First satellite observations of lightning-generated NO_x in volcanic eruption clouds

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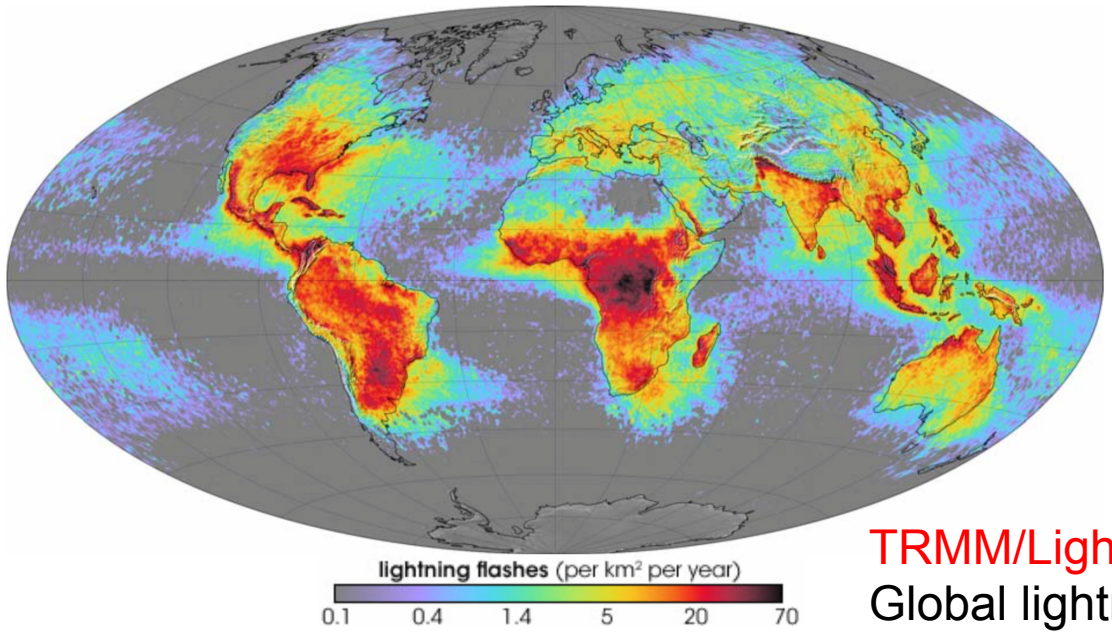
Michigan Tech
Create the Future

Do volcanic eruptions produce detectable lightning NO_x?

Introduction

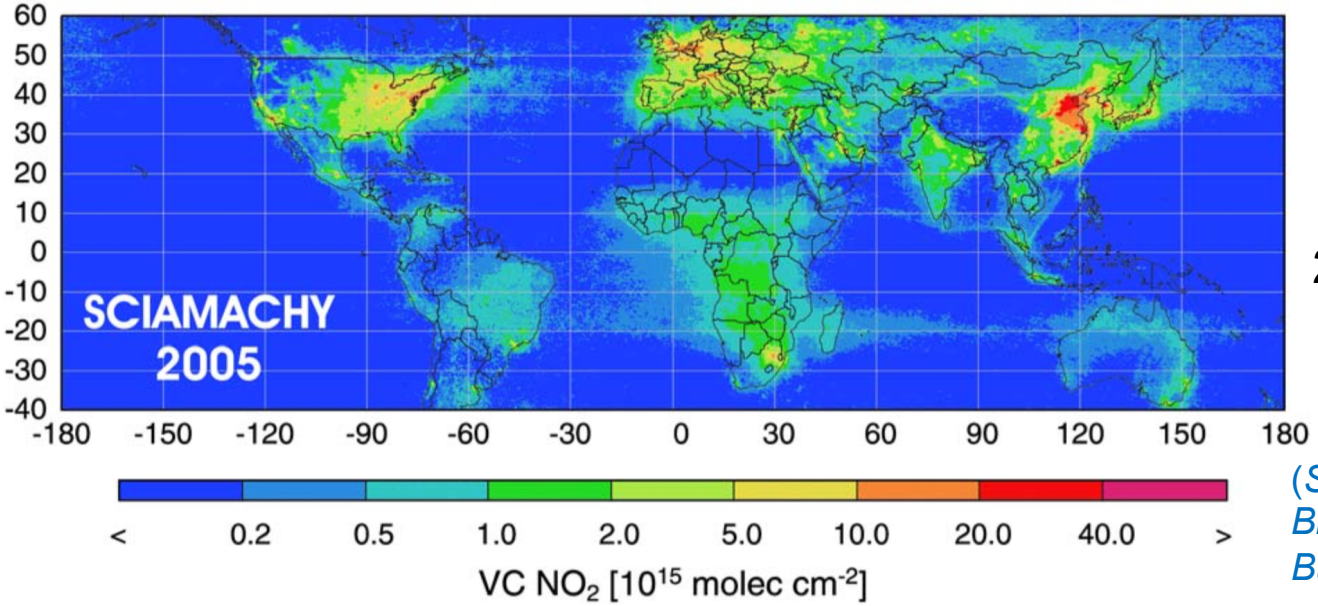
- First satellite observations of lightning generated NO_x (LNO_x) in volcanic clouds from OMI
  - NO_x has been sampled in-situ in explosive eruption plumes (e.g., Hobbs et al., 1982)
- Significant past work on LNO_x observations in thunderstorms
- LNO_x is the largest natural source of NO_x in free troposphere
  - Important role in stratospheric ozone chemistry
- Importance of volcanic lightning
  - Potential source of fixed nitrogen in early Earth's atmosphere (e.g., Mather et al., 2004)
  - Detection of explosive, ash-rich eruptions; linked to ash aggregation
- N_2 is a trace gas in volcanic emissions
  - ~11-107 ppm N_2 in primitive sub-arc melts (*Fischer and Marty*, 2005)
  - Can be magmatic or derived from shallow, air-saturated water
  - Implications of LNO_x for air entrainment in volcanic plumes?

Lightning-generated NO_x (LNO_x)



- $NO_x = NO + NO_2$
- $N_2 + O_2 \rightarrow 2NO$
- $2NO + O_2 \rightarrow 2NO_2$
- ~2-8 Tg N a^{-1} as LNO_x
- ~4-23% of global NO_x (highest in tropics)

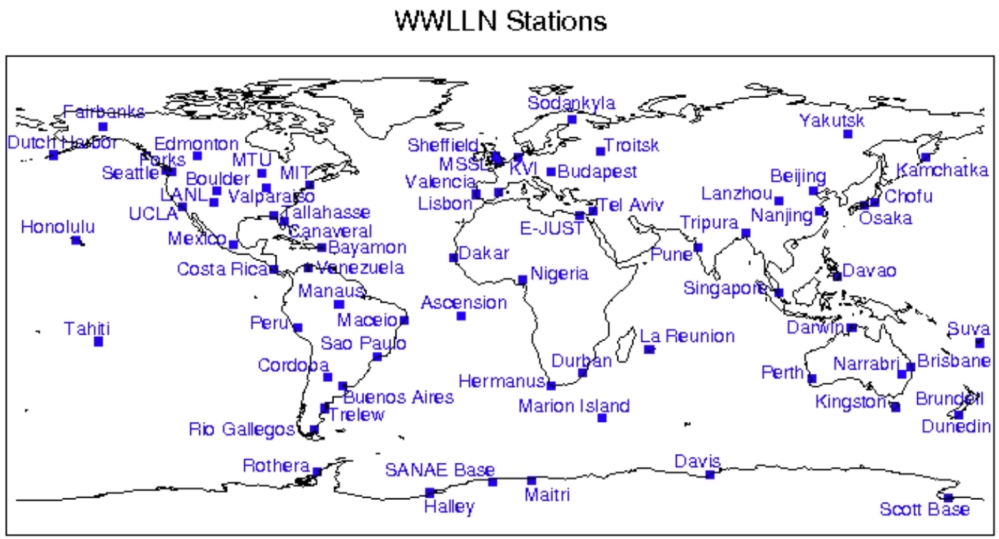
TRMM/Lightning Imaging Sensor (LIS)
Global lightning flashes (1997-2002)



ENVISAT
SCIAMACHY
2005 annual mean NO_2 column density
(*Richter et al.*, 2005)

(*Schumann and Huntrieser*, 2007; *Bierle et al.*, 2006, 2009, 2010; *Buscela et al.*, 2010)

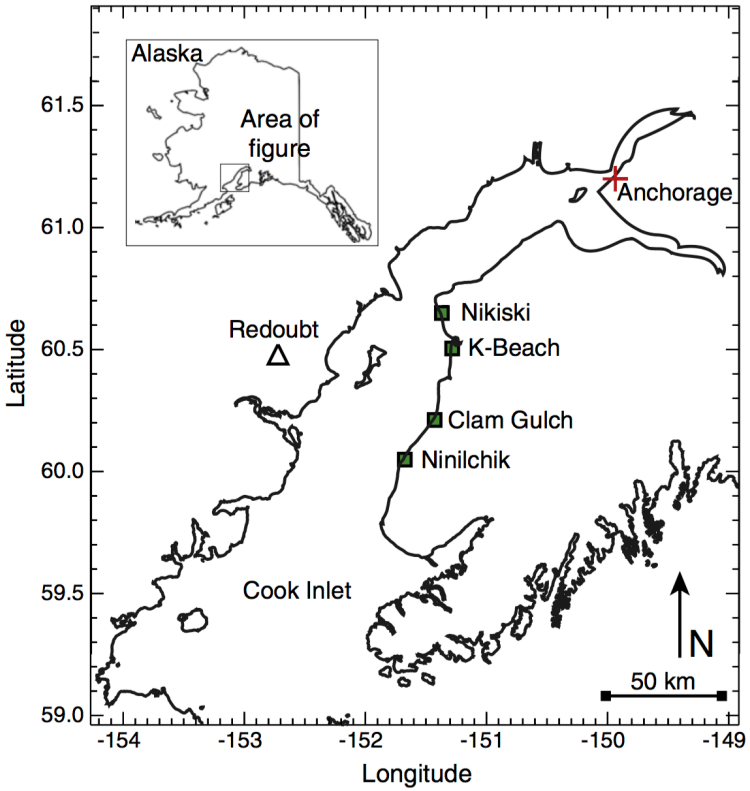
Lightning detection



World Wide Lightning Location Network (WWLLN)

(*Dowden et al.*, 2002; *Rodger et al.*, 2005)

- ~60 stations in 2016
- Detects radio atmospherics ('spherics') in the VLF band (3-30 kHz)
- Reports flash locations globally in near real-time
- Stations can detect flashes up to 10000 km away
- WWLLN detects cloud-ground and intra-cloud lightning (current thresholds approximately ≥ 30 kA)
- WWLLN detection efficiency ~10-26%
- Location accuracy is ~1 VLF wavelength (10 km)
- Details at: http://www.wwlln.net/



Lightning Mapping Arrays (LMAs)

e.g., Redoubt (Alaska)

(*Thomas et al.*, 2007; *Behnke et al.*, 2013)

Satellite sensors

- Lightning Imaging Sensor (LIS)
- Optical Transient Detector (OTD)
- Operational Linescan System (OLS)
- http://thunder.msfc.nasa.gov/

Volcanic lightning

Sakura-jima, Japan, Feb 2013 (*M. Rietze*)

Calbuco, Chile, Apr 2015

Vent lightning

Triboelectrification; fractoemission

[e.g., *James et al.*, 2008; *Cimarelli et al.*, 2013]

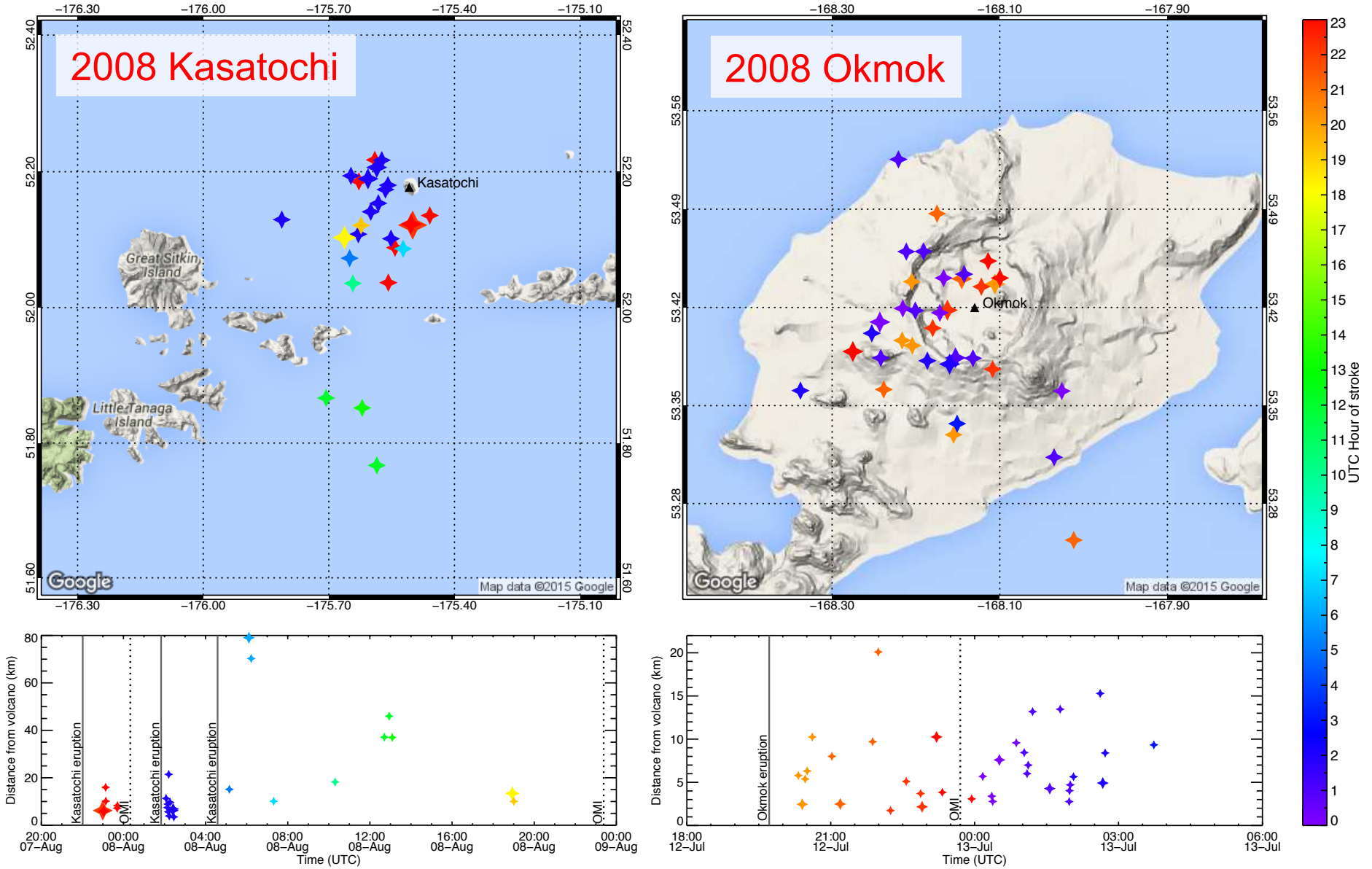
Plume lightning

'Dirty thunderstorm' (Hydrometeors)

[e.g., *Williams and McNutt*, 2005]

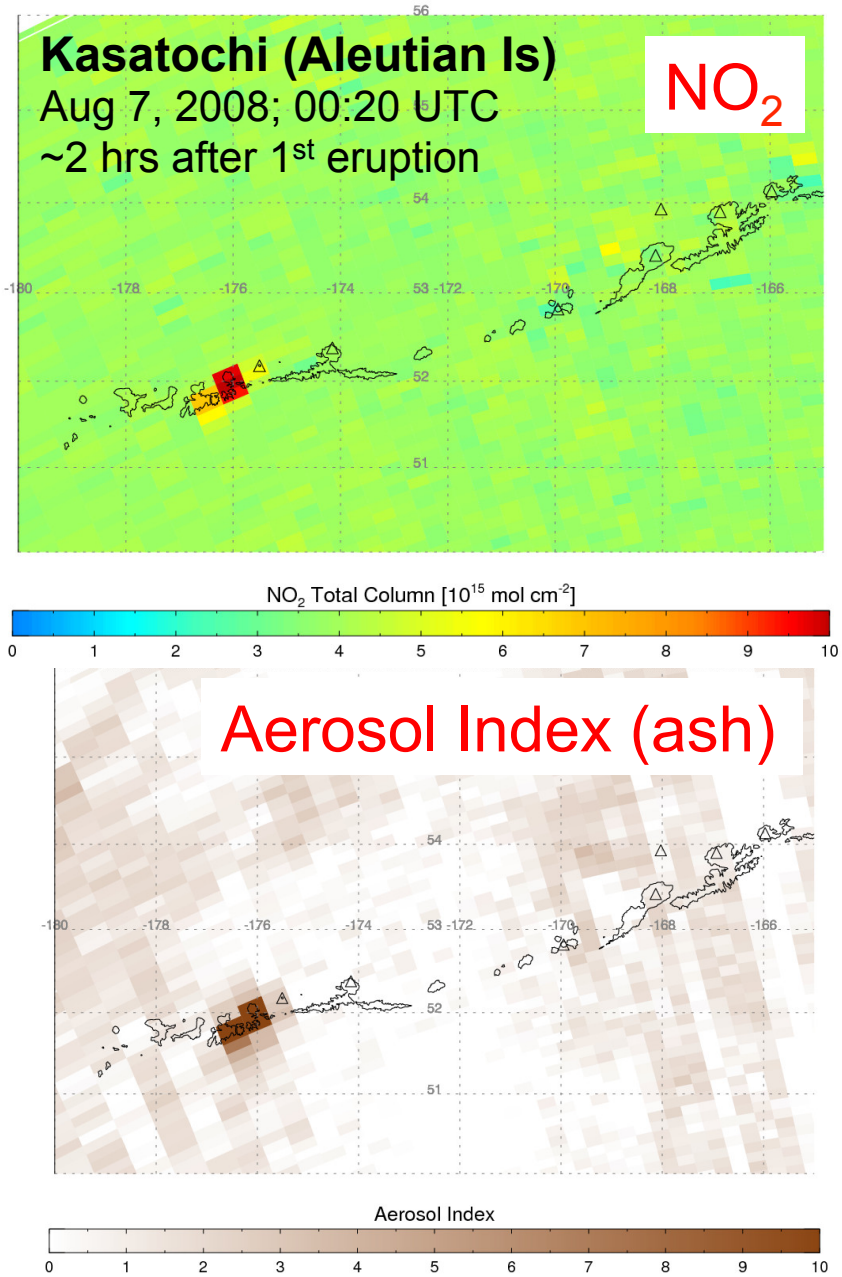
- NB. WWLLN detection efficiency of 26% for cloud-to-ground lightning and 10% for intra-cloud lightning (*Rodger et al.*, 2005; *Behnke et al.*, 2013)
- WWLLN flash counts adjusted based on OTD/LIS climatology – *but climatology does not contain volcanogenic flashes*

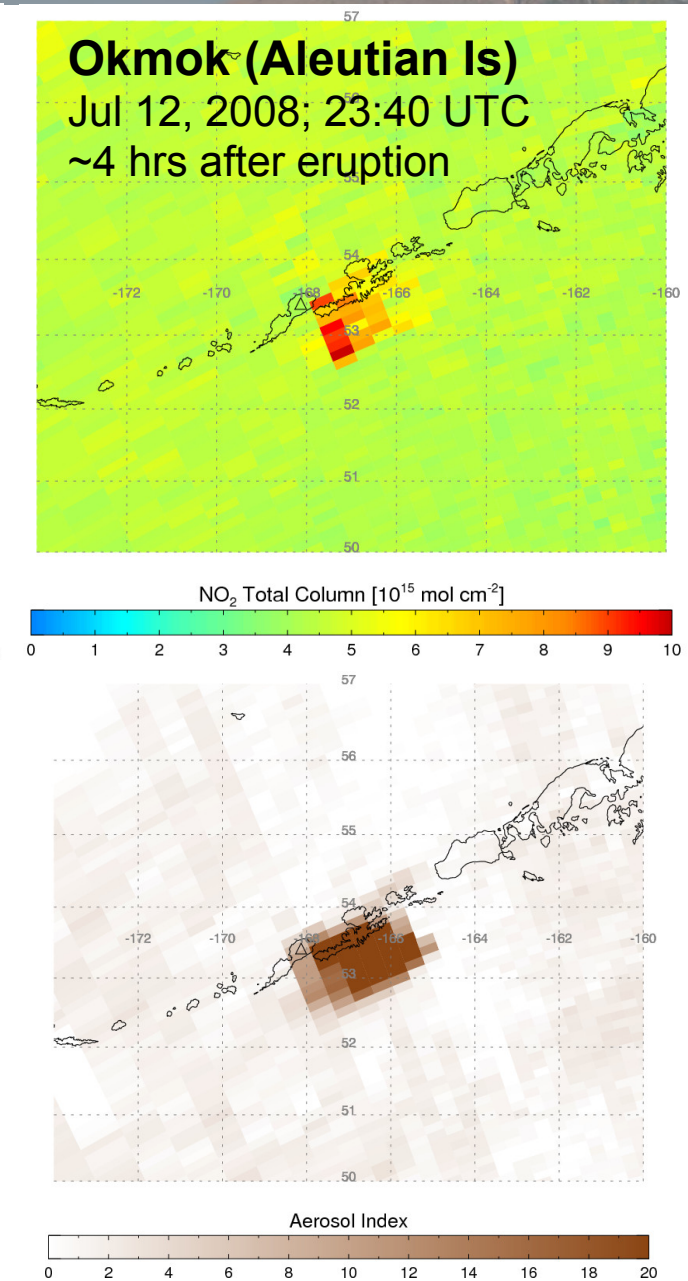
WWLLN flashes: Okmok and Kasatochi



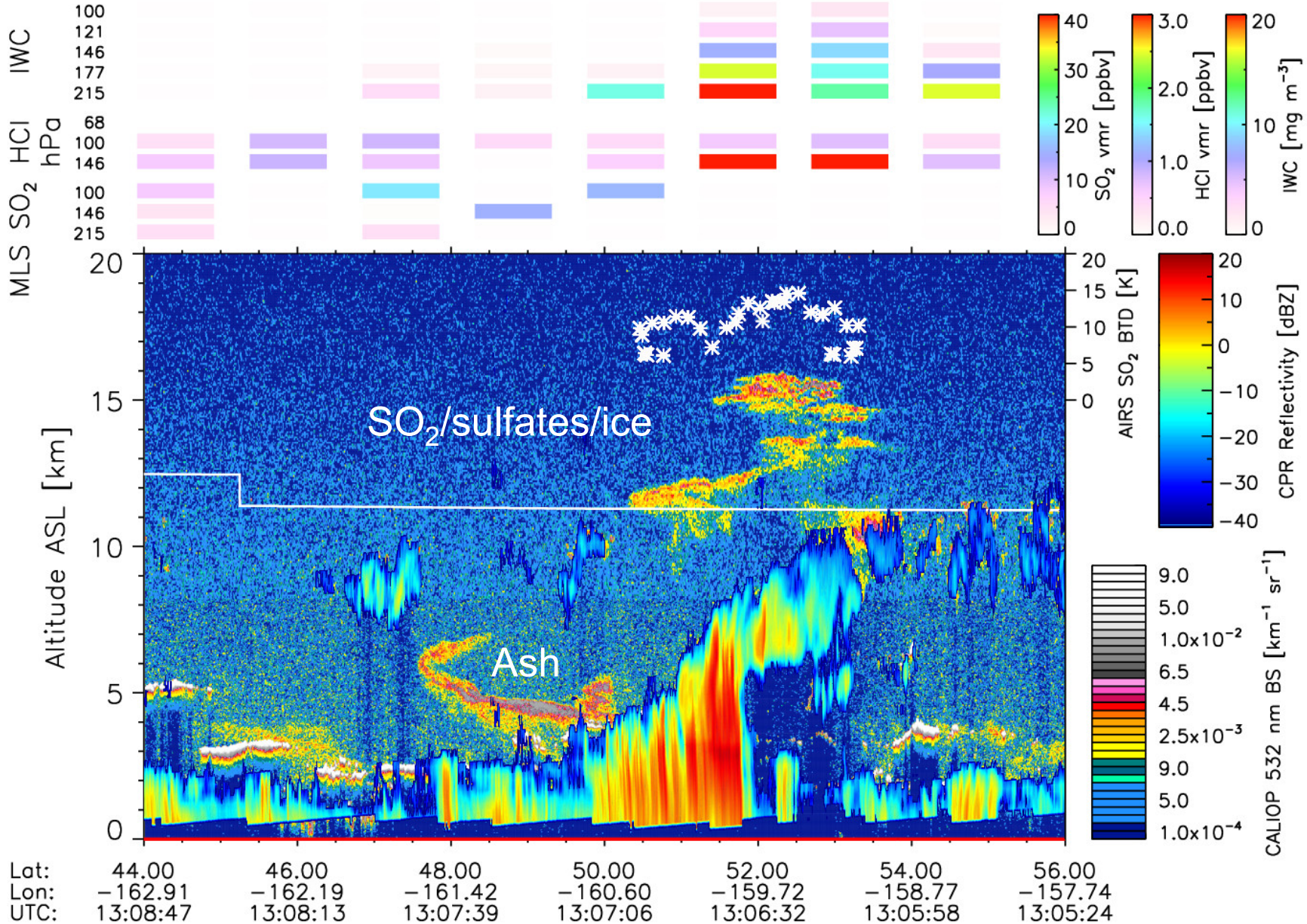
NB. WWLLN does not detect all flashes

vLNO$_x$ in volcanic clouds: ~2-4 hours after eruption





Okmok (Aleutian Is) – Jul 13, 2008: ~17 hrs post-eruption



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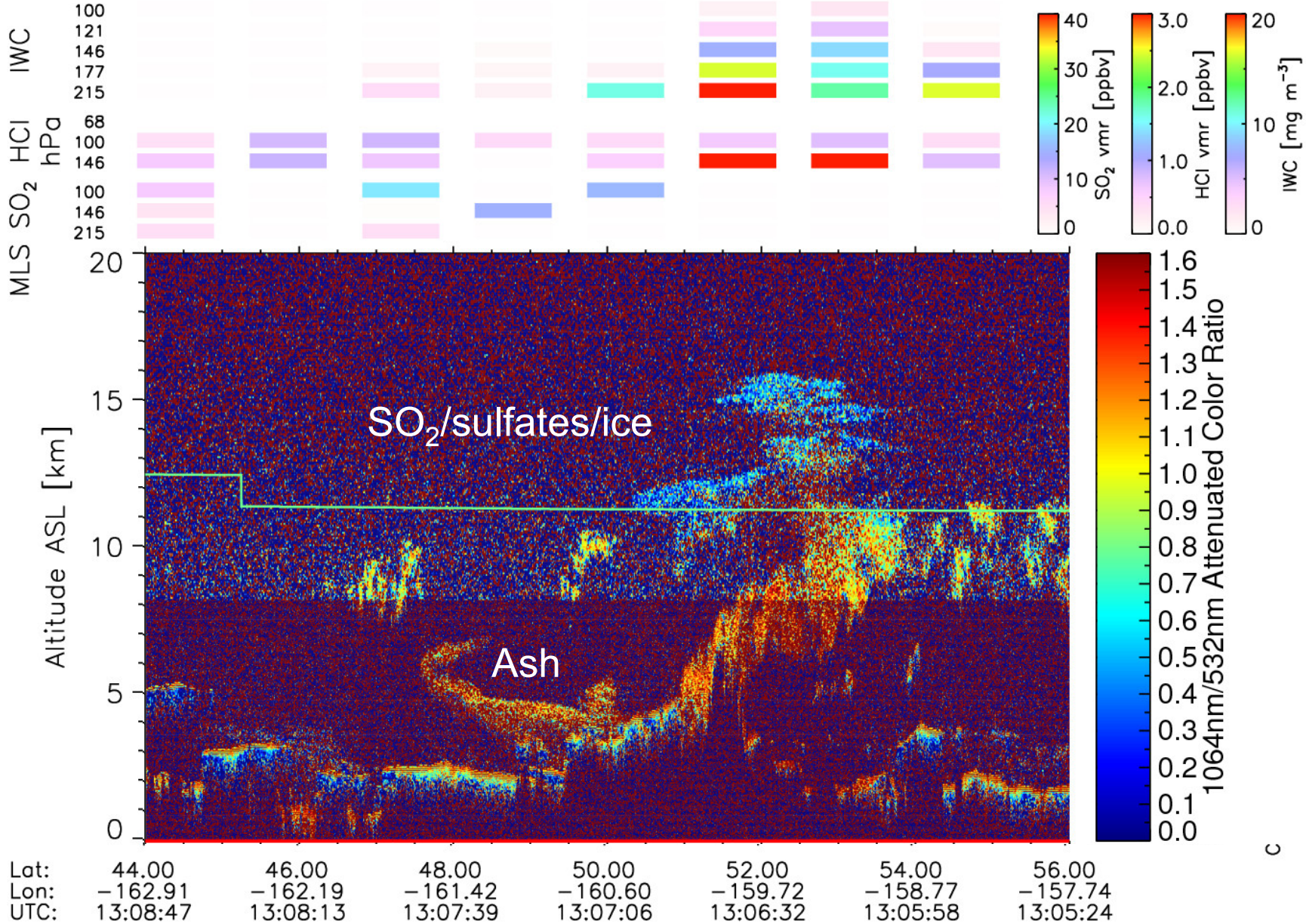
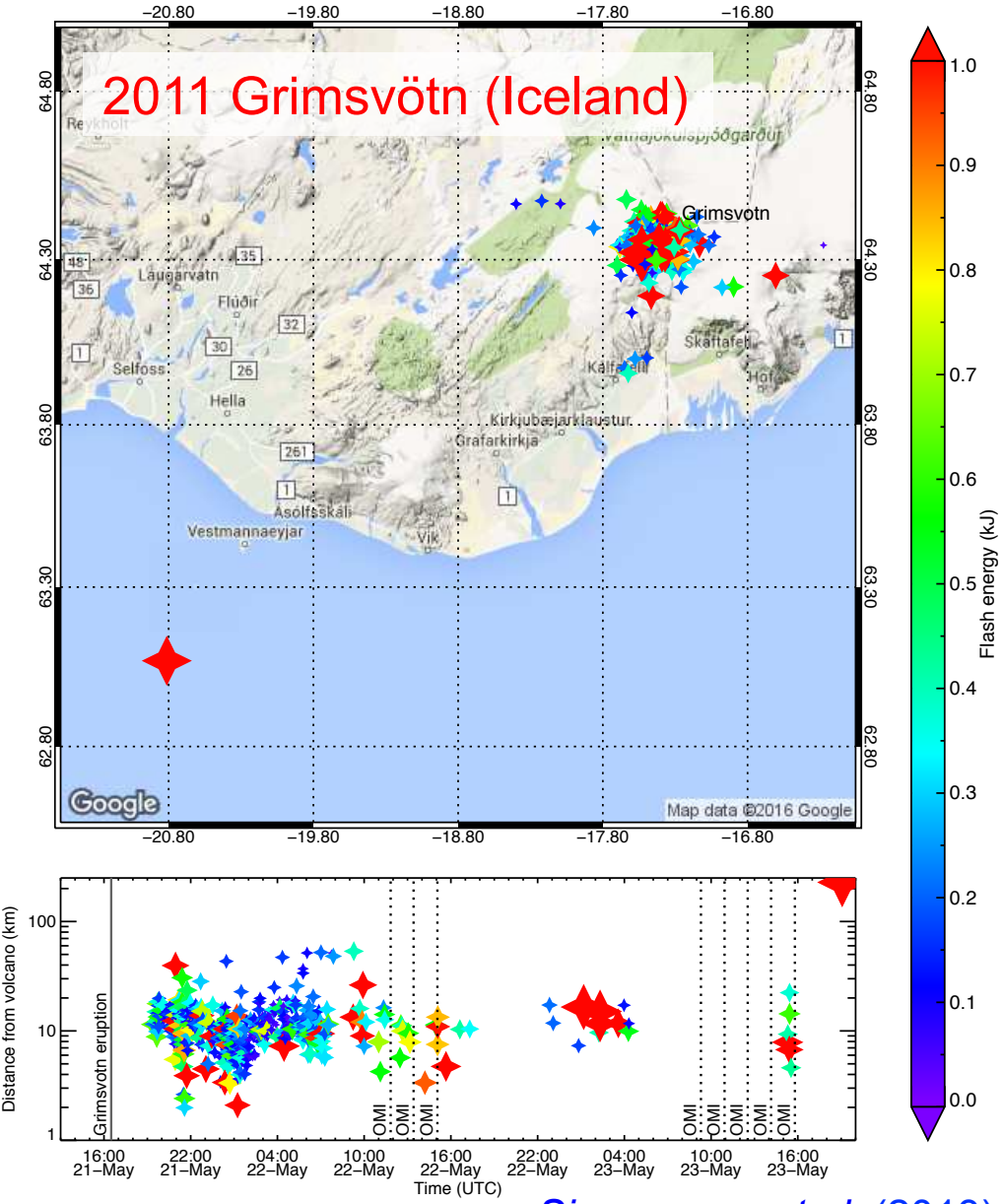
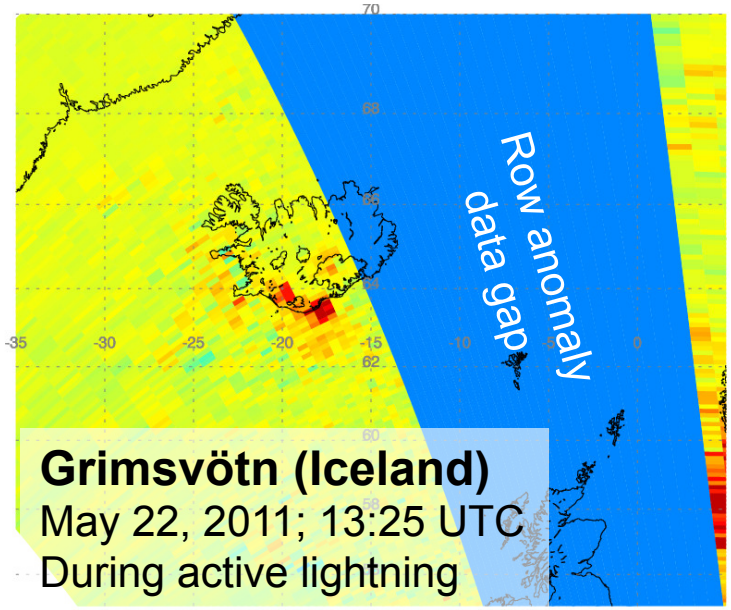
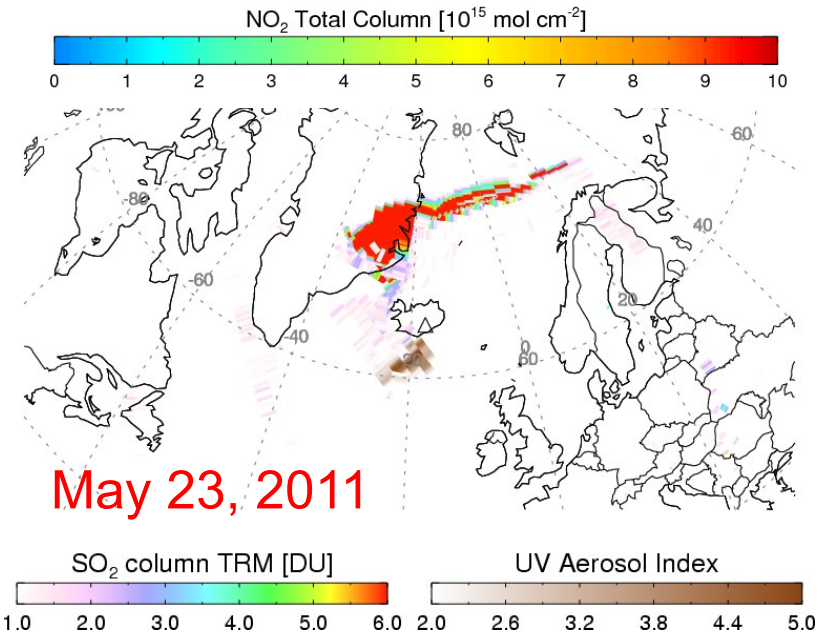


Grimsvötn – May 21-23, 2011: ash-gas separation

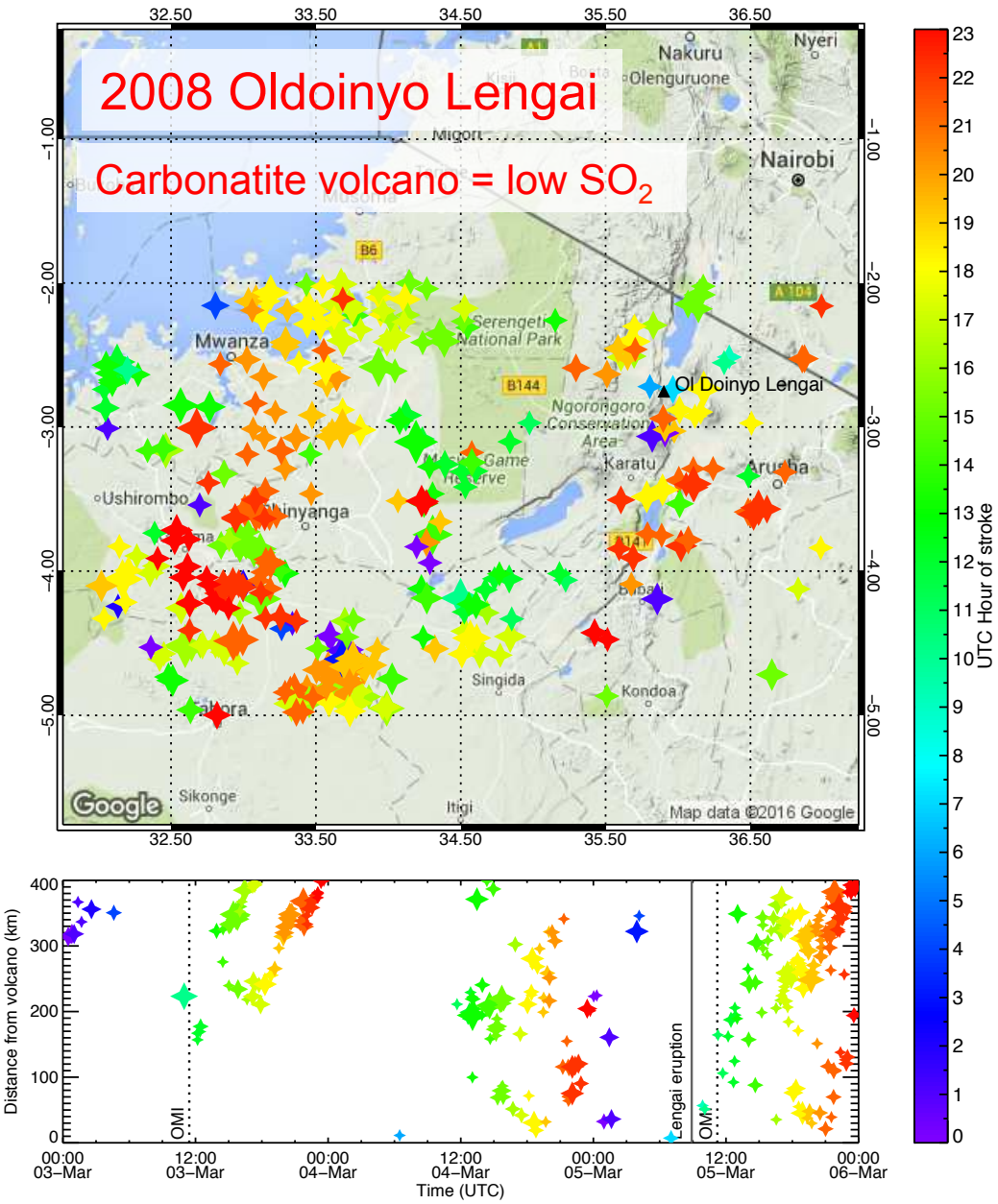


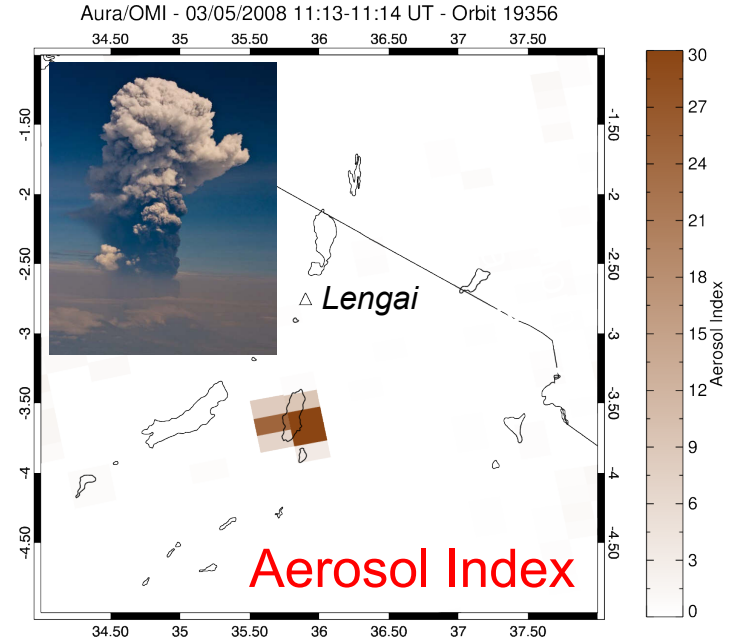


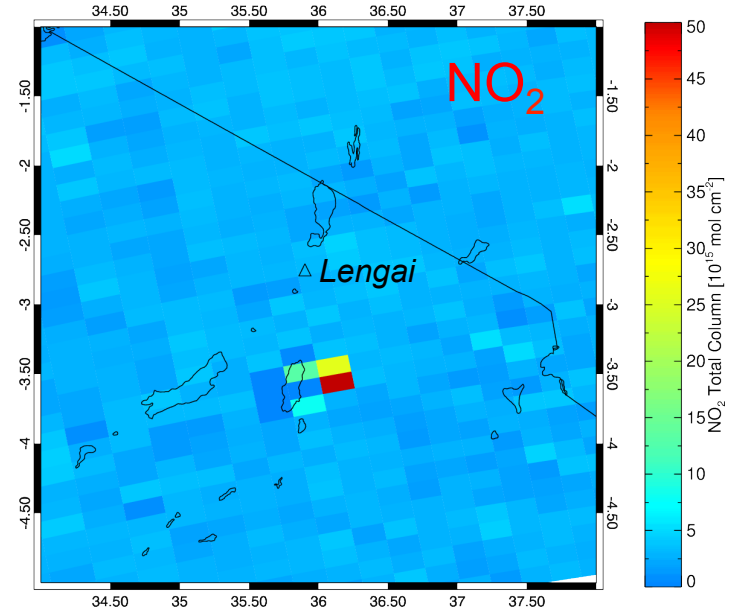


Sigmarsson et al. (2013)

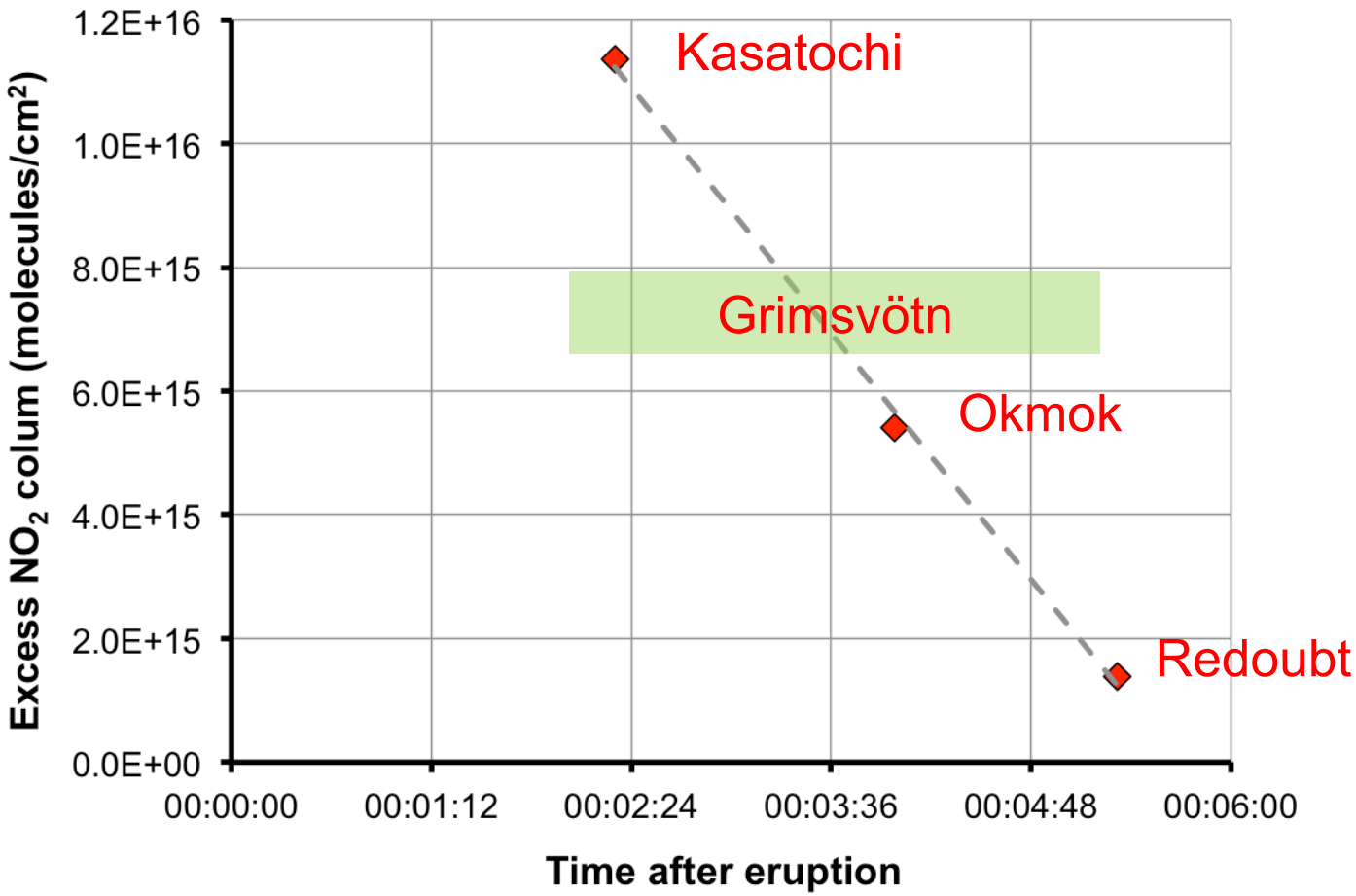
Oldoinyo Lengai (Tanzania) – March 2008







Temporal variation of excess $vLNO_x$



- Suggests that LNO_x signal can be detected from space up to ~5-6 hours after eruption (or after the most recent lightning activity)
- Lengai data do not conform (perhaps due to low-latitude location)

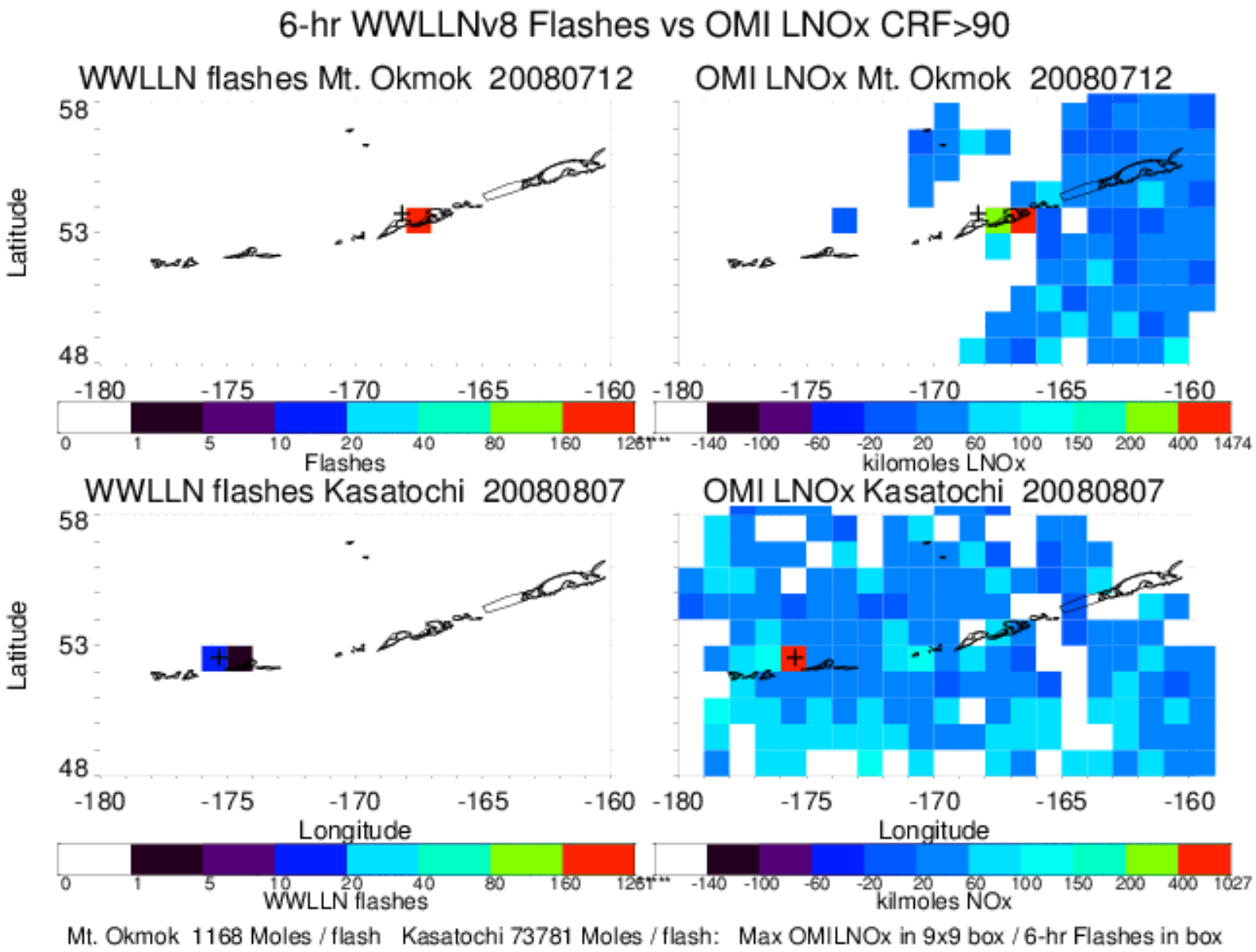
OMI LNO_x algorithm

$$\Omega_{LNOx} = \frac{\Omega_{total}^{slant} - \Omega_{strat}^{OMI} \times AMF_{strat} - \Omega_{BG}^{OMI} \times AMF_{trop}}{AMF_{LNOx}}$$

(*Buscela et al.*, 2010, 2013; *Pickering et al.*, 2014)

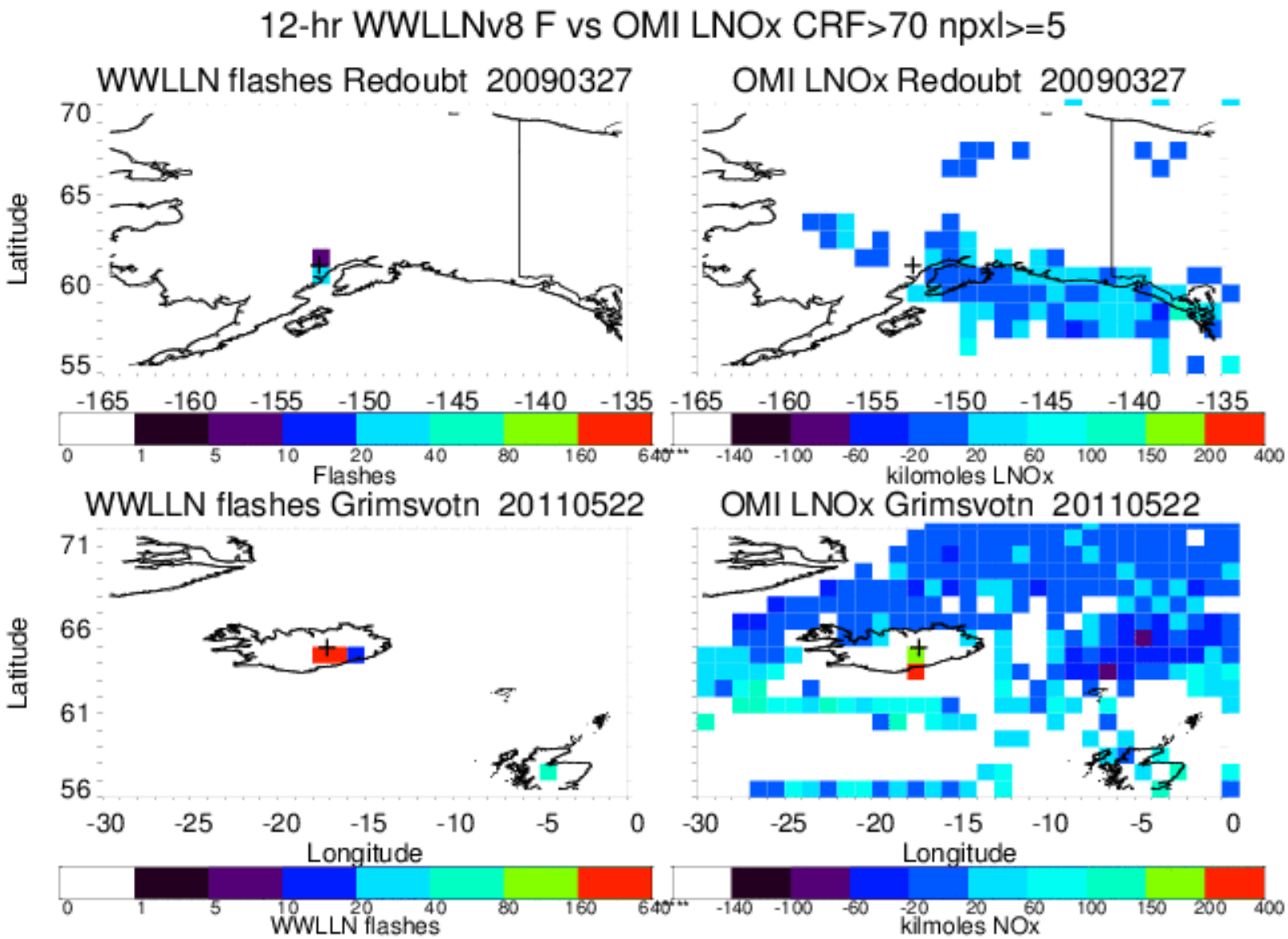
- Subtraction of stratospheric and tropospheric background columns (Ω) from OMI total column NO_2
  - Tropospheric background low in most volcanic regions
- Use of appropriate profile shapes and air mass factors (AMF) to convert NO_2 slant to vertical columns
- LNO_x estimates generated on a 1x1º grid
- Estimates of LNO_x production per flash generated using gridded total WWLLN flashes for 6 hour periods prior to OMI overpass (adjusted for WWLLN detection efficiency)

OMI LNO_x for Okmok and Kasatochi



Mt. Okmok 1168 Moles / flash Kasatochi 73781 Moles / flash: Max OMILNOx in 9x9 box / 6-hr Flashes in box

OMI LNO_x for Redoubt and Grimsvötn



$vLNO_x$ production per flash

Table 1: Compilation of literature estimates of lightning generated NO moles per flash.

	Method	Moles NO/flash (Notes)	Reference
	Theoretical	1100 (CG), 110 (IC)	Price et al., 1997
	Laboratory	~103	Wang et al., 1998
Mid-latitude	LMA/Theoretical	484 (CG), 35 (IC)	Koshak et al., 2014
Mid-latitude	Aircraft data, cloud model	345-460 (STERAO-A)	DeCaria, et al., 2005
Mid-latitude	Aircraft data, cloud model	360 (STERAO-A, EULINOX)	Ott et al., 2007; 2010
Mid-latitude	Aircraft data, cloud model	590-700 (CRYSTAL-FACE)	Ott et al., 2010
Mid-latitude		500 (Mean mid-latitude)	Ott et al., 2010
Tropics	Aircraft data, cloud model	500 – 600 (SCOUT-O3/ACTIVE)	Cummings et al., 2013
Tropics	Aircraft data	70-210 (TROCCINOX)	Huntrieser et al. 2008
Tropics	Aircraft data	121 – 385 (SCOUT-O3/ACTIVE)	Huntrieser et al., 2009
Tropics	Aircraft data	70 – 179 (AMMA)	Huntrieser et al., 2011
Tropics	Satellite (GOME)	32-240 (Sub-Tropical)	Beirle et al., 2006
Tropics	Satellite (SCIAMACHY)	33 – 50 (global, mostly marine)	Beirle et al., 2010
Tropics	Satellite (OMI)	87-246 (TC4 – tropical marine)	Bucsela et al., 2010
Tropics		174 (TC4 mean)	Bucsela et al., 2010

From *Ring* (2014)

- $vLNO_x$ moles per flash estimates:
  - Okmok: 4663 moles/flash
  - Kasatochi: 10242 moles/flash (*least flashes detected*)
  - Grimsvötn: 74 moles/flash (*most flashes detected*)
  - Redoubt: 234 moles/flash
  - Lengai: 2000-4000 moles/flash

Significance of $vLNO_x$ detection

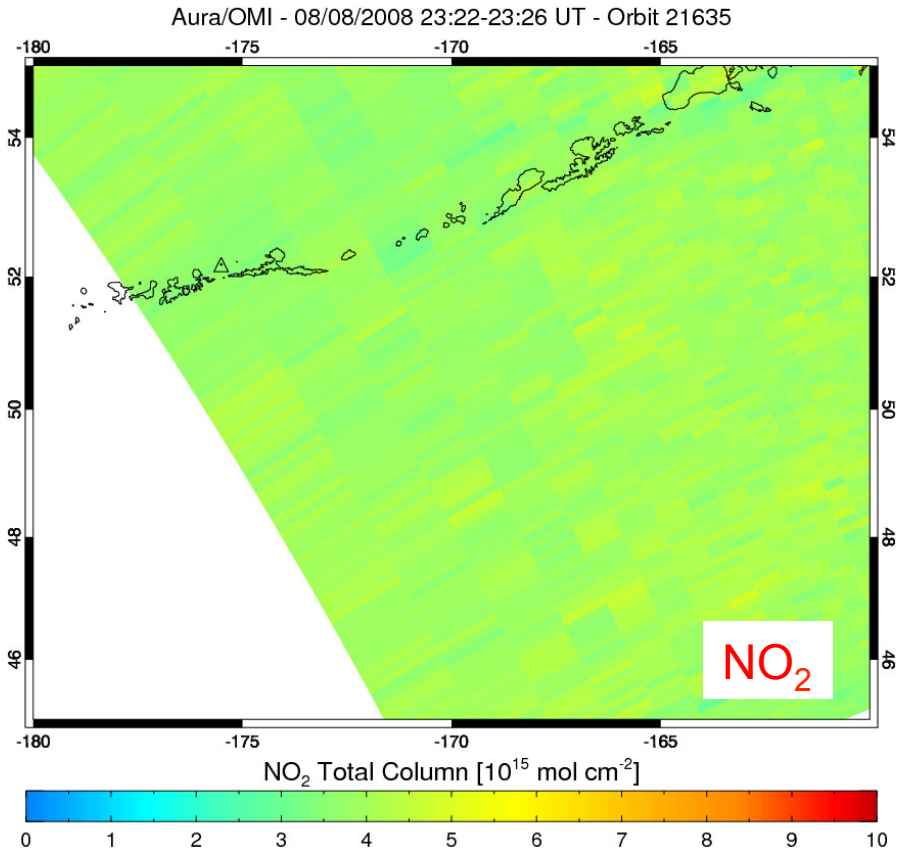
- Detection of convectively active, young volcanic clouds
  - Additional tool for aviation hazard mitigation
- Possible role of surface water/ice (Kasatochi, Okmok and Grimsvötn)
  - N_2 can be derived from surface/ground water, and boiling of surface water promotes plume electrification
  - No significant $vLNO_x$ detected in 2009 Sarychev Peak eruption
- Implications for air entrainment and ash mass in plumes?
  - Alternative source of precursor N_2
  - Links between ash mass and NO_2 production
- No significant $vLNO_x$ detected in a tropical eruption to date
  - Higher background LNO_x due to thunderstorm activity? Timing?
  - Effect of wind shear (greater flash lengths -> more LNO_x)
- In thunderstorms, LNO_x associated with increased ice/water aggregation near central part of anvils [*Stith et al.*, ACP, 2014]
  - Implications for ash aggregation processes in volcanic plumes?

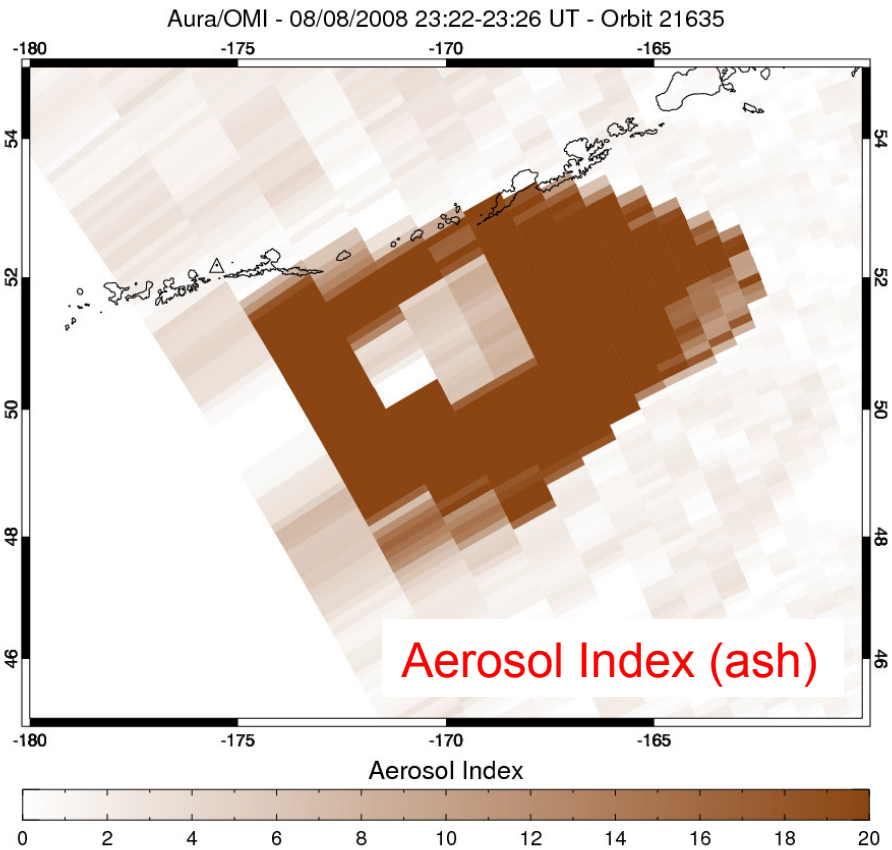
Summary

- **New technique for volcanic eruption detection**
  - **$vLNO_x$ detectable for up to 5-6 hours post-eruption/lightning**
  - **$vLNO_x$ production may be favored in eruptions involving surface water**
- **Estimates of $vLNO_x$ moles/flash still uncertain**
  - **Lightning flash rates may be significantly underestimated**
  - **Unclear which type(s) of volcanic lightning may produce LNO_x**
  - **Looking forward to 70-90% flash detection over Americas with GOES-R GLM**
- **Ongoing work:**
  - **Examine more eruptions**
  - **Use OMPS and GOME-2 NO_2 data to increase temporal coverage**
  - **Constrain N mass balance to investigate N_2 sources**

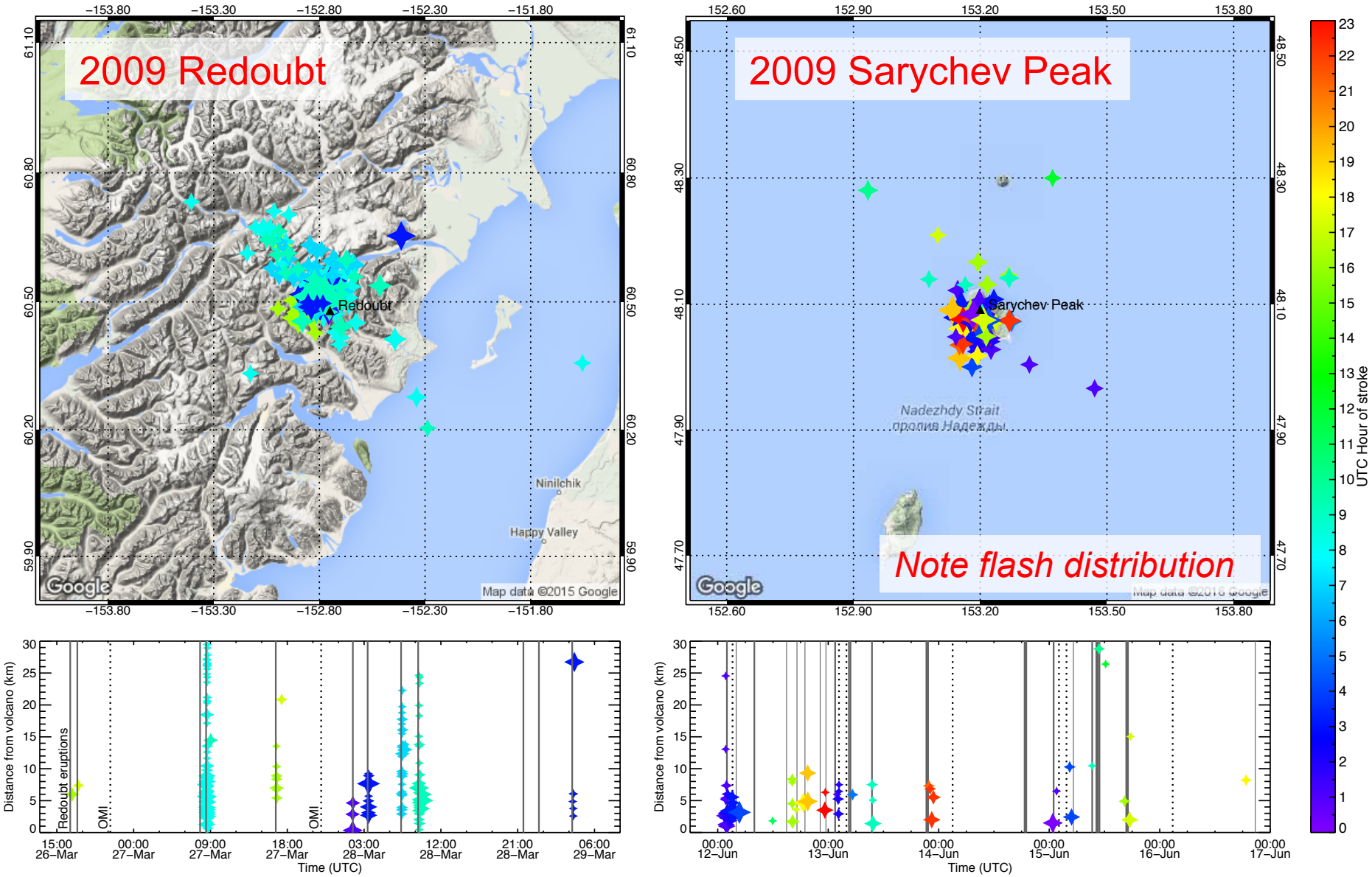
- Acknowledgments: NASA funding (Aura Science Team, MEaSUREs); Bob Holzworth (U. Washington, USA) for WWLLN data

OMI NO_2 and AI for Kasatochi – Aug 8



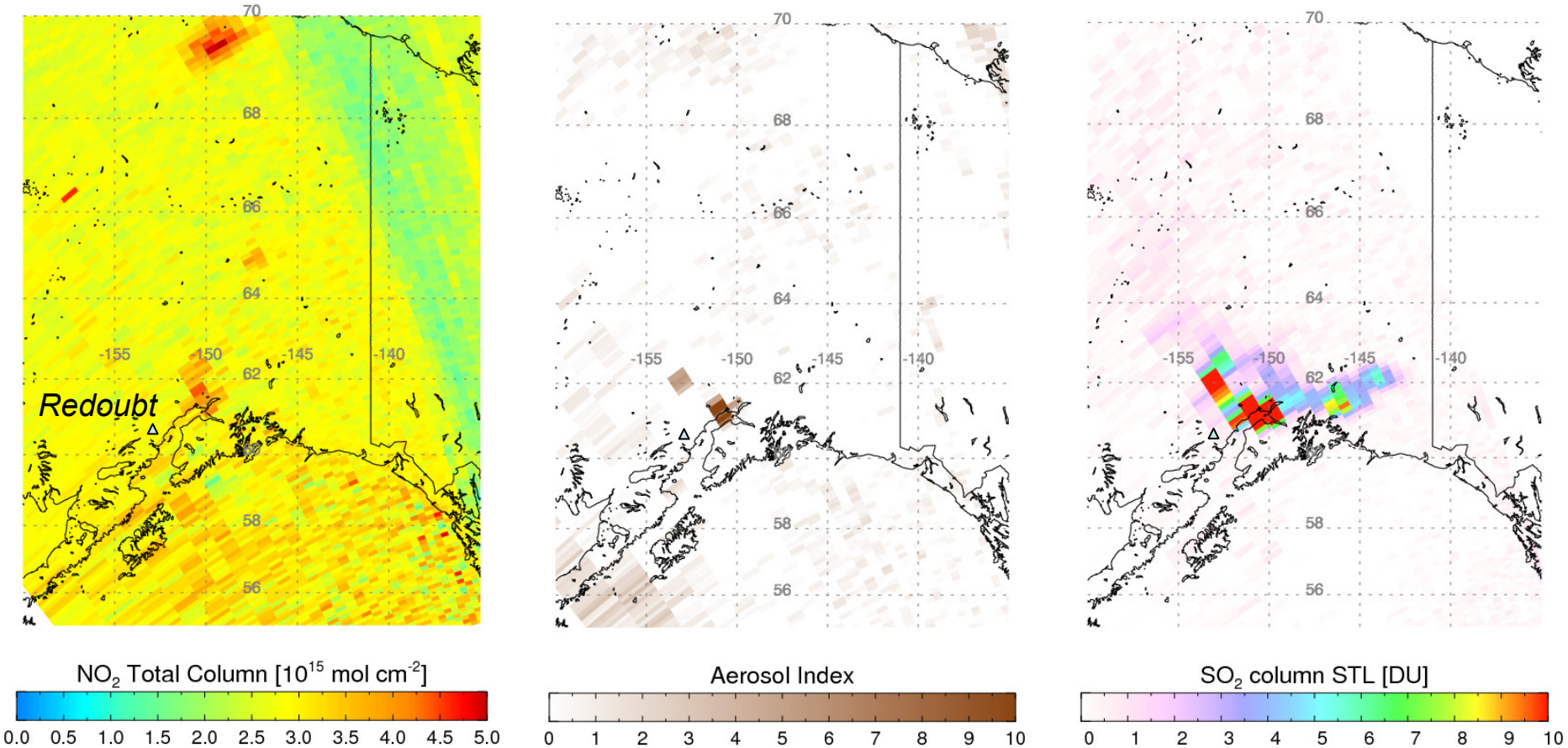


WWLLN flashes: Redoubt and Sarychev



NB. WWLLN does not detect all flashes (>10 kA)

Redoubt – March 27, 2009: pollution interference?



NO_2 | Aerosol Index (ash) | SO_2

- Detected NO_2 may be pollution from Anchorage