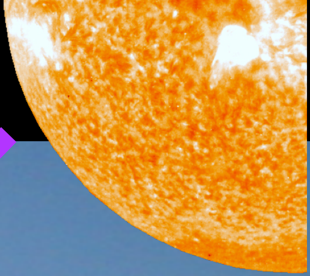
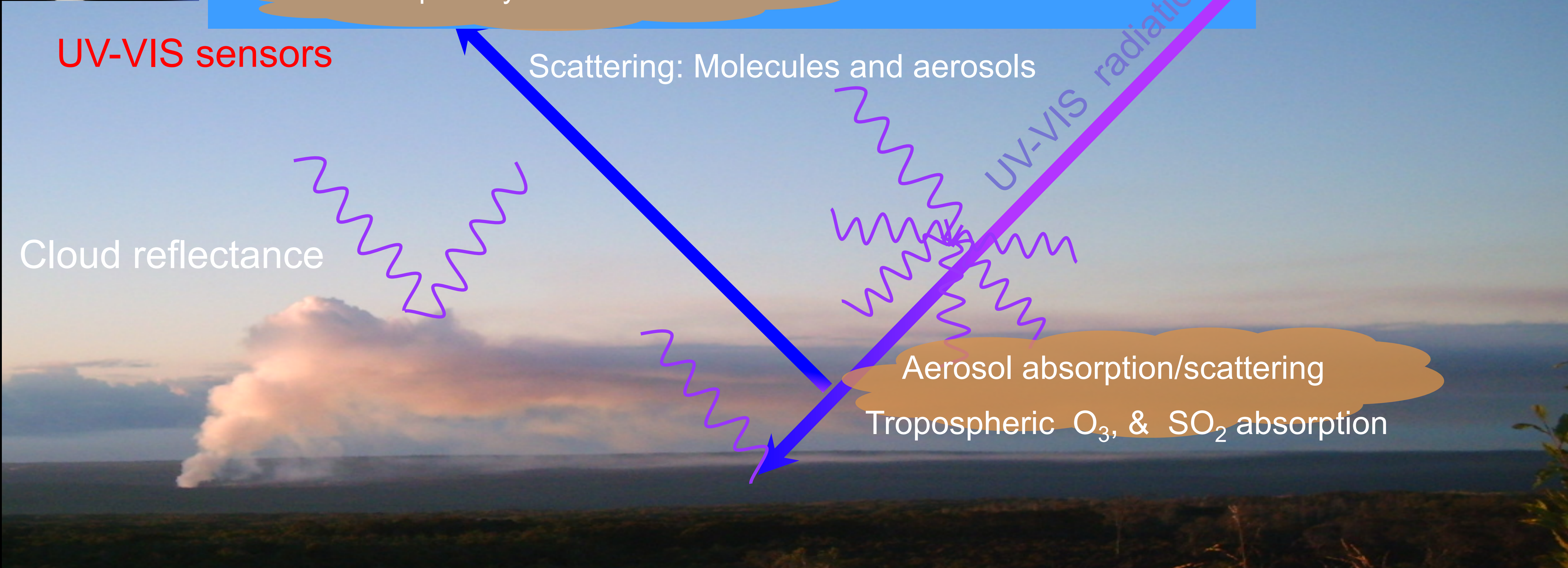
Satellite retrievals of volcanic and anthropogenic SO_2 emissions

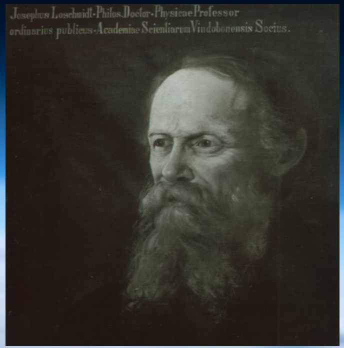


N. Krotkov , P. K. Bhartia, S. Carn, Can Li, Bradford Fisher, Eric Hughes

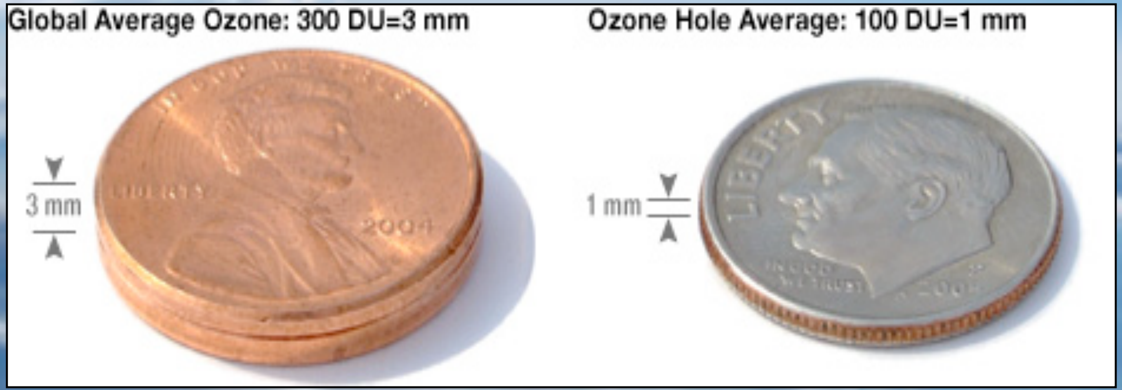


Chapman conference March 19 2018

1 Dobson Unit [DU] $=2.69 \cdot 10^{16}$ molecules/cm^2



Loschmidt's number $=2.69 \cdot 10^{19}$ molecules/cm^3 at STP

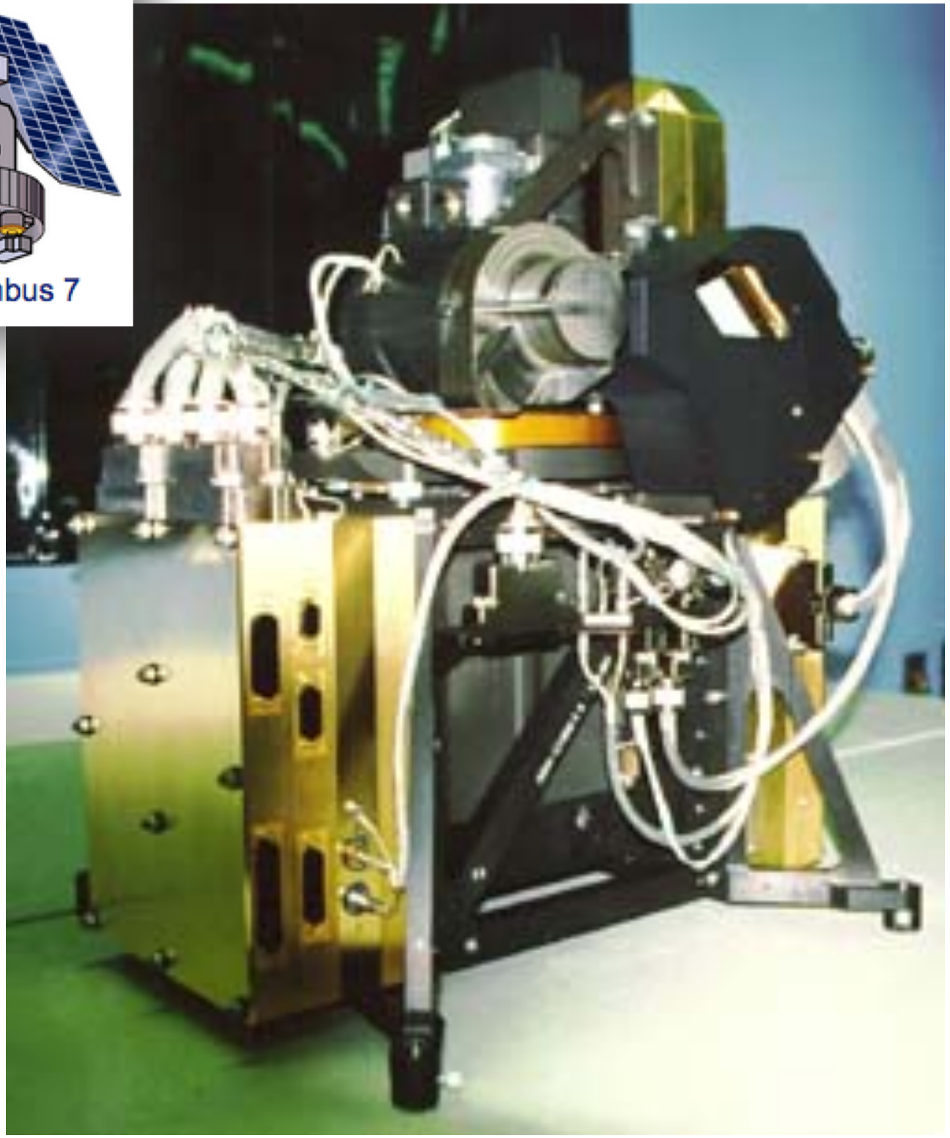


Volcanic SO_2 : PBL to low strat
1 ~ 1000 DU @ 20 km res.
Pollution SO_2 : PBL to free trop
0.1 ~ 10 DU @ 20 km res.

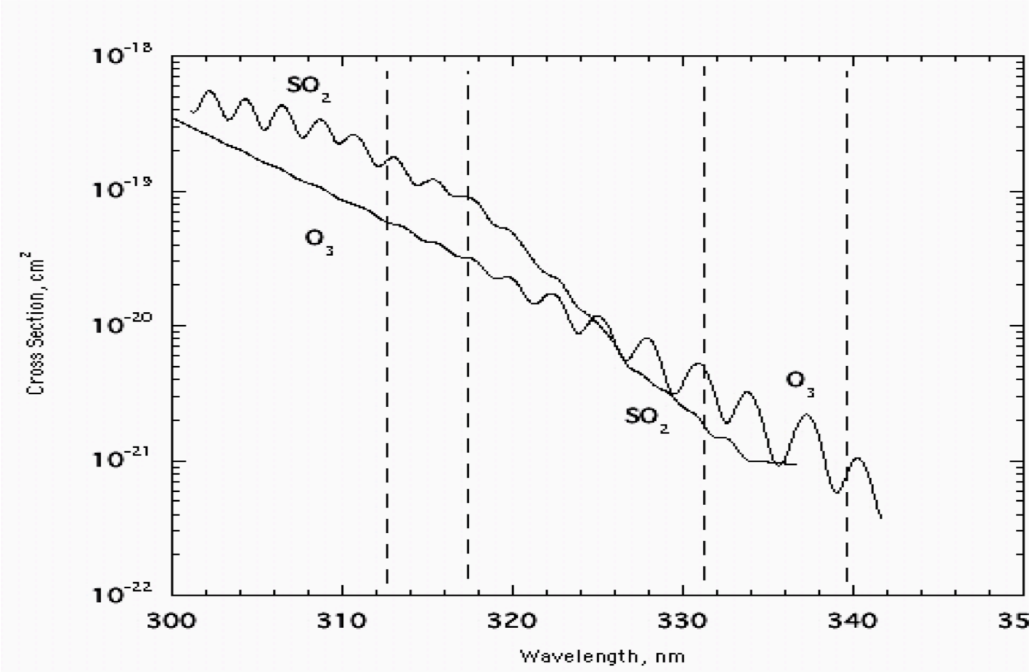
One Dobson Unit is the number of molecules of trace gas that would be required to create a layer of pure gas 0.01 millimeters thick at a temperature of 0 degrees Celsius and a pressure of 1 atmosphere (STP)

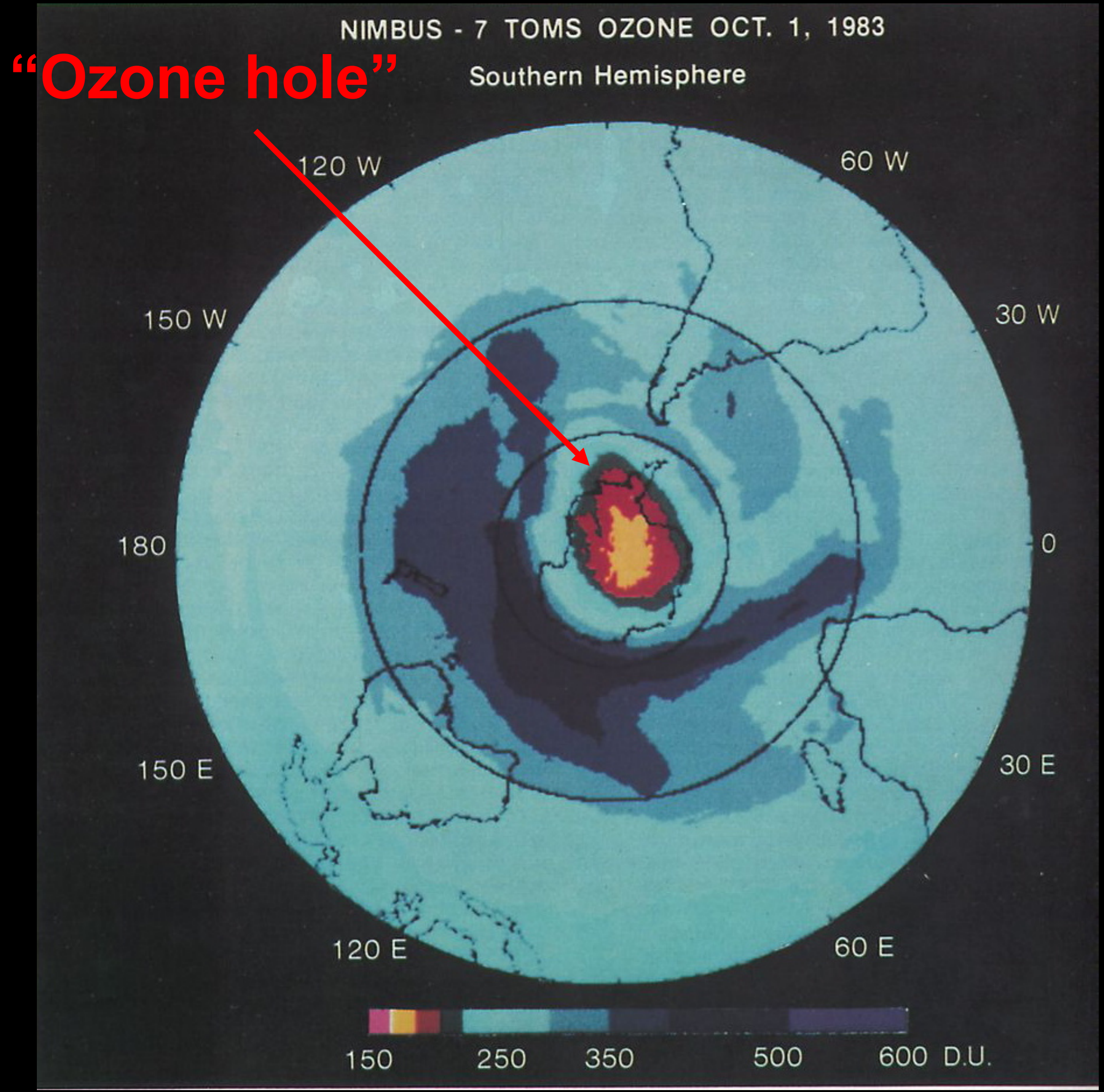
http://ozonewatch.gsfc.nasa.gov/index.html

NASA's Total Ozone (O_3) Mapping spectrometer (TOMS)

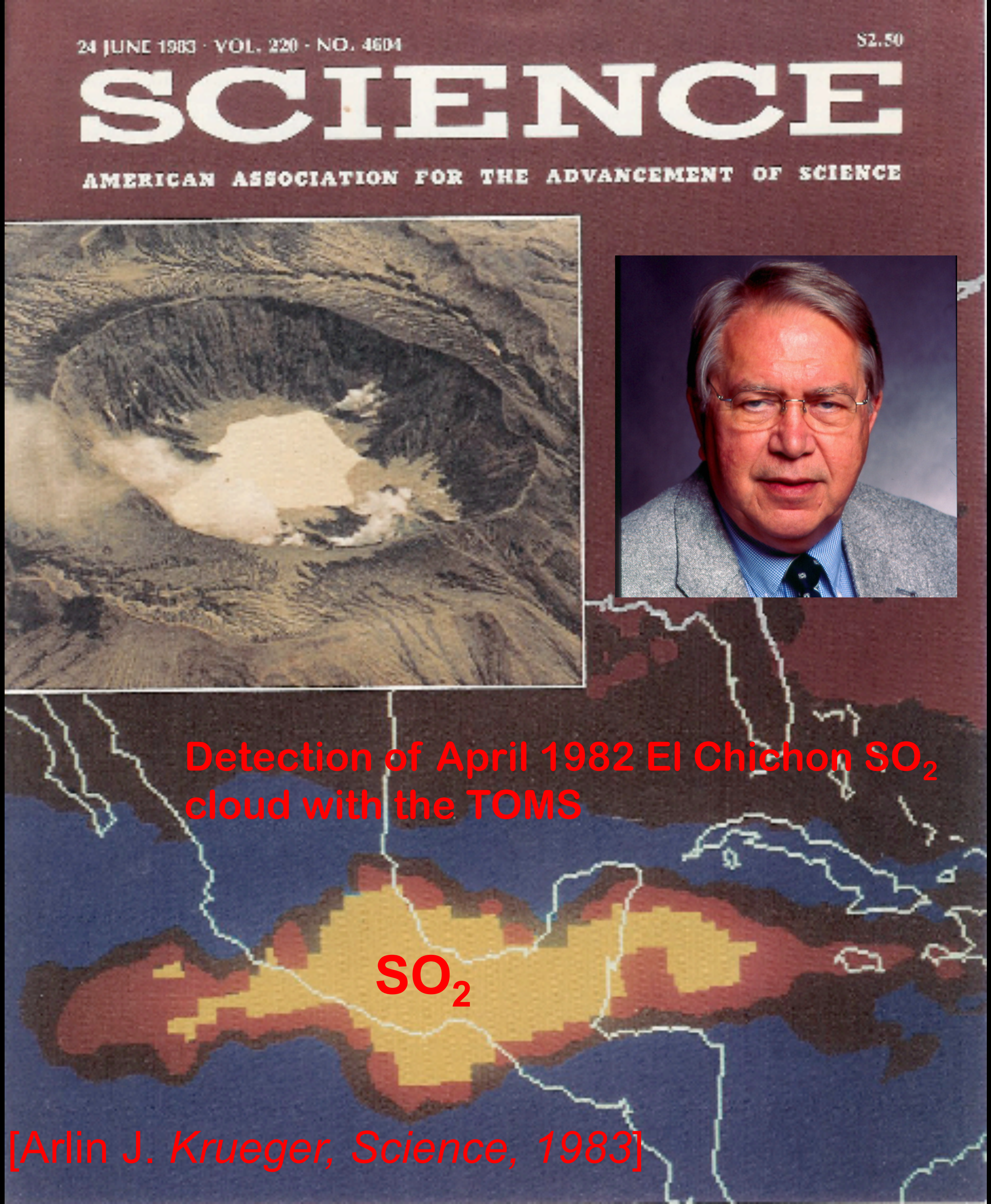


- Designed to measure 2D total column O_3 maps [Dave & C. Mateer 1965]
- Six Discrete near UV wavelengths:
- 312, 317, 325, 331, 340, 360, 380nm
- PMT detector
- Global daily coverage @ 50km x 50km resolution
- Channels optimized for Ozone retrievals
- But also allow volcanic SO_2 retrievals

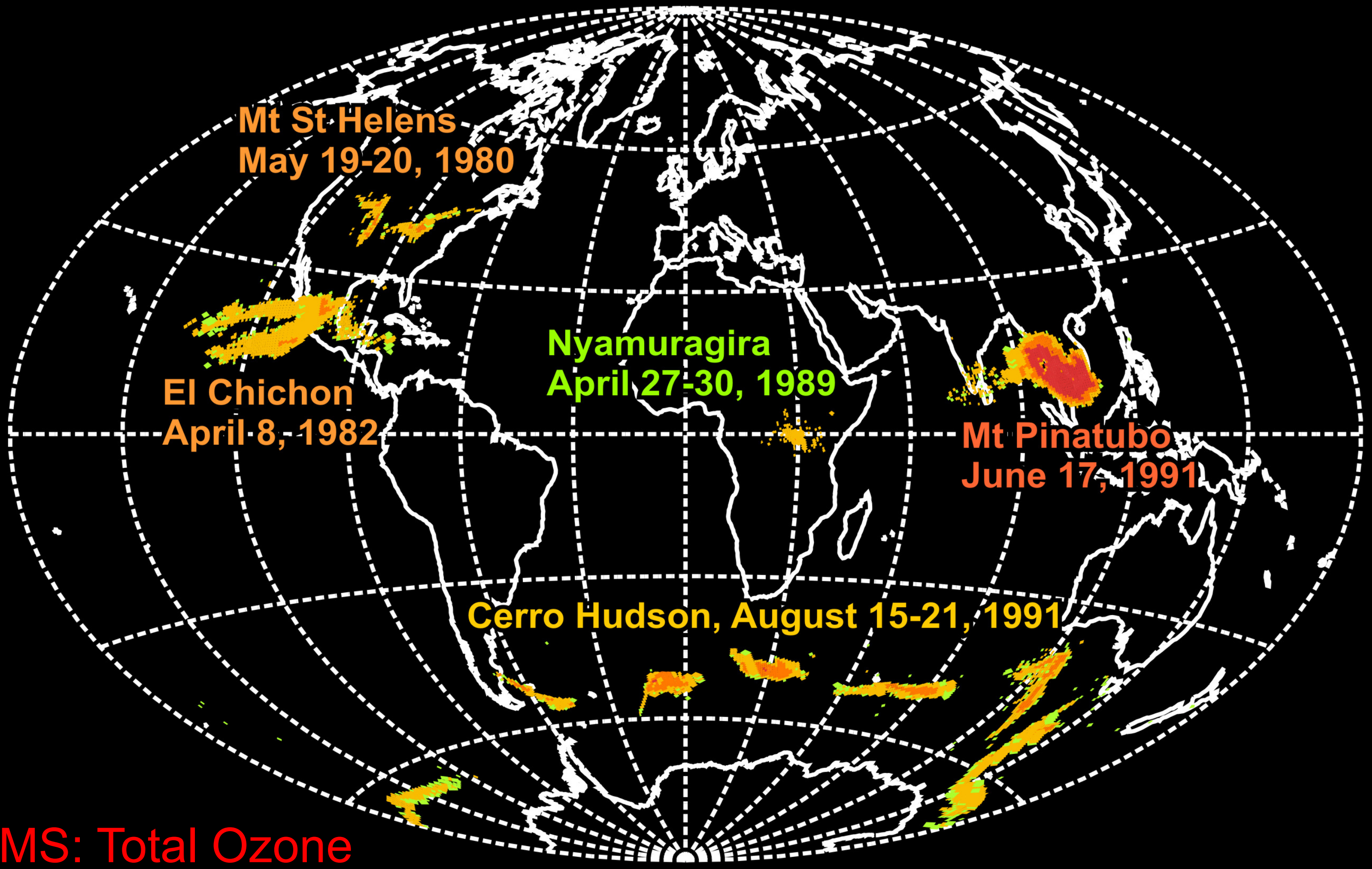




At an August 1985 meeting in Prague, atmospheric scientist Pawan Bhartia presented this satellite-based image that revealed for the first time the size and magnitude of the Antarctic ozone hole.

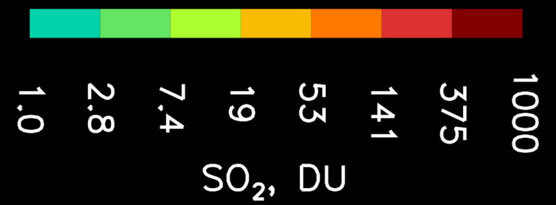


80s-90s: Large Volcanic SO_2 clouds measured by TOMS: http://so2.gsfc.nasa.gov



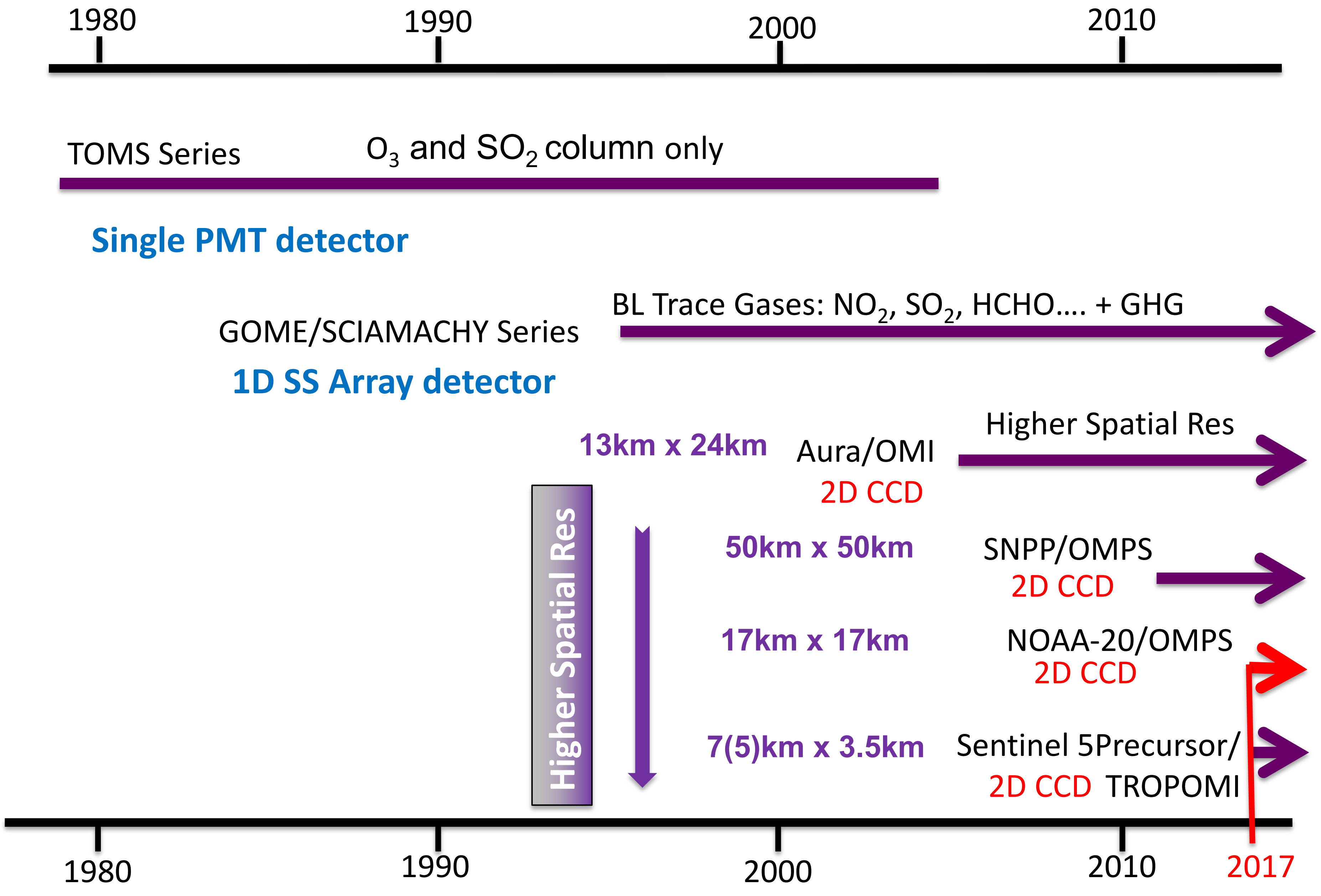
TOMS: Total Ozone Mapping Spectrometer

1978-2005



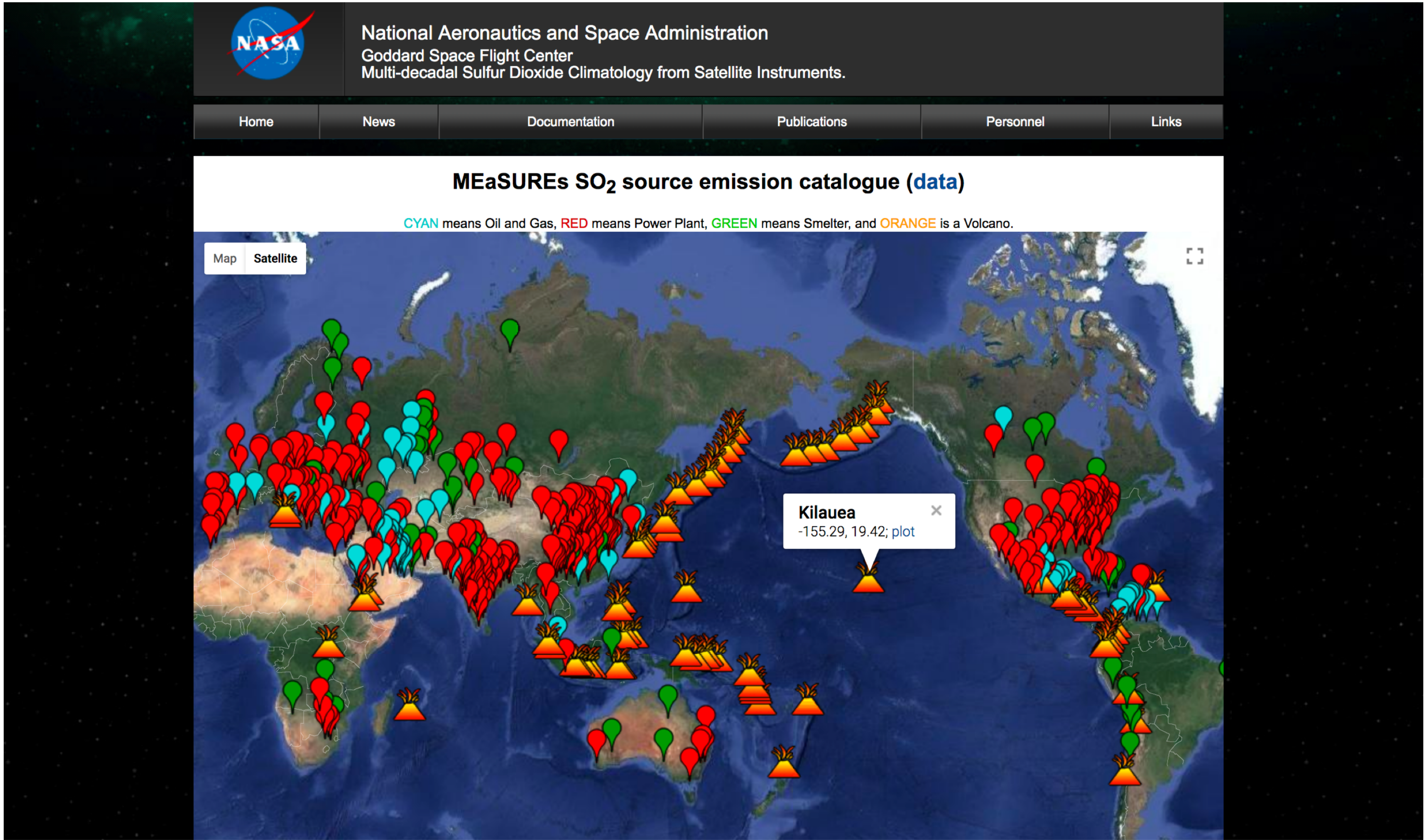
Bluth *et al.*, 1993
Krueger *et al.*, 1995, 2000
Carn *et al.*, 2003

Past & Present UV/VIS Instruments- for Trop Gases



Annual SO_2 emissions and plots (2005-2017) for > 500 point sources are posted on Making Earth System Data Records for Use in Research Environments (MEaSUREs):

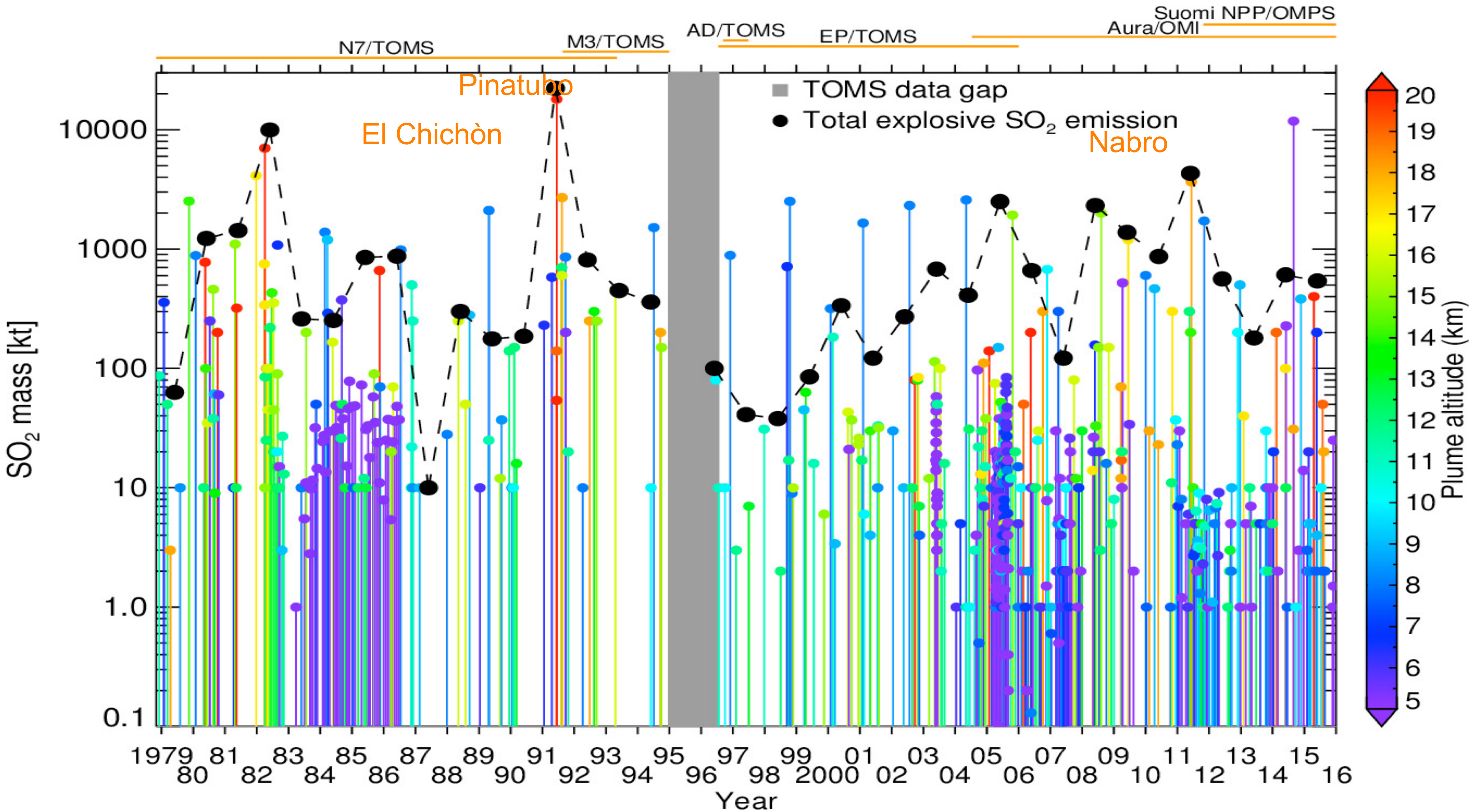
https://SO2.gsfc.nasa.gov/MEaSUREs/



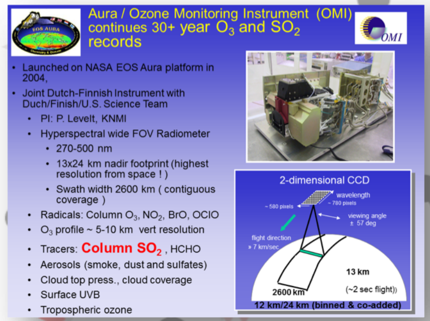
MSVOLSO2L4: UV multi-satellite volcanic SO_2

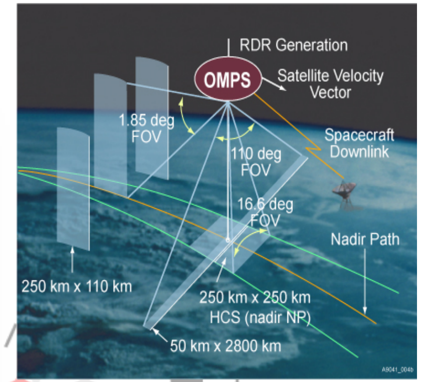
https://SO2.gsfc.nasa.gov/MEaSUREs/

[Bluth et al., 1993; Carn et al., 2003, 2015]



Re-processing with consistent SO_2 algorithms





Heritage TOMS SO_2 and Ash algorithms:

"Krueger – Kerr" algorithm [Krueger et al *JGR* 1995]

O3+ SO_2+Ash RT: [Krotkov, Krueger, Bhartia, *JGR* 1997];

TOMPSPlot: [Colin Seftor, Tom Kelly, Dave Flittner]

UV Ash retrievals [Krotkov et al., GRL 1998, JQRST 1998]

First generation OMI SO_2 algorithms:

BRD [Krotkov et al., 2006]

Linear Fit [Yang et al., 2007]

Next generation OMI & OMPS SO_2 algorithms:

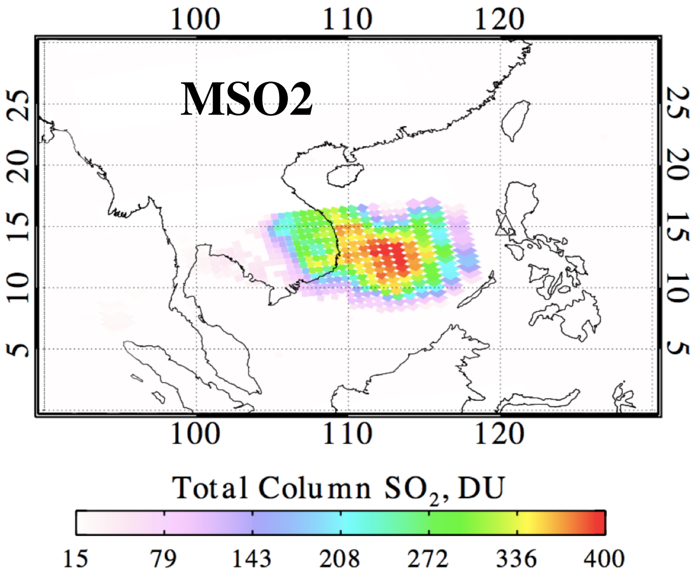
979 81 83 85 87 89 91 93 95 97 99 01 03 05 07 09 11 13 15 17
80 82 84 86 88 90 92 94 96 98 2000 02 04 06 08 10 12 14 16 18

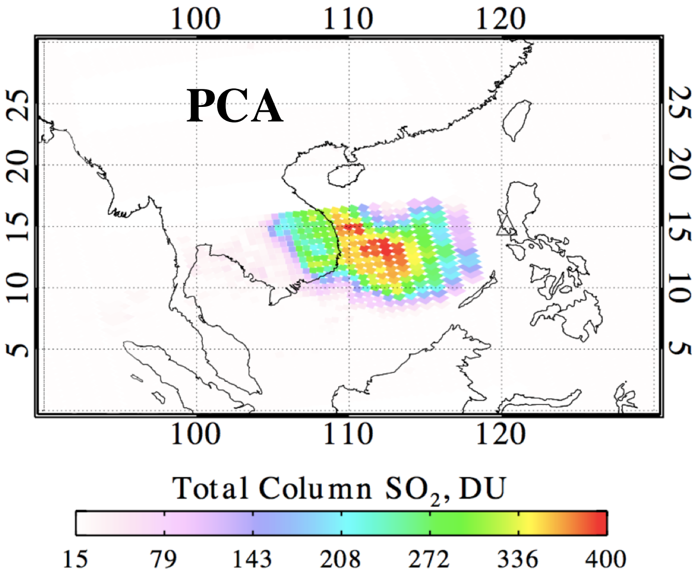
PCA: Principal Component Analysis (PCA) algorithm [Li AMT 2017, Zhang AMT2017]

MSO2: Multi Satellite SO_2 (MSO2) discrete wavelengths algorithm [Fisher 2018]

Re-processing TOMS record applying modern SO_2 algorithms

June 16. 1991 Pinatubo SO_2 cloud





Lower retrievals of Pinatubo SO_2 mass ~12-13 Tg
(compare with Bluth et al., GRL 1993)

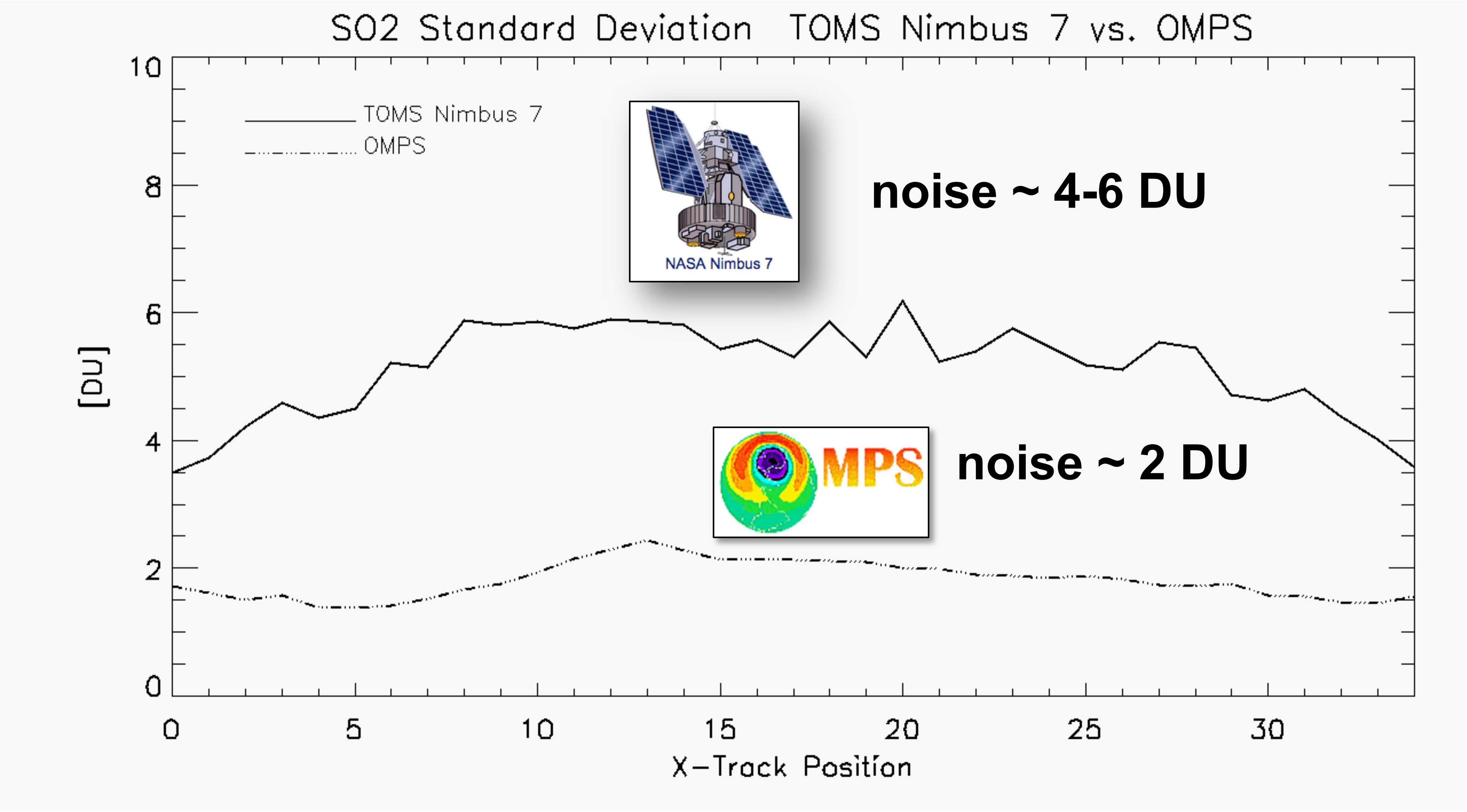
Day 1991	SO_2 Burden (kt) MSO2	Maximum SO_2 (DU) PCA	SO_2 Burden (kt) MSO2	Maximum SO_2 (DU) PCA	Mass Percent Difference (%)
June 16	9755	410	9607	418	+1.5%
June 17	12,134	389	12080	399	+0.4%
June 18	12,011	279	12389	280	-3%
June 19	10,846	173	11636	180	-6%
June 20	12,610	148	13,248	157	-5%
June 21	11763	125	—	—	

[Fisher, et al., in preparation, 2018]

Volcanic aerosols (ash, ice and primary sulfates) could cause plume rise and SO_2 underestimation

- "Pinatubo cloud contained particles of ice, ash, and **[primary] sulfate**" [Guo et al., G^3 2004]
- Ash proxies: positive UV Aerosol Index and negative BTD = BT11 –BT12micron [Prata 1989];
- "Ice and ash … declined very rapidly to values that were <10Mt within 3days" [Guo et al., G^3 2004]
- "The initially detected sulfate mass was 4Mt (equivalent to 3Mt SO_2) and after 5days was 12–16Mt" [Guo et al., G^3 2004]
- Sulfate aerosol interference leads to the SO_2 underestimation.
- Sulfate absorption of IR radiation causes volcanic plume to rise from ~18km to > 25km

Instrumental SO_2 noise reduction (MSO2 algorithm: 4 UV wavelengths)



MS_SO2 algorithm applied to OMPS data reduces background SO_2 noise

Algorithmic noise reduction: PCA algorithm applied to Hyperspectral UV OMI/OMPS reduces noise to ~0.3-0.5 DU

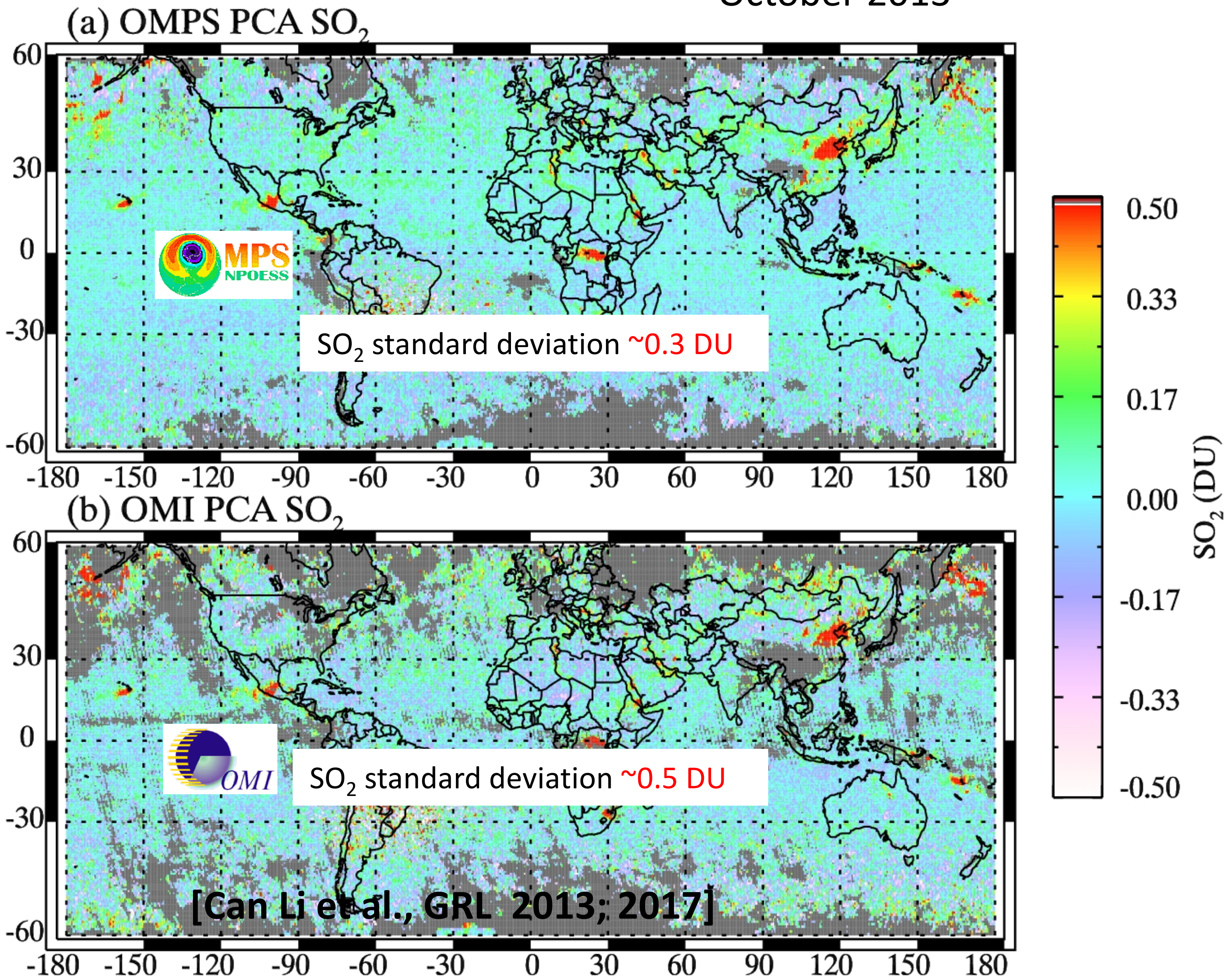
- ***Low bias, low noise*** (OMPS standard deviation ~0.3 DU for clear sky IFOV over equatorial Pacific assuming mid-lat PBL profiles (~0.1 DU or less if mid-trop profile and tropical O_3 amount used for Jacobians), for OMI ~0.5 DU)

- ***Computation efficiency*** (CPU time ~20s/OMPS orbit. with simple AMF)

- ***No soft calibration is necessary***
- ***Less affected by clouds/aerosols than discrete wavelengths algorithms***

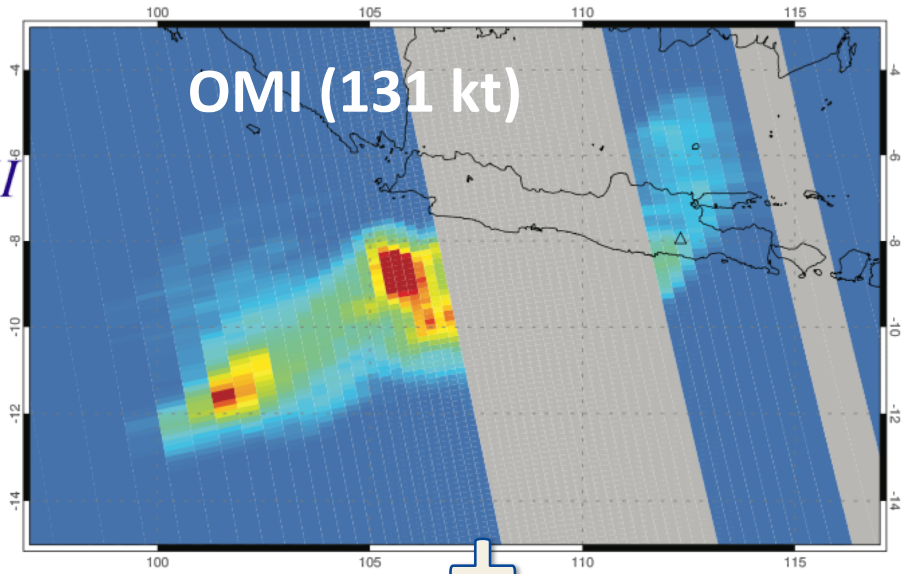
- ***Max data continuity*** (best agreement between OMI and OMPS)

October 2013



[Can Li et al., GRL 2013; 2017]

Consistent OMI/OMPS PCA SO_2 retrievals
2014 Kelut eruption



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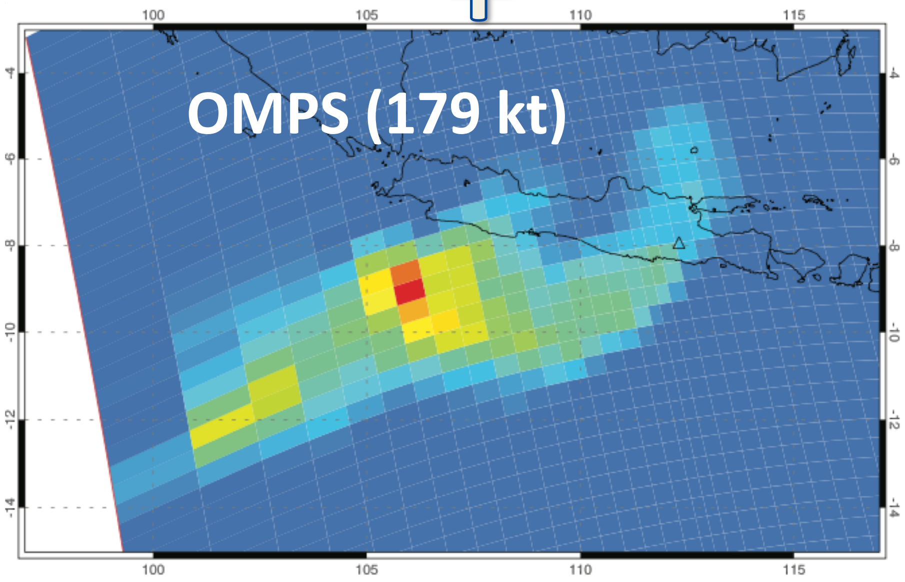

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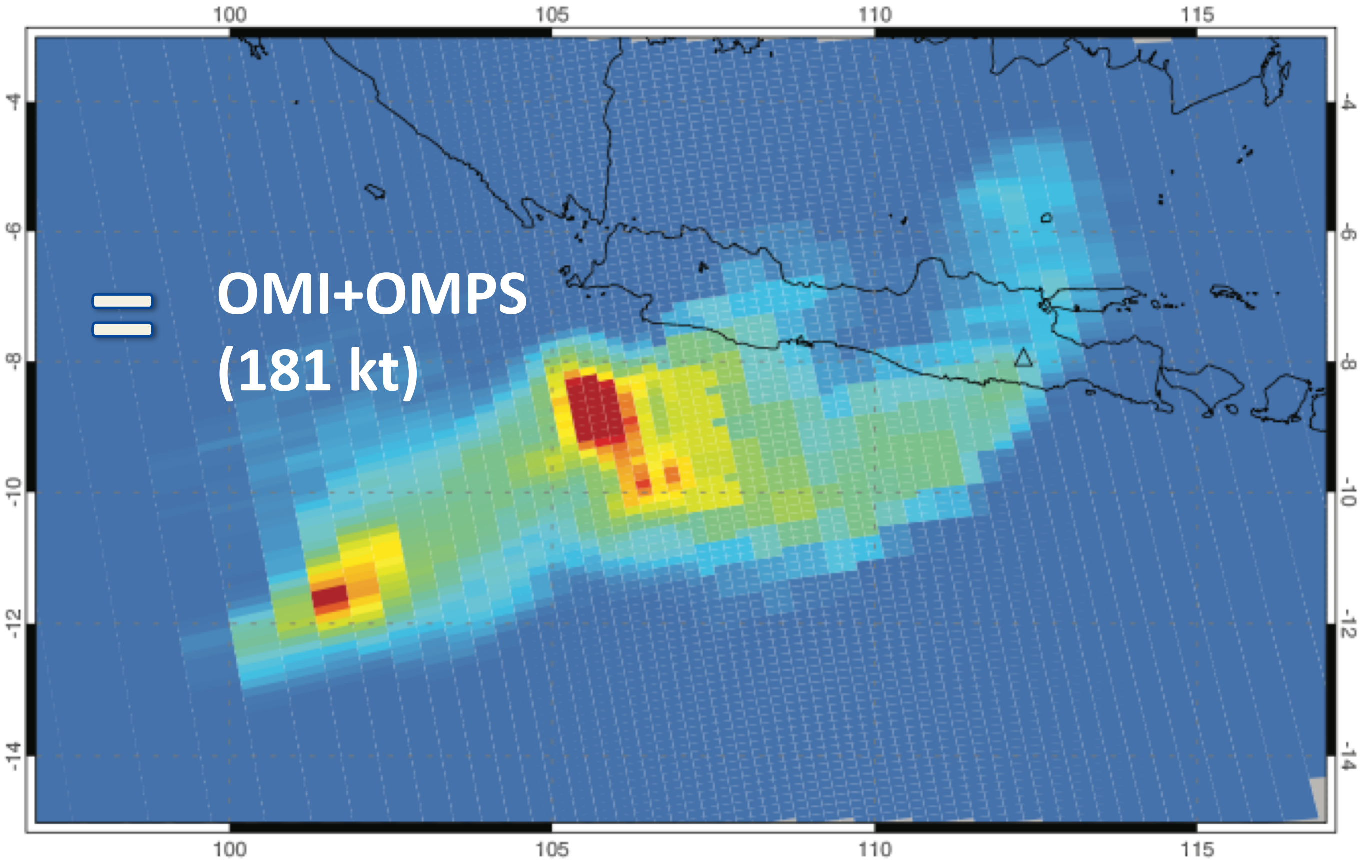
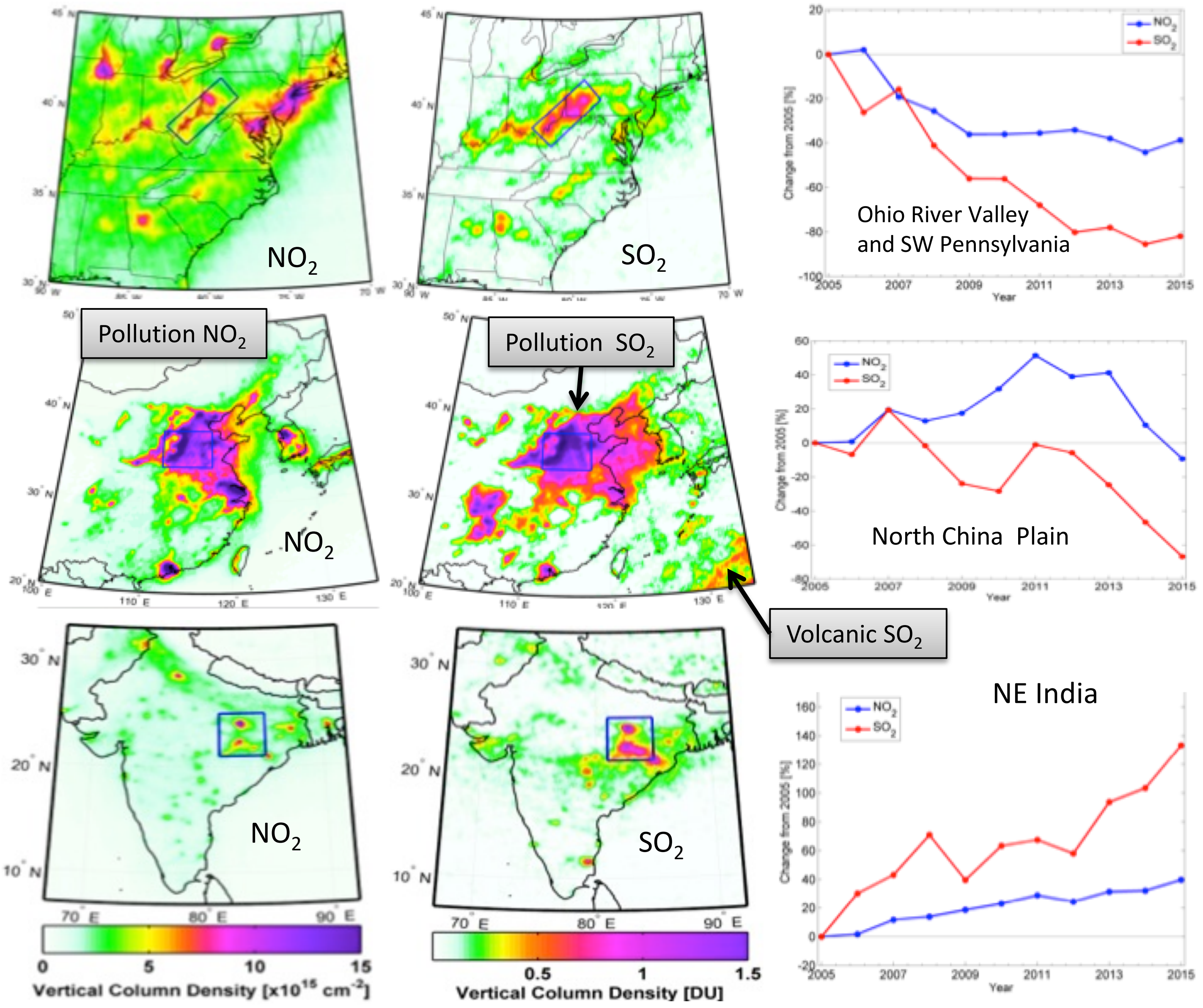


- ✓ **Merged OMI+OMPS provides full coverage and fine spatial detail**
- ✓ **Agrees with OMPS only SO_2 mass to within 3%**

Li, C., Krotkov, N. A., Carn, S., Zhang, Y., Spurr, R. J. D., and Joiner, J.: Atmos. Meas. Tech., 10, 445-458, doi:10.5194/amt-10-445-2017

OMI measured Complex Regional Trends in regional NO_2 and SO_2 Pollution



Over Eastern US NO_2 and SO_2 pollution have decreased by 40% & 80%, "*thanks in large part to new rules to protect our air".* US Environmental Protection Agency's (EPA) uses OMI NO_2 in Air Trends Report (https://gispub.epa.gov/air/trendsreport/2016)

NO_2 pollution over NE China has declined by 50% since its peak in 2011 and is now at the same level as in 2005. SO_2 pollution has declined by 80% since its peak in 2007 and is now 60% less than in 2005.

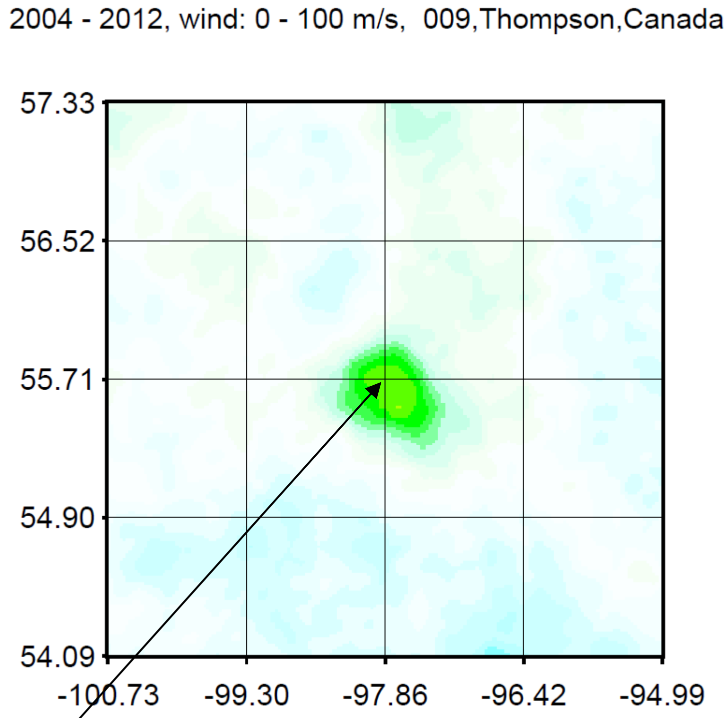
Over NE India where many new coal-fired power plants were built, NO_2 pollution increased by ~40%, while SO_2 pollution increased by 140%

Krotkov et al., ACP 2016

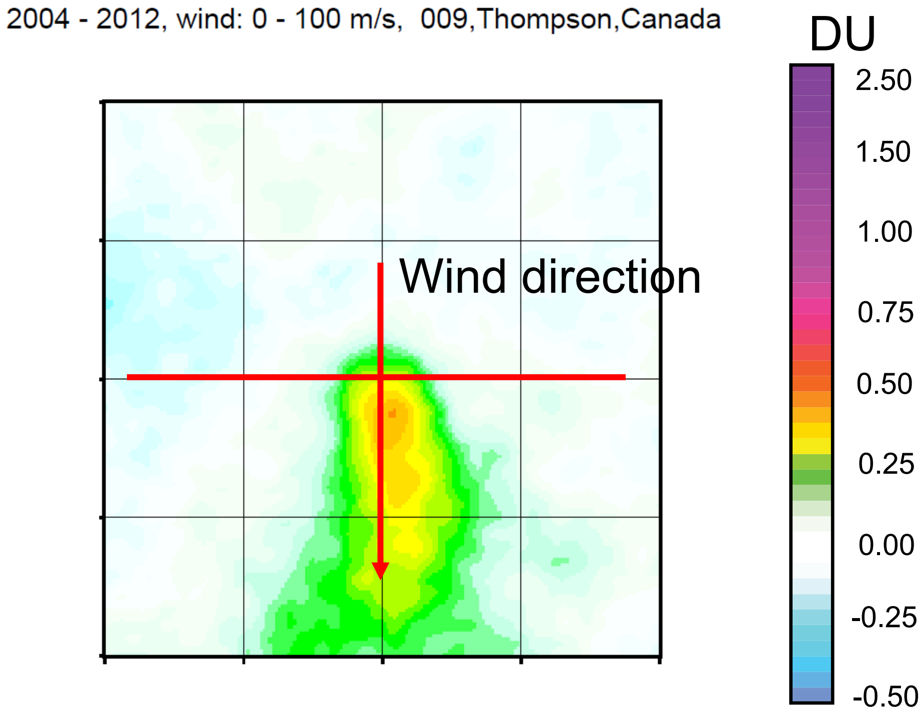
Merging OMI/OMPS SO_2 data and wind data allows deriving SO_2 emissions for point sources

Environment Canada Environnement Canada

Mean SO_2 from OMI near Thompson, Manitoba (55N, 98 W).



The same data after rotation of all pixels around the source in a upwind-downwind direction.



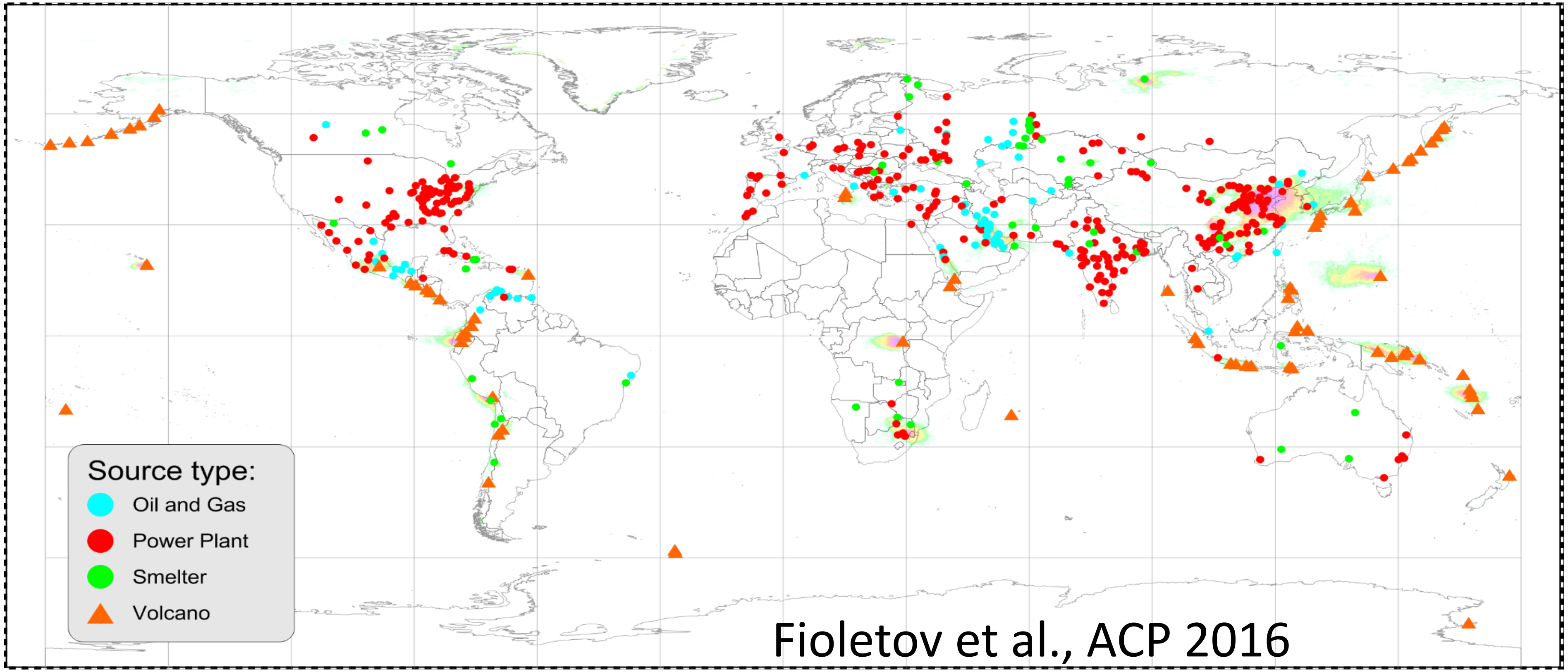
Downwind decay of pollutants can be studied using a rotation scheme in which the locations of all observation are adjusted so that the have a common wind-direction [Fioletov et al., 2015]

Environment Canada Environnement Canada

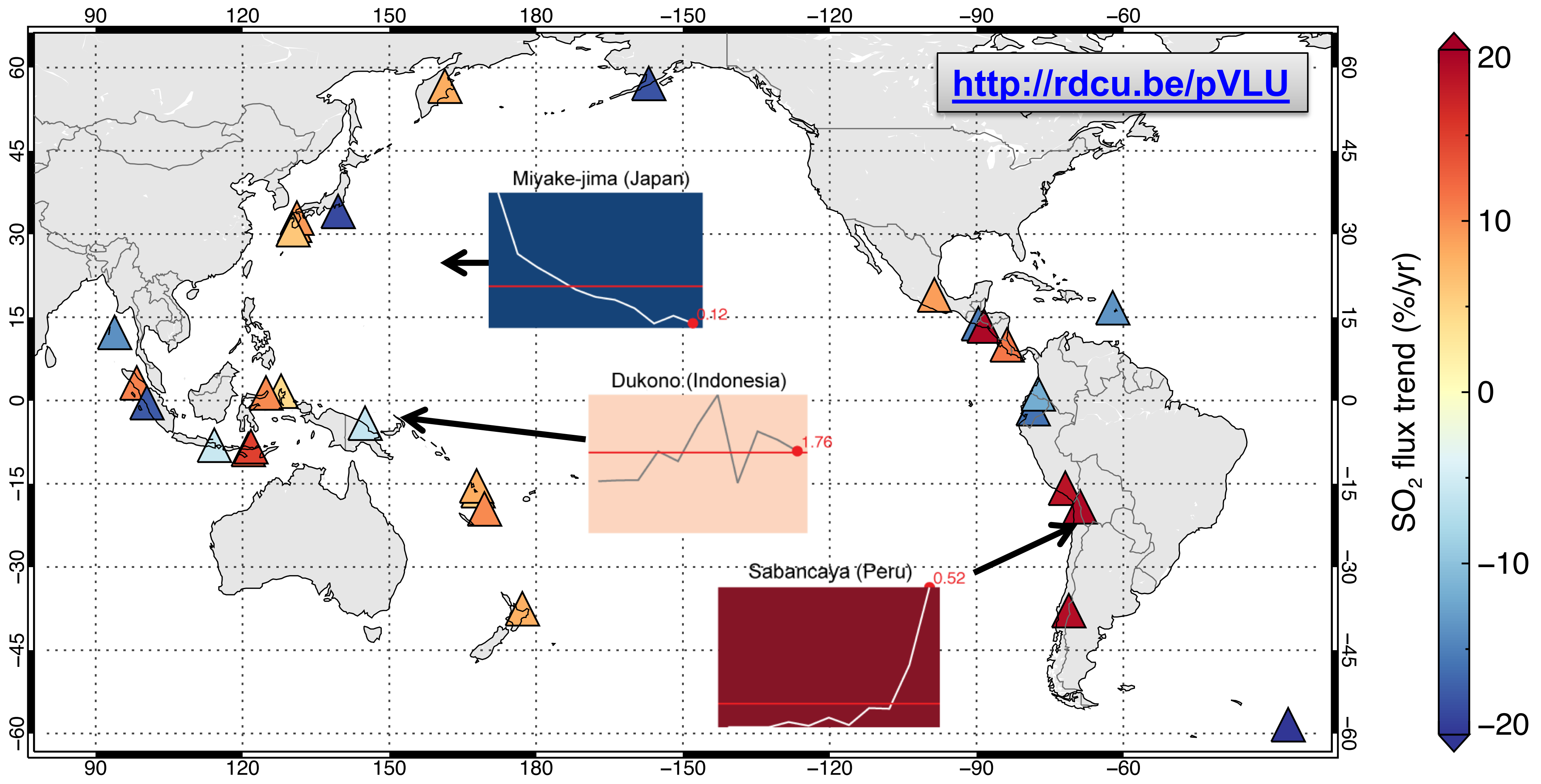
Multi-Satellite Air Quality SO2 Database

https://disc.gsfc.nasa.gov/datasets/MSAQSO2L4_V1/summary?keywords=aura

- Determine “hotspots” as areas where mean values are above 0.1 DU and over ~5 sigma level
- Check “hotspots” against databases of power plants, smelters, oil and gas refineries, other industrial sources, and volcanoes
- Updated version released in 2018: >500 sites including 2017 data with annual emissions from 30 to 5000 kt.
- ***The catalogue includes site locations, source types and annual emission estimates for 2005-2017***



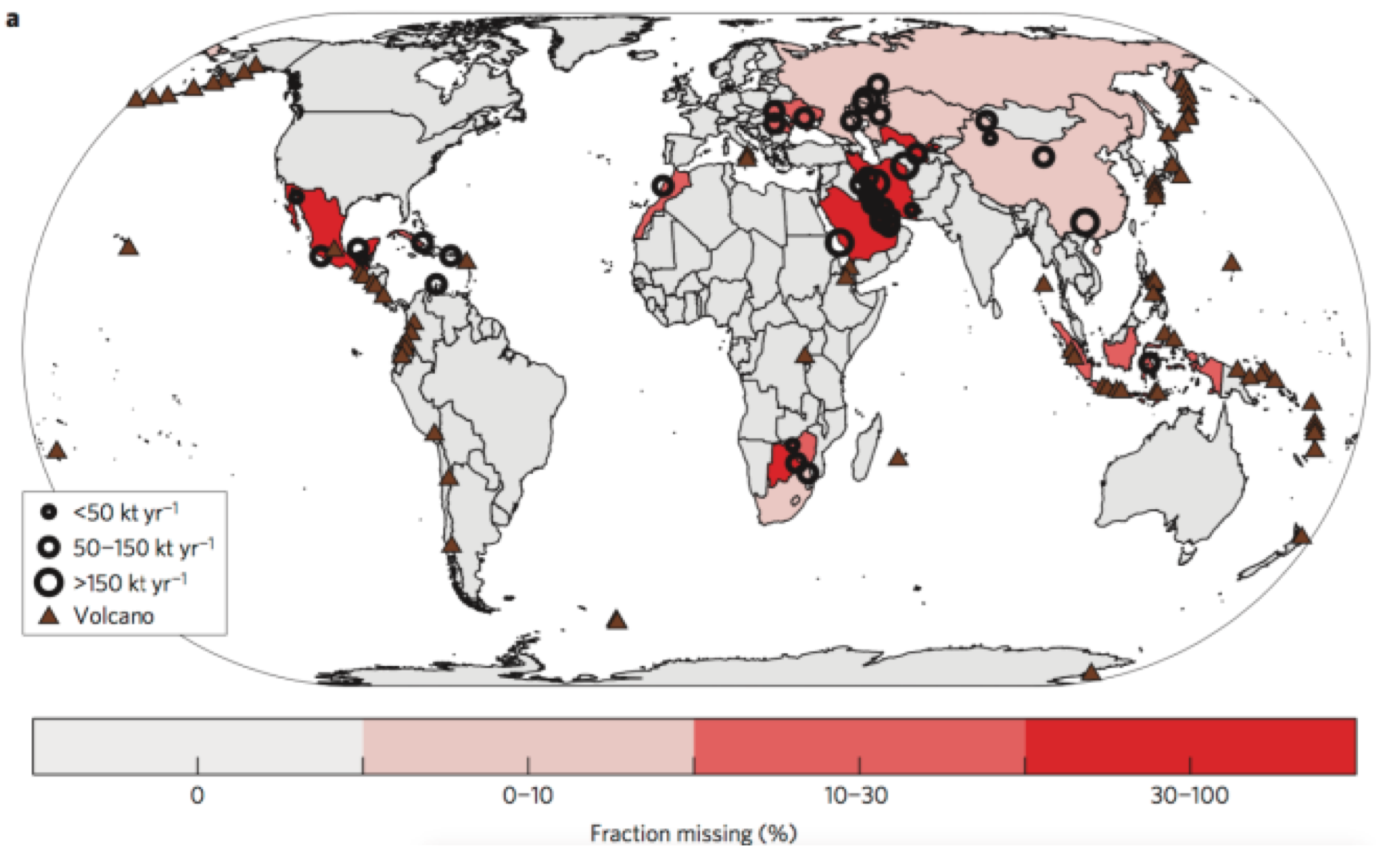
NASA Satellite Data Reveal Global Trends in Volcanic SO_2 Emissions



A decade of NASA Aura/OMI volcanic SO_2 measurements (2005-2015) has been used to create the first *global* volcanic emissions inventory, providing new insights into the variability and trends in volcanic degassing. [Carn et al., Sci. Rep. 2017]

Environment Canada Environnement Canada

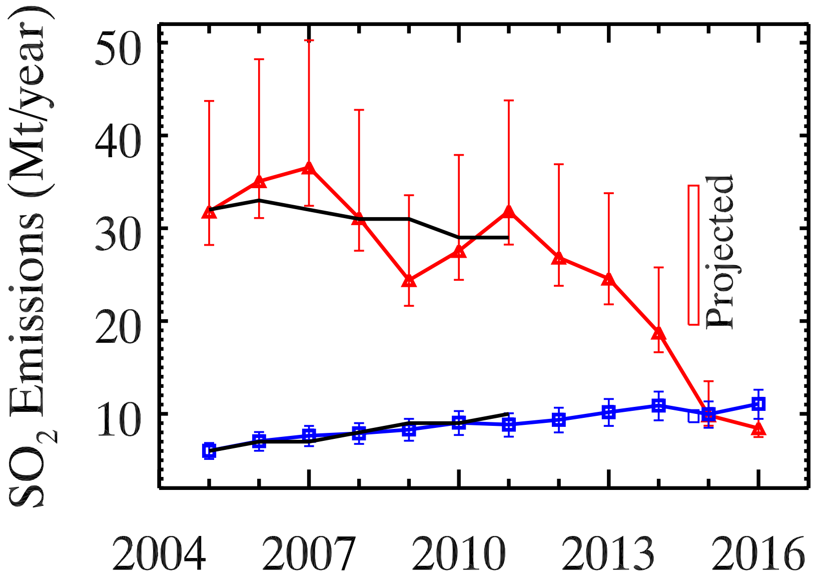
OMI detects "missing" SO_2 sources from traditional "bottom-up" inventories

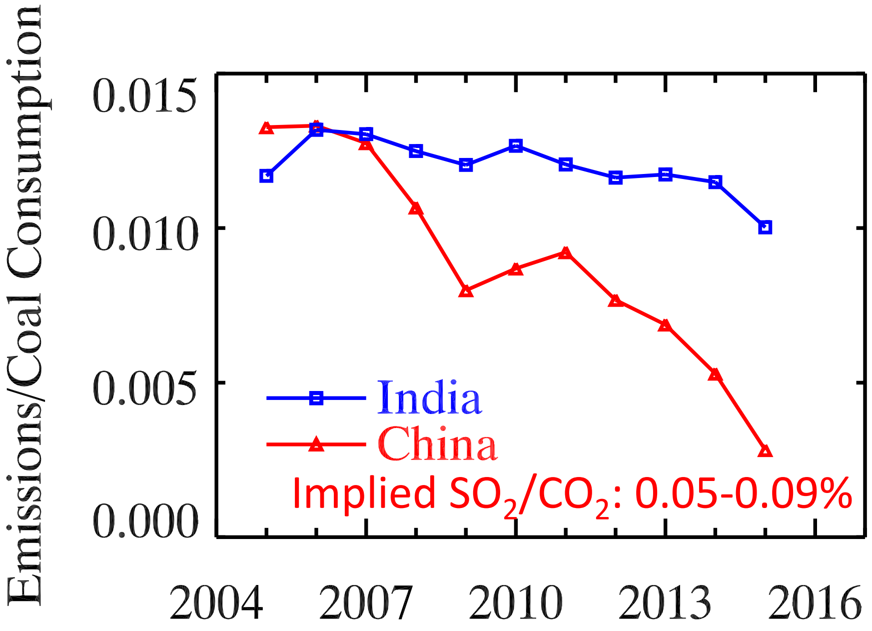


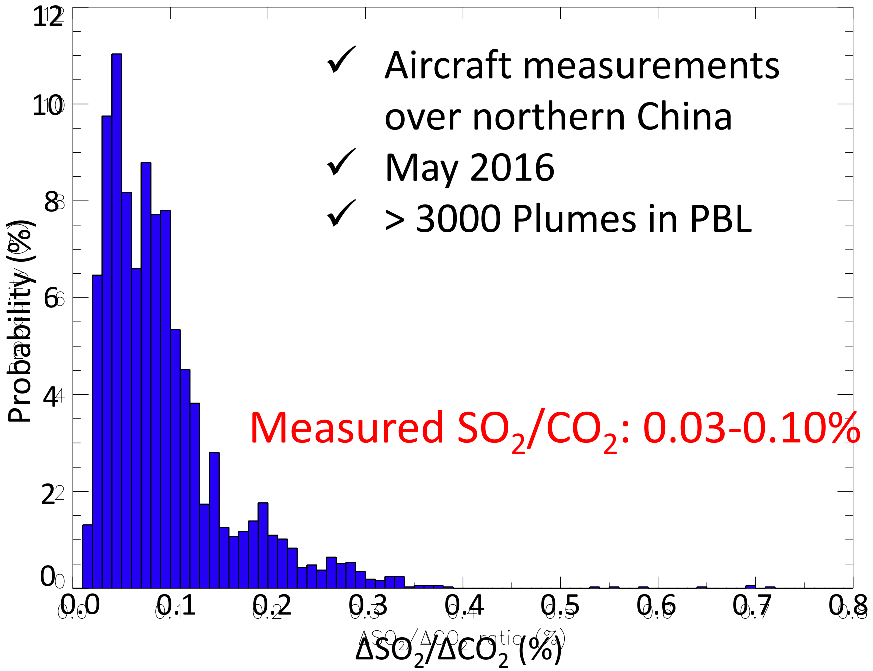
- An independent "top-down" global SO_2 emission inventory
- Annual emissions quantified for ~500 large sources, ~40 missing or unreported in "bottom-up" inventories, or ~6-12% of the total anthropogenic sources;
- Emissions quantified for 75 volcanoes – large differences between OMI measurements and the Aerocom database.

[*McLinden et al.*, NG 2016];

A New Top Emitter of Anthropogenic SO_2?



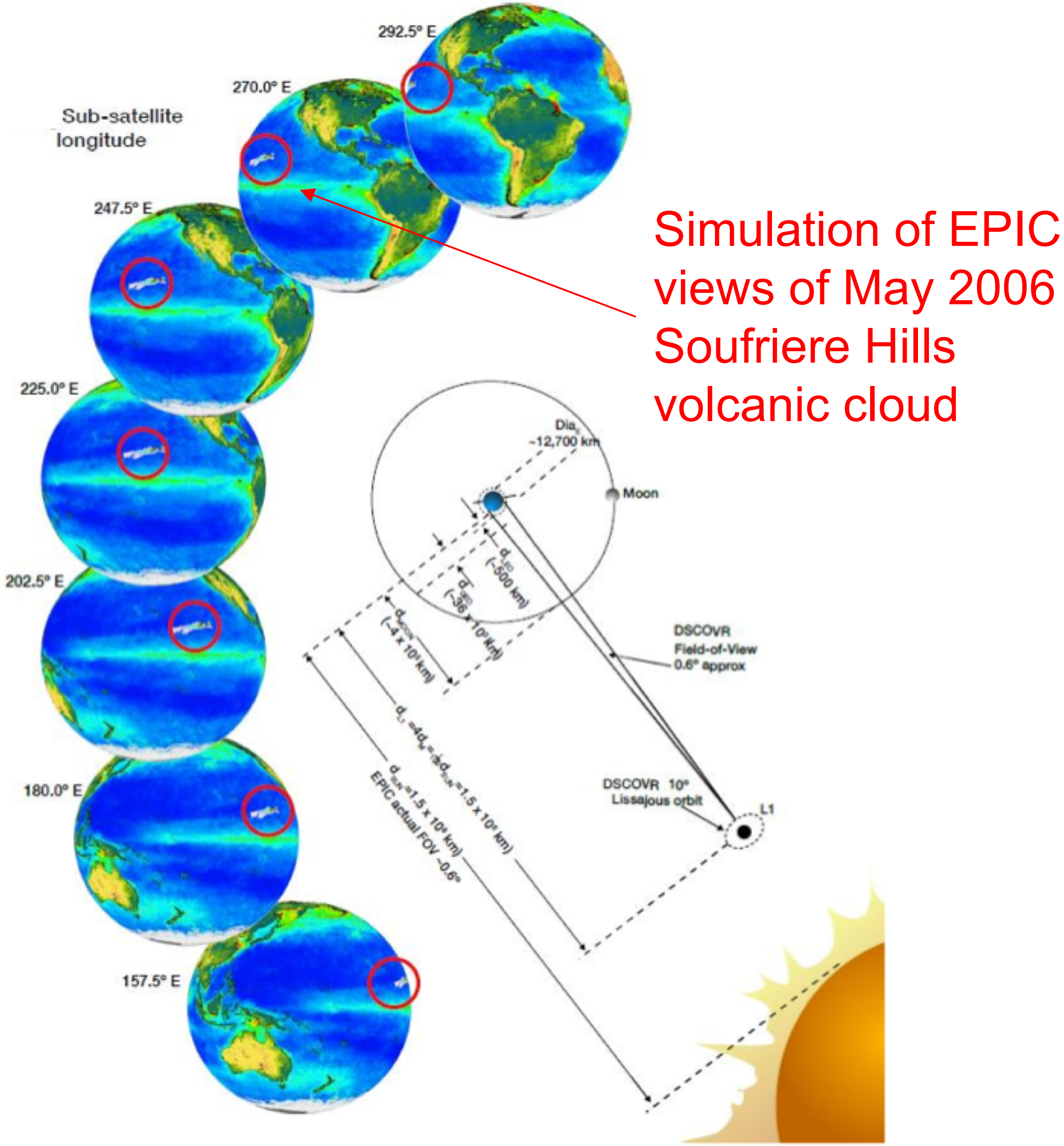


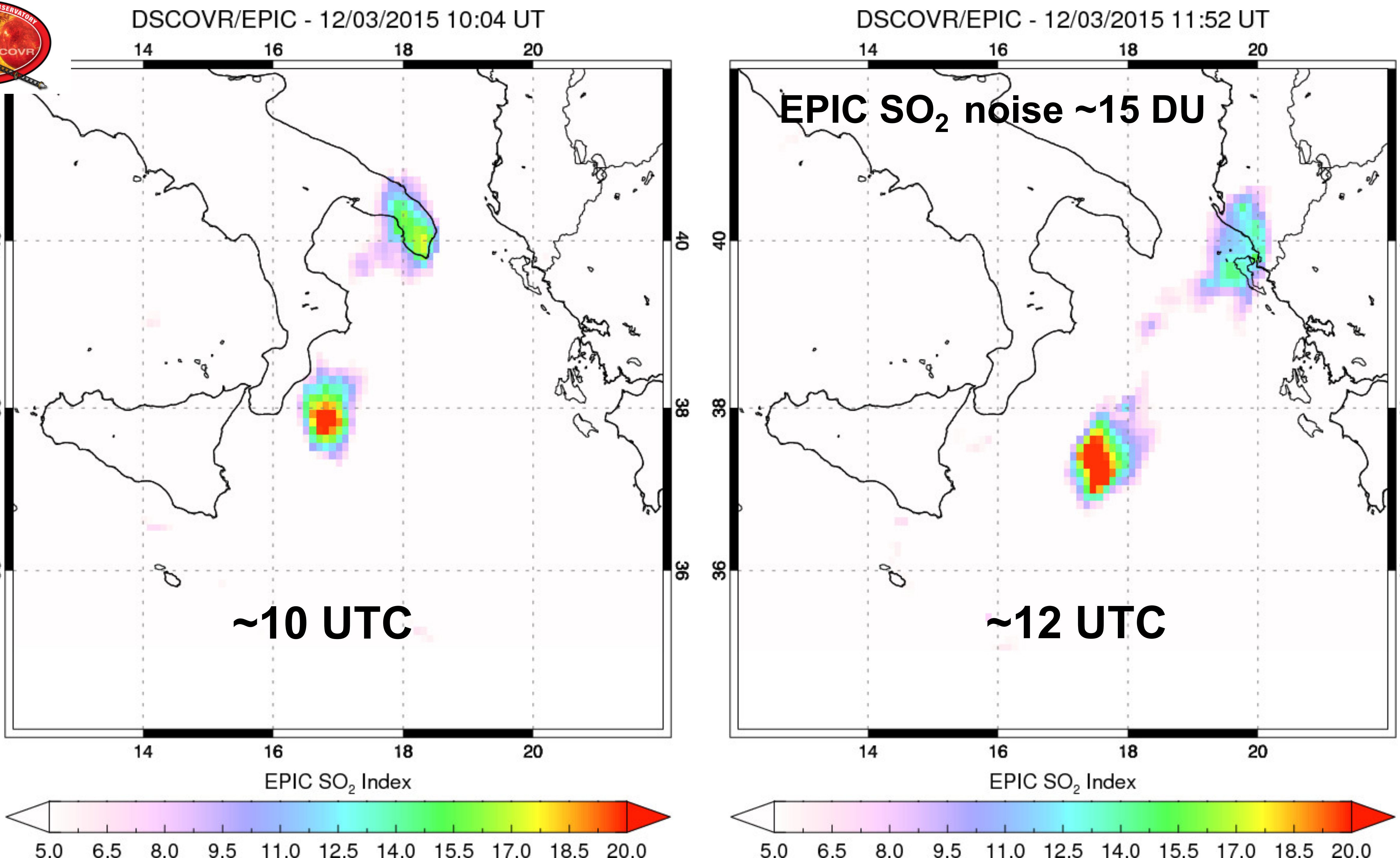


- Estimated emissions for 2016 (after correction for the undetected part by OMI):
  - <u>9.5-12.6</u> Mt/year for India
  - <u>7.5-11.6</u> Mt/year for China
- Aggressive emission control in China since 2007;
- Continued lack of emission control in India;
- <u>NOT</u> projected by bottom-up inventories.
- Evidence from aircraft campaign.

Deep Space Climate Observatory (DSCOVR) at L_1 since 2015-

- Earth Polychromatic Imaging Camera (EPIC)
  - ~68-100 min temporal resolution
  - Spatial resolution similar to OMI at sub-satellite point (~20 km)
  - Unique vantage point for volcanic SO_2 and ash observations



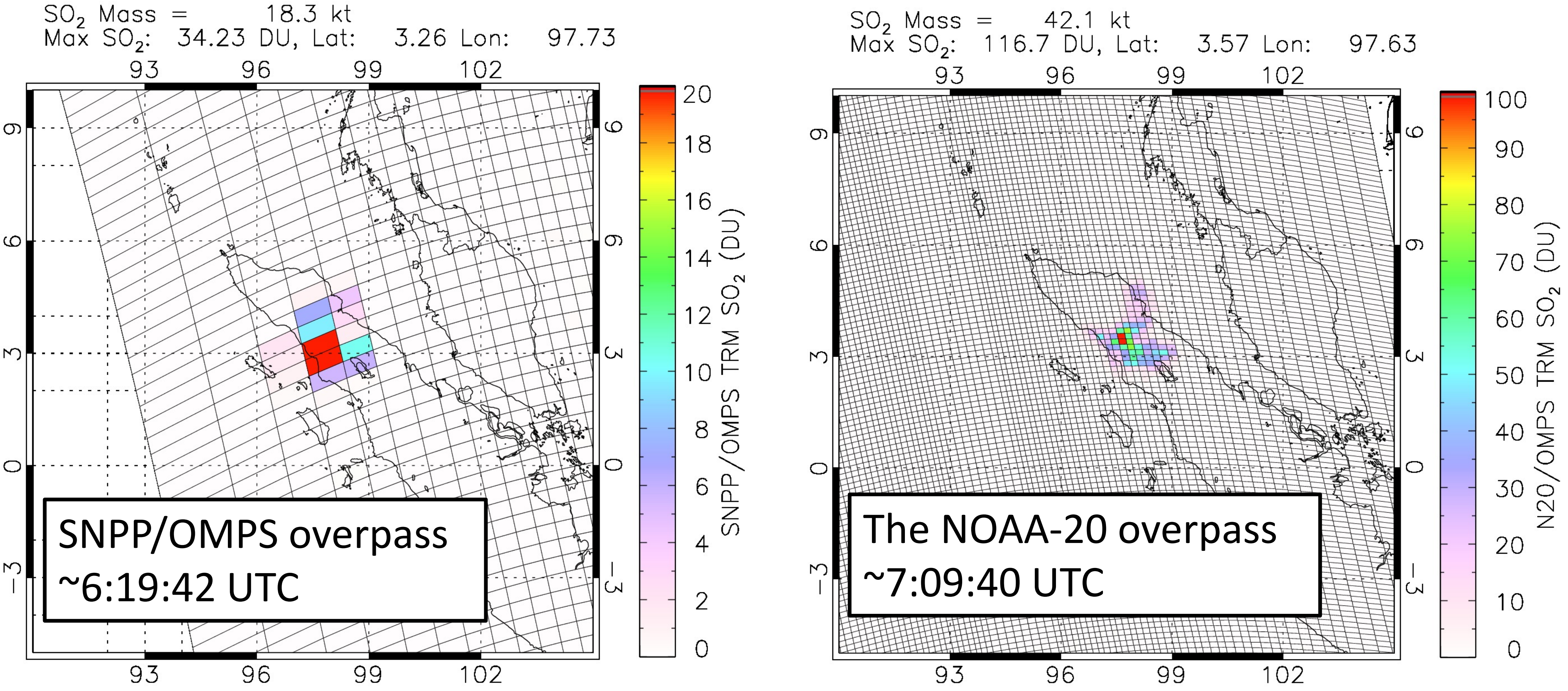

DSCOVR/EPIC - 12/03/2015 10:04 UT
DSCOVR/EPIC - 12/03/2015 11:52 UT
EPIC SO$_2$ noise ~15 DU
~10 UTC
~12 UTC
14 16 18 20
40 38 36
EPIC SO$_2$ Index
5.0 6.5 8.0 9.5 11.0 12.5 14.0 15.5 17.0 18.5 20.0

Ten volcanic eruptions detected by EPIC (2015 -)

Volcano	Eruption Time (UTC)	1st EPIC Image (UTC)	EPIC exposures	Max SO_2 Column (DU)
2015				
Etna (Italy)	Dec 3, 02:30	Dec 3, 08:16	5 (12/3-4)	46
2016				
Bromo (Indonesia)	Jan 1, 12:00	Jan 2, 04:09	3	38
Pavlof (USA)	Mar 27, 23:53	Mar 28, 21:54	2	25
Aso-san (Japan)	Oct 7, 16:46	Oct 8, 00:55	4	33
2017				
Bogoslof (USA)	Mar 8, 07:36	Mar 8, 20:15	3	29
Kambalny (Russia)	Mar 24, 21:20	Mar 25, 02:43	5-6 (3/25-6)	18
Bogoslof (USA)	**May 28, 22:16**	**May 29, 01:23**	**4**	**38**
Tinakula (Solomon Is)	**Oct 20, 19:20**	**Oct 20, 20:53**	**5**	**68**
Agung (Indonesia)	Nov 25, 09:30	Nov 27, 03:53	1	28
Sinabung (Indonesia)	**2018**		4	TBD

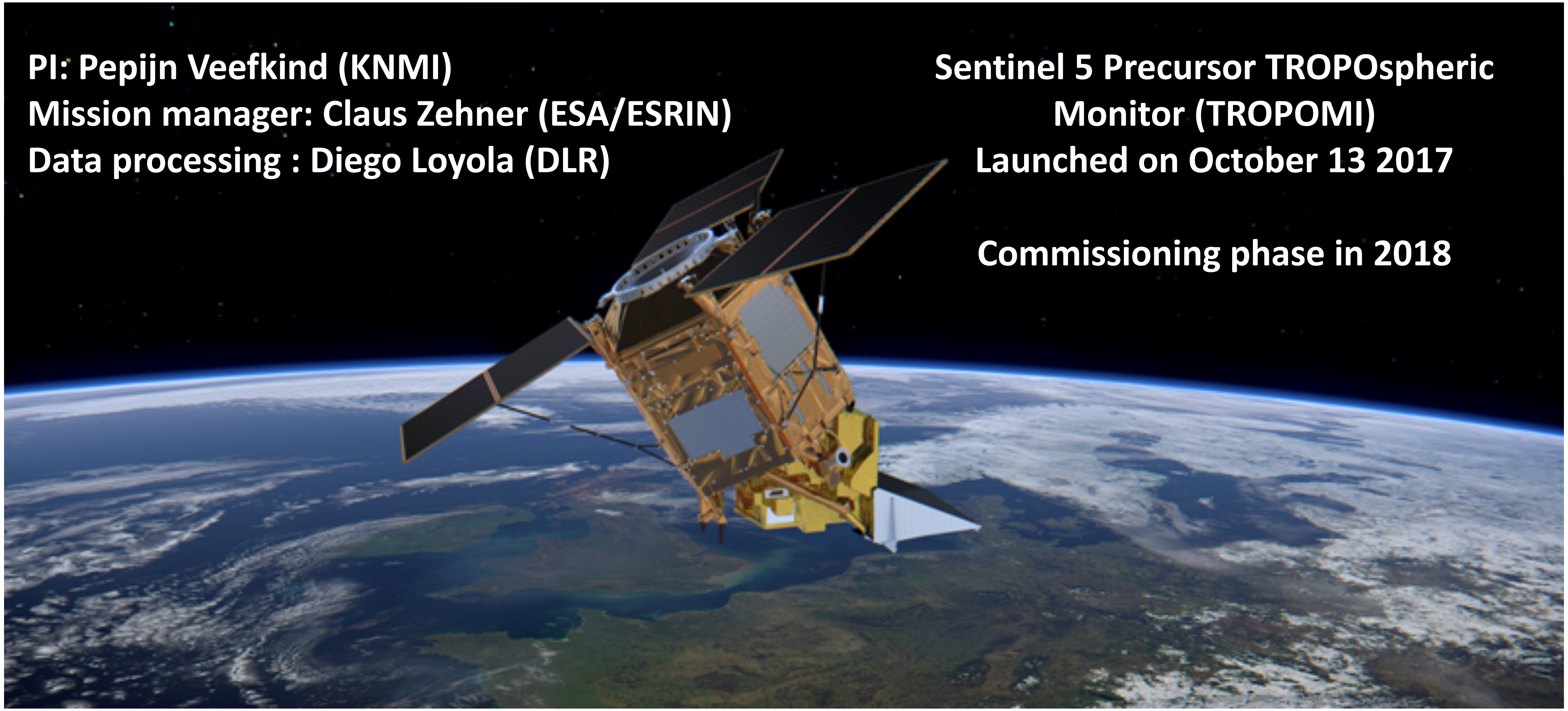
Carn et al, in prep 2018

High resolution SO_2 Retrievals from JPSS-1/NOAA-20 OMPS Reveal Greater Details of Volcanic Plume



Sinabung volcanic SO_2 cloud measured on February 19 2018

Sentinel 5 Precursor

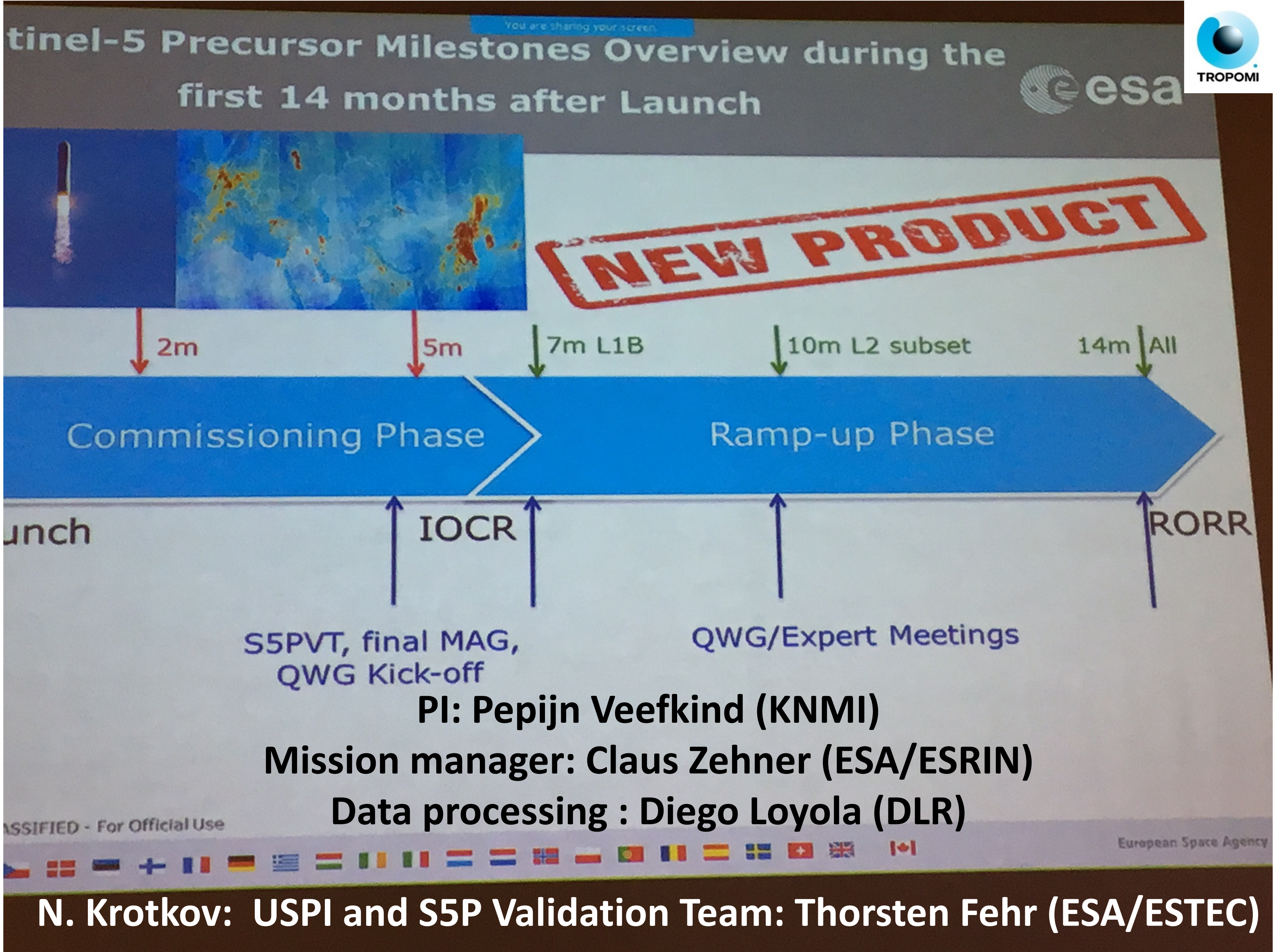


PI: Pepijn Veefkind (KNMI)
Mission manager: Claus Zehner (ESA/ESRIN)
Data processing : Diego Loyola (DLR)

Sentinel 5 Precursor TROPOspheric Monitor (TROPOMI)
Launched on October 13 2017

Commissioning phase in 2018

- **High ground resolution: 3.5km by 7 (5) km**
- High Signal- to - Noise (S/N)
- O_3(column and profile),SO_2, NO_2, HCHO, plus CO and CH_4, UV Aerosol Index
- TROPOMI measurements will be assimilated into Copernicus Atmospheric Measurement System (CAMS) for operational air quality forecasts



PI: Pepijn Veefkind (KNMI)

Mission manager: Claus Zehner (ESA/ESRIN)

Data processing : Diego Loyola (DLR)

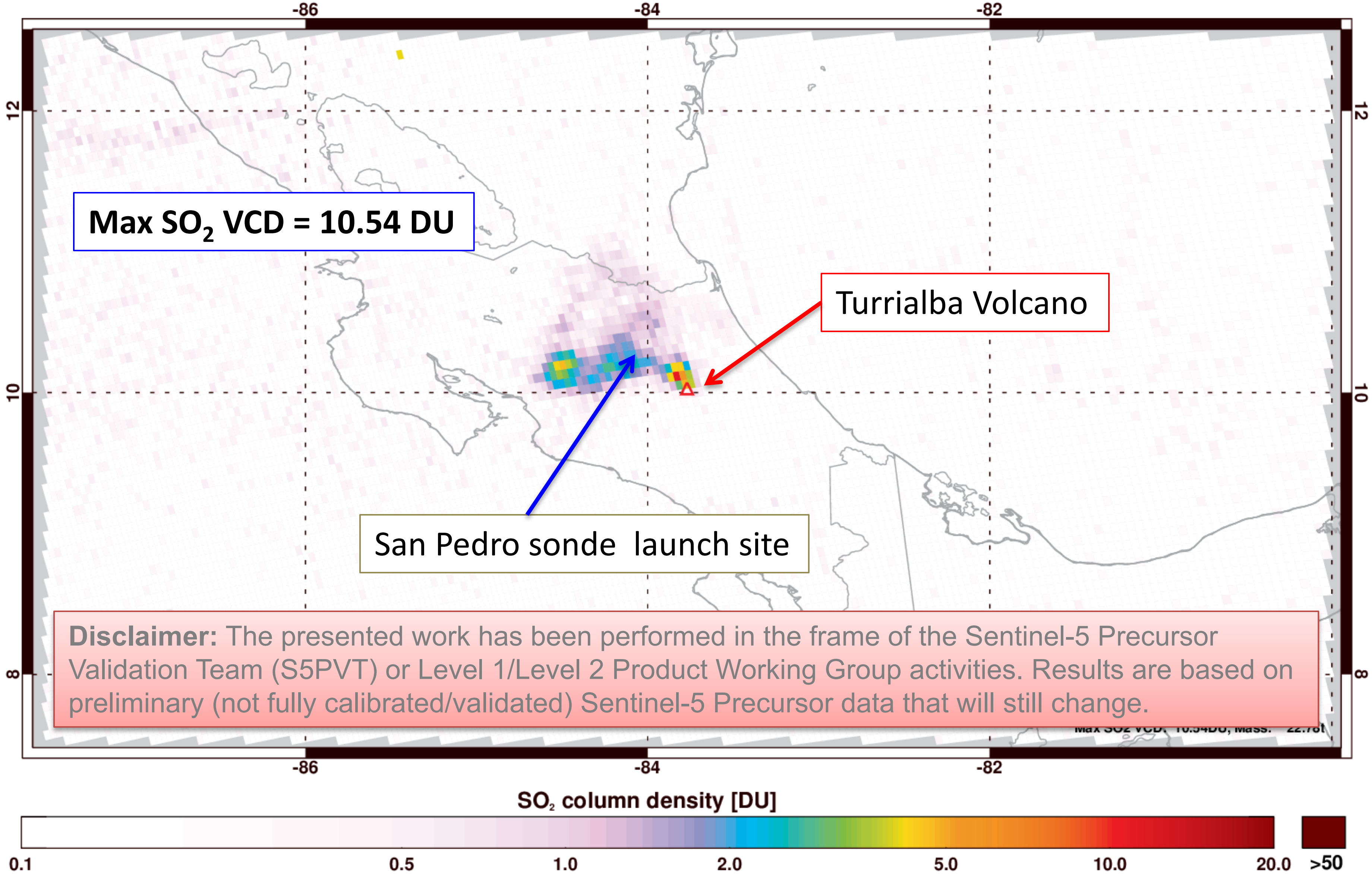
N. Krotkov: USPI and S5P Validation Team: Thorsten Fehr (ESA/ESTEC)

European Space Agency

Sentinel-5 Precursor
11/02/2018
Turrialba (10.03N, 83.77W)

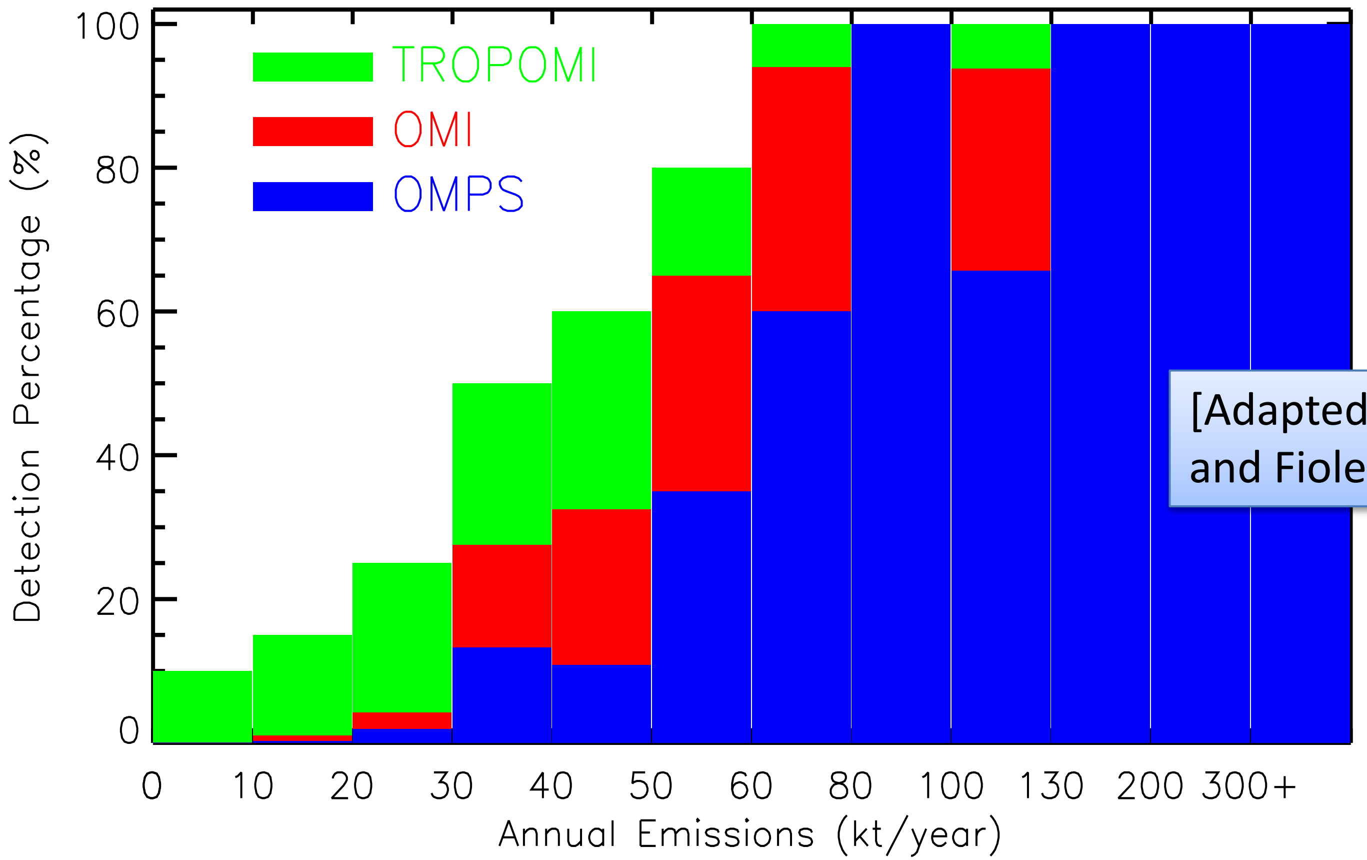
DLR

TROPOMI



Credit: DLR/BIRA/ESA

High resolution enables measuring smaller SO_2 emissions



[Adapted from Zhang et al., AMT, 2017 and Fioletov et al., ACP, 2016]

The percentage of emission sources within each bin of emission strength that is detected by **OMI (red)** and **SNPP/OMPS (blue).** Both instruments can detect nearly 100% of sources that emit over 80 kt of SO_2/year, but OMI detects a larger fraction of small sources than OMPS owing to its superior ground resolution. **S5P/TROPOMI (green)** will be several times more sensitive than OMI and is expected to be able to detect even more relatively small sources.