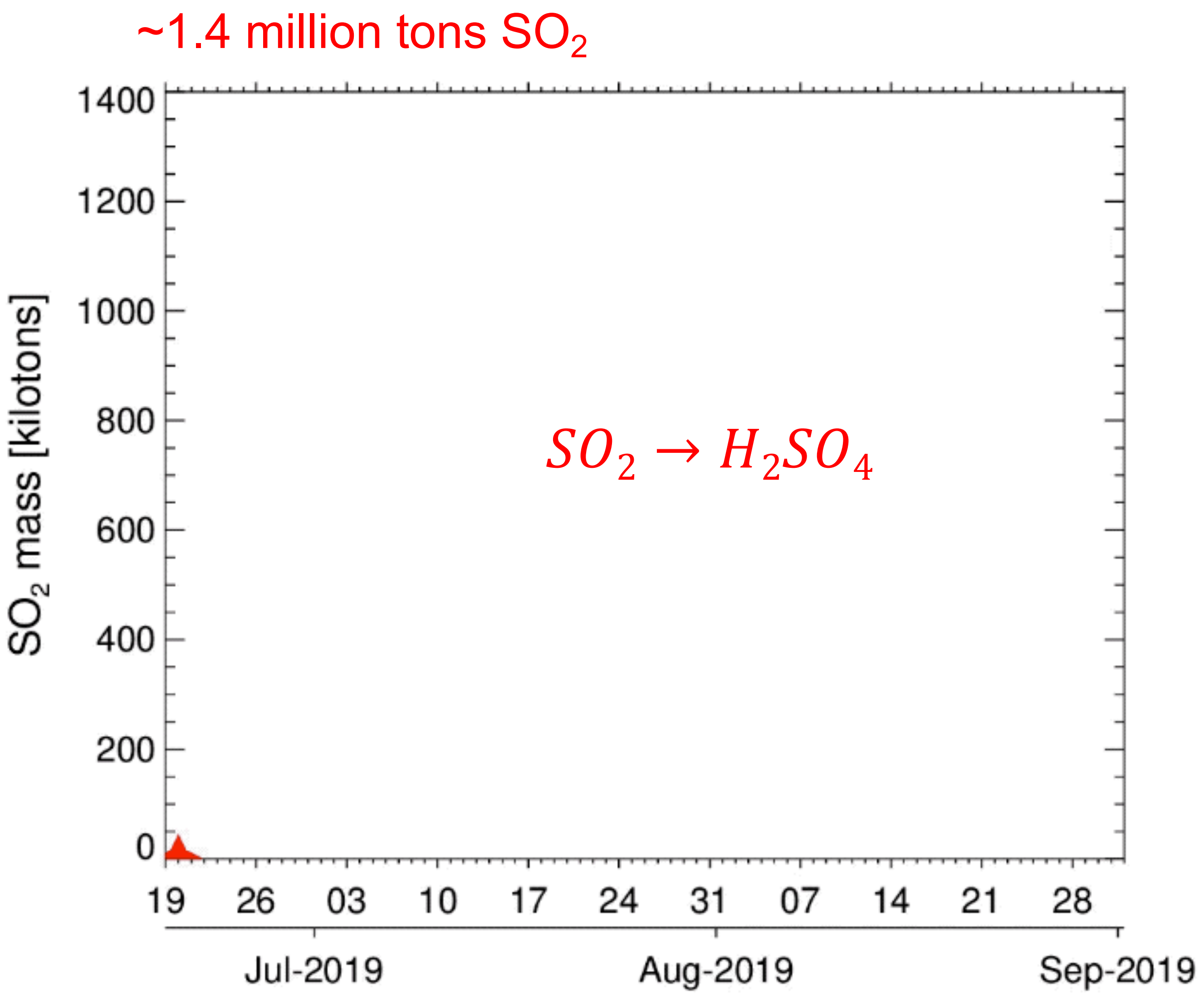
2019 Raikoke eruption

Fedkin et al., 2020

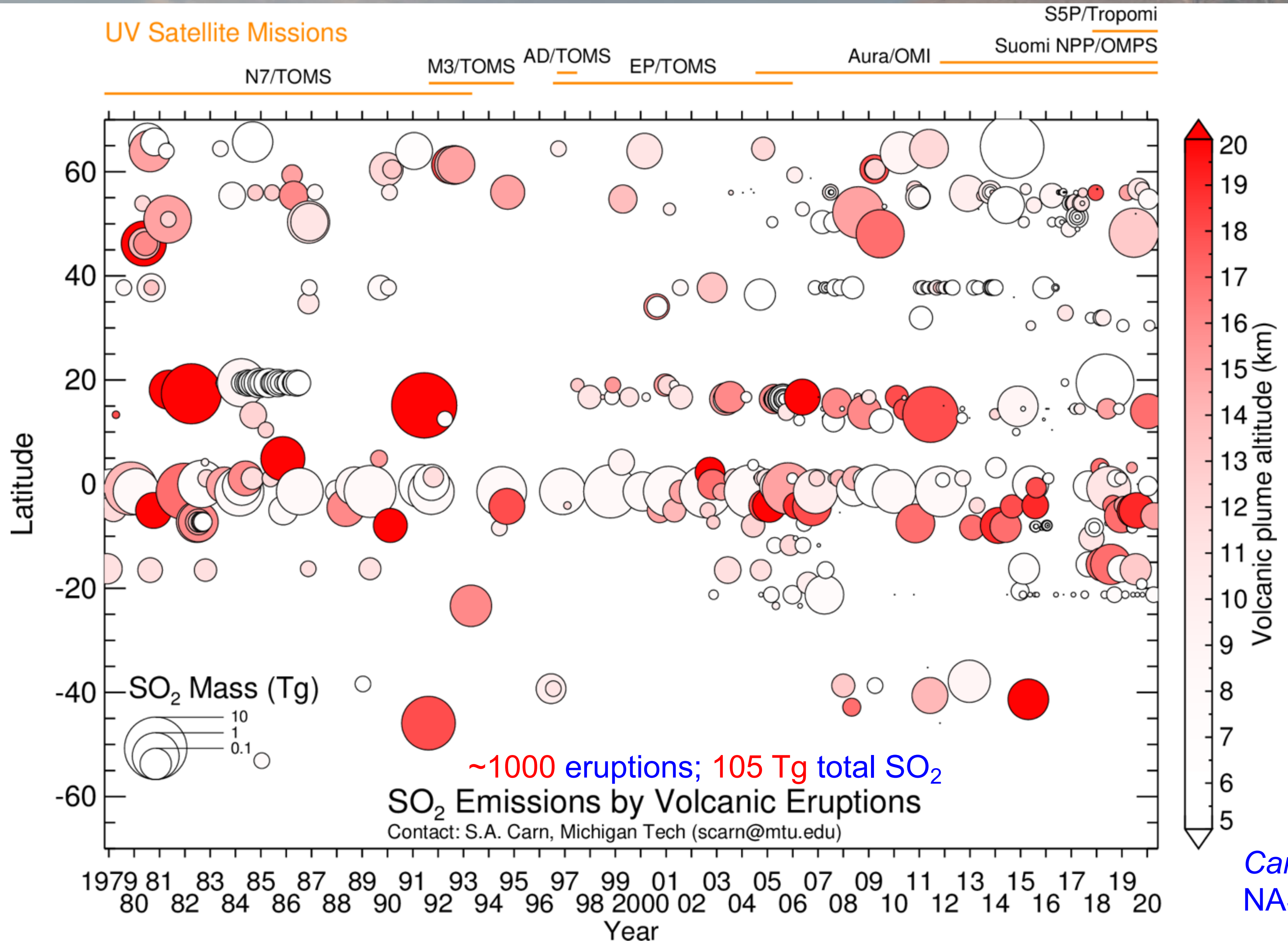


Raikoke eruption (Kuril Islands, Russia) – June 2019



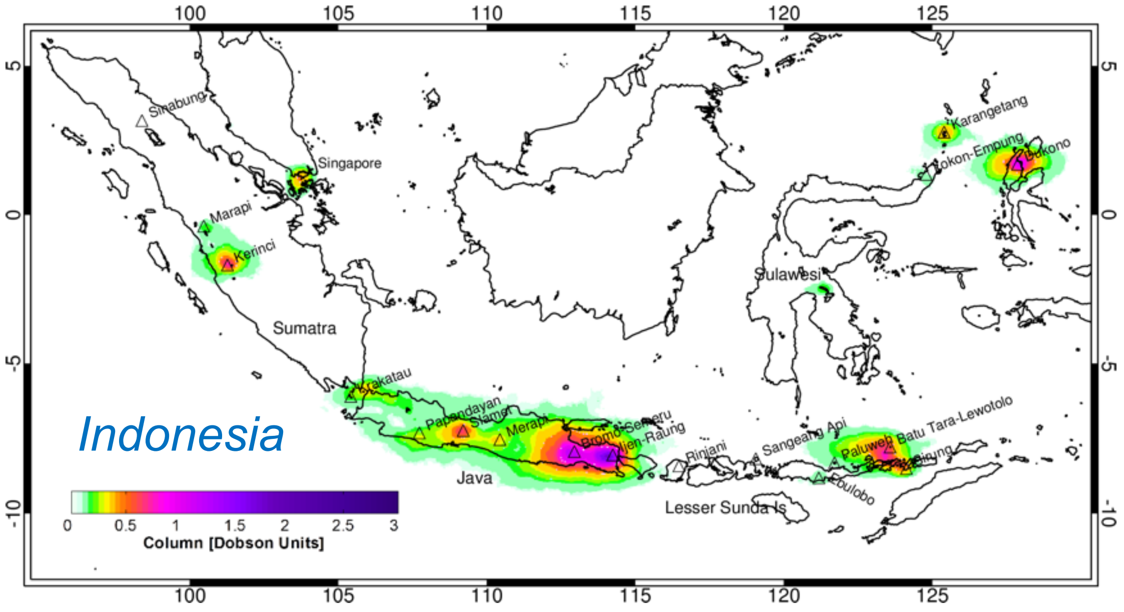


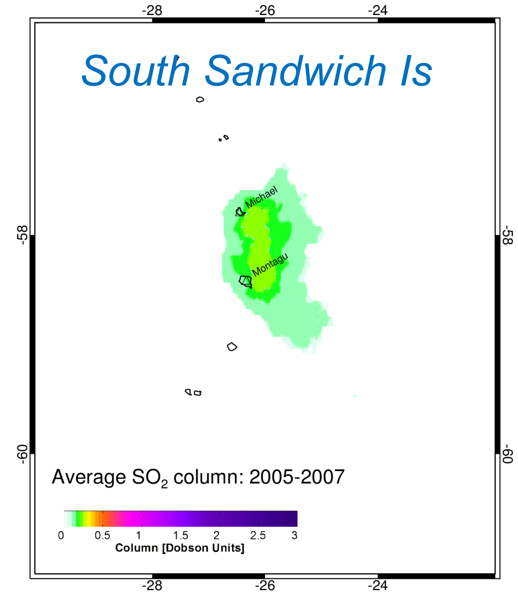
Volcanic SO_2 emissions database (since 1978) – all eruptions



Carn et al., JVGR [2016]
NASA MEaSUREs

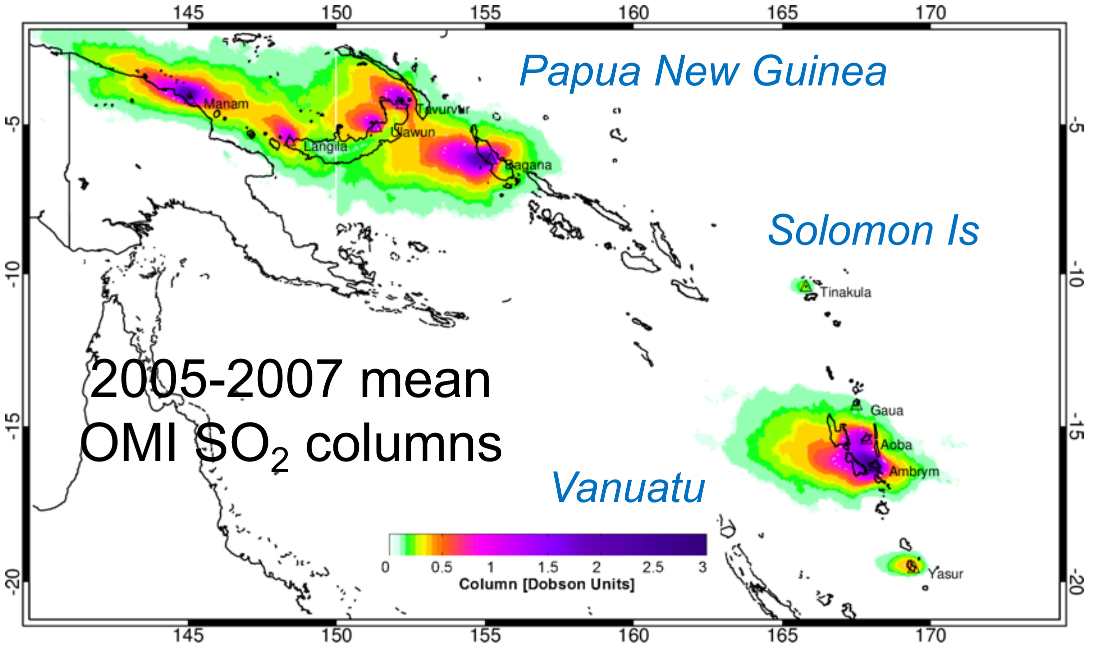
Satellite-based global volcanic SO_2 emission inventory



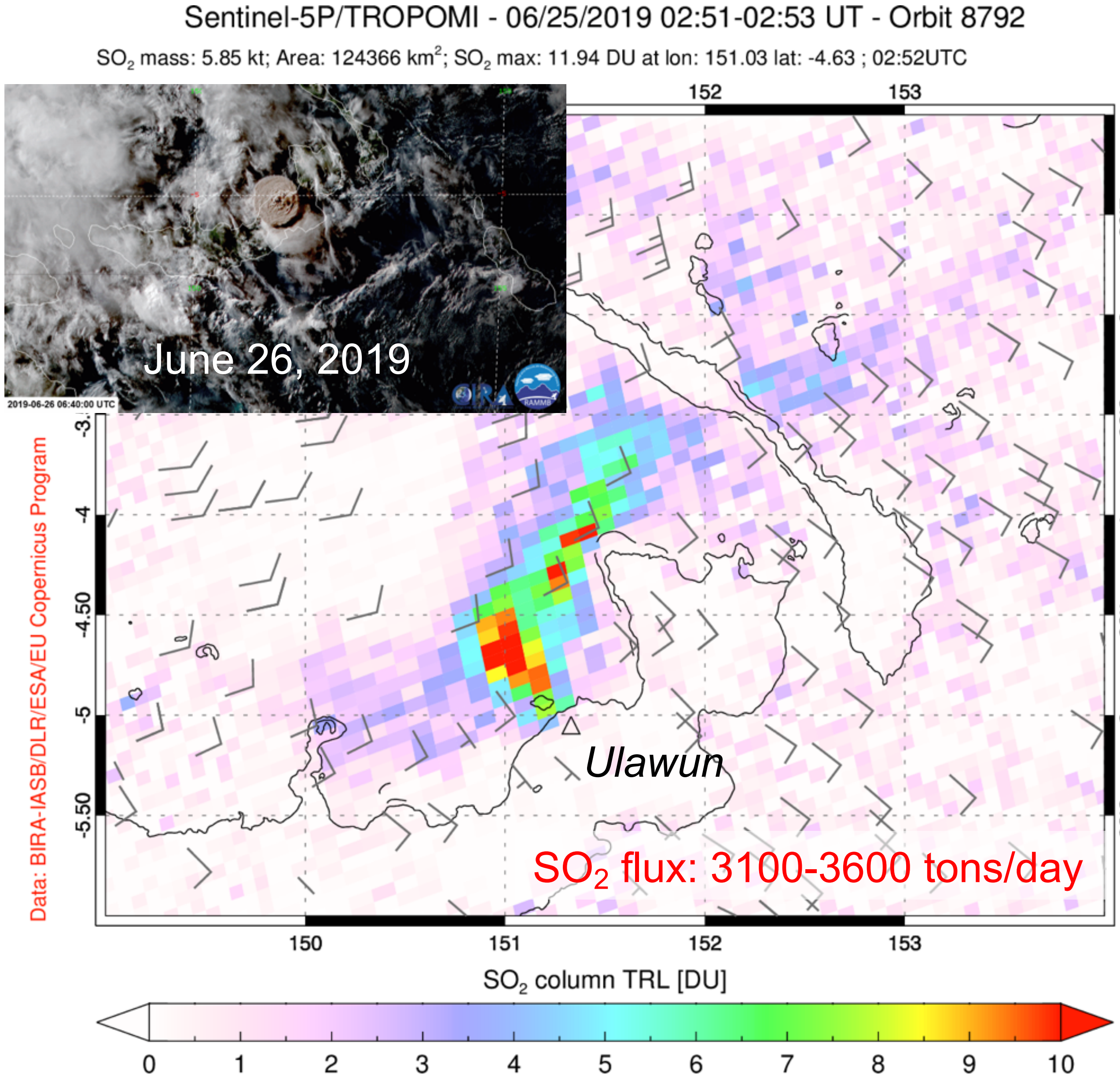


- Globally, 90-100 volcanic SO_2 sources quantified (10-20% ‘new’) using NASA Aura/OMI data
- Total SO_2 flux of 23+/-2 Tg/yr (~63 kt/day); ~80-90% of total volcanic SO_2 flux from passive + eruptive degassing
- Lowest flux: ~32 t/d; can be extended to weaker sources with new Sentinel-5P/TROPOMI data

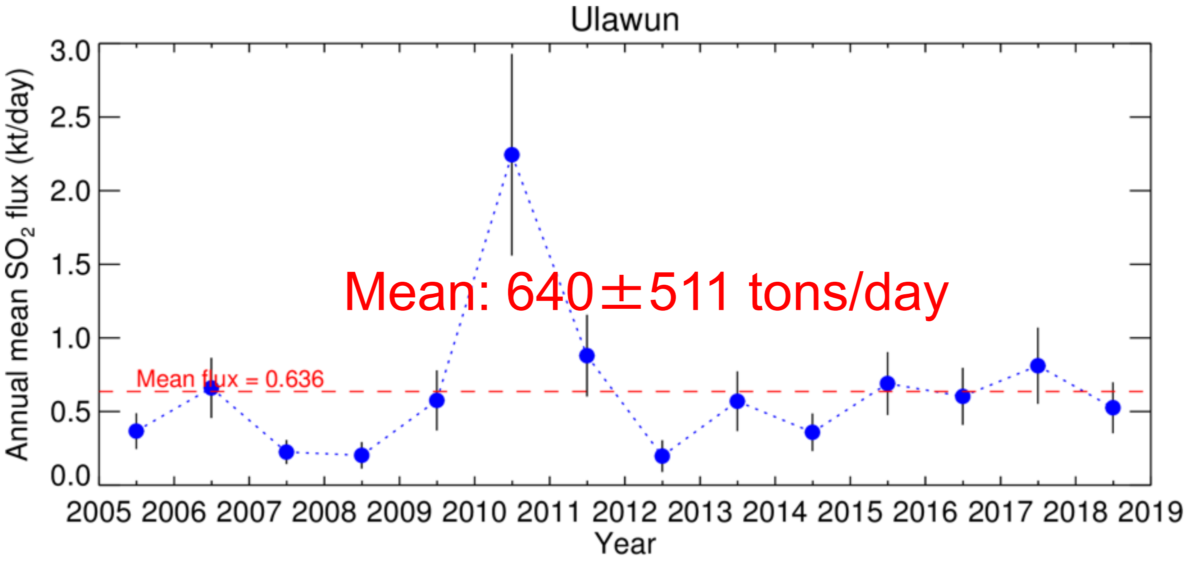
Fioletov et al. (2016); Carn et al. (2017)



Identifying ‘pre-eruptive’ SO_2 emissions

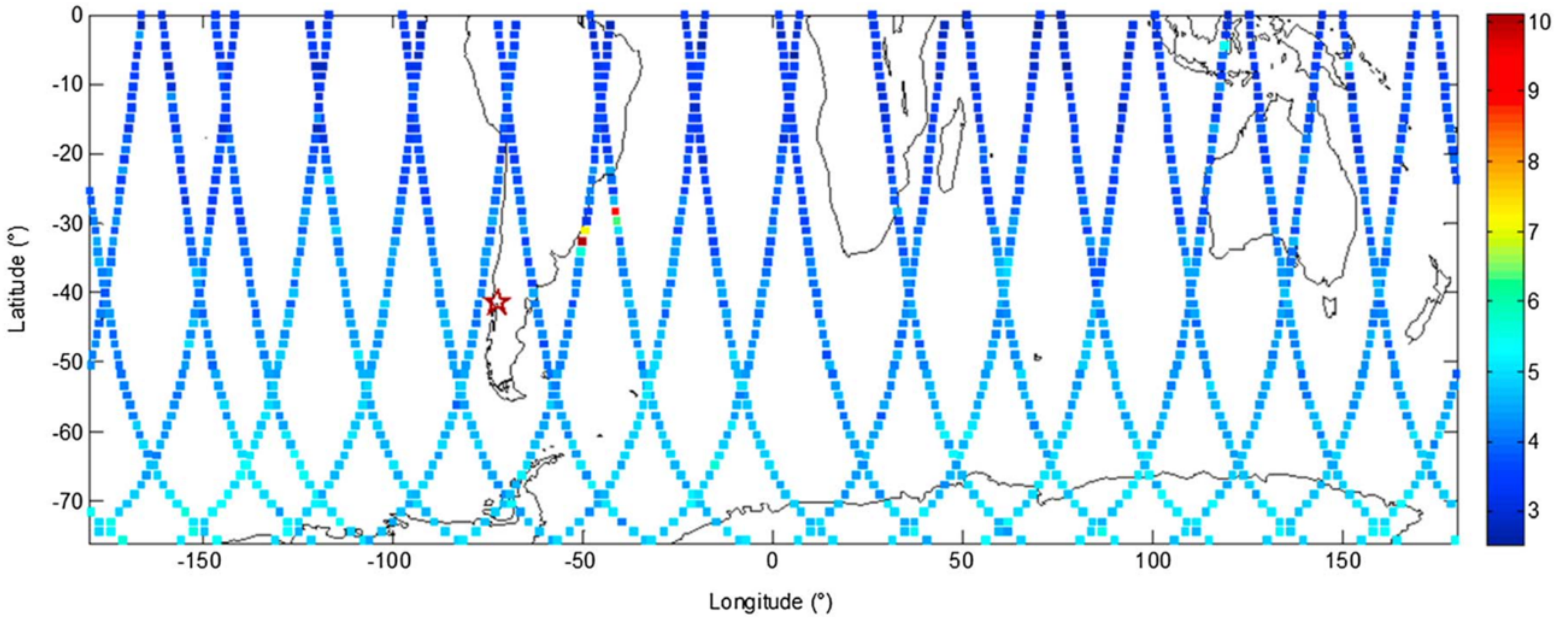


- Long-term Aura/OMI satellite record (2005-present) constrains magnitude of ‘typical’ volcanic SO_2 emissions, *at open-system volcanoes*
- At Ulawun volcano (PNG), *SO_2 emissions ~5σ above the decadal mean measured prior to major (VEI 4) eruption on June 26, 2019*
- Short-Term Average/Long-Term Average (STA/LTA) approach (also used as seismic trigger algorithm)



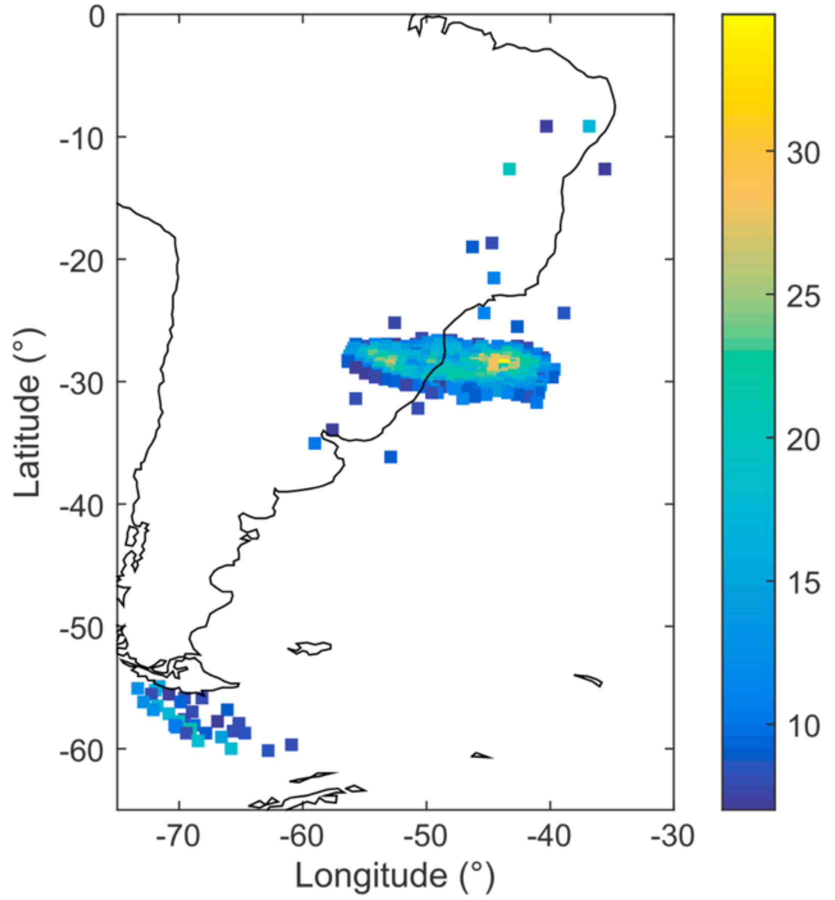
Detection of stratospheric volcanic H_2O

2015 Calbuco (Chile) eruption



Aura/Microwave Limb Sounder (MLS) H_2O data on April 25, 2015

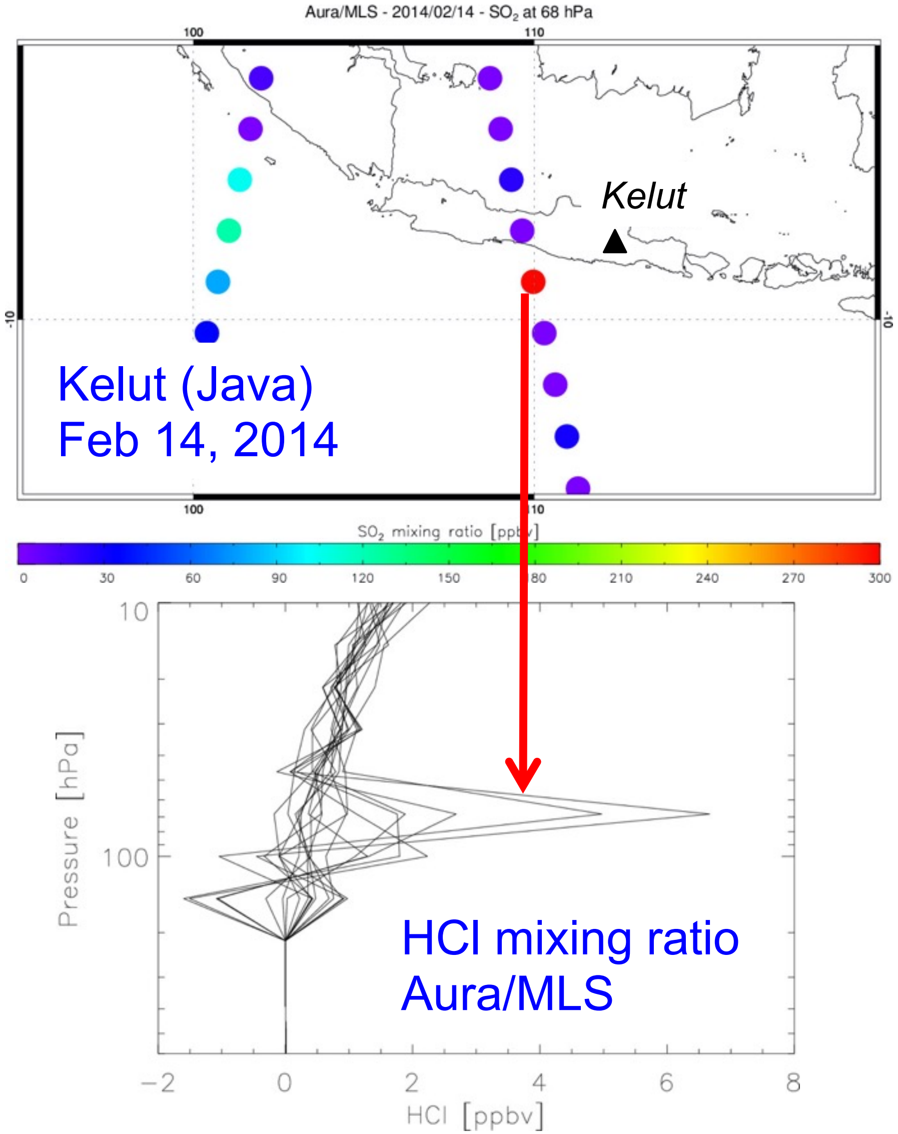
Sioris et al., GRL (2016)

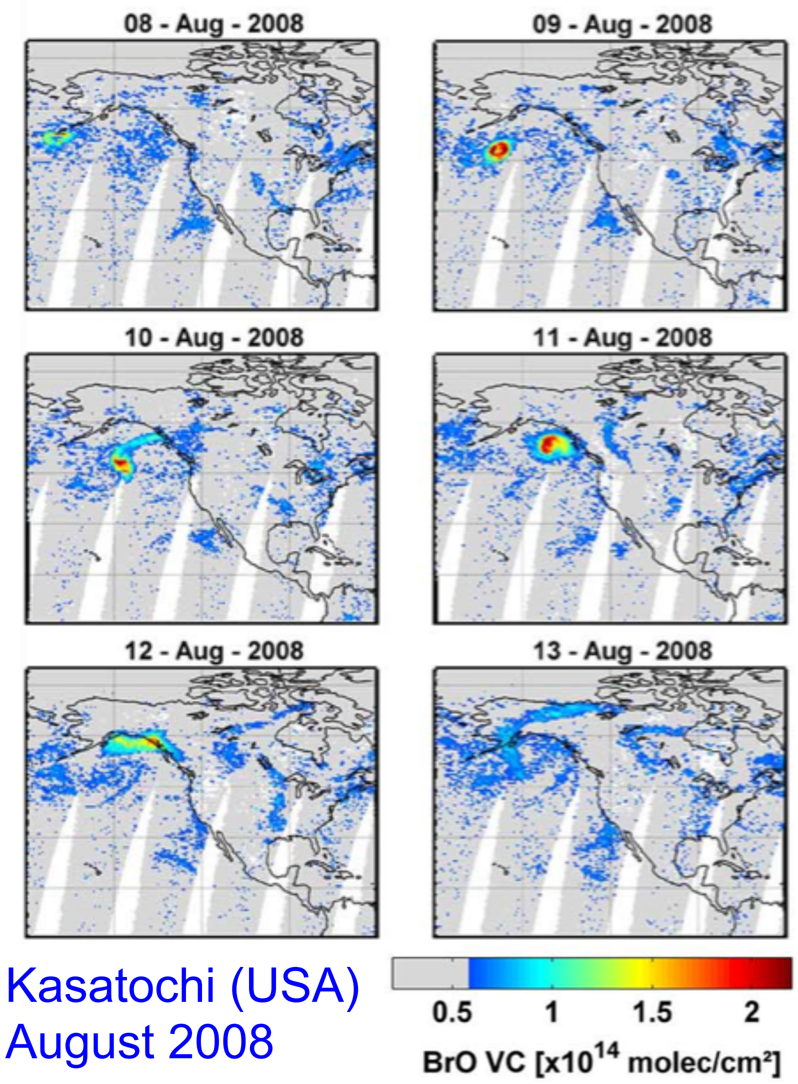


MetOp-B/GOME-2 SO_2 data

- Stratospheric water vapor (WV) anomalies detected by limb-sounding instruments after some explosive volcanic eruptions.
- Canada's SCISAT-1/Atmospheric Chemistry Experiment Fourier Transform Spectrometer (ACE-FTS) and NASA's Aura/Microwave Limb Sounder (MLS)
- WV anomalies reported after 2010 Eyjafjallajökull, 2011 Cordon Caulle and 2015 Calbuco eruptions (all high latitude).

Satellite measurements of volcanic halogens

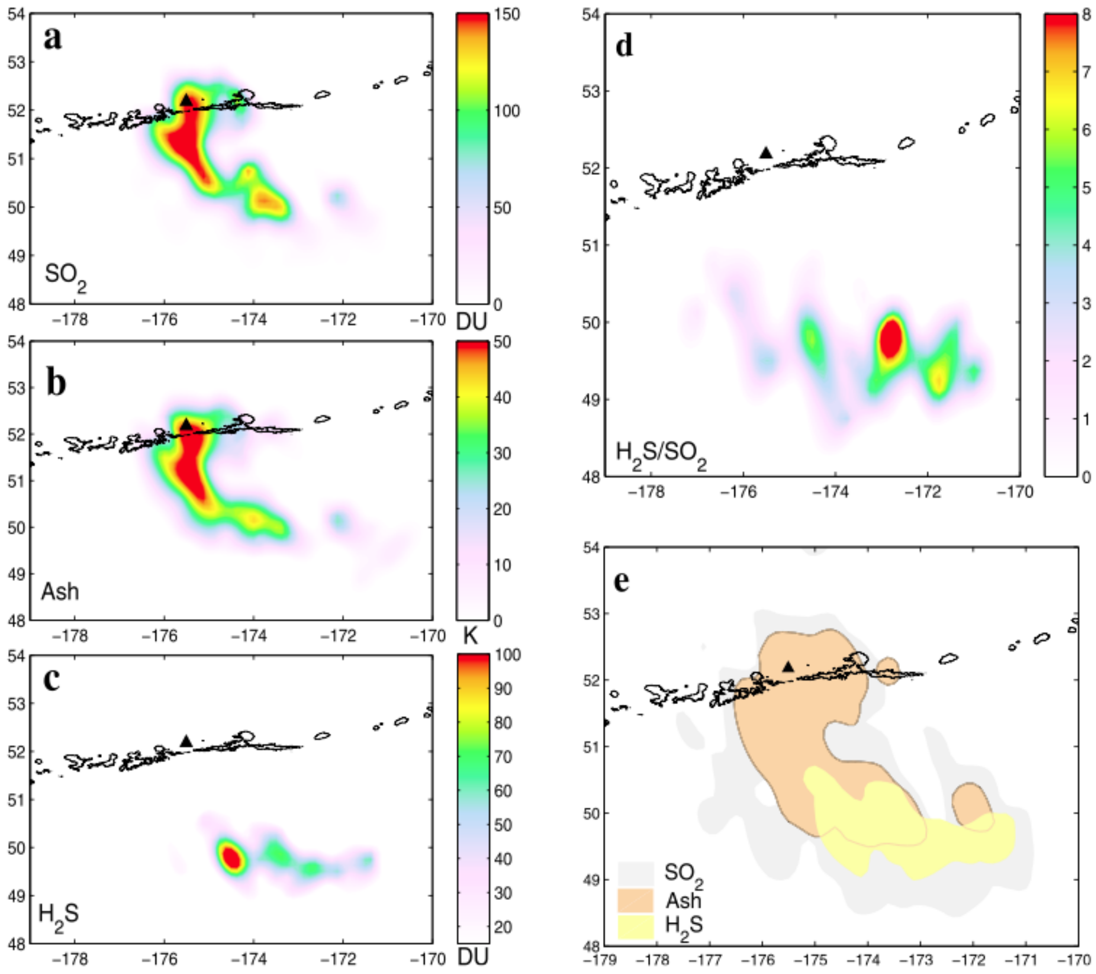




Theys et al. (2009, 2014); *Carn et al.* (2016)

- Satellites have measured HCl, BrO, and OClO in explosive volcanic eruption clouds
- New IASI nadir HCl retrievals recently developed (*Clarisse et al.*, 2020)

Satellite measurement of volcanic H_2S emissions



2008 Kasatochi eruption
Clarisse et al. (2011)

Pressure →

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

← Temperature / fO_2

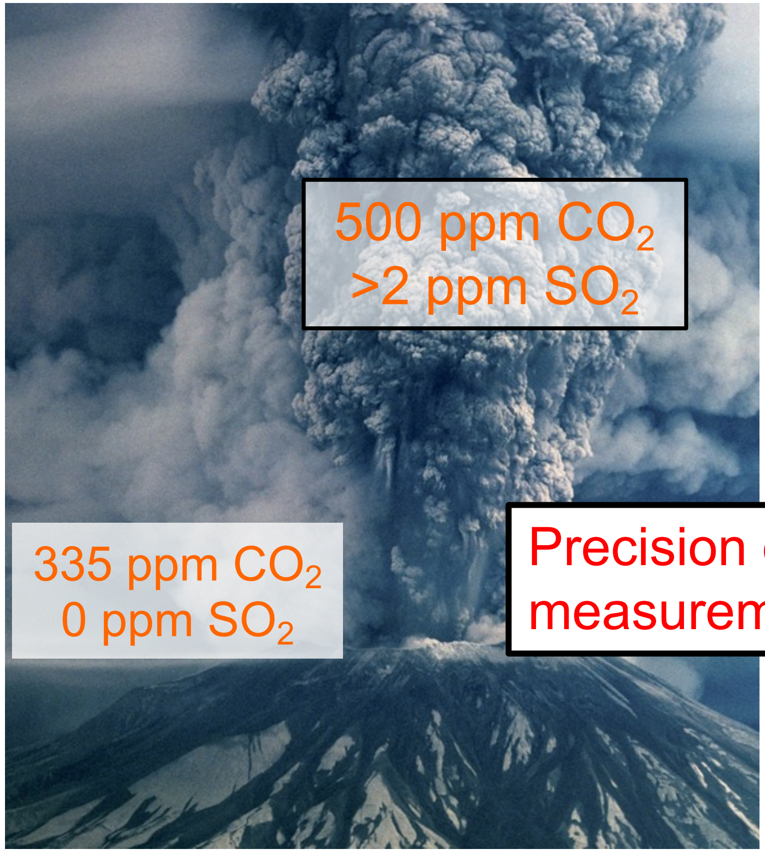
$$\log (SO_2/H_2S) = \log K_T - 3 \log (H_2/H_2O) - \log P \,.\, X_{H2O}$$

Symonds et al., 1994

- May be a significant component of the total sulfur budget at some volcanoes (*Aiuppa et al.*, 2005)
- IR absorption bands are very weak, hence can only be detected from space in large eruptions (IASI; *Clarisse et al.*, 2011)

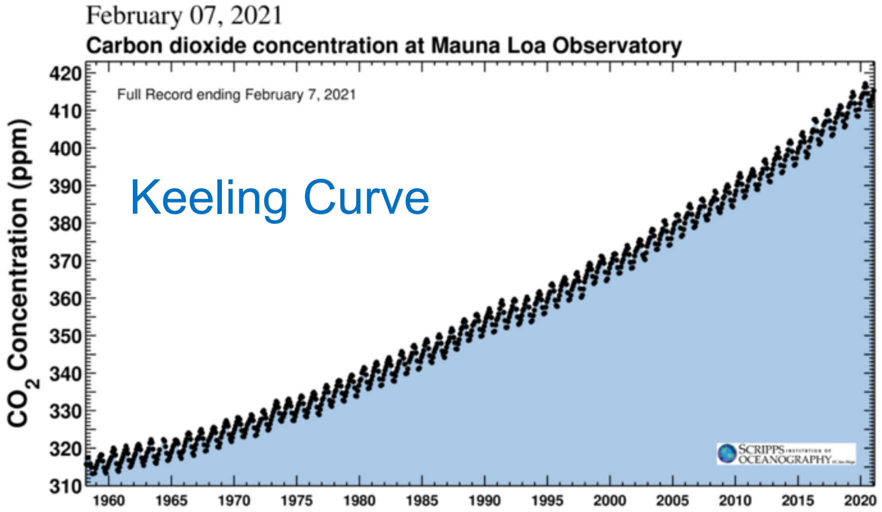
Can we monitor volcanic CO_2 from space?

Explosive eruption

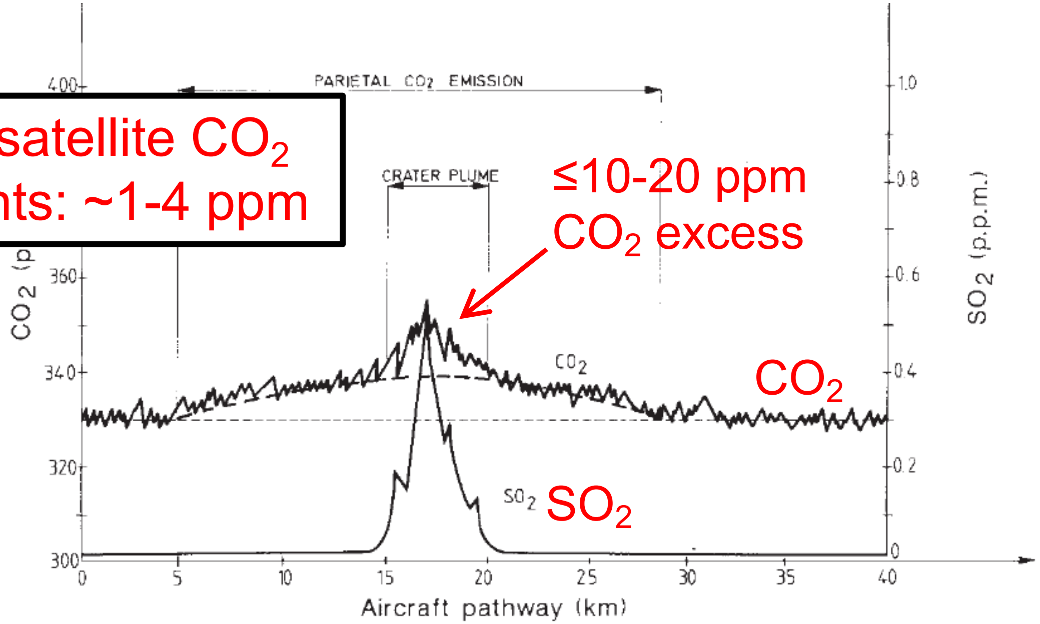


May 1980 Mt St Helens eruption
(*Hobbs et al.*, 1982)

CO_2/SO_2 = 55 -> ~55 Tg CO_2

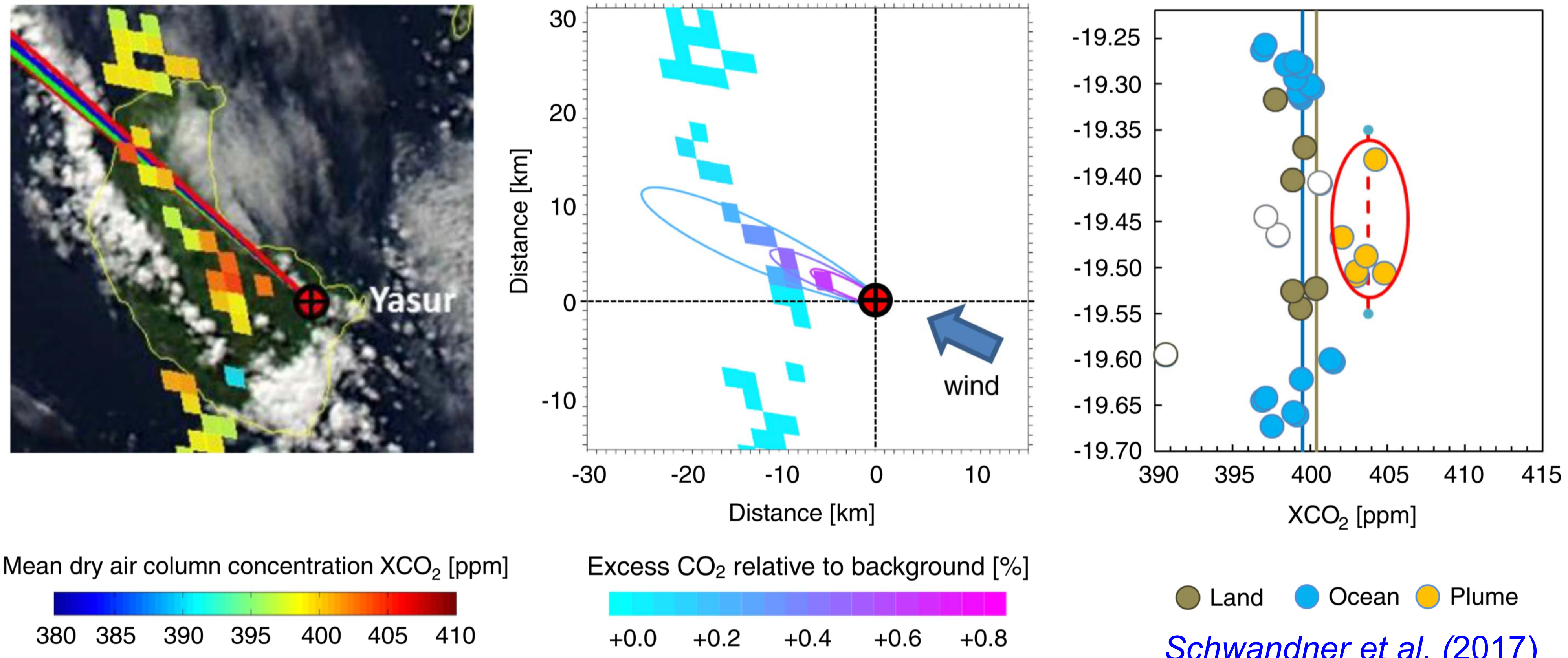


Precision of satellite CO_2 measurements: ~1-4 ppm



Etna, Italy: 13 Tg yr^{-1} CO_2 (*Allard et al.*, 1991)

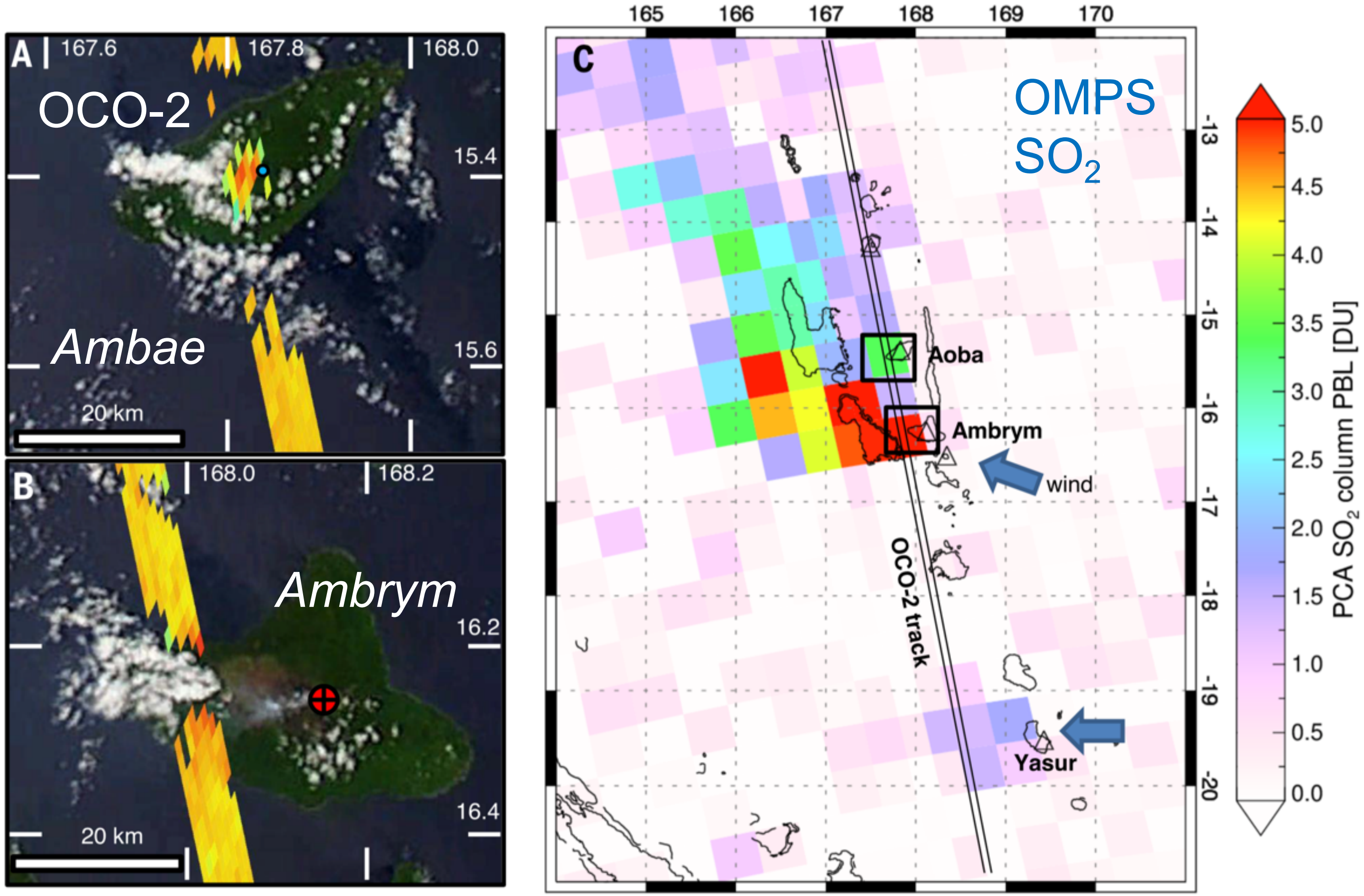
Detection of passive volcanic CO_2 emissions



Schwandner et al. (2017)

- Due to its lower solubility in magmas, CO_2 is a more reliable eruption ‘precursor’ than SO_2, but much more difficult to detect from space
- CO_2 sensing satellites include the NASA Orbiting Carbon Observatory-2 (OCO-2), the Japanese Greenhouse Gases Observing Satellite (GOSAT) and NASA’s OCO-3 aboard the International Space Station.
- Spatial coverage is poor and measurement precision is a few ppm CO_2; measurements are significantly impacted by clouds and aerosols.

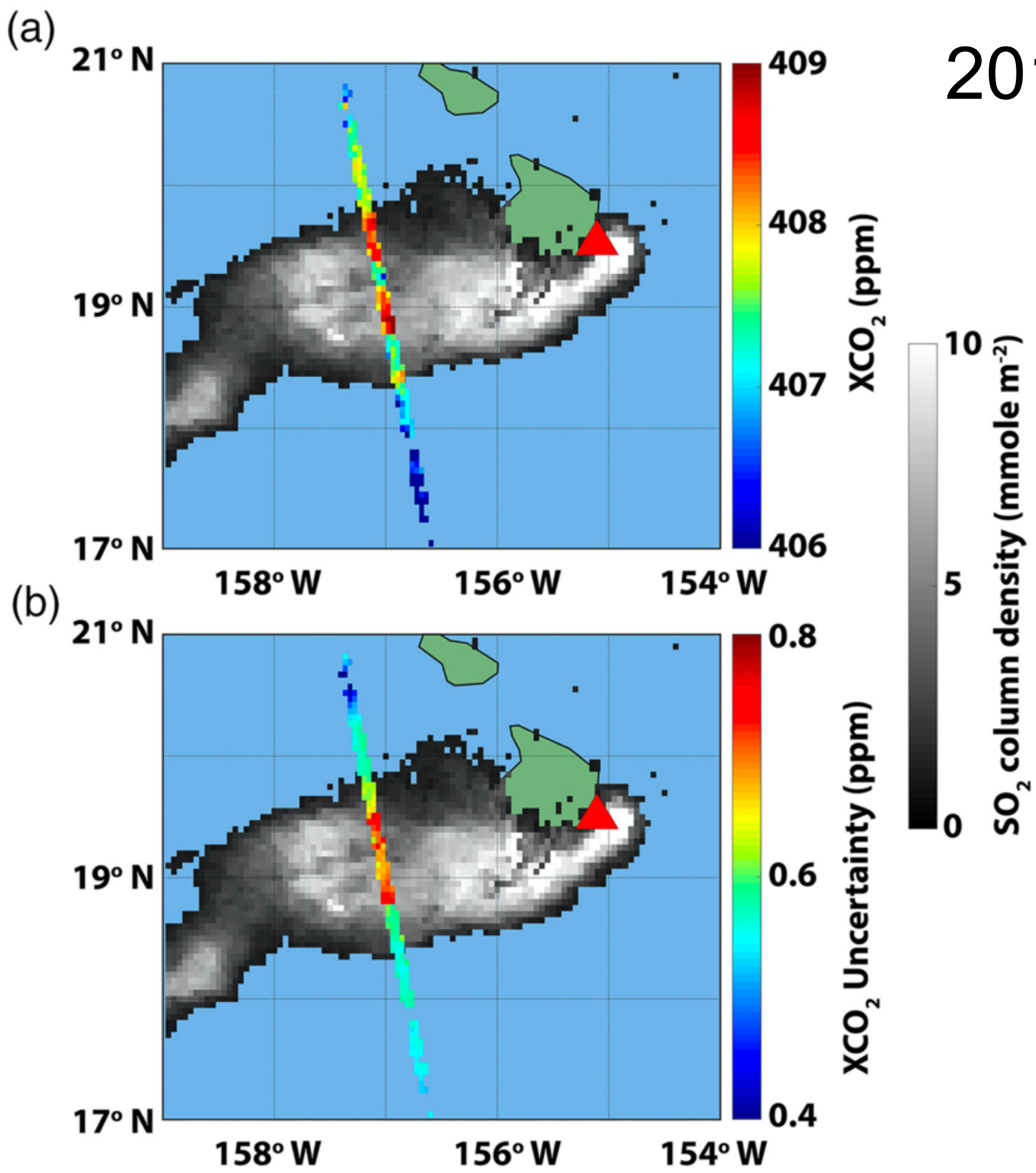
Detection of passive volcanic CO_2 emissions



Schwandner et al. (2017)

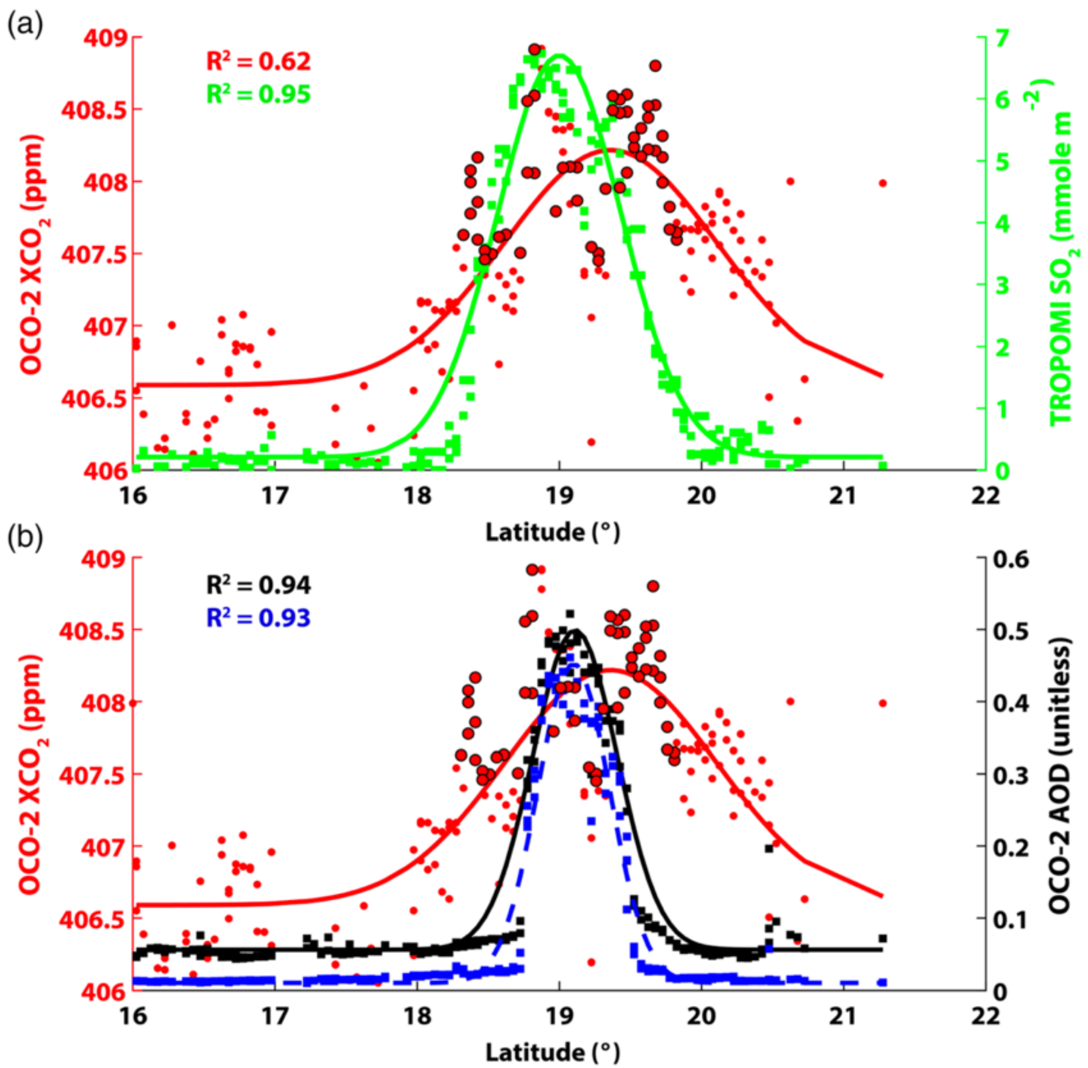
- Orbiting Carbon Observatory-3 (OCO-3) was deployed on the International Space Station in May 2019. Can be pointed at targets ('stare mode') such as volcanoes.
- Proxy methods for CO_2 (e.g., based on vegetation impacts) may be a useful alternative to direct measurement

Detection of eruptive volcanic CO_2 emissions

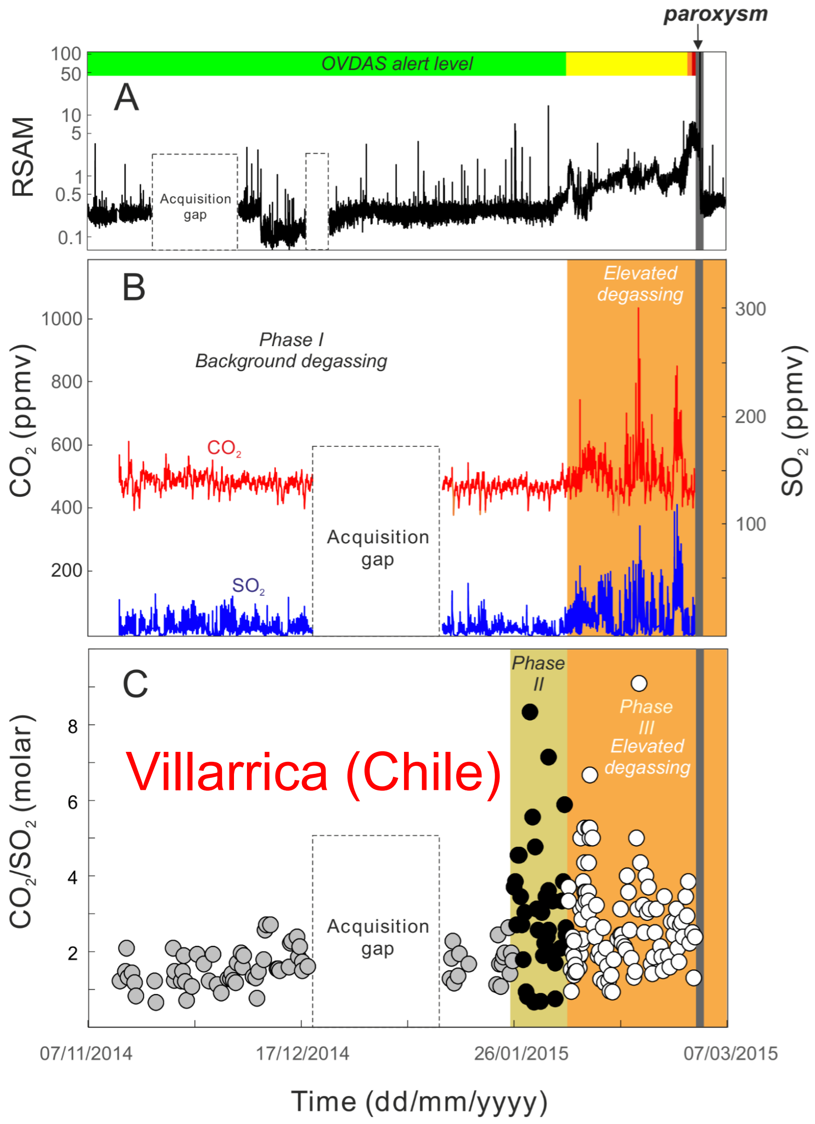


2018 Kilauea eruption

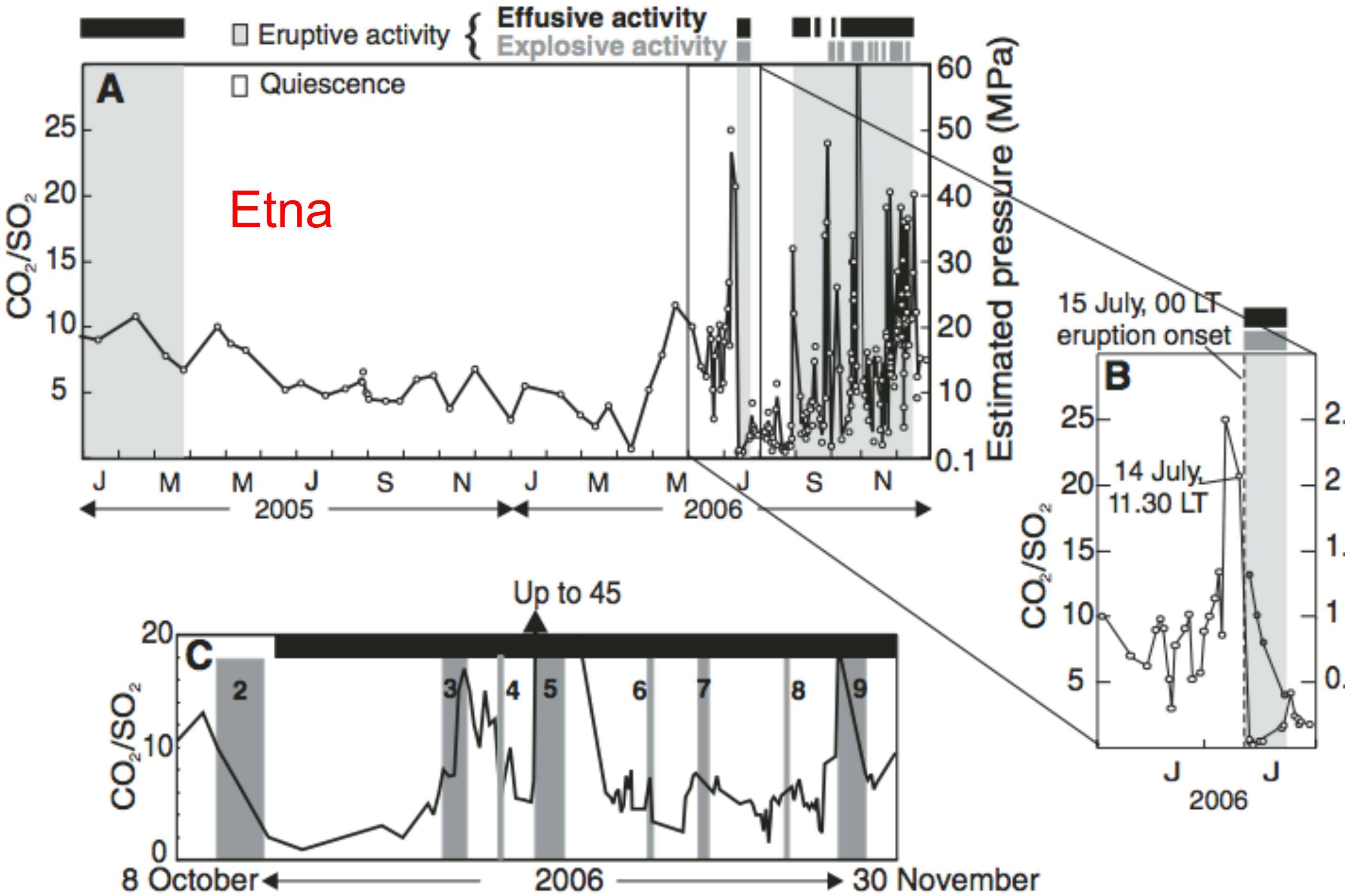
Johnson et al., GRL (2020)



Variable CO_2/SO_2 ratios before explosive eruptions

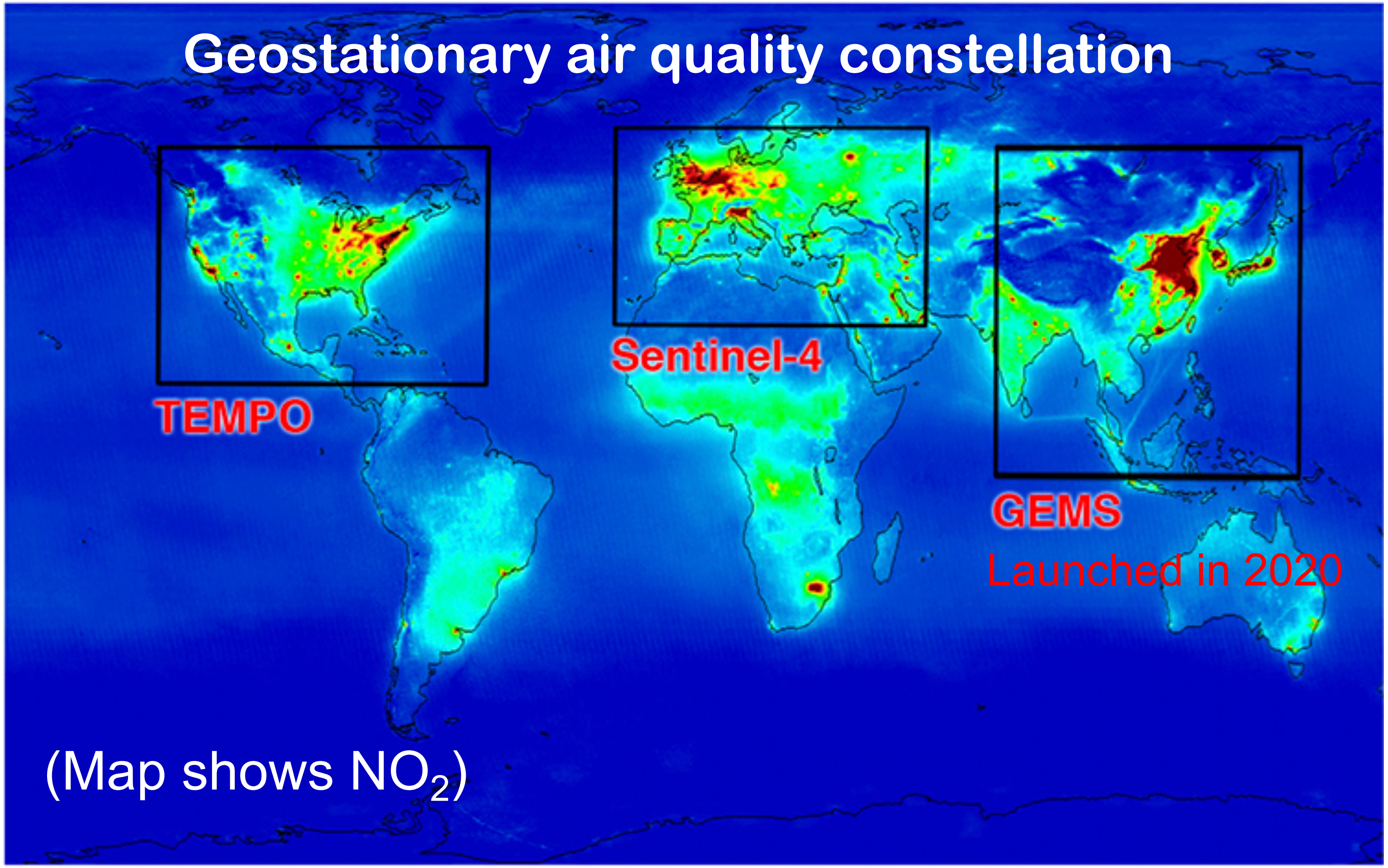


[e.g., Aiuppa et al., 2007, 2009, 2017; de Moor et al., 2016]



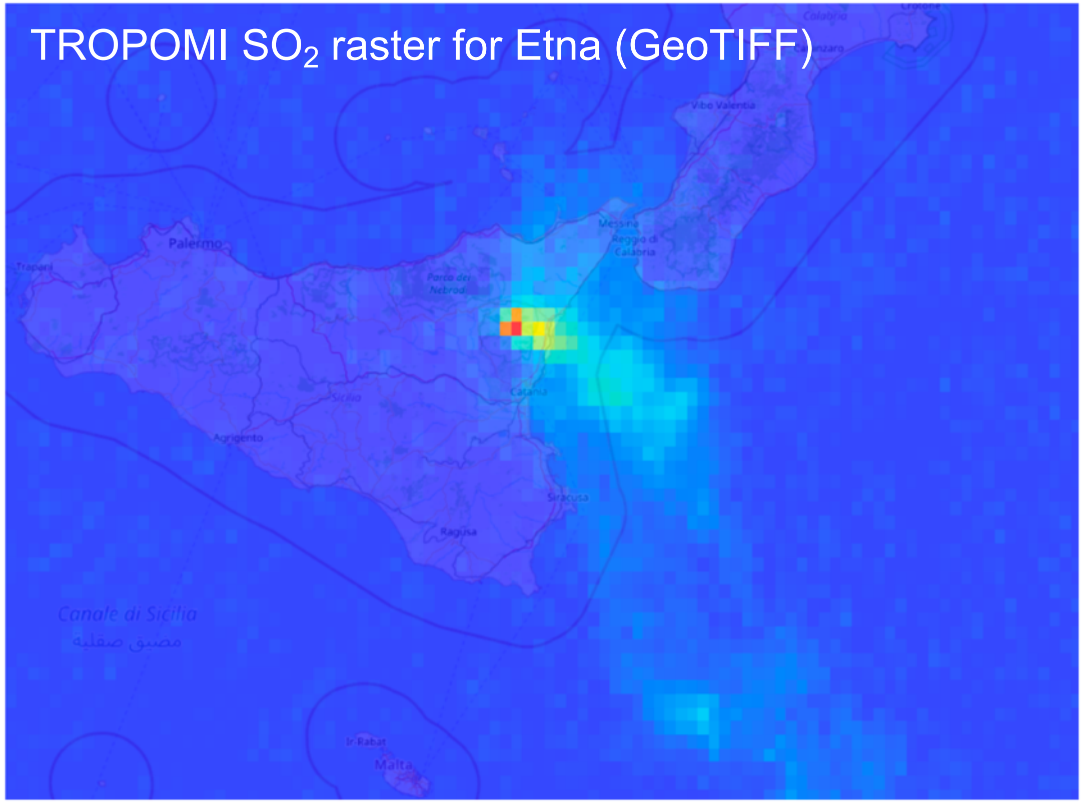
- Excursions in CO_2/SO_2 (and H_2O/CO_2) observed weeks-months prior to eruptions at basaltic, open-vent volcanoes (in-situ data)
- But *gas ratios remain difficult to measure from space, despite recent advances in CO_2 measurements (e.g., NASA OCO-2,OCO-3)*

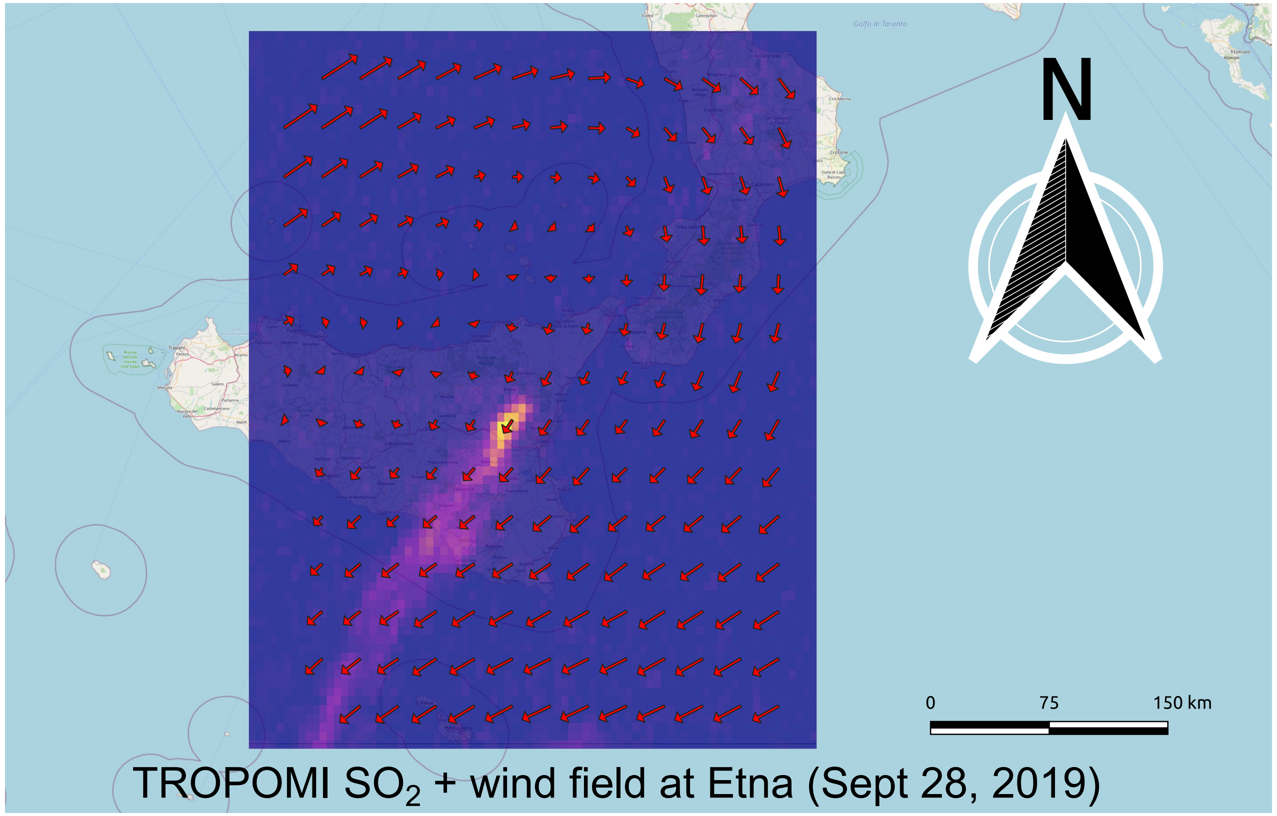
Future attractions



- Geostationary UV measurements (driven by air quality)
  - Some volcanic regions covered; SO_2 is a key measurement
- Cubesat constellations (e.g., GHGSat - targeted CO_2 measurements), GeoCarb

Future attractions





- Data volume is a major obstacle to operational use of satellite measurements by many VOs
- One NRT TROPOMI SO_2 data granule = 100 Mb; one TROPOMI SO_2 orbit = ~800 Mb
- Solution: satellite SO_2 data analysis using NASA Earthdata API (*Epiard and Carn*, EGU, 2021)
- *We are looking for volcano observatory partners to test new open-source Python software*

Online satellite emissions data tools

NASA Global SO_2 monitoring: https://so2.gsfc.nasa.gov/ (UV satellite SO_2 data; SO_2 mass time-series)

MOUNTS: http://www.mounts-project.com/home (TROPOMI SO_2 data; SO_2 mass time-series; alerts)

FMI SAMPO: https://sampo.fmi.fi/ (Direct Readout OMI/OMPS SO_2; high latitude eruption detection)

NOAA OMI SO_2: https://satepsanone.nesdis.noaa.gov/pub/OMI/OMISO2/ (Near real-time [NRT] OMI SO_2; global eruption detection)

NOAA OMPS SO_2: https://www.ospo.noaa.gov/Products/atmosphere/ompsso2/ (NRT OMPS SO_2; global eruption detection)

BIRA/SACS: https://sacs.aeronomie.be/nrt/ (NRT OMI/OMPS/GOME-2/IASI/AIRS SO_2; global eruption detection; SO_2 alerts)

TROPOMI SO_2 explorer: https://phedelt.users.earthengine.app/view/so2explorer (average TROPOMI SO_2 maps)

NASA WorldView: https://worldview.earthdata.nasa.gov/ (NASA data visualization; OMI/OMPS/MLS/AIRS SO_2, OCO-2/3 CO_2)

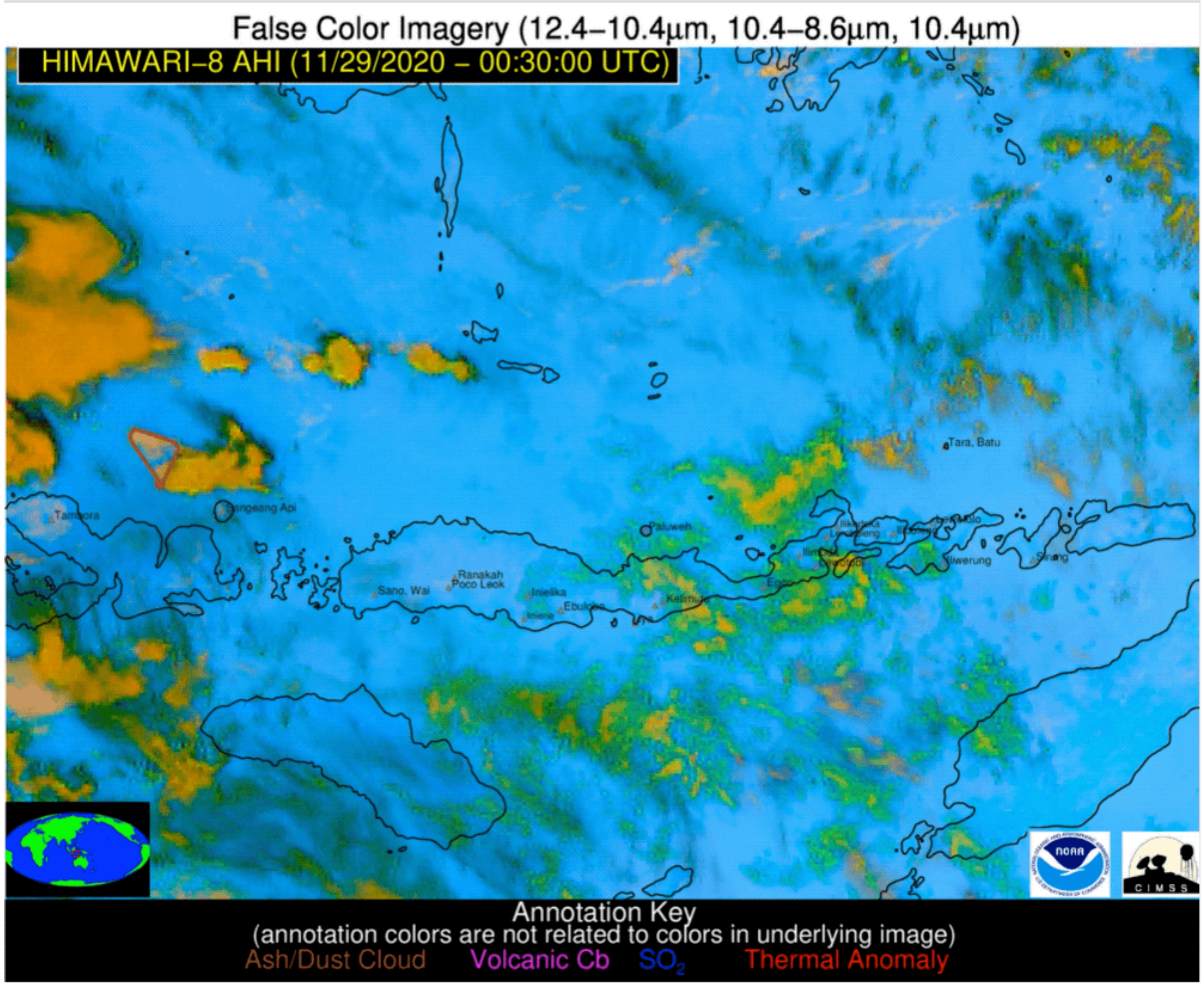
NOAA/CIMSS VOLCAT: https://volcano.ssec.wisc.edu/ (IR GEO and LEO satellite volcanic ash and SO_2 detection)

AIRS SO_2 plume detection (NASA/JPL): http://airs.jpl.nasa.gov/volcanic_plumes (IR SO_2 and volcanic ash detection)

EUMETSAT EUMETView: https://view.eumetsat.int/productviewer?v=default (Geostationary SEVIRI Ash RGB images)

Sentinel Hub EO Browser: https://apps.sentinel-hub.com/eo-browser (ESA Sentinel satellite data including TROPOMI SO_2)

Geostationary satellite detection of volcanic eruptions



Nov 2020 Lewotolo eruption (Indonesia)

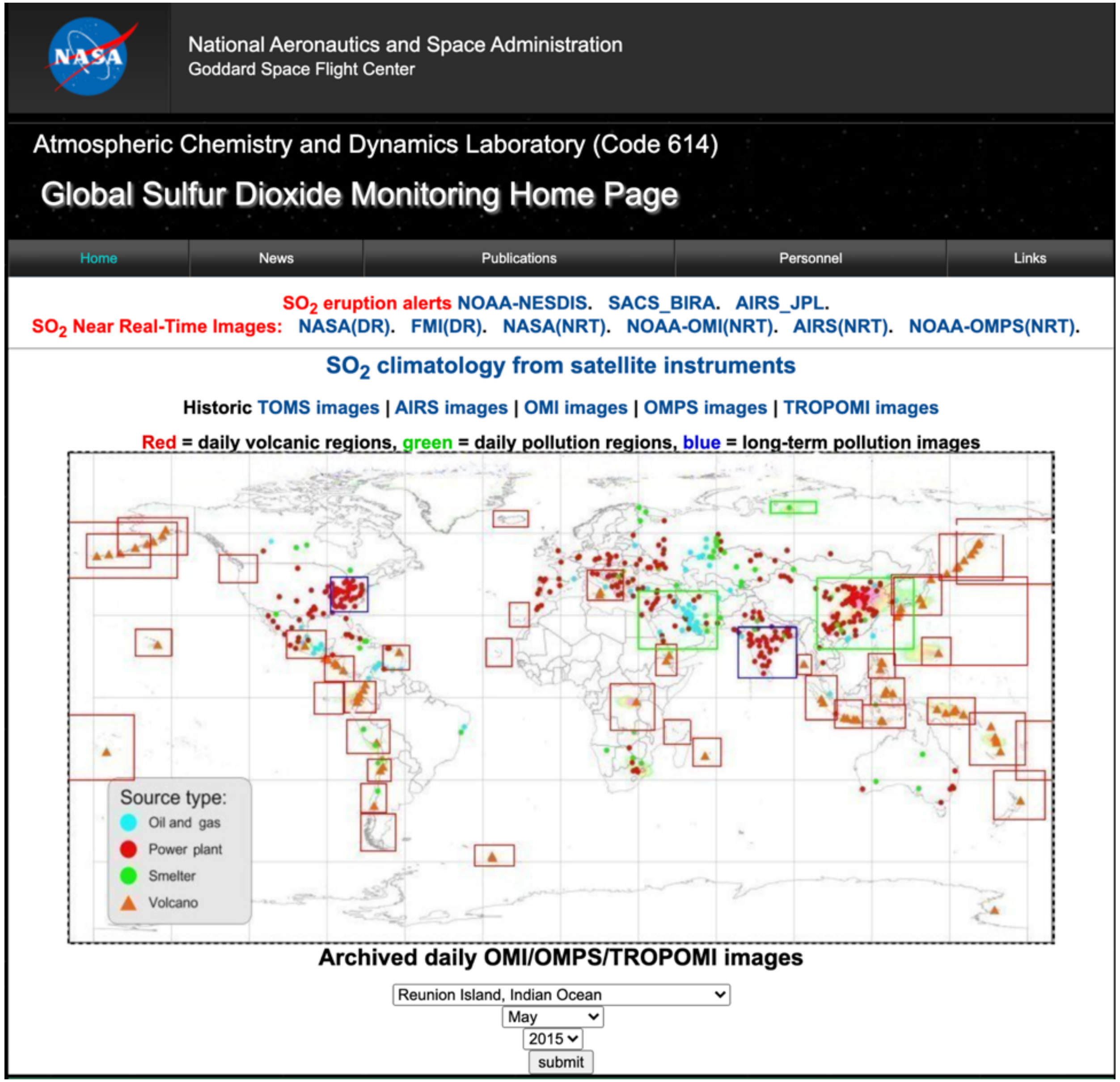
- Thermal anomaly
- Volcanic Cb
- Ash cloud

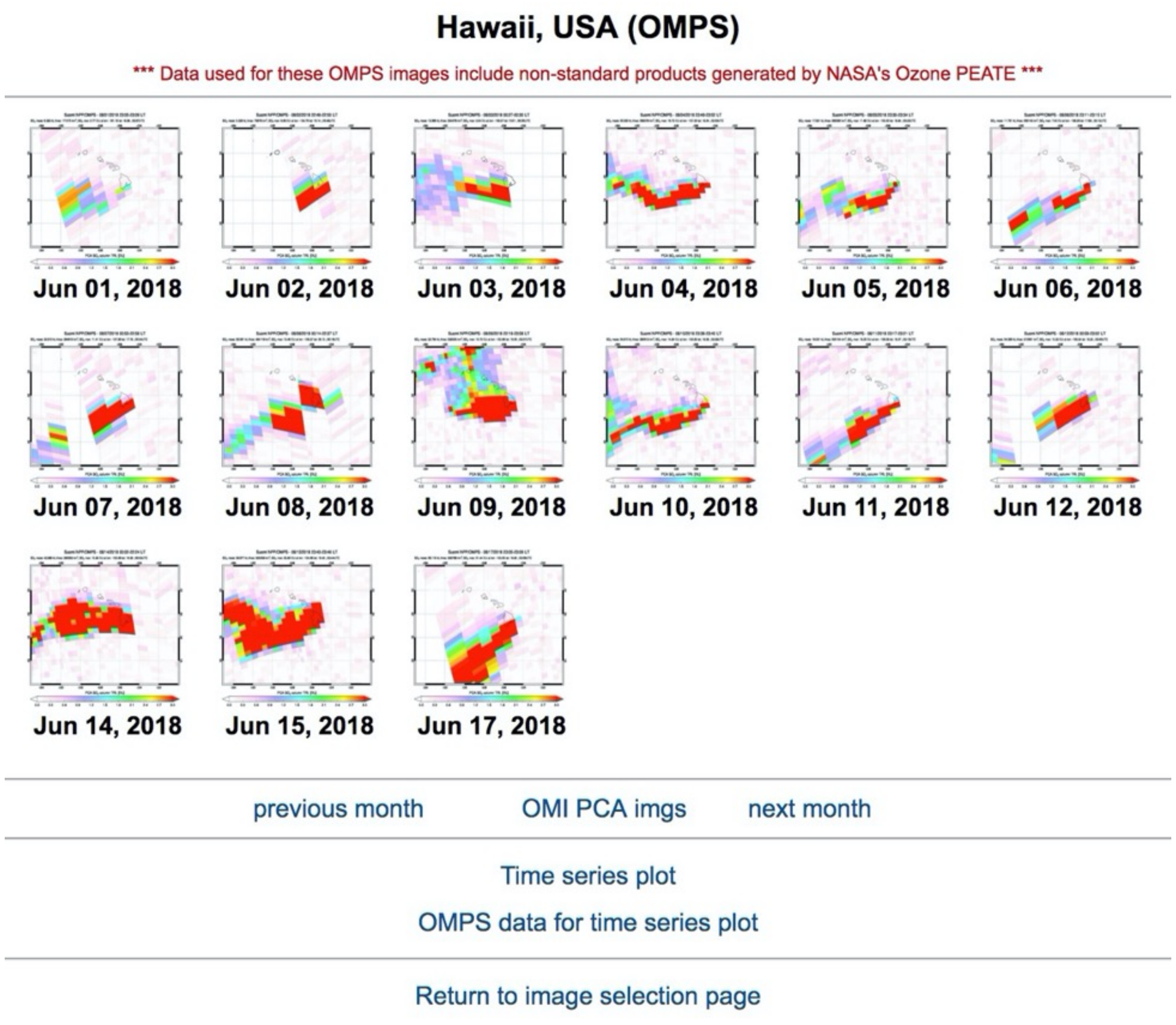
VOLCAT SO_2 alerts (using LEO data) available to VAACs, MWOs, VOs.

- VOLCAT: https://volcano.ssec.wisc.edu

Pavolonis et al., 2015a, 2015b, 2018

NASA Global SO_2 monitoring website

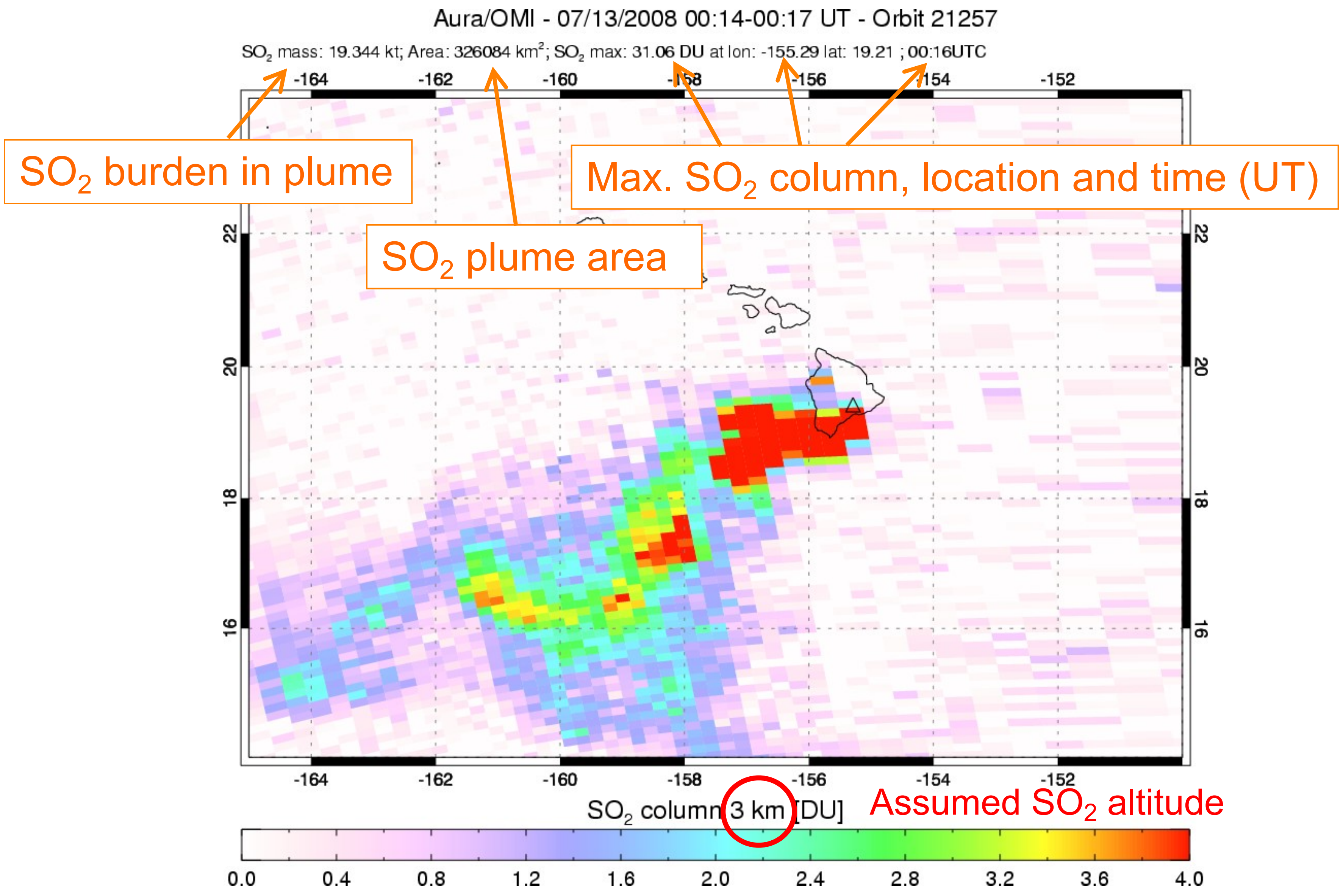




Archived images: https://so2.gsfc.nasa.gov

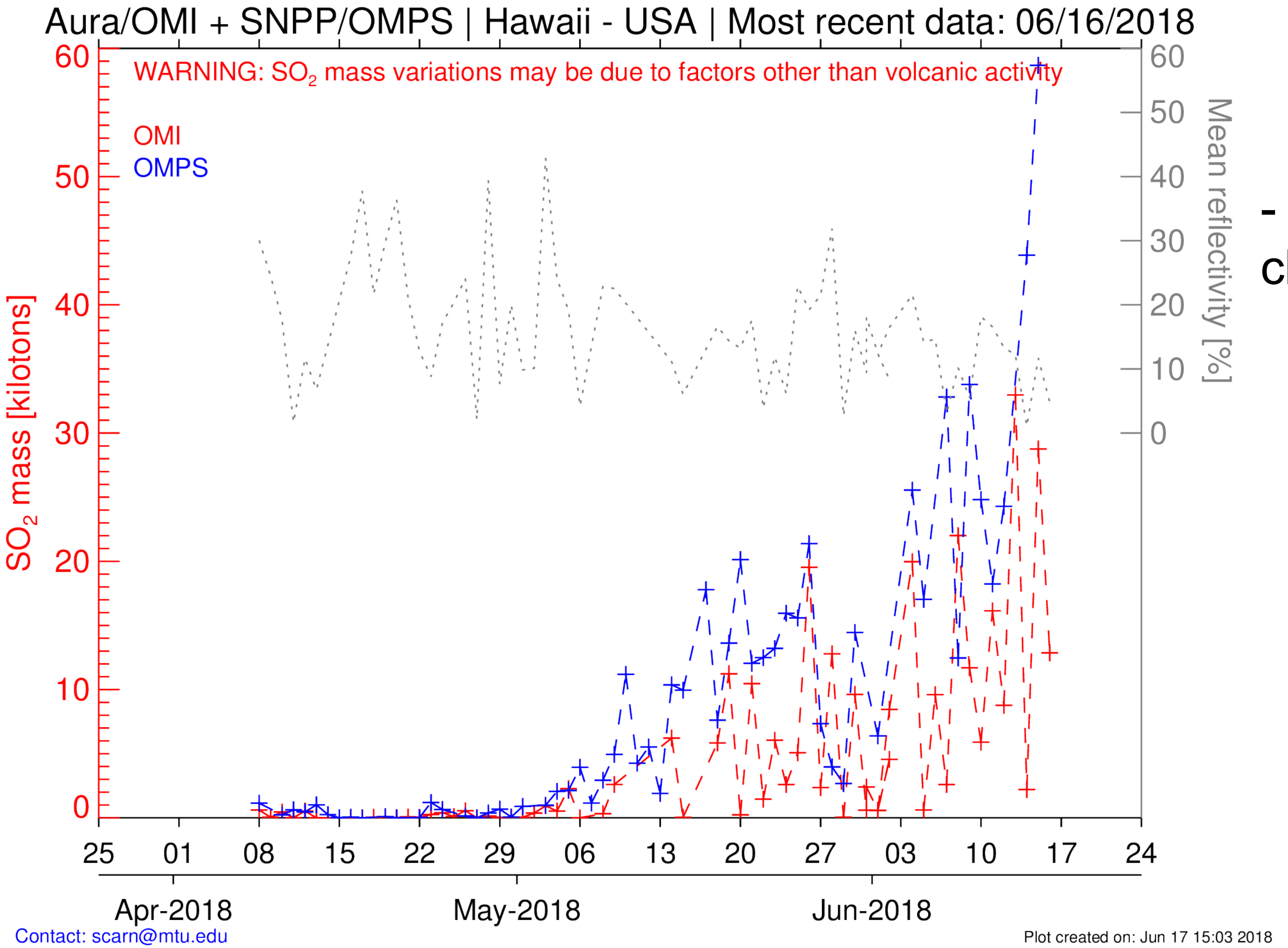
Daily OMI SO_2 measurements for Kilauea

http://so2.gsfc.nasa.gov



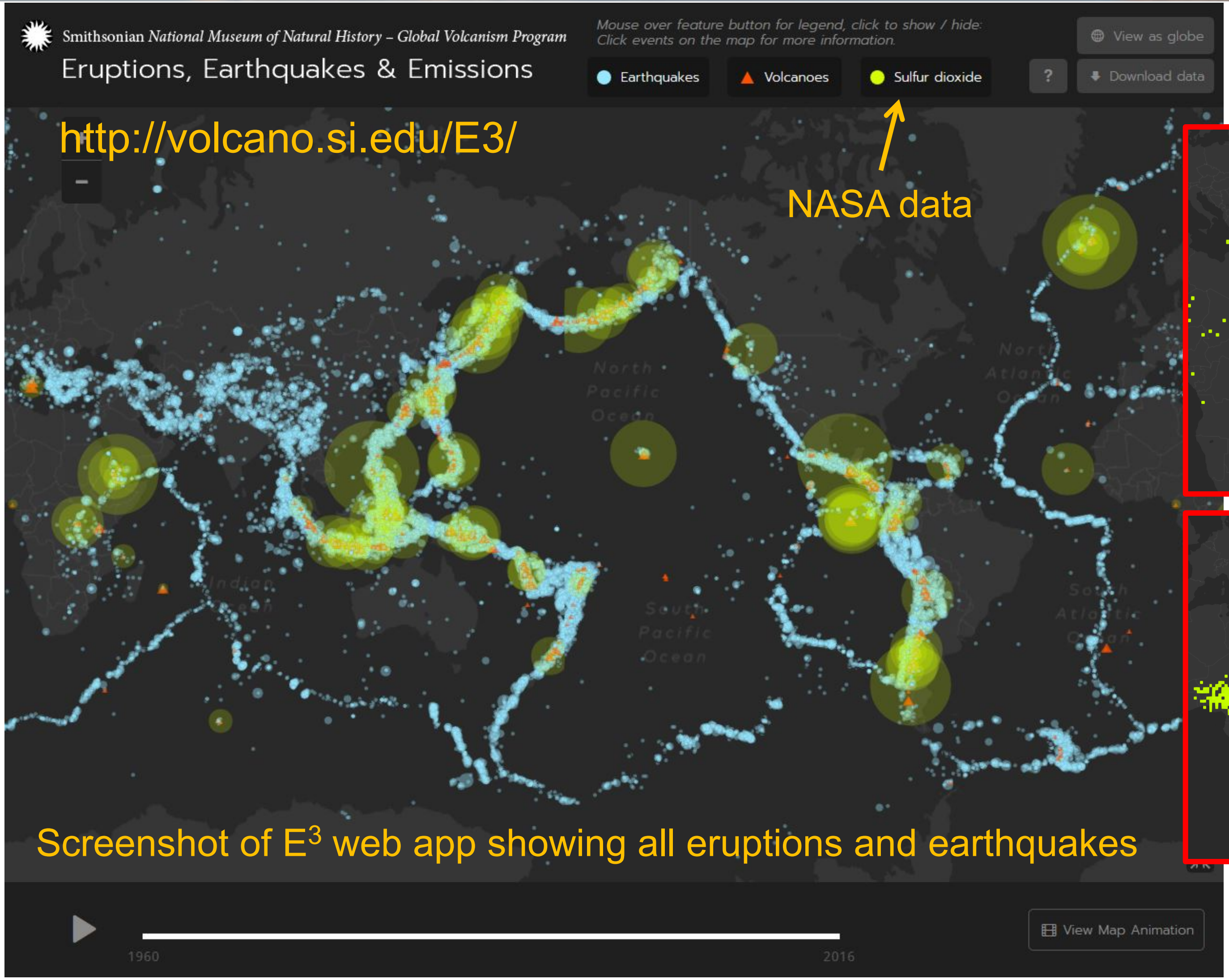
Operational OMI+OMPS (+TROPOMI) SO_2 time-series plots

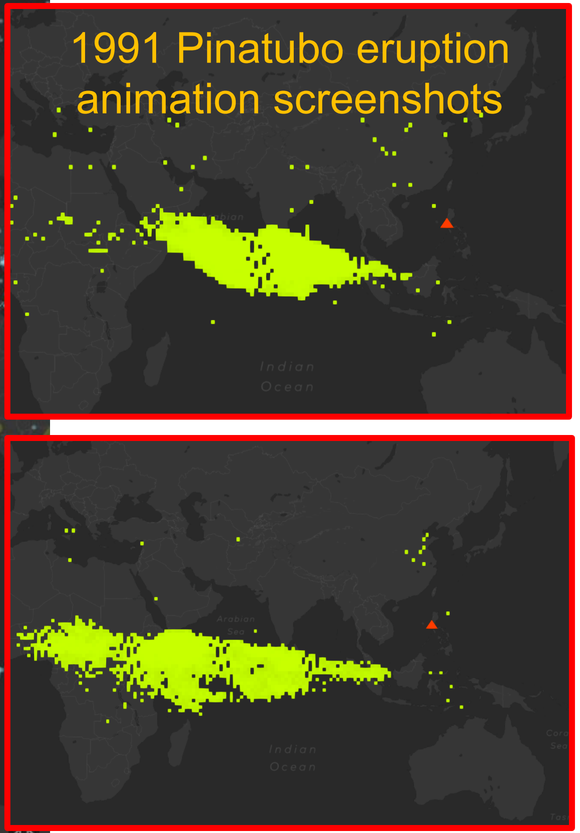
Assumes fixed SO_2 altitude



- Proxy for cloud cover

NASA SO_2 data in GVP database





The Global Volcanism Program at the Smithsonian Institution National Museum of Natural History has created an Eruptions, Earthquakes and Emissions web visualization using NASA volcanic SO_2 data from multiple satellites.

Michigan Technological University

Smithsonian Institution
National Museum of Natural History
Global Volcanism Program

Volcanic SO_2 database text file (MSVOLSO2L4)

volcano	lat	lon	v_alt	yyyy	mm	dd	type	vei	p_alt_obs	p_alt_est	so2(kt)
Ambrym	-16.25	168.12	1.334	1978	12	5	exp	2	-999	11.334	87
Cerro_Azul	-0.92	-91.408	1.69	1979	2	1	eff	2	2	-999	10
Cerro_Azul	-0.92	-91.408	1.69	1979	2	2	eff	2	7	-999	60
Cerro_Azul	-0.92	-91.408	1.69	1979	2	3	eff	2	2	-999	40
Cerro_Azul	-0.92	-91.408	1.69	1979	2	4	eff	2	3	-999	10
Cerro_Azul	-0.92	-91.408	1.69	1979	2	5	eff	2	7	-999	70
Cerro_Azul	-0.92	-91.408	1.69	1979	2	6	eff	2	10	-999	70
Cerro_Azul	-0.92	-91.408	1.69	1979	2	7	eff	2	4	-999	60
Cerro_Azul	-0.92	-91.408	1.69	1979	2	8	eff	2	6	-999	9
Cerro_Azul	-0.92	-91.408	1.69	1979	2	9	eff	2	2	-999	9
Cerro_Azul	-0.92	-91.408	1.69	1979	2	10	eff	2	2	-999	9
Cerro_Azul	-0.92	-91.408	1.69	1979	2	11	eff	2	2	-999	9
Cerro_Azul	-0.92	-91.408	1.69	1979	2	12	eff	2	2	-999	2
Karkar	-4.649	145.964	1.839	1979	3	8	exp	2	-999	11.839	50
Soufriere_St_Vincent	13.33	-61.18	1.22	1979	4	13	exp	3	18	-999	3
Etna	37.734	15.004	3.35	1979	8	4	exp	3	-999	8.35	10
Sierra_Negra	-0.83	-91.17	1.49	1979	11	13	eff	3	14	-999	500
Sierra_Negra	-0.83	-91.17	1.49	1979	11	14	eff	3	8	-999	500
Sierra_Negra	-0.83	-91.17	1.49	1979	11	15	eff	3	3	-999	500
Sierra_Negra	-0.83	-91.17	1.49	1979	11	16	eff	3	3	-999	90
Sierra_Negra	-0.83	-91.17	1.49	1979	11	17	eff	3	2	-999	300
Sierra_Negra	-0.83	-91.17	1.49	1979	11	18	eff	3	3	-999	300
Sierra_Negra	-0.83	-91.17	1.49	1979	11	19	eff	3	10	-999	70
Sierra_Negra	-0.83	-91.17	1.49	1979	11	20	eff	3	3	-999	100
Sierra_Negra	-0.83	-91.17	1.49	1979	11	21	eff	3	2	-999	40
Sierra_Negra	-0.83	-91.17	1.49	1979	11	22	eff	3	8	-999	70
Sierra_Negra	-0.83	-91.17	1.49	1979	11	23	eff	3	7	-999	10
Sierra_Negra	-0.83	-91.17	1.49	1979	11	24	eff	3	9	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	25	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	26	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	27	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	28	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	29	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	11	30	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	1	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	2	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	3	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	4	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	5	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	6	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	7	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	8	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	9	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	10	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	11	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	12	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	13	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	14	eff	3	2	-999	2
Sierra_Negra	-0.83	-91.17	1.49	1979	12	15	eff	3	2	-999	2
Nyamuragira	-1.408	29.2	3.058	1980	1	31	eff	3	8	-999	135
Nyamuragira	-1.408	29.2	3.058	1980	2	1	eff	3	7	-999	23
Nyamuragira	-1.408	29.2	3.058	1980	2	2	eff	3	8	-999	42
Nyamuragira	-1.408	29.2	3.058	1980	2	3	eff	3	10	-999	49

- Volcano name, location, altitude
- Eruption date
- Eruption type
- VEI
- Observed plume altitude
- Estimated plume altitude
- SO_2 mass (kilotons)
- One line per day for continuous (i.e., effusive) eruptions
  - Variable SO_2 emissions and plume altitude
- Need to add uncertainty
  - SO_2 loading
  - SO_2 altitude

https://disc.gsfc.nasa.gov/datasets/MSVOLSO2L4_3/summary?keywords=msvolso2l4

Satellite-based SO_2 alerts

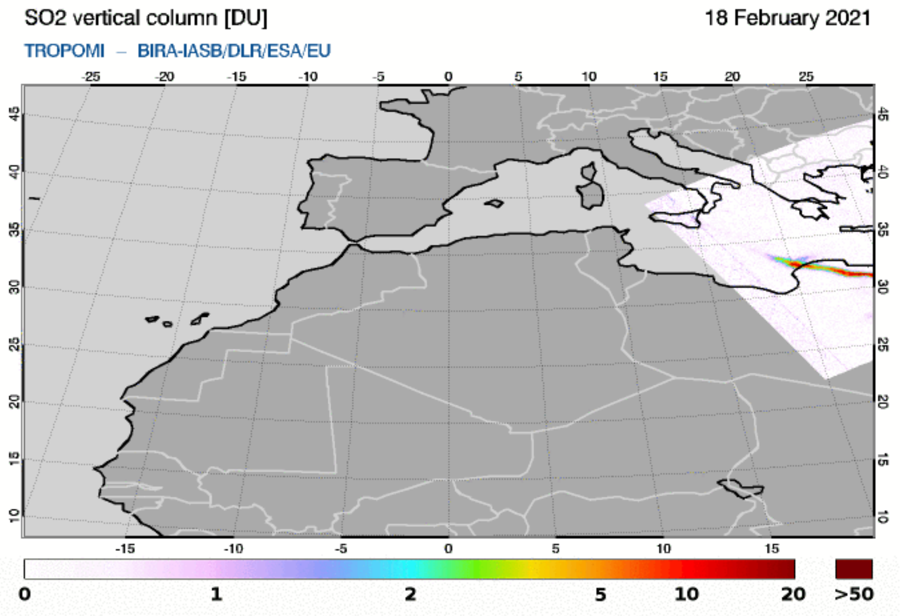
SACS multi-sensor notification of exceptional SO2 concentration
===

Process date : 2021/02/18
Process time : 13:15 UTC
Instrument : TROPOMI

http://sacs.aeronomie.be/nrt
SACS – Support to Aviation Control Service

Notification region: 206
----
http://sacs.aeronomie.be/TROPOMIalert/2021/02/alertsTROPOMI_20210218_11h02_206.php?alert=20210218_131549_206

Date : 2021/02/18
Time : 11:06 UTC
Longitude : 15.0 deg. East
Latitude : 37.6 deg. North
Max. SO2 column : 1.5 DU (assuming 15 km plume height)
SO2 mass loading : 7.116 kt (assuming 15 km plume height)
SO2 plume area : 140433 km²
Notification level : HIGH
Volcano erupting : Etna (most likely)
Cloud data : used for VCD
SZA : 49.1 deg.
Name data source :
S5P_NRTI_L2__SO2____20210218T110230_20210218T110730_17366_01_020104_20210218T120112.nc



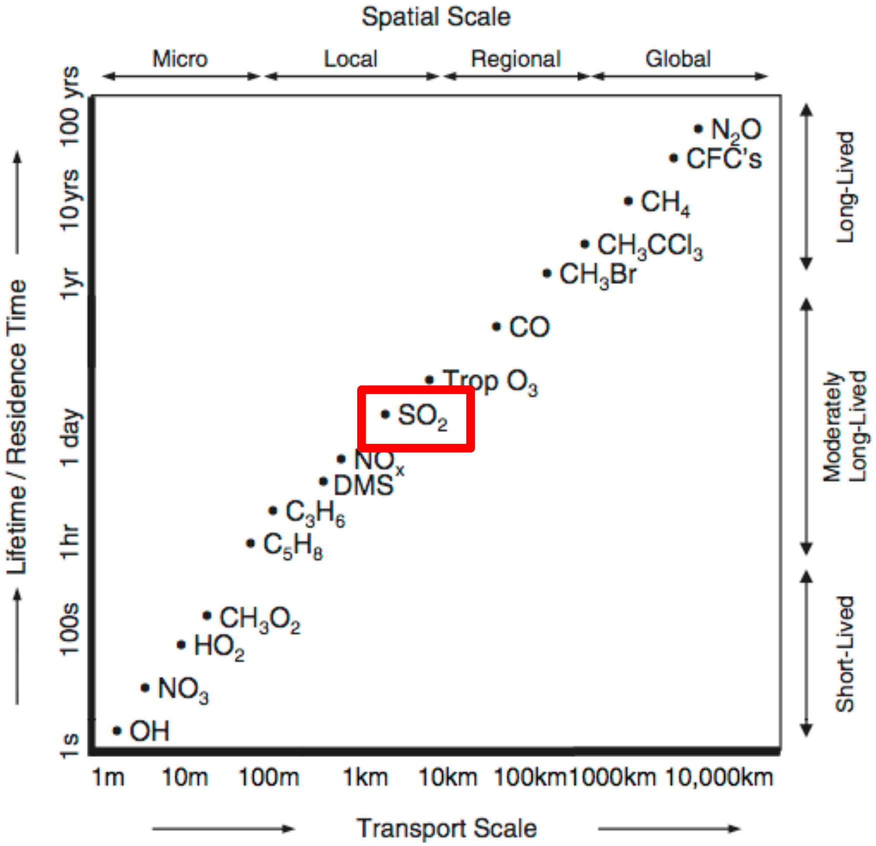
- Detect degassing and eruptions (depends on threshold)
- Few 'false' alerts

SO_2 flux estimation from satellite data - lifetime

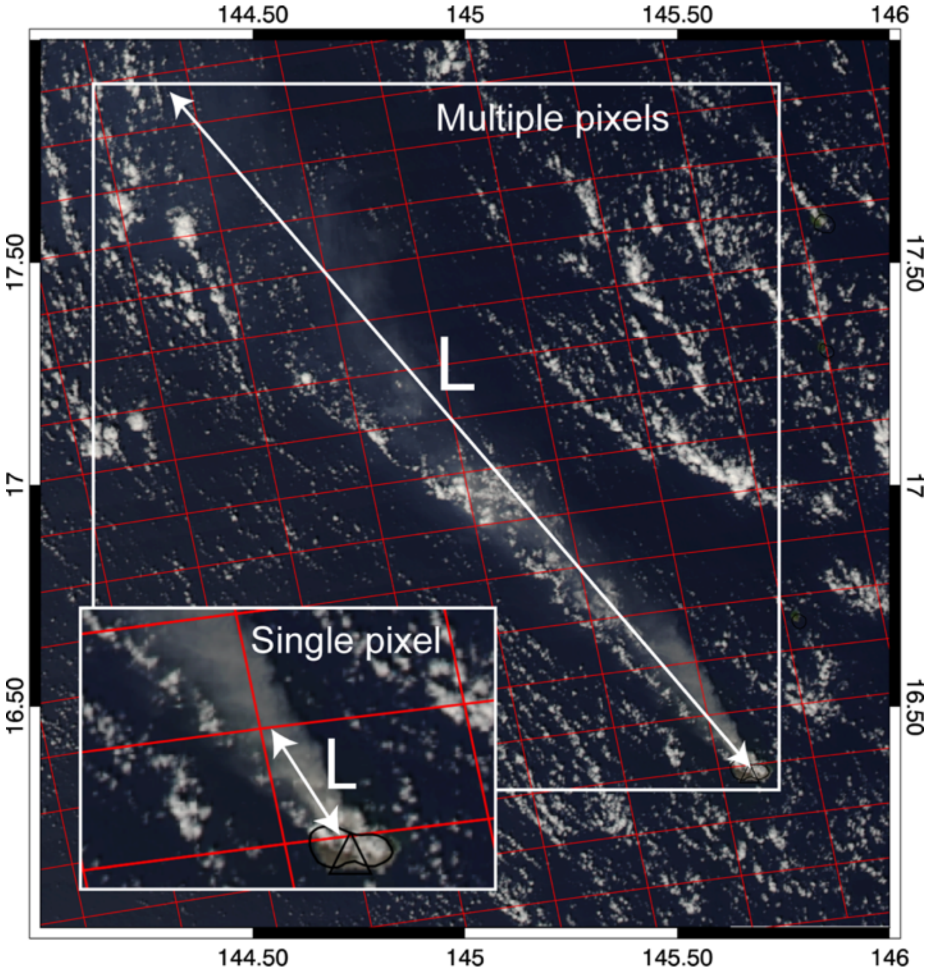
- Satellite 'snapshots' measure SO_2 burden, not flux
- To first order, SO_2 emission rates can be inferred using the SO_2 burden and an estimate of the SO_2 lifetime
- SO_2 lifetime short (hours) at low altitudes and in humid environments
- Few hours in tropical boundary layers

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

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



SO_2 emission rate estimation from satellite data



$$Q_{meas} = Q_{init}\tau t_c^{-1}\left[1 - \exp(-\tau^{-1} t_c)\right]$$

$$t_c = Lv^{-1}$$

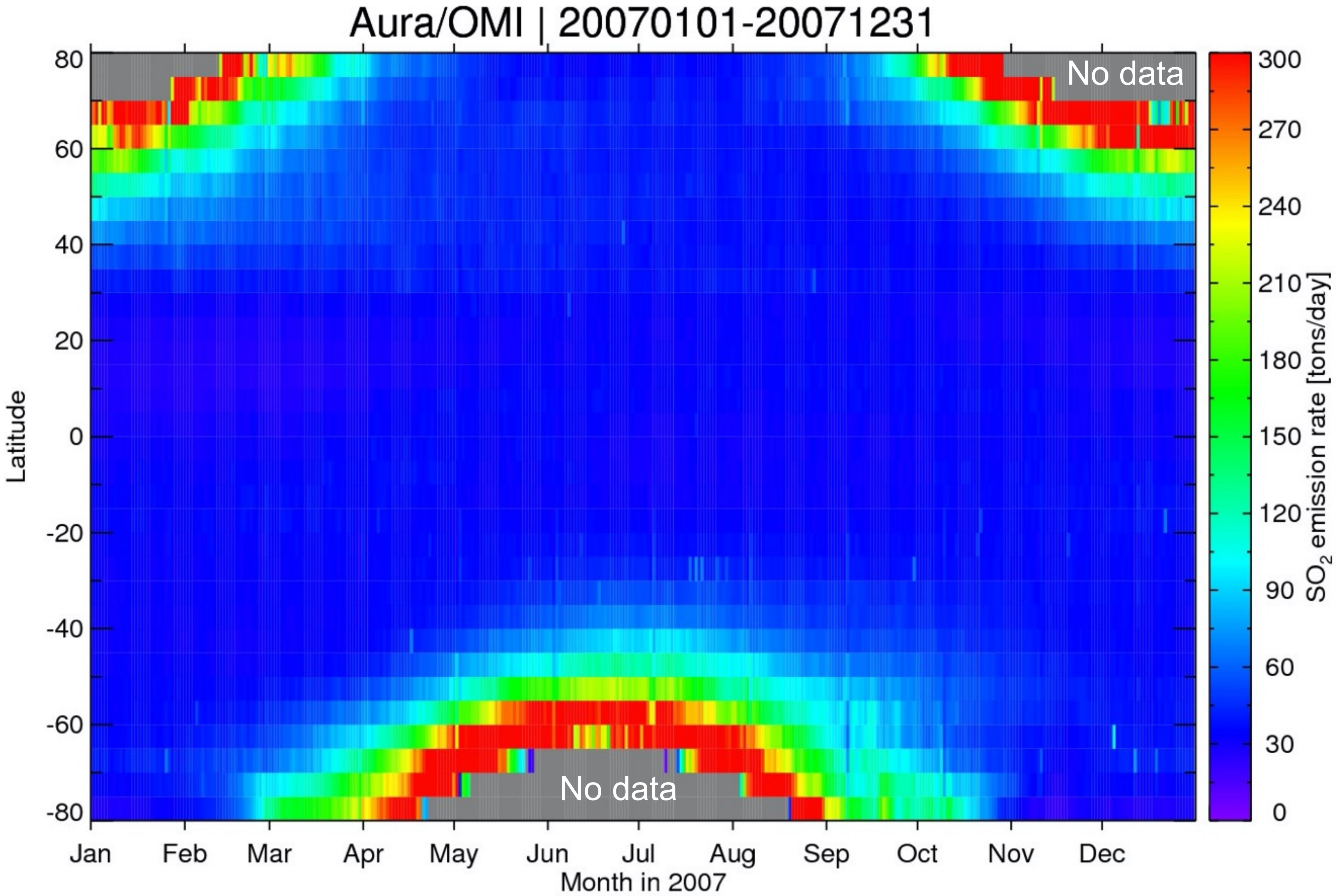
$$Q_{meas} = \left[\frac{vM}{L}\right]$$

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

- Similar approach used to estimate smoke and NO_2 emissions from fires [*Ichoku and Kaufman*, 2005; *Mebust et al.*, 2011]
- Note that asymmetry of OMI pixel affects plume detection
- Chemistry correction [*Mebust et al.*, 2011] can be applied if SO_2 lifetime is known

[*Carn et al.*, Spec. Pub. Geol. Soc. Lon., 2013]

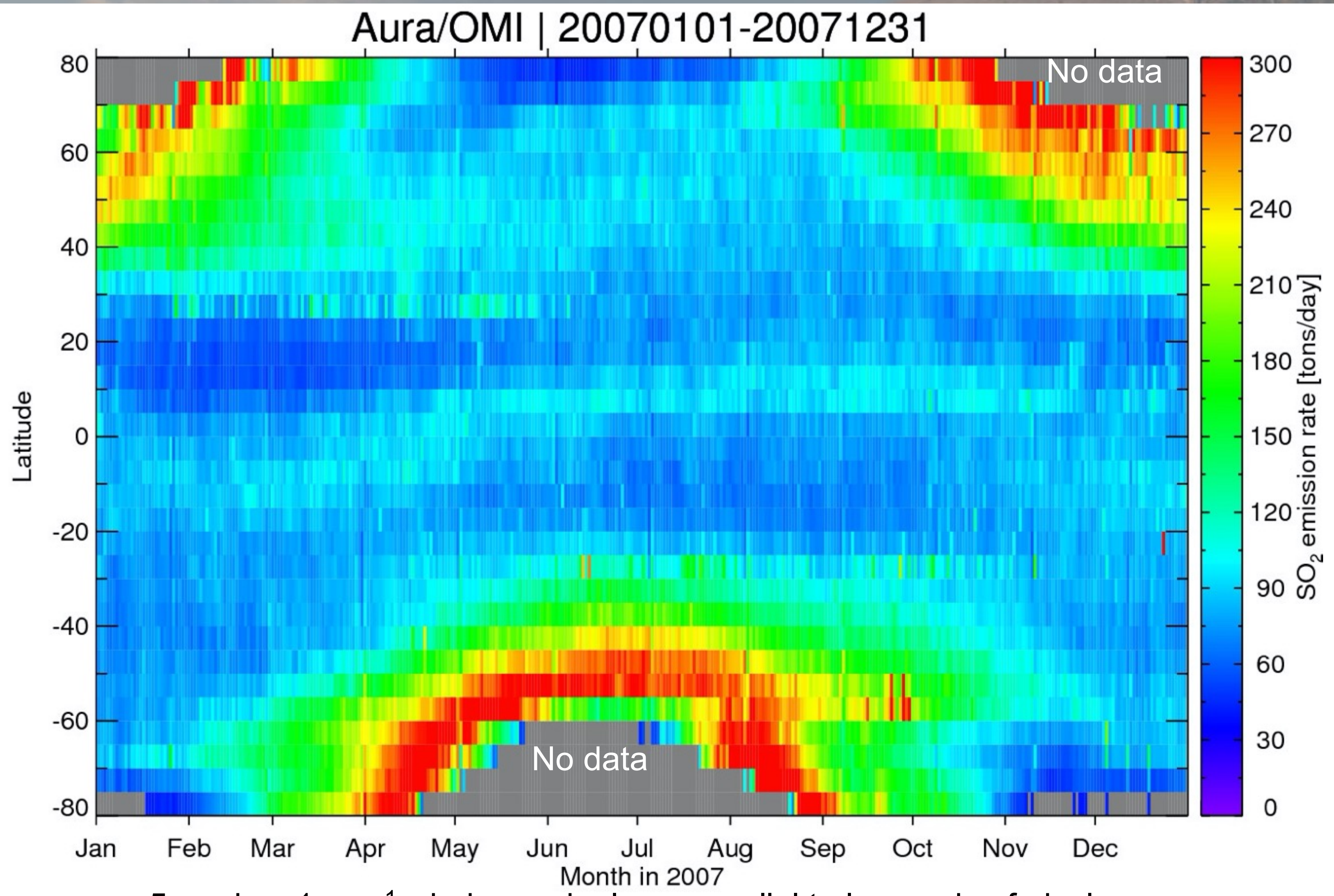
SO_2 flux detection limits – zonal means (TRM)



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

[*Carn et al.*, Spec. Pub. Geol. Soc. Lon., 2013]

SO_2 flux detection limits – zonal means (TRL)



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

[*Carn et al.*, Spec. Pub. Geol. Soc. Lon., 2013]