A decade of volcanic observations from Aura and the A-Train

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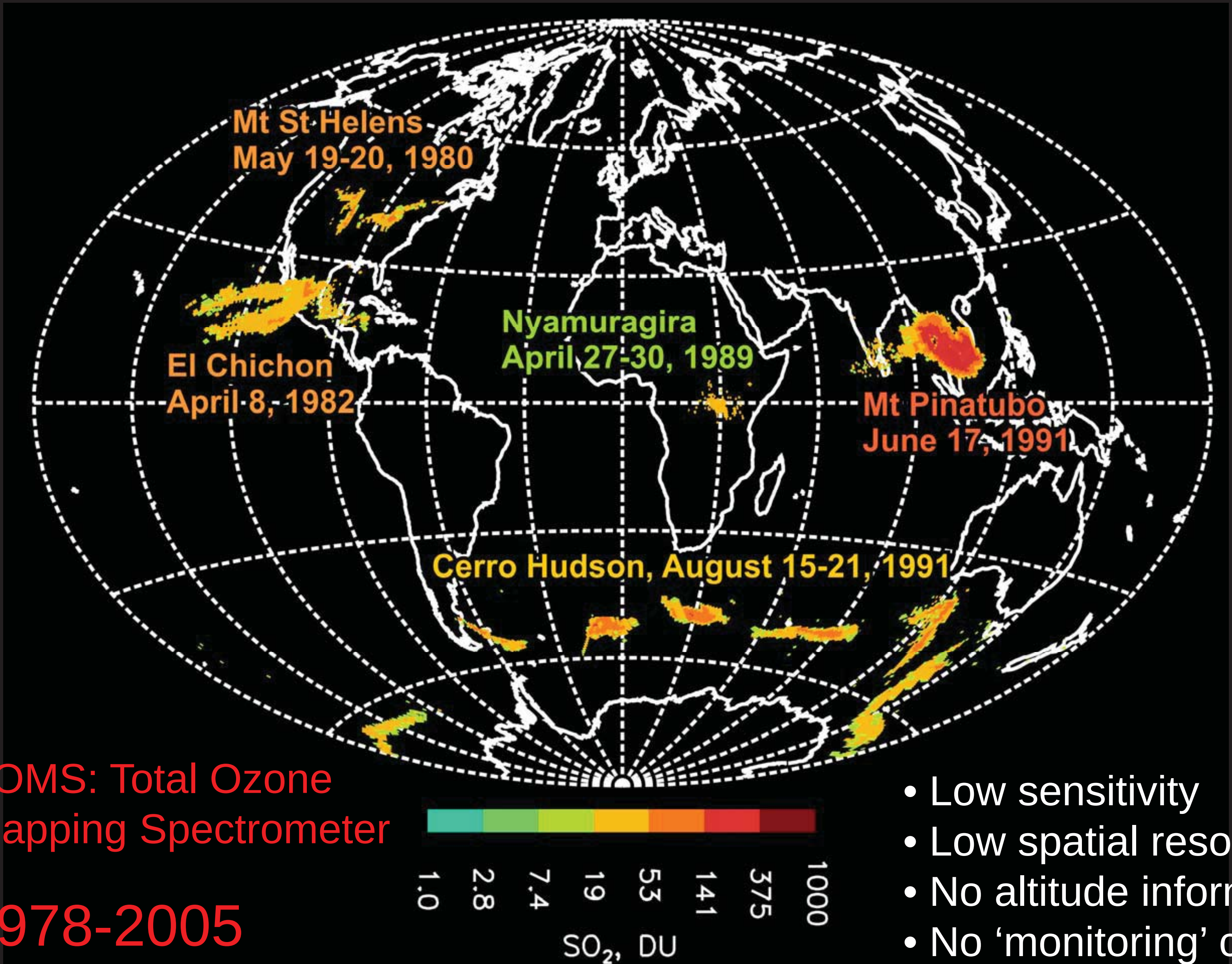
Volcanic SO_2 clouds measured by TOMS



TOMS: Total Ozone Mapping Spectrometer

1978-2005

- Low sensitivity
- Low spatial resolution
- No altitude information
- No 'monitoring' capability

Pre-Aura view of global volcanic SO_2 emissions

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 103, NO. D19, PAGES 25,251–25,261, OCTOBER 20, 1998

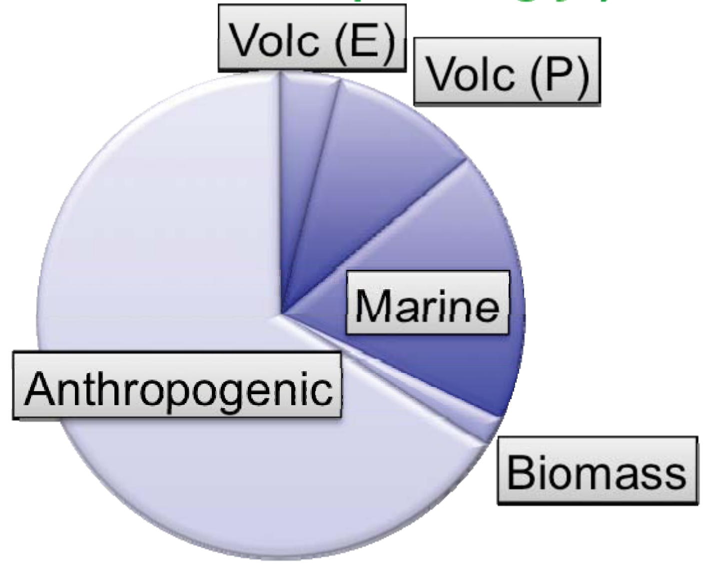
A time-averaged inventory of subaerial volcanic sulfur emissions

R.J. Andres and A.D. Kasgnoc

Institute of Northern Engineering, University of Alaska Fairbanks

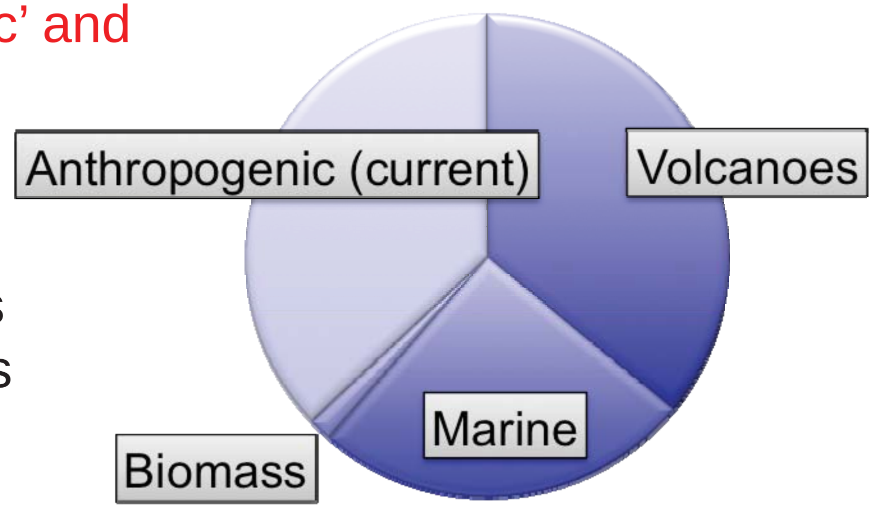
Abstract. A time-averaged inventory of subaerial volcanic sulfur (S) emissions was compiled primarily for the use of global S and sulfate modelers. This inventory relies upon the 25-year history of S, primarily sulfur dioxide (SO_2), measurements at volcanoes. Subaerial volcanic SO_2 emissions indicate a 13 Tg/a SO_2 time-averaged flux, based upon an early 1970s to 1997 time frame. When considering other S species present in volcanic emissions, a time-averaged inventory of subaerial volcanic S fluxes is 10.4 Tg/a S. These time-averaged fluxes are conservative minimum fluxes since they rely upon actual measurements. The temporal, spatial, and chemical inhomogeneities inherent to this system gave higher S fluxes in specific years. Despite its relatively small proportion in the atmospheric S cycle, the temporal and spatial distribution of volcanic S emissions provide disproportionate effects at local, regional, and global scales. This work contributes to the Global Emissions Inventory Activity.

Sulfur emissions (~100 Tg/yr)



• Volcanic S emission inventories ‘static’ and used ground-based data

Sulfate burden

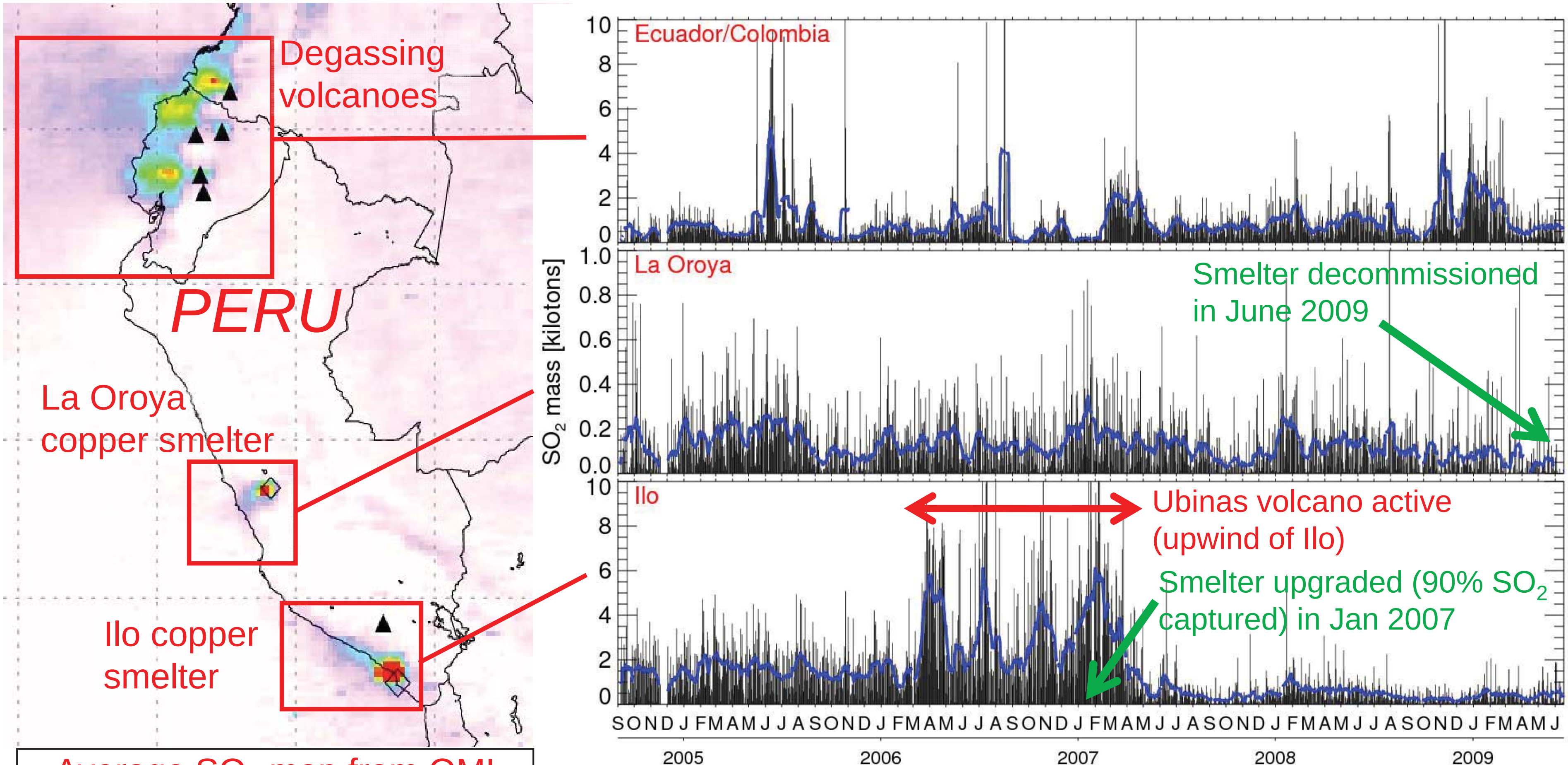


Motivation:

• Climate impact of volcanic emissions
• Global fluxes of other volatile species
• Field sites for volcanic gas studies

[*Graf et al.*, 1997; *Andres & Kasgnoc*, 1998; *Halmer et al.*, 2002; *Smith et al.*, 2011]

OMI monitors SO_2 emissions in South America

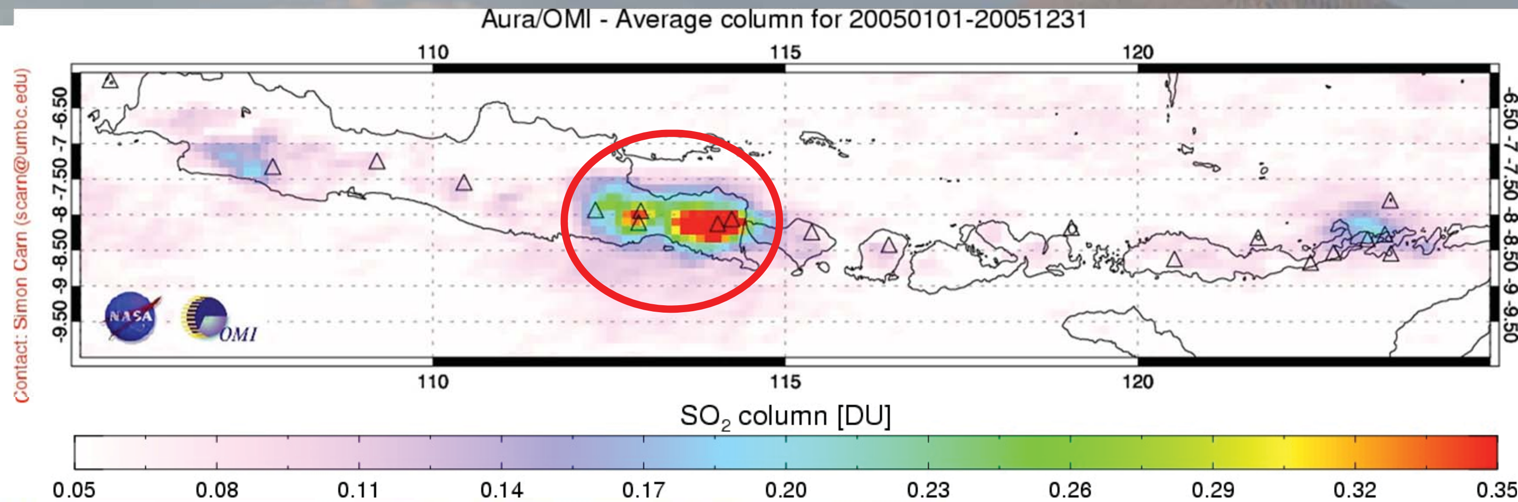


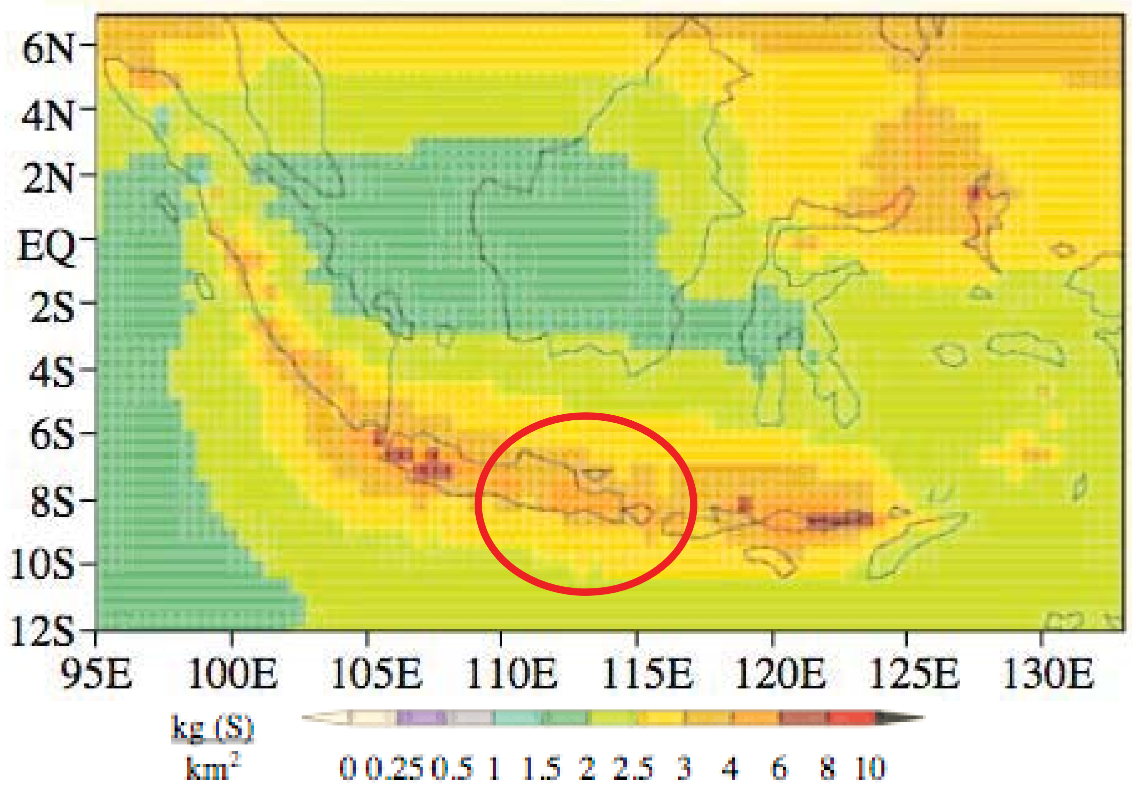
Average SO_2 map from OMI 2004-2005

Carn, S.A., N.A. Krotkov, A.J. Krueger, K. Yang, P.F. Levelt, "Sulfur dioxide emissions from Peruvian copper smelters detected by the OMI", GRL, 2007.

- SO_2 emissions in Ecuador and Colombia from Tungurahua, Reventador, Galeras and Huila volcanoes
- Volcanic emissions from Ubinas volcano (Peru) drift over Ilo region in 2006-2007
- Upgraded sulfur capture technology at Ilo reduces SO_2 emissions
- Shut-down of La Oroya smelter in mid-2009; reduction expected

Volcanic SO_2 emissions inventories are inaccurate

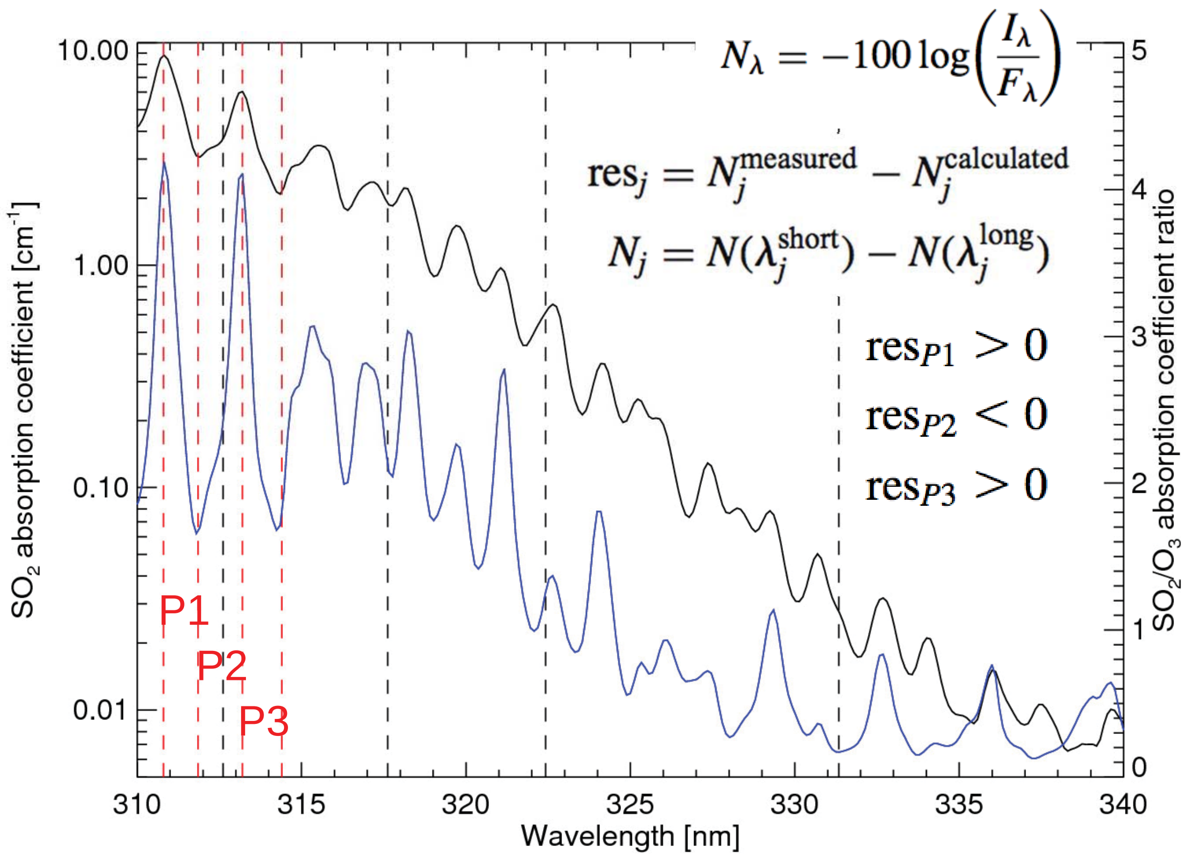


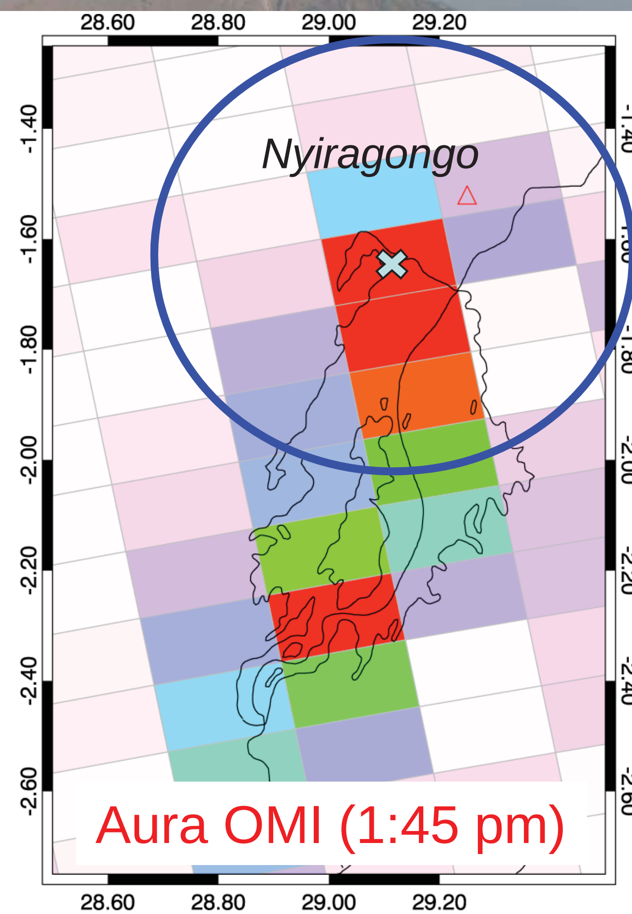


- OMI measurements indicate deficiencies in current ‘bottom up’ volcanic SO_2 emission inventories used in CTMs

REMOTE model simulation of annual mean SO_2 columns over Indonesia [*Pfeffer et al., ACP, 2006*]

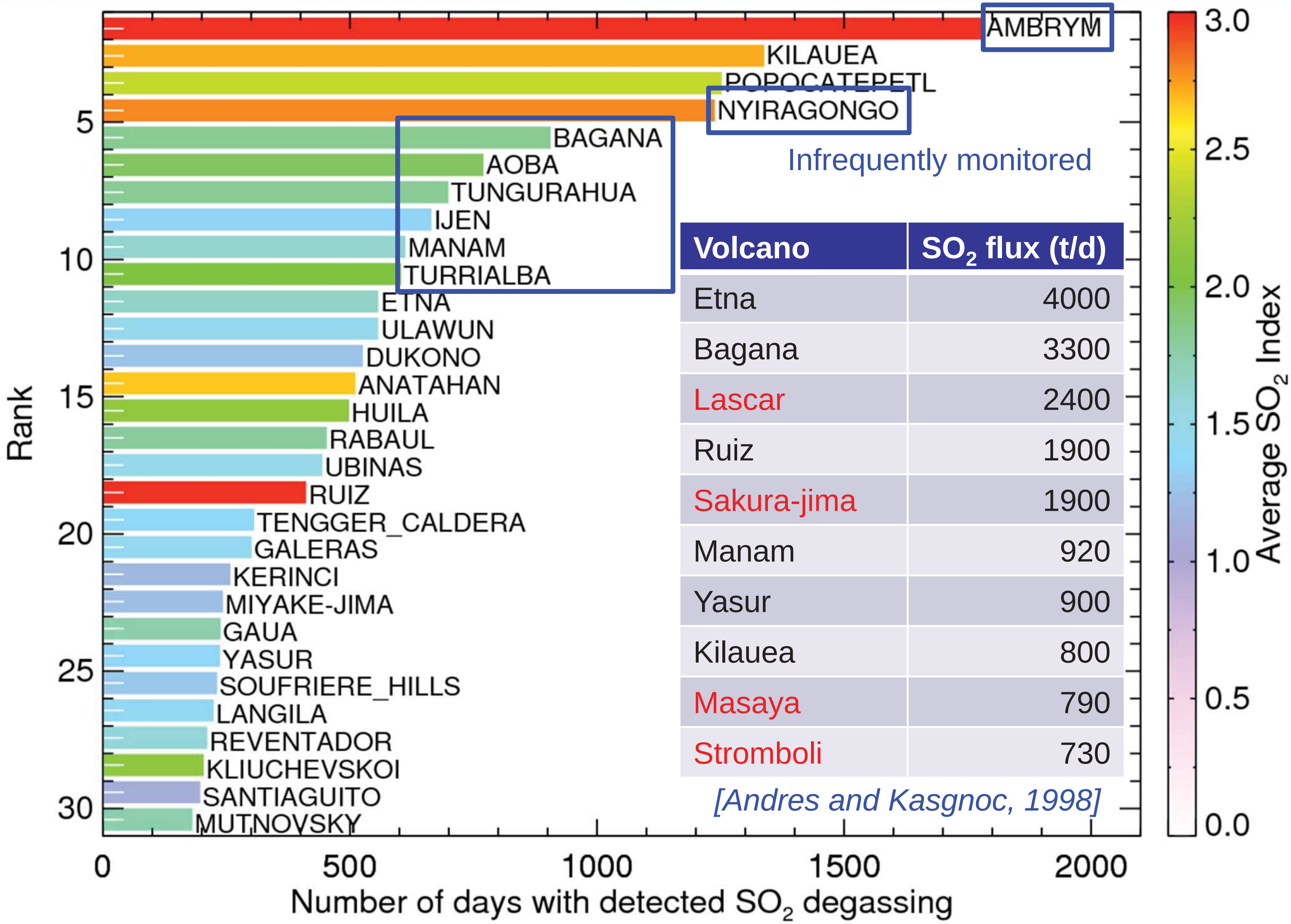
Identification of global volcanic SO_2 sources





- SO_2 index defined using OMI ozone algorithm residuals (sensitive to SO_2)
- Rank top 1000 values of SO_2 index on each day (lat 65ºS – 80ºN)
- Locate active volcanoes within 50 km radius of these OMI pixels (using modified Smithsonian Global Volcanism Program database)
- Record unique volcanic sources for each day
- Repeat for each day of OMI measurements (>3200 from Sep 2004 – Dec 2013)

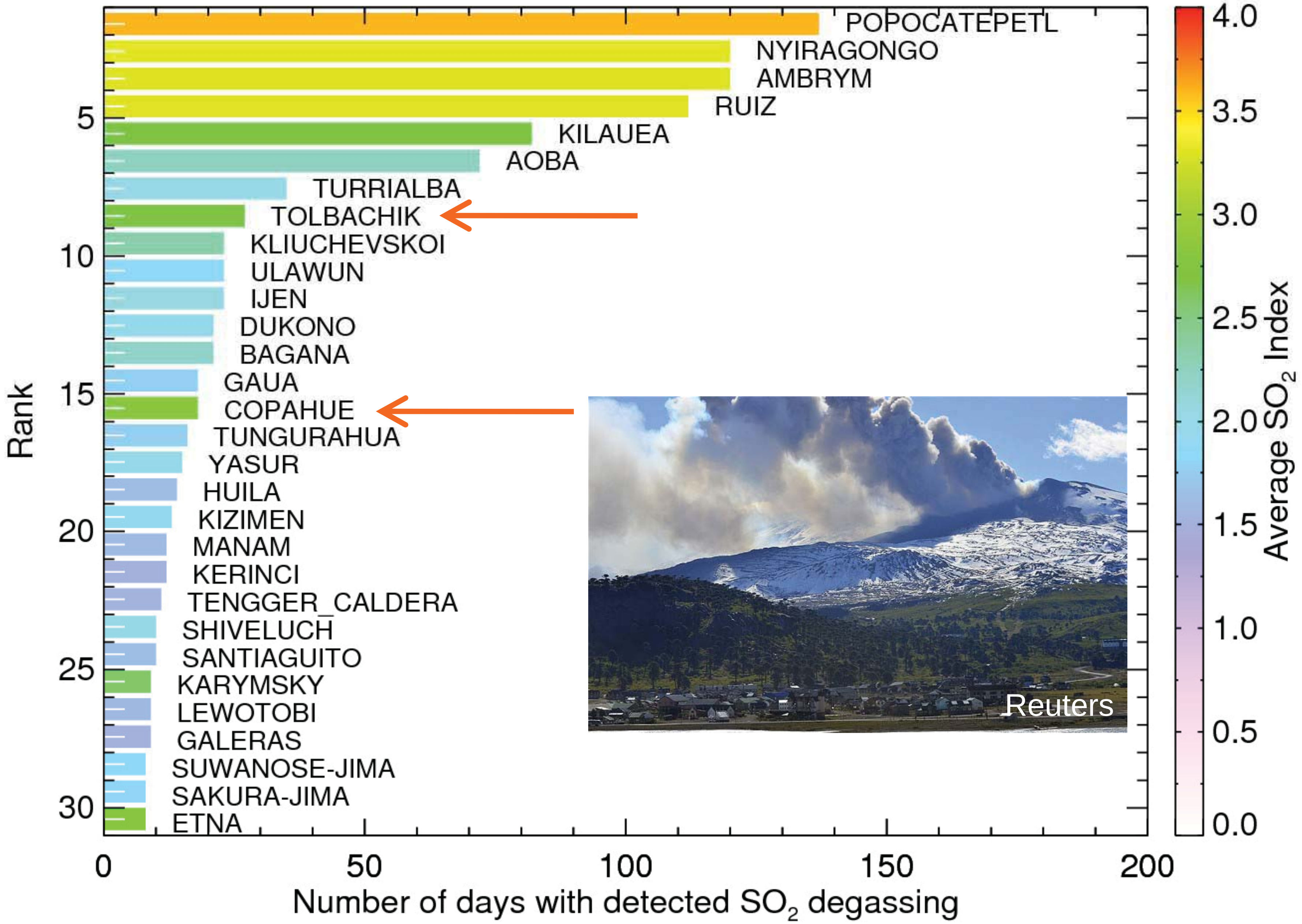
Persistent volcanic SO_2 sources (2004-2013; ~3200 days)



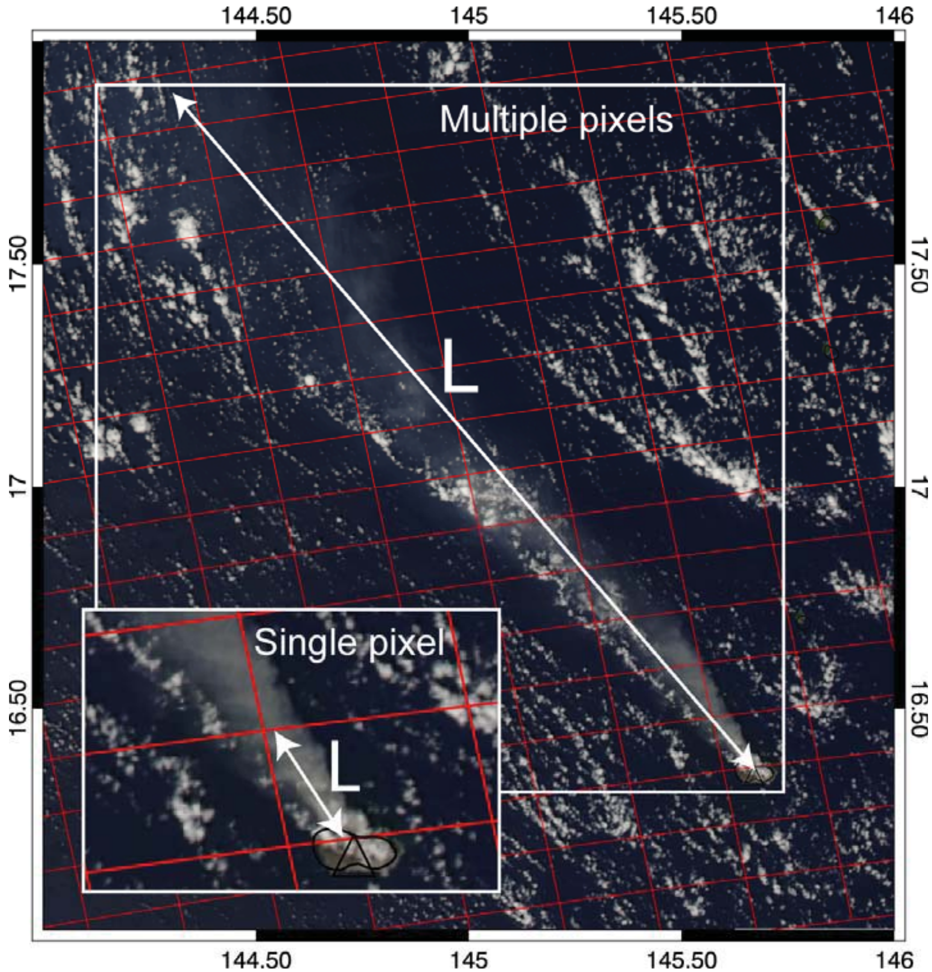
Volcano	SO_2 flux (t/d)
Etna	4000
Bagana	3300
Lascar	2400
Ruiz	1900
Sakura-jima	1900
Manam	920
Yasur	900
Kilauea	800
Masaya	790
Stromboli	730

[Andres and Kasgnoc, 1998]

Most persistent volcanic SO_2 sources in 2013



SO_2 emission rate estimation from satellite data



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

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})

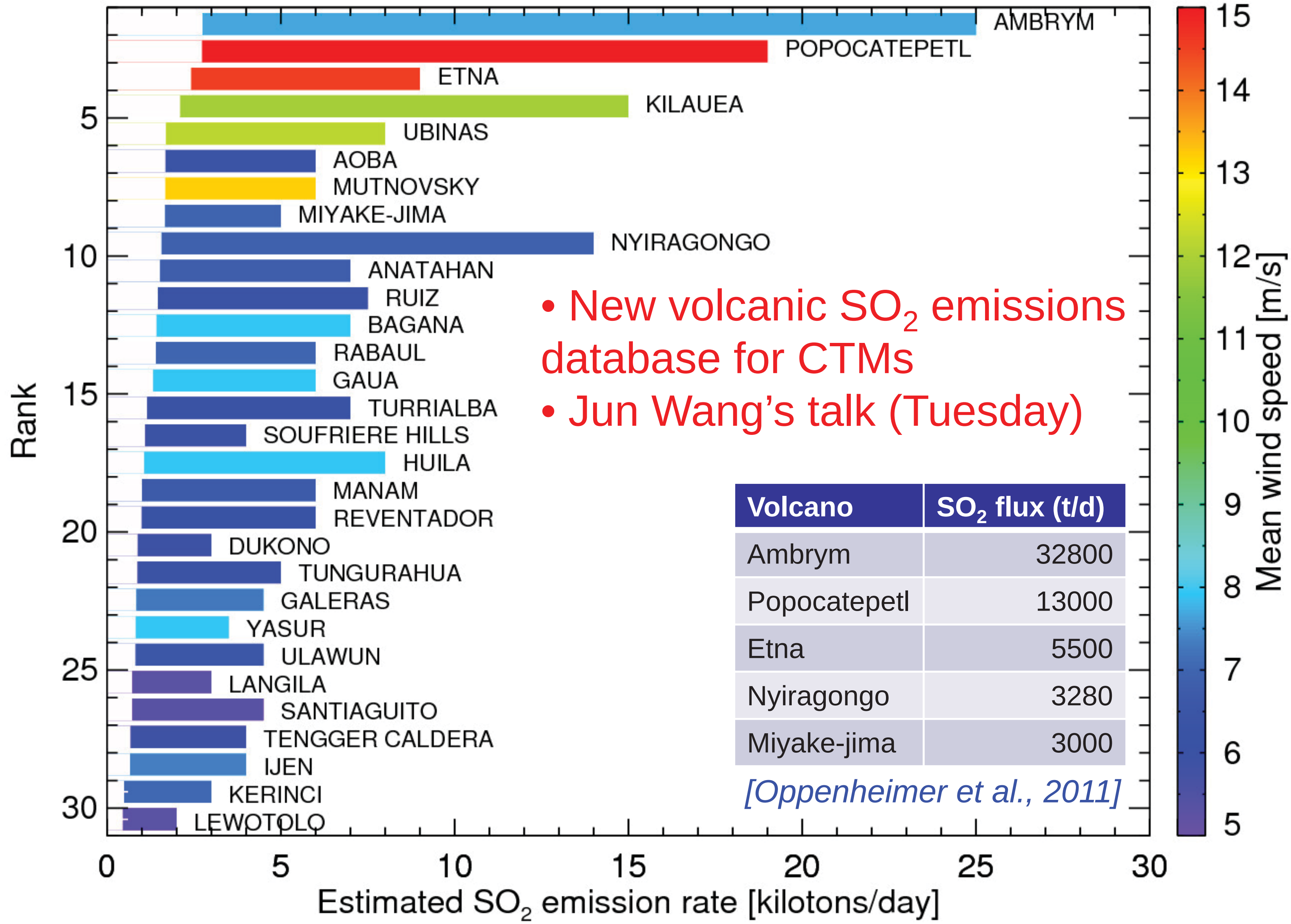
- Similar approach used to estimate smoke and NO_2 emissions from fires [*Ichoku and Kaufman*, 2005; *Mebust et al.*, 2011]
- Note that asymmetry of OMI pixel affects plume detection
- Chemistry correction [*Mebust et al.*, 2011] can be applied if SO_2 lifetime is known

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

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

[*Carn et al.*, Spec. Pub. Geol. Soc. Lon., 380, 2013]

Estimated SO_2 fluxes (2004-2013; ~3200 days)

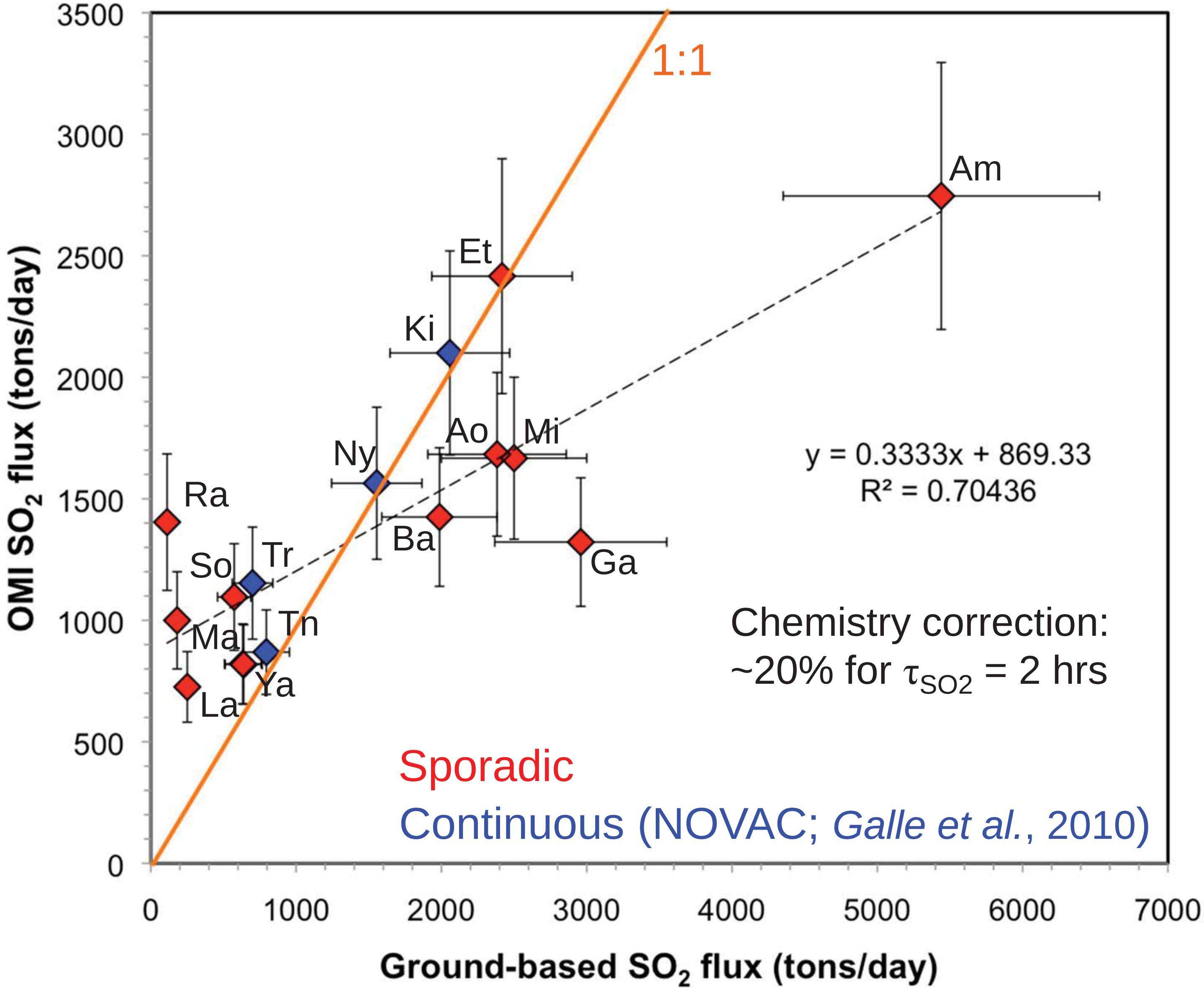


- New volcanic SO_2 emissions database for CTMs
- Jun Wang's talk (Tuesday)

Volcano	SO_2 flux (t/d)
Ambrym	32800
Popocatepetl	13000
Etna	5500
Nyiragongo	3280
Miyake-jima	3000

[Oppenheimer et al., 2011]

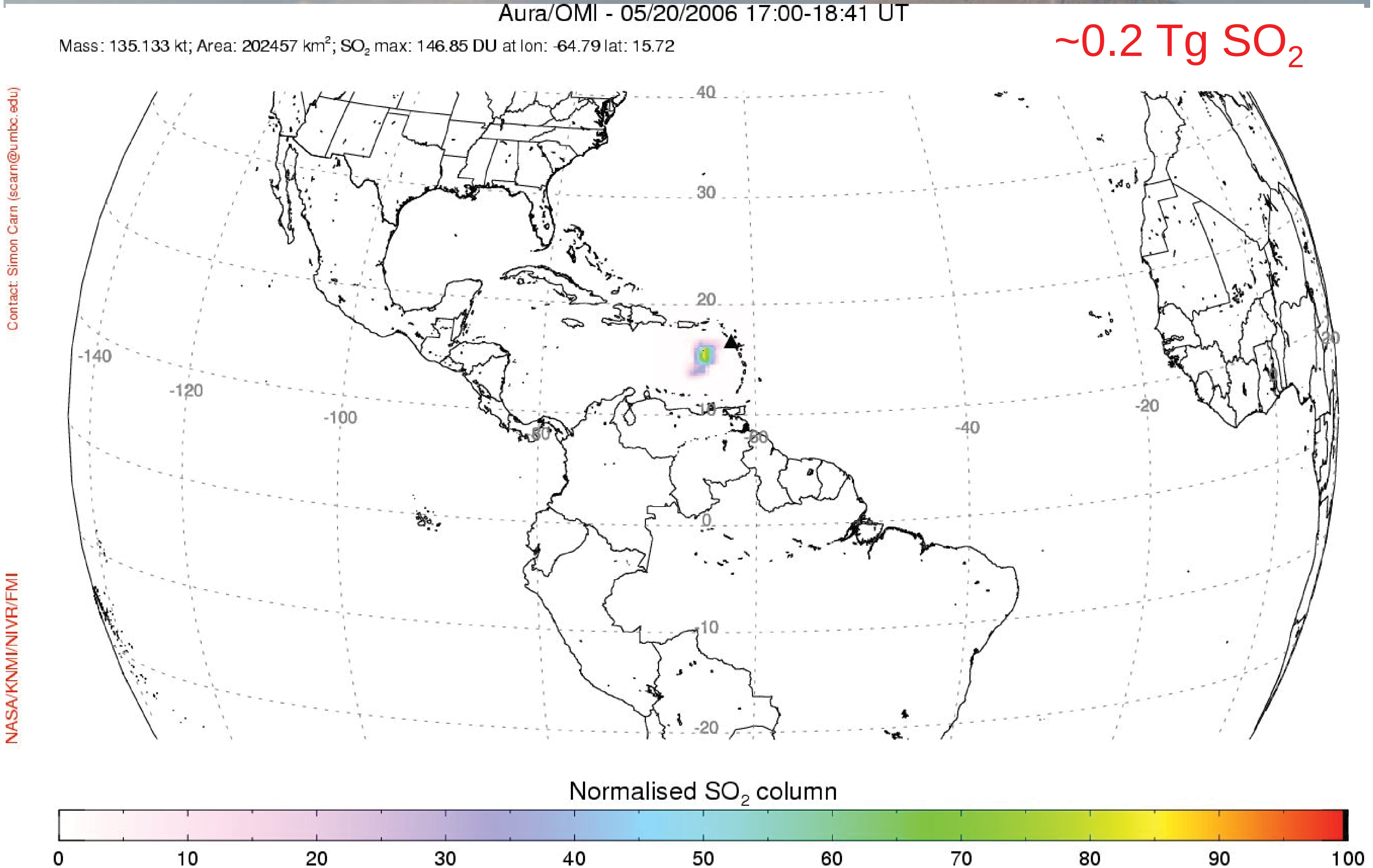
Validation with ground-based SO_2 measurements



- Good agreement with long-term, ground-based datasets

Soufrière Hills volcano (Montserrat) eruption, May 2006

~0.2 Tg SO_2



[*Carn et al.*, 2007; *Prata et al.*, 2007]

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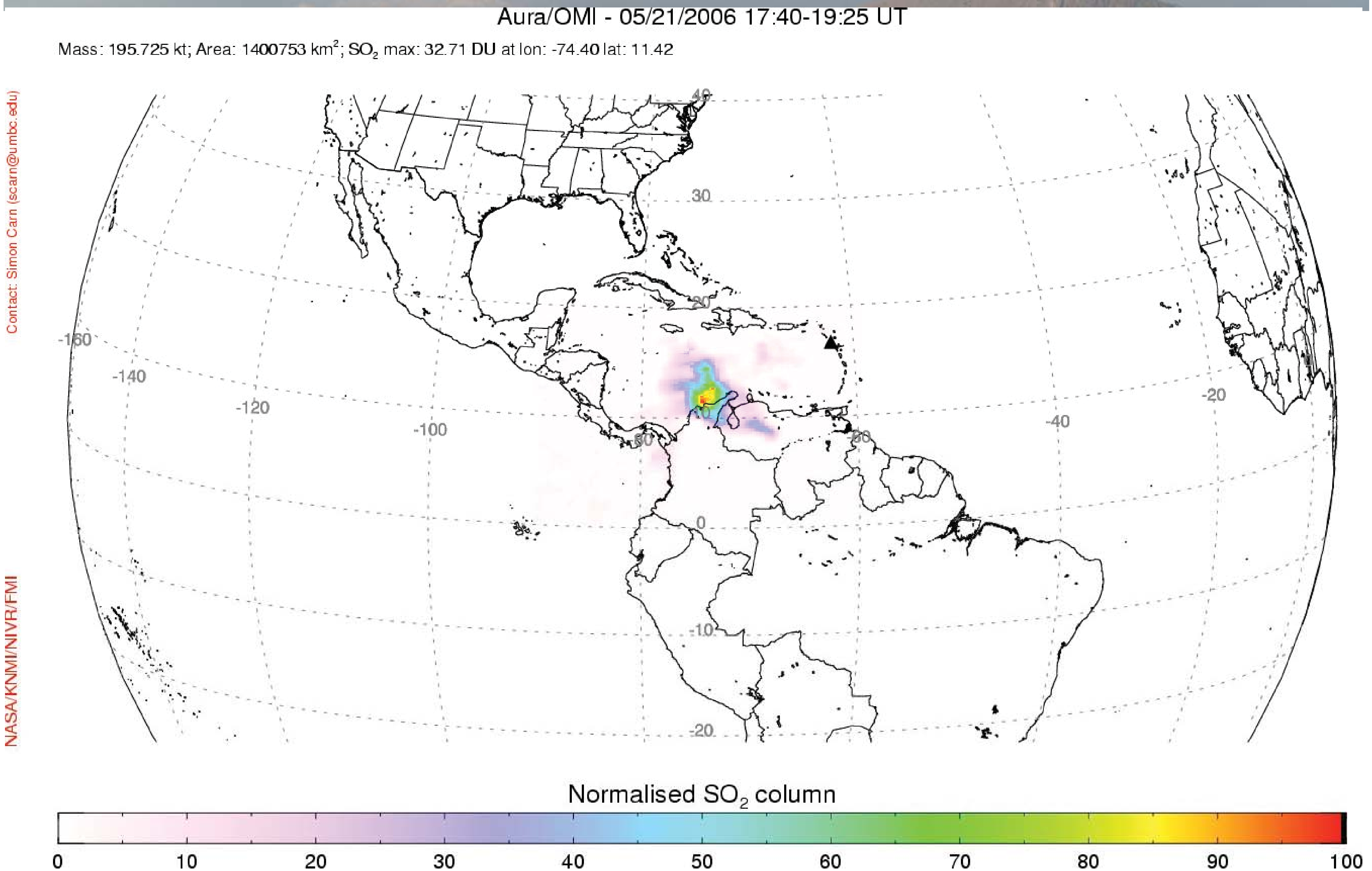

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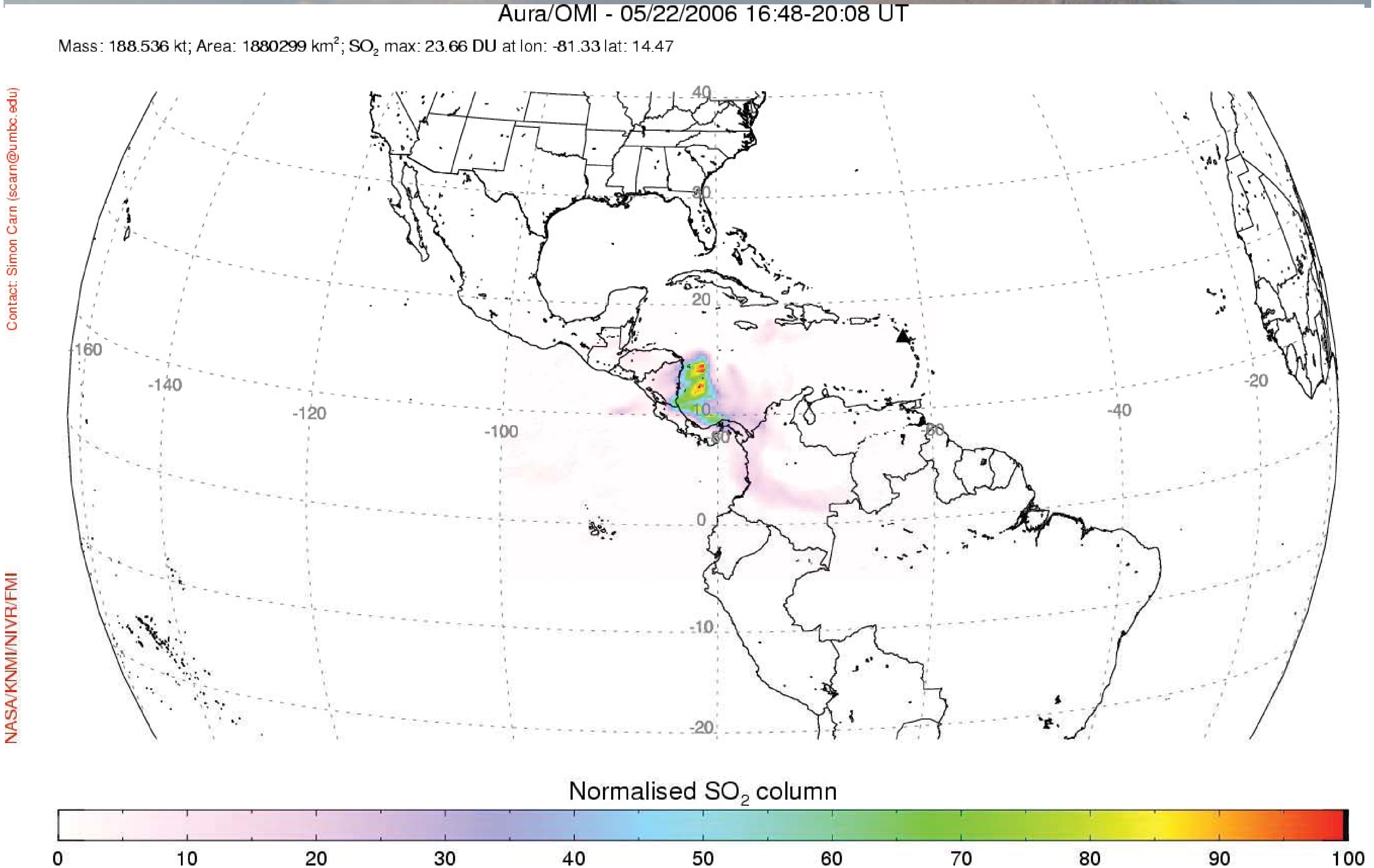

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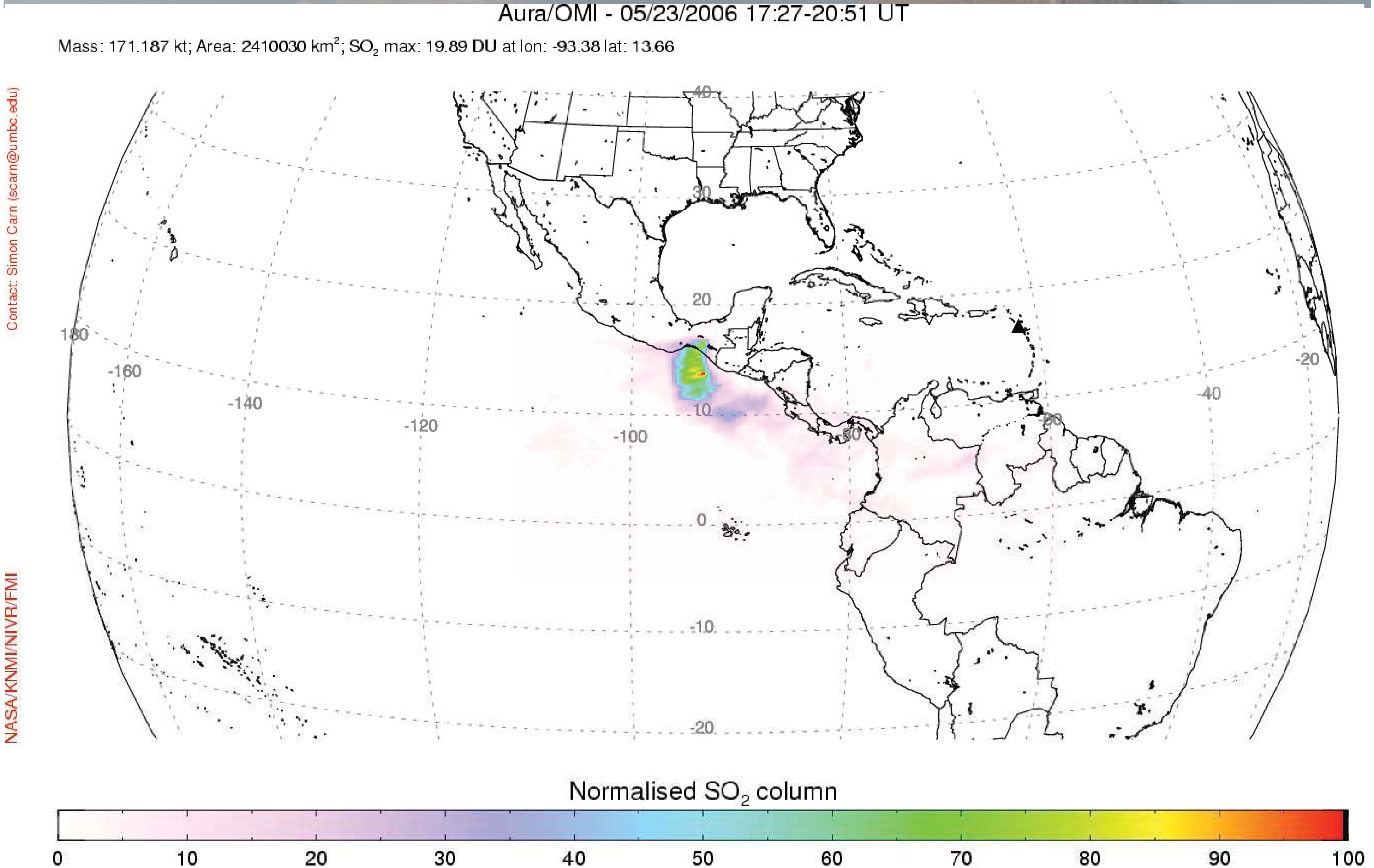

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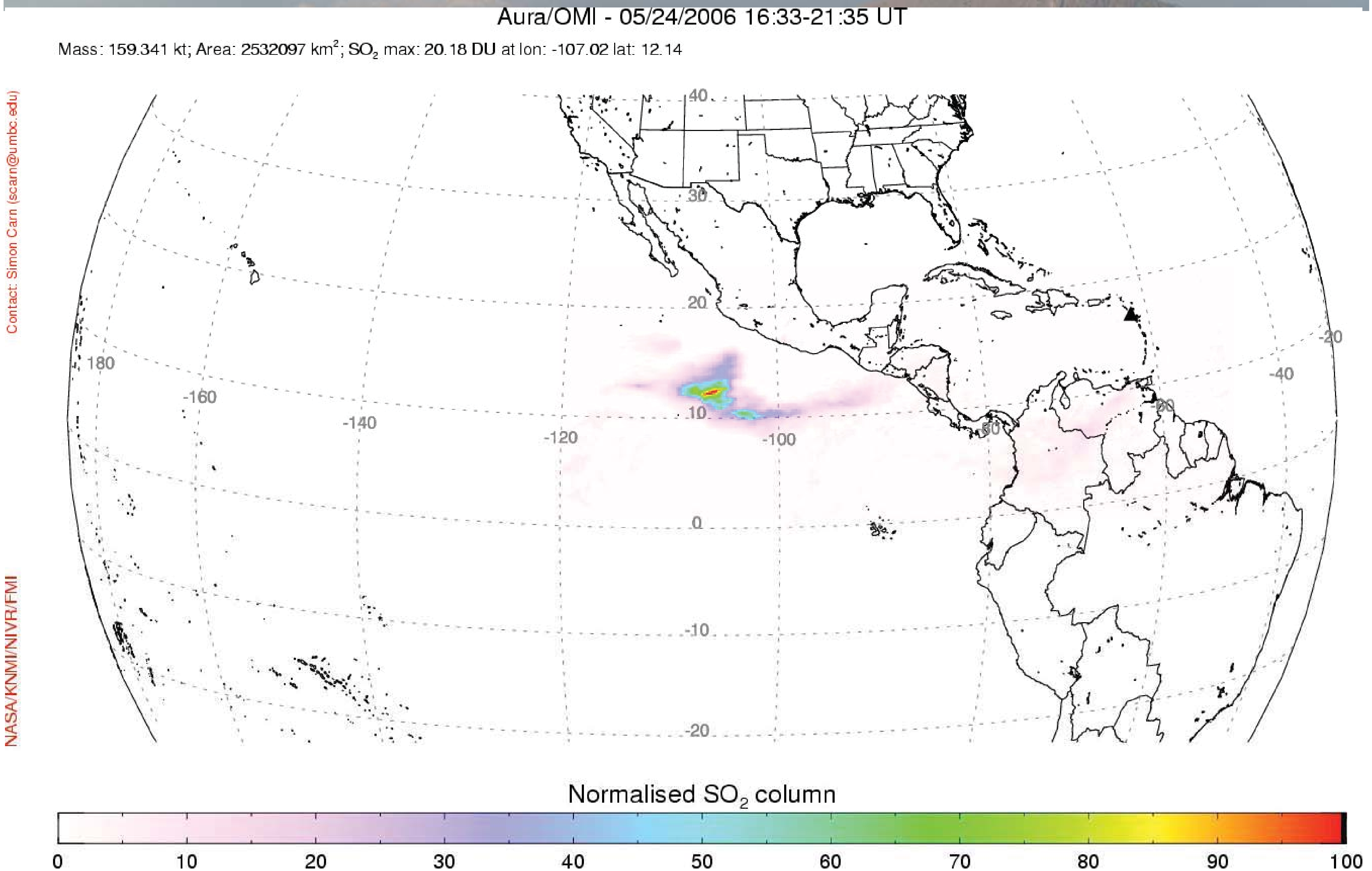

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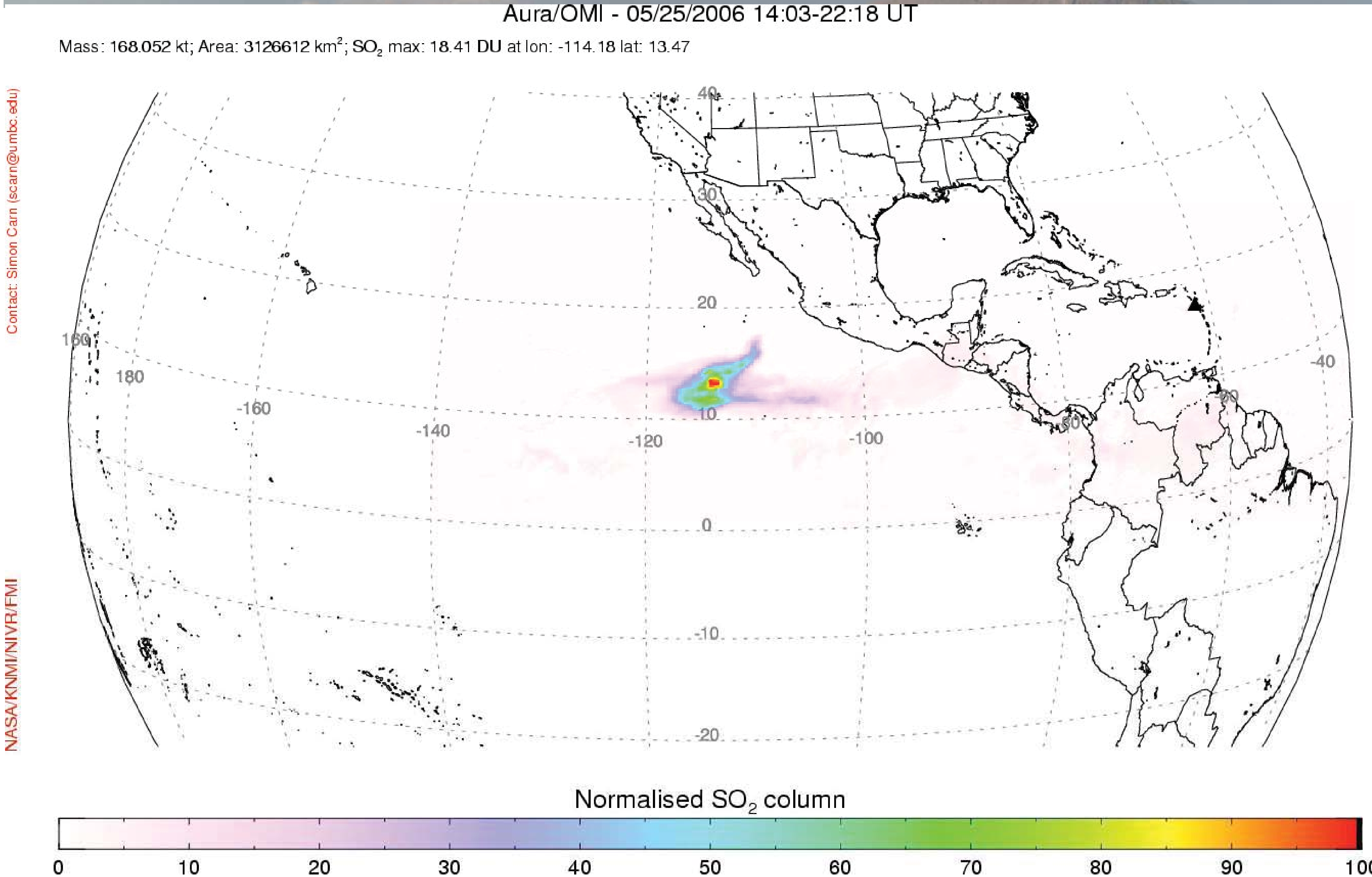

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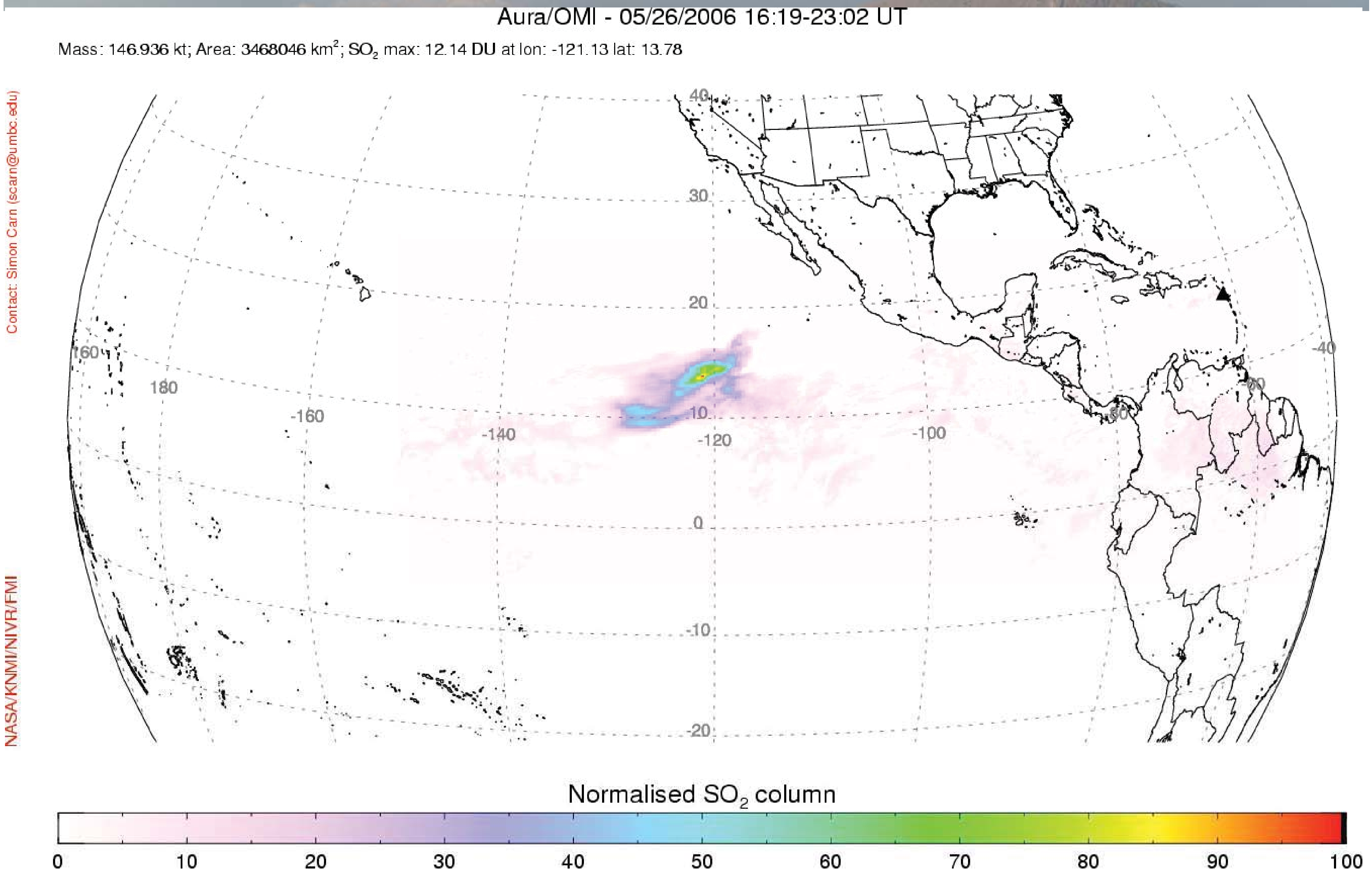

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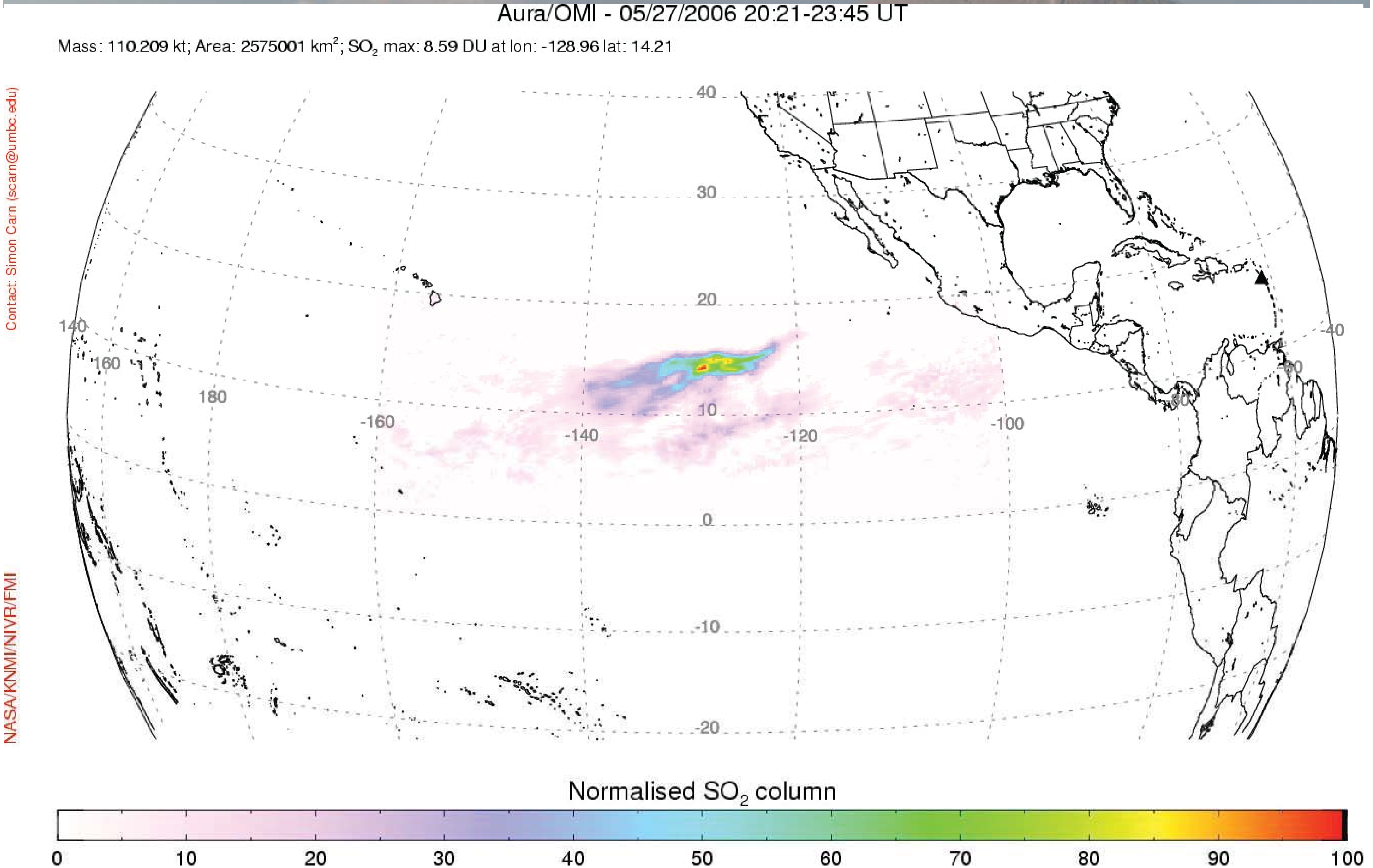

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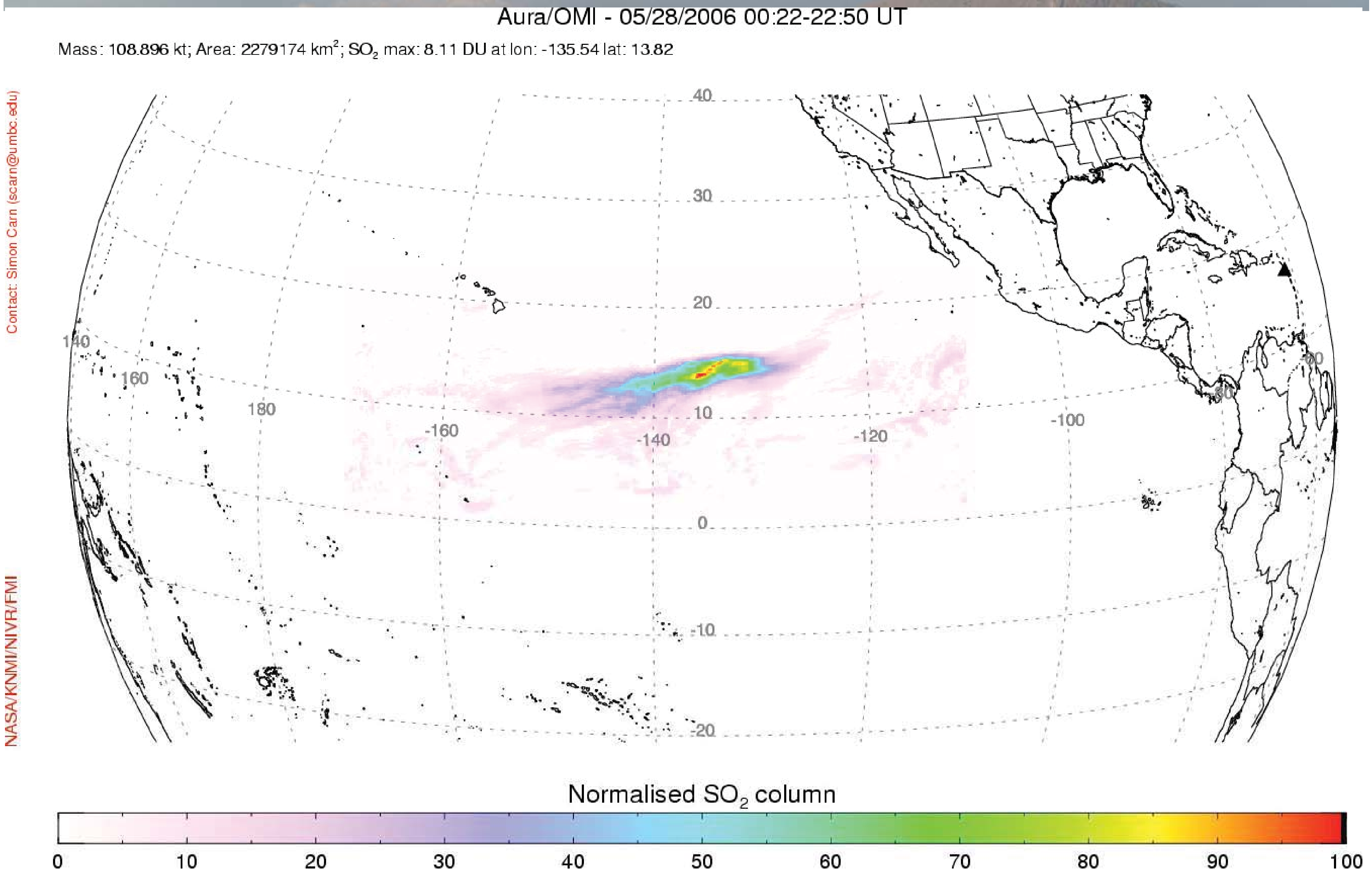

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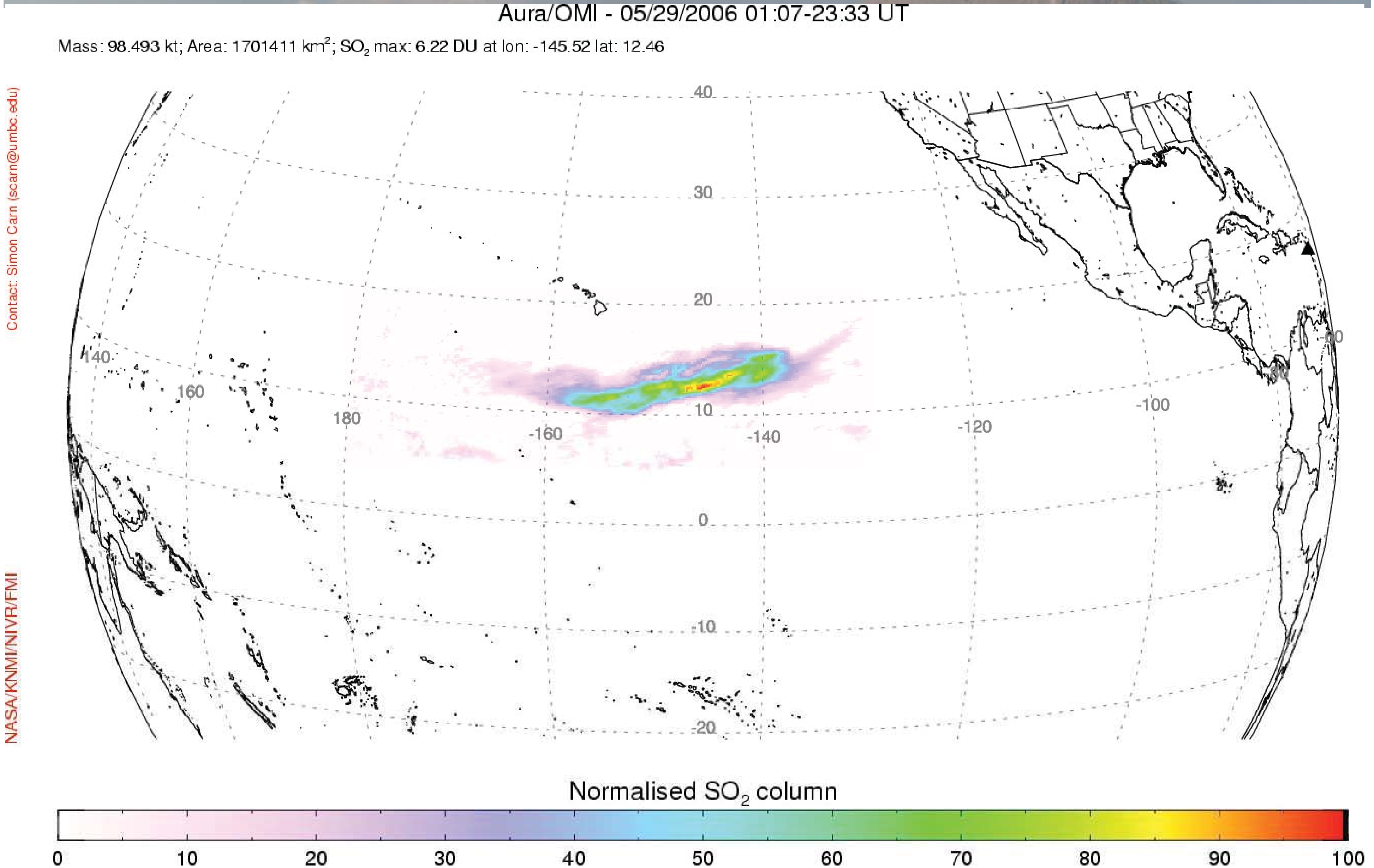

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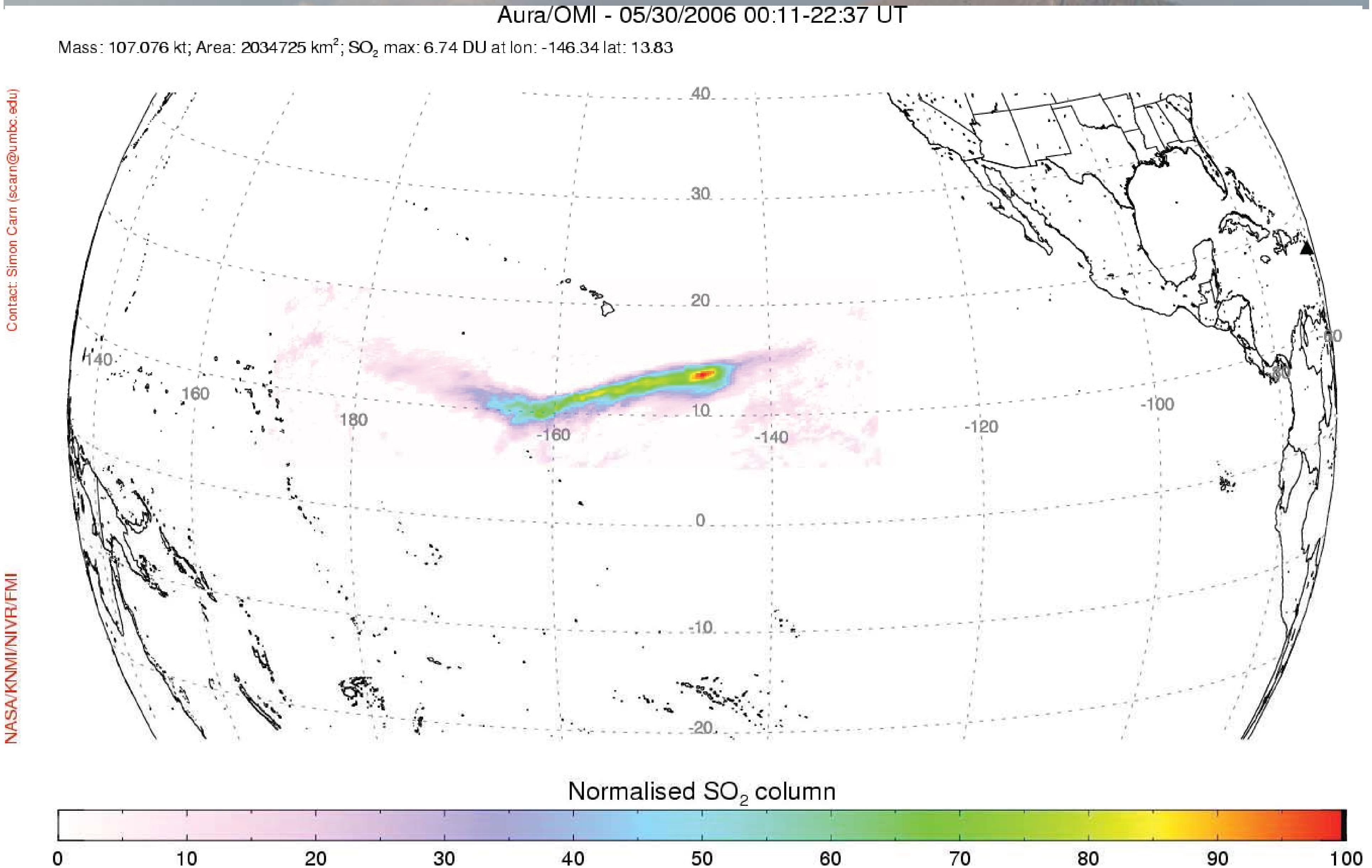

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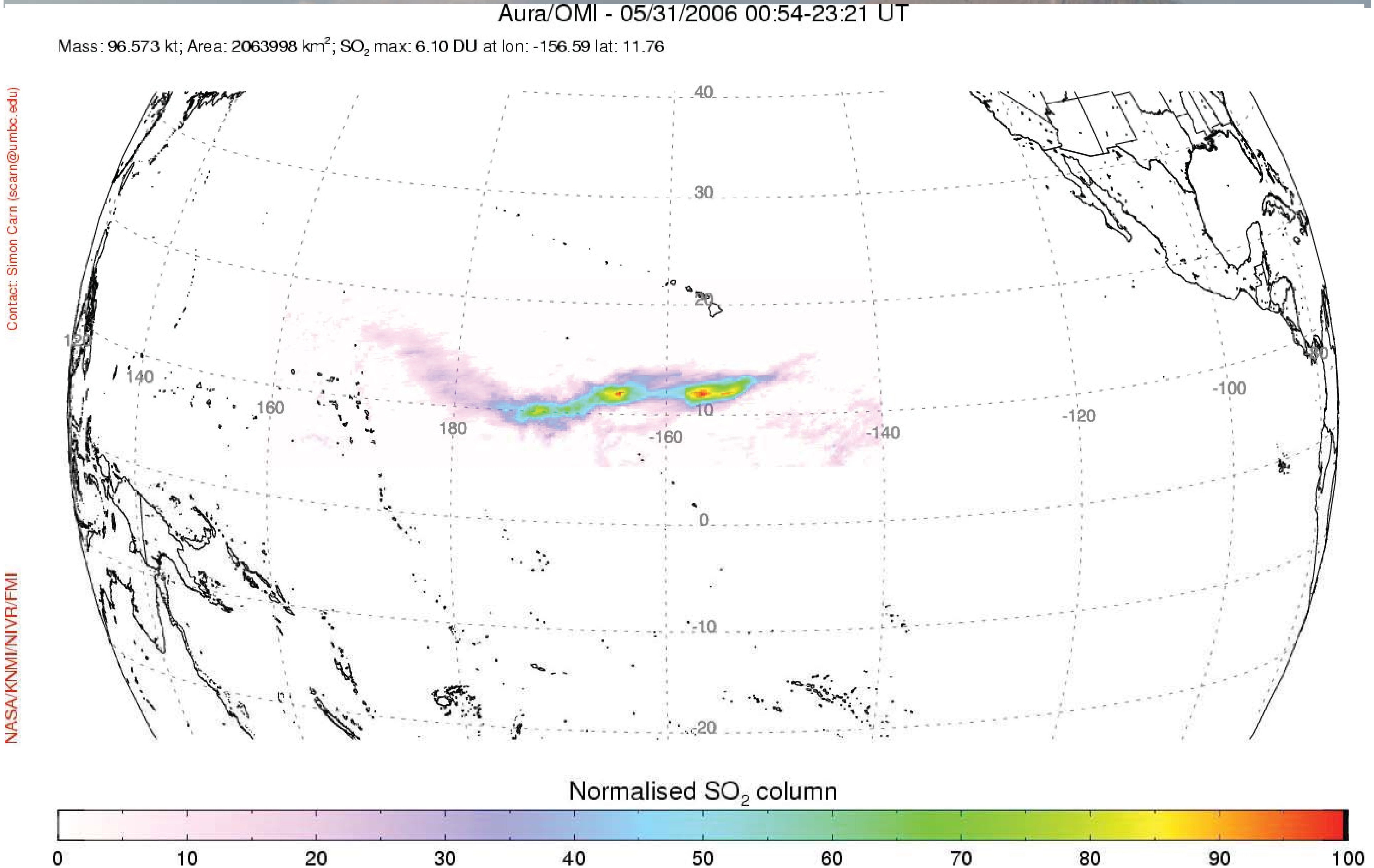

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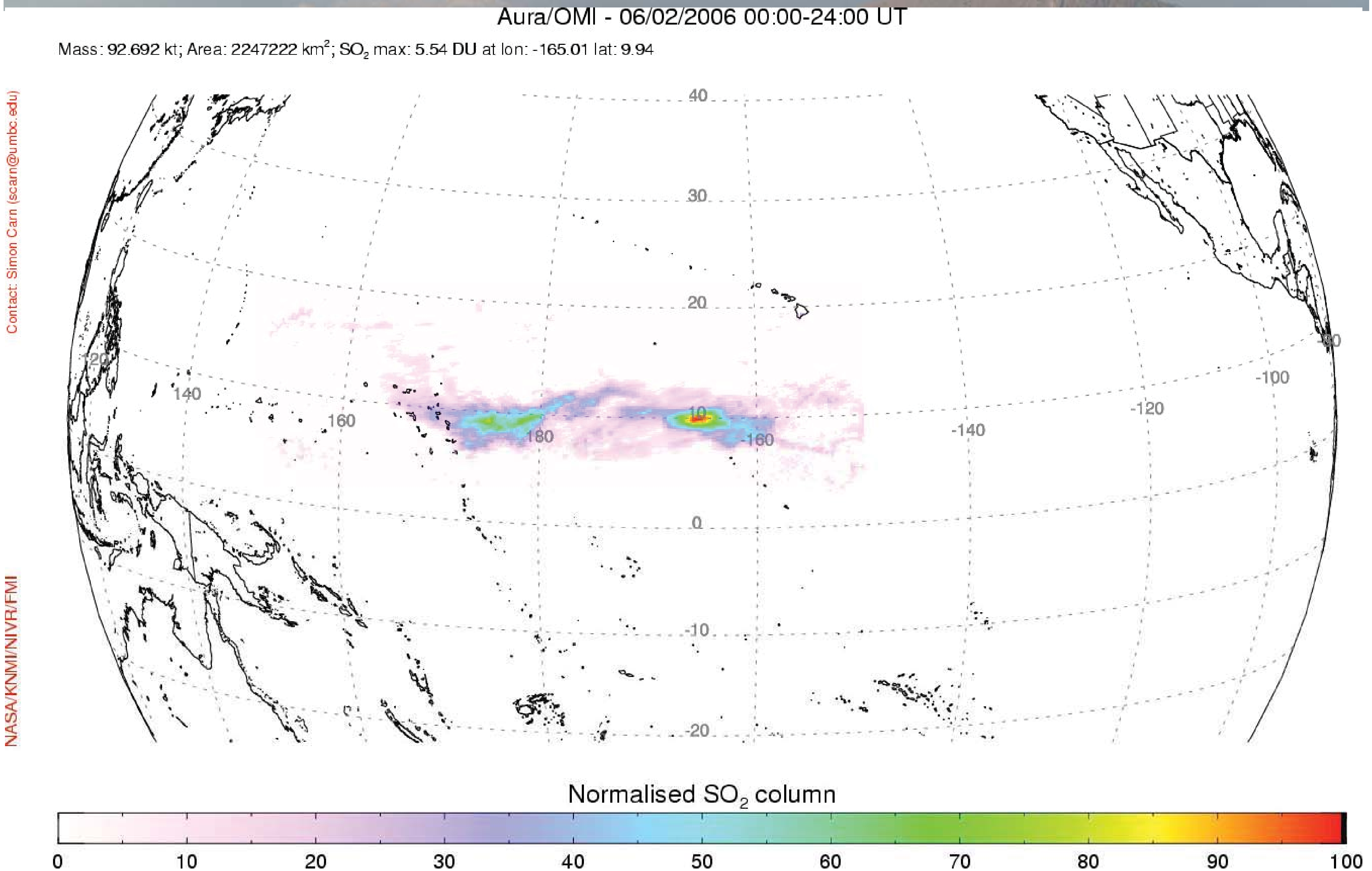

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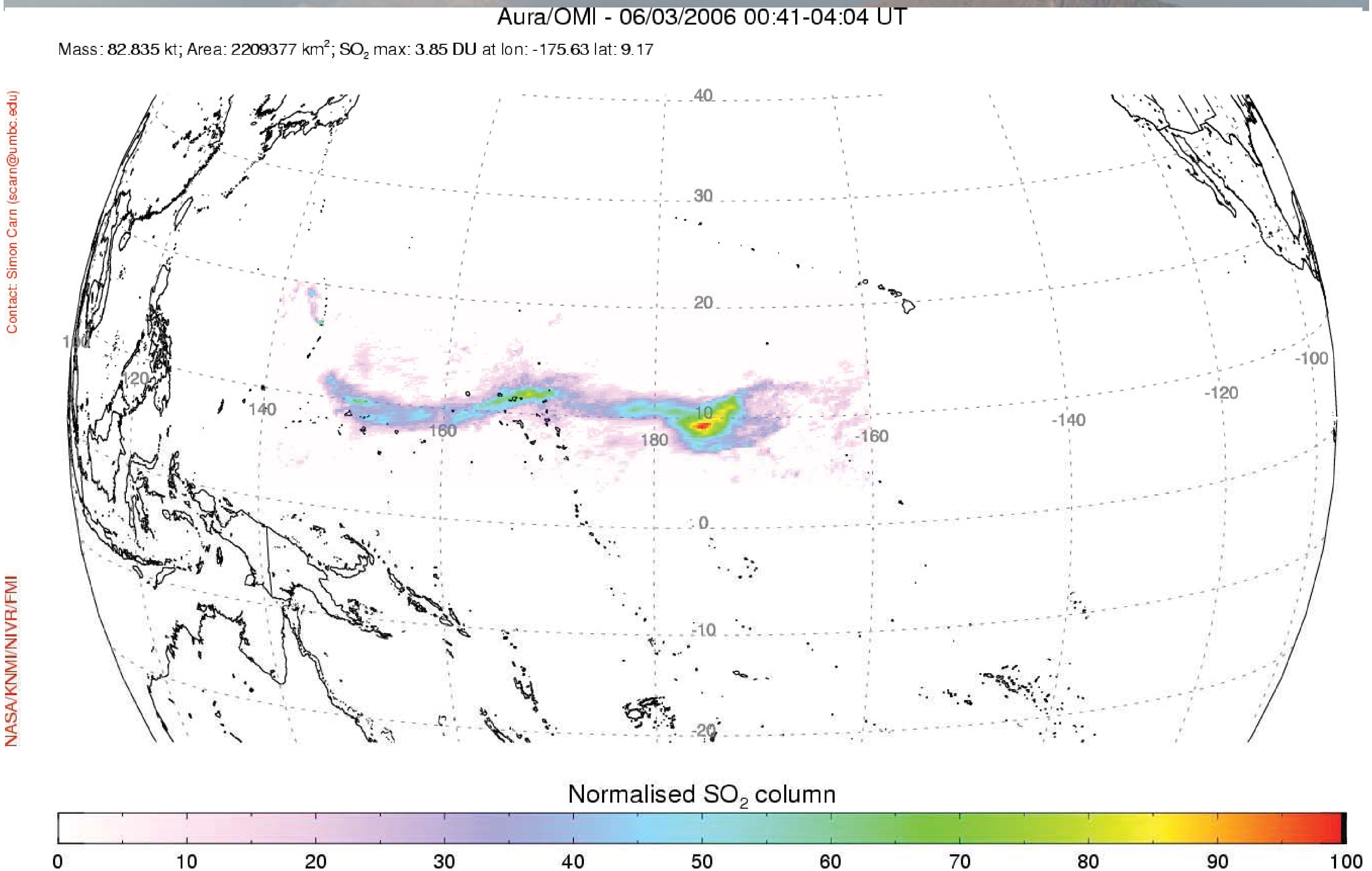

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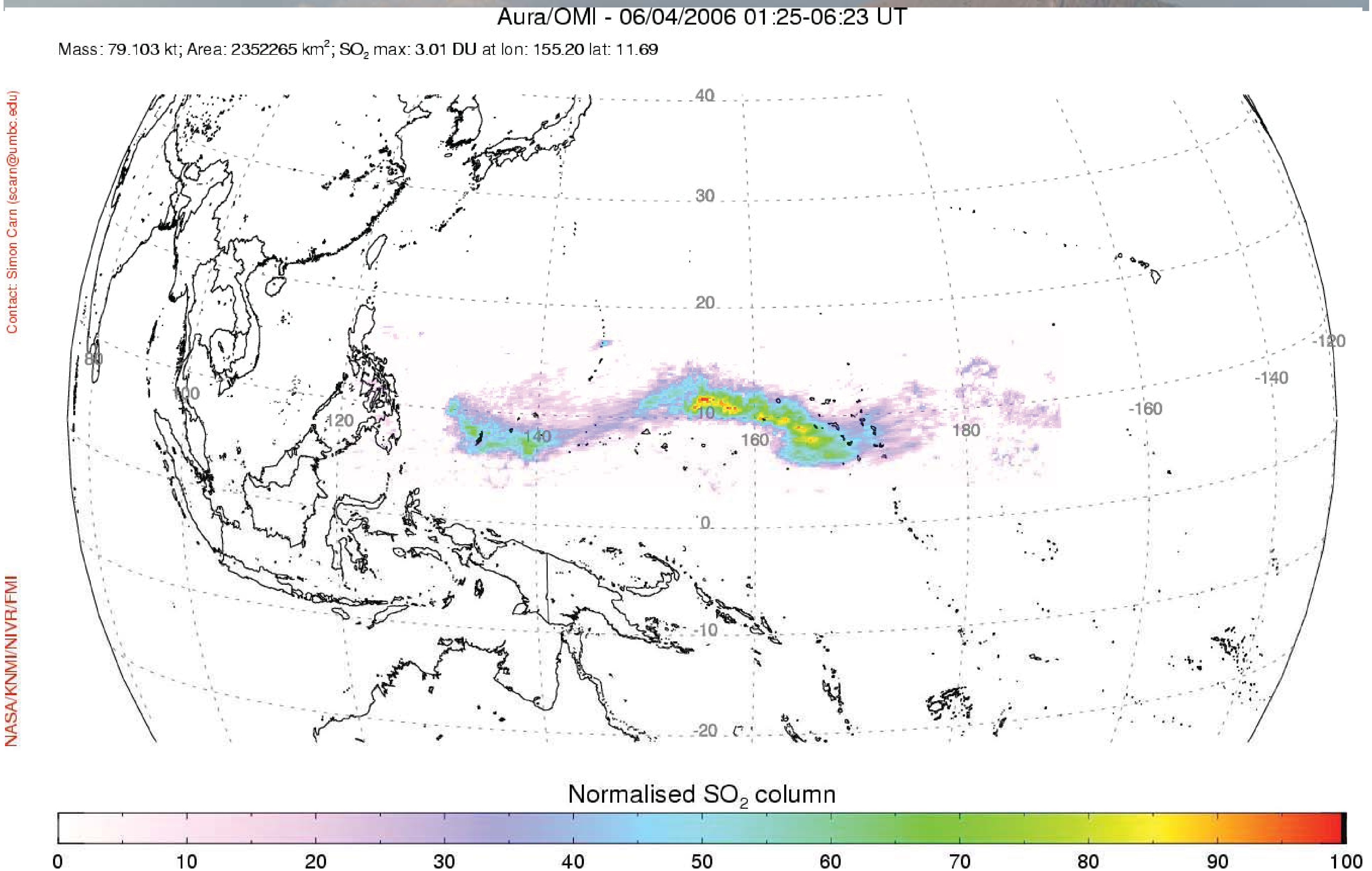

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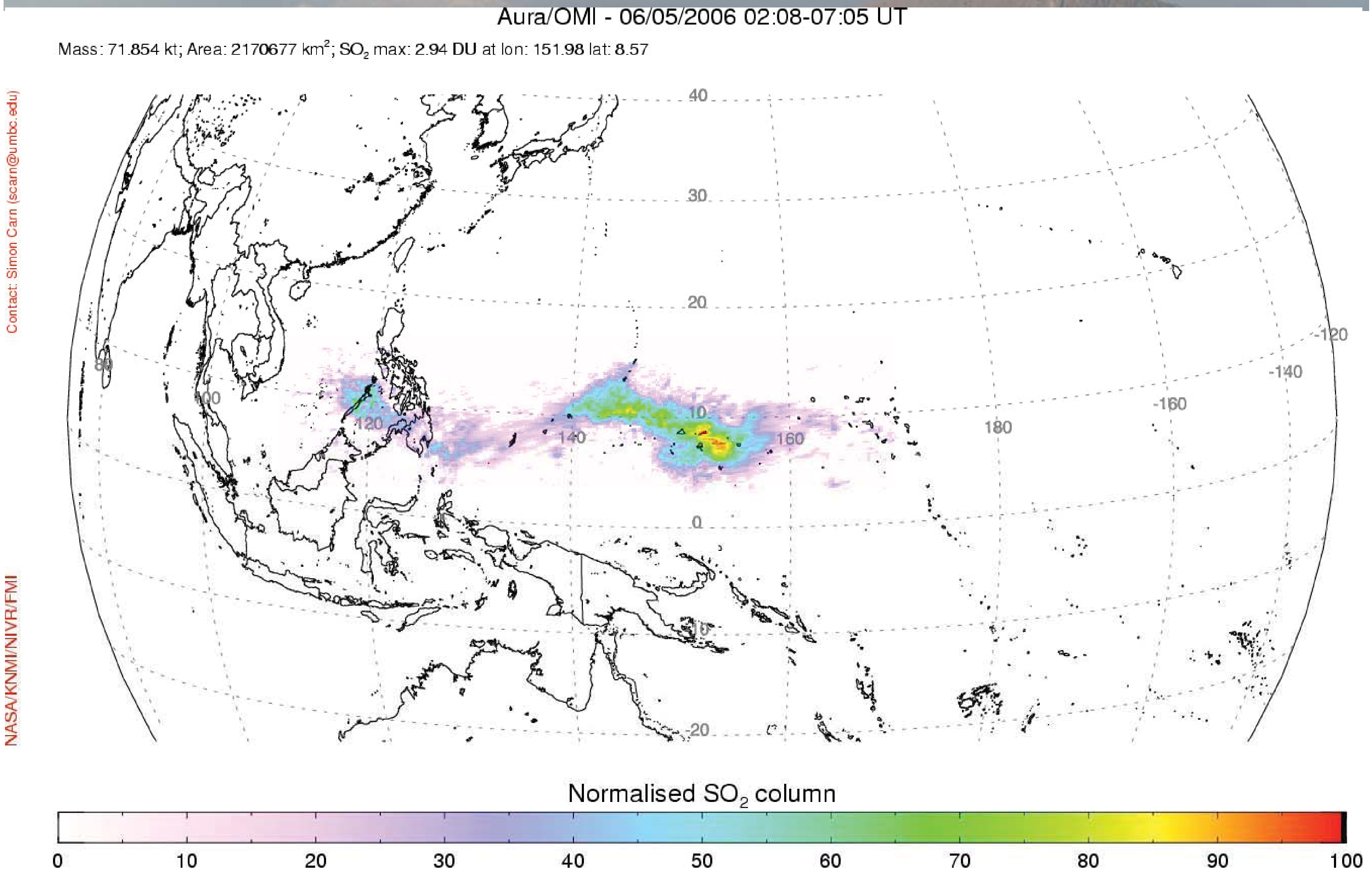

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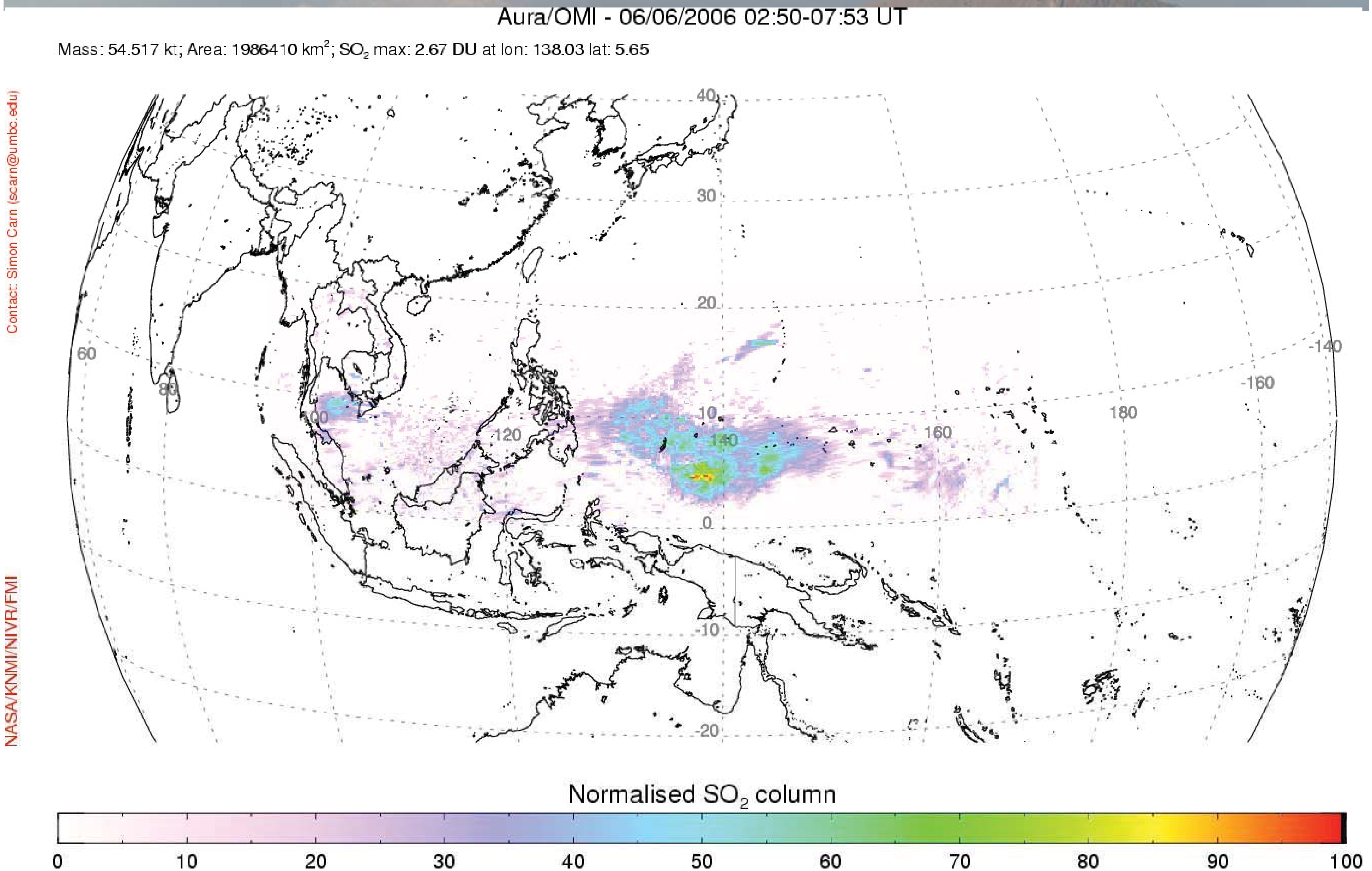

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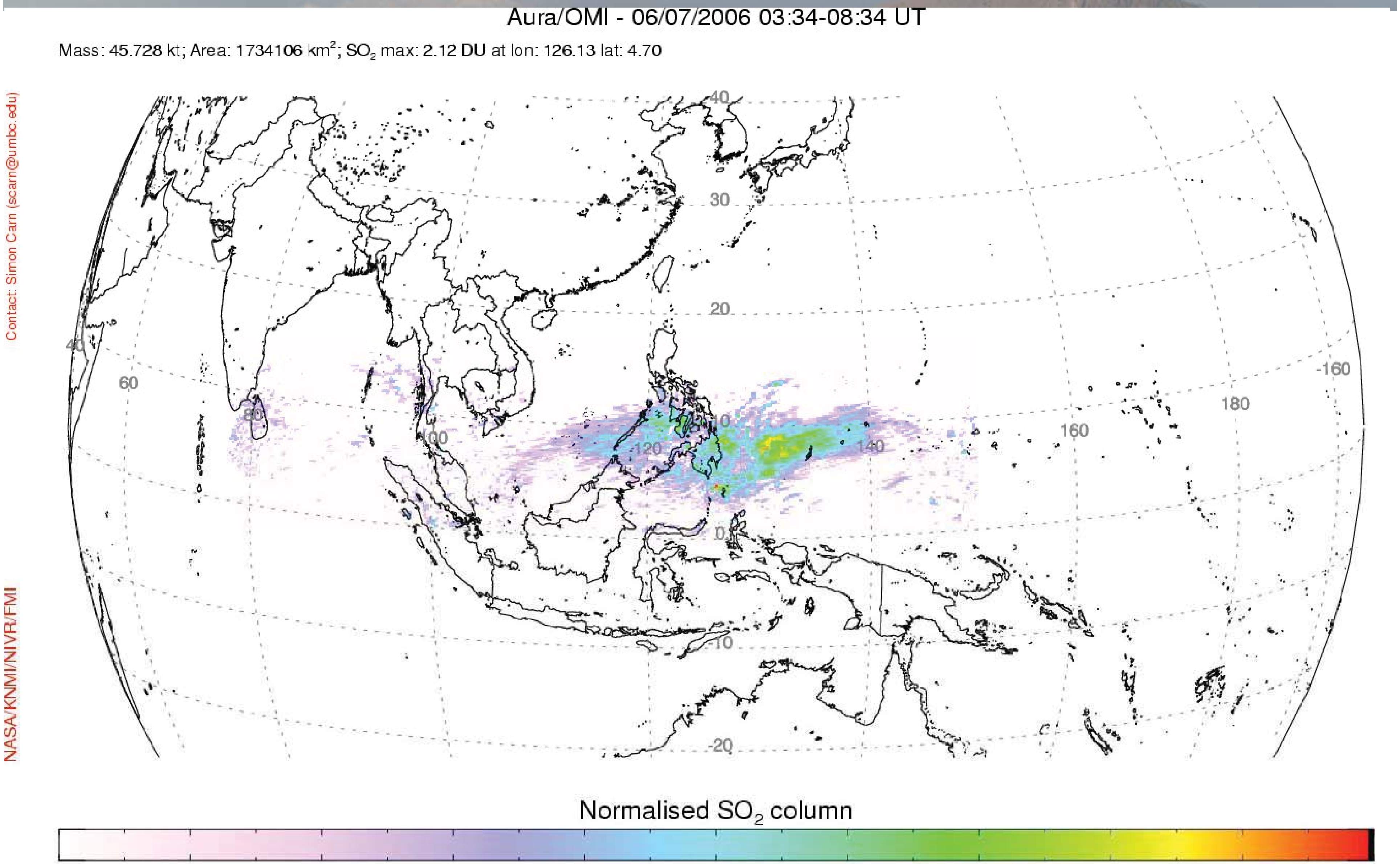
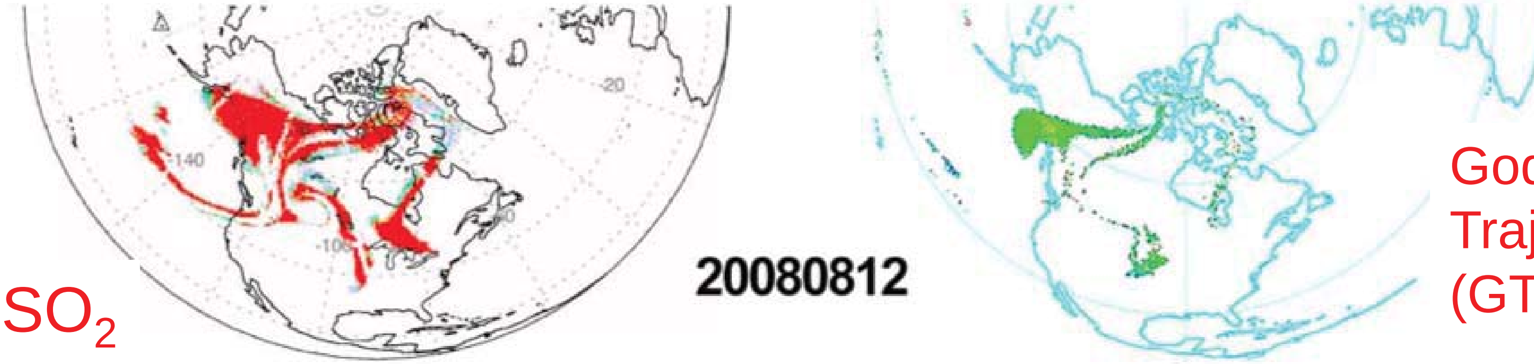


No volcanic SO_2 cloud of similar size tracked for more than 7 days by TOMS

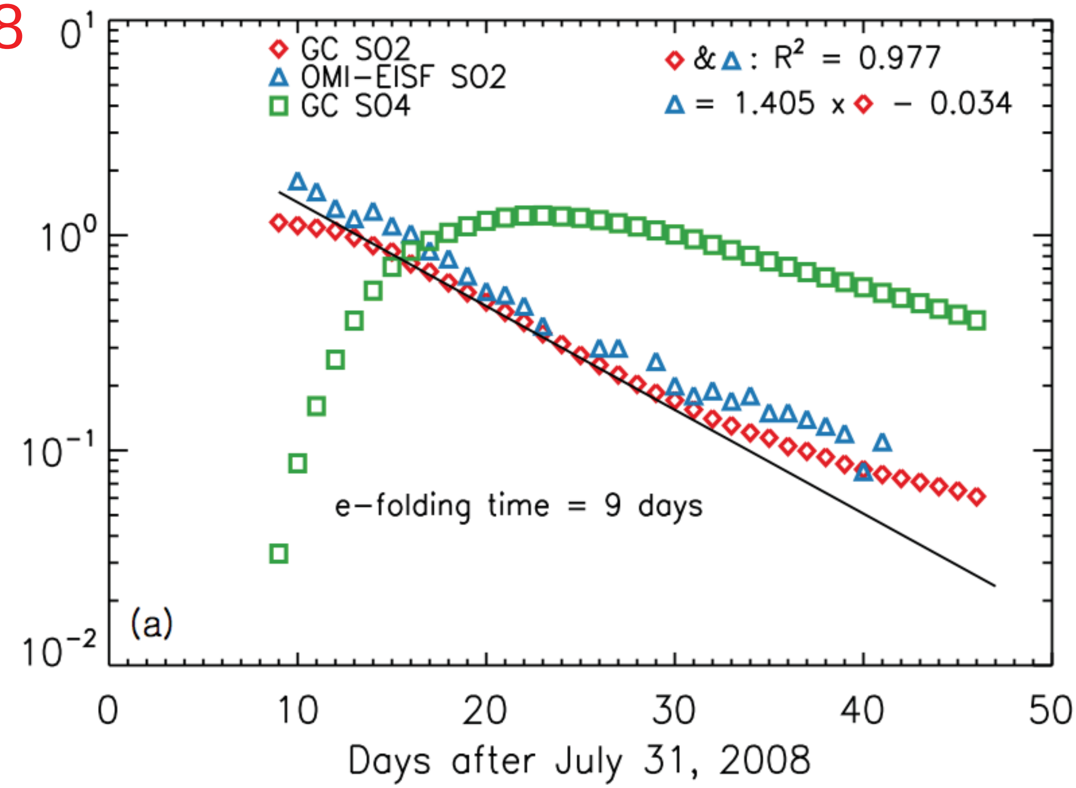
New insights into volcanic SO_2 plume dispersion

OMI SO_2



Goddard Traj. Model (GTM)

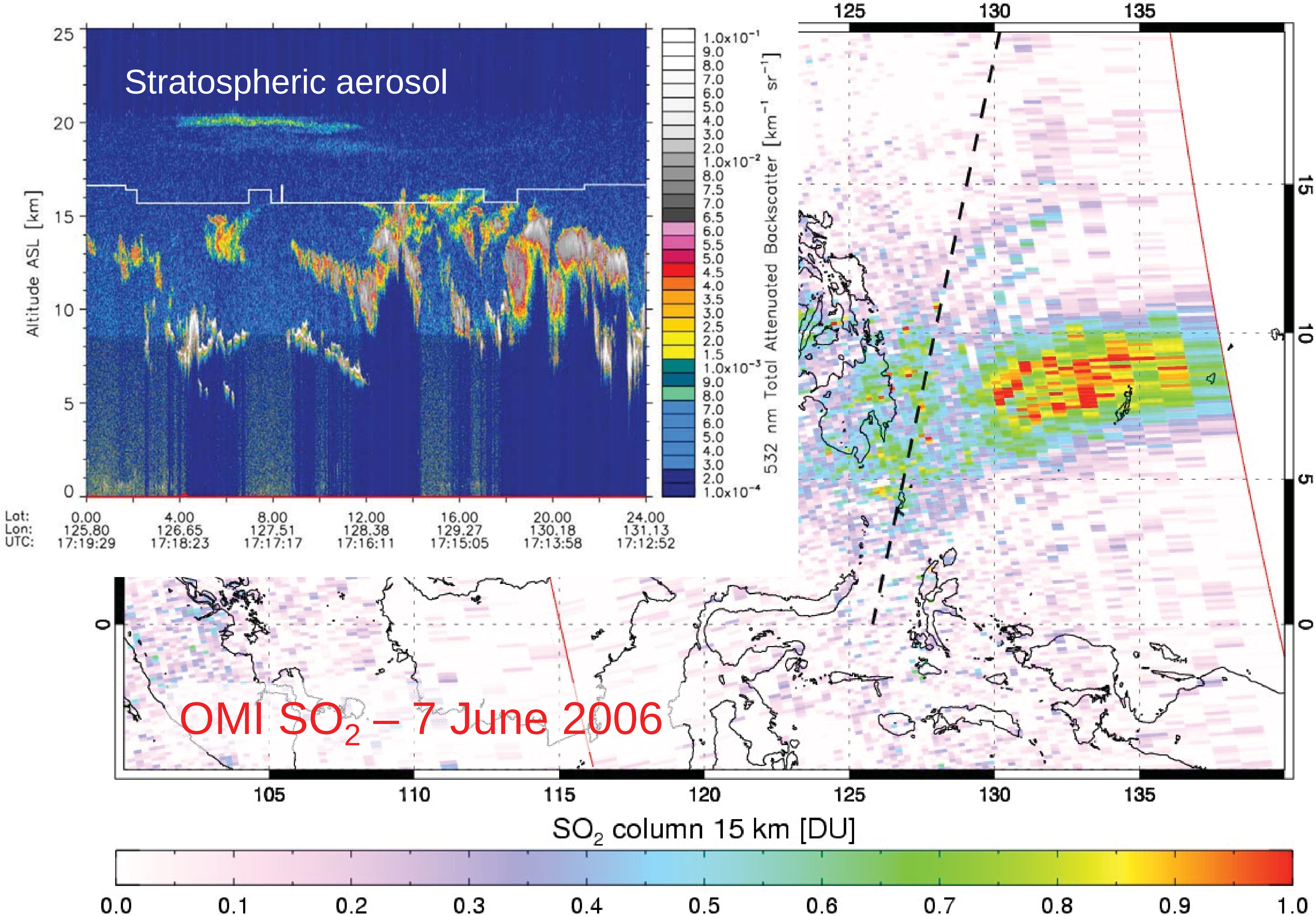
Kasatochi eruption, Aug 2008



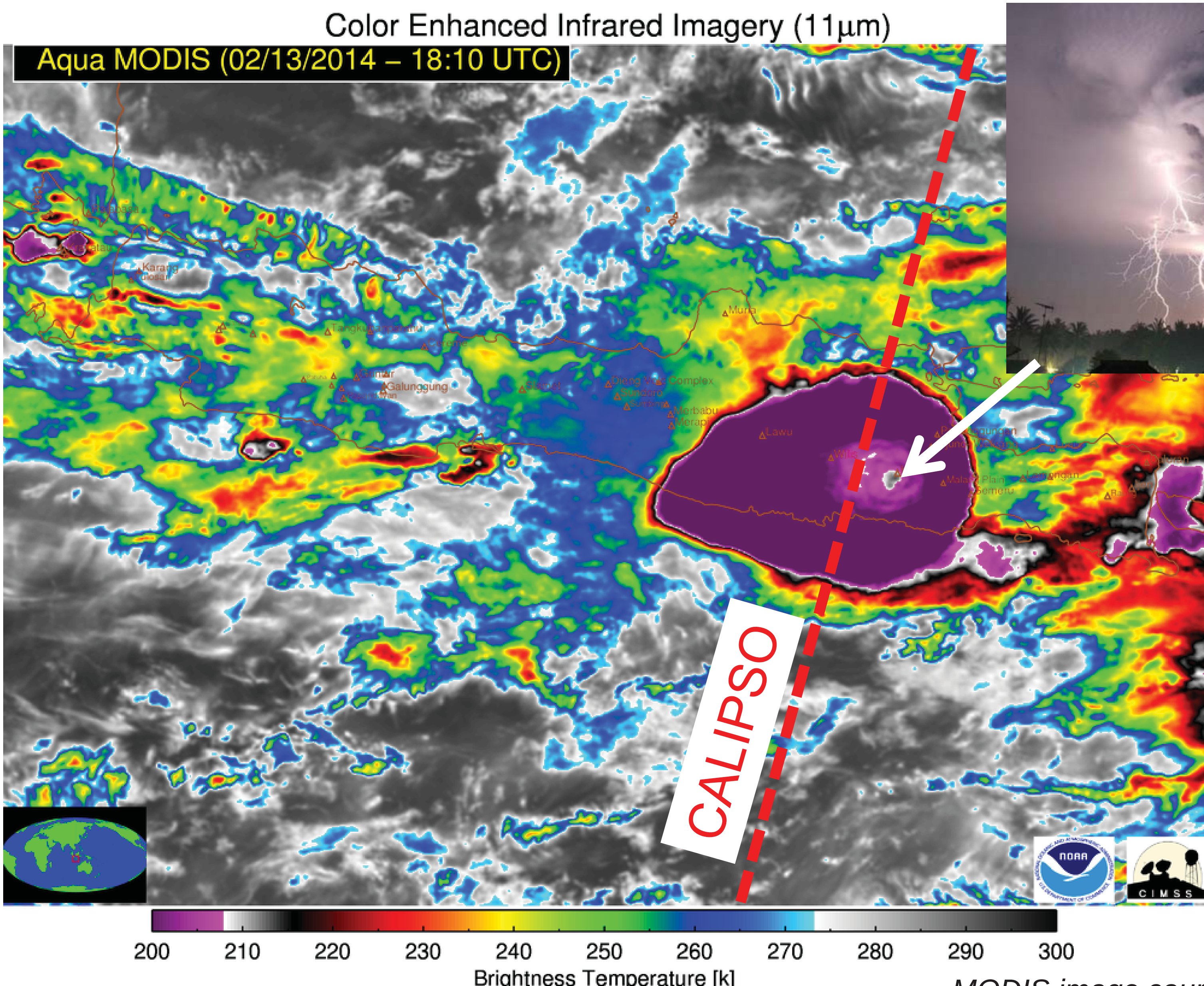
- New constraints on SO_2 lifetime in UTLS
- Improve sulfur chemistry scheme in CTMs

[*Krotkov et al.*, JGR, 2010; *Wang et al.*, ACP, 2013]

CALIPSO first light – 7 June 2006

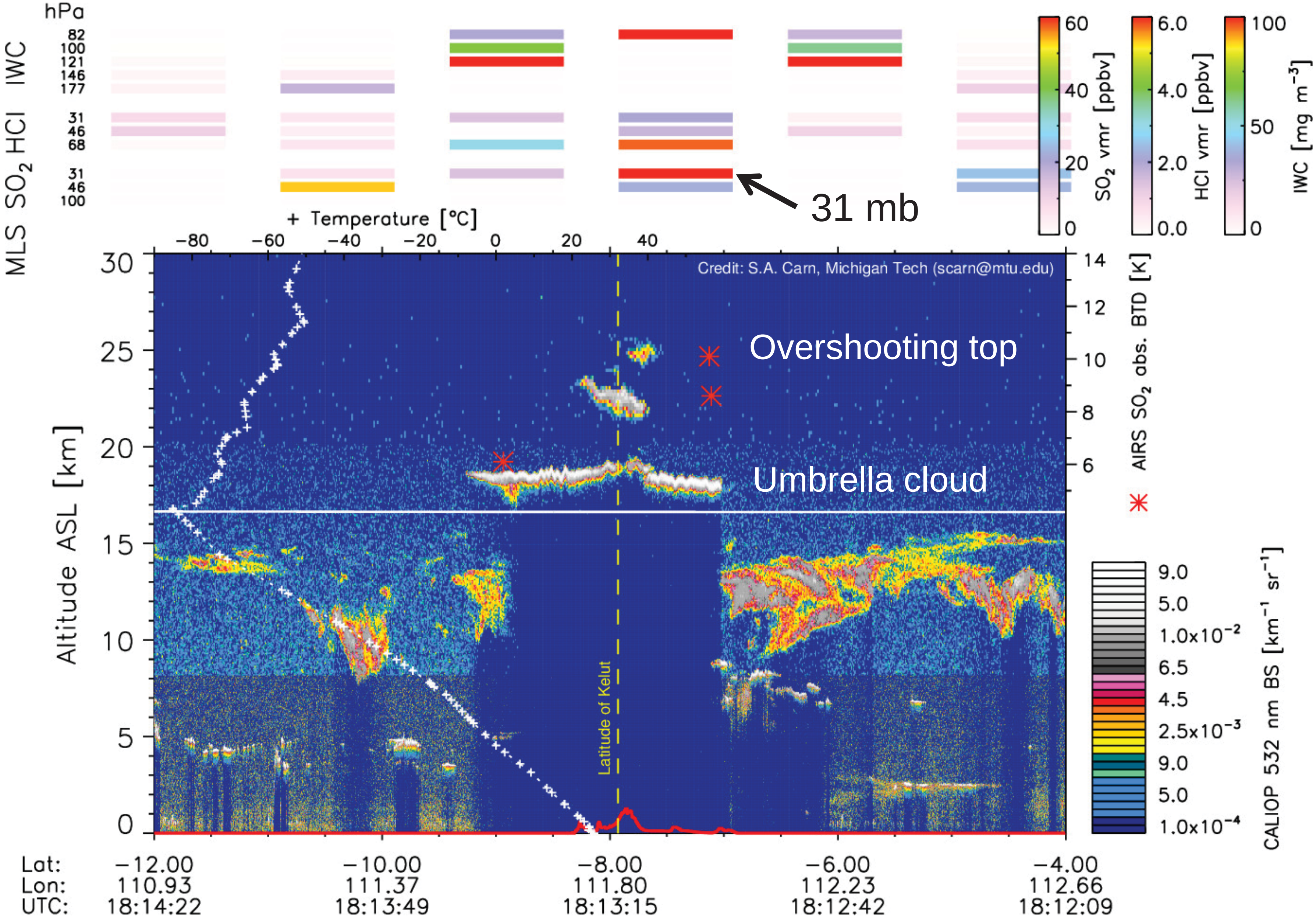


A-Train data for February 2014 Kelut eruption



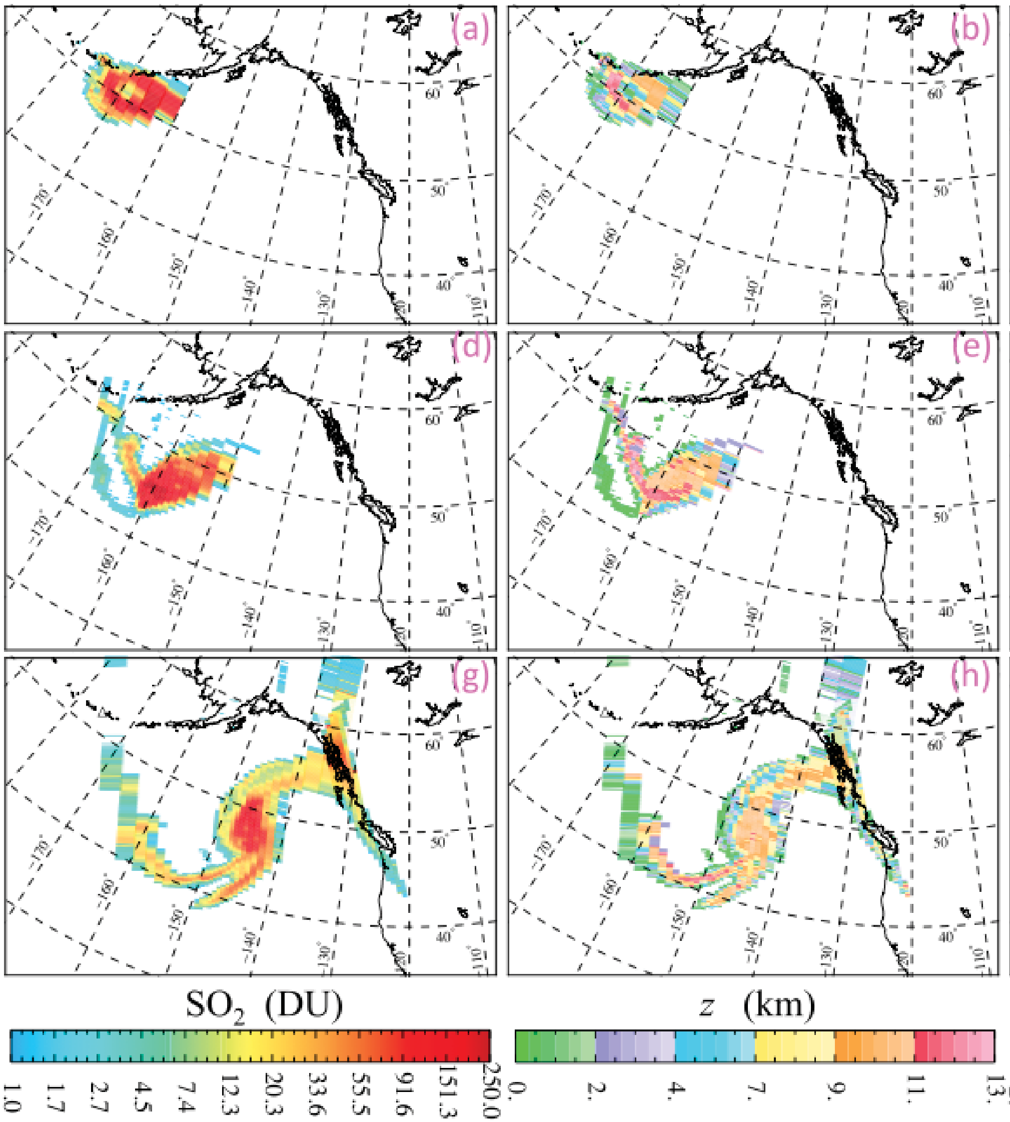
MODIS image courtesy of NOAA/CIMSS

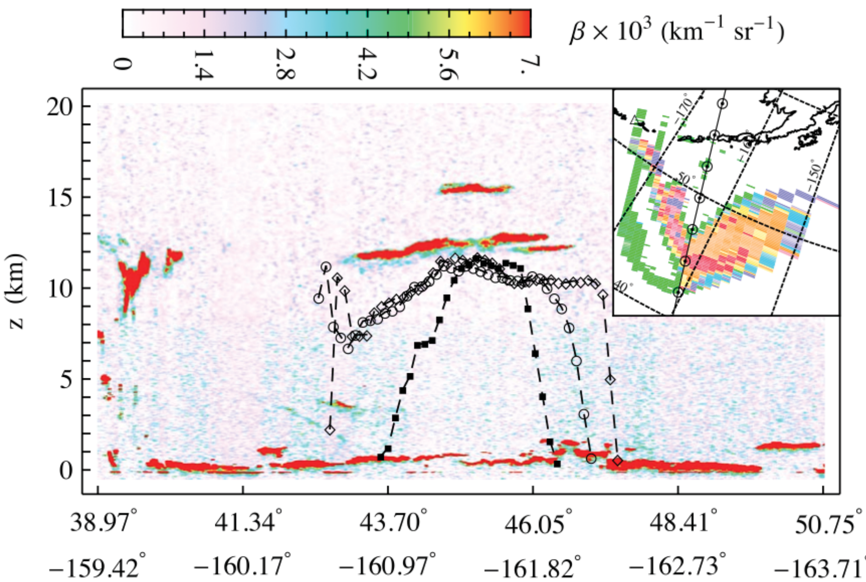
A-Train data for February 2014 Kelut eruption



Kristiansen et al., GRL, in prep.

Direct retrieval of SO_2 altitude from UV radiances





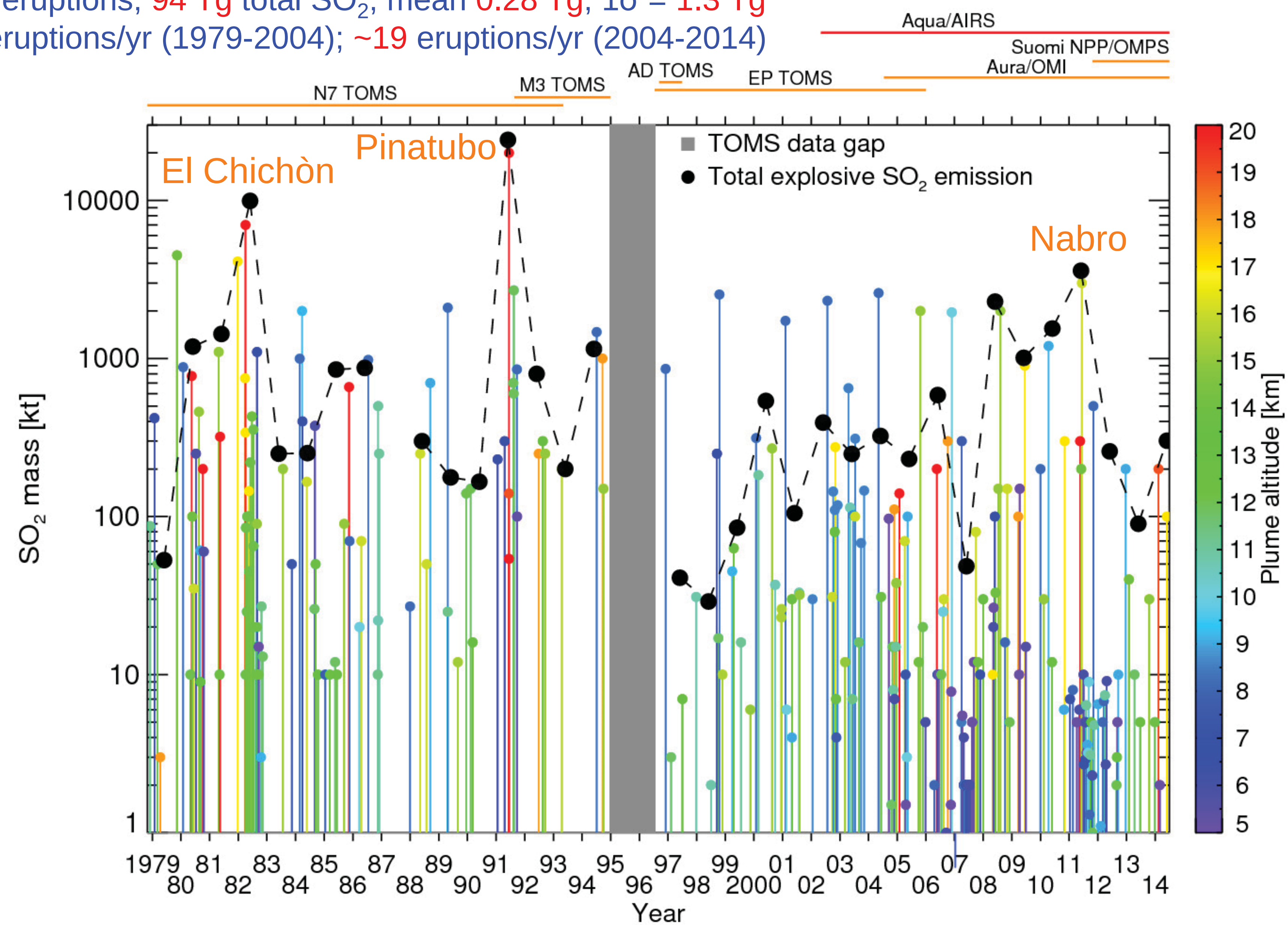
- SO_2 altitude directly retrieved from hyperspectral UV radiances
- Validate with CALIPSO, MLS
- Critical for climate impact, aviation hazards and CTM source term

- SO_2 altitude retrievals for 2008 Kasatochi eruption

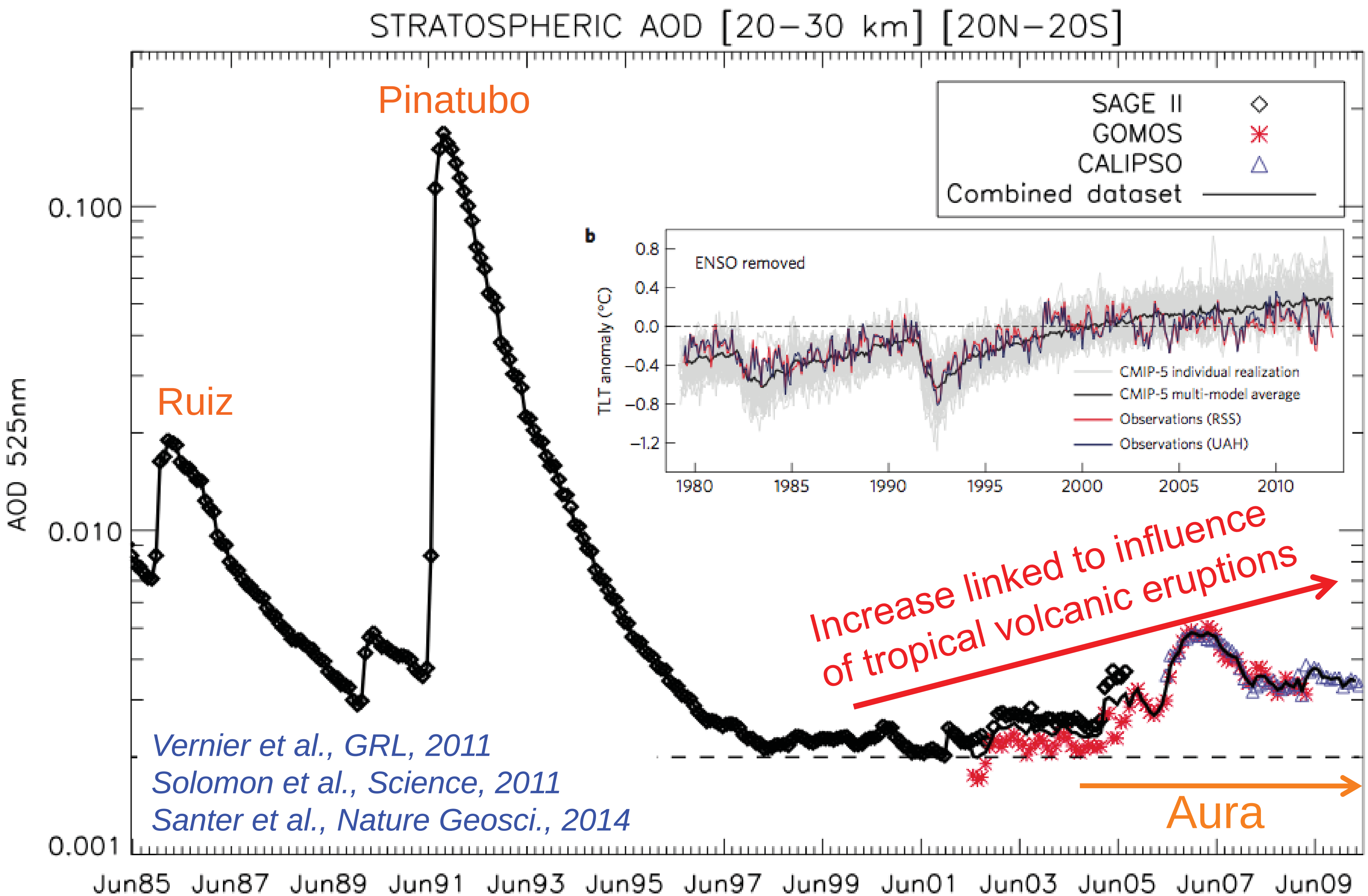
[Yang *et al.*, JGR, 2010]

UV satellite volcanic SO_2 inventory (1978 – 2014)

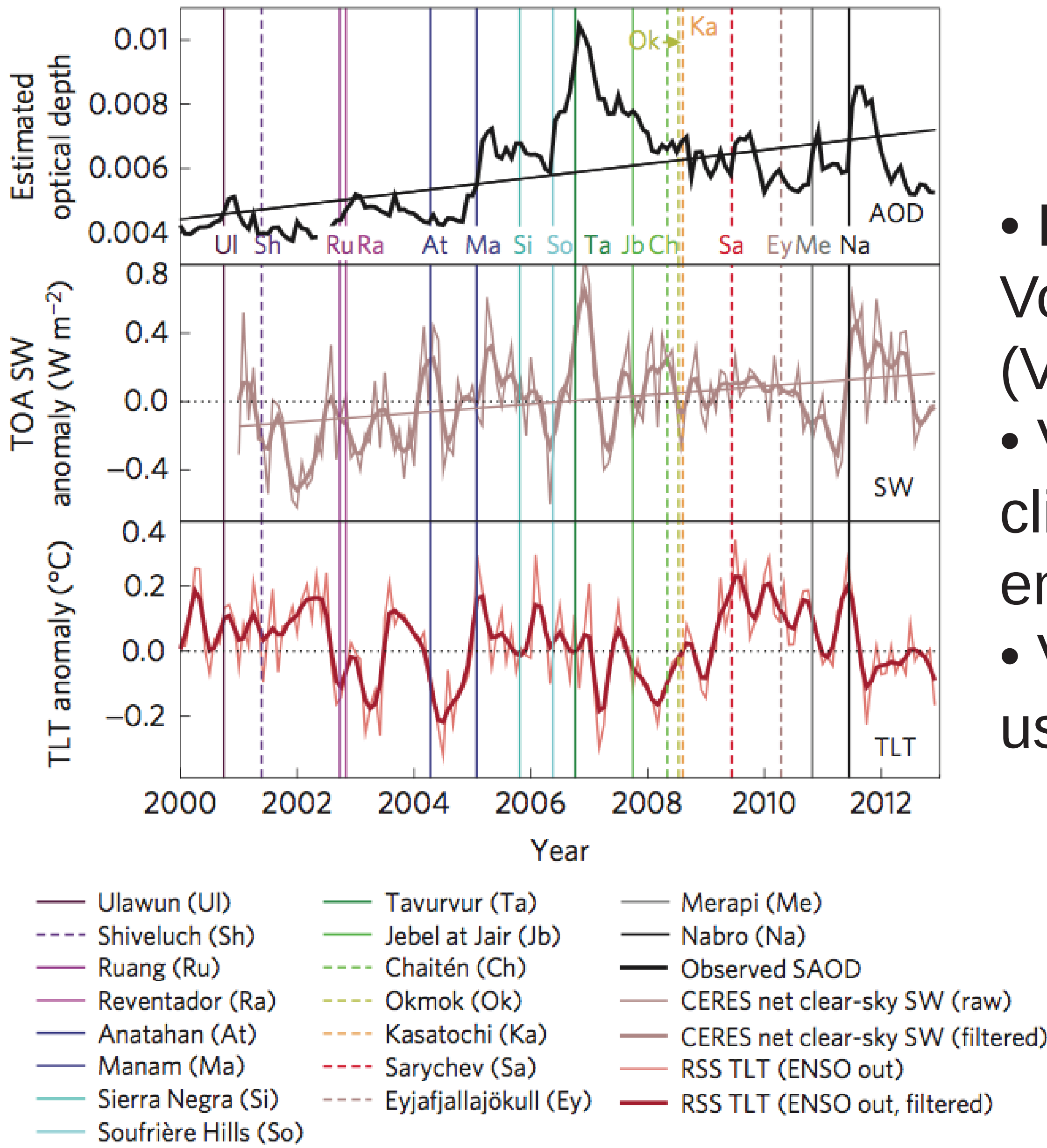
333 eruptions; 94 Tg total SO_2; mean 0.28 Tg; 1σ = 1.3 Tg
~6 eruptions/yr (1979-2004); ~19 eruptions/yr (2004-2014)



Stratospheric AOD and the global warming ‘hiatus’



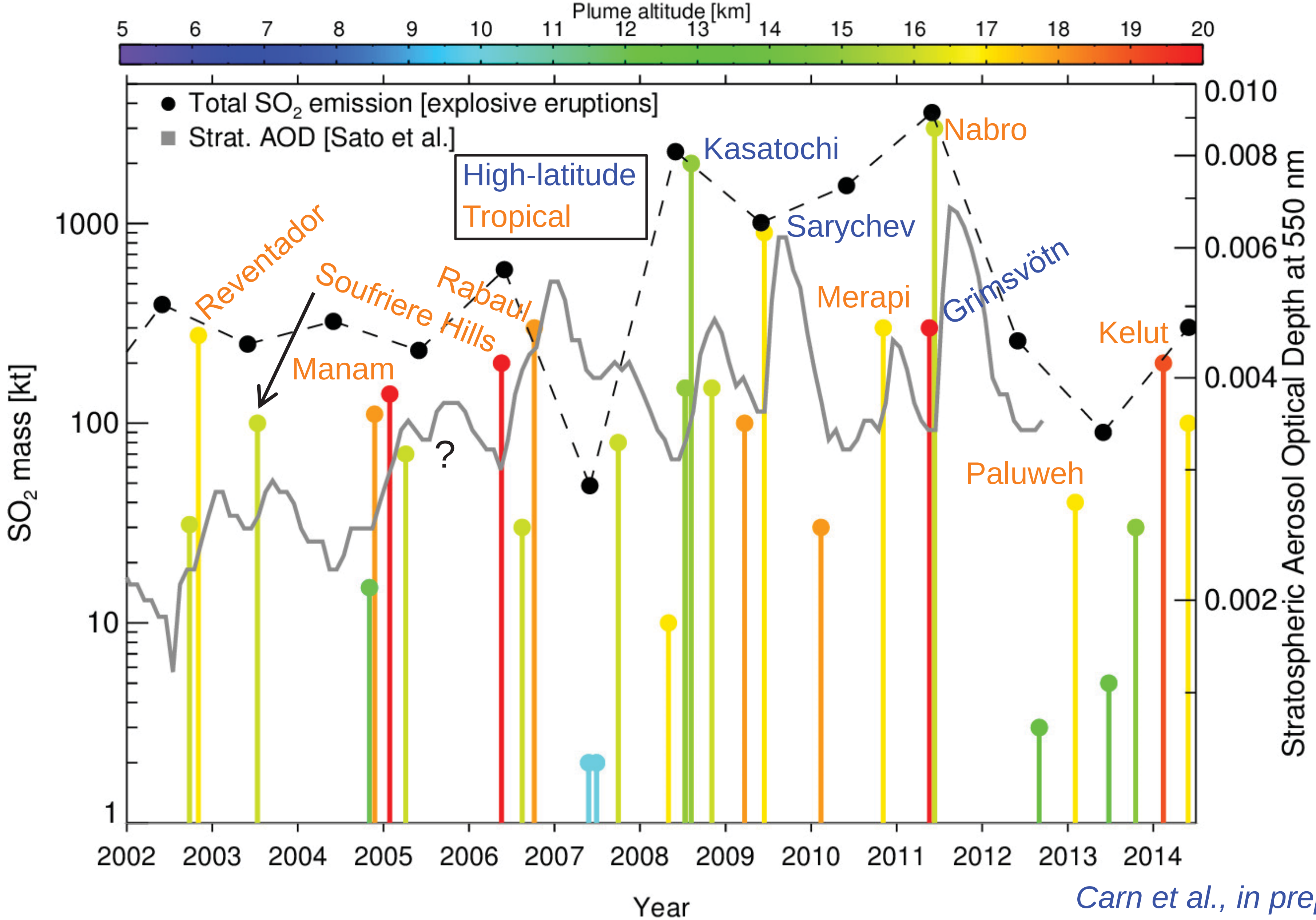
Increase in tropical stratospheric AOD since 2000



- Eruptions filtered using Volcanic Explosivity Index (VEI)
- VEI not a good proxy for climate impact (i.e., SO_2 emissions)
- VEI no longer needed -> use satellite observations

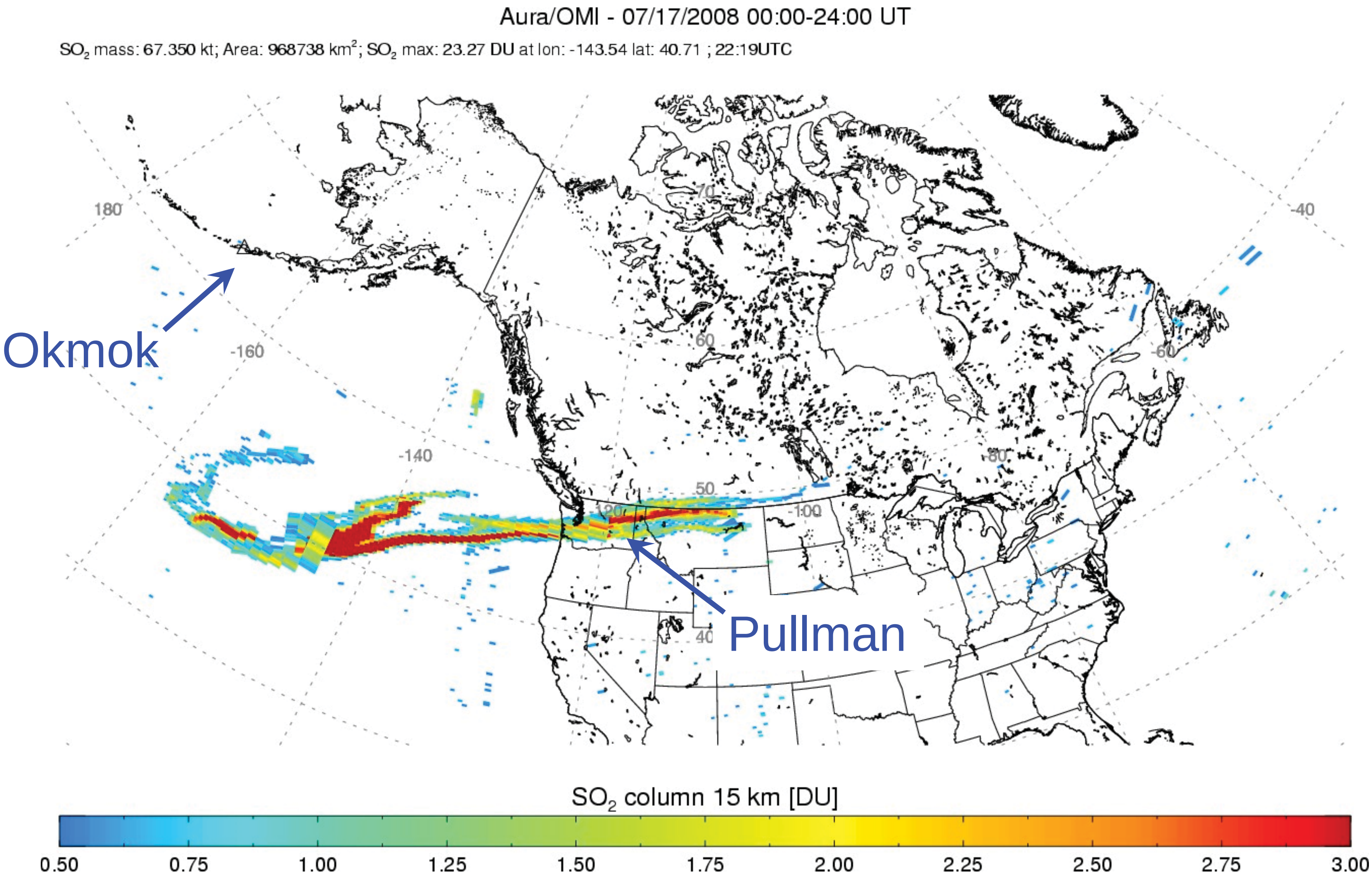
Santer et al., *Nature Geosci.* [2014]

Volcanic SO_2 and stratospheric aerosol since 2002



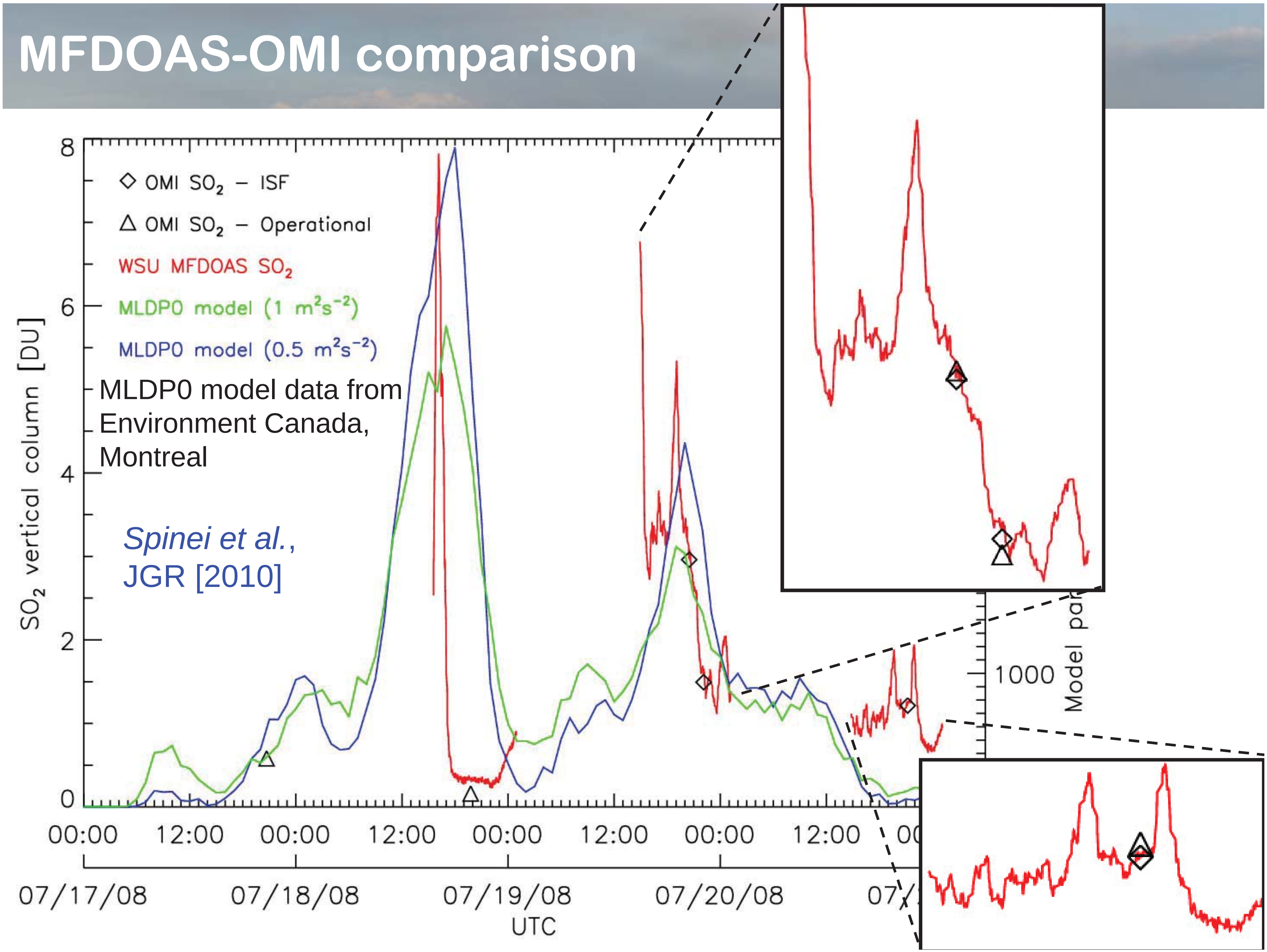
Carn et al., in prep.

OMI SO_2 validation - Okmok (Aleutian Is) eruption



Spinei et al., JGR [2010]

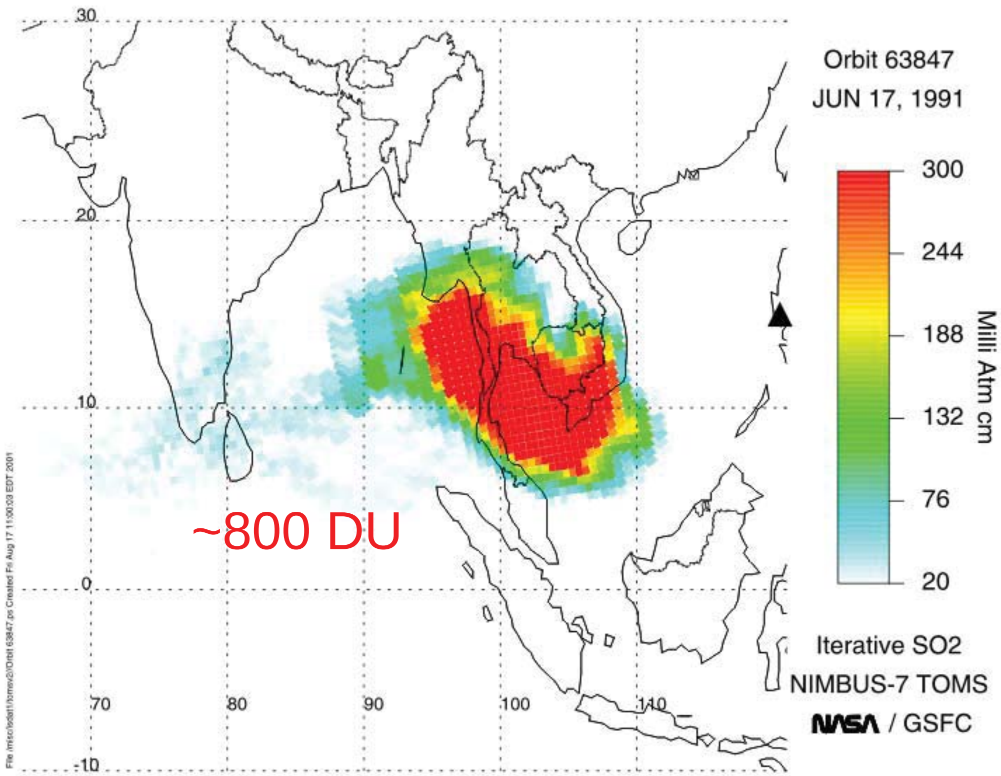
MFDOAS-OMI comparison

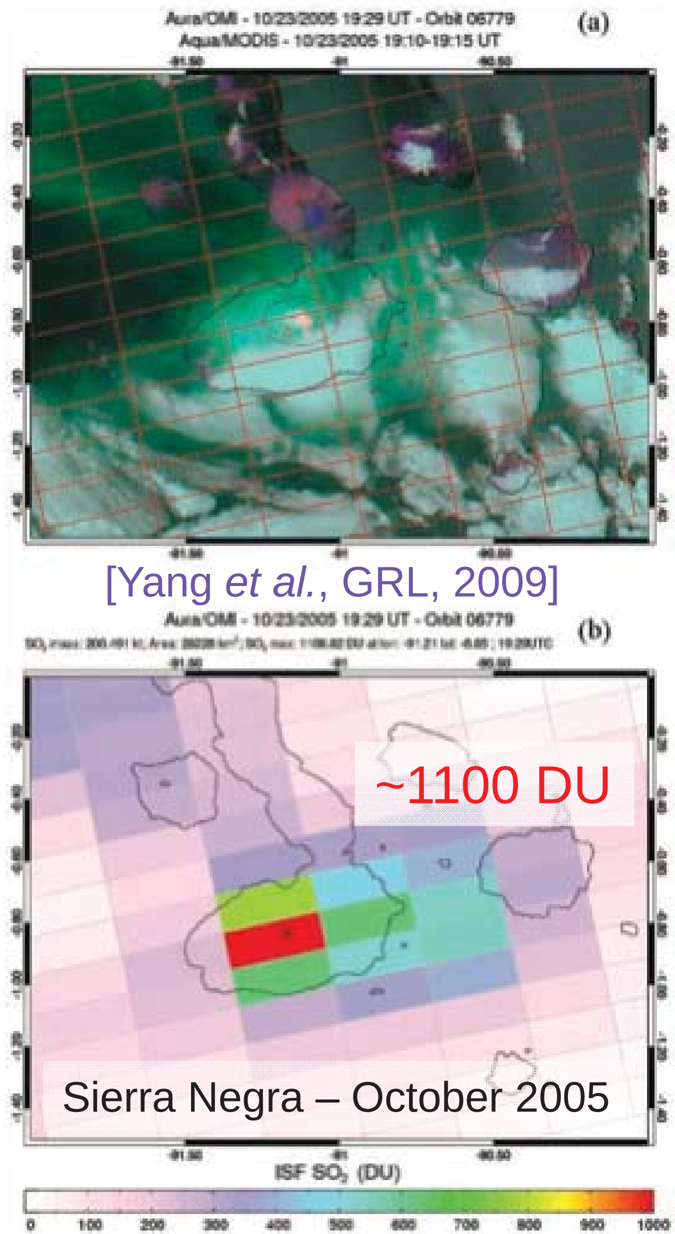


MLDP0 model data from Environment Canada, Montreal

Spinei et al., JGR [2010]

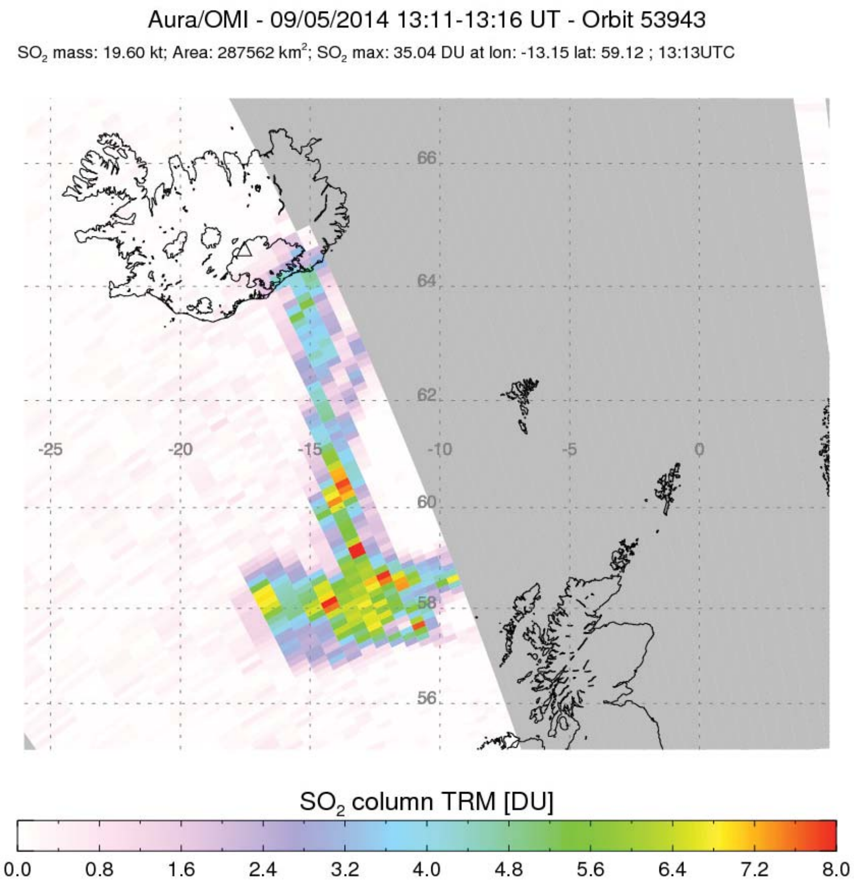
Extreme SO_2 columns in volcanic clouds

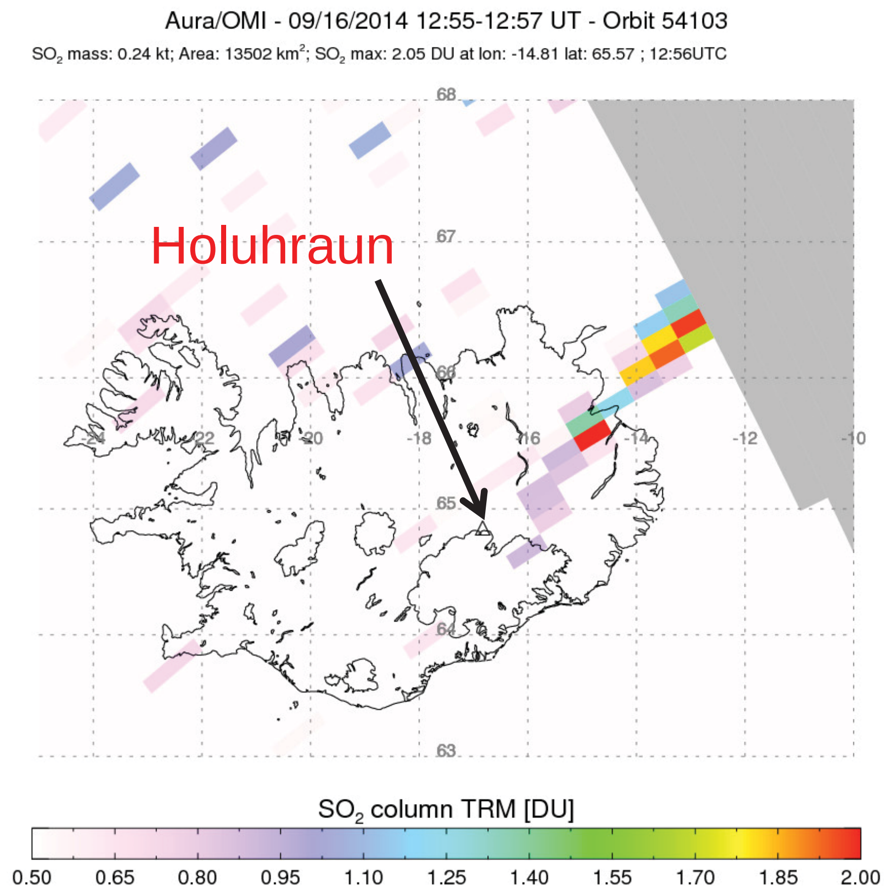




- SO_2 in fresh eruption clouds – highest trace gas columns measured
- Challenge to validate extreme SO_2 column amounts – UAVs, balloons?
- More volc. SO_2 validation needed in general
- Complex radiative transfer (ash, hydrometeors)

Current Bardabunga/Holuhraun eruption (Iceland)





Request from Icelandic Meteorological Office: *'We are getting very nice OMI images of the SO_2 rich eruption cloud from the Holuhraun eruption. Could you help us to set up a way of turning the OMI observations into daily SO_2 mass and daily SO_2 emission rates? It's possible this eruption will last weeks or months and so we need such a technique to be automated and fast.'*

OMI SO_2 data used in: U.S., Mexico, Guatemala, El Salvador, Costa Rica, Montserrat, Ecuador, Colombia, Peru, Chile, New Zealand, Vanuatu, Indonesia, Papua New Guinea, Philippines, DR Congo, Ethiopia, Russia, France

Summary

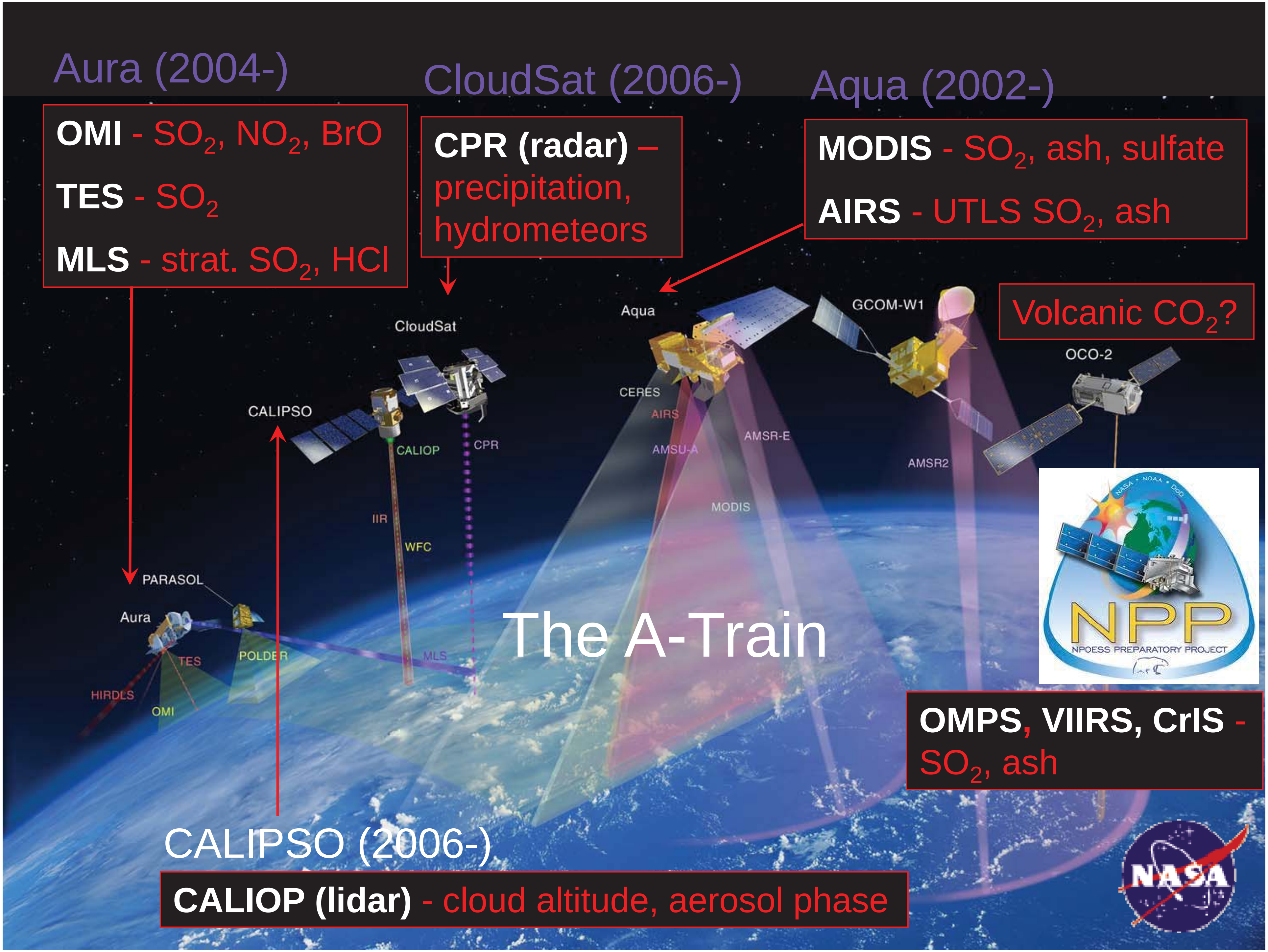
- Science contributions and applications of Aura/OMI SO_2
  - Identification of new volcanic and anthropogenic SO_2 sources
  - Updated volcanic SO_2 emissions inventory
  - Effect of small volcanic eruptions on climate
  - Radiative forcing of volcanic sulfate aerosol
  - Volcanic aerosol enhancement of lightning activity
  - Cloud seeding by volcanic aerosol downwind of volcanoes
  - Lifetime of SO_2 in upper troposphere and lower stratosphere
  - Sulfur gas scavenging in eruption columns
  - Improving sulfur chemistry in CTMs
  - Volcanic plume tracking for aviation hazard mitigation
  - Detection of eruptions in remote regions
- Future developments in satellite SO_2 observations
  - Improved spatial resolution (e.g., TROPOMI) -> better monitoring capability
  - Direct assimilation of volcanic SO_2 observations into CTMs

Thanks to:

the Aura Science and OMI SIPS Teams

NASA for support from the Aura Validation program, Aura Science Team, ACMAP program, MEaSUREs program

Ambrym volcano (Vanuatu) – one of the strongest SO_2 sources on Earth


Aura (2004-)
OMI - SO_2, NO_2, BrO
TES - SO_2
MLS - strat. SO_2, HCl
CloudSat (2006-)
CPR (radar) – precipitation, hydrometeors
Aqua (2002-)
MODIS - SO_2, ash, sulfate
AIRS - UTLS SO_2, ash
Volcanic CO_2?
Aqua
CloudSat
GCOM-W1
OCO-2
CALIPSO
CERES
AIRS
AMSU-A
AMSR-E
AMSR2
CALIOP
CPR
MODIS
IIR
WFC
PARASOL
Aura
TES
POLDER
MLS
HIRDLS
OMI
The A-Train
NPP
NPOESS PREPARATORY PROJECT
NASA NOAA DoD
OMPS, VIIRS, CrIS - SO_2, ash
CALIPSO (2006-)
CALIOP (lidar) - cloud altitude, aerosol phase
NASA

2008

MLS HCl

MLS SO_2

OMI SO_2