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Remote sensing of volcanic gas emissions in the East African Rift

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Remote Sensing of Volcanic Gas Emissions in the East African Rift

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Features of EAR volcanism

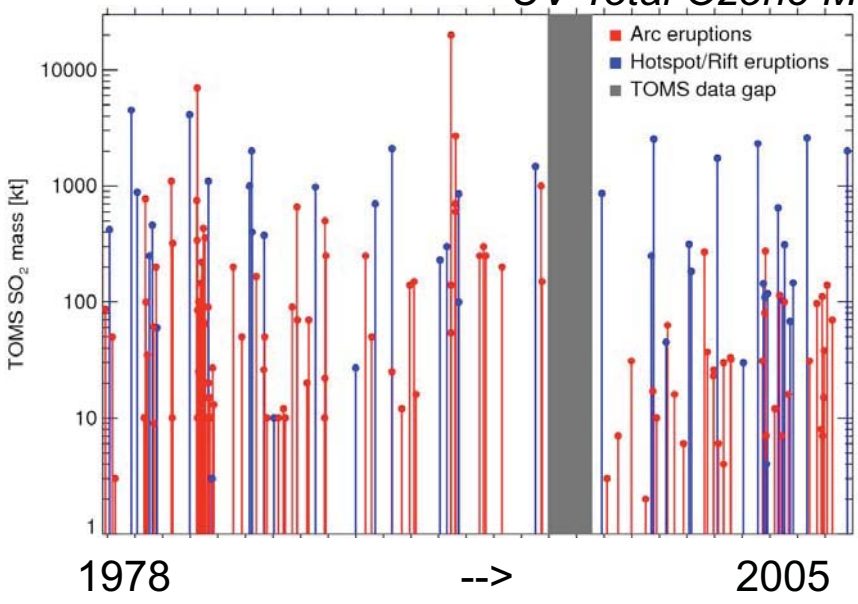
- Lava lakes (Nyiragongo, Erta'Ale, Karthala)
  - Excellent targets for IR spectroscopy (FTIR)
  - Fresh magmatic gases
- Low viscosity, alkaline magmas
  - Efficient degassing
  - CO_2-rich gases
- Tectonically-controlled eruptions
  - e.g., Nyiragongo, Jan 2002
  - Rapid onset
  - Eruption precursors?
- Lake overturn and degassing
  - Nyos, Monoun, Kivu (CO_2, CH_4)

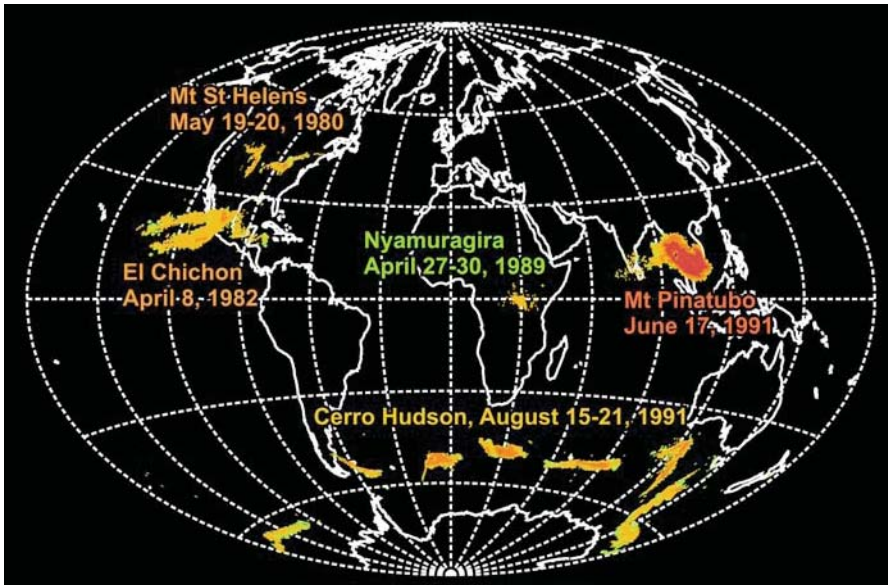
Overview of current satellite capabilities

- Measurements at UV, Visible, IR and microwave wavelengths
  - UV: daytime only
  - IR, microwave: day/night
- Passive (UV, IR) and active (RADAR, LIDAR)
  - Passive sensors: mapping volcanic clouds and plumes
  - Active sensors: measure volcanic cloud altitude; poor spatial sampling
- Volcanic emissions measured by >10 satellite sensors
  - SO_2 measured using UV, IR and microwave wavelengths
  - Sensitivity to passive degassing in UV and IR
  - Spatial resolution: 90 m to 80 km
  - Volcanic HCl and BrO can also be measured in large eruptions
  - Near real-time (NRT) data available from some instruments
  - Volcanic CO_2 detection: very challenging but under investigation

Advantages of satellite measurements

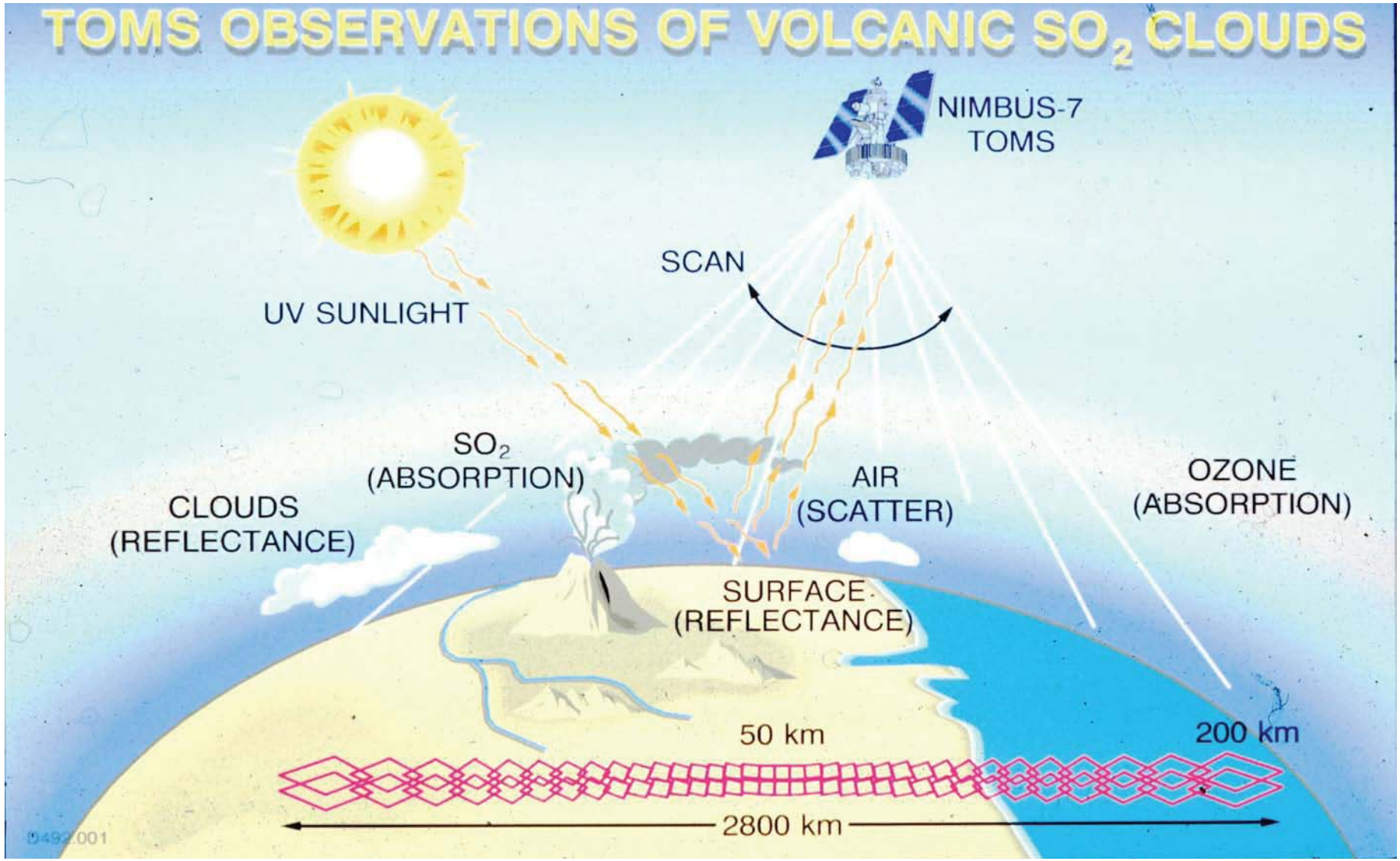
UV Total Ozone Mapping Spectrometer (TOMS)





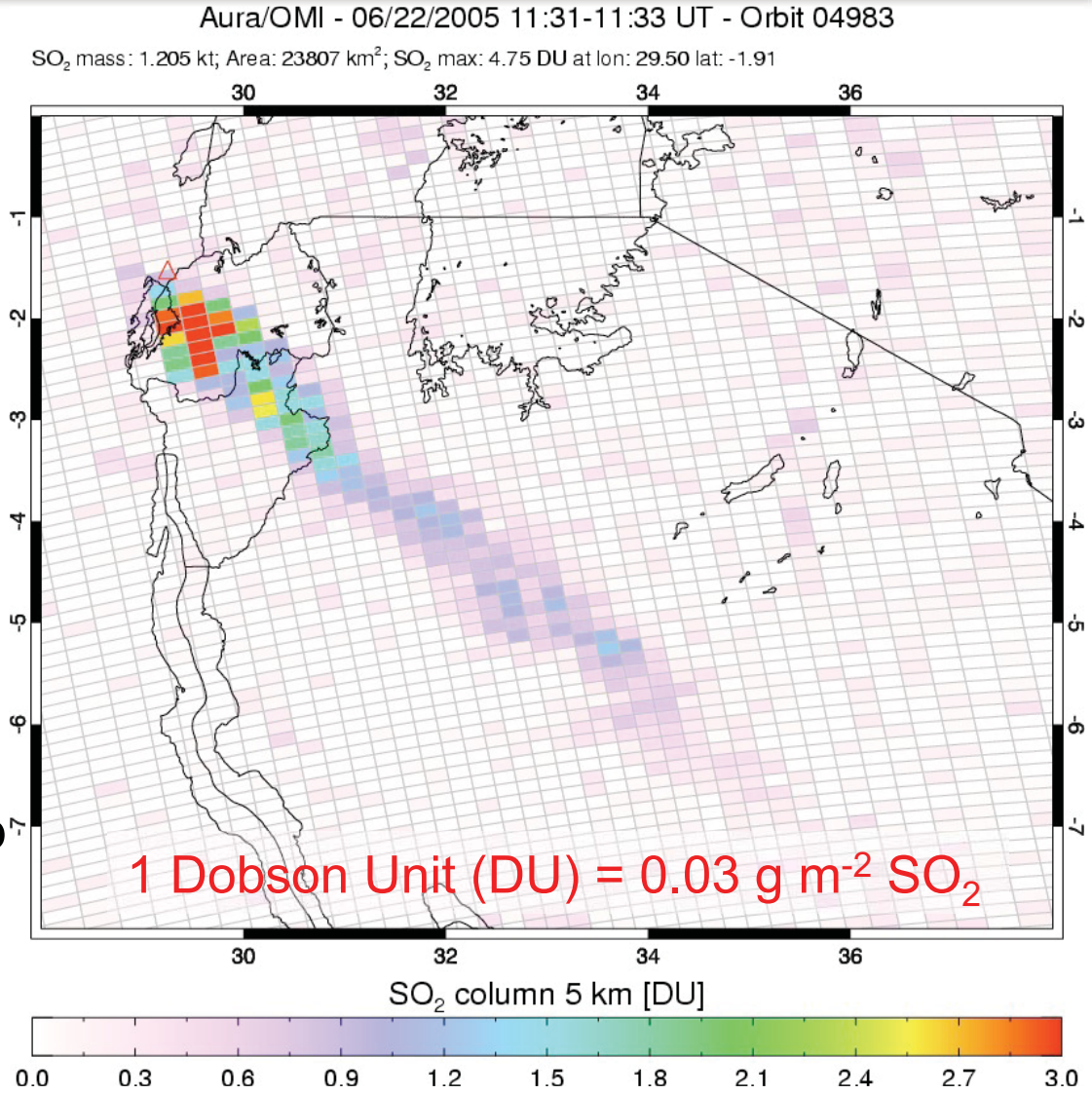
- Always ‘on’
- Global scale measurements
- Capture unexpected events
- Long-term data from a single sensor
- No risk
- Low-cost (after initial investment)

UV Backscatter measurements from space



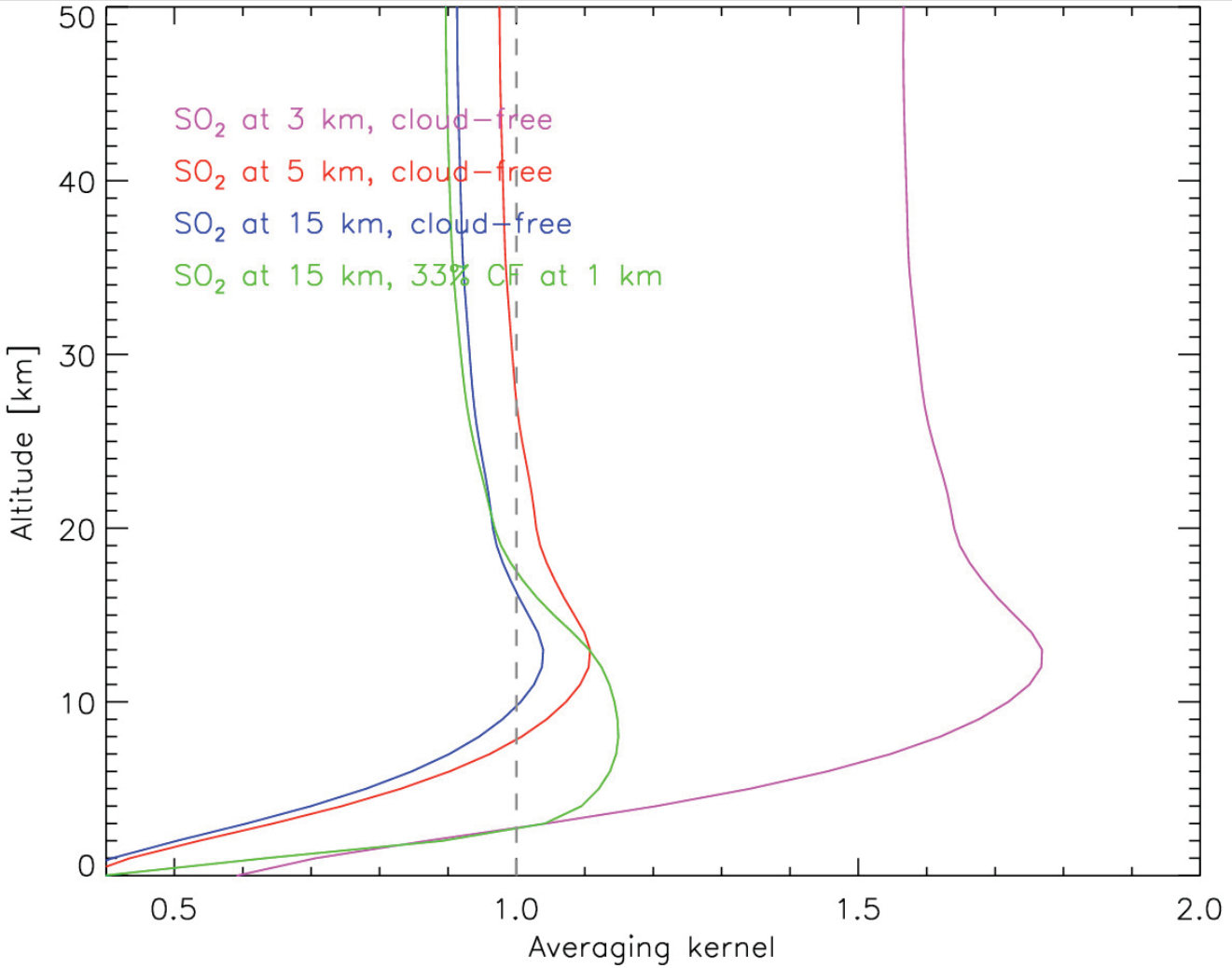
Ozone Monitoring Instrument (OMI)

- UV/Visible sensor
- On NASA/Aura satellite
- Launched July 2004
- Daily contiguous global coverage
- 13 x 24 km nadir pixel
- Overpass at 1:30-2:00 pm local time
- Measures SO_2 total column (plus other gases and aerosols)
- NRT SO_2 data available on web
- Data publicly available and free



- The first satellite sensor to provide daily, global SO_2 measurements with sensitivity to the lower troposphere (i.e., passive degassing)

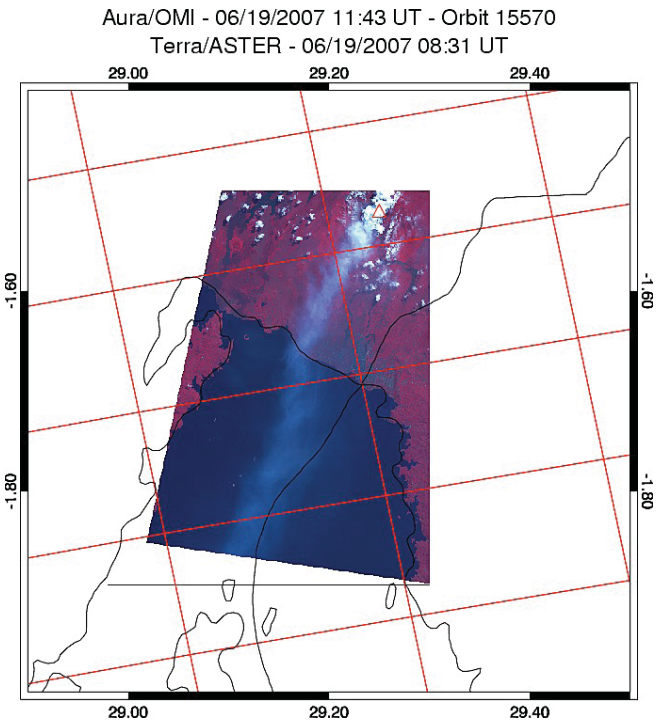
Effect of volcanic plume altitude

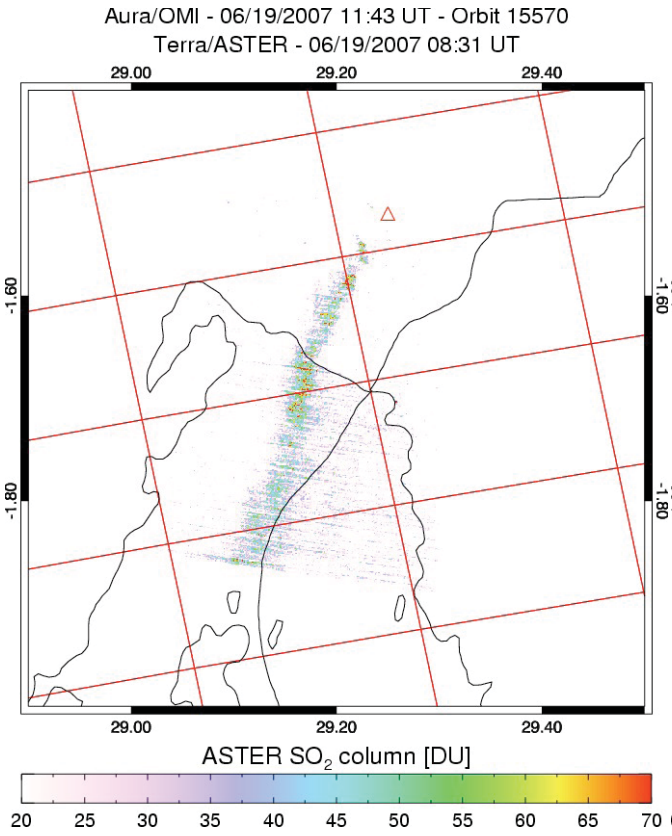


- Knowledge of SO_2 cloud altitude critical for accurate SO_2 retrieval
- Increasing the altitude of the SO_2 cloud increases sensitivity and vice versa

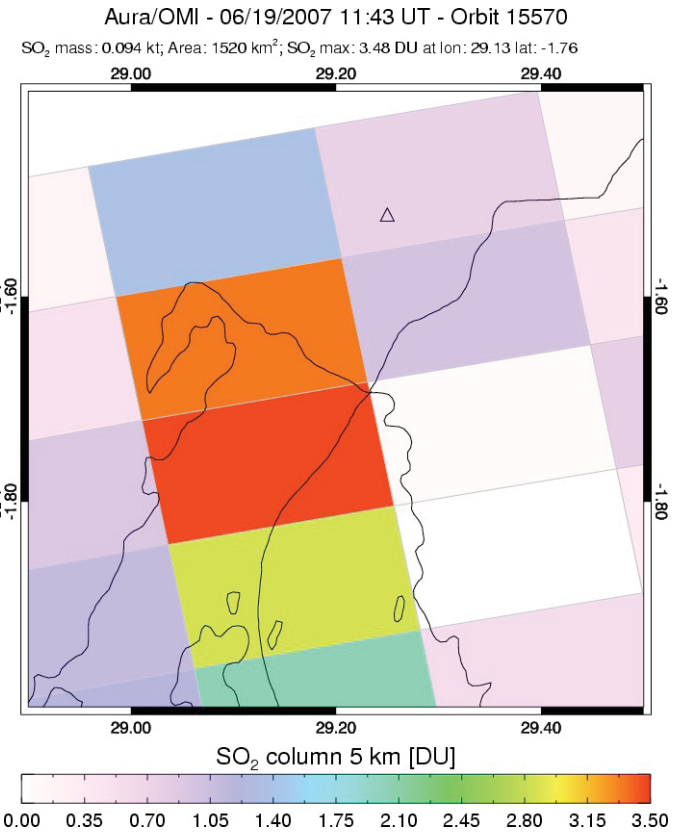
Effect of sensor spatial resolution

Terra ASTER (10:30 am)



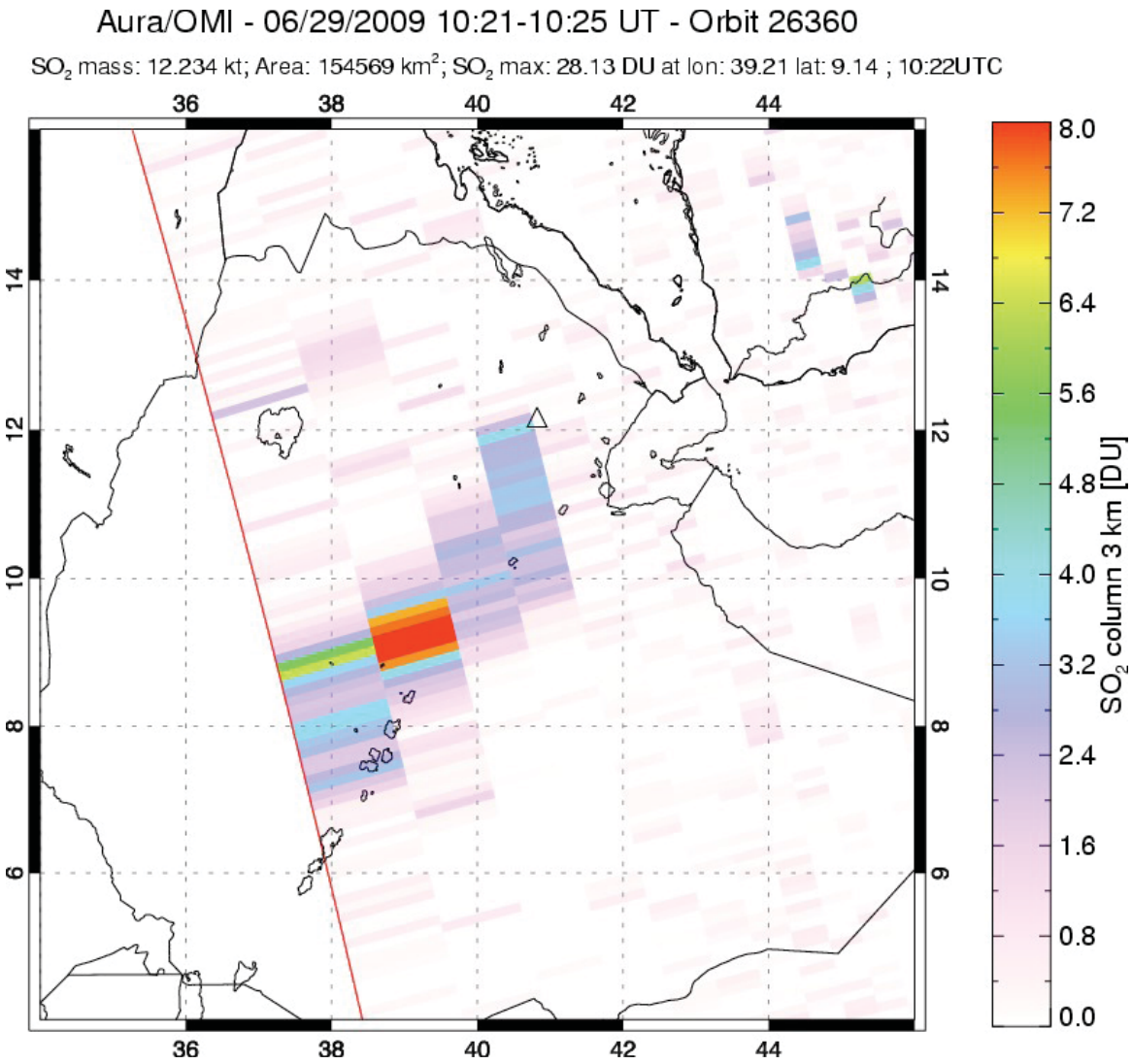


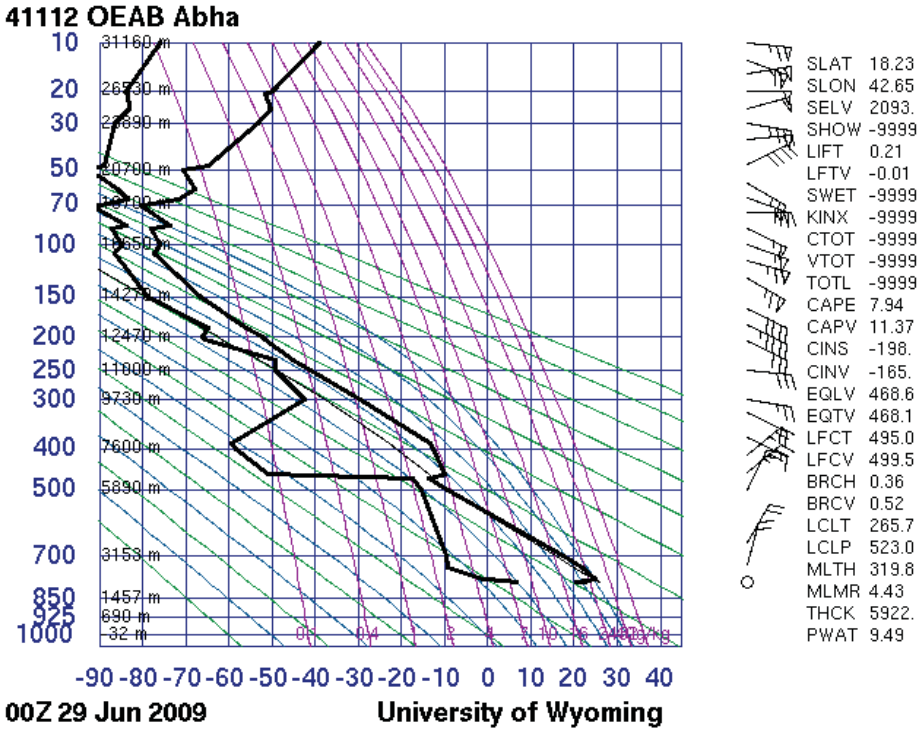
Aura OMI (1:45 pm)



- SO_2 concentration is averaged over the area of each sensor pixel
- Limits detection of volcanic plumes of sub-pixel spatial extent

Manda Hararo eruption – June 29, 2009



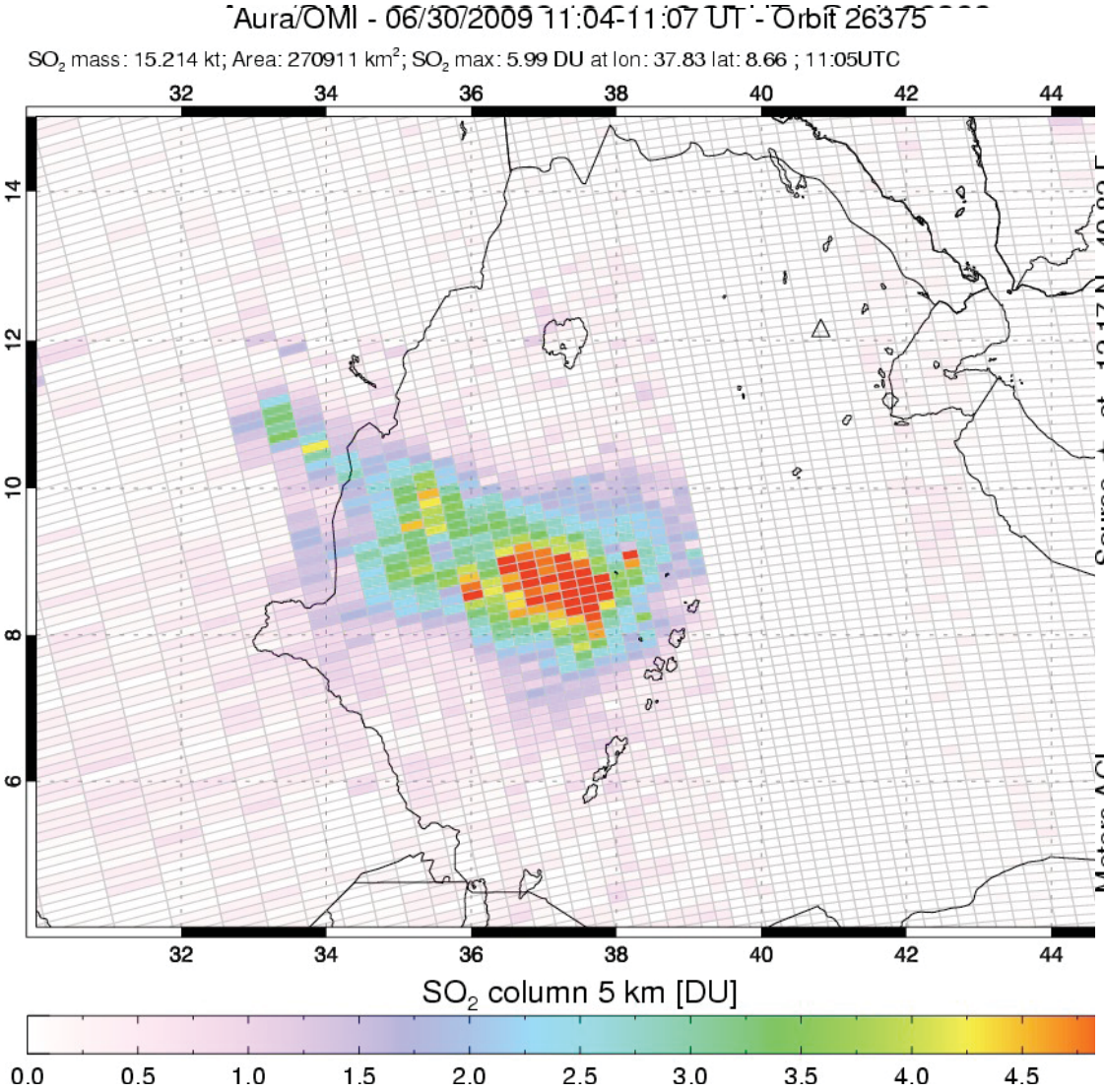


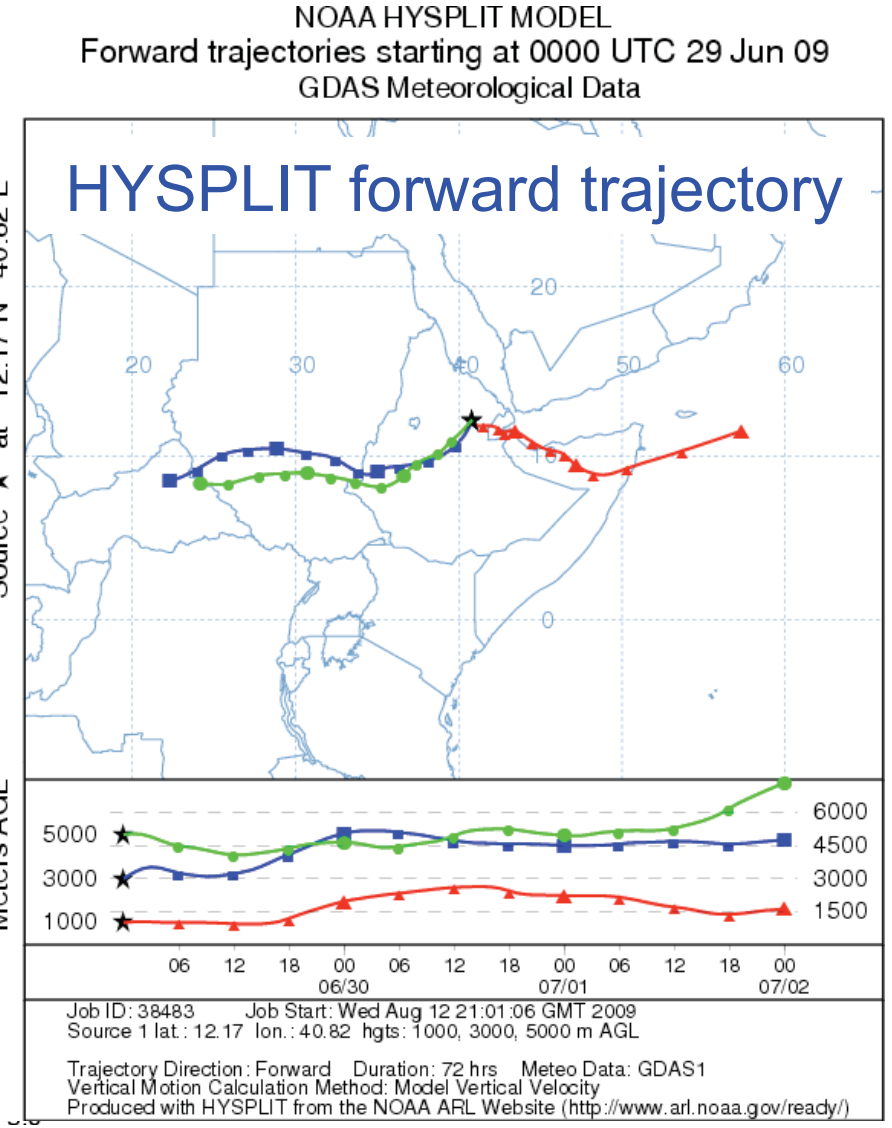
Radiosonde sounding
Abha, Saudi Arabia
29 June 2009 00:00 UT

Eruption @ ~00:00 UT June 29

MichiganTech

Manda Hararo eruption – June 29, 2009





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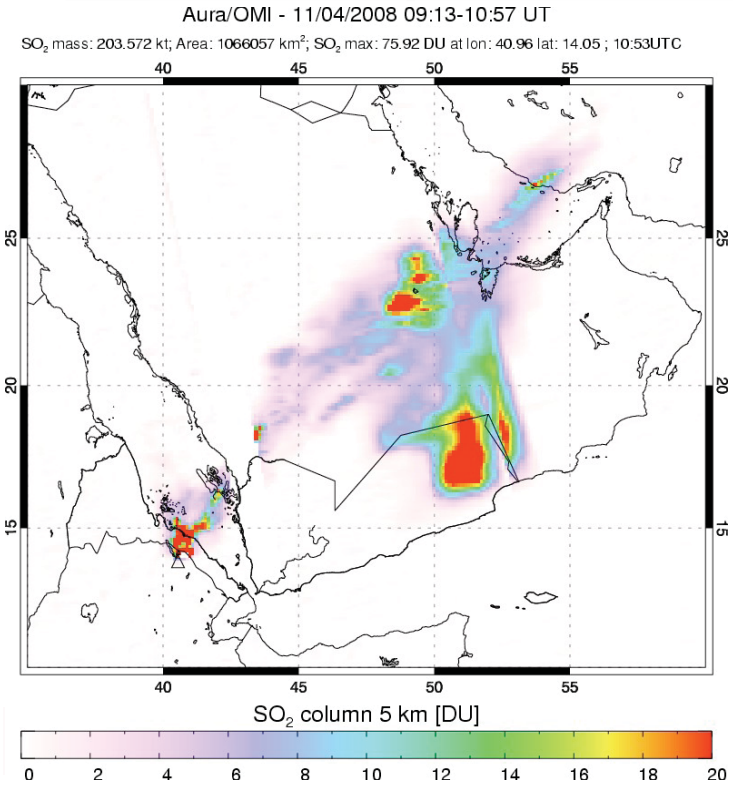
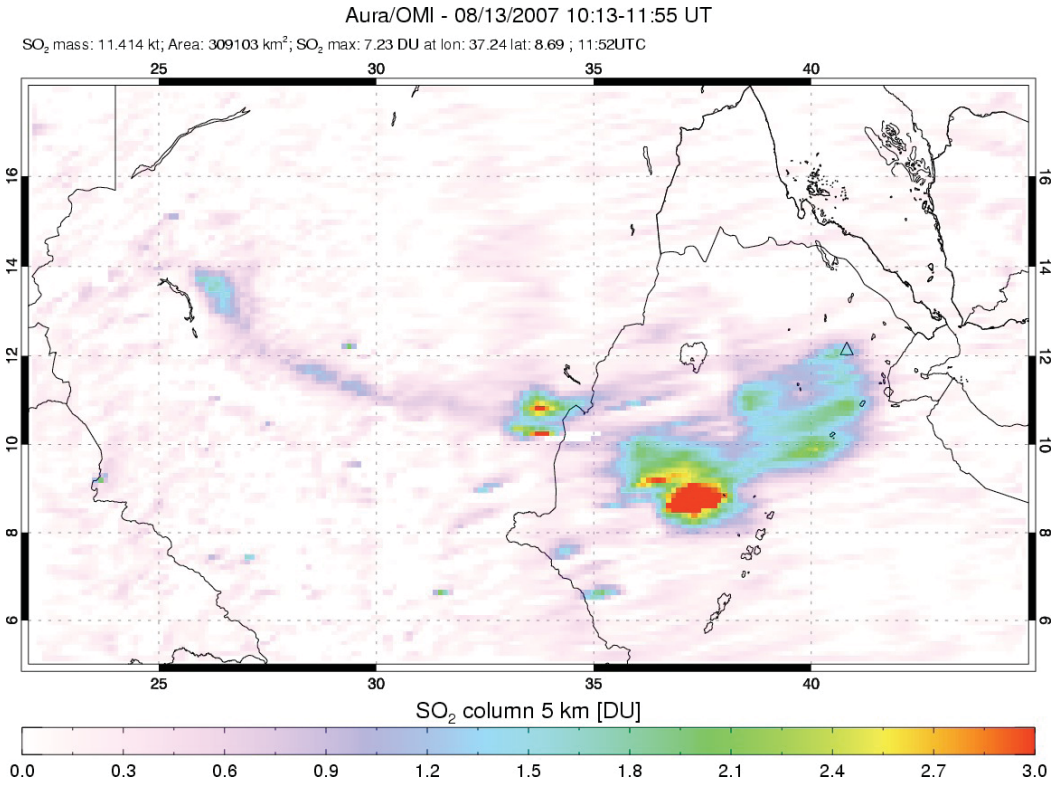
Afar-Red Sea eruption sequence

Lava flow volumes courtesy Matt Patrick, HVO (from ASTER)

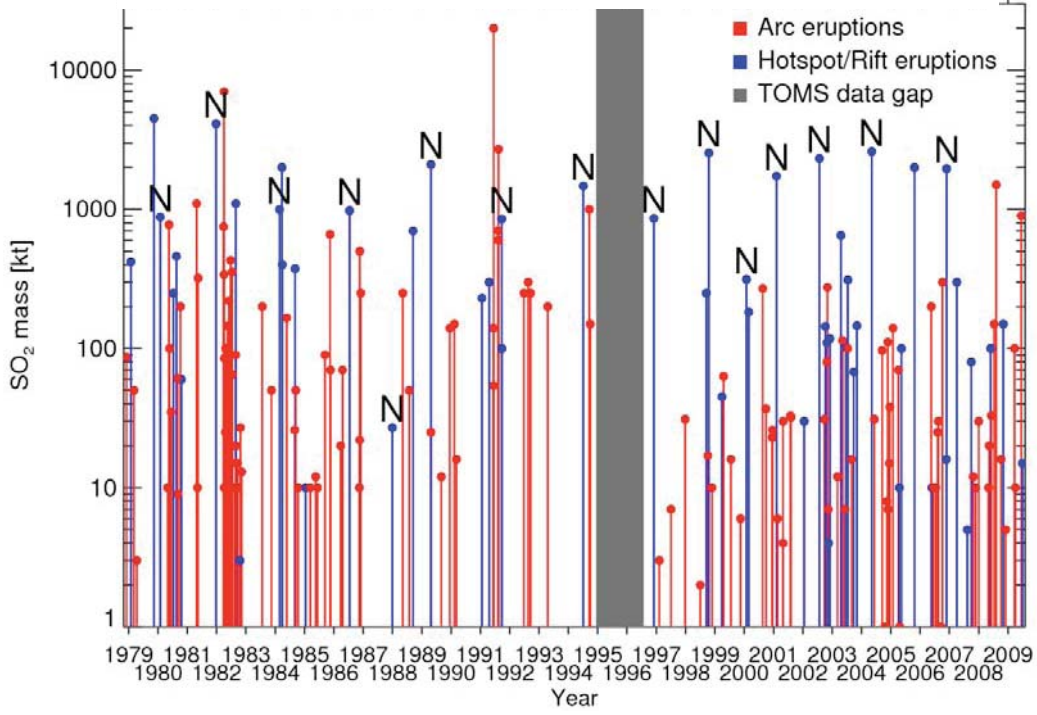
Date	Volcano	Eruption volume (km^3)	SO_2 emission (kt)
Sept 2005	Dabbahu	? (small)	None detected
Aug 12, 2007	Manda Hararo	tbd	14
Sep 30, 2007	Jebel at-Tair	tbd	80
Nov 3, 2008	Alu/Dalaffilla	0.03-0.045	100-200
Jun 28, 2009	Manda Hararo	0.008-0.012	18-20



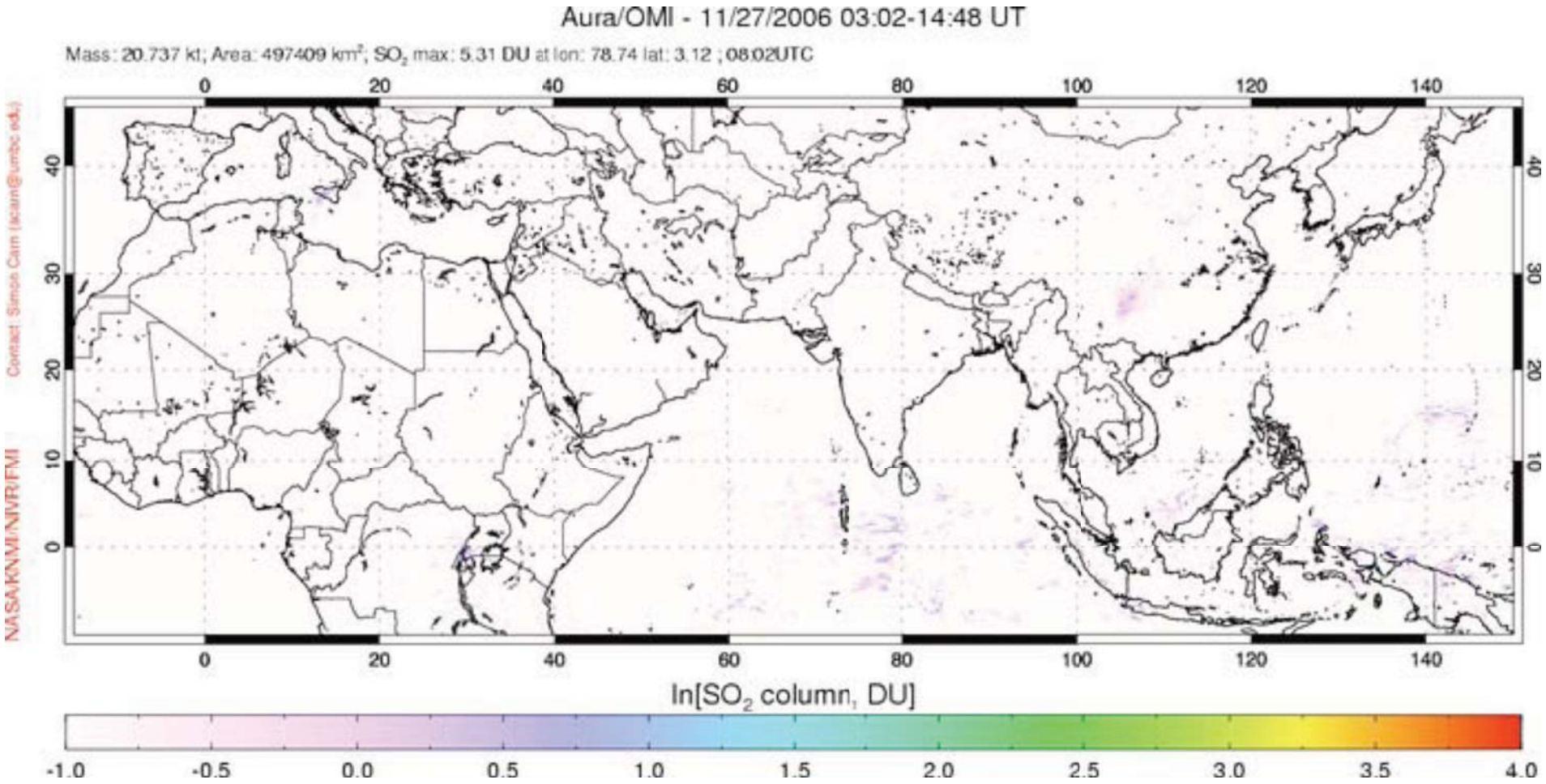


Frequent effusive eruptions at Nyamulagira (DR Congo)

Volcanic SO_2 emissions 1979-2009

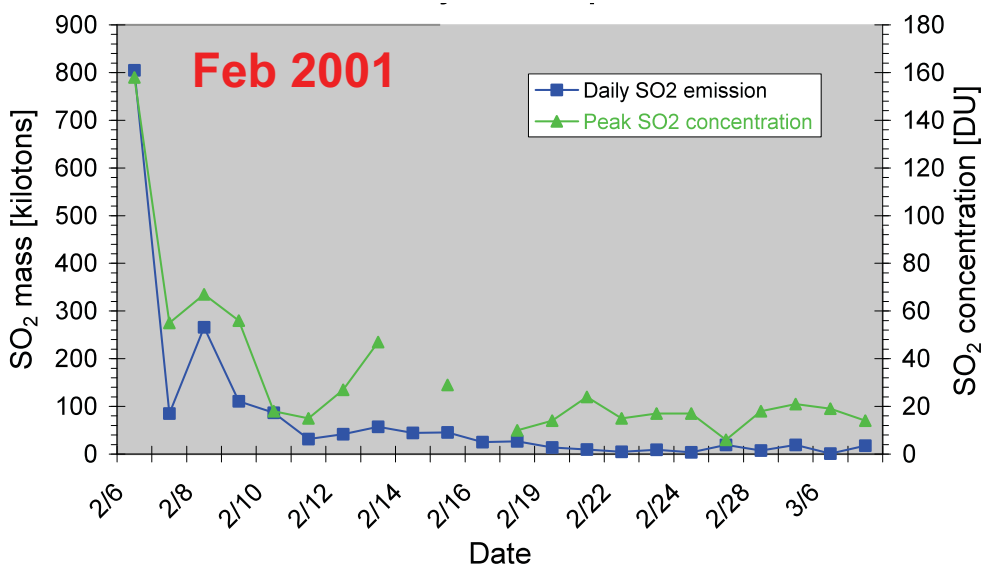


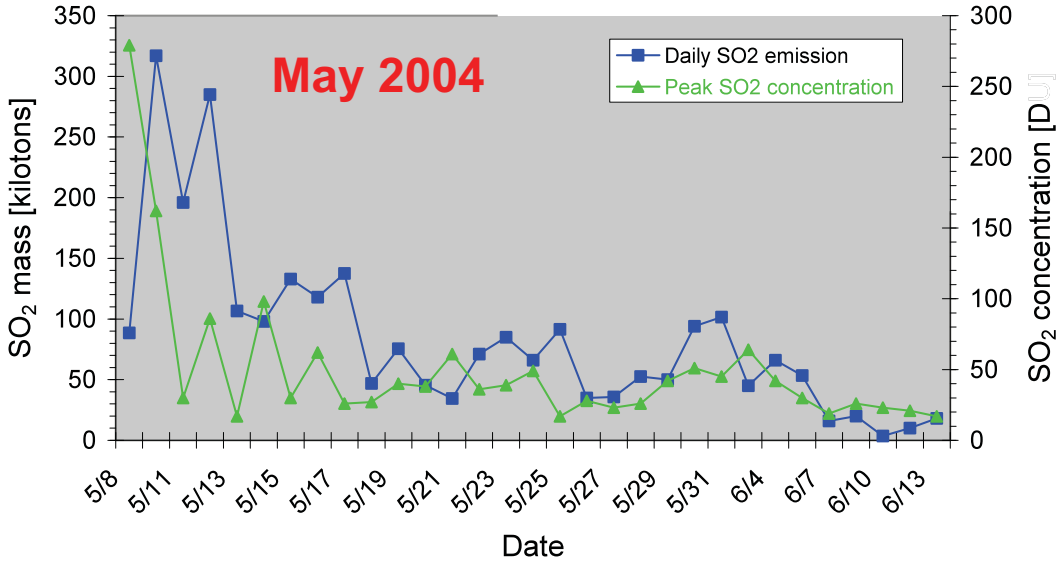
Nyamulagira eruption, November 2006



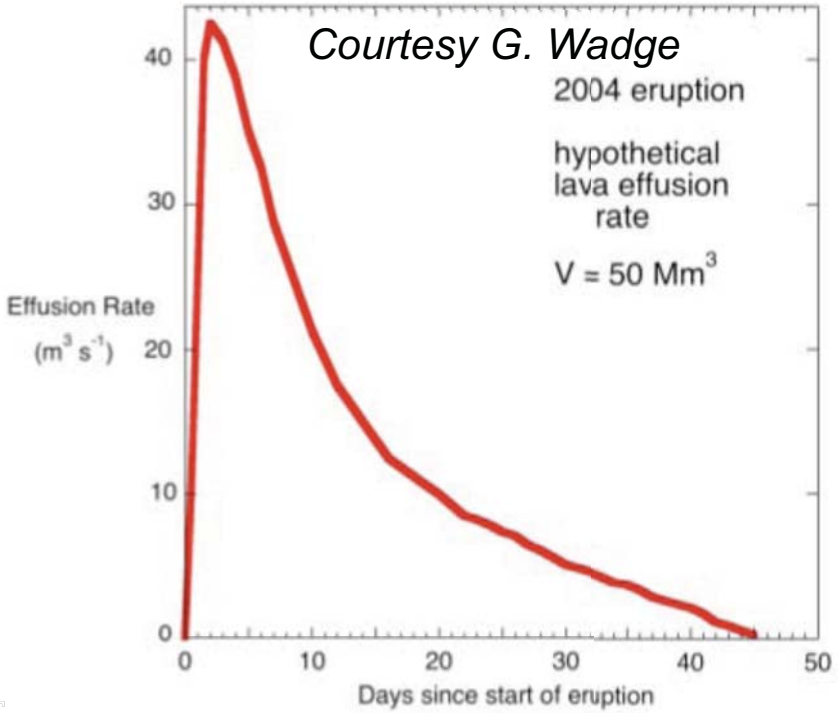
Nov 27 – Dec 6; ~2 Tg SO_2

SO_2 emission trends for Nyamulagira eruptions



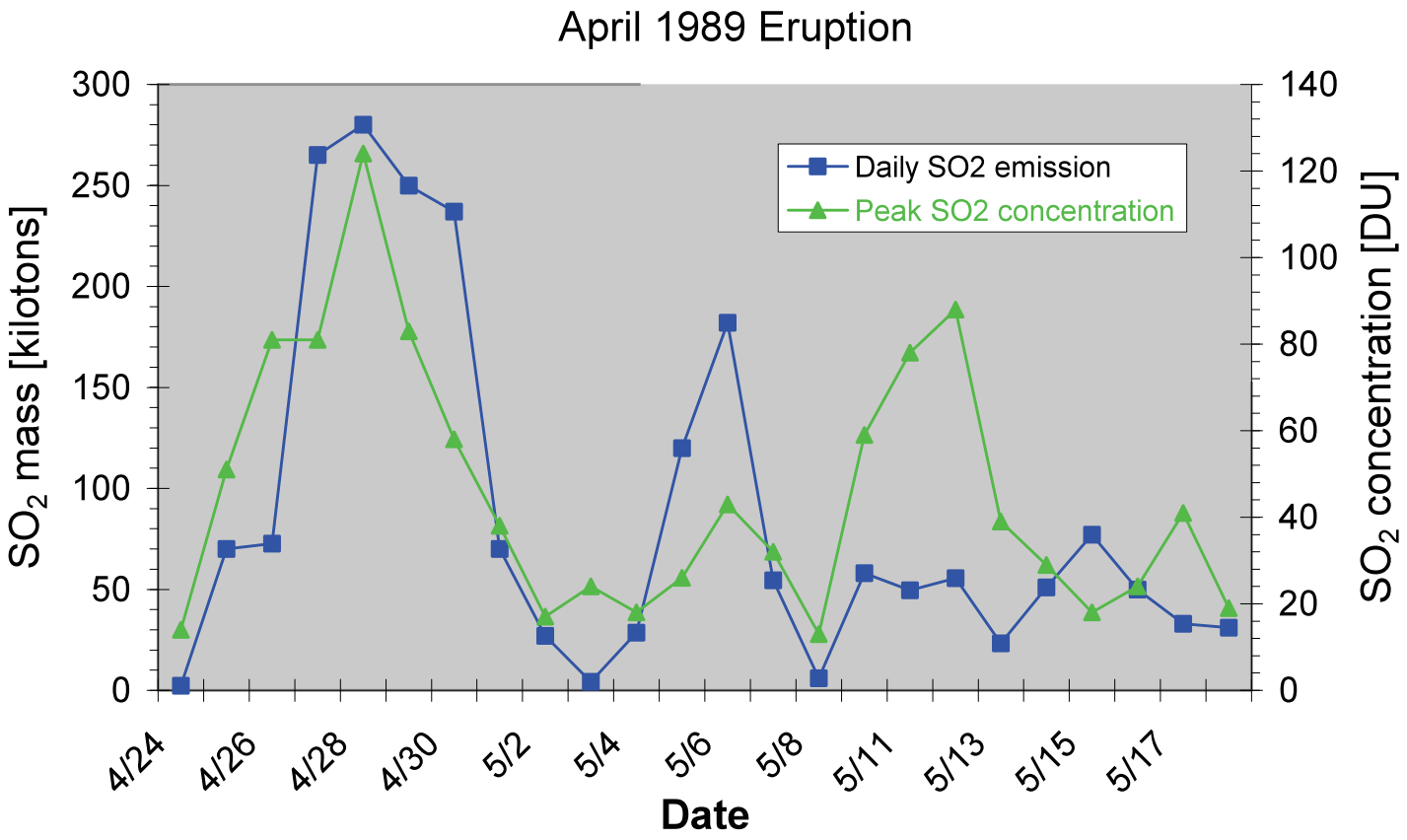


[Bluth and Carn, IJRS, 2008]



- Most eruptions show an early peak in SO_2 production.
- ~50% of SO_2 released in first few days of eruptions.
- Similar to expected trend in lava effusion for depressurizing source
- Can be monitored using SO_2 concentration over the vent.

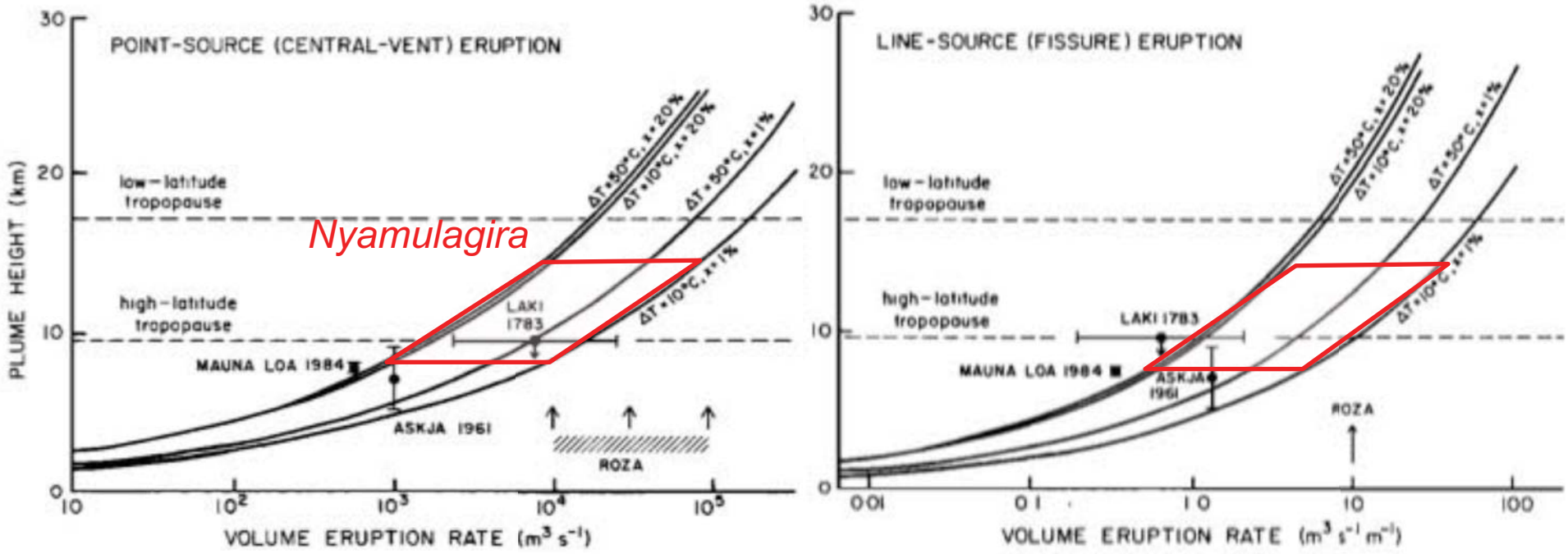
SO_2 emission trends for Nyamulagira eruptions



- Some eruptions have less regular patterns of SO_2 production
- Multiple magma batches?

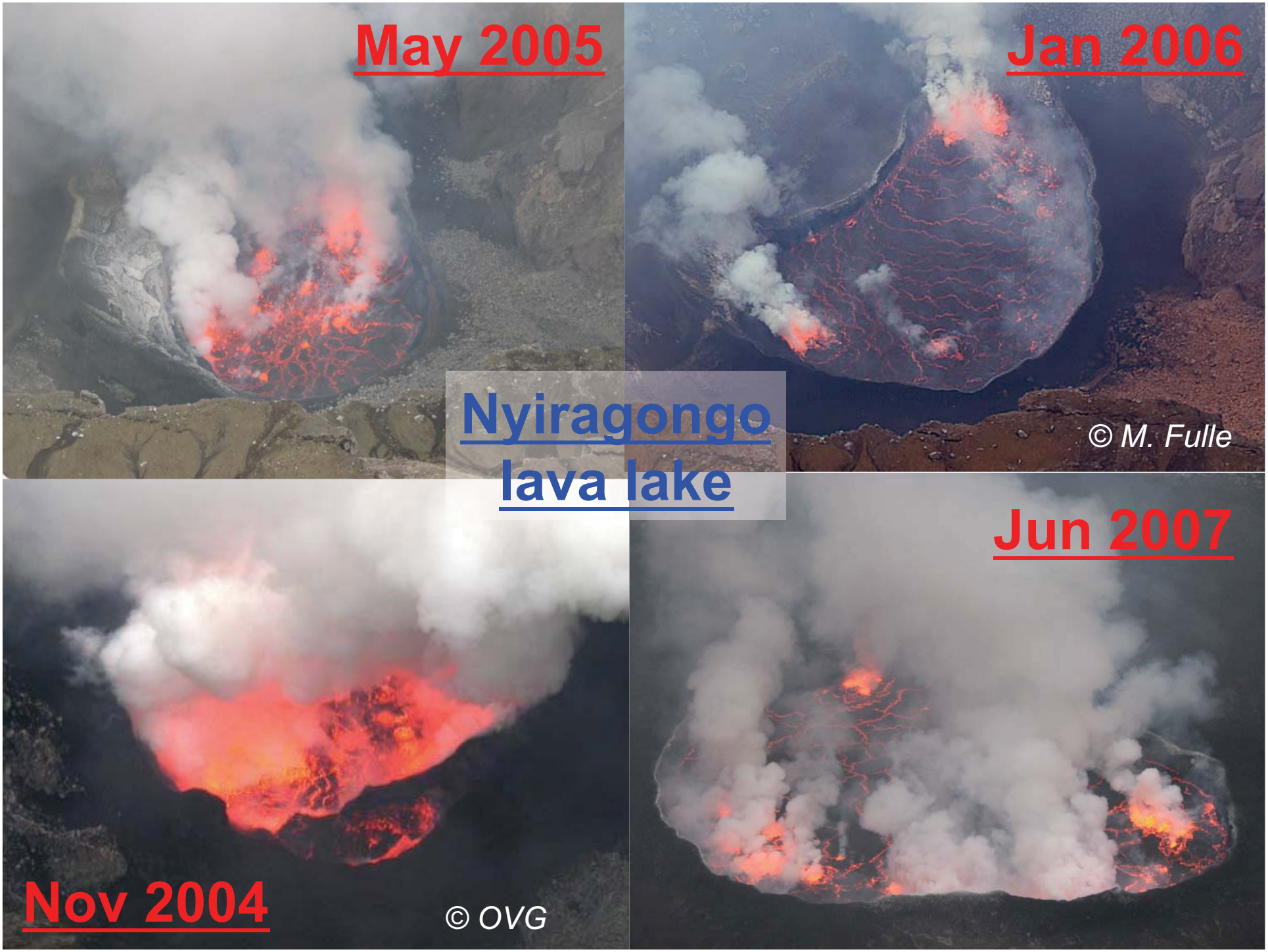
Effusive eruption column heights

Stothers et al., GRL, 1986

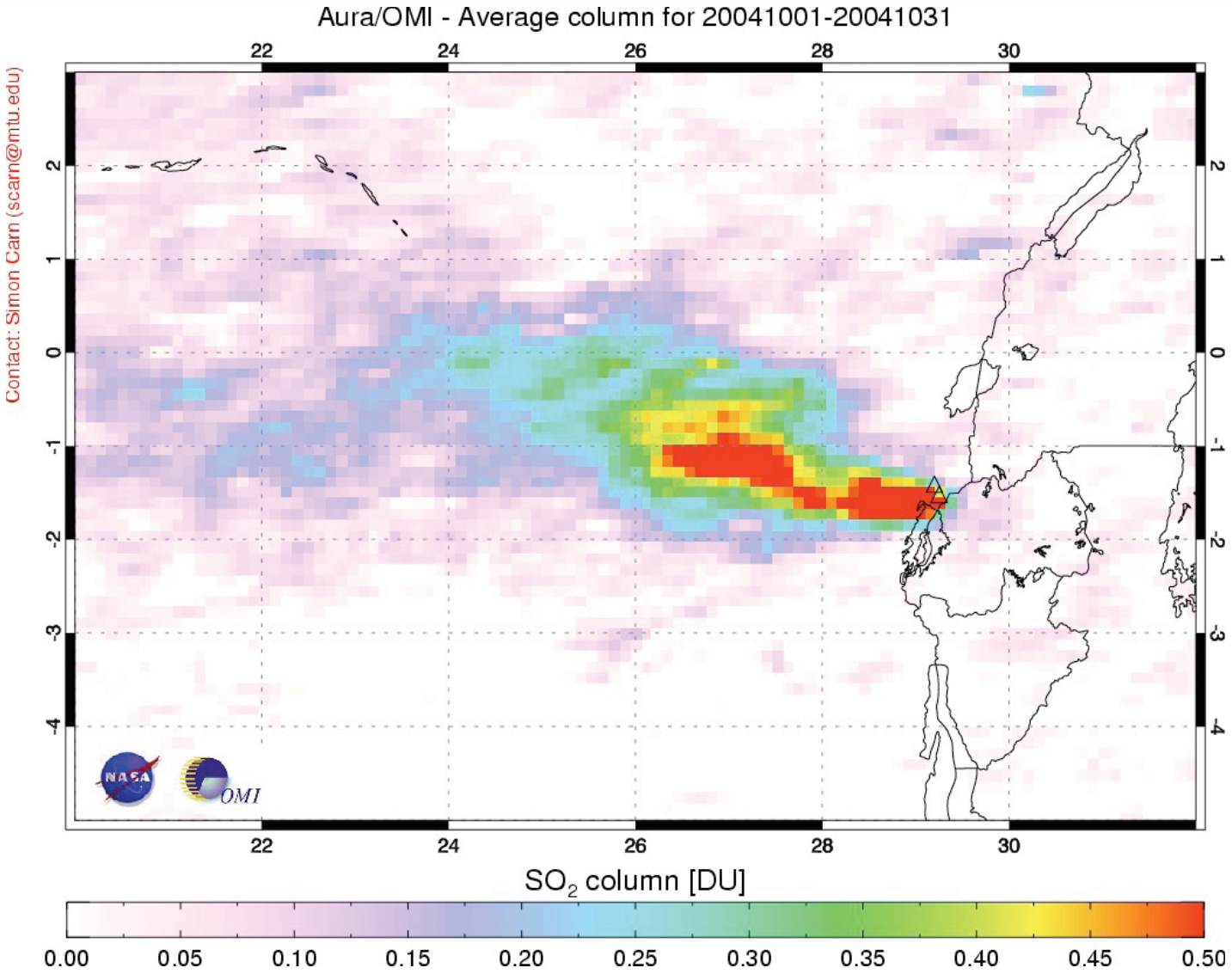


- Observed Nyamulagira max. column heights ~8-16 km
- Imply volume eruption rates comparable to major flood basalt eruptions
- Plumes can reach aircraft cruising altitudes: aviation hazard?
- Alu/Dalaffilla (Nov 2008): 14-16 km; Jebel at-Tair (Oct 2007): >16 km

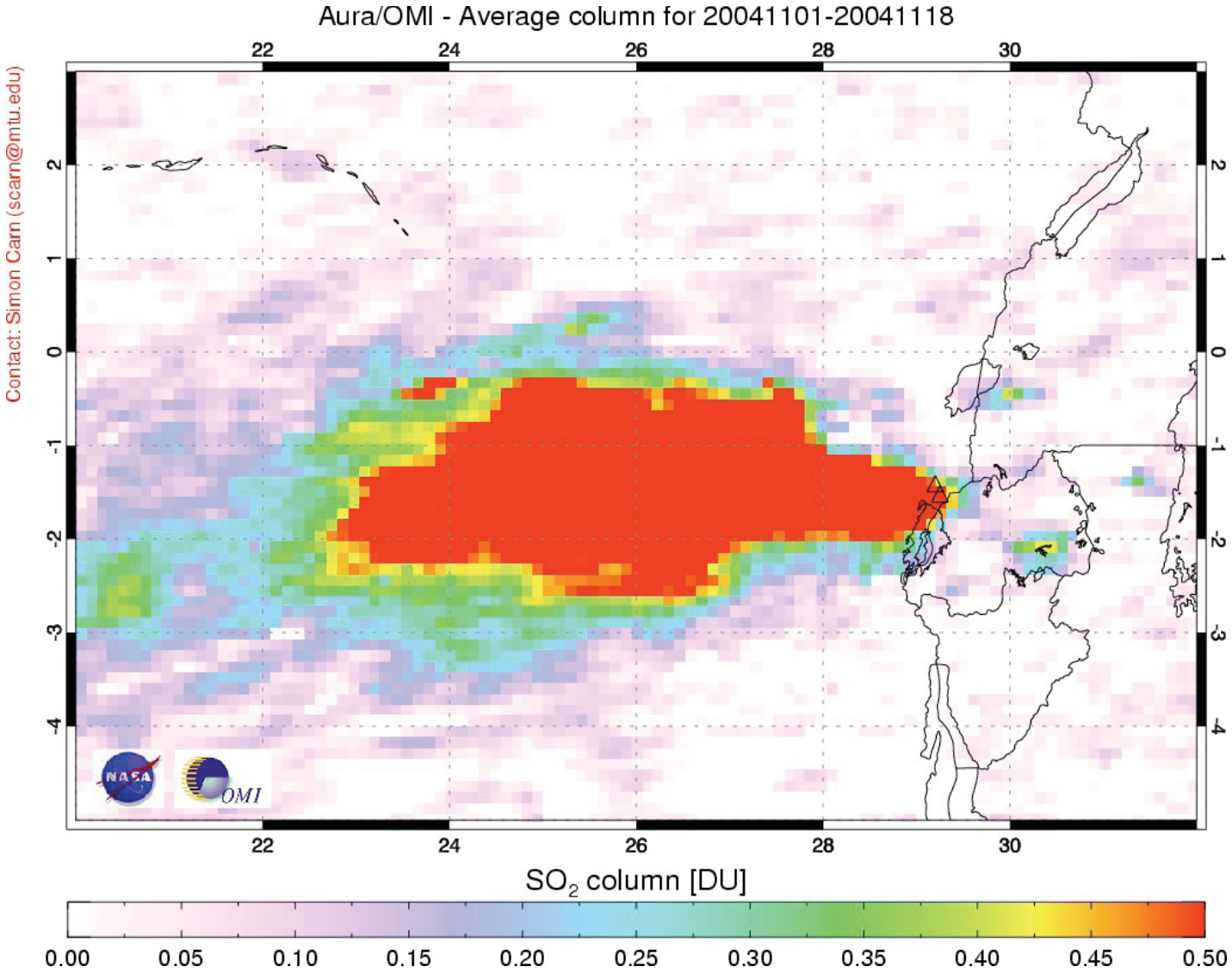
Persistent degassing at Nyiragongo


May 2005
Jan 2006
Nyiragongo
lava lake
© M. Fulle
Jun 2007
Nov 2004
© OVG

Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



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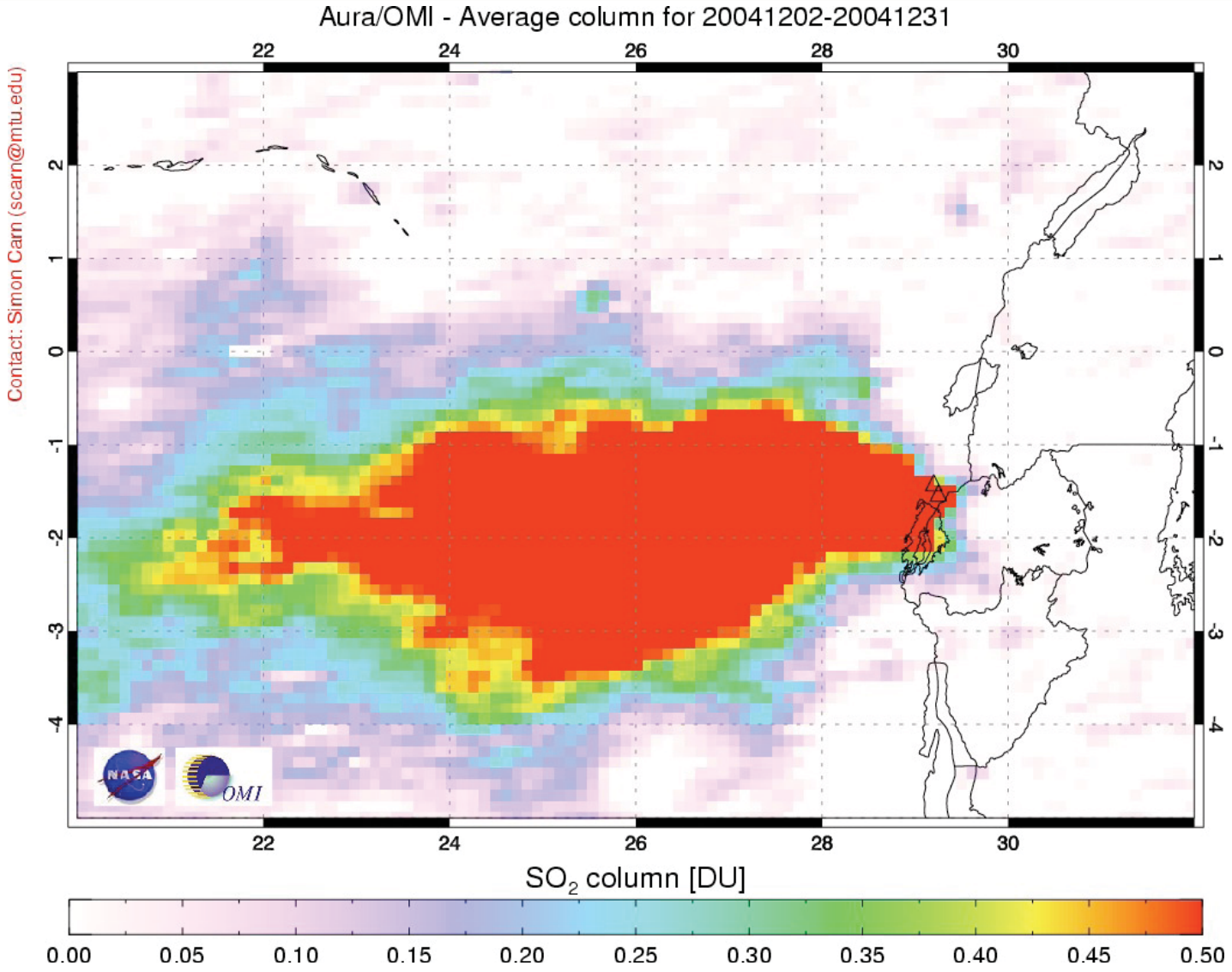
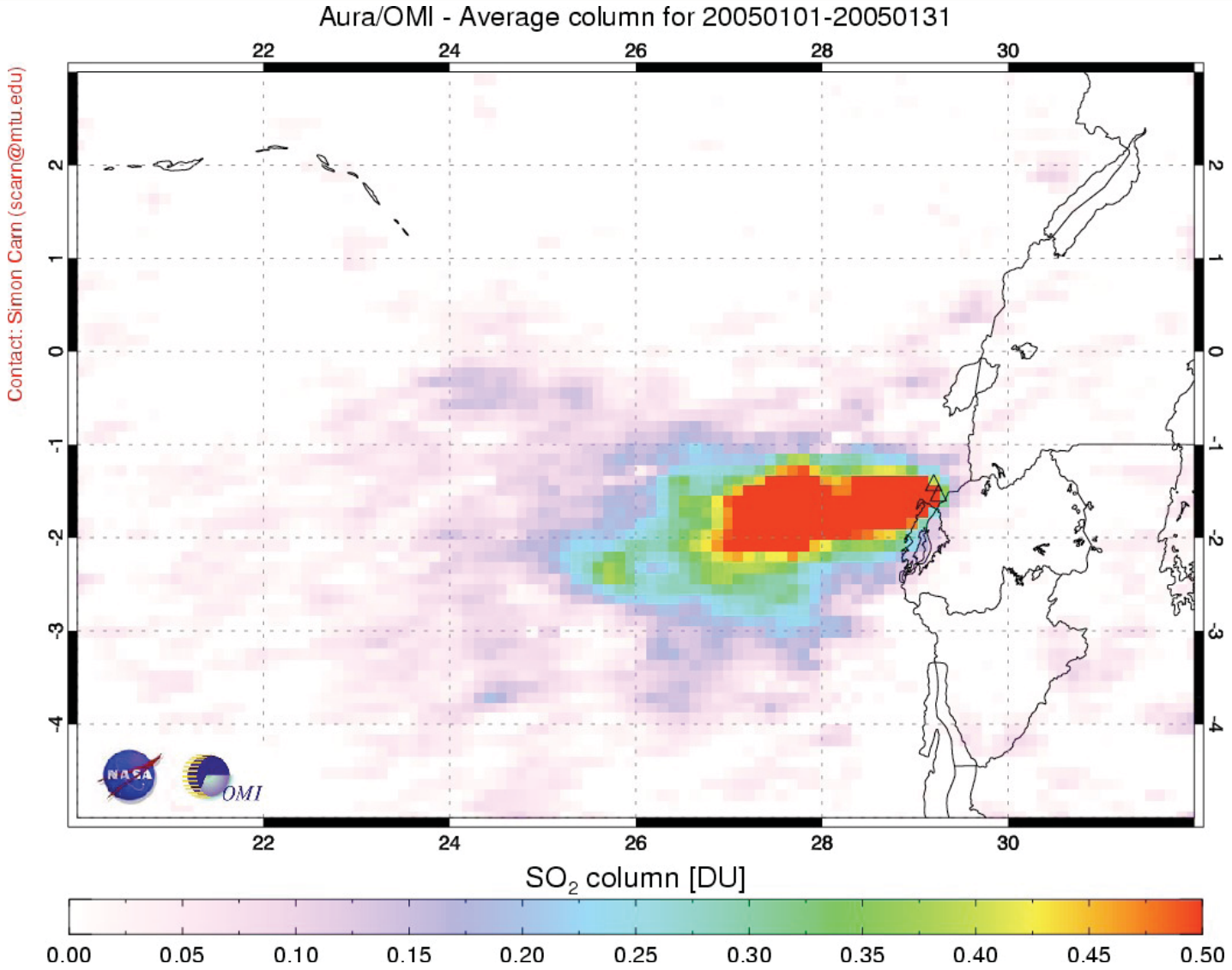


Nyiragongo – monthly average SO_2 columns



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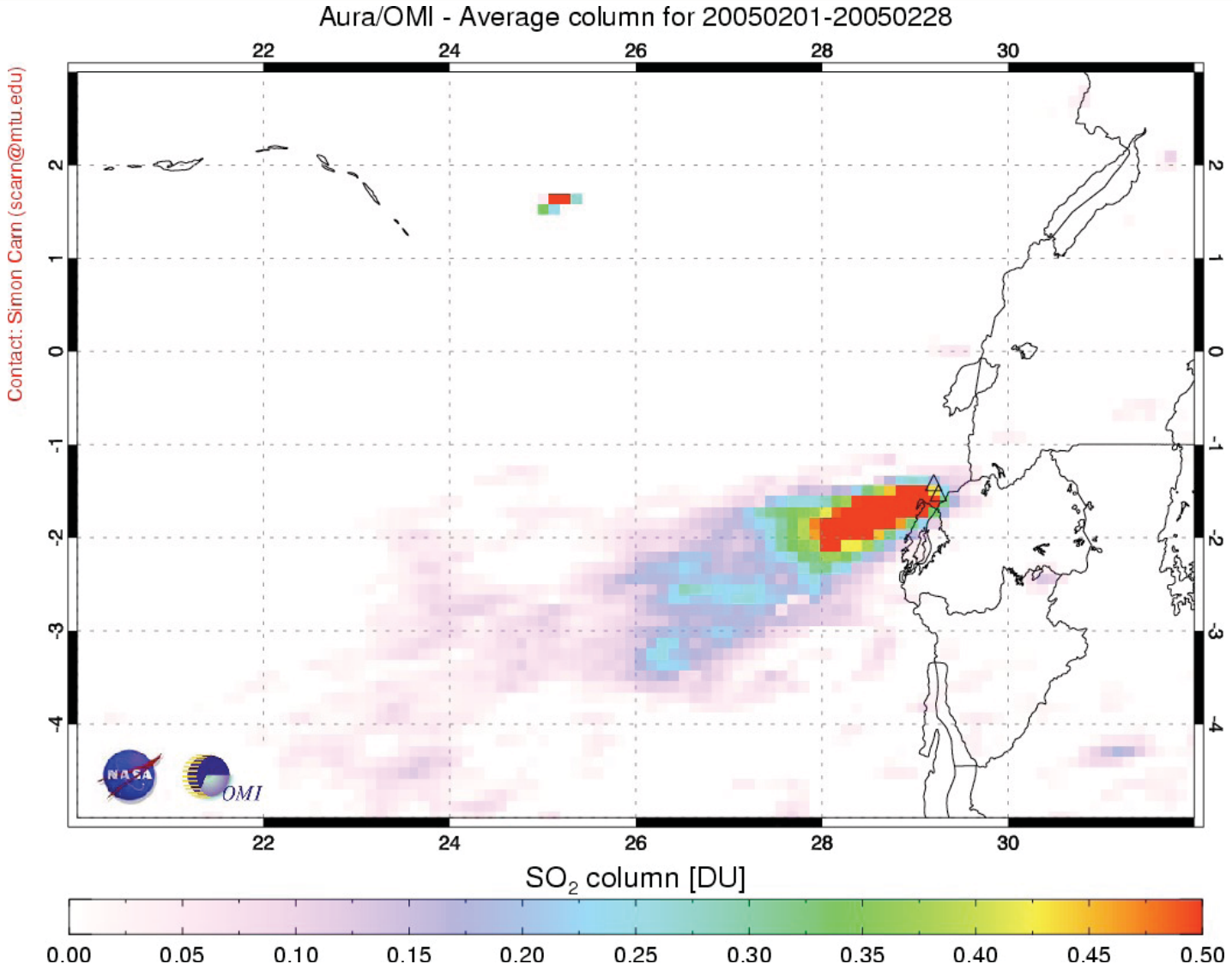
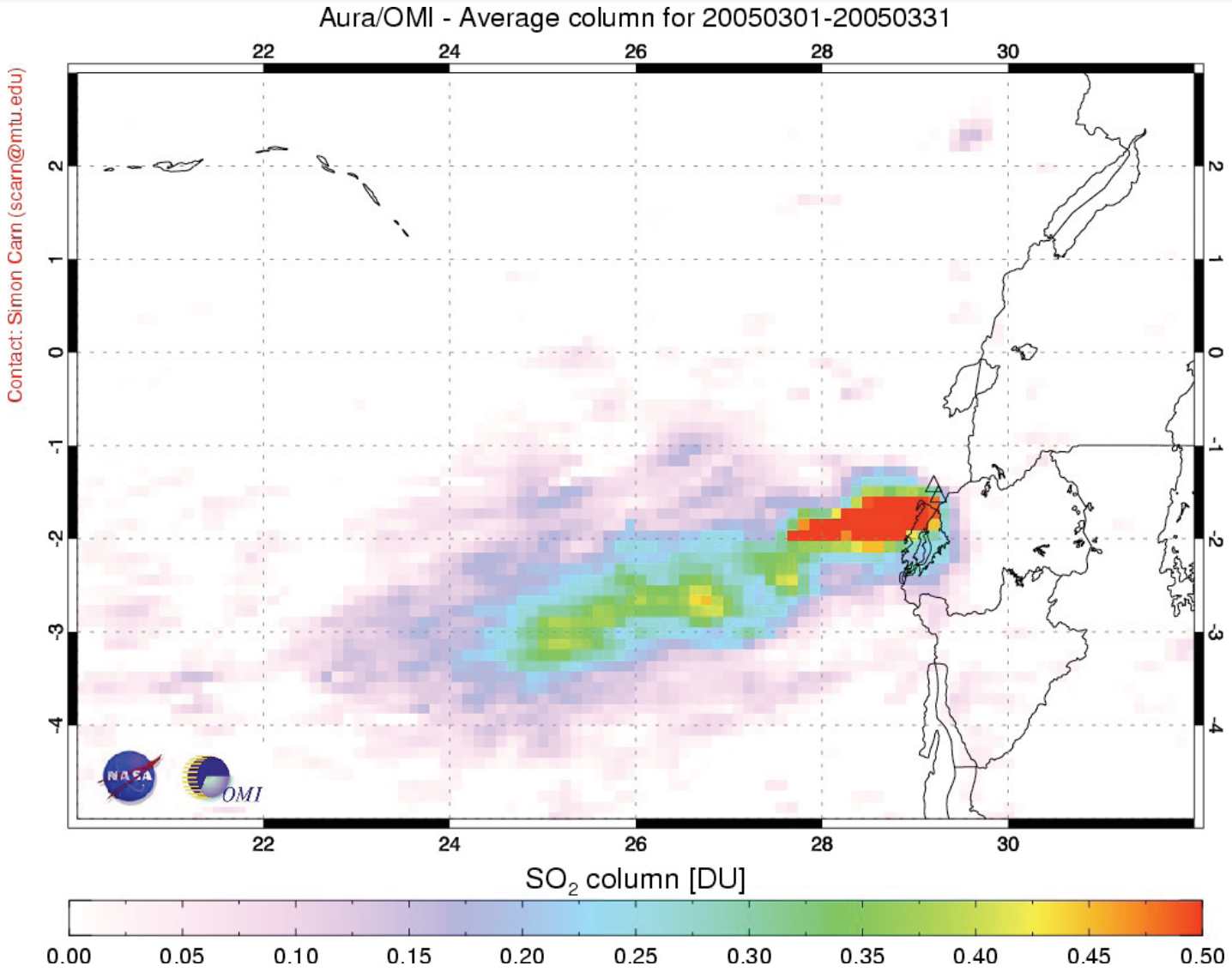
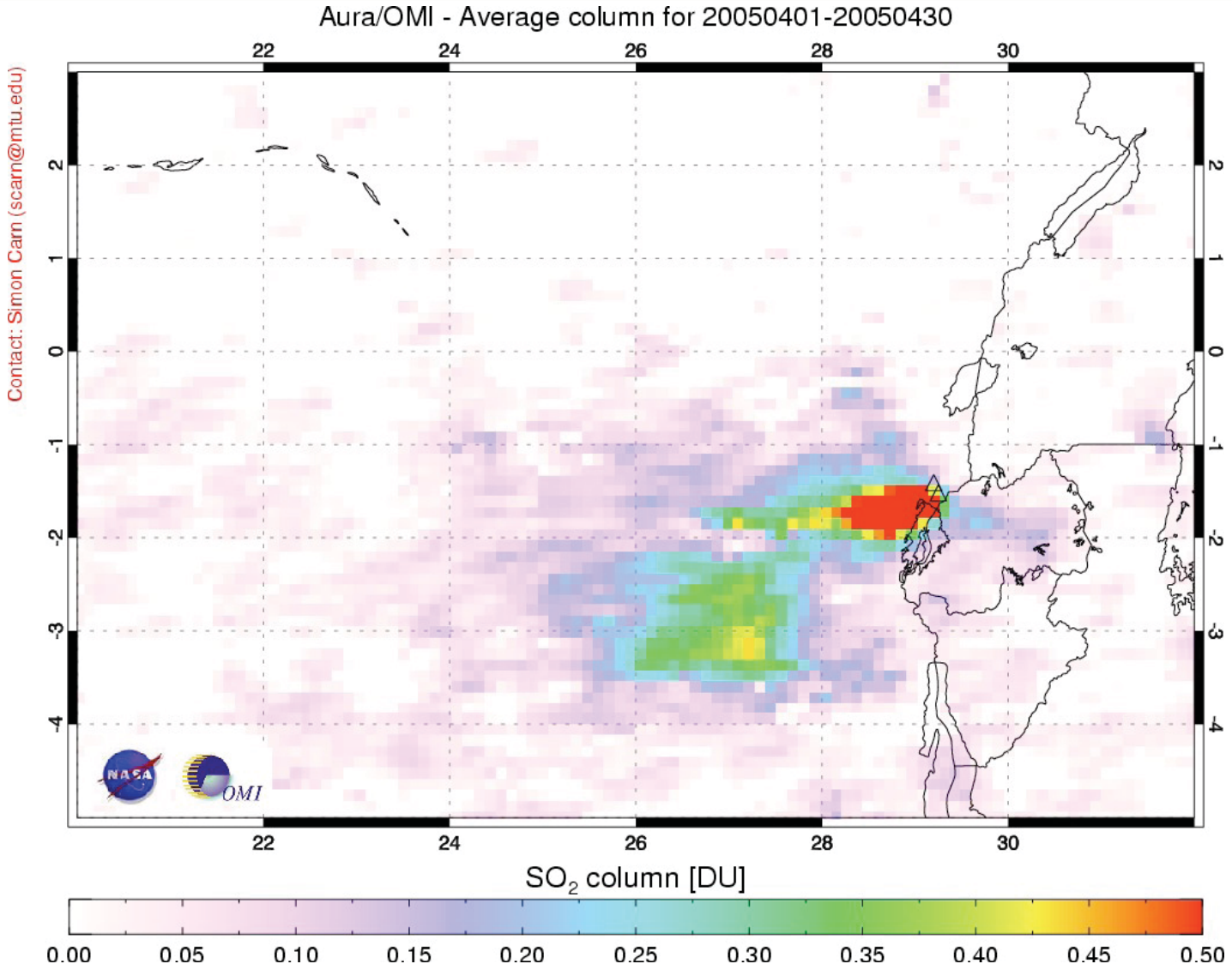


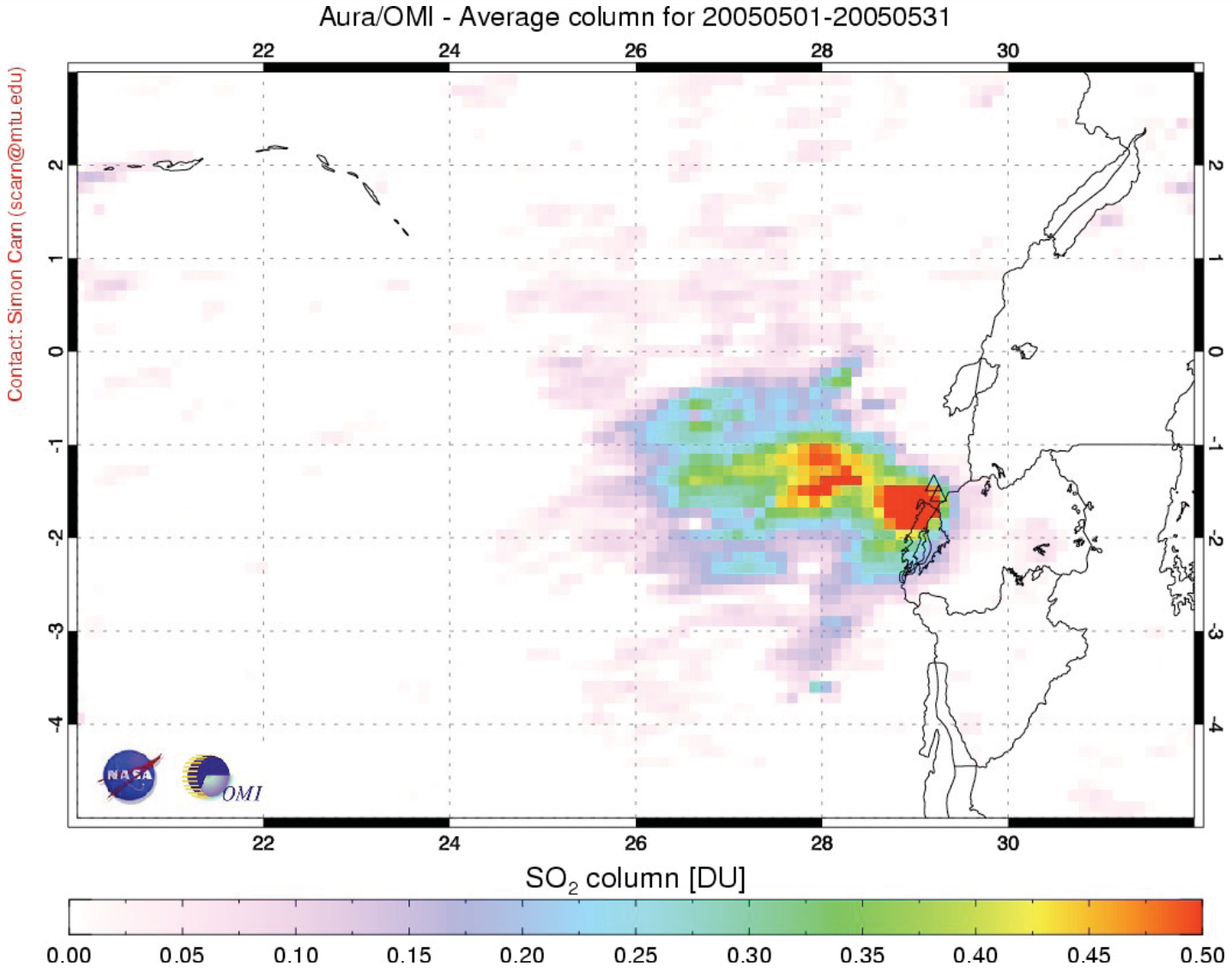
Nyiragongo – monthly average SO_2 columns



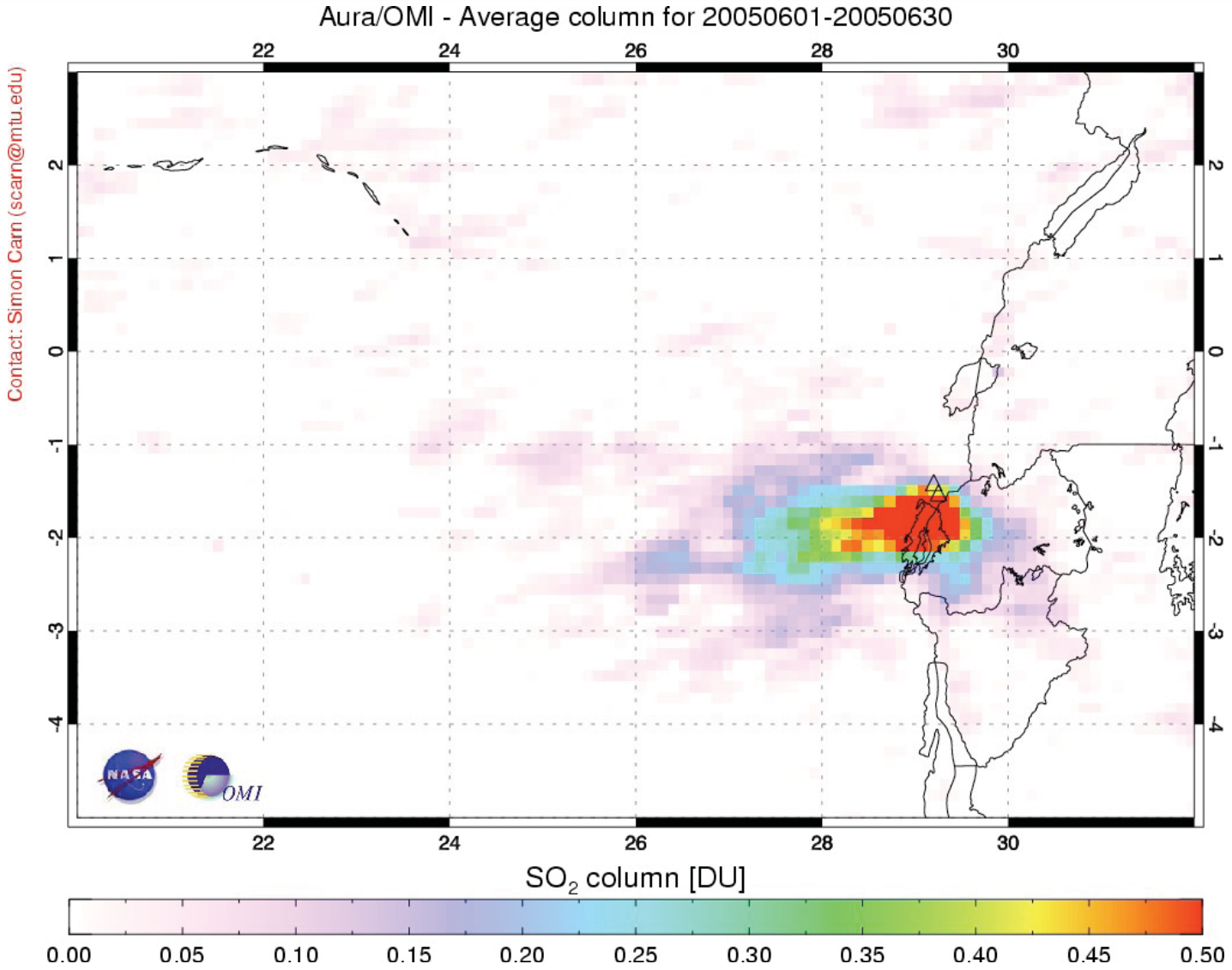
Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



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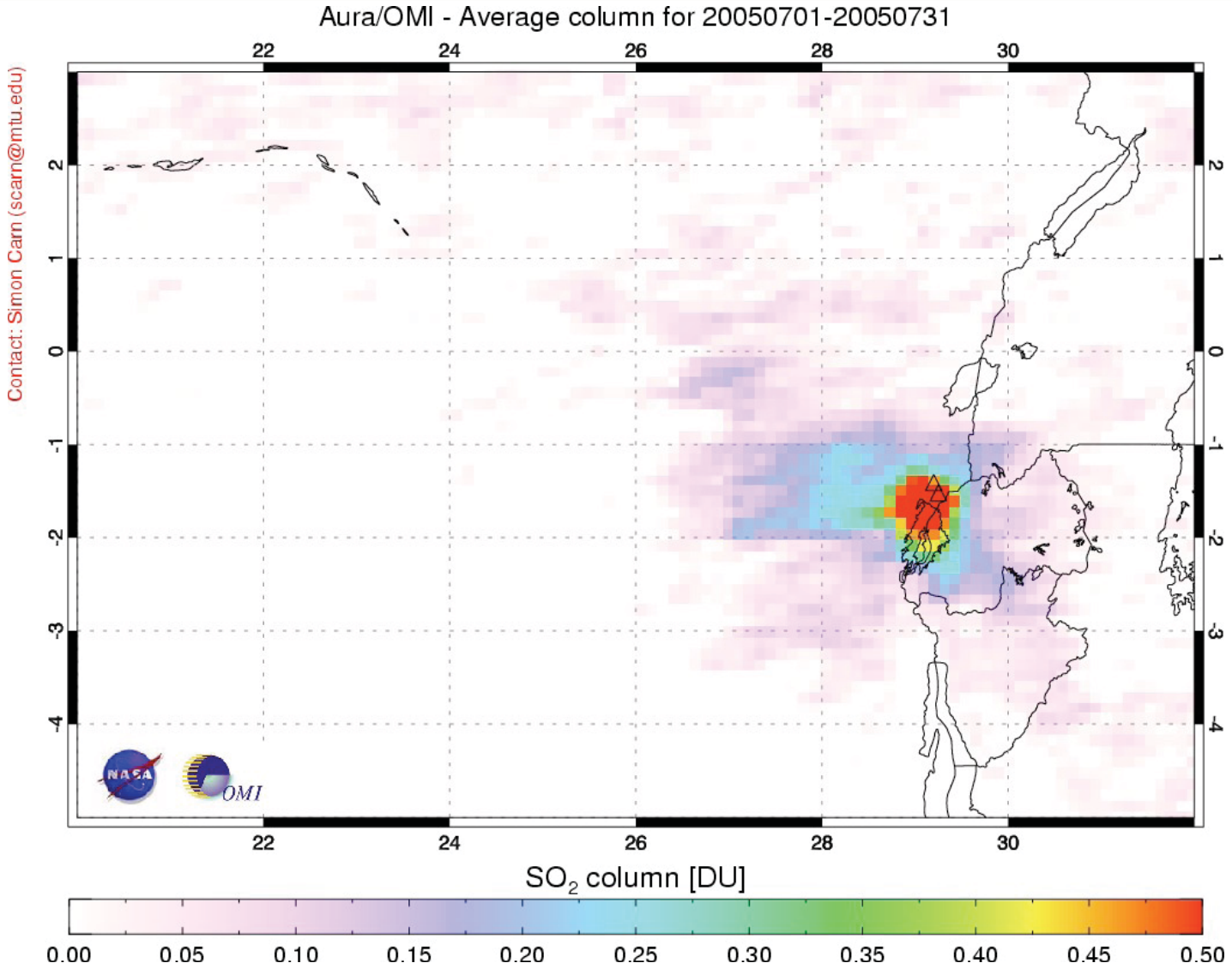

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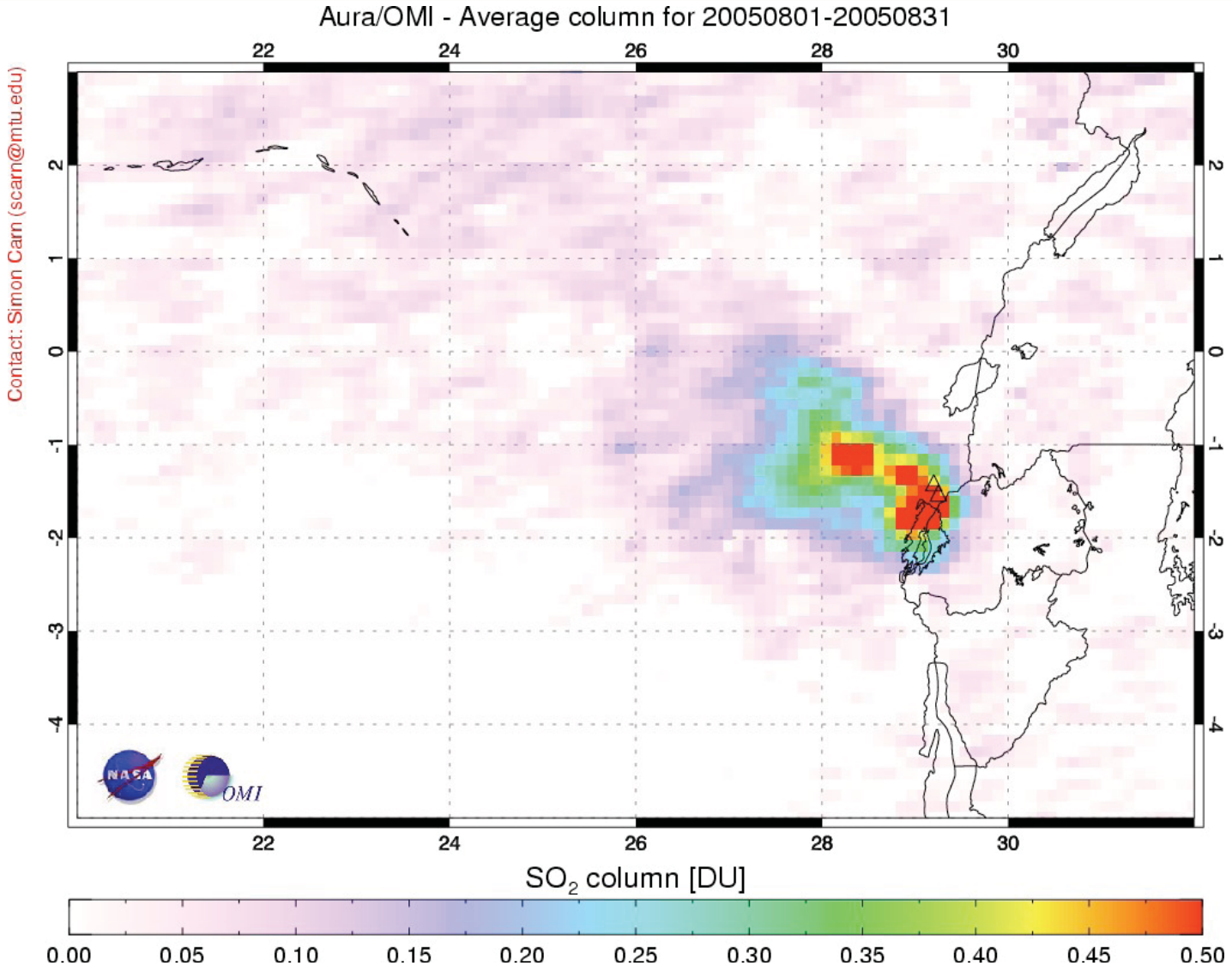

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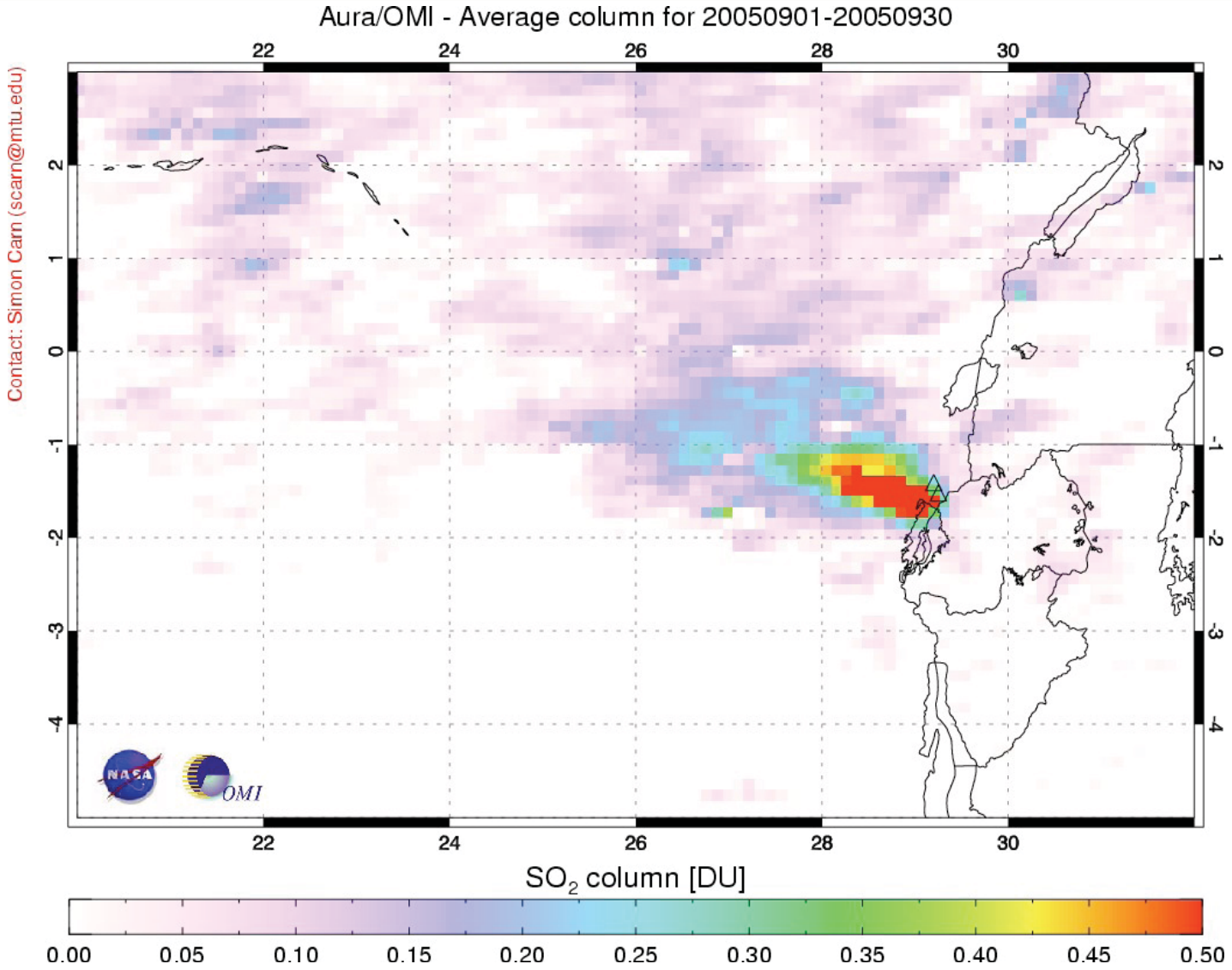

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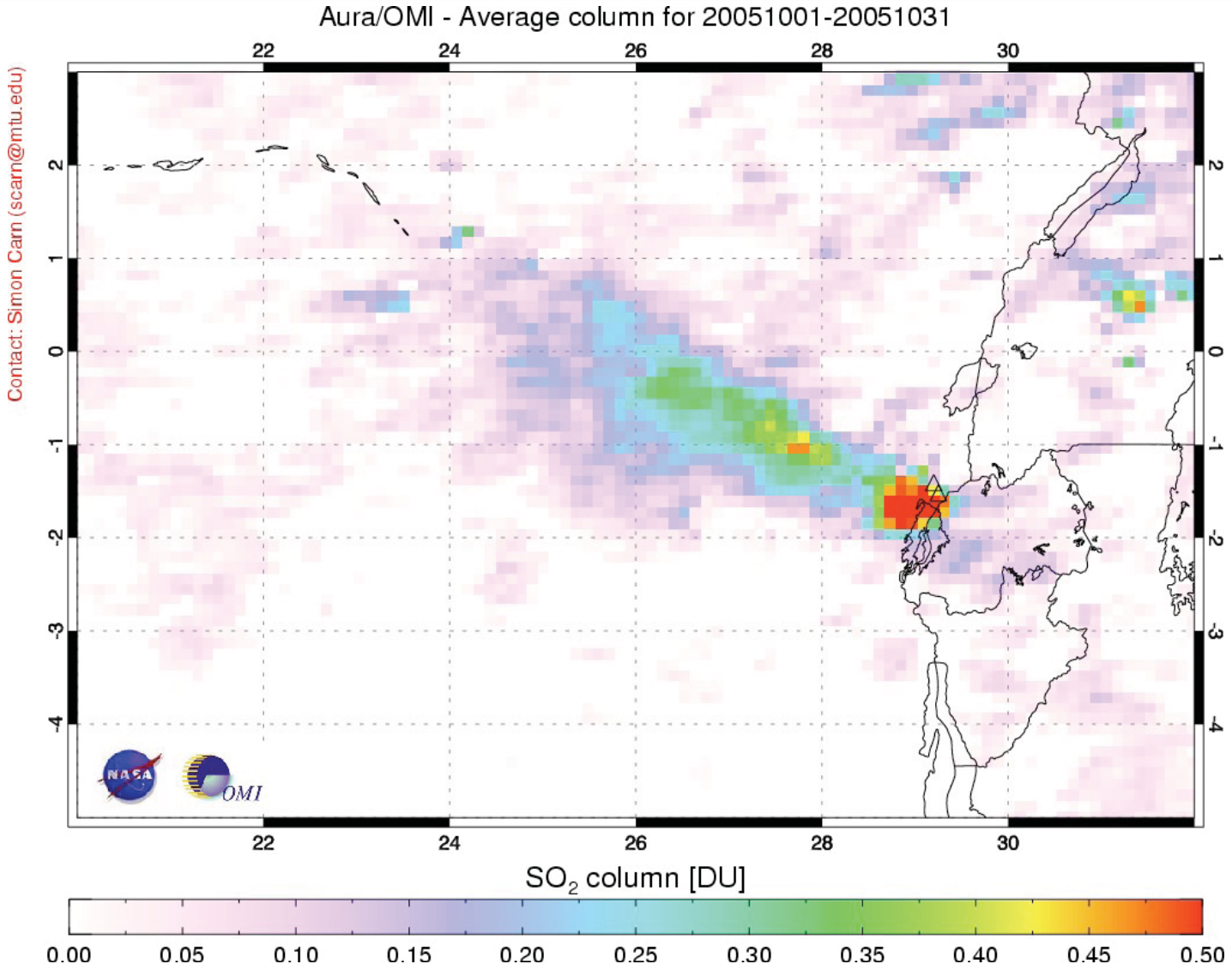
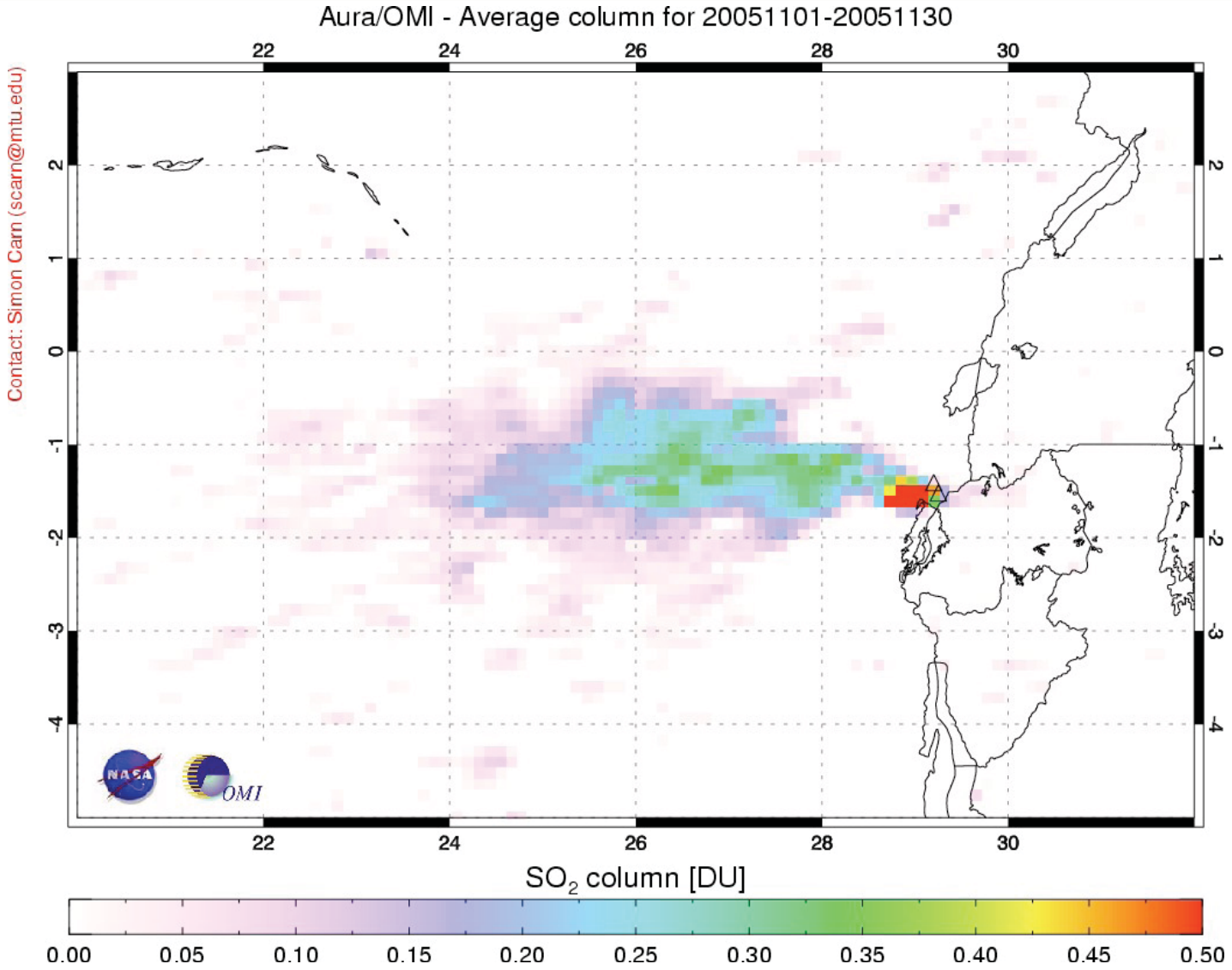


Nyiragongo – monthly average SO_2 columns



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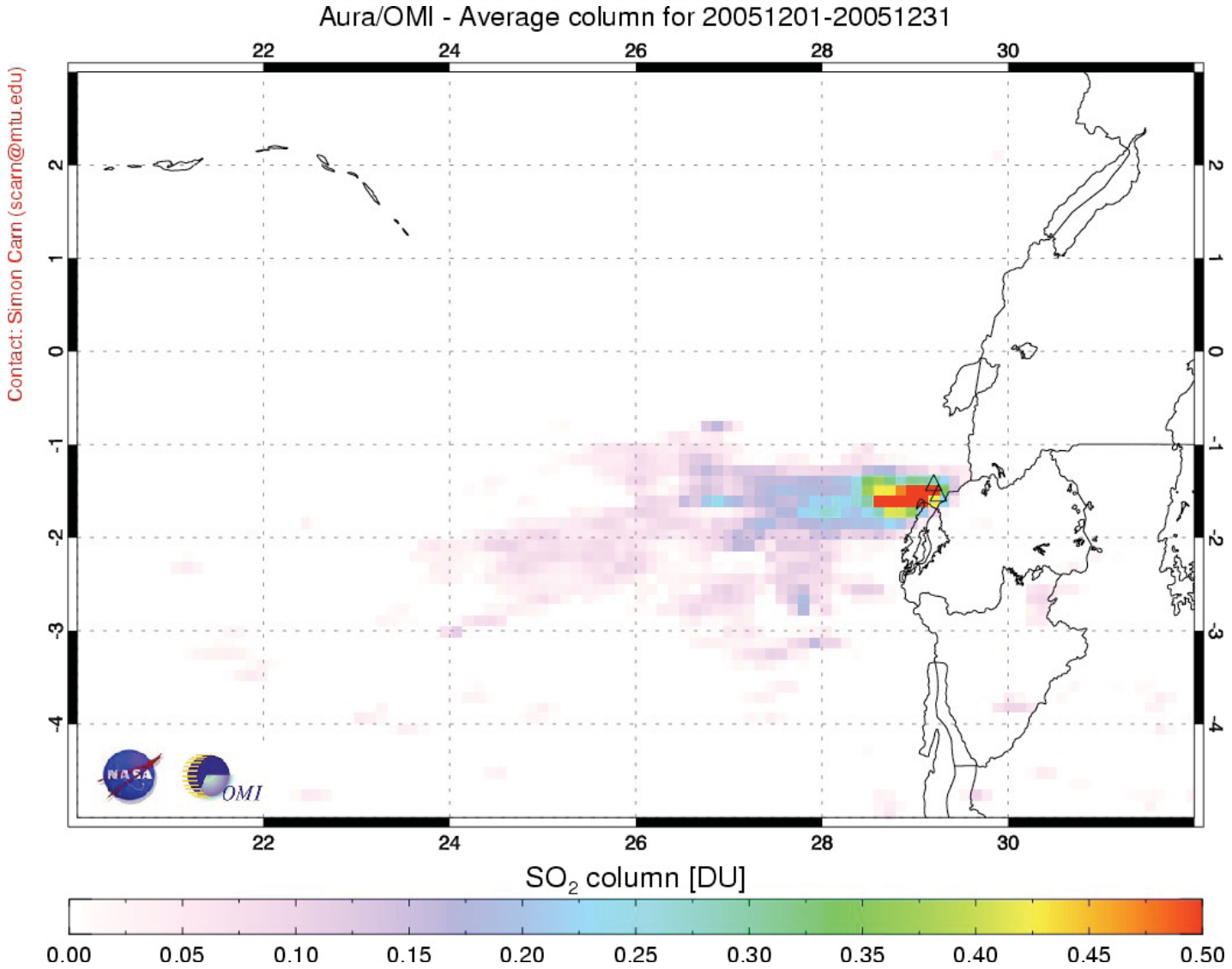

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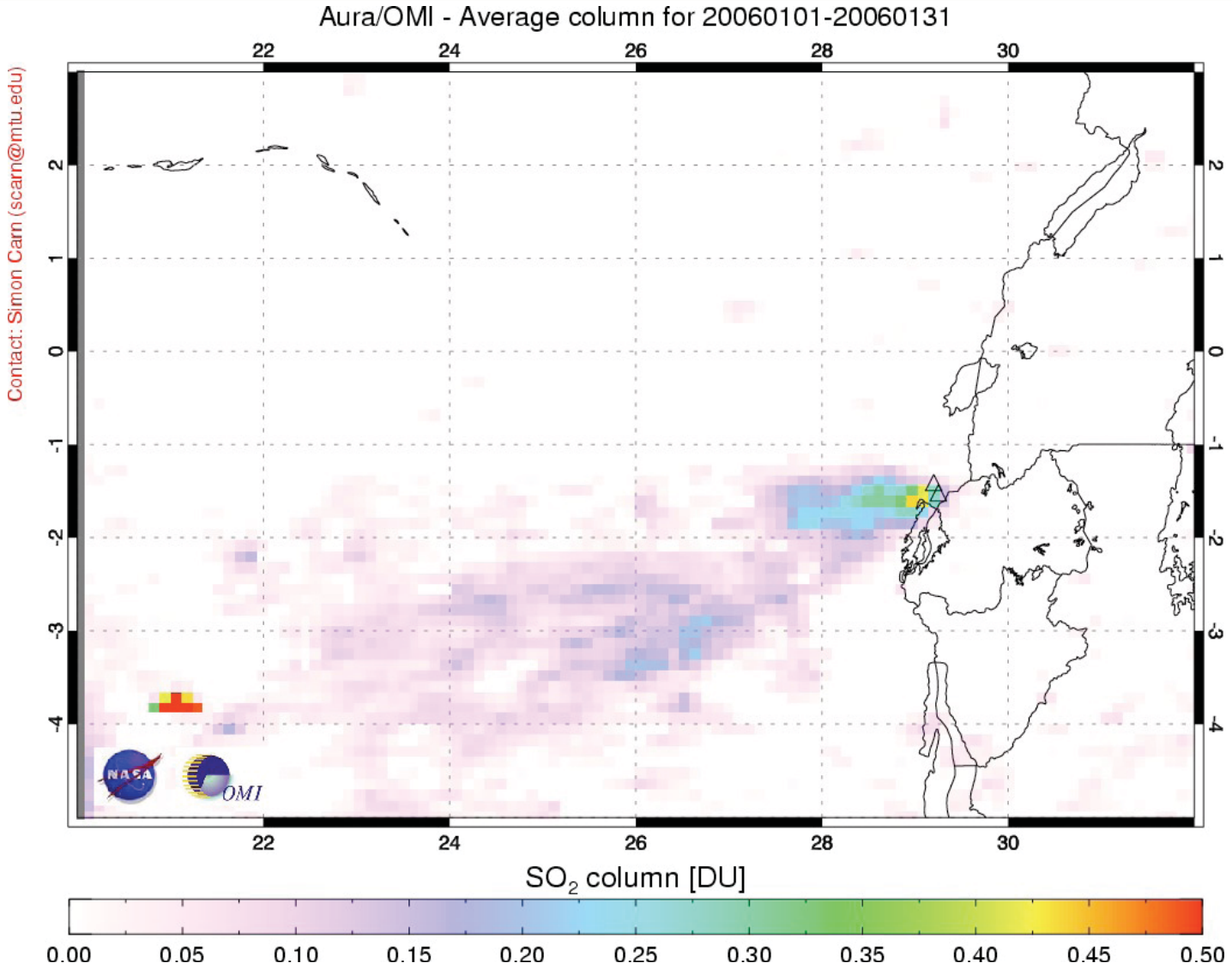

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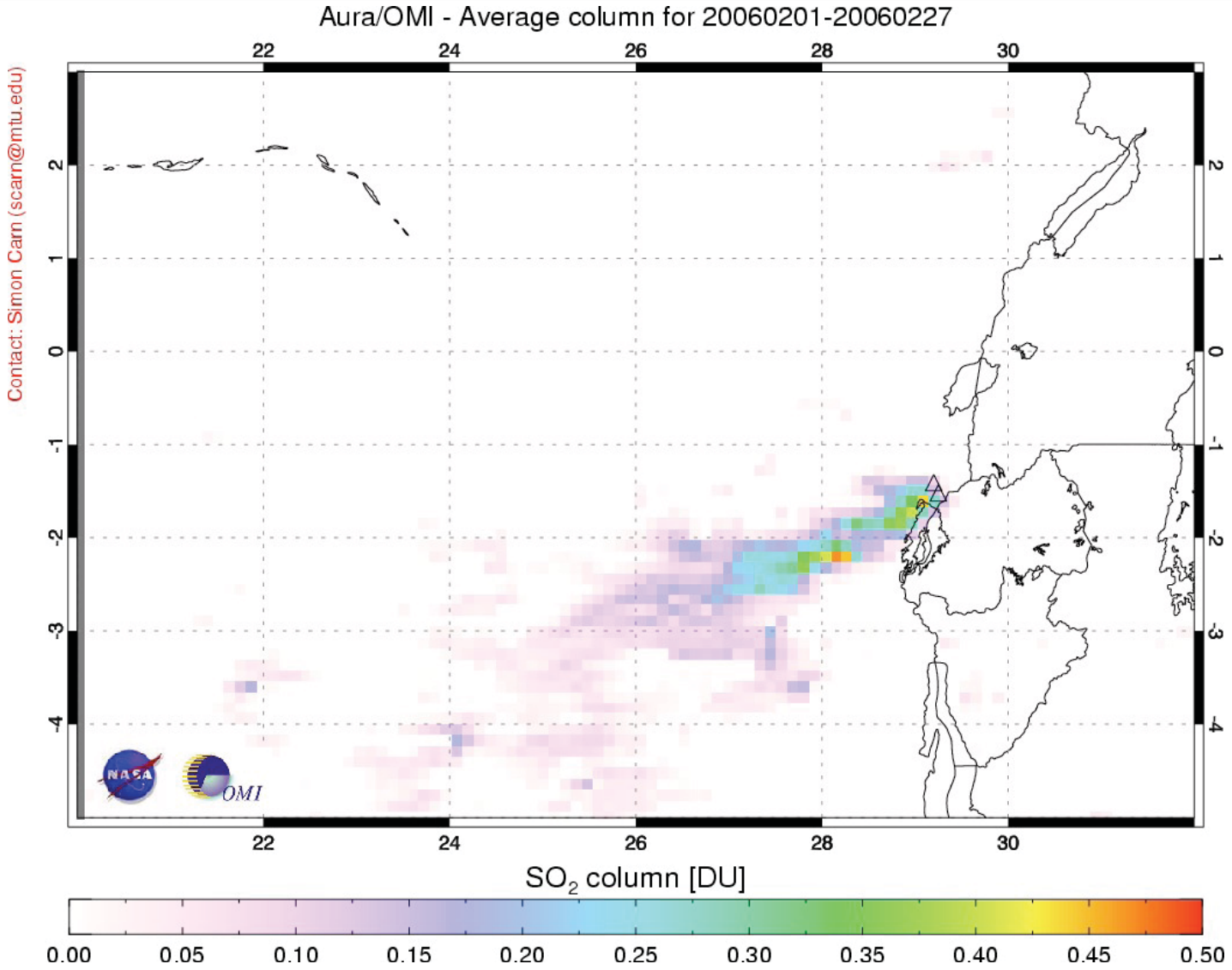
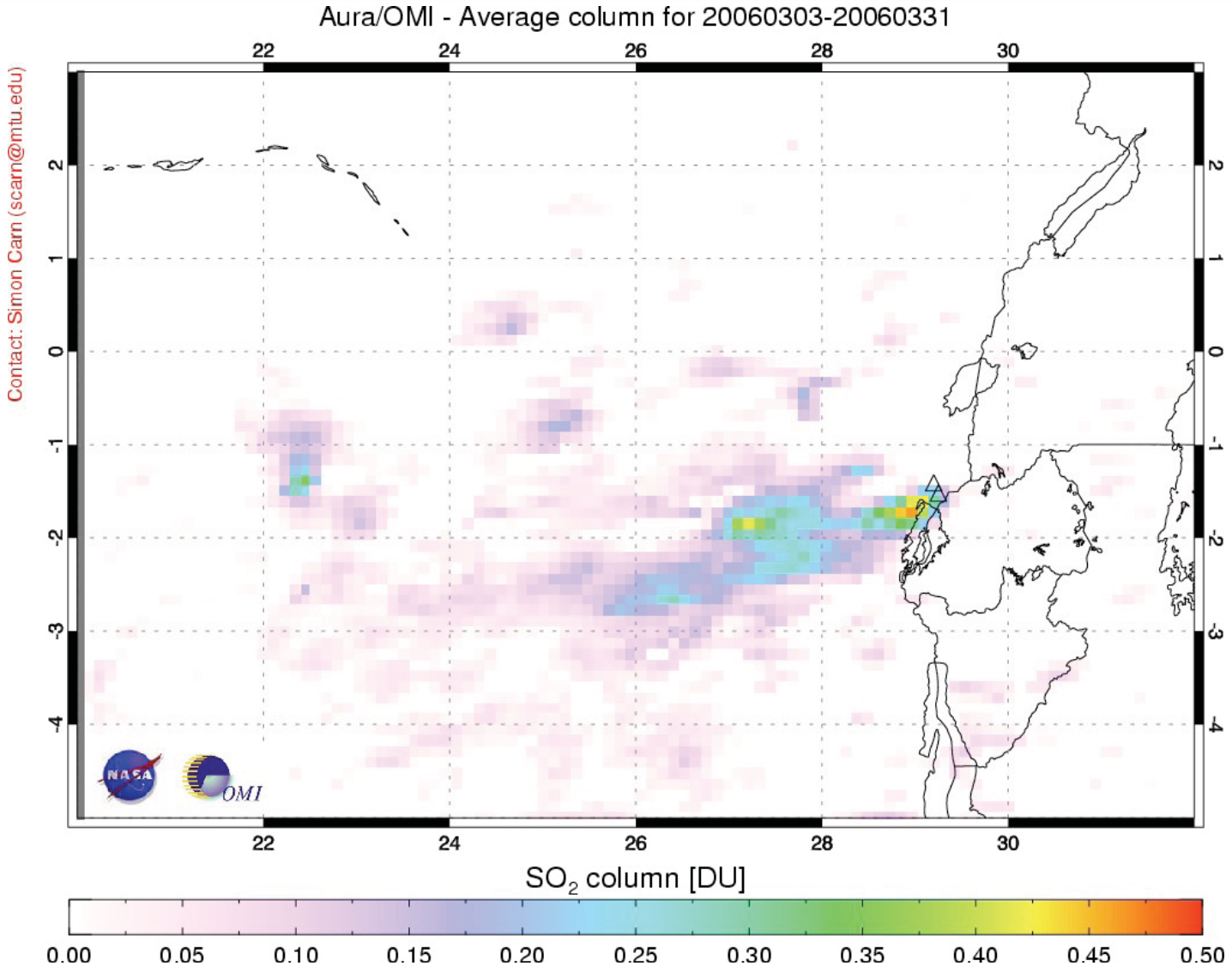


Nyiragongo – monthly average SO_2 columns



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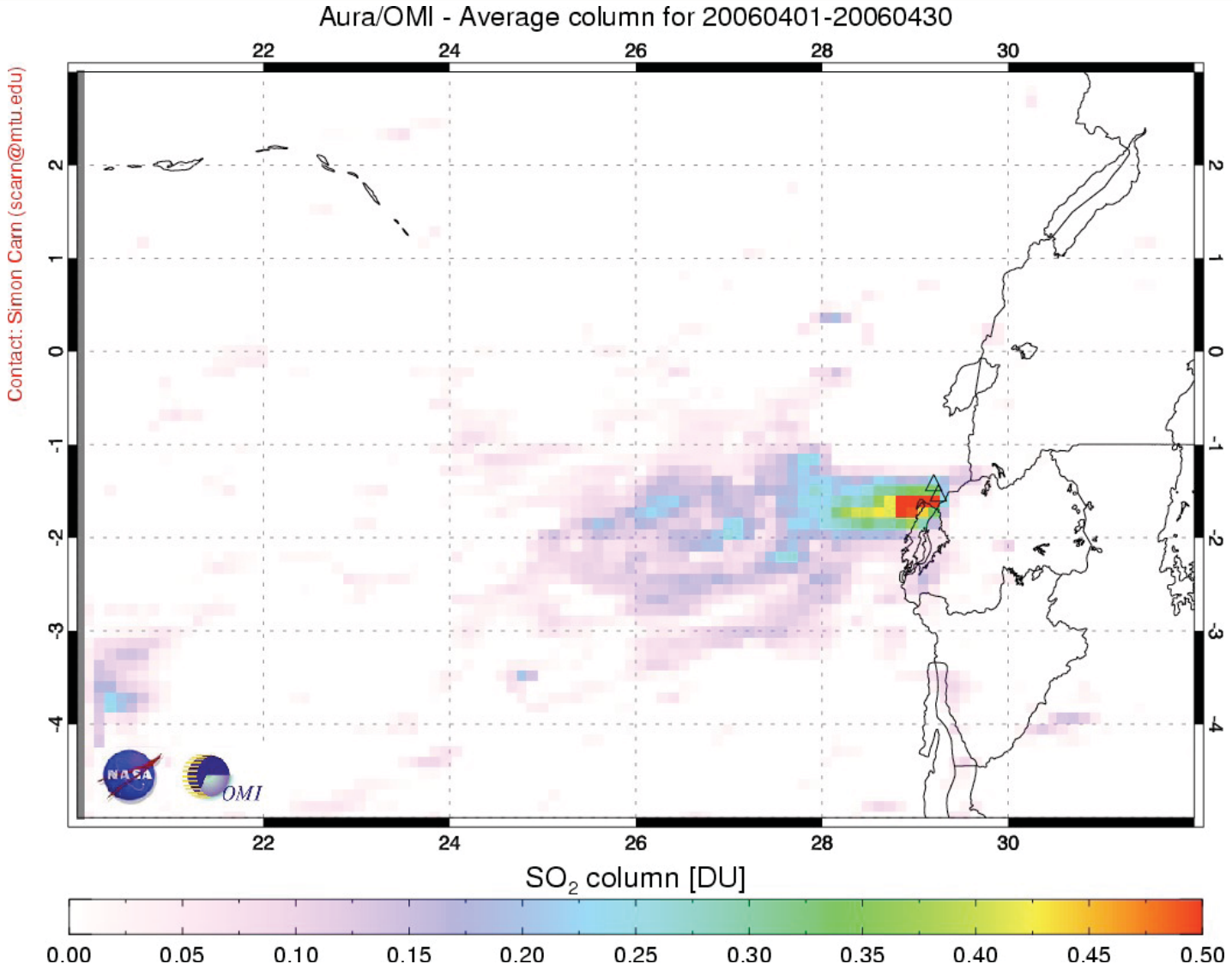

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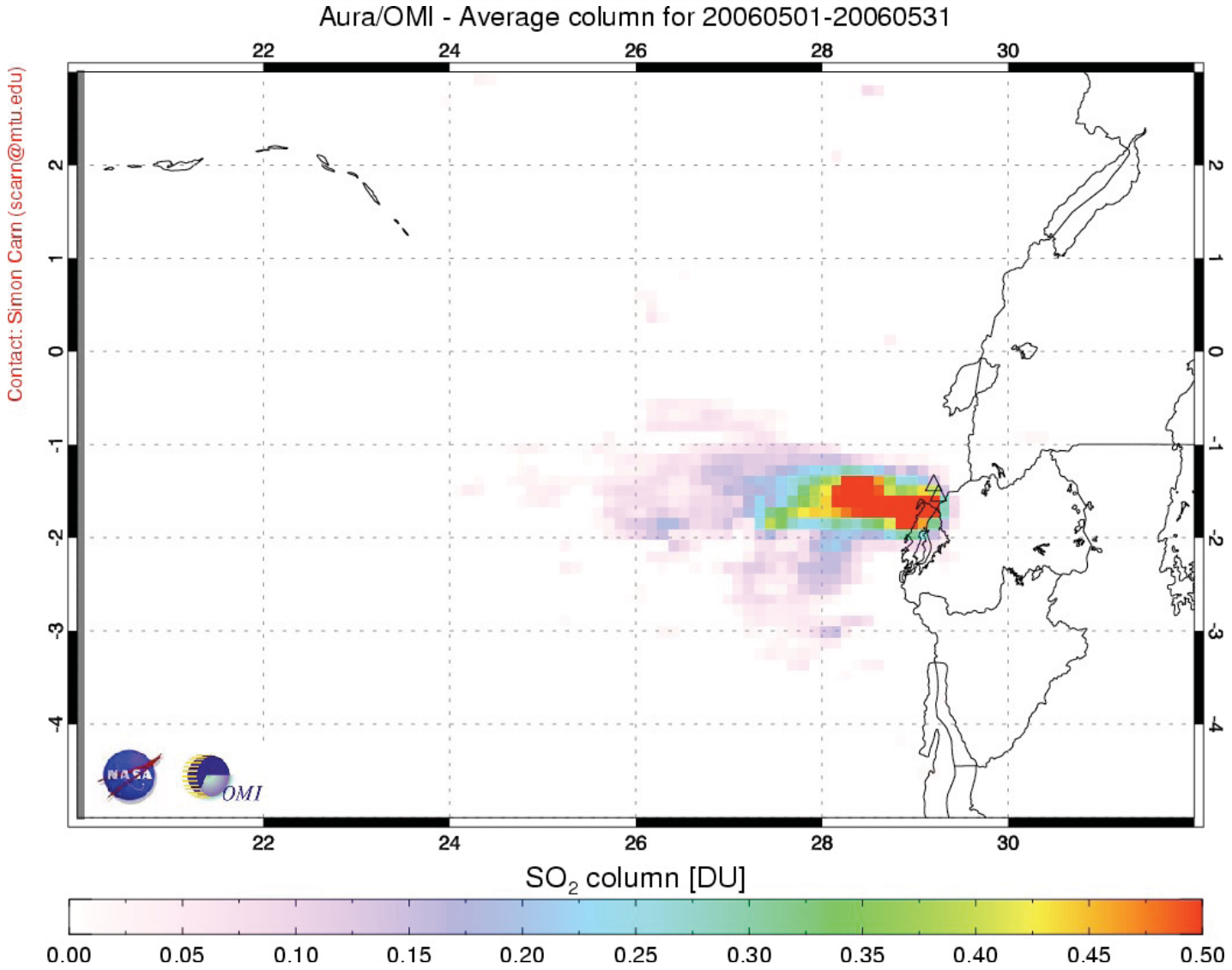

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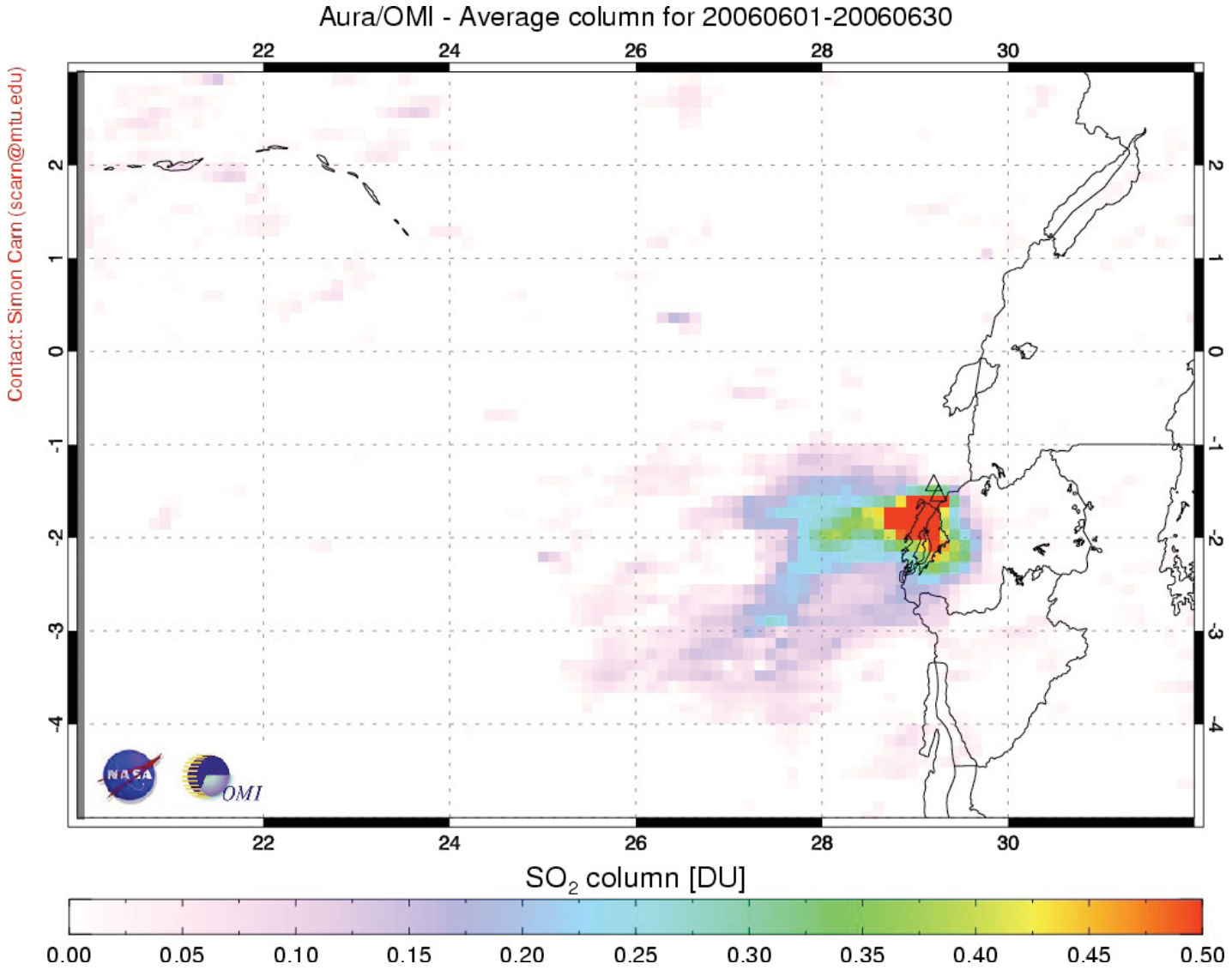

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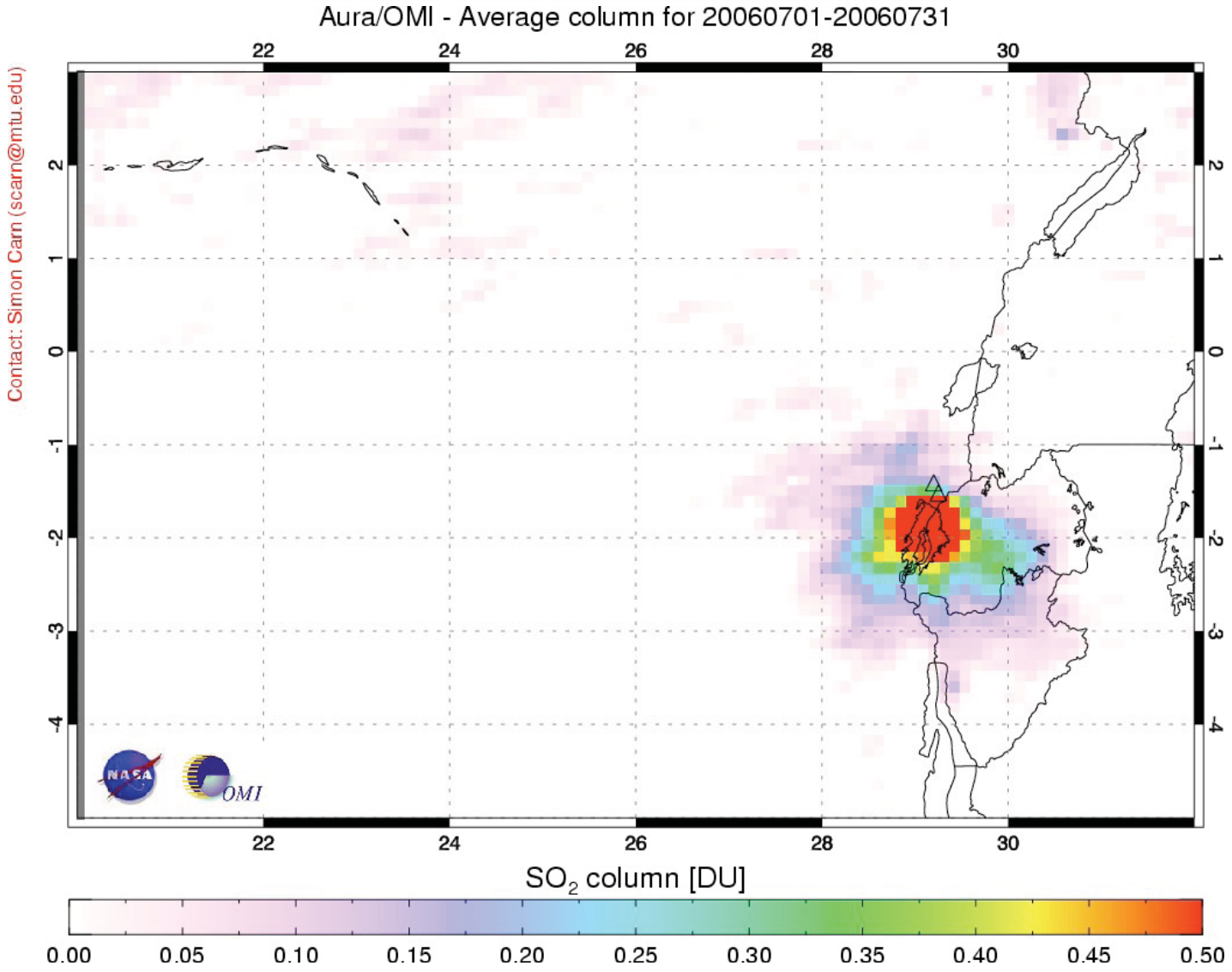

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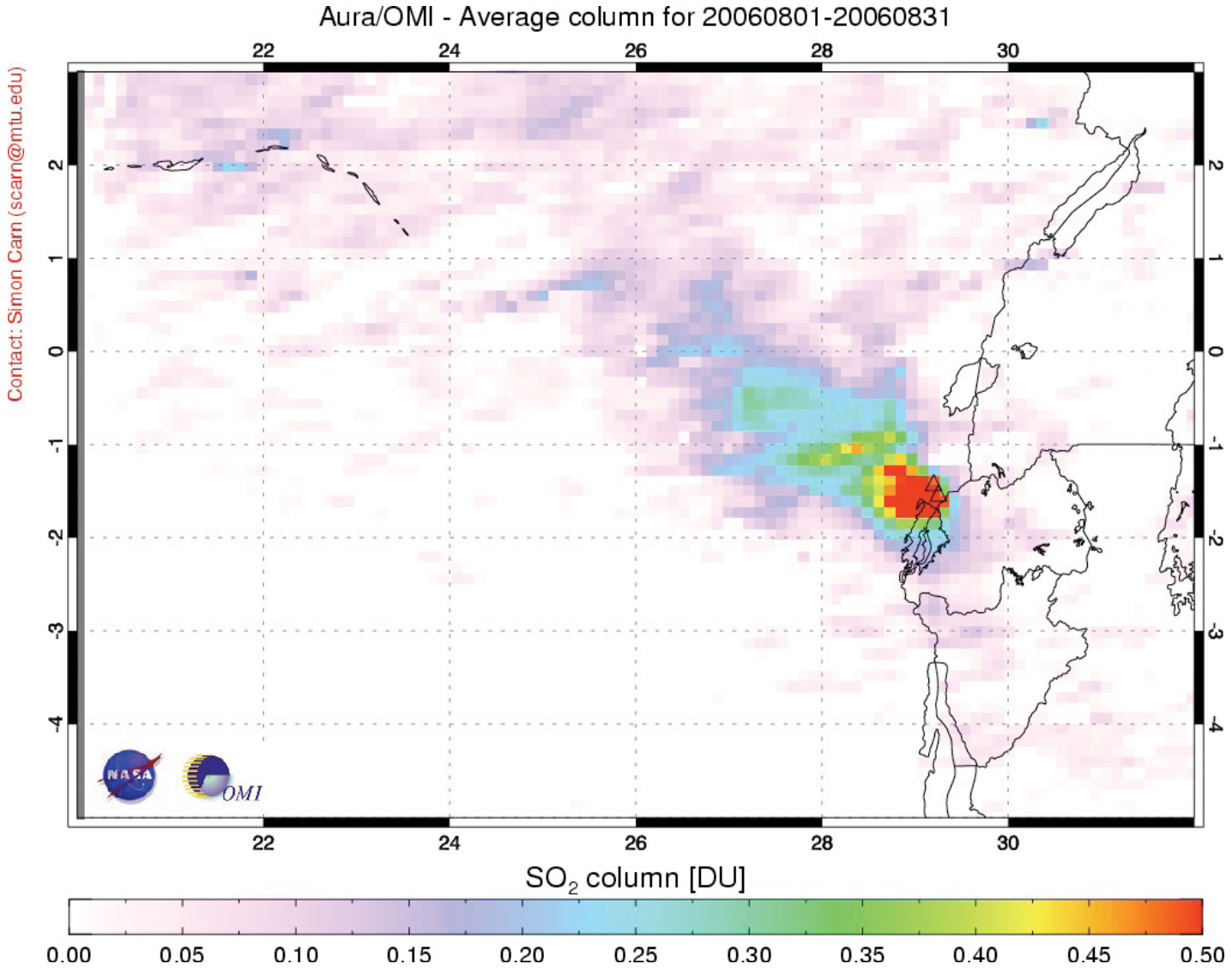

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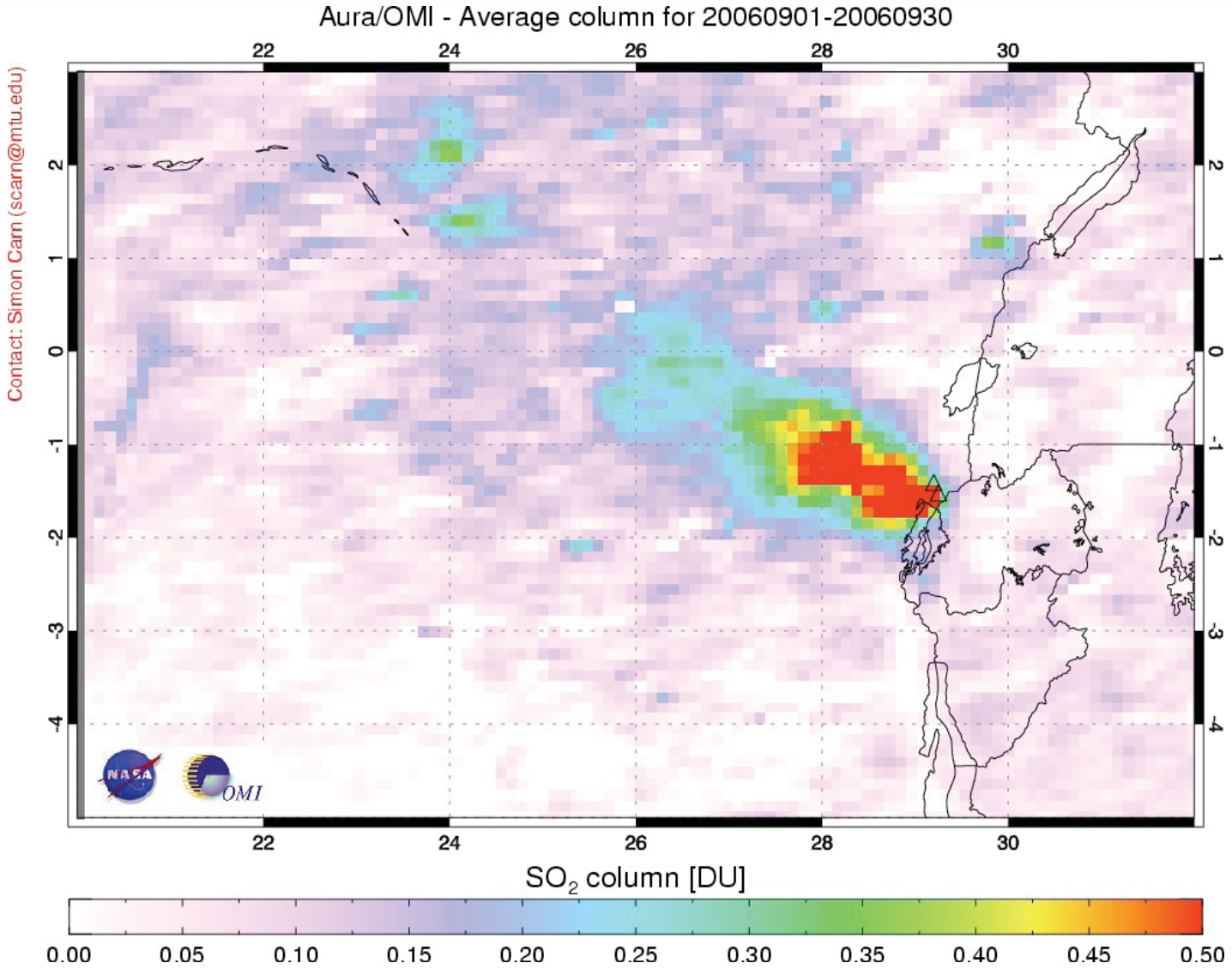

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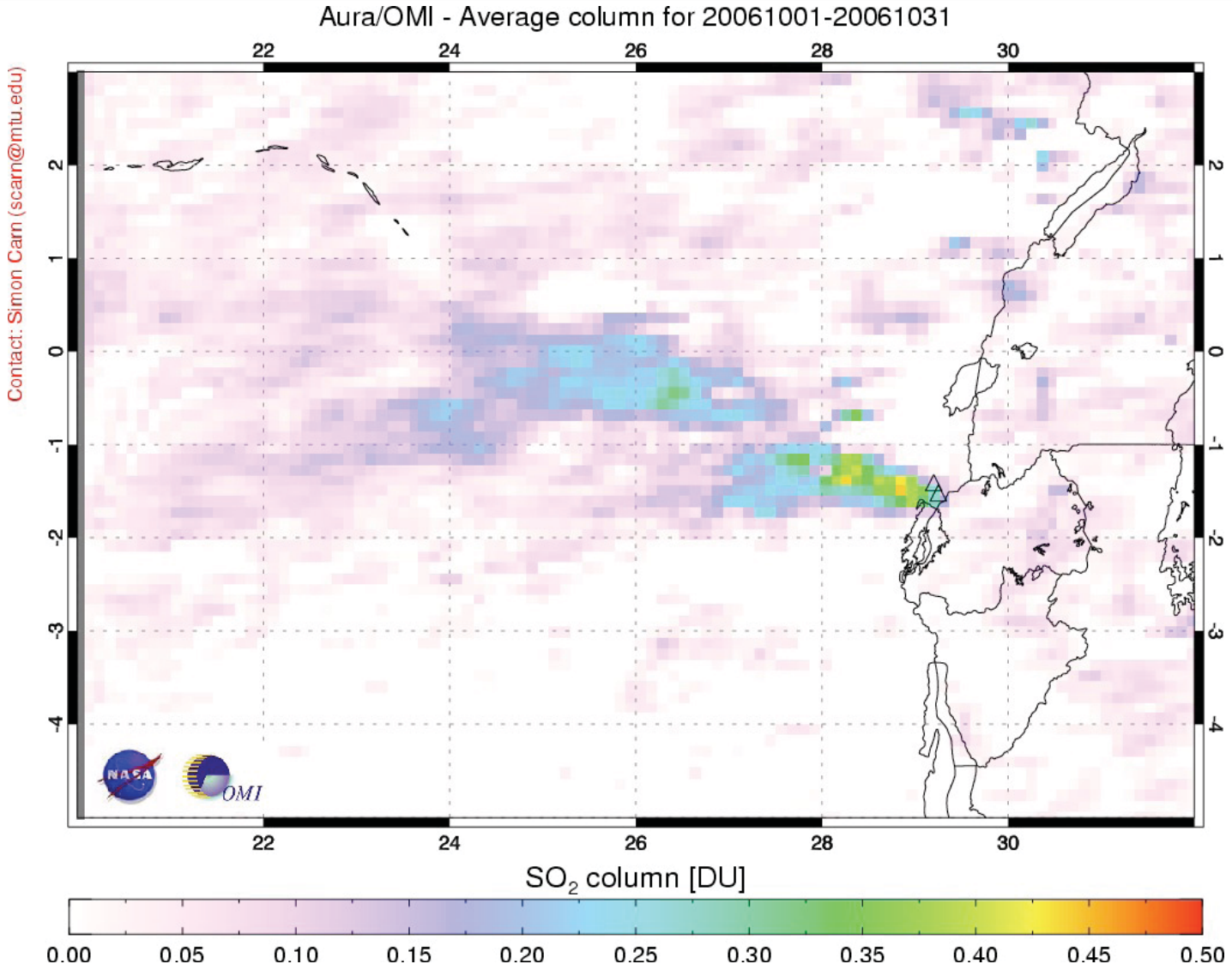

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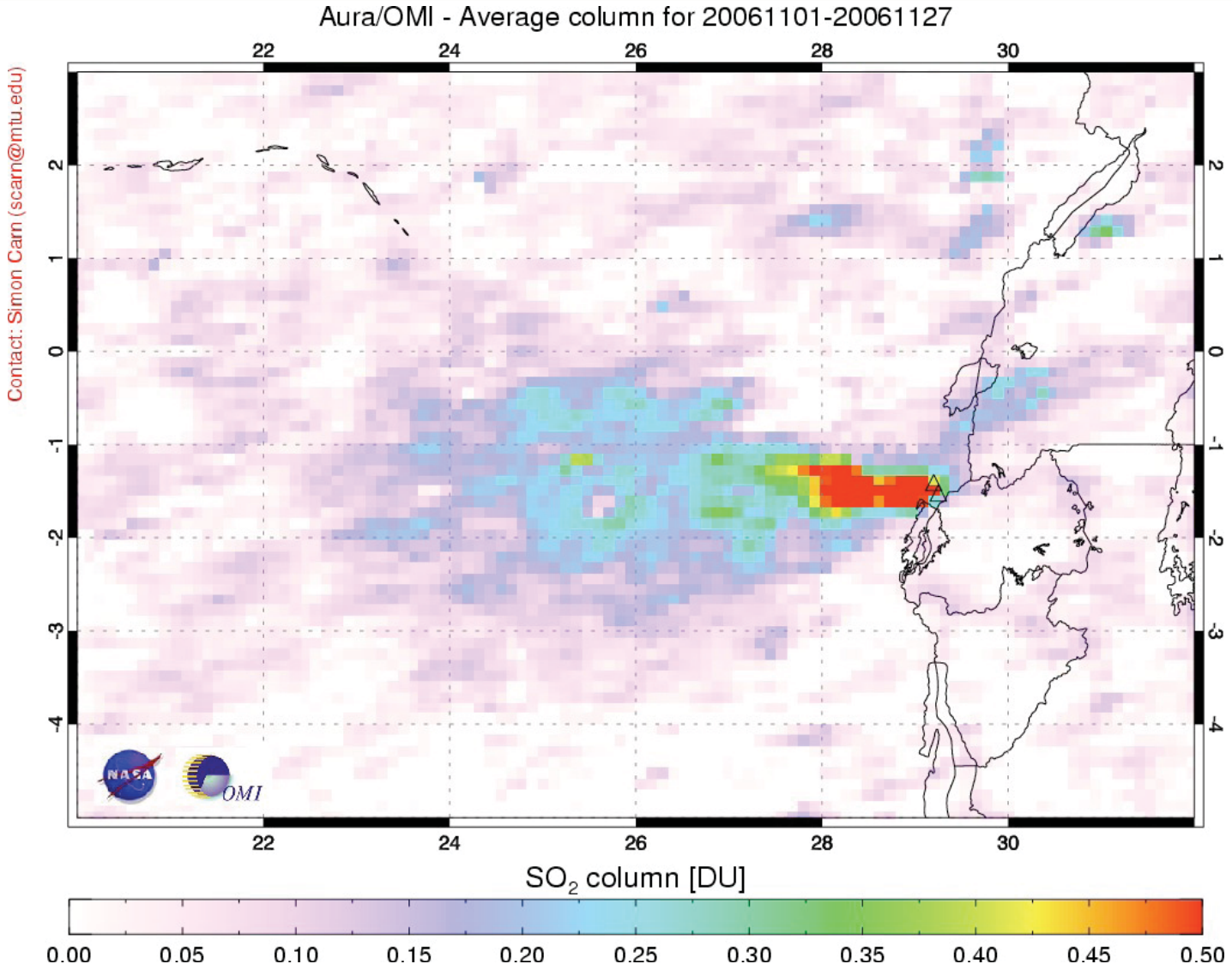

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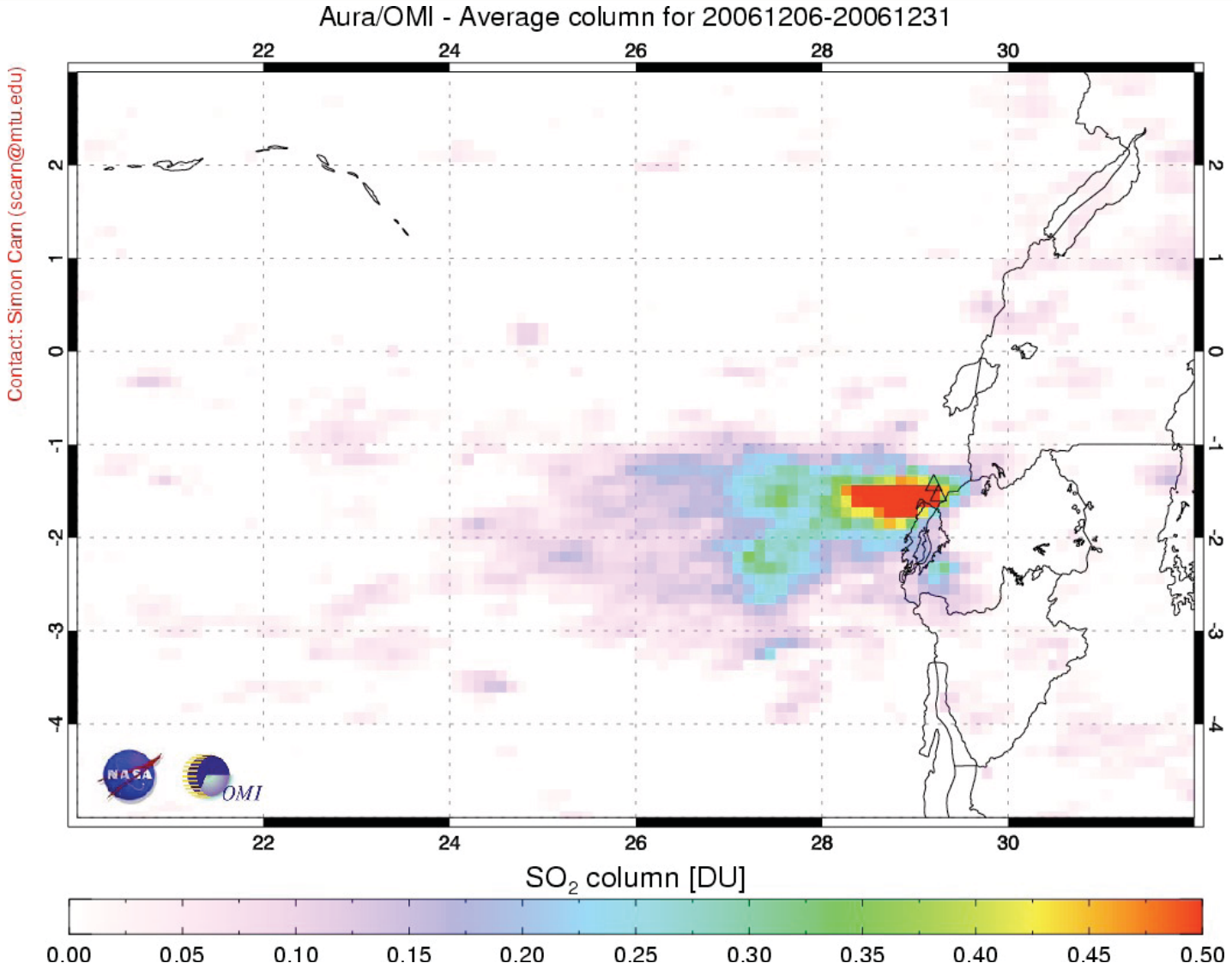
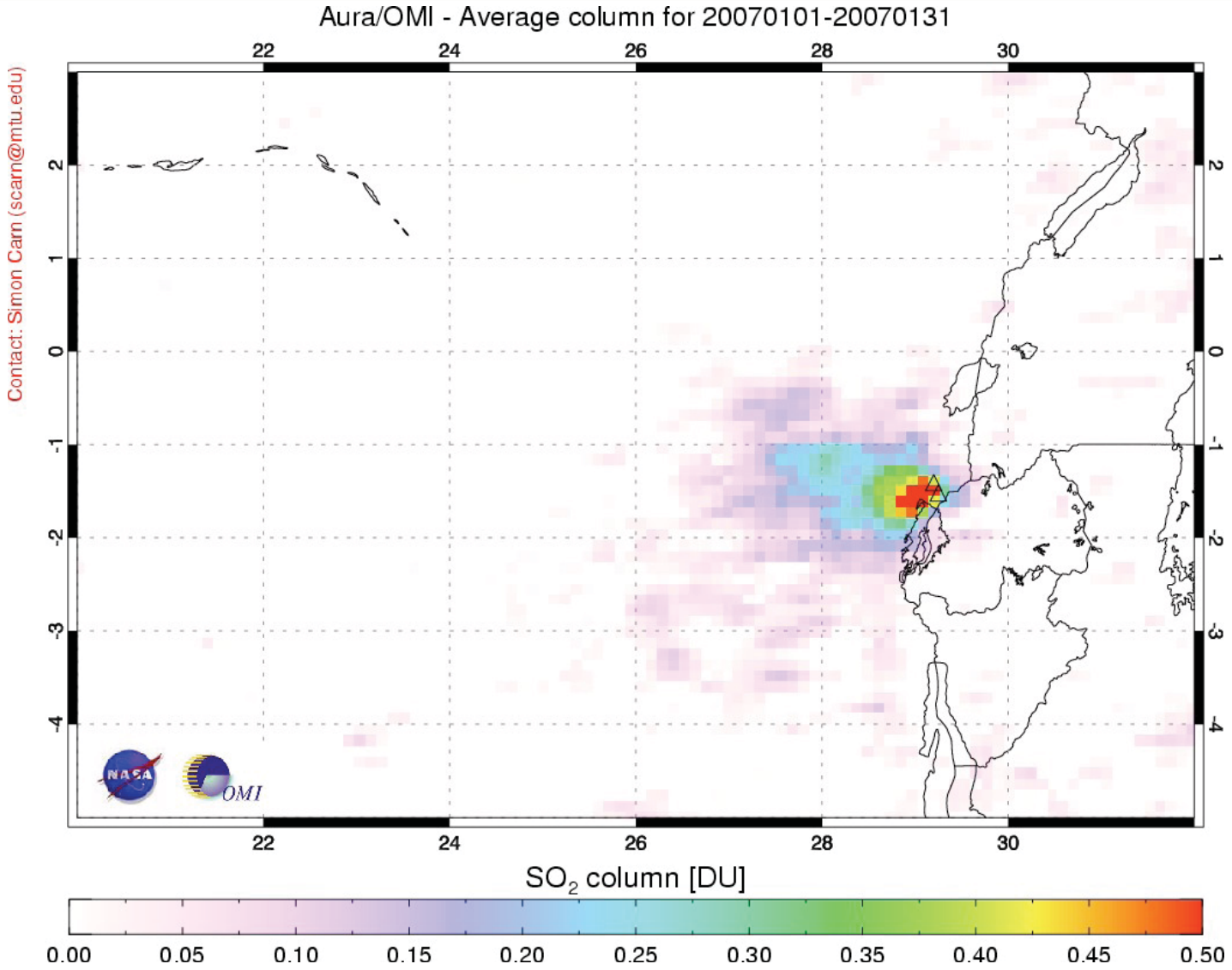
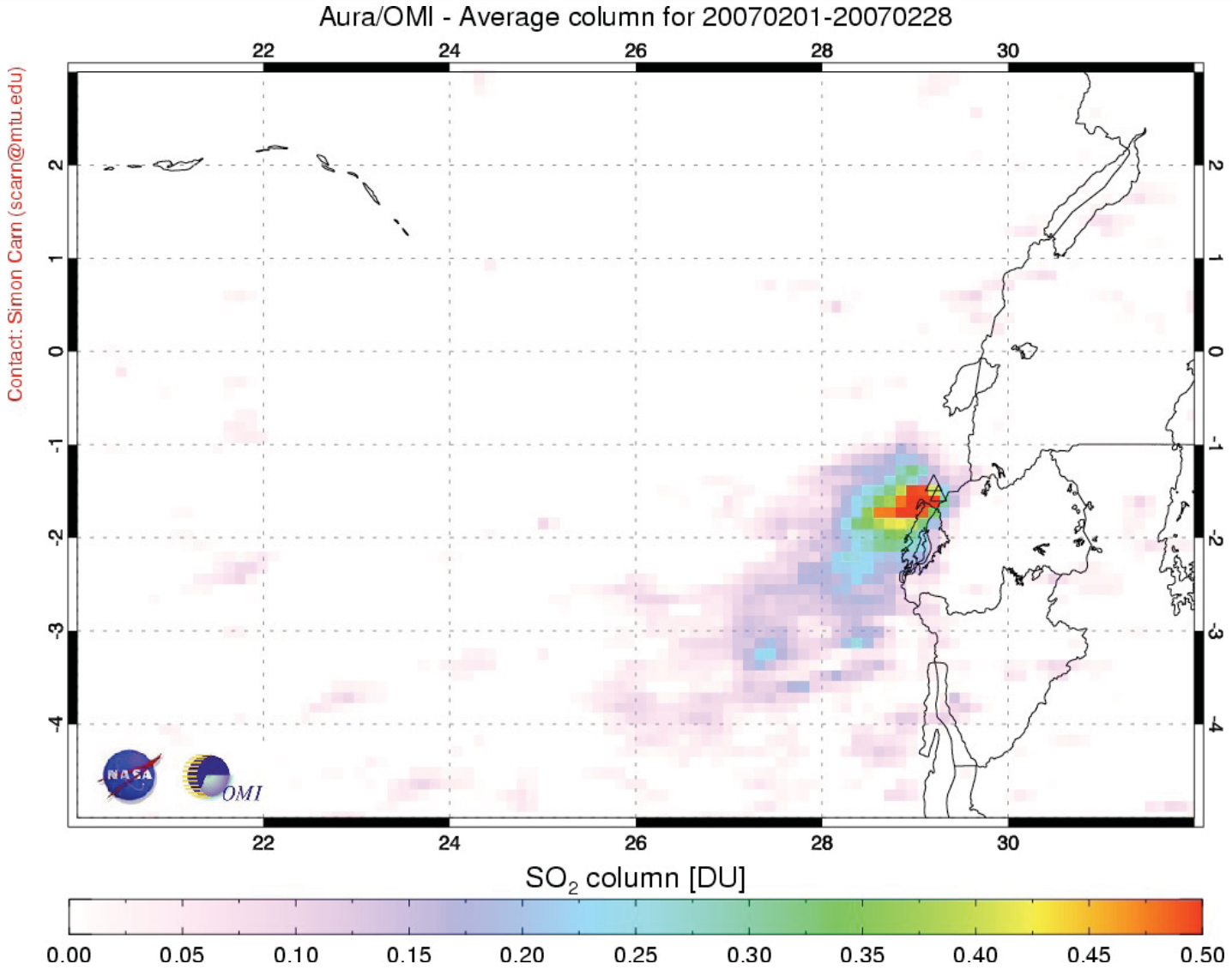


Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



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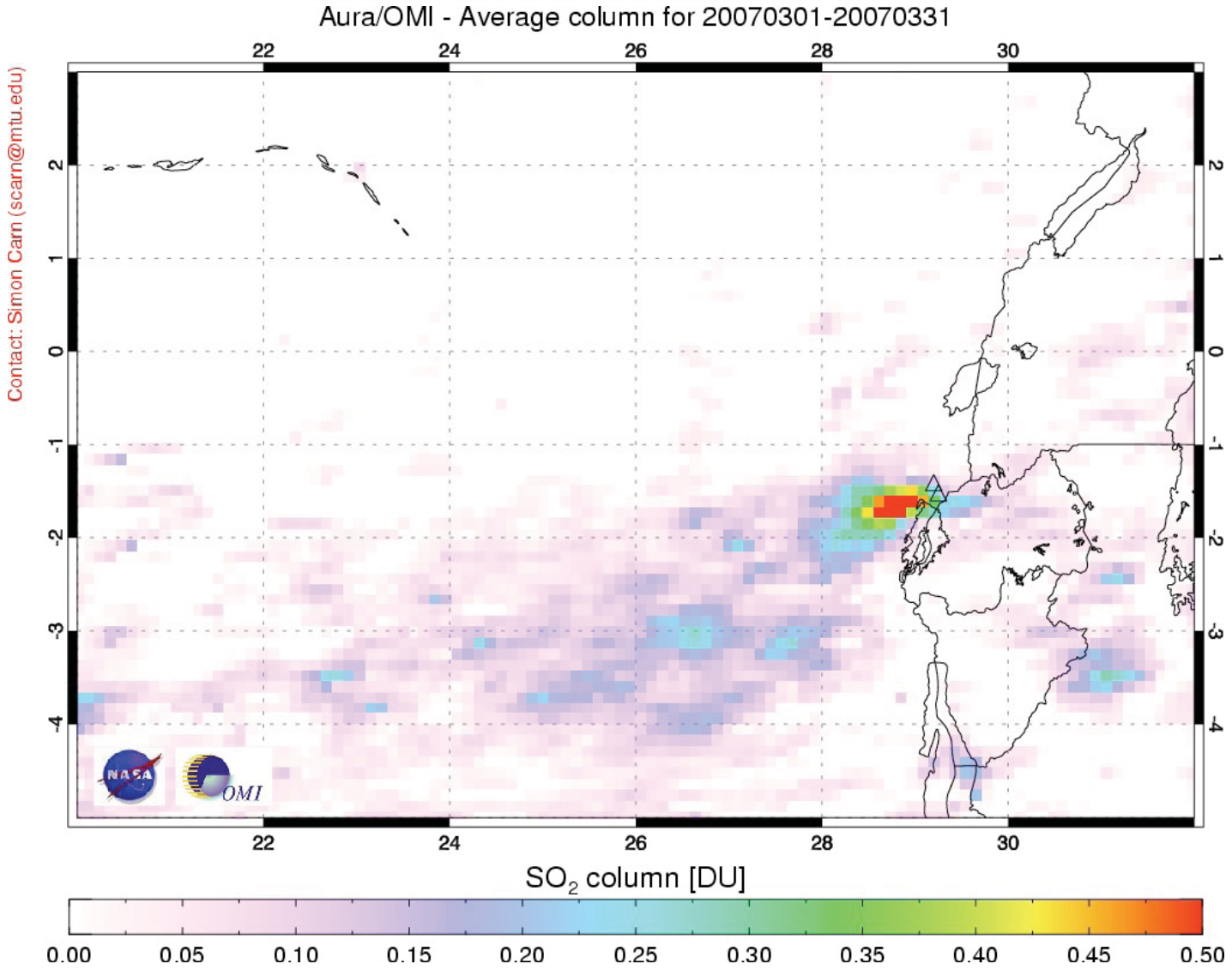

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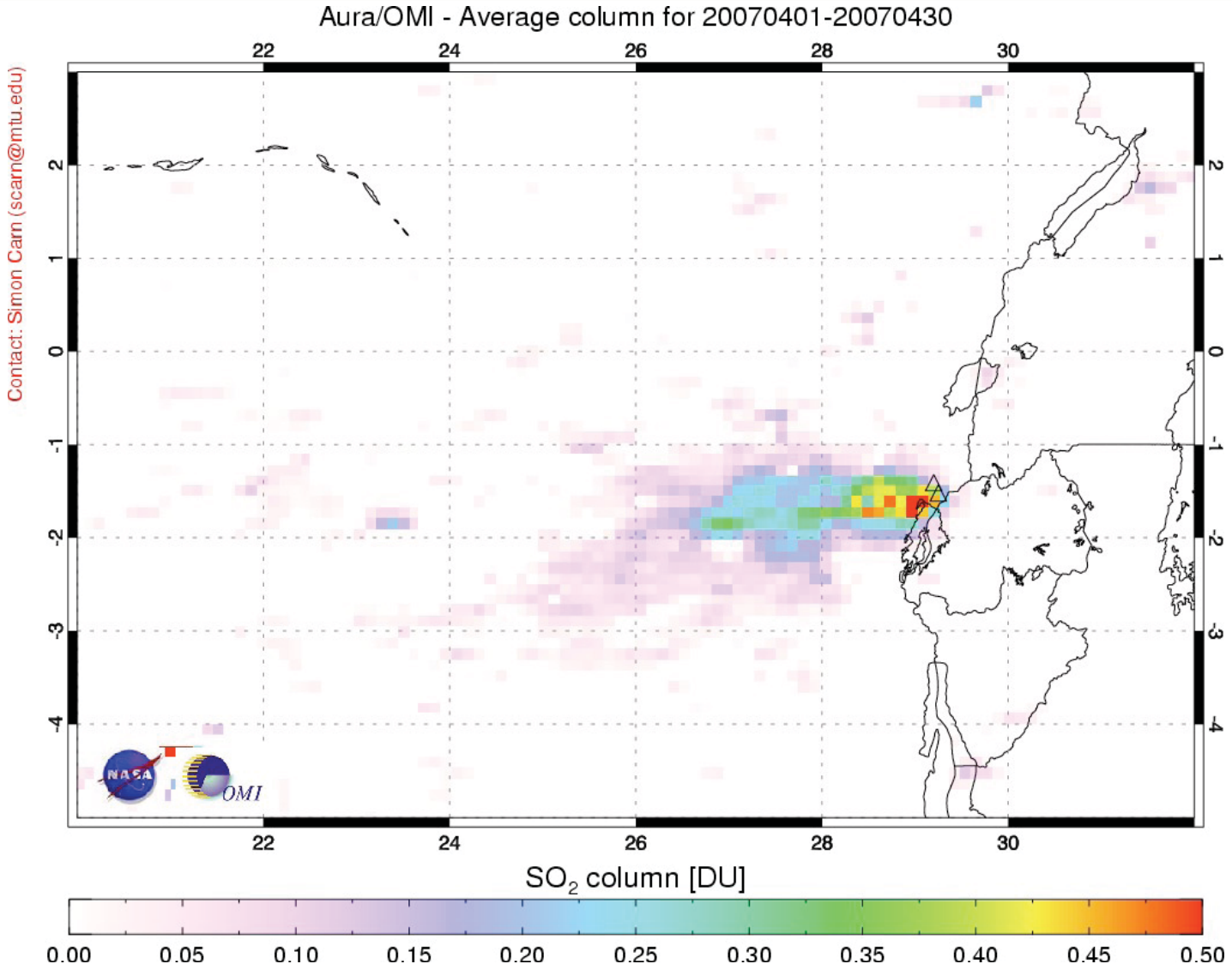

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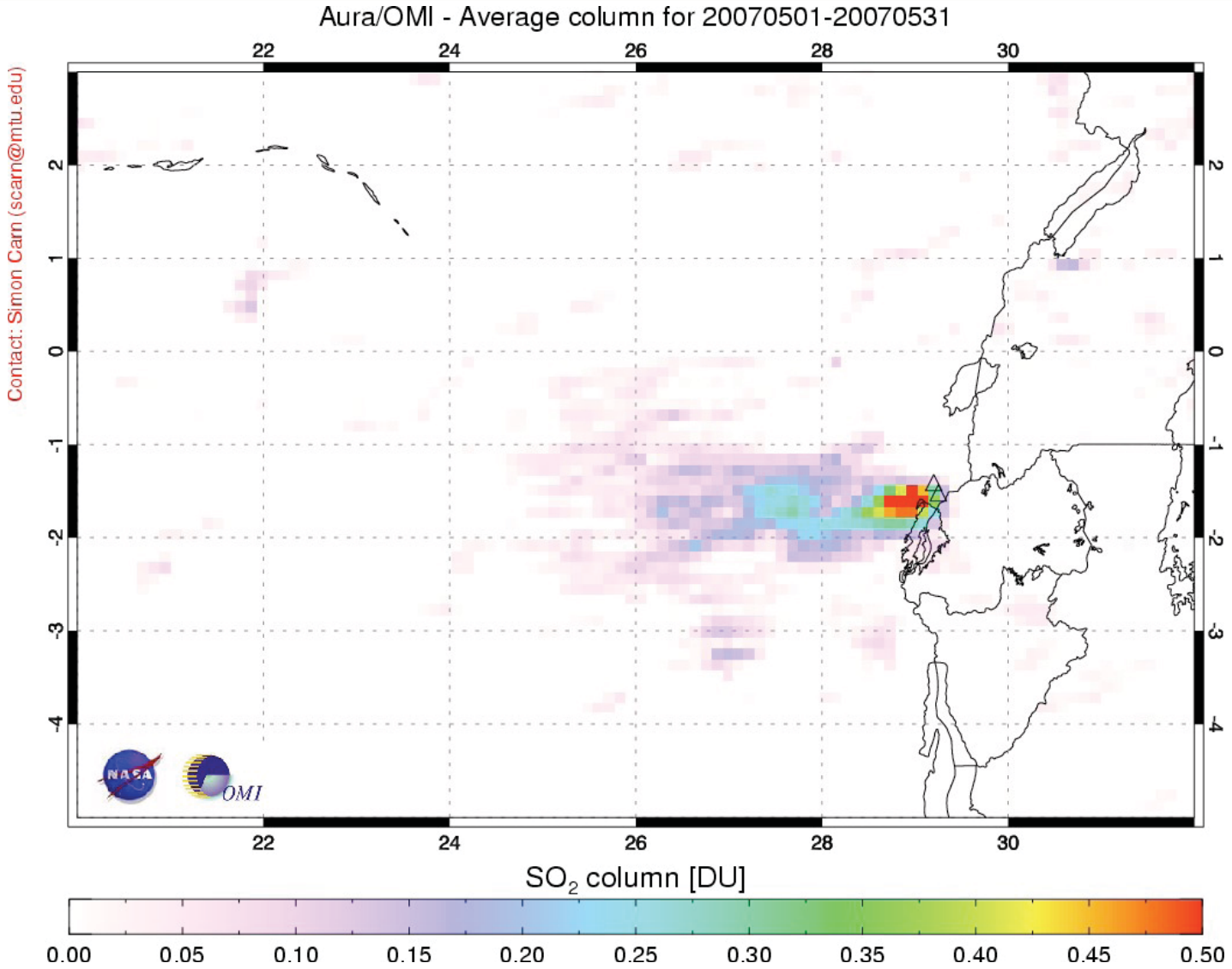

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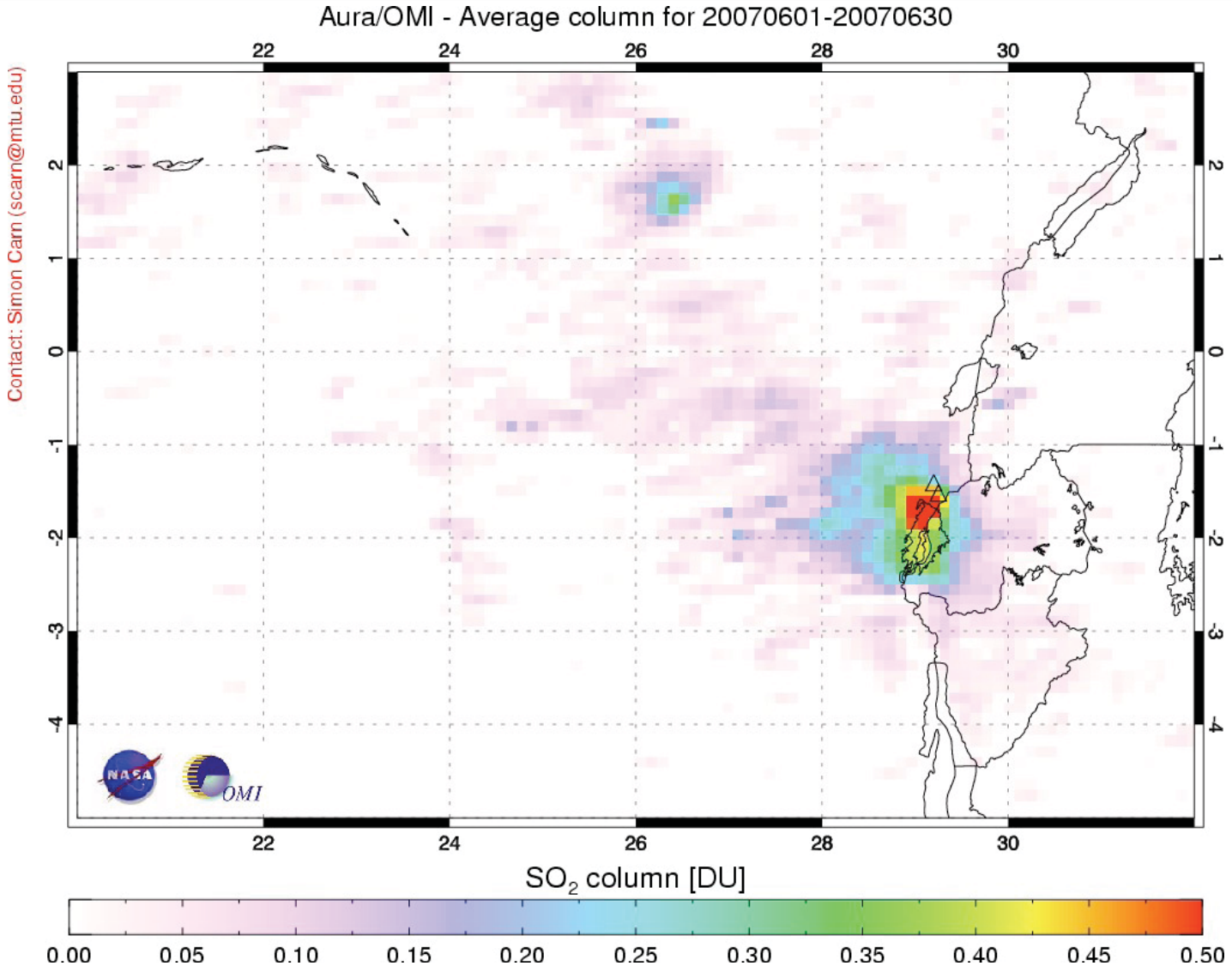
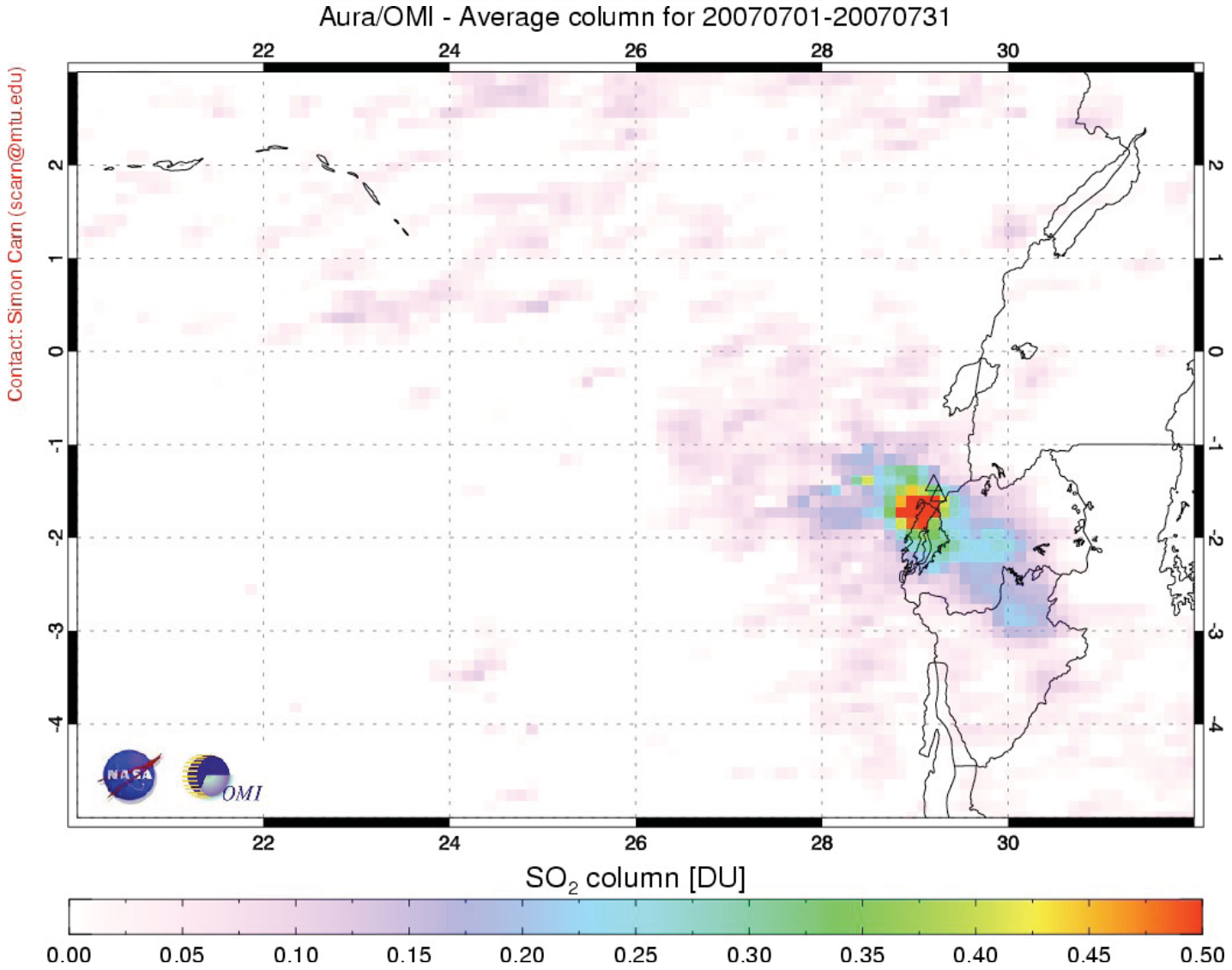


Nyiragongo – monthly average SO_2 columns



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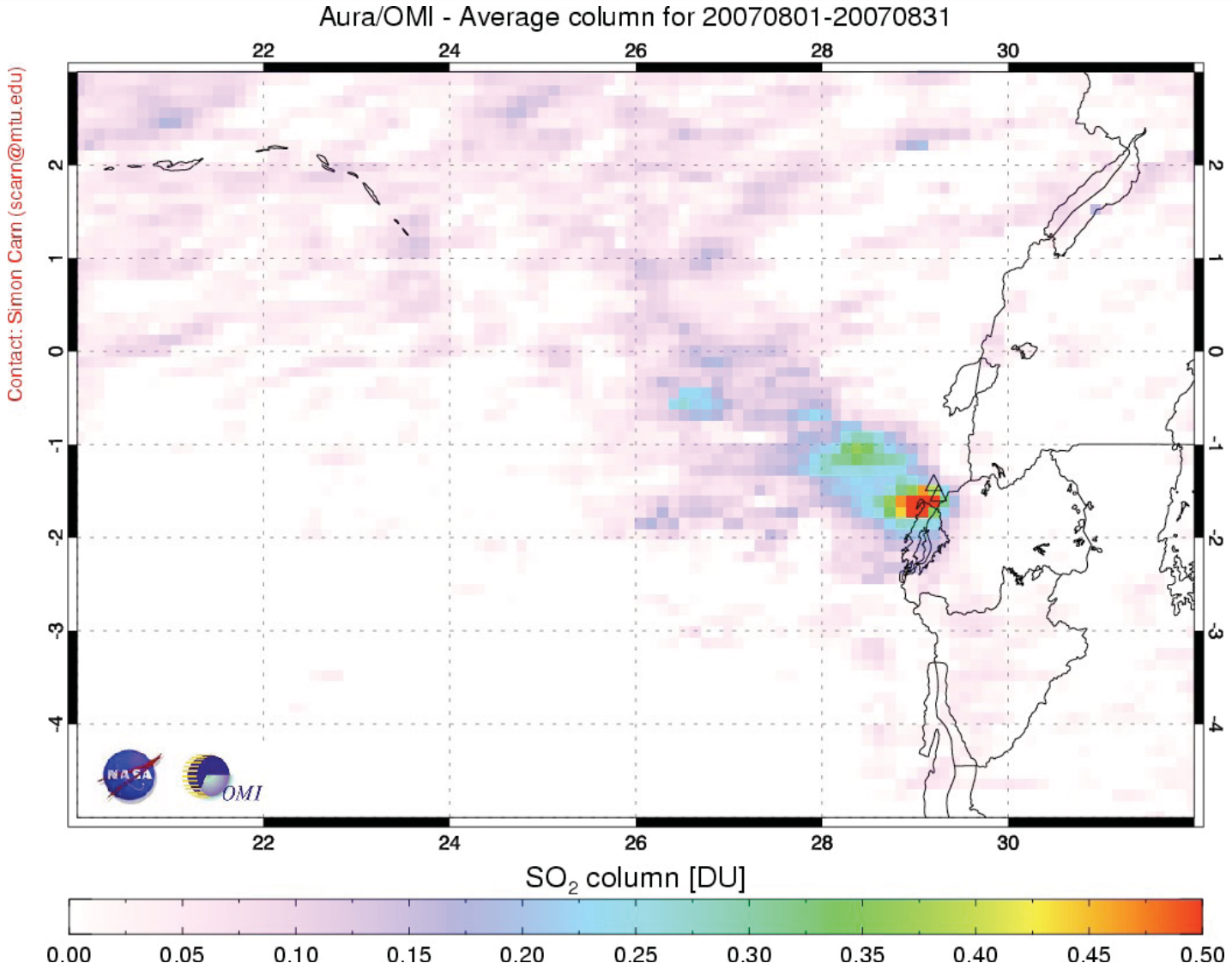
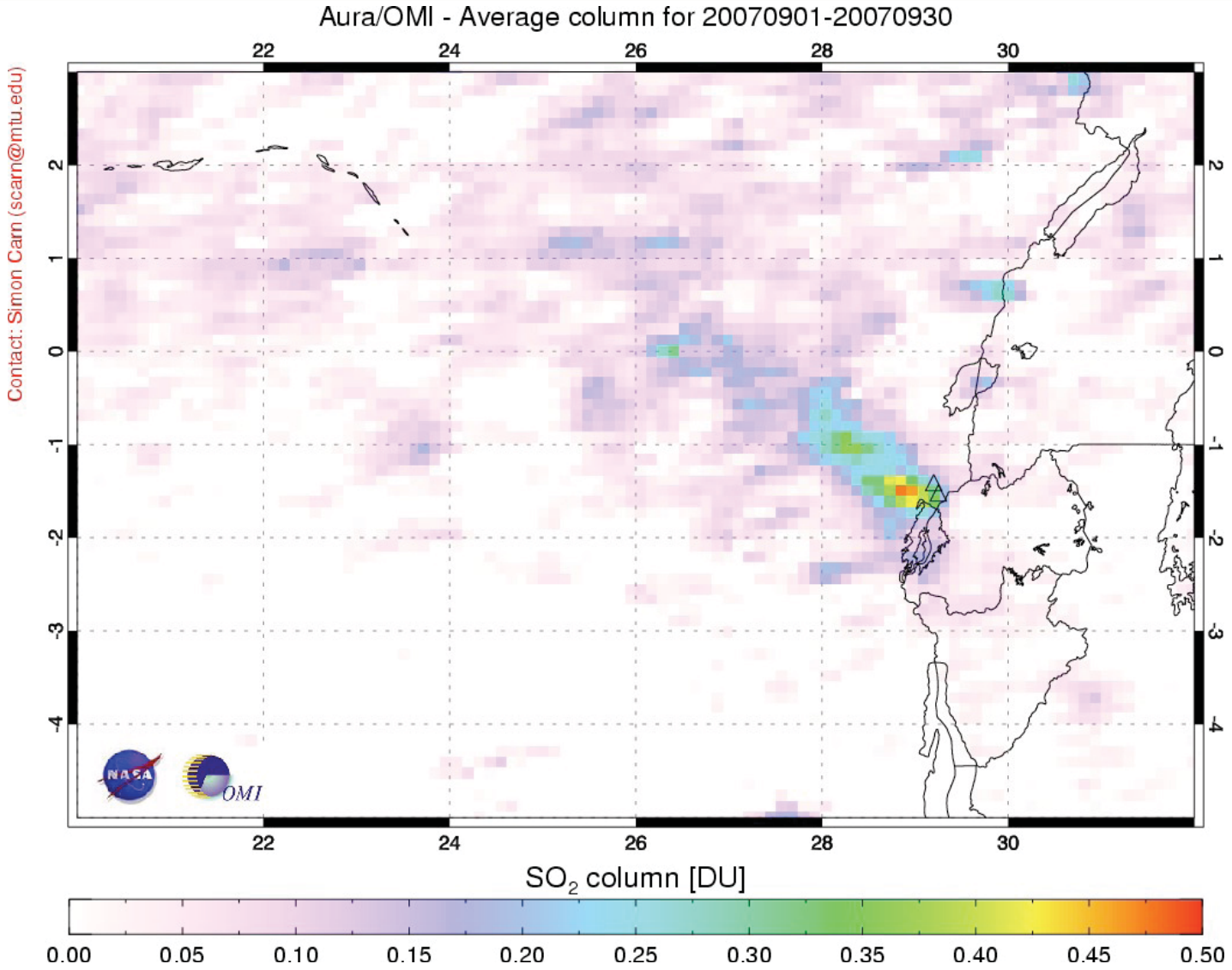


Nyiragongo – monthly average SO_2 columns



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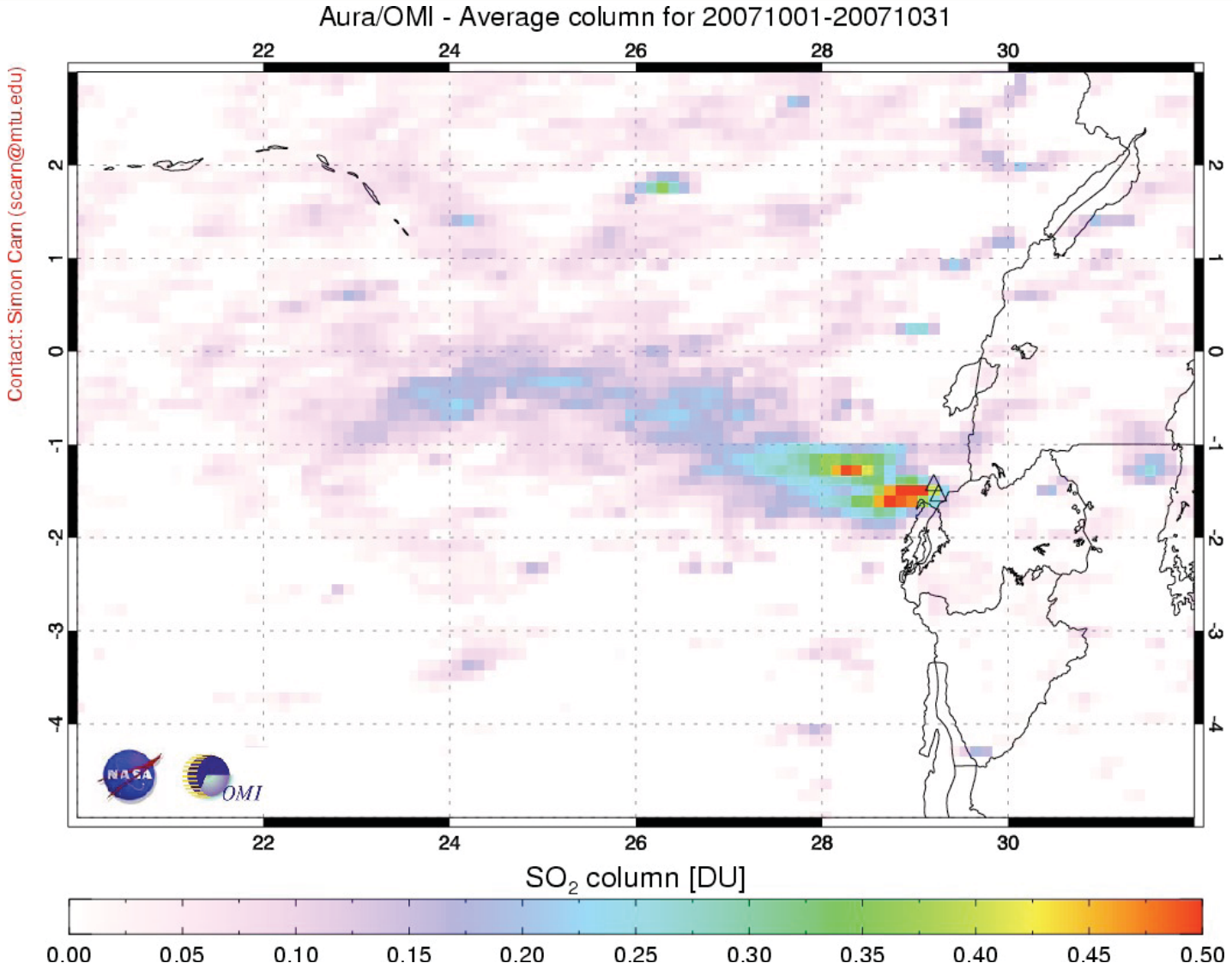
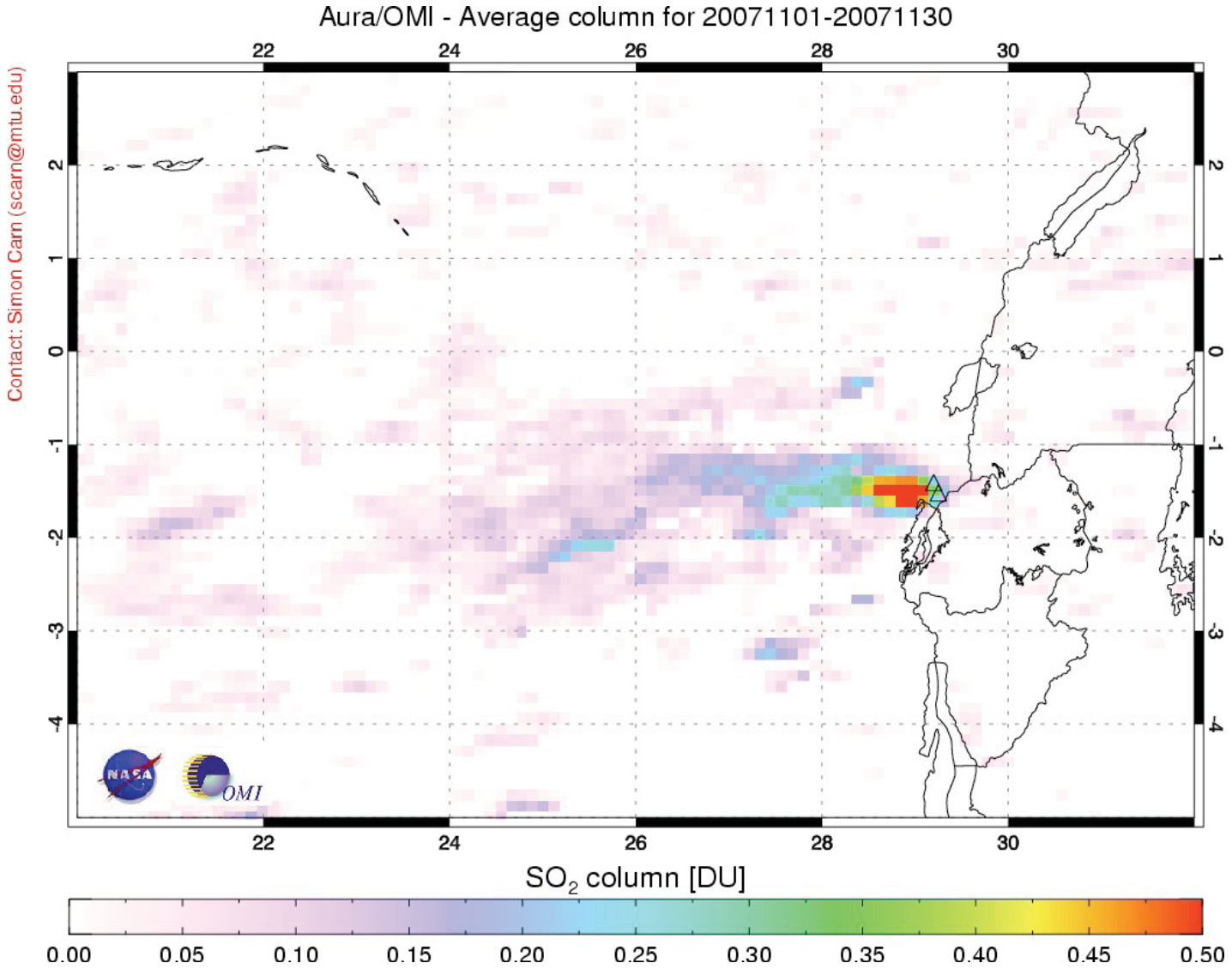
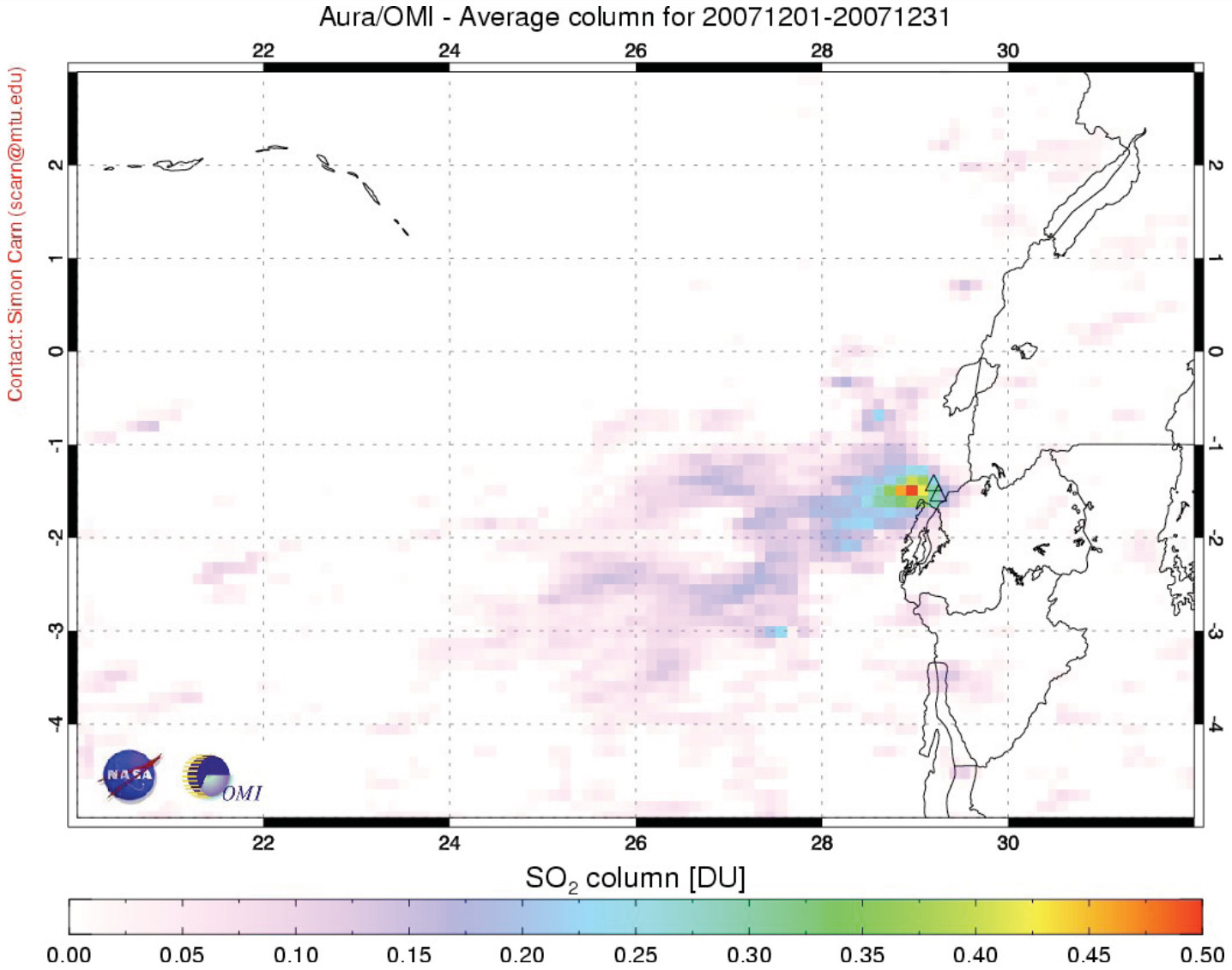


Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



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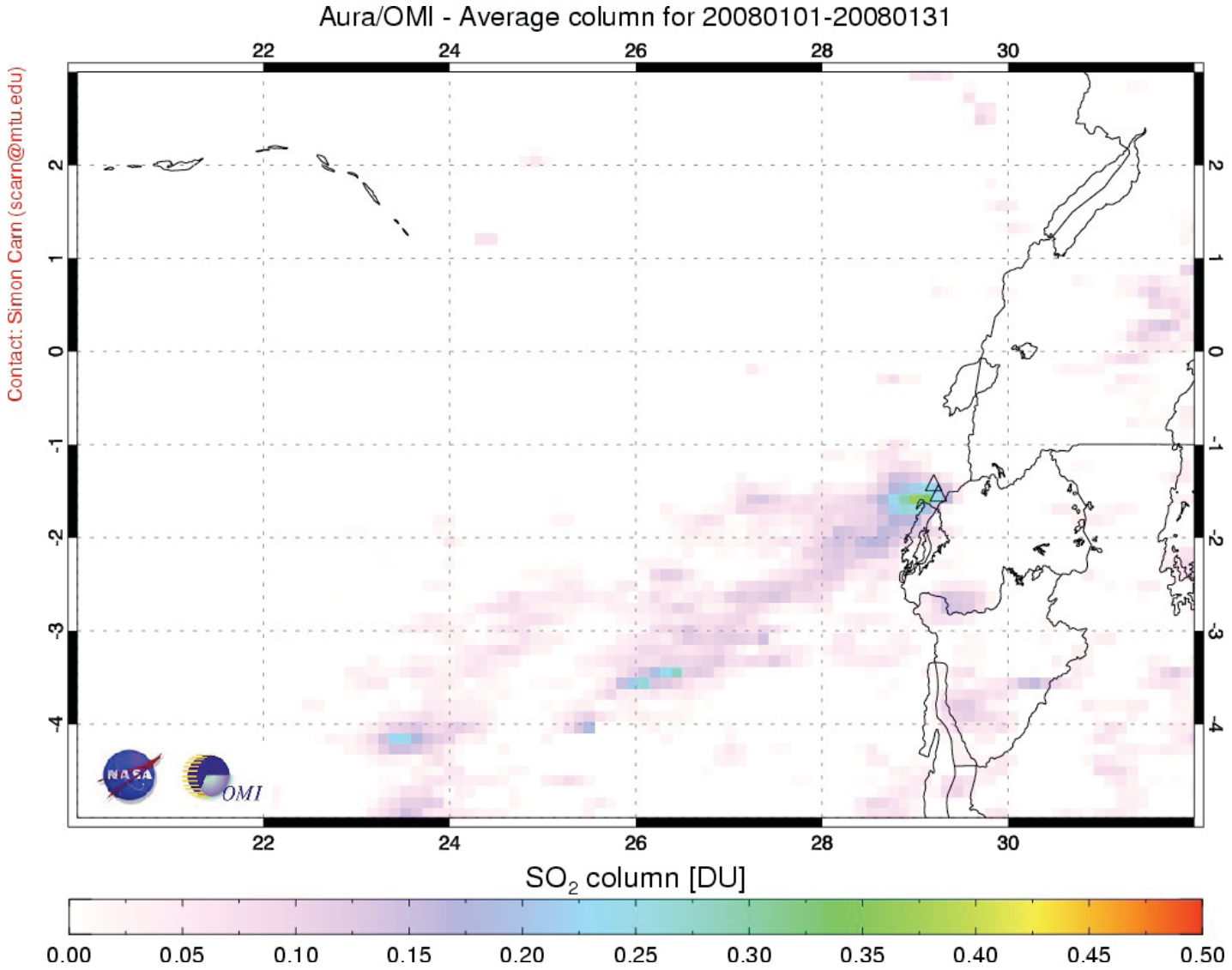
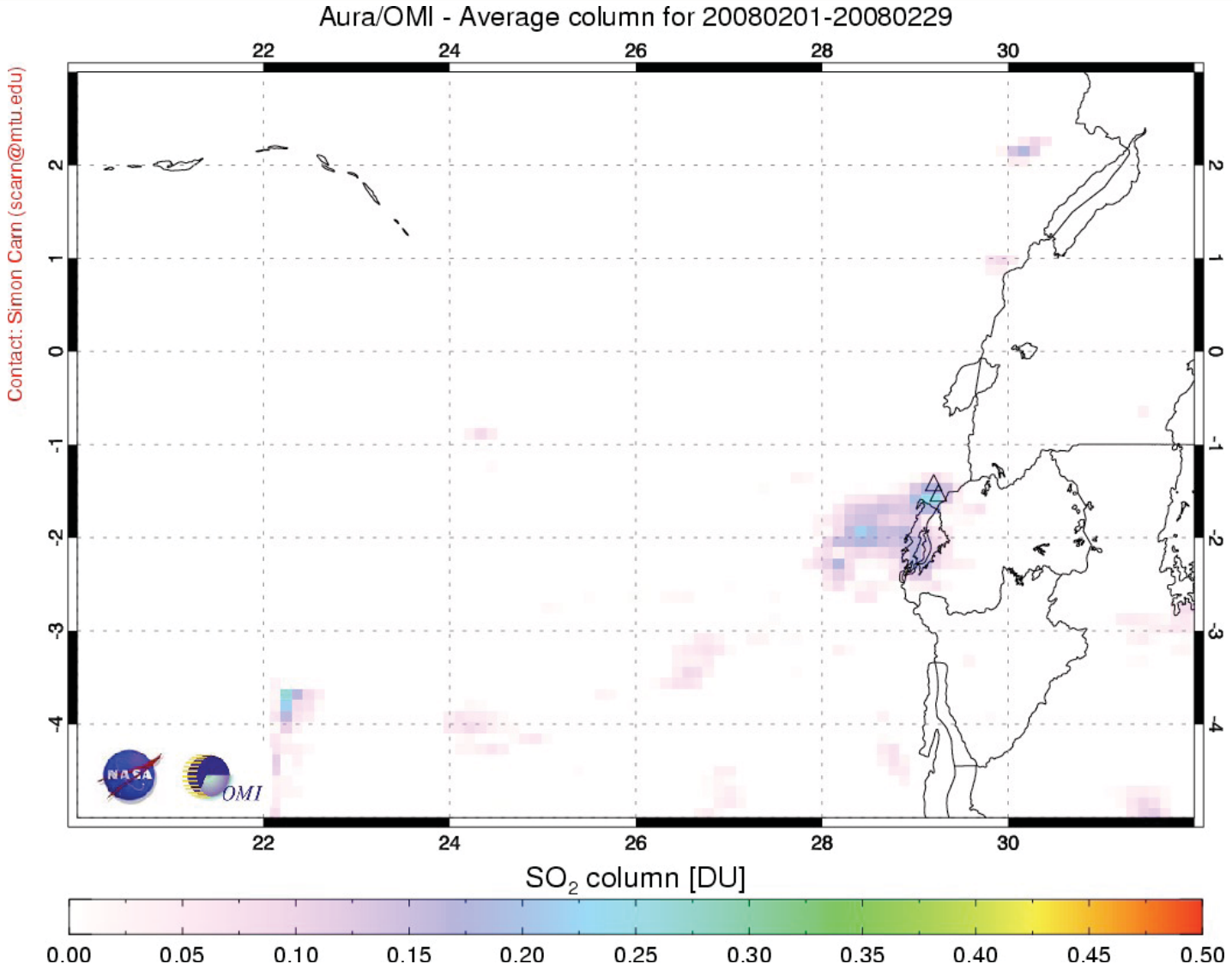


Nyiragongo – monthly average SO_2 columns



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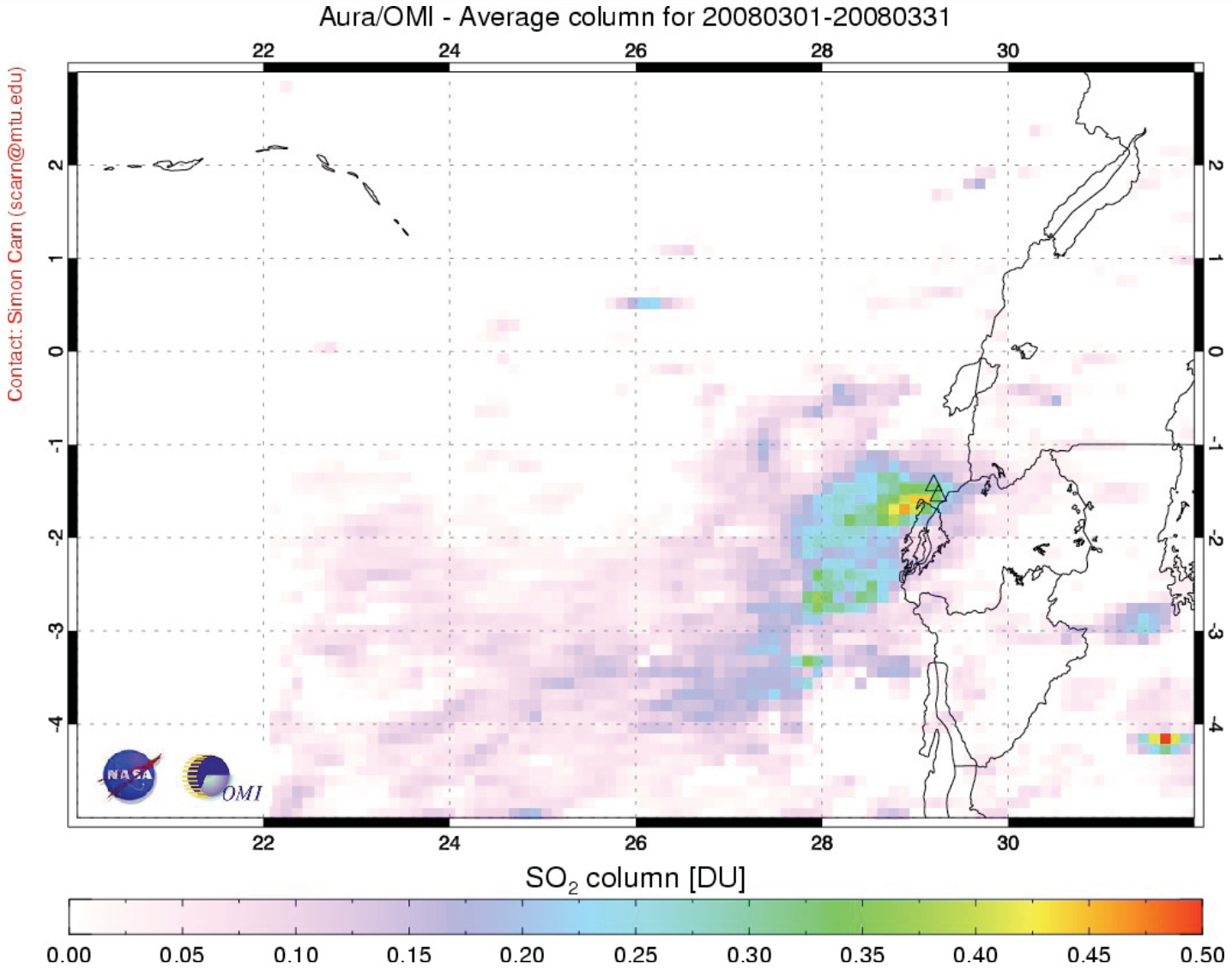

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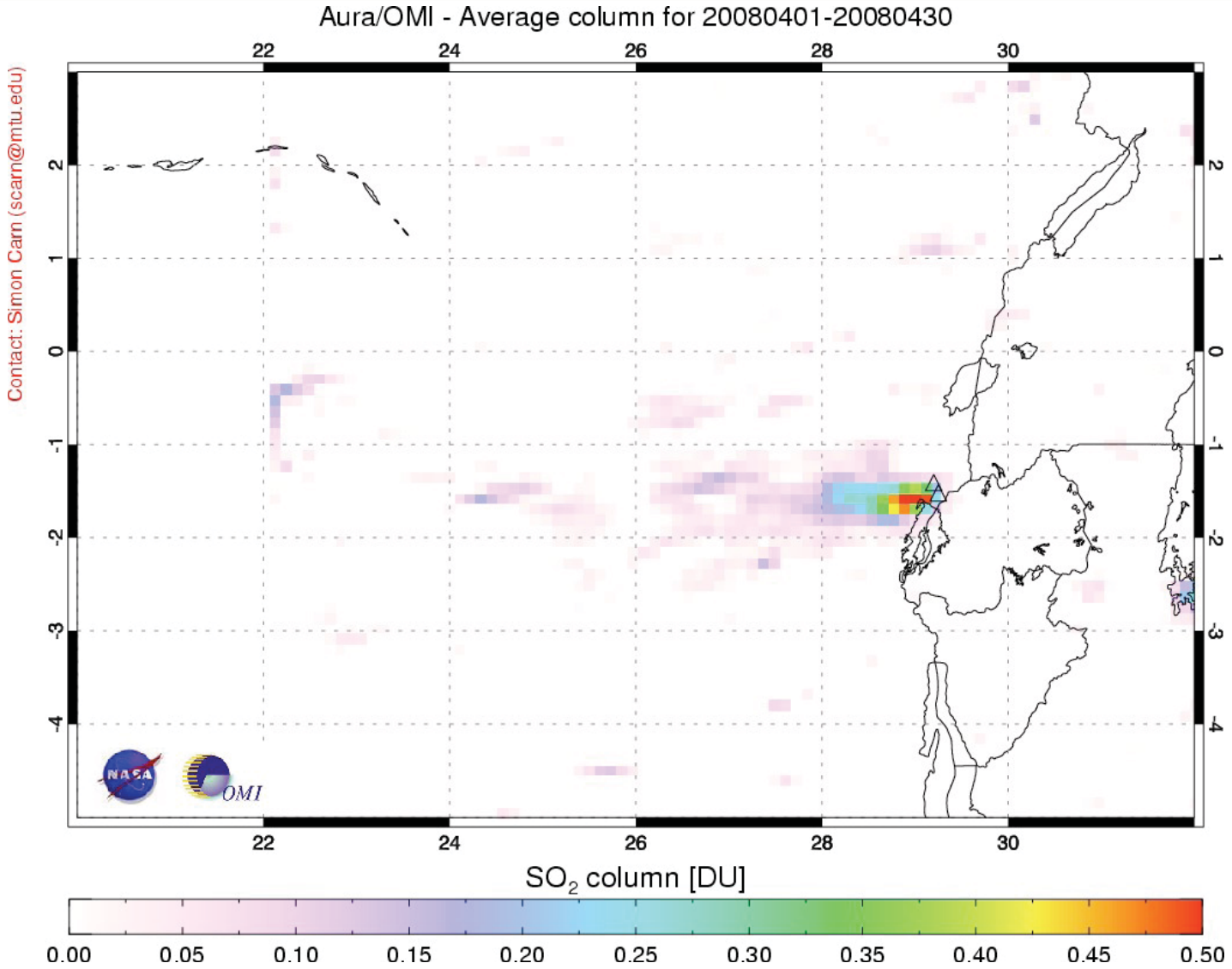

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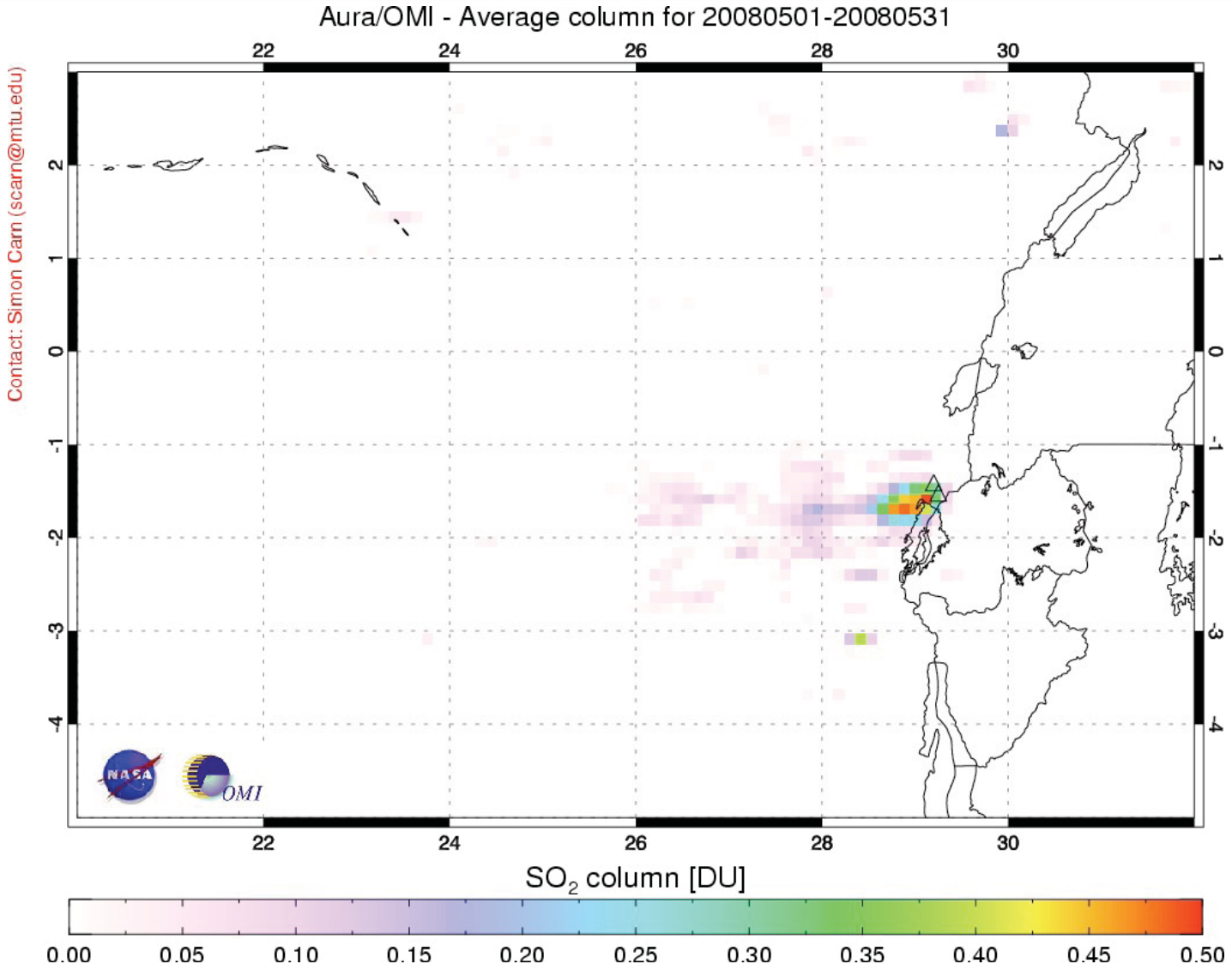

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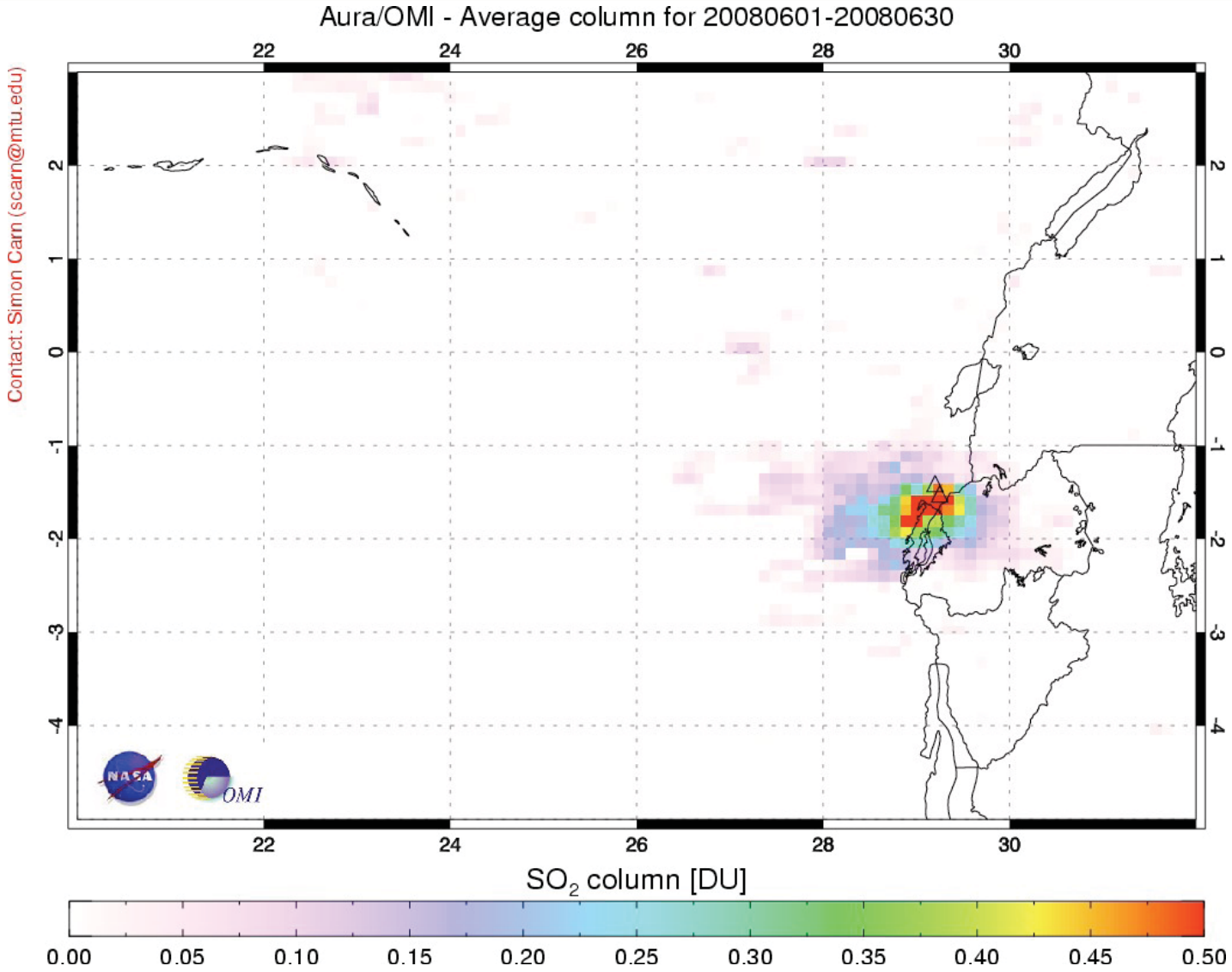
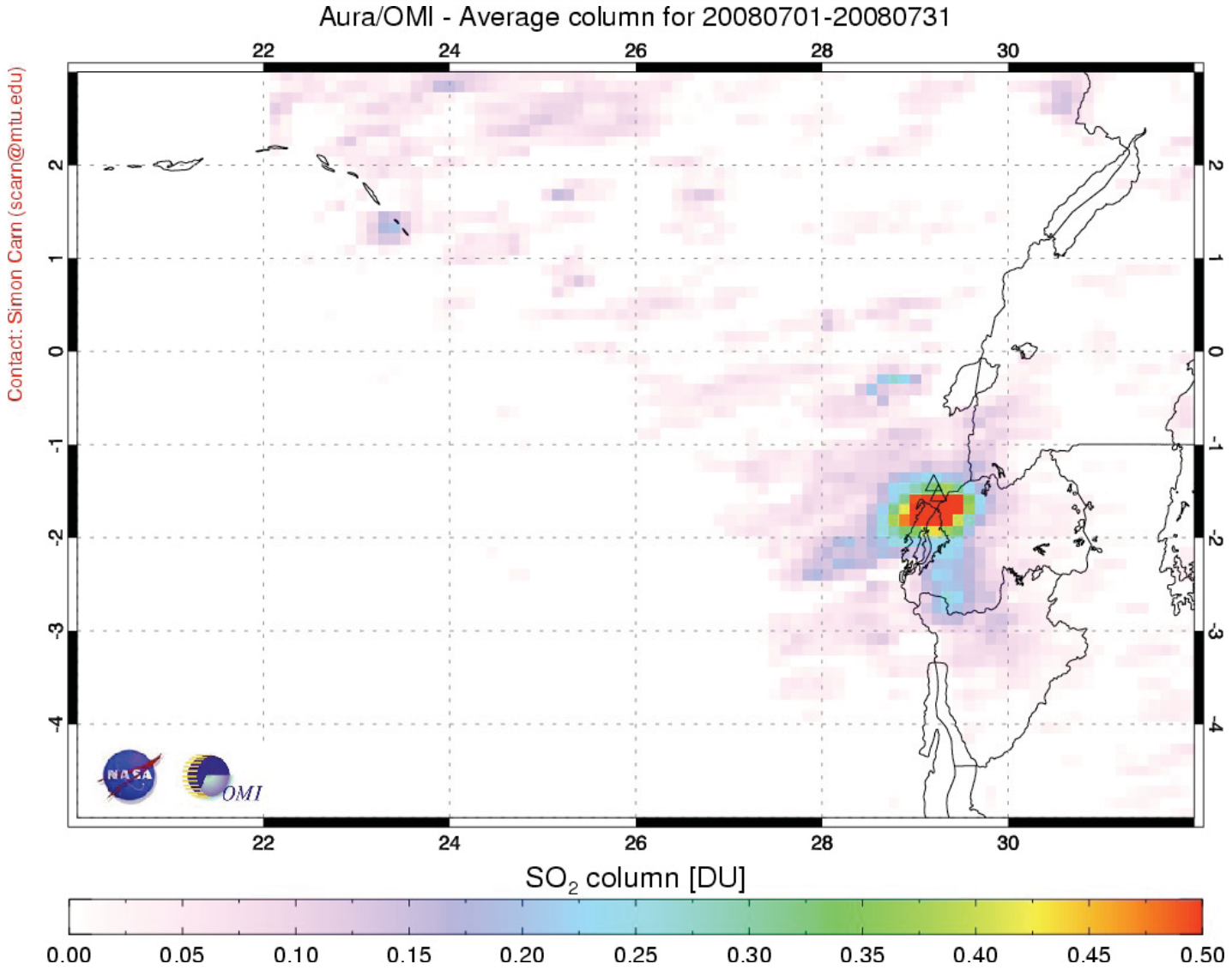
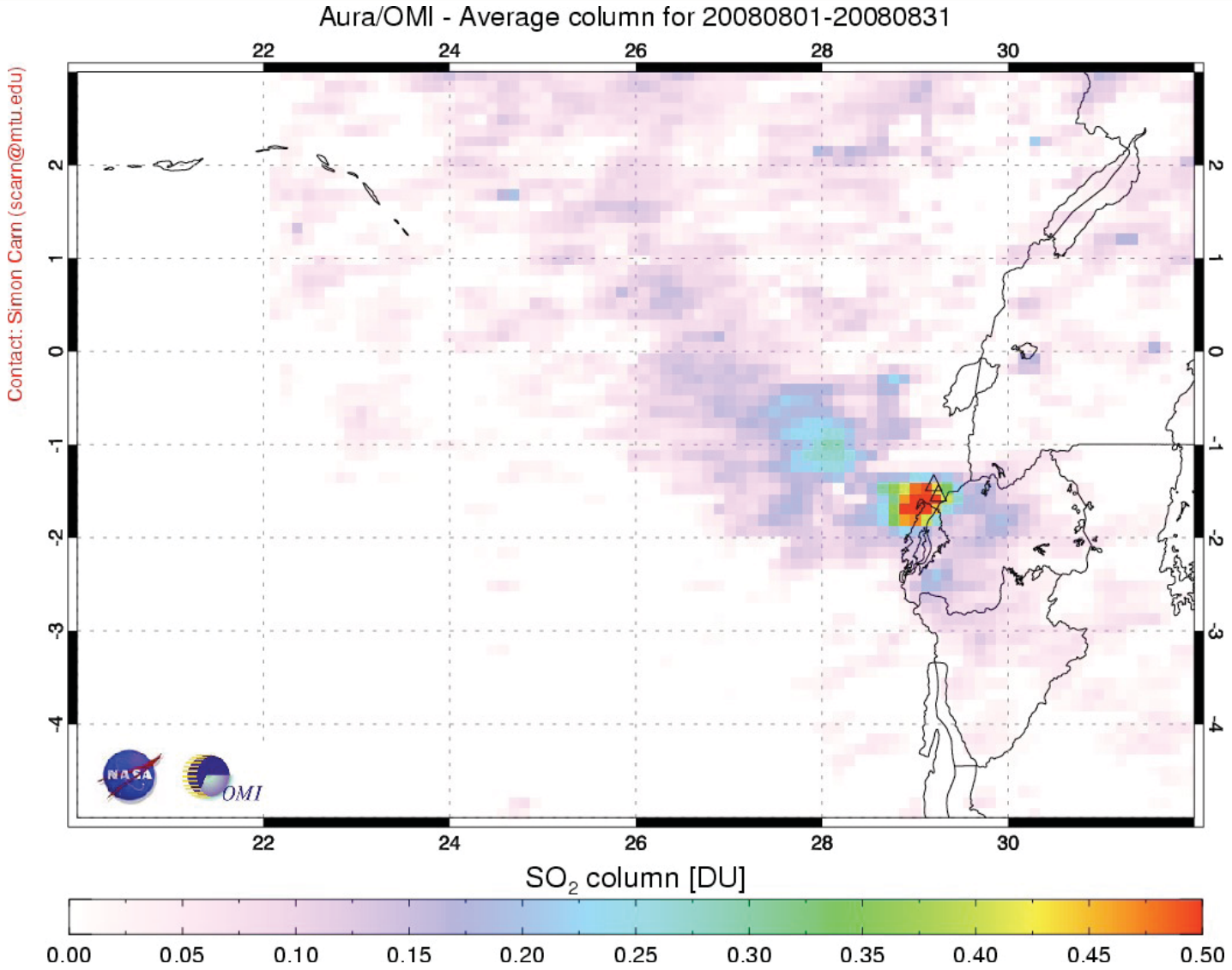


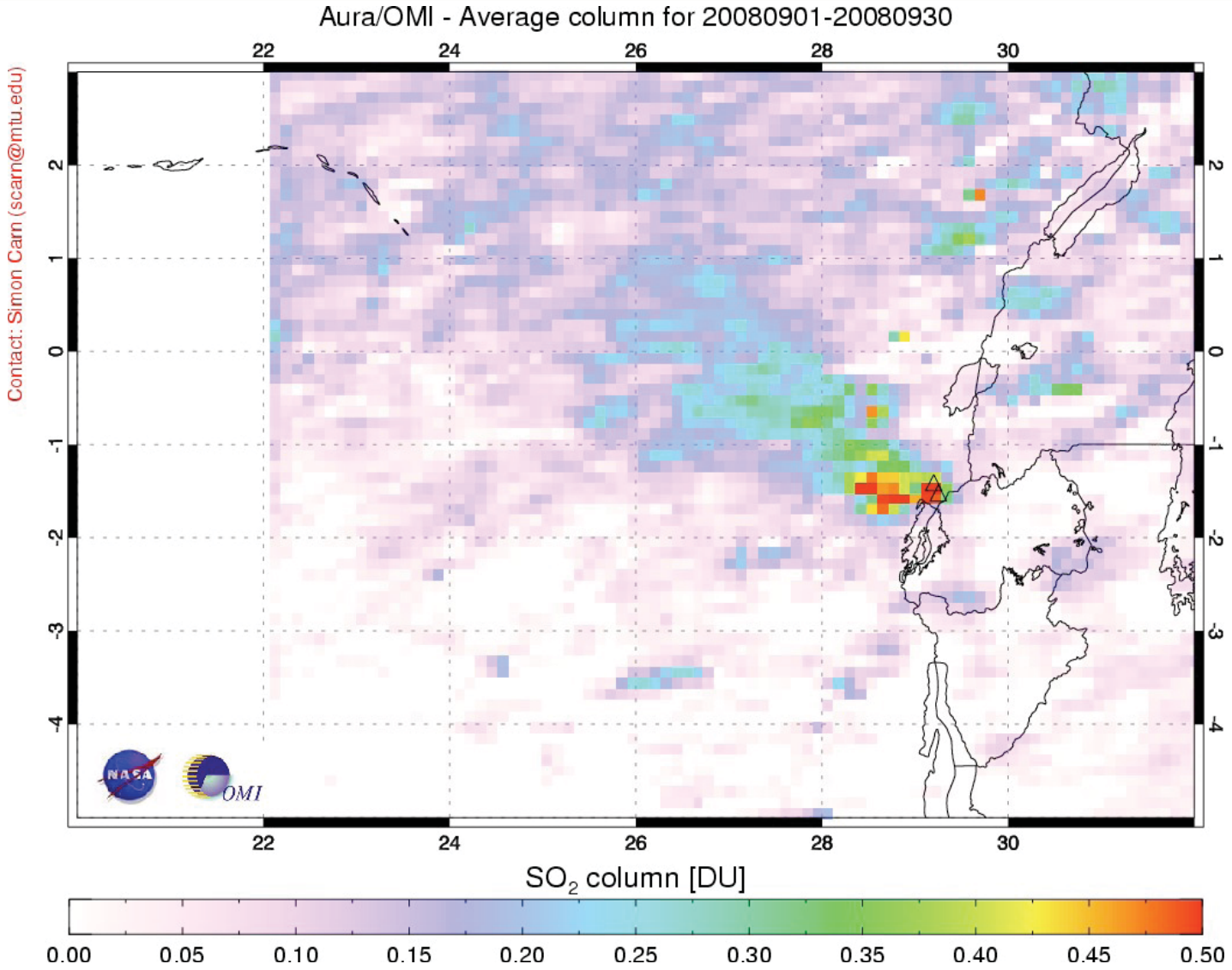
Nyiragongo – monthly average SO_2 columns



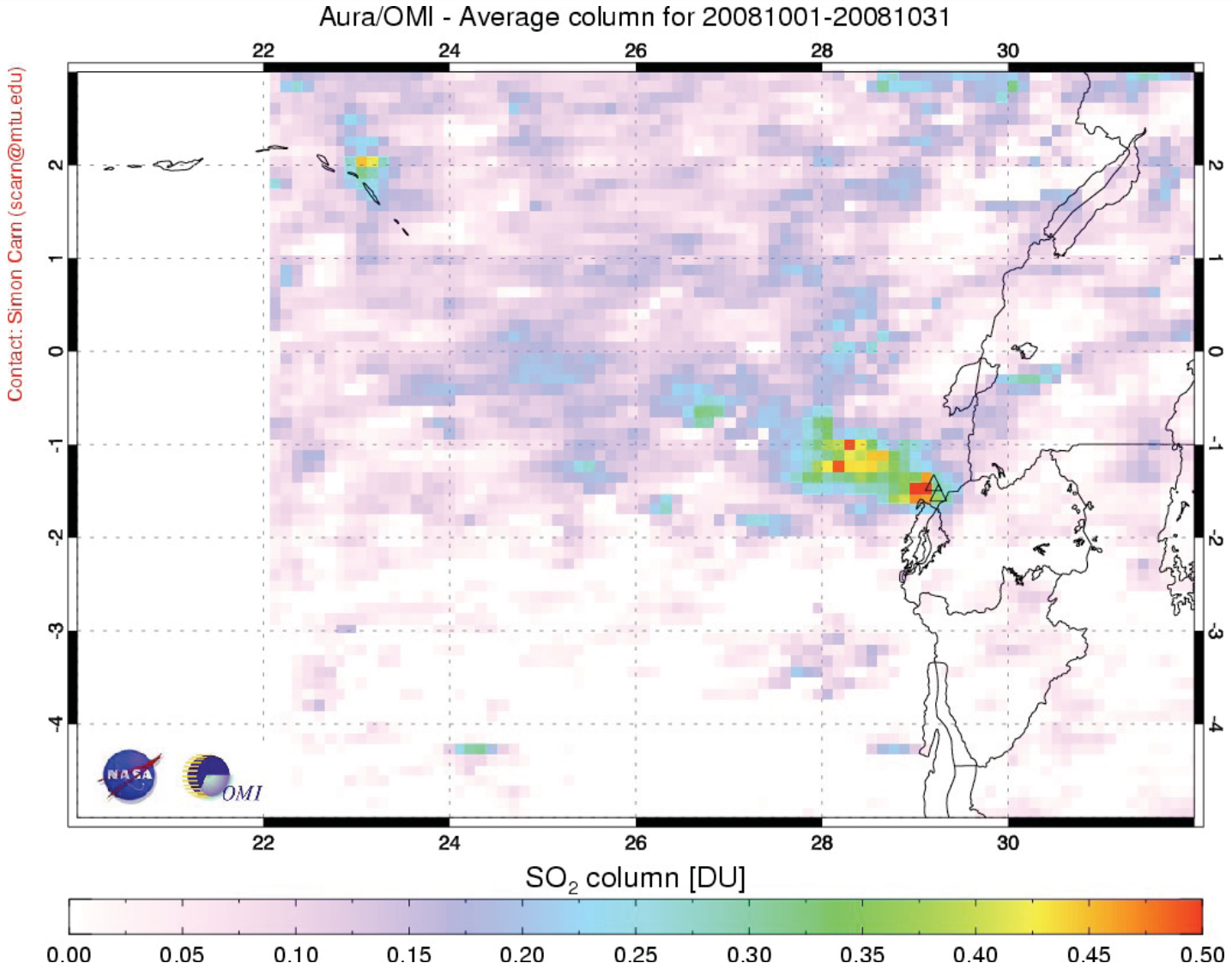
Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns



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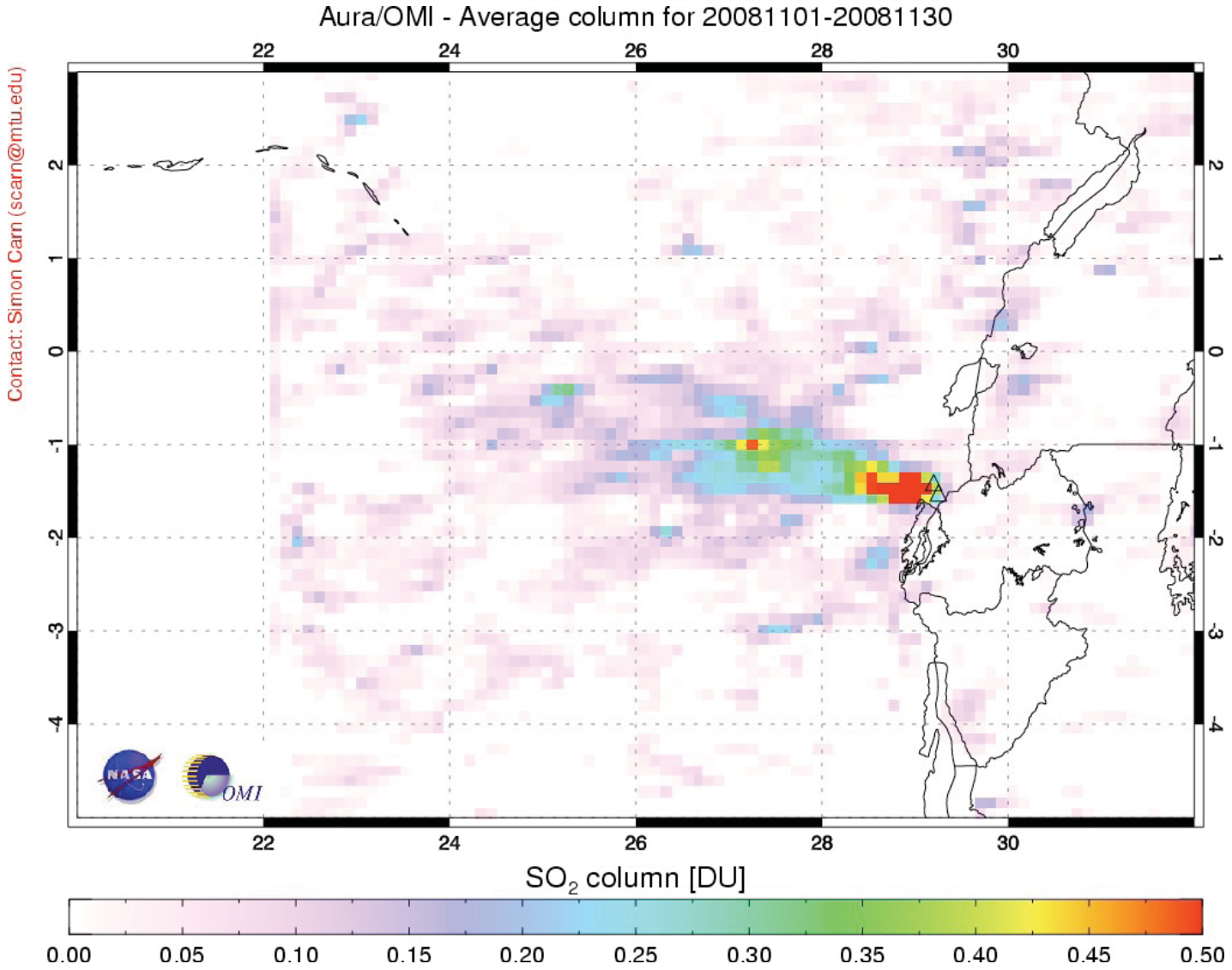

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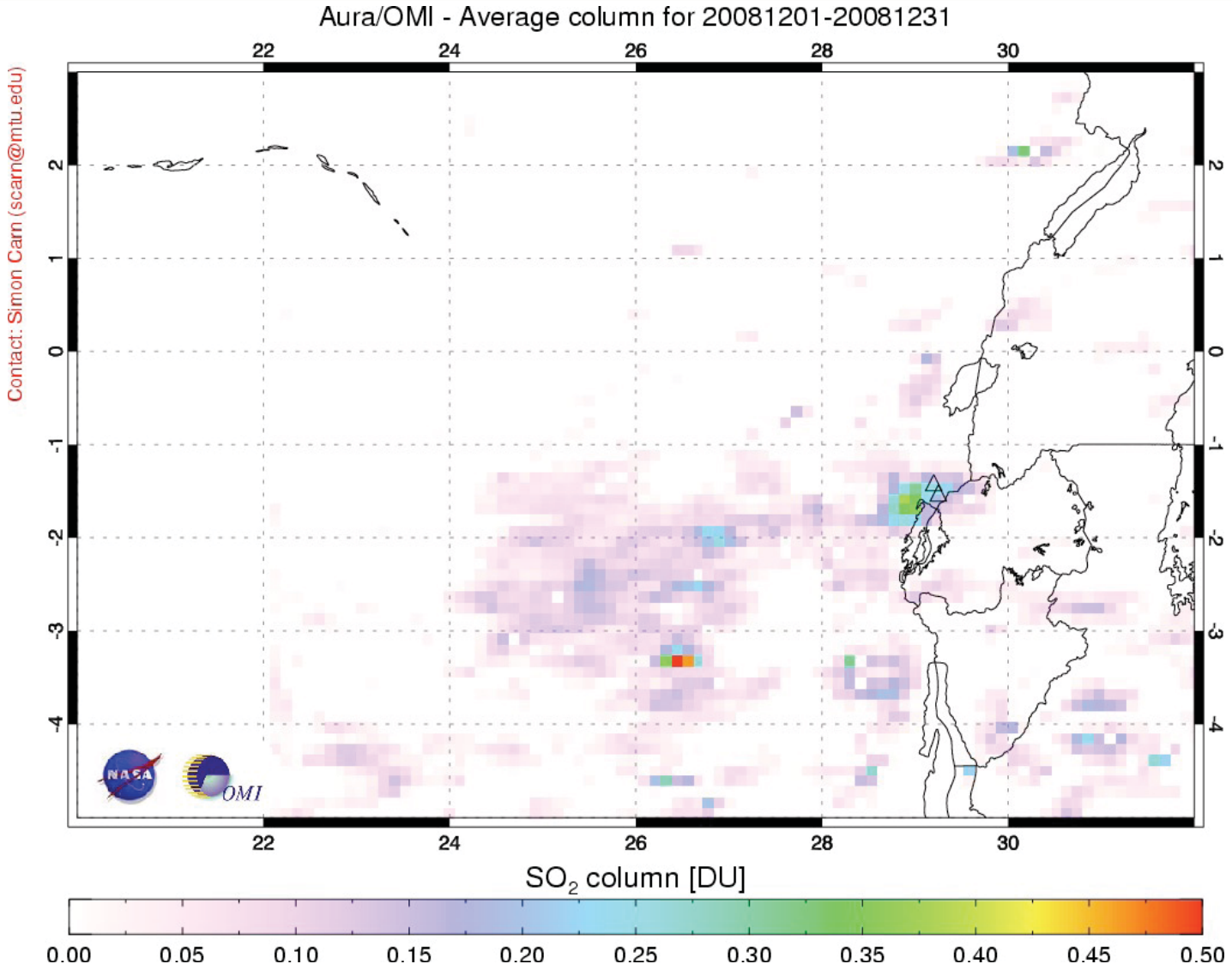
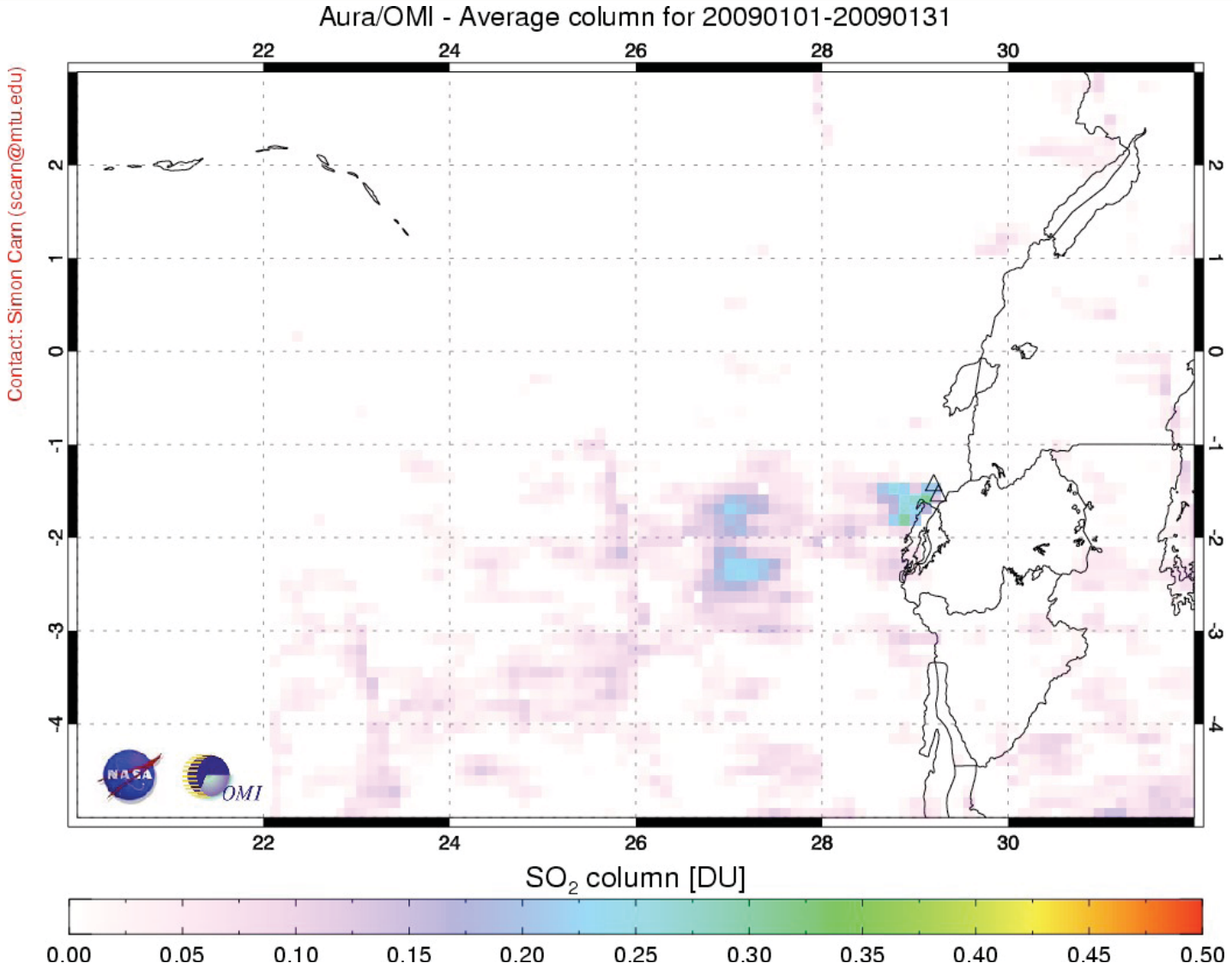
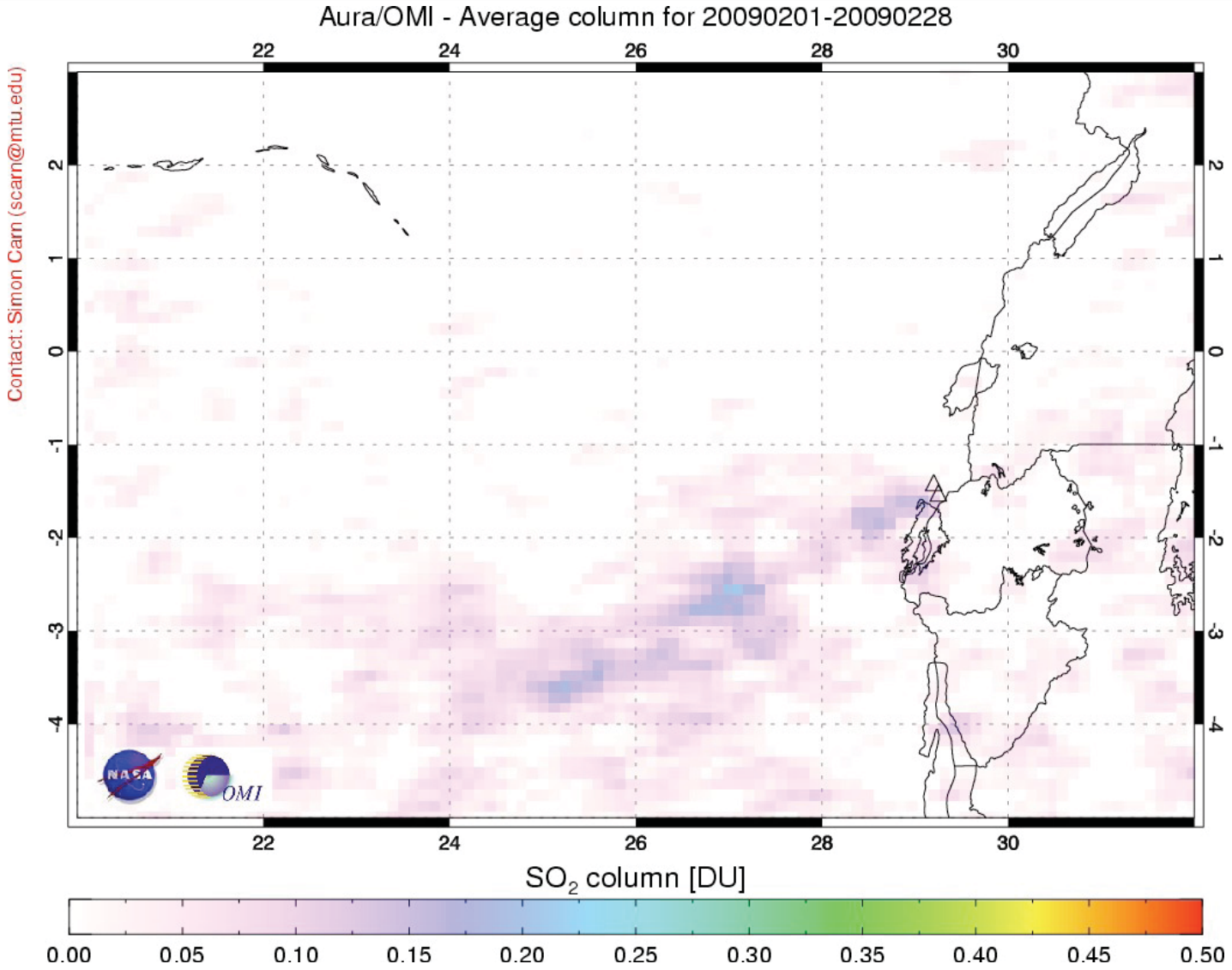


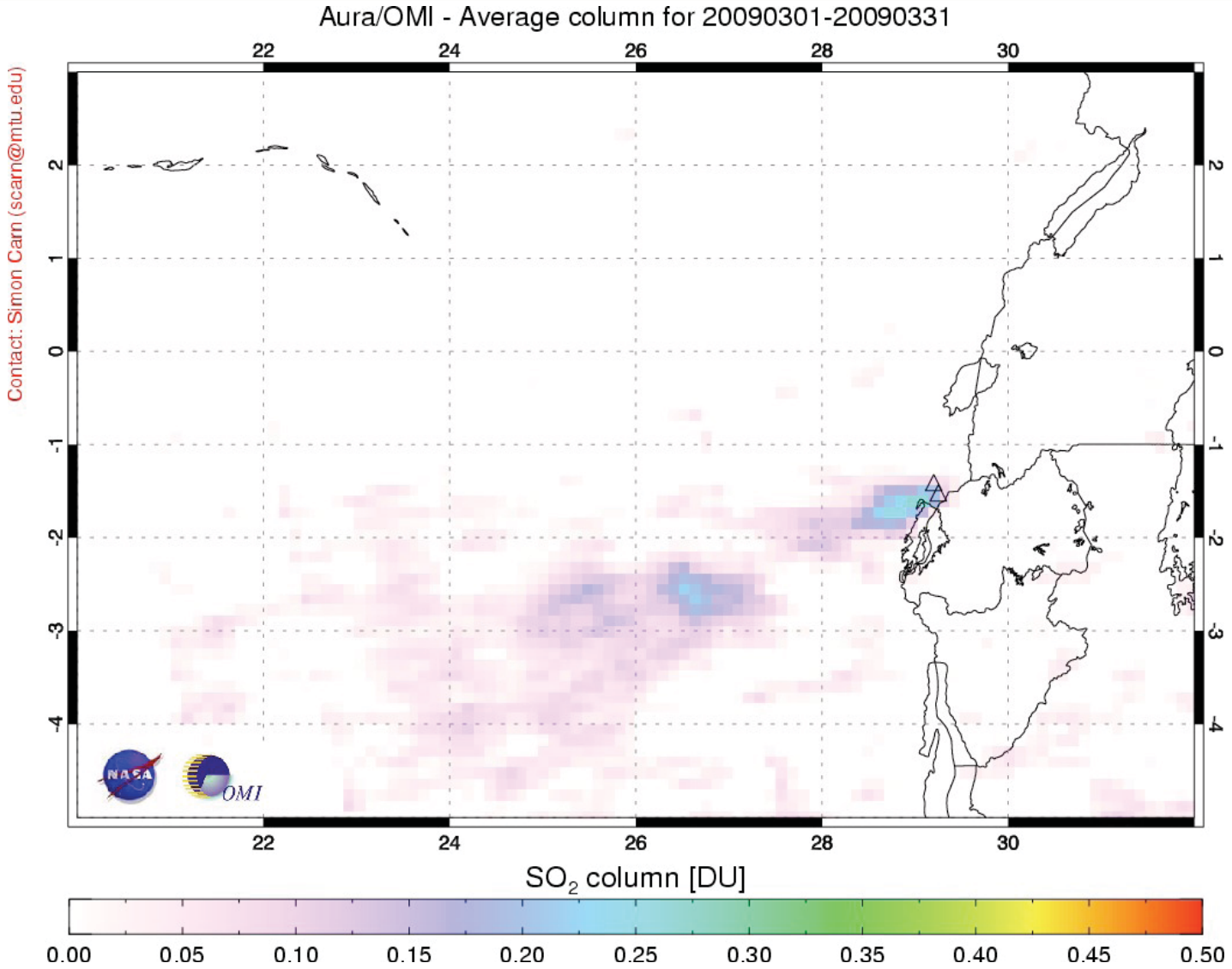
Nyiragongo – monthly average SO_2 columns



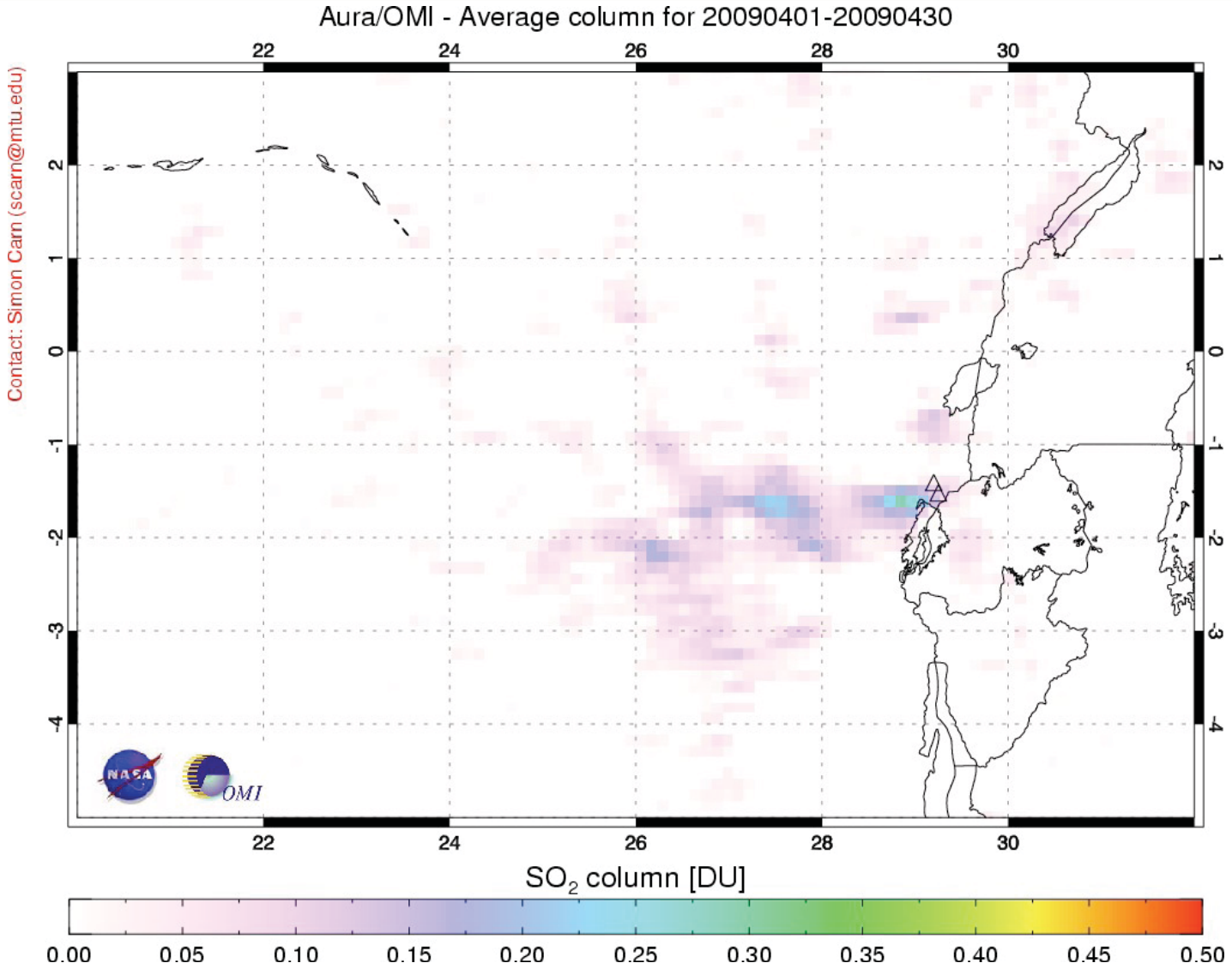
Nyiragongo – monthly average SO_2 columns



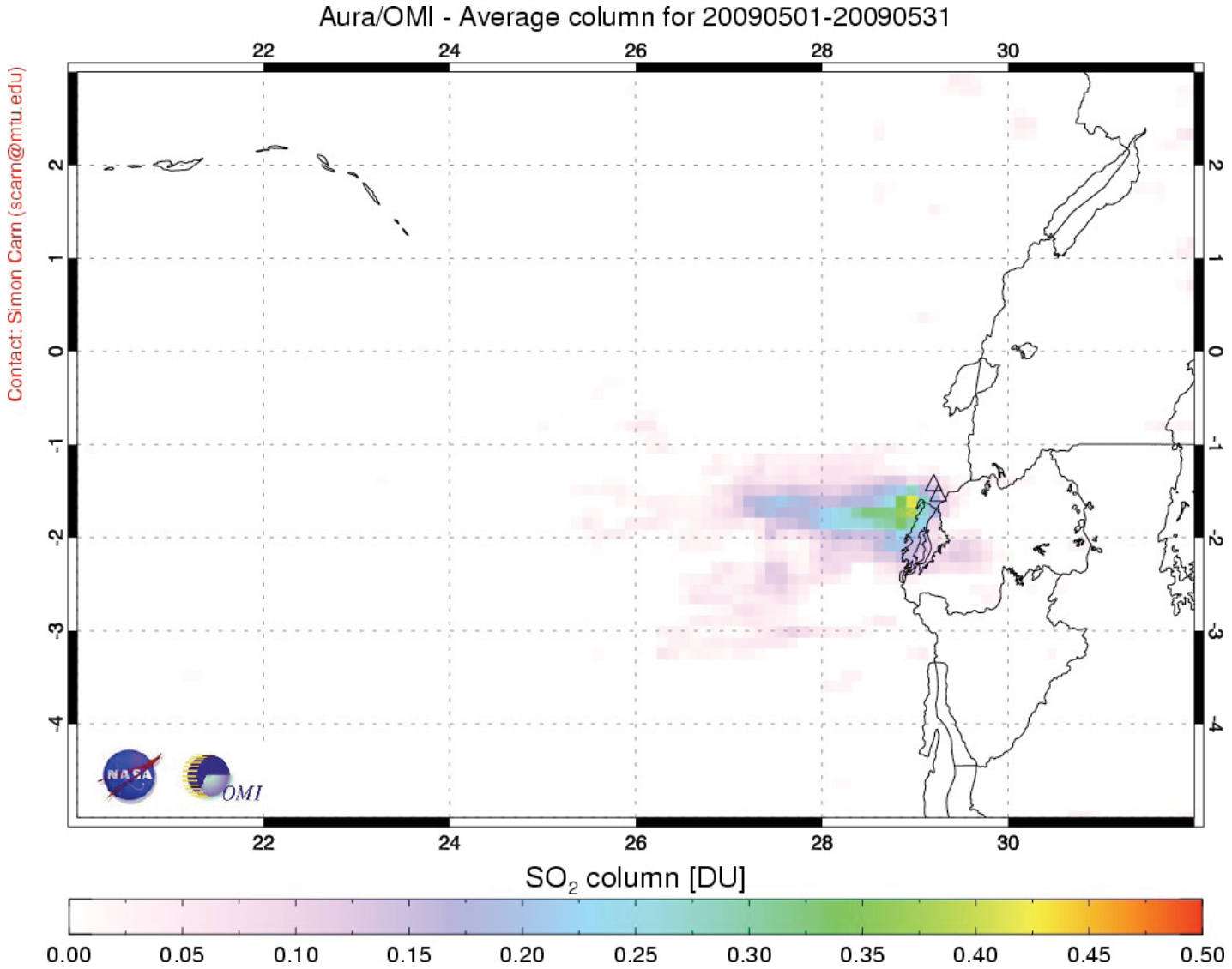
Nyiragongo – monthly average SO_2 columns



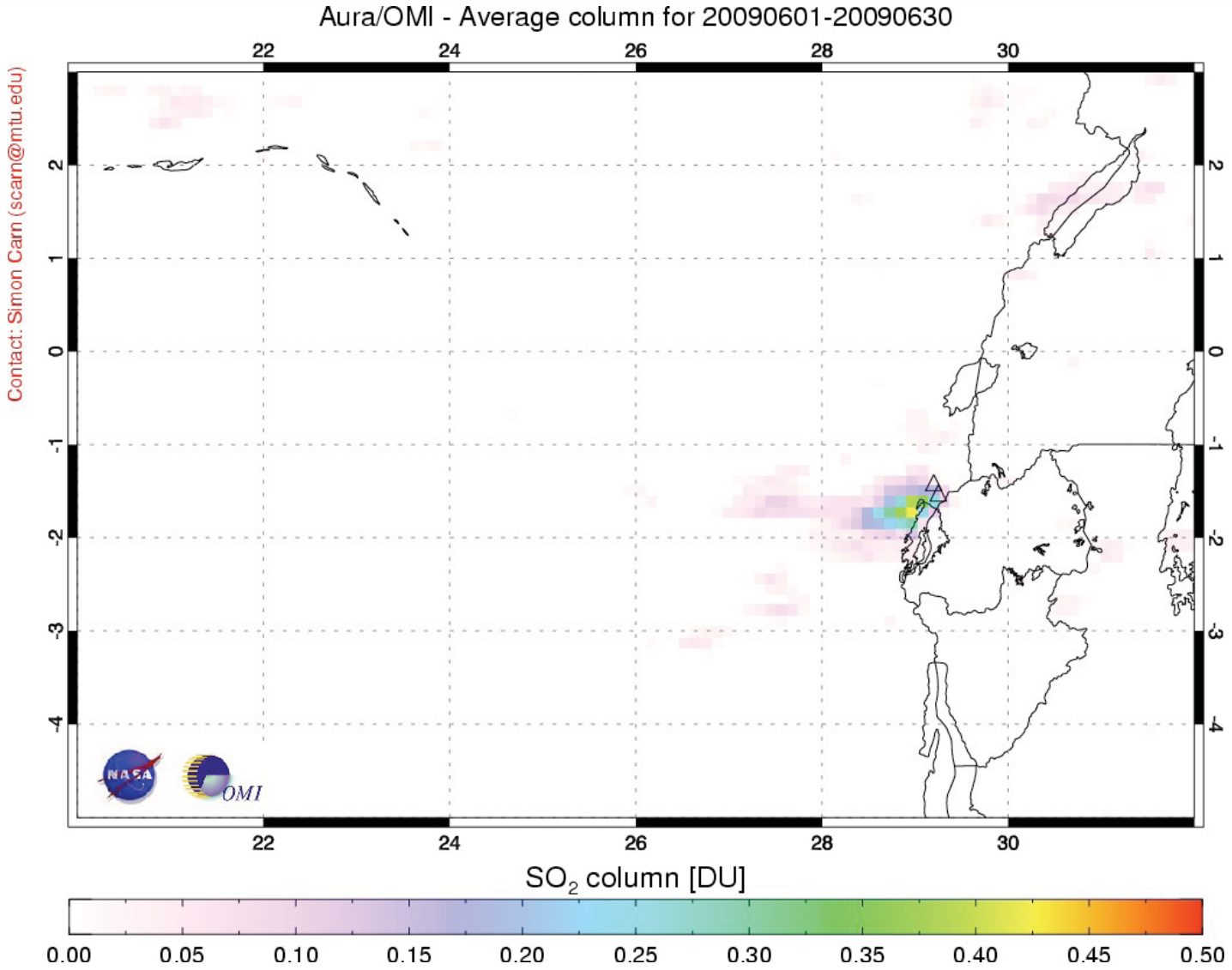
Nyiragongo – monthly average SO_2 columns



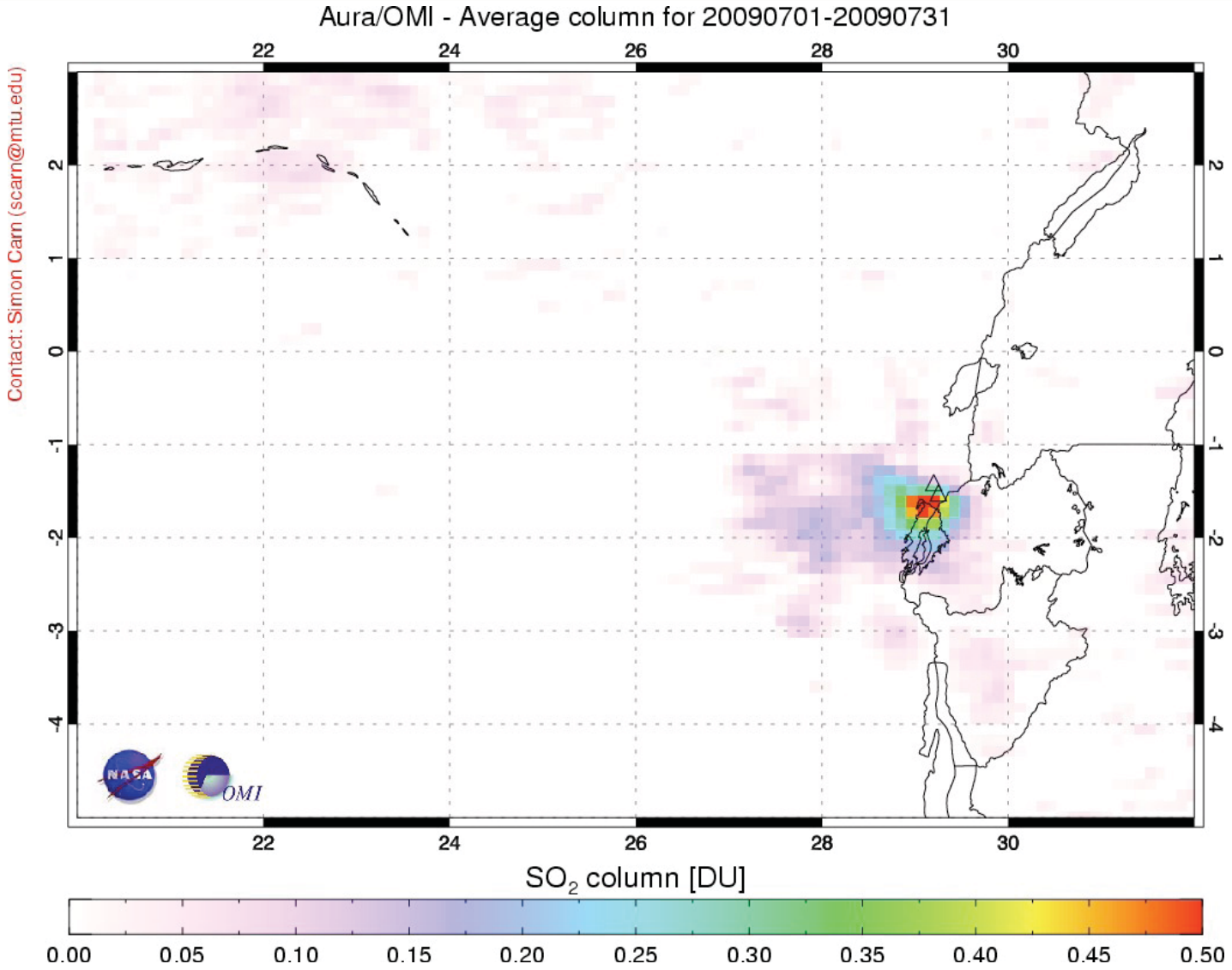
Nyiragongo – monthly average SO_2 columns



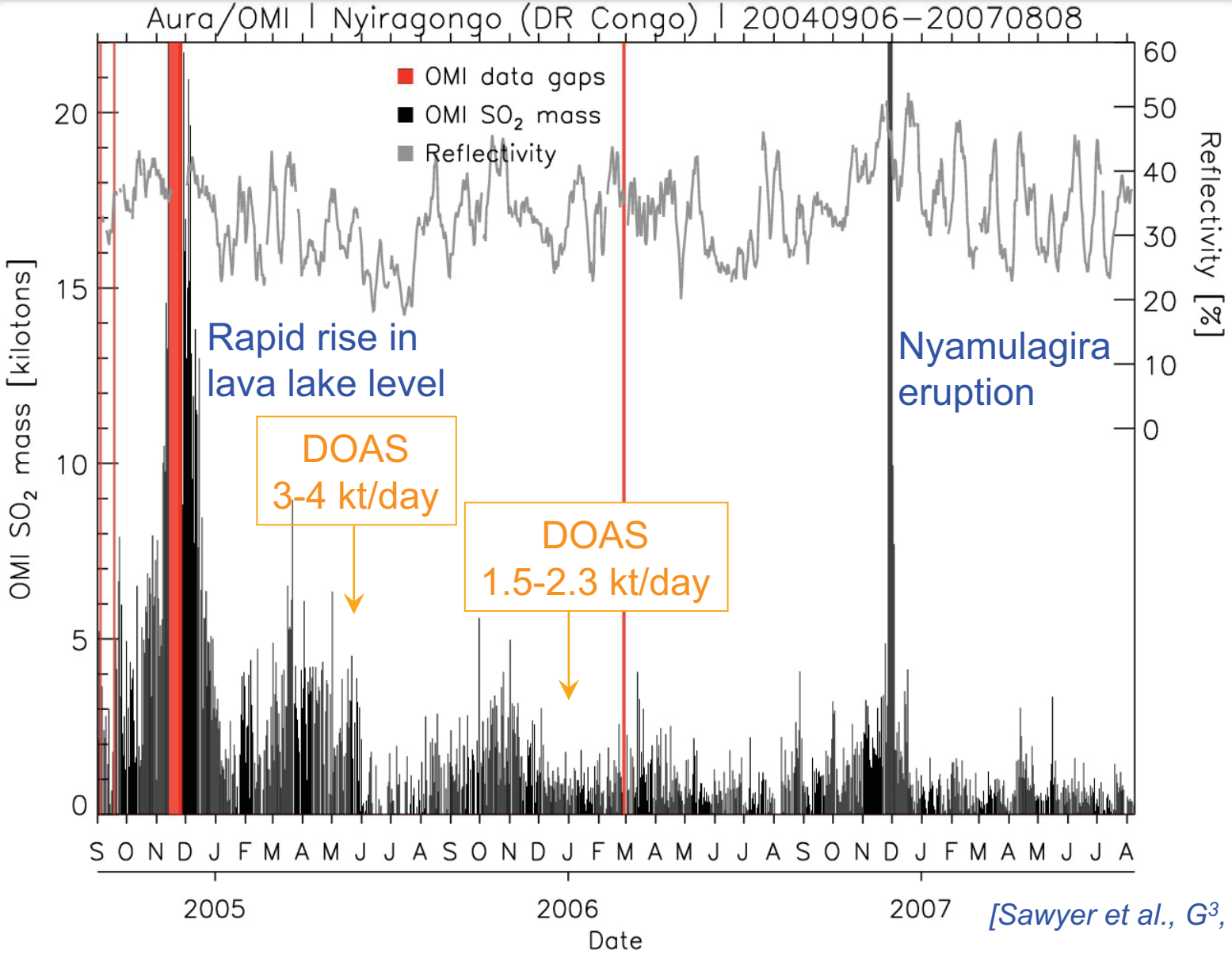
Nyiragongo – monthly average SO_2 columns



Nyiragongo – monthly average SO_2 columns

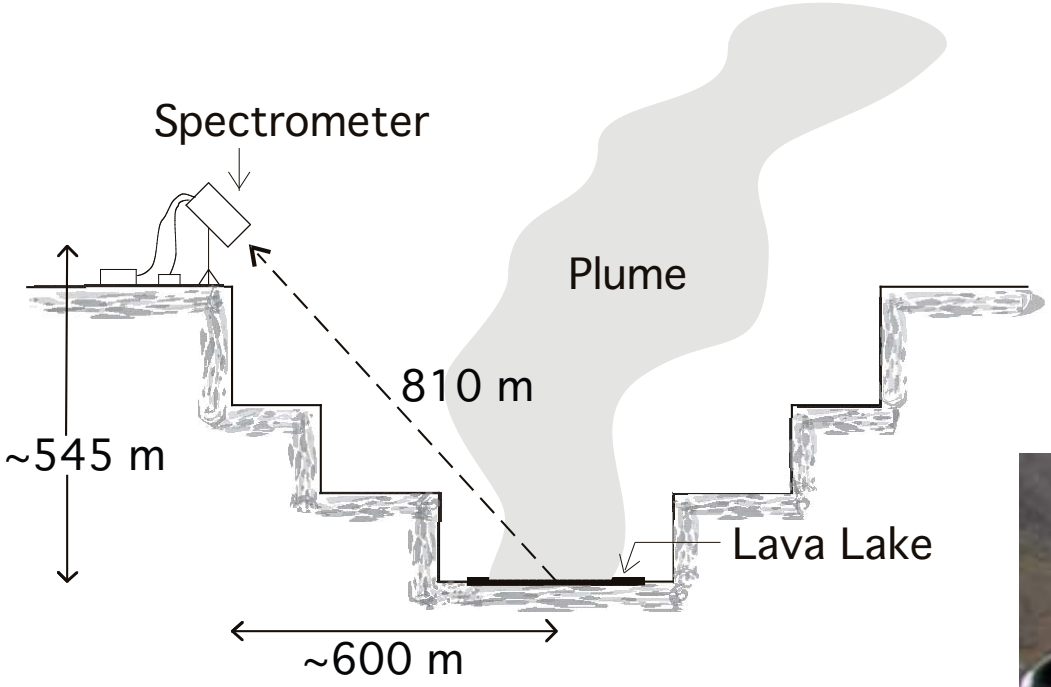


Nyiragongo SO_2 emissions



[Sawyer et al., G³, 2008]

Nyiragongo FTIR setup

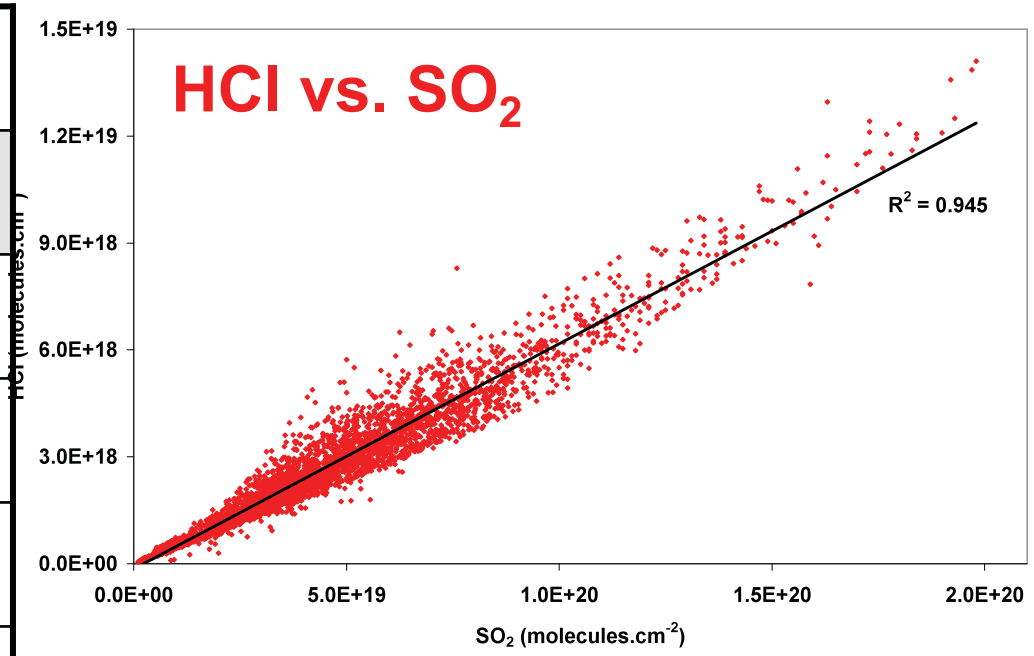


- Fourier Transform Infrared (FTIR) spectroscopy – measures SO_2, H_2O, CO_2, HCl, HF, CO, COS
- Deployed at Nyiragongo in May 2005, Jan 2006, June 2007

- Equilibrium gas temperature ~1000-1100°C (i.e. magmatic)

Nyiragongo FTIR data – 2005 and 2006

Fluxes in tons day^{-1}		
	2005	2006
H_2O	14800	8260
CO_2	11340	7430
SO_2	3330	1940
CO	280	170
HCl	110	70
HF	30	-
OCS	1	-
TOTAL	30000	18000

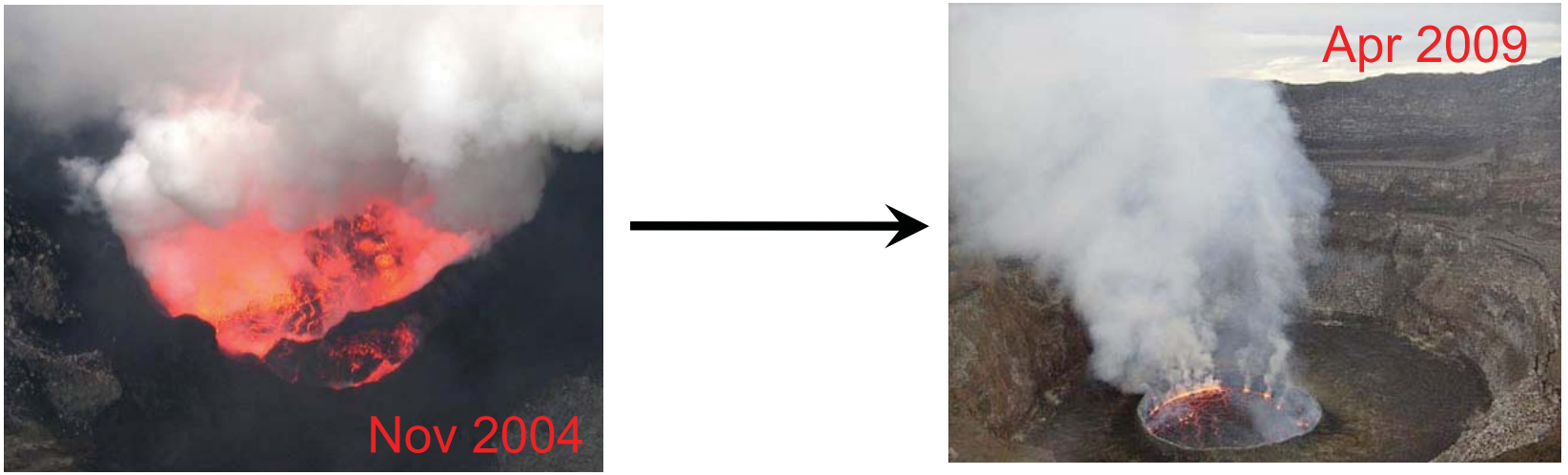


- FTIR yields gas ratios – convert to fluxes using SO_2 flux and X/SO_2 ratio
- Decrease in total volatile emissions between 2005 and 2006
- Little change in gas composition

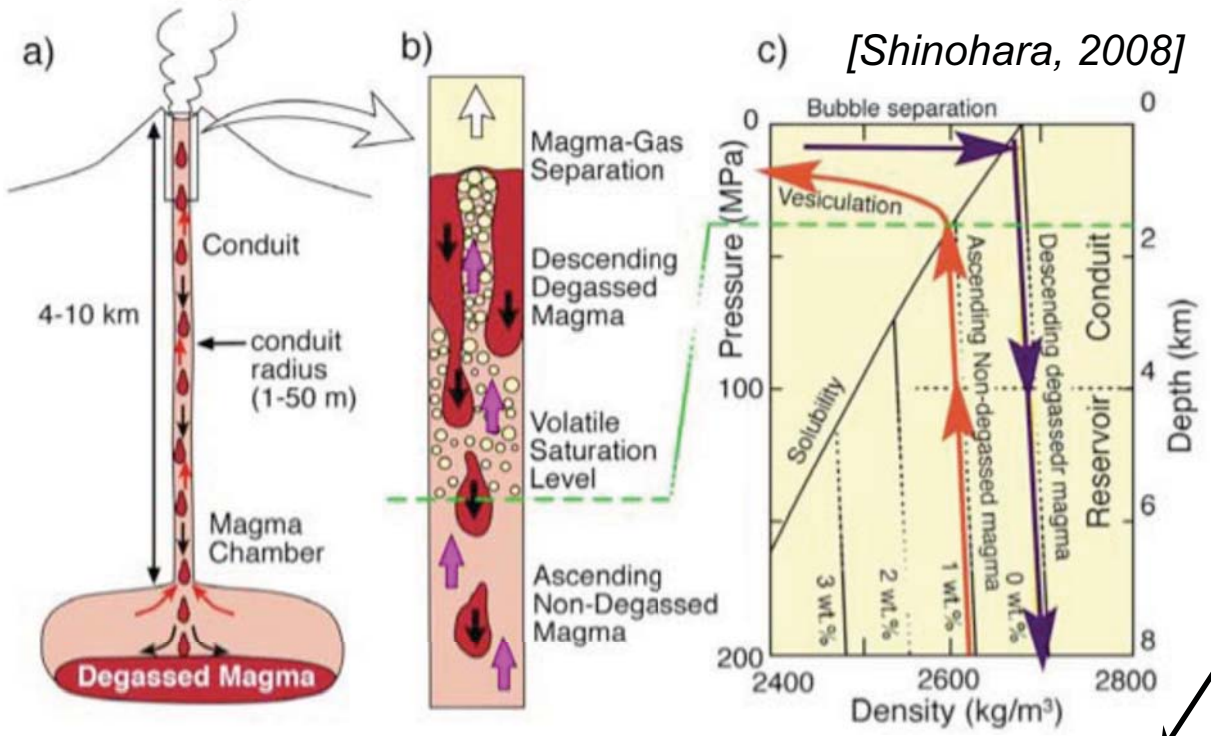
[Sawyer et al., G^3, 2008]

Summary of Nyiragongo observations

- SO_2 emissions *appear* to be slowly declining since 2004
  - Decrease in magma supply rate?
- Possible effects of plume altitude need to be quantified
  - Effect of varying size/level/activity of lava lake/gas vent on plume altitude (Bernouilli's principle)
- Little change in composition of volatile phase in 2005-2007
  - Source of volatiles unchanged (equilibrium degassing of rising magma)



Conduit convection model for Nyiragongo



Density difference

Conduit radius

Magma flow rate $$Q = \pi(R')^2 v = \pi(R^*)^2 Ps \left(\frac{g \Delta\rho R^4}{\mu_{ld}} \right)$$

Viscosity of degassed magma

[Kazahaya et al., 1994; Stevenson and Blake, 1998]

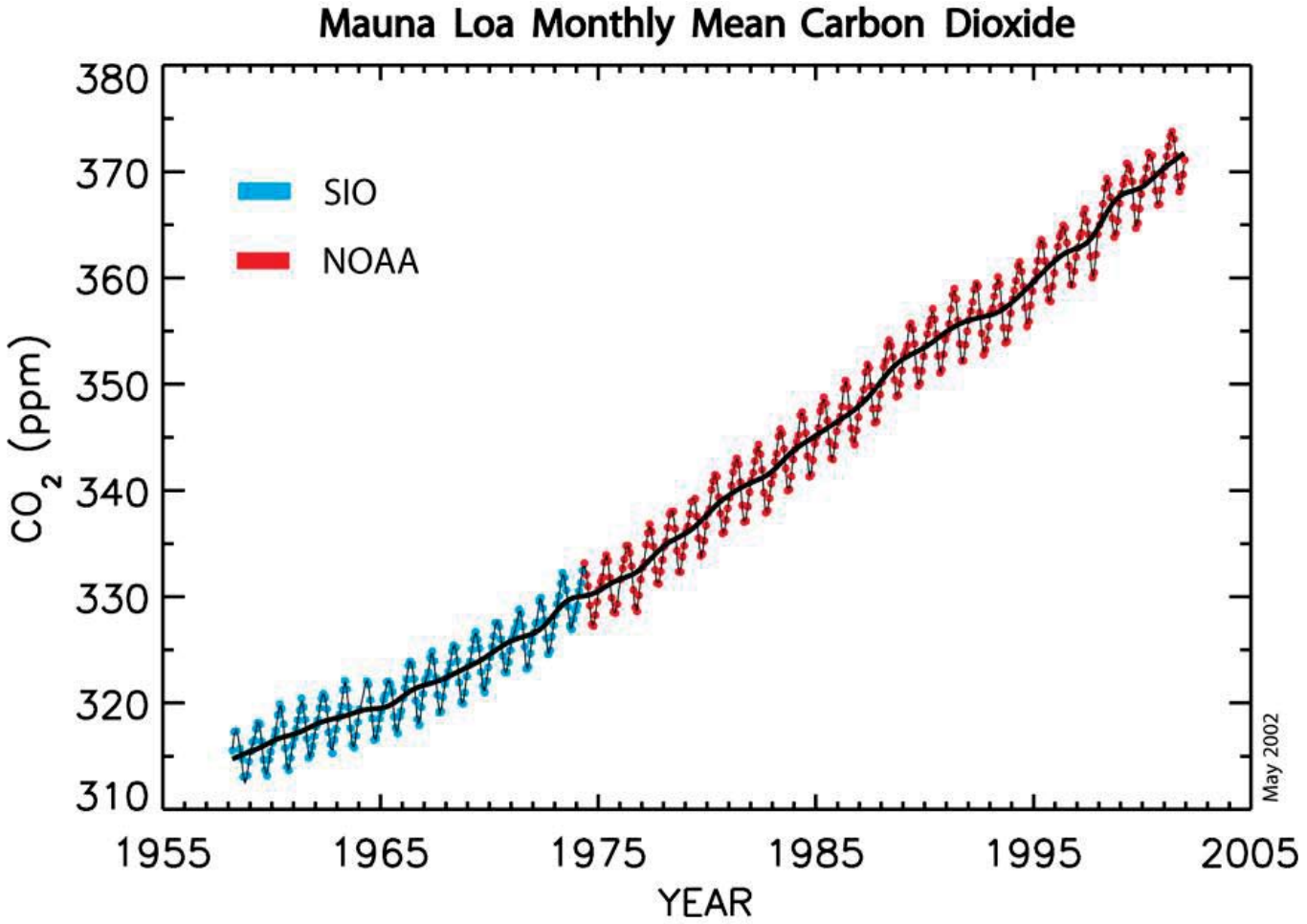
- Efficient degassing dampens convection
- Total SO_2 emission of ~3 Tg since Nov 2004: degassing of ~0.23 km^3 magma containing 2500 ppm Sulfur

EAR volcanic gas compositions

Mol %	Erta'Ale (Afar)		Ardoukoba (Djibouti)	Nyiragongo (DR Congo)		O. Lengai (Tanzania)
	1971-74 DS	Oct 2005 FTIR	Nov 1978 DS	1959/1972 DS	2005-2007 FTIR	June 1999 FTIR
H_2O	70	94	78	48	70	76
CO_2	18	3.7	4	46	24	24
SO_2	11	2.5	16	2.6	5	0.02
CO	0.8	0.1	0.2	2.7	1	0.08
HCl	-	0.2	-	-	0.3	-
HF	-	0.04	-	-	0.1	-
CO_2/SO_2	1.6	1.5	0.25	18	4.8	1200

Data from Symonds *et al.* [1994]; Sawyer *et al.* [2008; in prep.]; Oppenheimer *et al.* [2002].

Measuring CO_2 from space

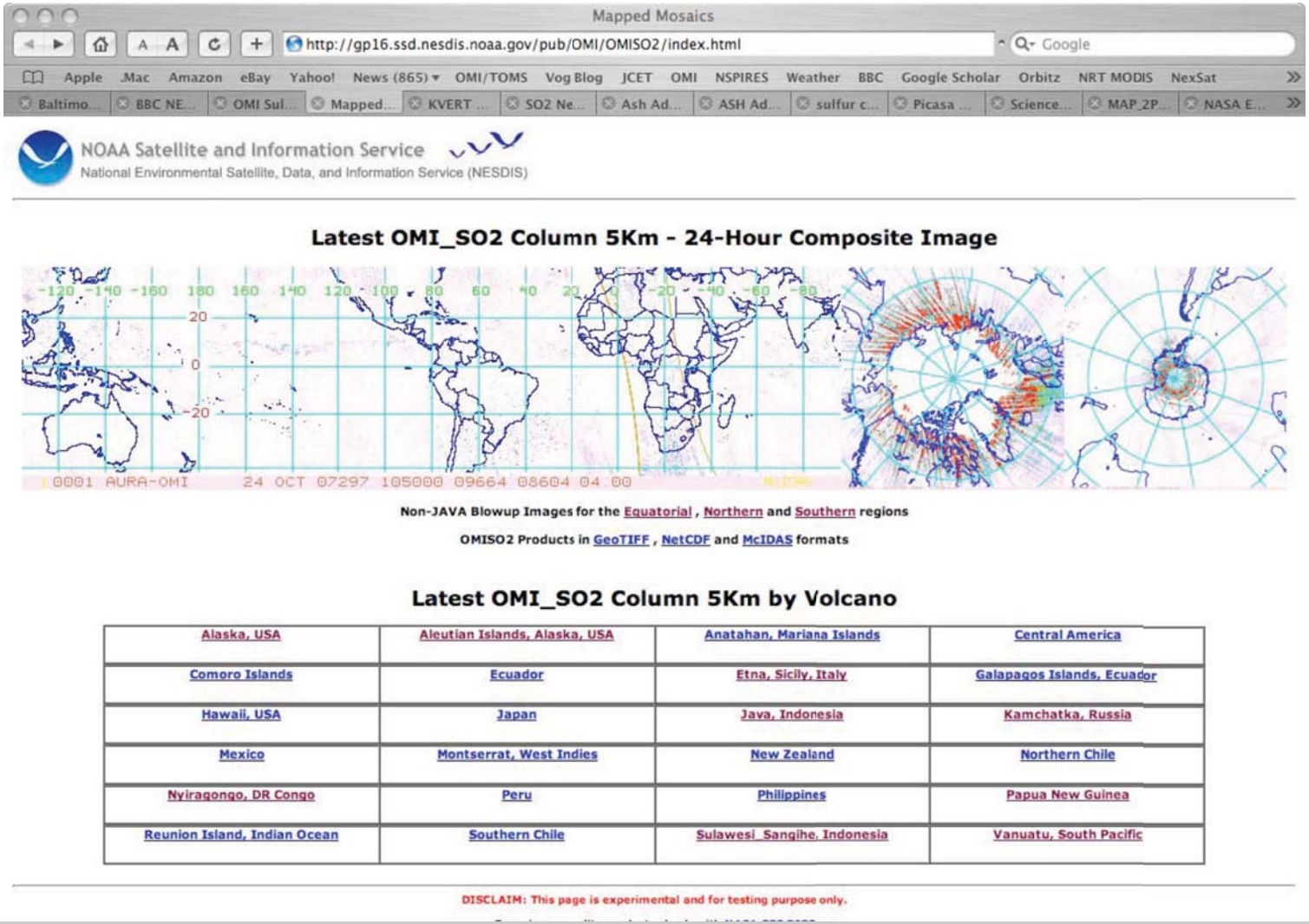


- Most interesting volcanic gas for eruption prediction (exsolves before SO_2)
- Possible synergy with deformation measurements (InSAR etc.)

Measuring CO_2 from space

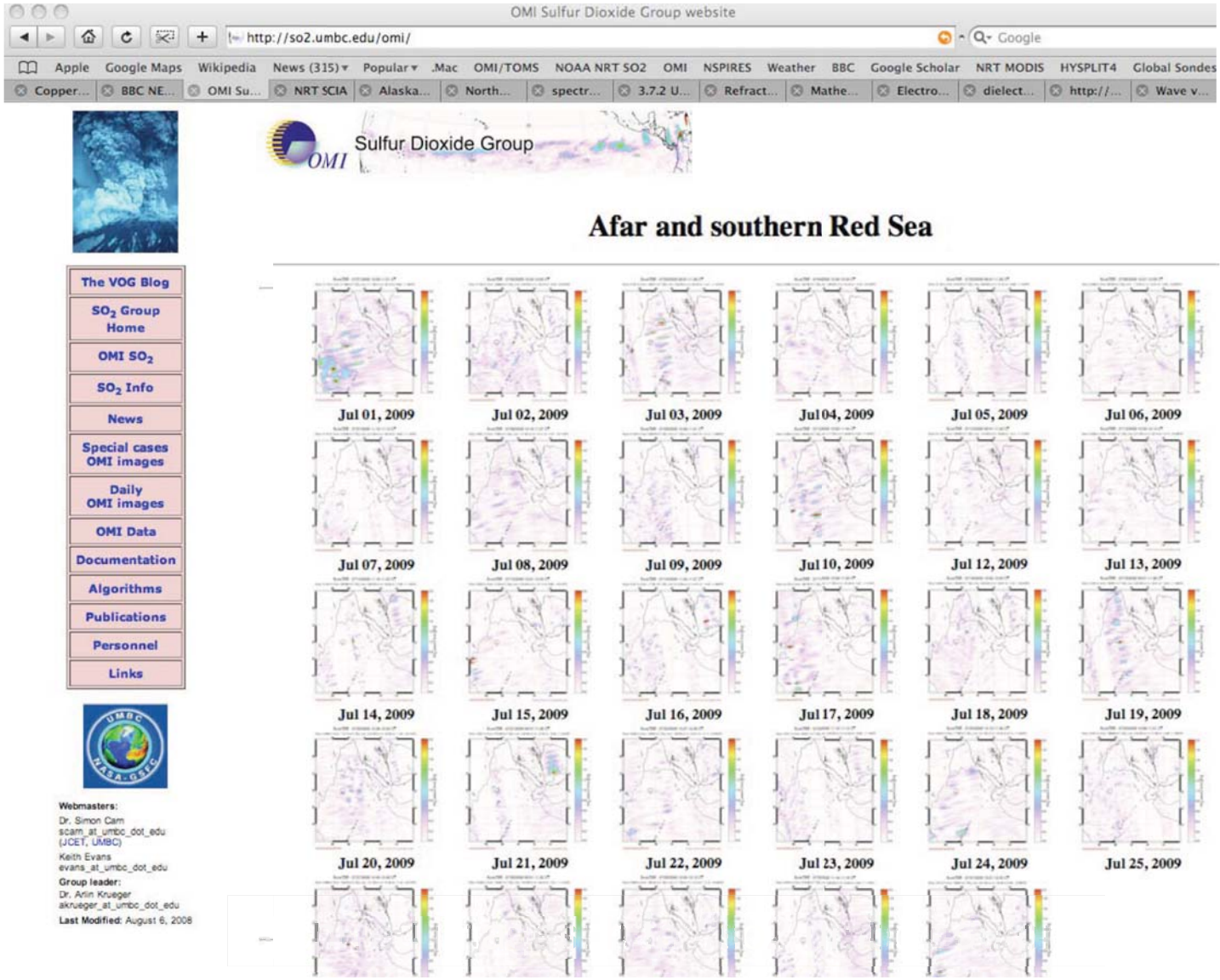
- Challenging due to high background CO_2 concentrations
- Need ~1 ppm accuracy or better
- NASA Orbiting Carbon Observatory (OCO) – failed at launch
- Japanese Greenhouse Gas Observing Satellite (GOSAT)
  - Launched January 2009
  - TANSO-FTS sensor measures CO_2 column amounts in SWIR/TIR
  - 10 km spatial resolution; 'stare' mode
  - Proposal submitted to evaluate GOSAT data for volcanic CO_2 detection
- ASCENDS (Atmospheric CO_2 through Nights, Days and Seasons)
  - CO_2 lidar instrument
  - High sensitivity, poor spatial coverage
  - Still in planning stage

OMI SO_2 websites - NRT



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

OMI SO_2 websites



Archive: http://so2.umbc.edu/omi

Gas monitoring in the EAR

- The EAR is a great location for volcanic degassing studies
  - Lava lake degassing – primary magmatic volatiles
  - Degassing of alkaline magmas – understudied and significant
  - Effusive eruptions (Nyamulagira)
  - CO_2 emissions?
- Research questions and recommendations
  - Links between geophysics (InSAR) and gas measurements (CO_2)
  - Eruption duration/dynamics
  - Duration of dike emplacement vs. duration of degassing
  - Is CO_2 detectable from space?
  - Effects of extreme topographic variations on satellite SO_2 measurements (e.g., Danakil Depression at -155 m – Ethiopian Highlands at 4500 m).
  - Possibility of atmospheric observations (winds etc.) from a Pan-African seismic-geophysical network – *very useful* for gas studies
  - EAR volcano observatory for remote sensing of EAR volcanoes
  - Aviation hazards


Thanks!

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 – 2005	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
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)	2010?	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

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

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

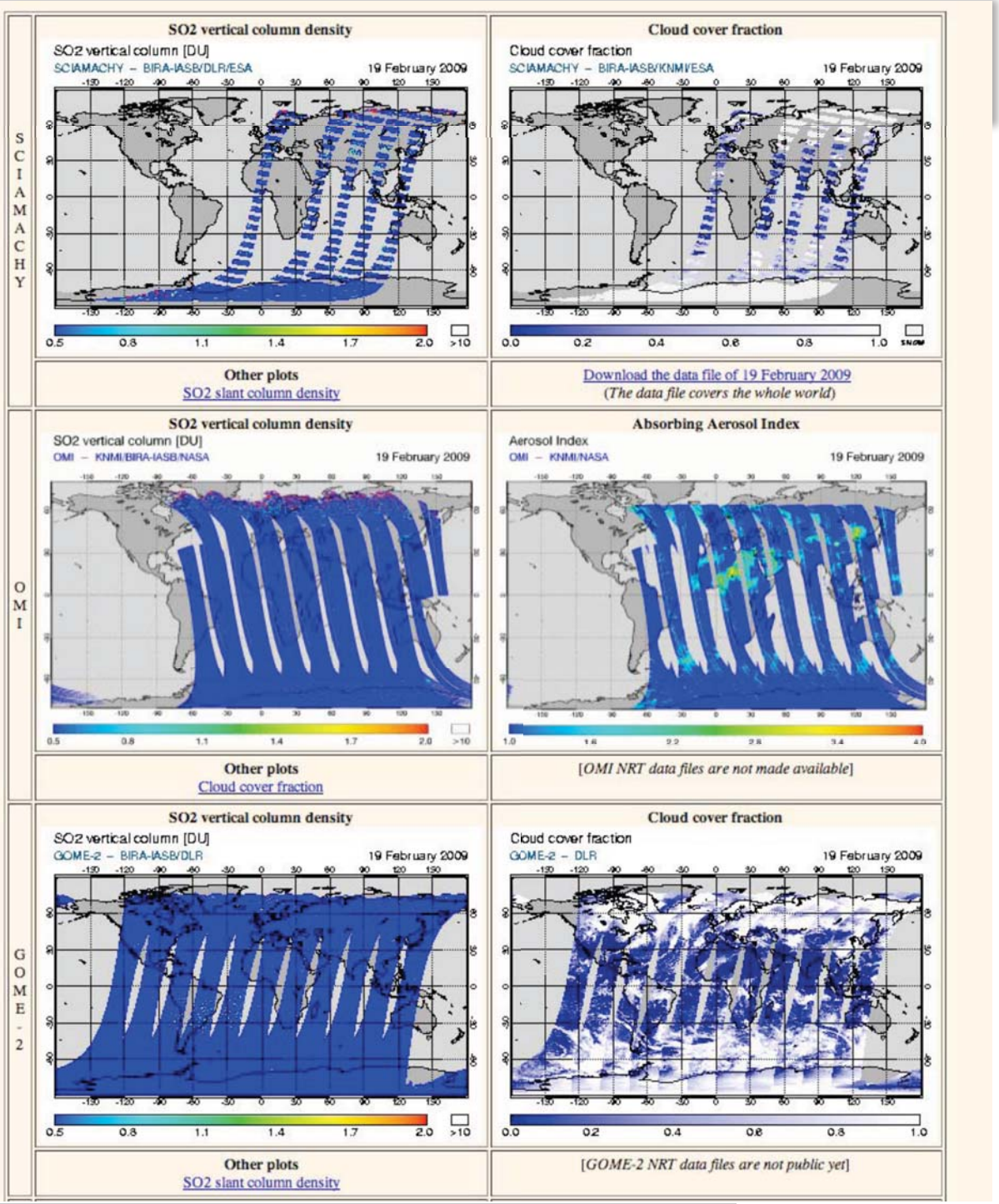
*Based on *Realmuto* [1999], AGU Geophysical Monograph 116, p101-115 (except AIRS)

BIRA website

SCIAMACHY

OMI

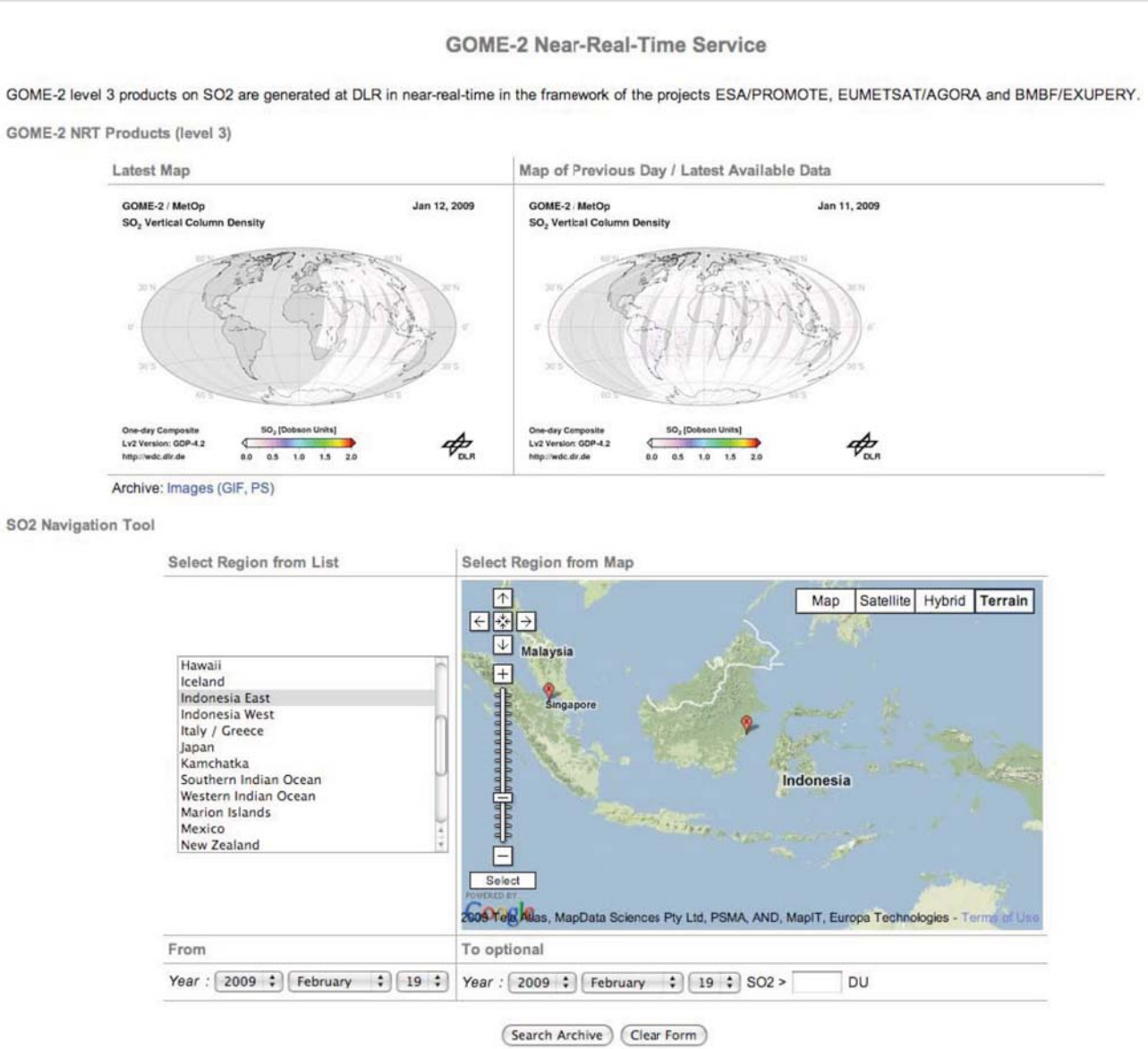
GOME-2



http://www.oma.be/BIRA-IASB/Molecules/SO2nrt/vs/orbit.php

DLR GOME-2 website

German Aerospace Center



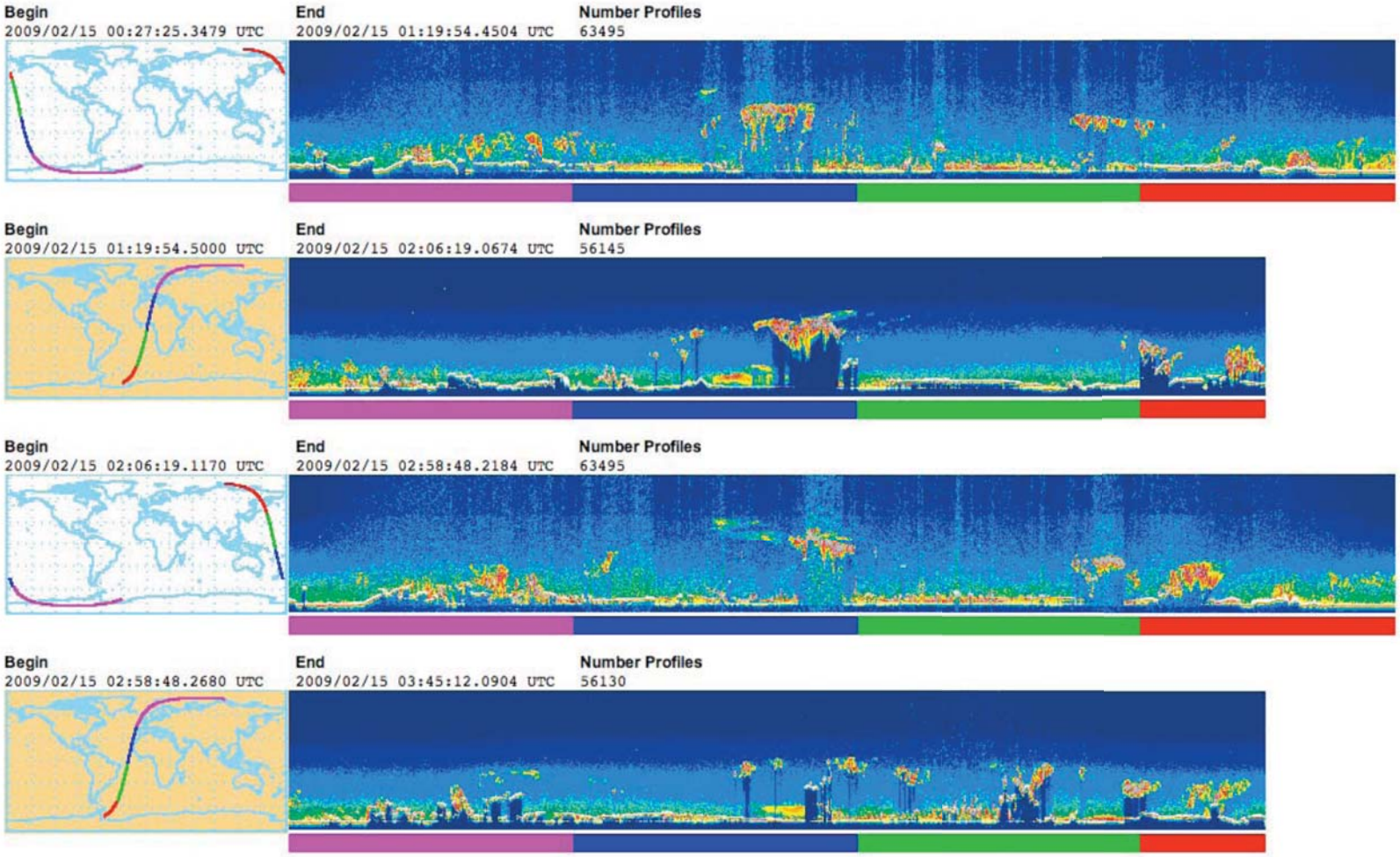
http://wdc.dlr.de/data_products/SERVICES/GOME2NRT/so2.php

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/airs/so2.html

CALIPSO website



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

Exploiting A-Train synergy for volcanic cloud studies

OMI - SO_2, aerosols, BrO

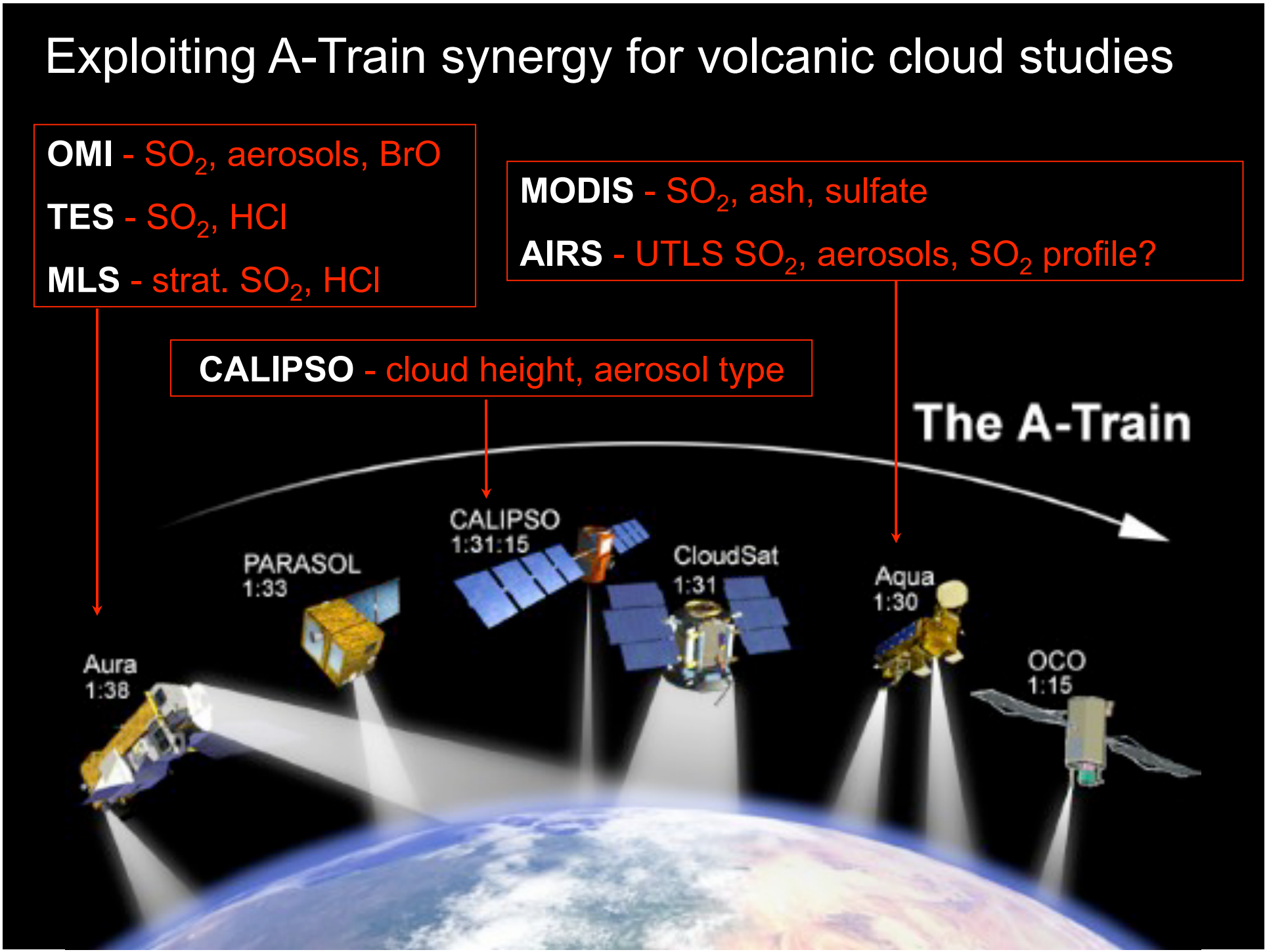
TES - SO_2, HCl

MLS - strat. SO_2, HCl

MODIS - SO_2, ash, sulfate

AIRS - UTLS SO_2, aerosols, SO_2 profile?

CALIPSO - cloud height, aerosol type



Kilauea degassing – April 7, 2008