# Plume Tracker Analyses of TIR Data from Recent Eruptions in Iceland and Japan

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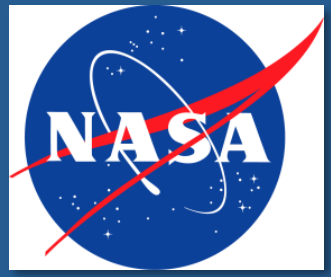
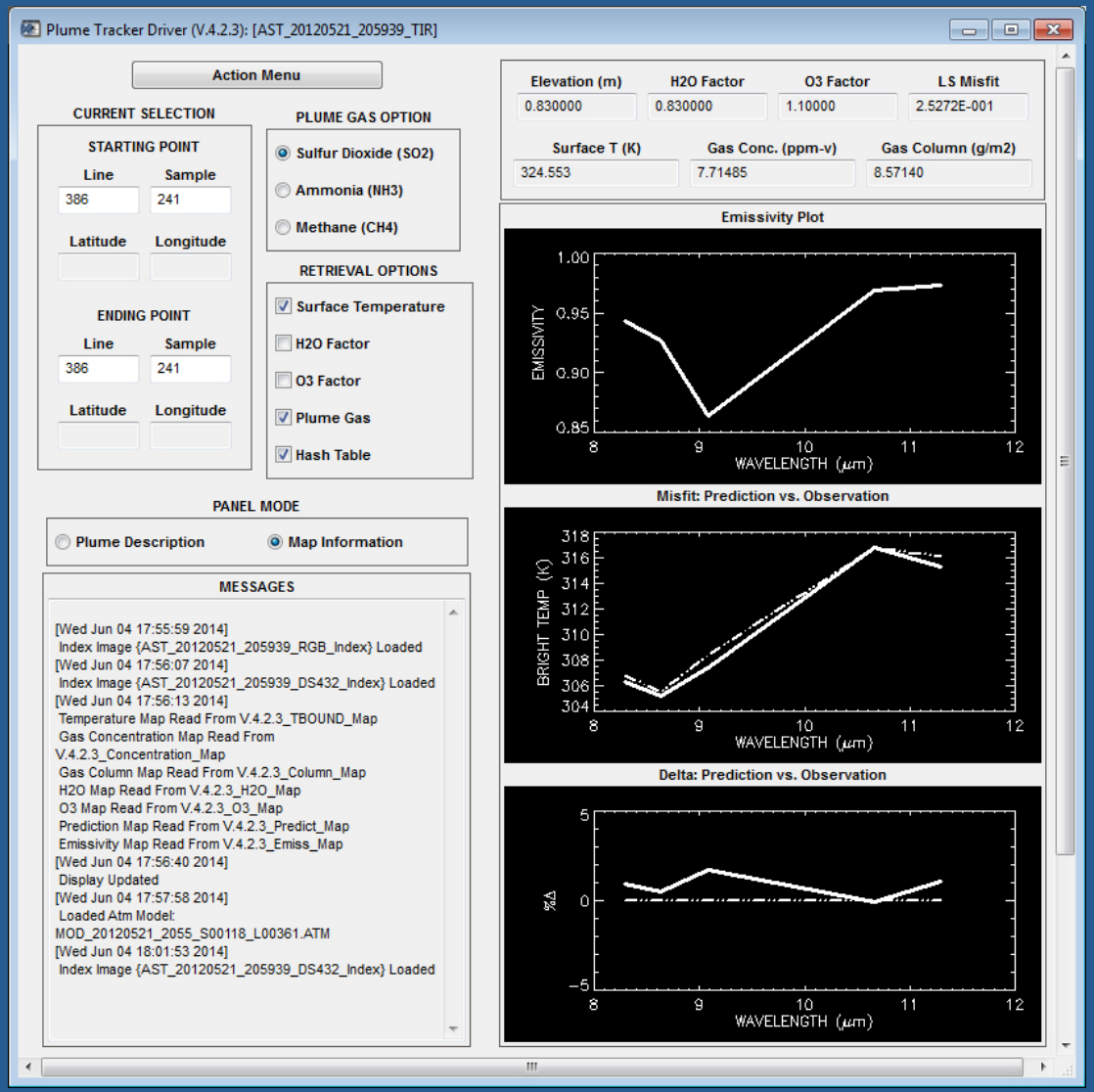


# Plume Tracker: Interactive Toolkit for Deep Analysis of TIR Image Data

1. Graphic User Interface
2. Radiative Transfer Model Based on MODTRAN
3. Retrieval Procedures

- Surface Temperature and Emissivity
- $H_2O$ Vapor and $O_3$ Scaling Factors
- $SO_2$, $NH_3$, and $CH_4$ Concentrations
- Optimized for 2-Component Retrievals (Temperature + Gas Concentration)




*Plume Tracker Driver Widget*

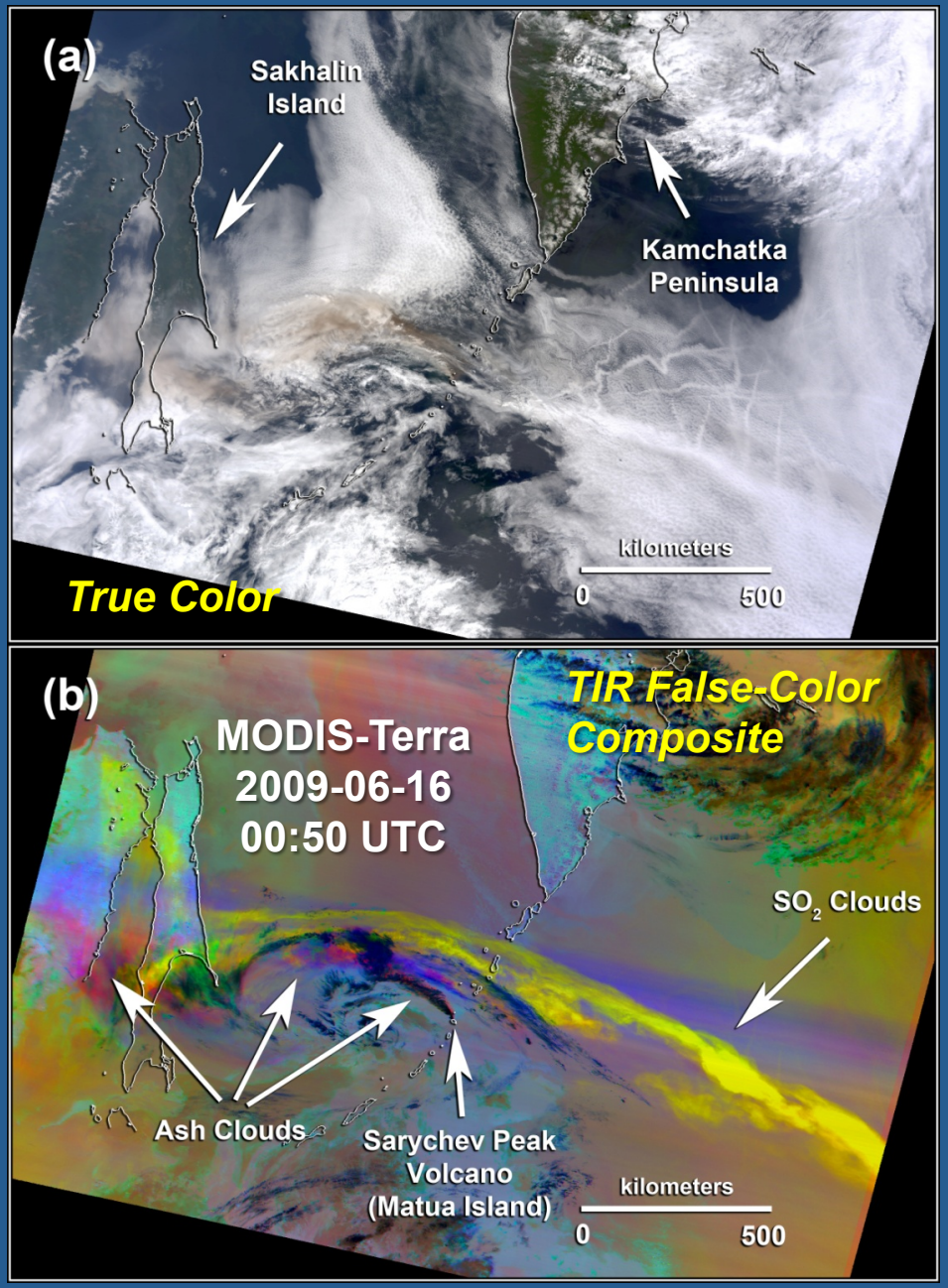
# Detection of Volcanic Plumes in the Thermal Infrared (TIR)

## (a) True-Color Composite

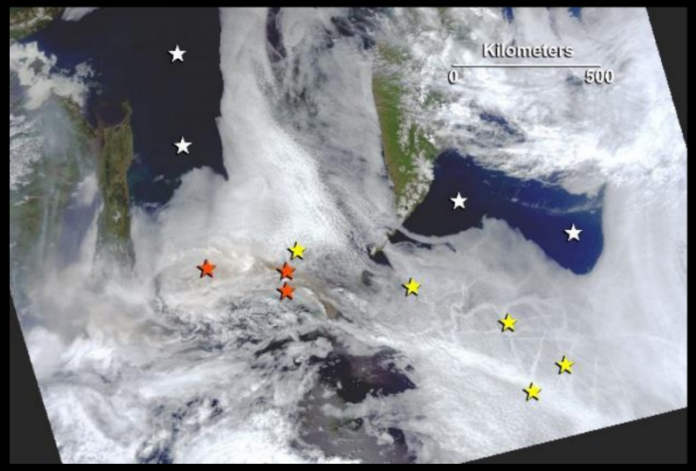
- Difficult to Discriminate Volcanic Clouds from Meteorological (Met) Clouds
- Recognition of Ash Clouds Requires Fairly High Mass Loads
- $SO_2$ Clouds are Invisible

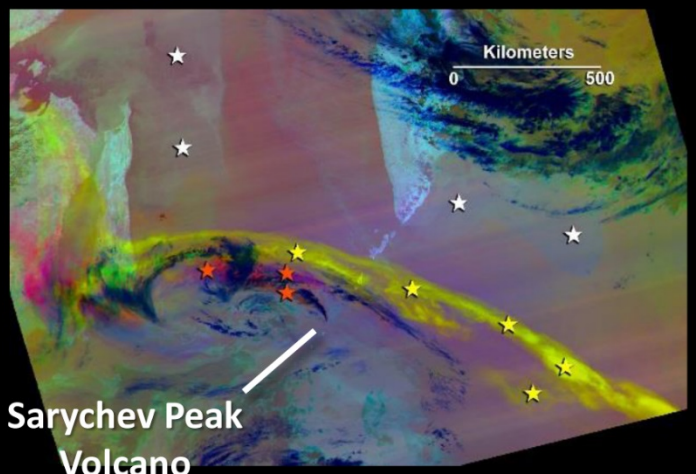
## (b) TIR False-Color Composite

- Met Clouds and Volcanic Products are Easy to Discriminate in TIR
- Quantification of Ash or $SO_2$ Content is Challenging!

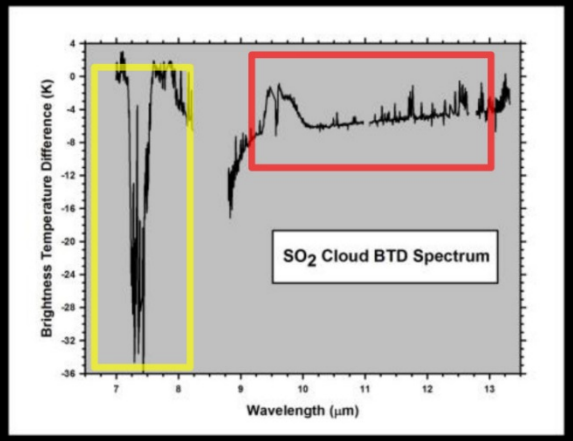


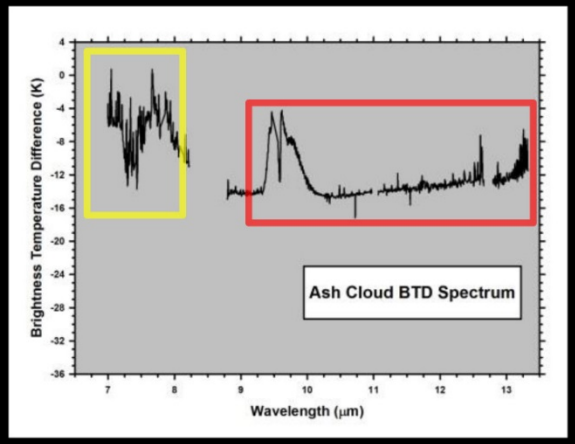
# AIRS High-Resolution (2000+ Channels) Spectra: Unique Identification of Plume Constituents



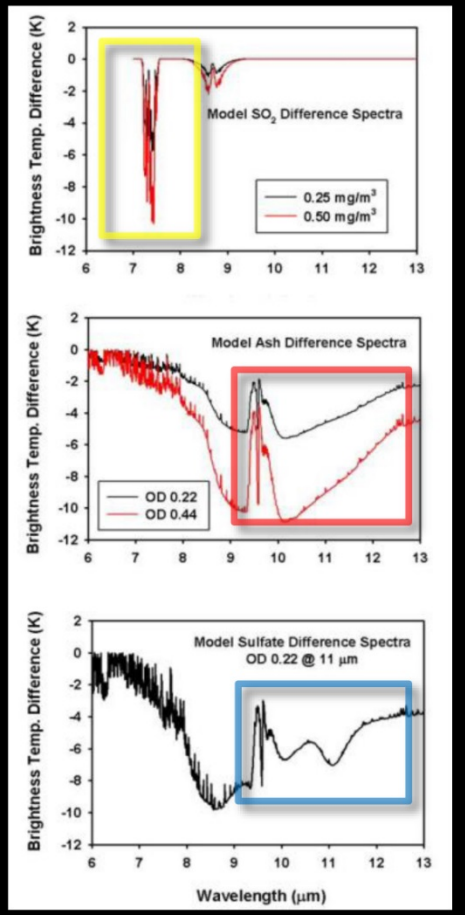




MODIS-Aqua
2009-06-16




AIRS BTD Spectra
2009-06-16




Model BTD
Spectra

# Plume Tracker Development: Progress on Two Fronts

## Improved the Performance of the Retrieval Algorithms

- Hash Table Implementation
- Brent Minimization of Misfit
- Reconstruction of Observed Radiance

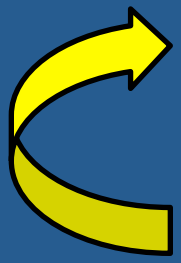
## Improved the Accuracy of the Retrievals

- Misfit Calculated with Vector Projection
- Step-Wise Interpolation of Reflectance/Emissivity Spectra

# Hash Table (Associative Array): Acceleration of Retrieval Algorithm

*(2011 Edition)*

| | |
|---|---|
| *Key(1)* | *MODTRAN Spectrum(1)* |
| *Key(2)* | *MODTRAN Spectrum(2)* |
| *Key(3)* | *MODTRAN Spectrum(3)* |
| *Key(4)* | *MODTRAN Spectrum(4)* |
| … | … |



**Key(i) = [*zenith angle*][*surface elevation*][*surface temp*] [$H_2O$ *factor*][$O_3$ *factor*][$SO_2$ *factor*]**

**Scan Key List for Matches to Existing Keys**

**Associated Spectrum used for Matching Keys;**
**New Table Entry for Unique Keys**

**More Efficient/Flexible than Table Look-Up**

- **Tables Store Values Encountered in Scene, Not Every Possible Value**
- **Hash Tables Augmented or Purged Dynamically**

# Version 4.2: Reconstruction of Observed Radiance

Observed Radiance is Composed of Surface Radiance, Atmospheric Transmission (T), Upwelling Path Radiance (U), and Downwelling Sky Radiance (D)

- Surface Radiance (Surface Temperature and Emissivity) is Independent of $SO_2$ Concentration of Plume
- Transmission, Path and Sky Radiance Depend on $SO_2$ Concentration

Three Hash Tables for T, U, and D

- Index Each Table with the Same Key
- Surface Temperature: No Longer Explicit Component of Key
- Emissivity: No Longer Implicit Component of Key

<u>Increased Utilization of Hash Tables: Success Rates > 95%</u>

# Retrieval Algorithm Performance (2011 – 2013)

| | Domain Refinement *(V.2.2.9)* | Multi-Pass Brent Minimization *(V.3.0)* | Single-Pass Brent Minimization *(V.3.2)* | Reconstructed Radiance *(V.4.2b)* |
|---|---|---|---|---|
| **Calls to RT Model** *ROI = 1296 pixels* | *264,398 (204 calls/pix)* | *144,508 (112 calls/pix)* | *58,361 (45 calls/pix)* | *29,485 (23 calls/pix)* |
| **No Hash Table** | *6.4 sec/pix* | *3.2 sec/pix* | *1.26 sec/pix* | *0.61 sec/pix* |
| **Hash Table** | *1.6 sec/pix* | *0.8 sec/pix* | *0.16 sec/pix* | *0.019 sec/pix* |
| **Success Rate** *Hash Table Utilization* | *77.4 %* | *77.0%* | *88.0%* | *97.8%* |

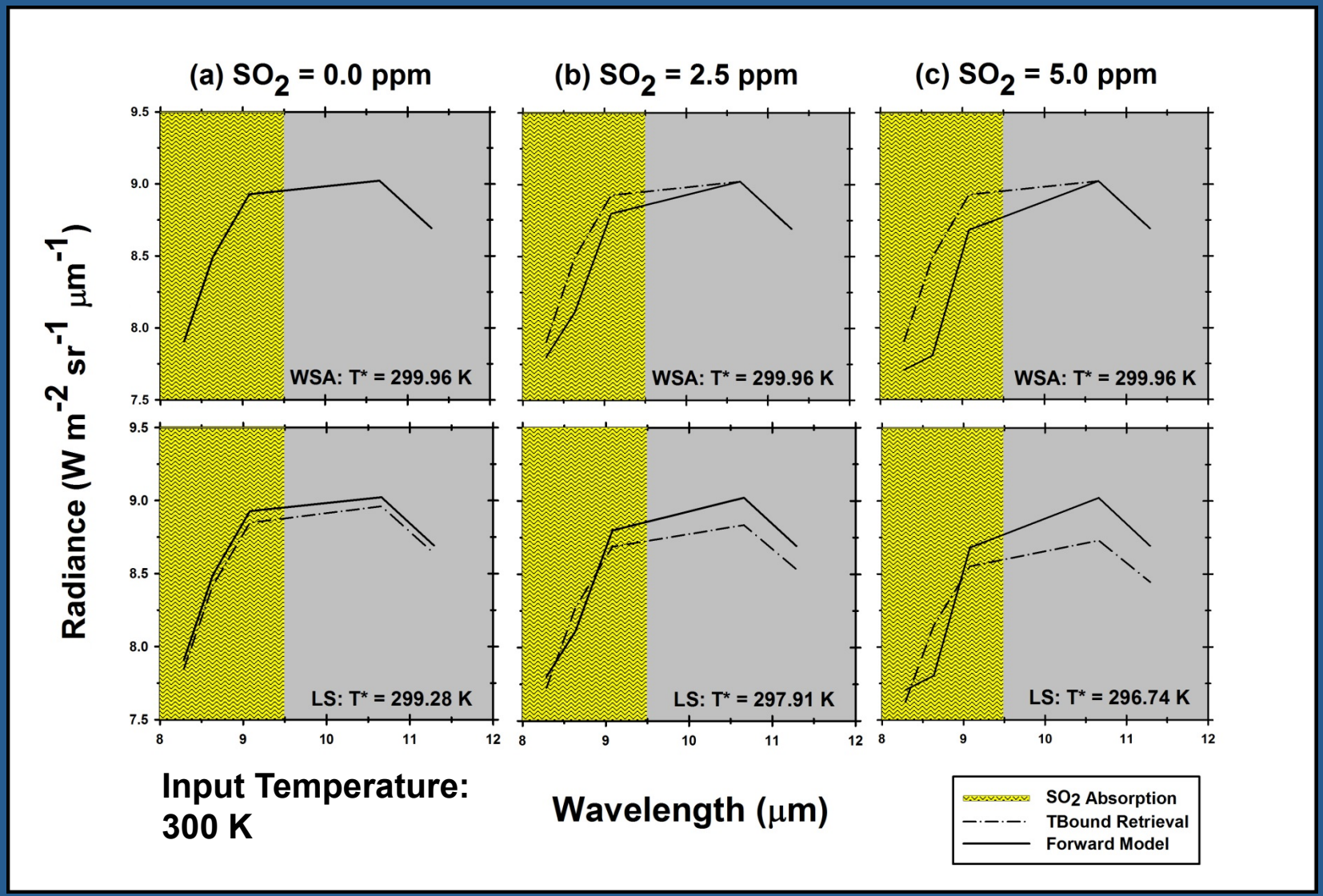
# Misfit Calculation:
# Least Squares vs. Weighted Spectral Angle

**Least Squares (LS):**

- Designed to Fit Noisy Data
- Equal Weight to Outliers
- Not Ideal for Temperature Estimation

**Weighted Spectral Angle (WSA):**

- Observed and Model Radiance Spectra Represented as Vectors in Data Space
- Minimize Angle Between Vectors (*Spectral Angle*)
- Minimization Weighted to Favor Solutions with Model Spectrum > Observed Spectrum
- Optimum Temperature Estimate Given Imperfect Knowledge of Atmospheric Composition

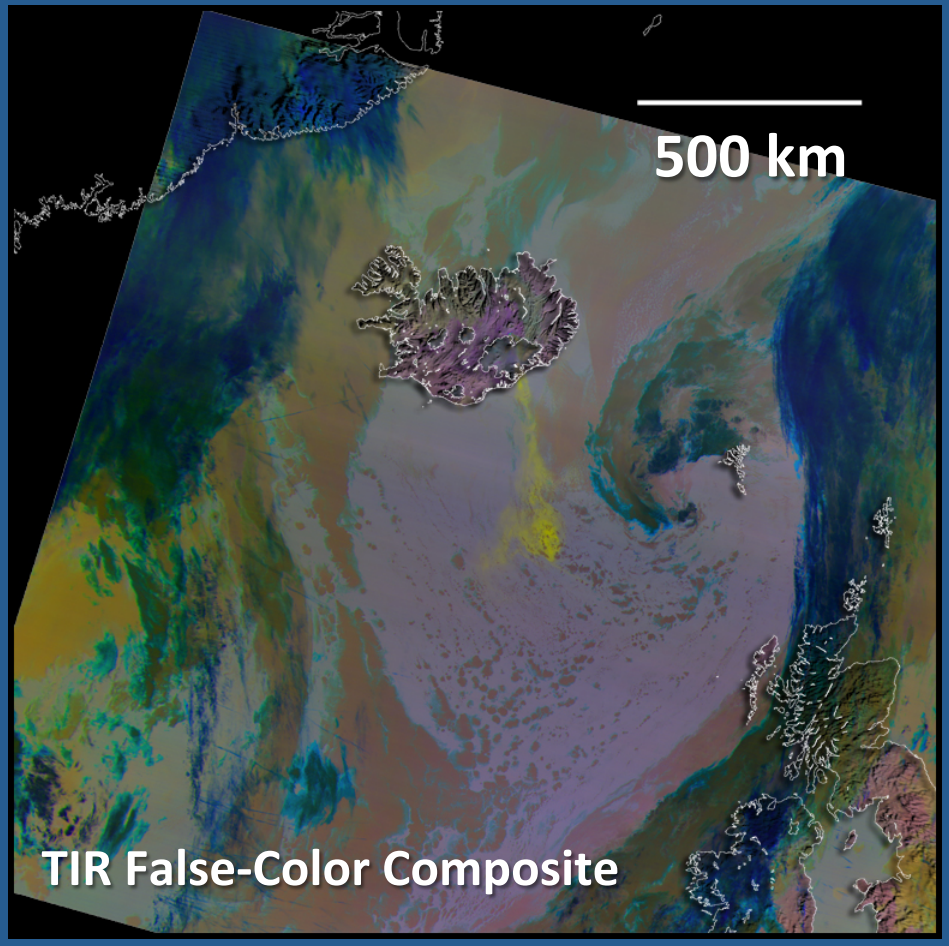

(a) SO2 = 0.0 ppm
(b) SO2 = 2.5 ppm
(c) SO2 = 5.0 ppm
Radiance (W m-2 sr-1 μm-1)
WSA: T* = 299.96 K
WSA: T* = 299.96 K
WSA: T* = 299.96 K
LS: T* = 299.28 K
LS: T* = 297.91 K
LS: T* = 296.74 K
9.5
9.0
8.5
8.0
7.5
8
9
10
11
12
Input Temperature: 300 K
Wavelength (μm)
SO2 Absorption
TBound Retrieval
Forward Model

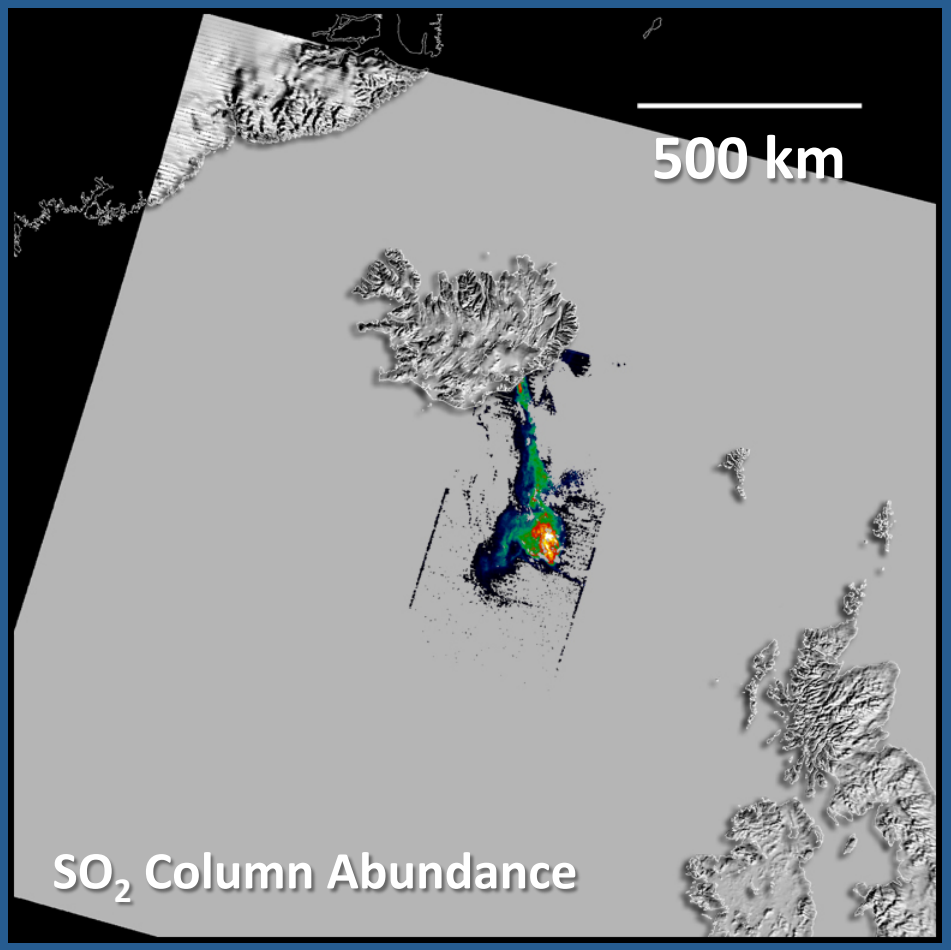



Holuhraun Fissure, Bardarbunga Volcano, Iceland

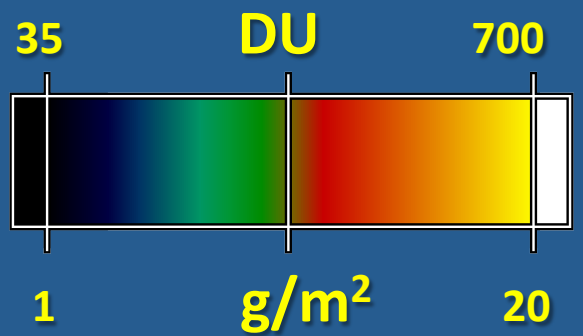
- Lava Fountains Give Rise to Gas Plumes
- Multiple Sources for Plumes along Fissure
- Gas Plume Lies Beneath Opaque Steam plume

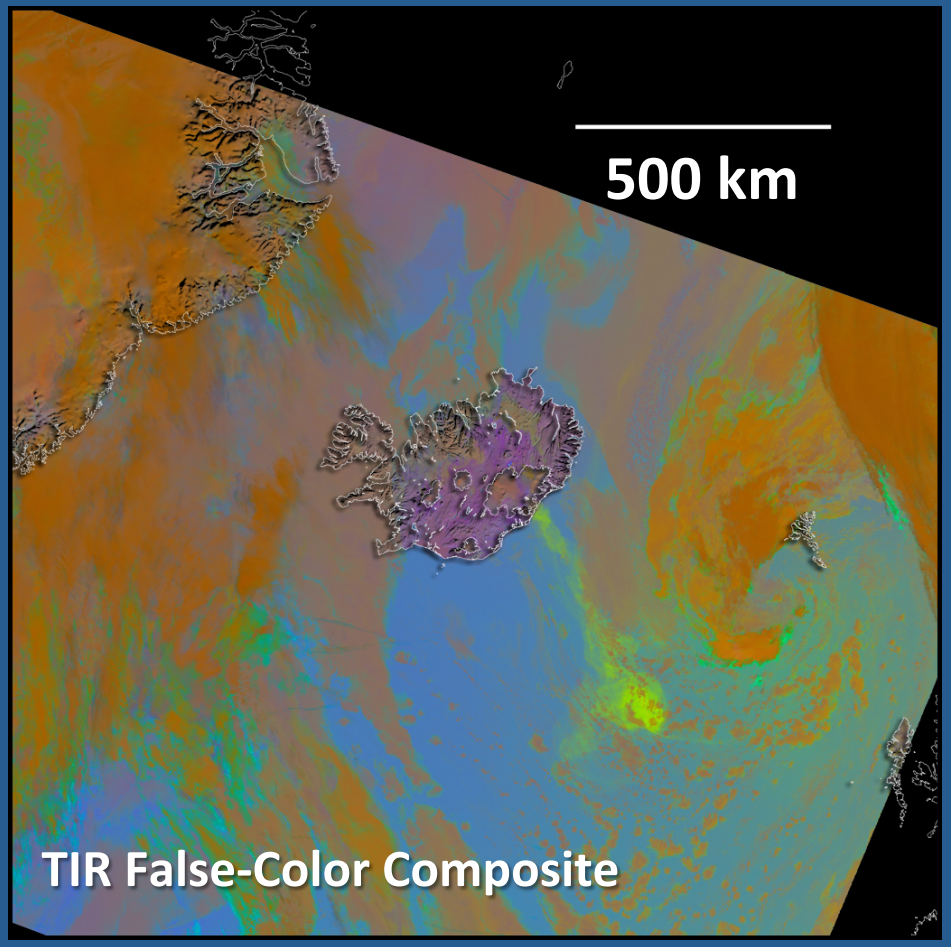
*Photos Courtesy Thorvaldur Thordarson*

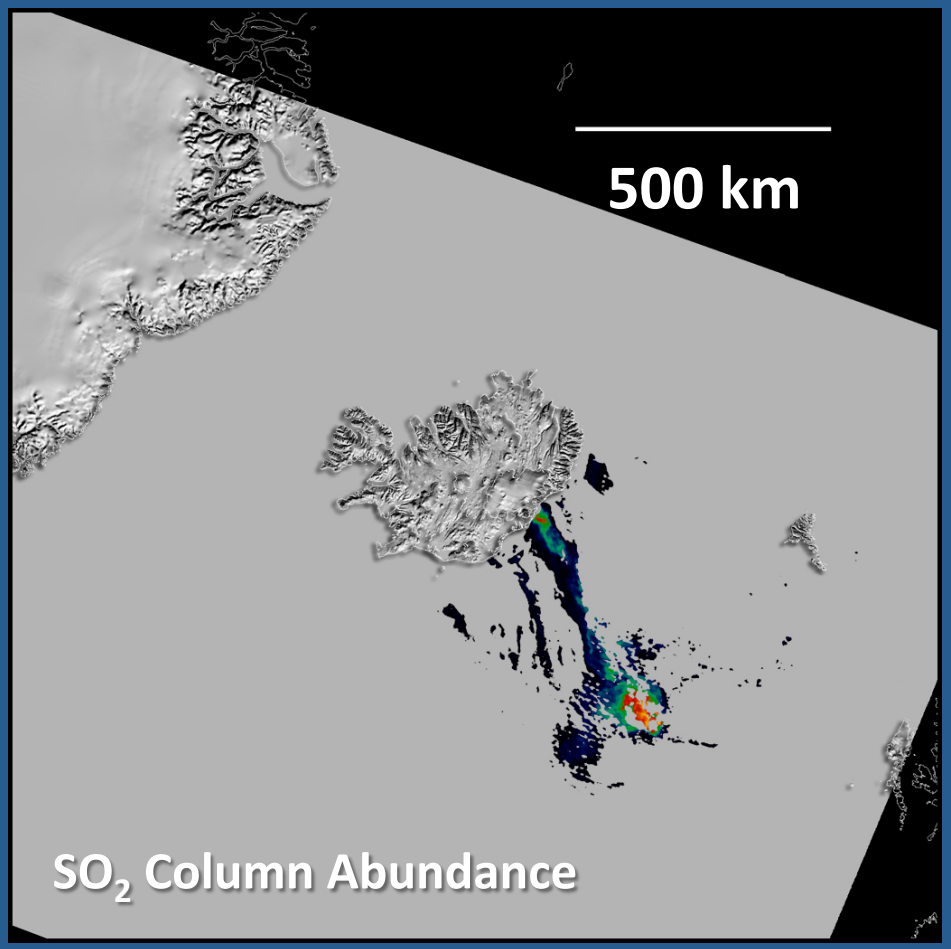


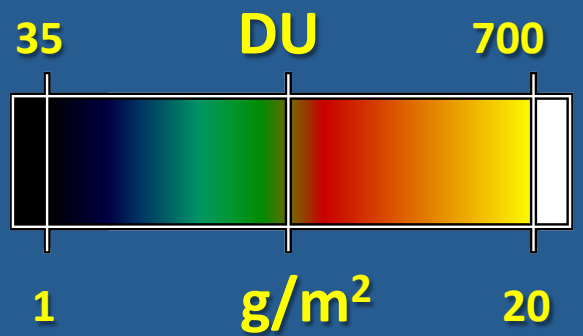

**Bardarbunga Volcano: 2014-09-05**
**MODIS-Aqua: 03:25 UTC**
**Plume Area: 6.67 x $10^4$ $km^2$**
**Total Mass $SO_2$: 248.5 kt**






**Bardarbunga Volcano: 2014-09-05**
**VIIRS: 04:55 UTC**
**Plume Area: 5.87 x $10^4$ $km^2$**
**Total Mass $SO_2$: 177.3 kt**

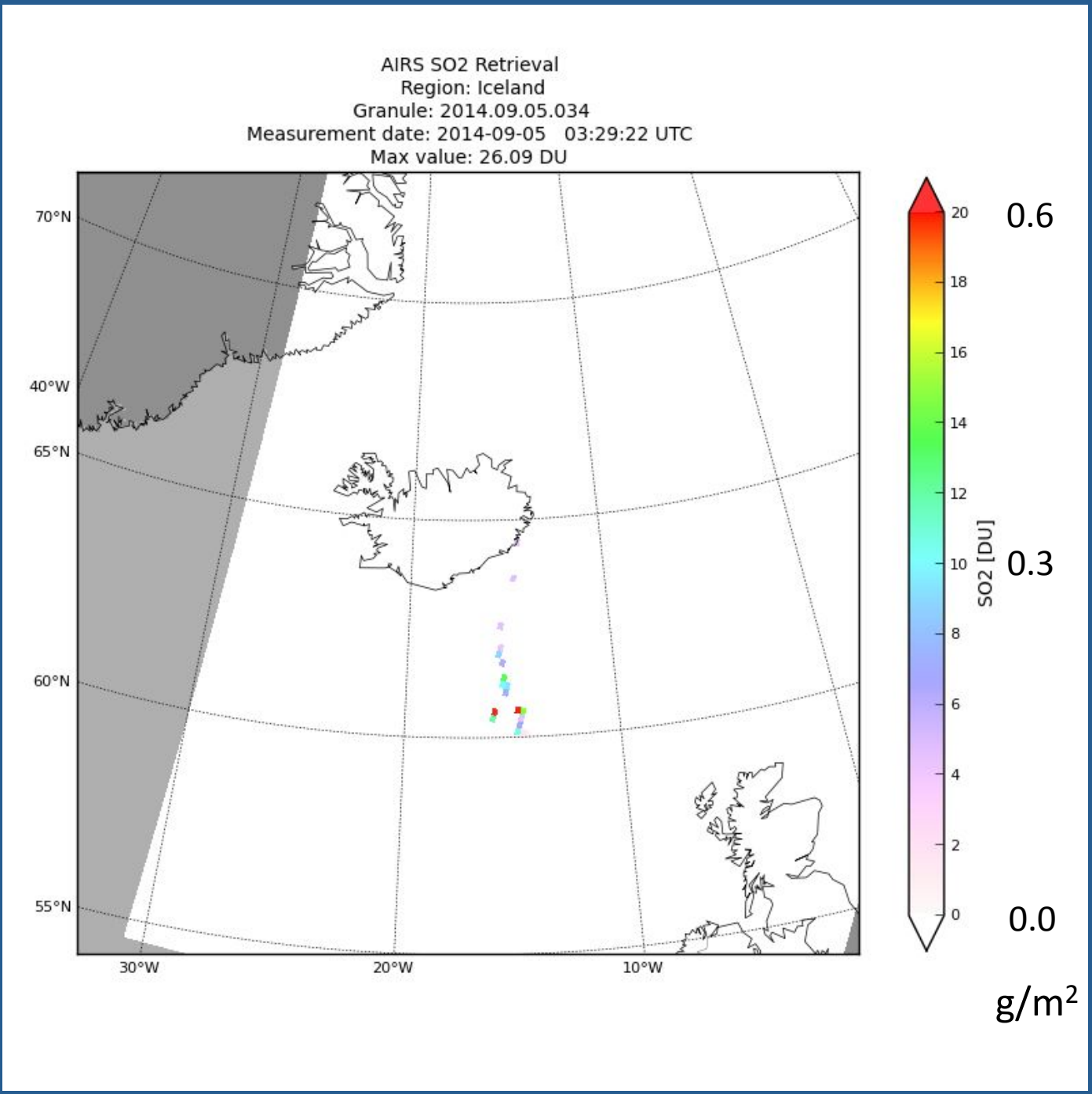


# Bardarbunga Volcano

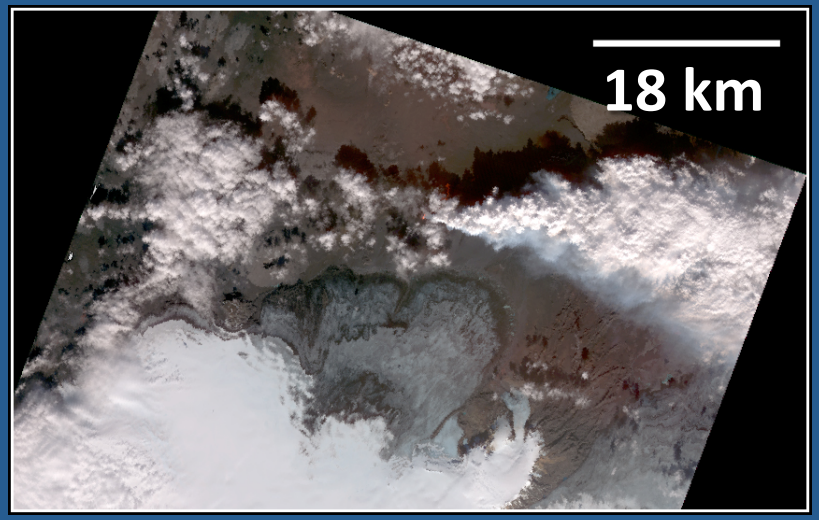
**AIRS Operational $SO_2$ Retrieval**

**2014-09-05 03:29 UTC**

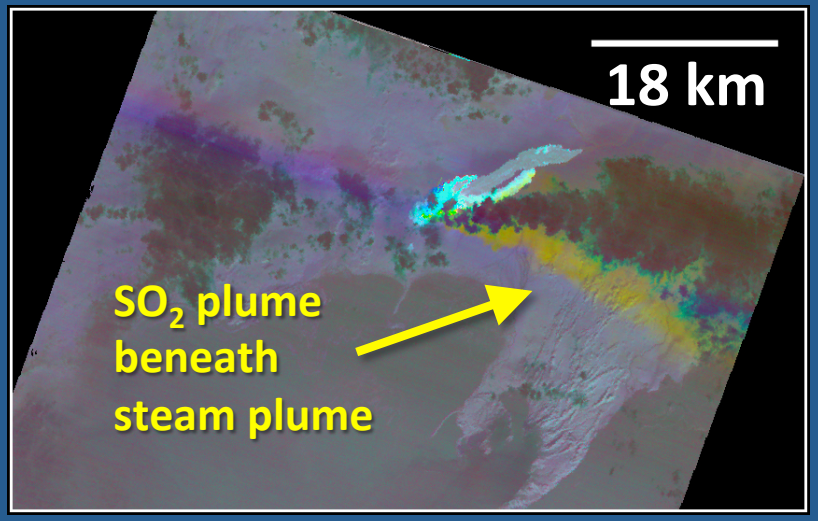
**Coarse Spatial Resolution (~15 km) Dilutes SO2 Conc. Relative to MODIS (1 km) or VIIRS (750 m)**



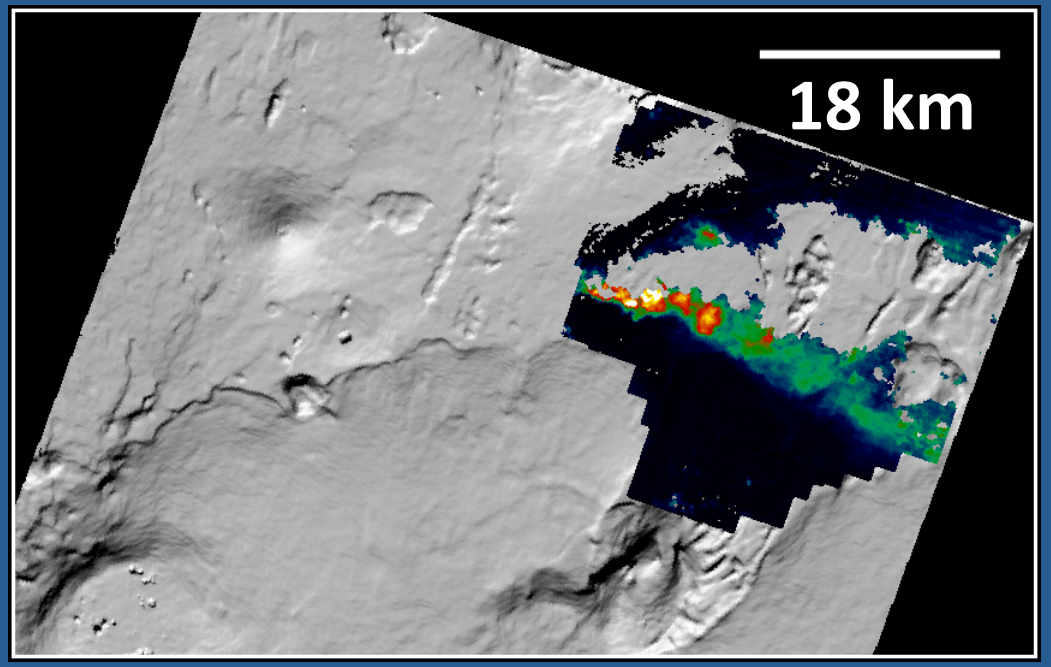
# Bardarbunga Volcano
# 2014-09-23
# 12:39 UTC

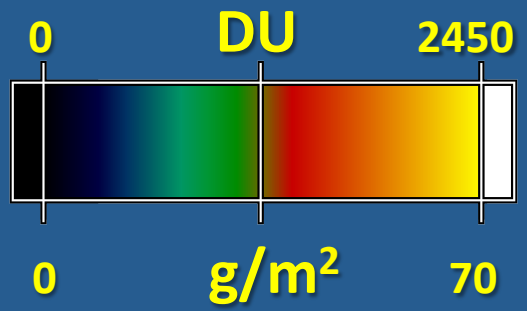


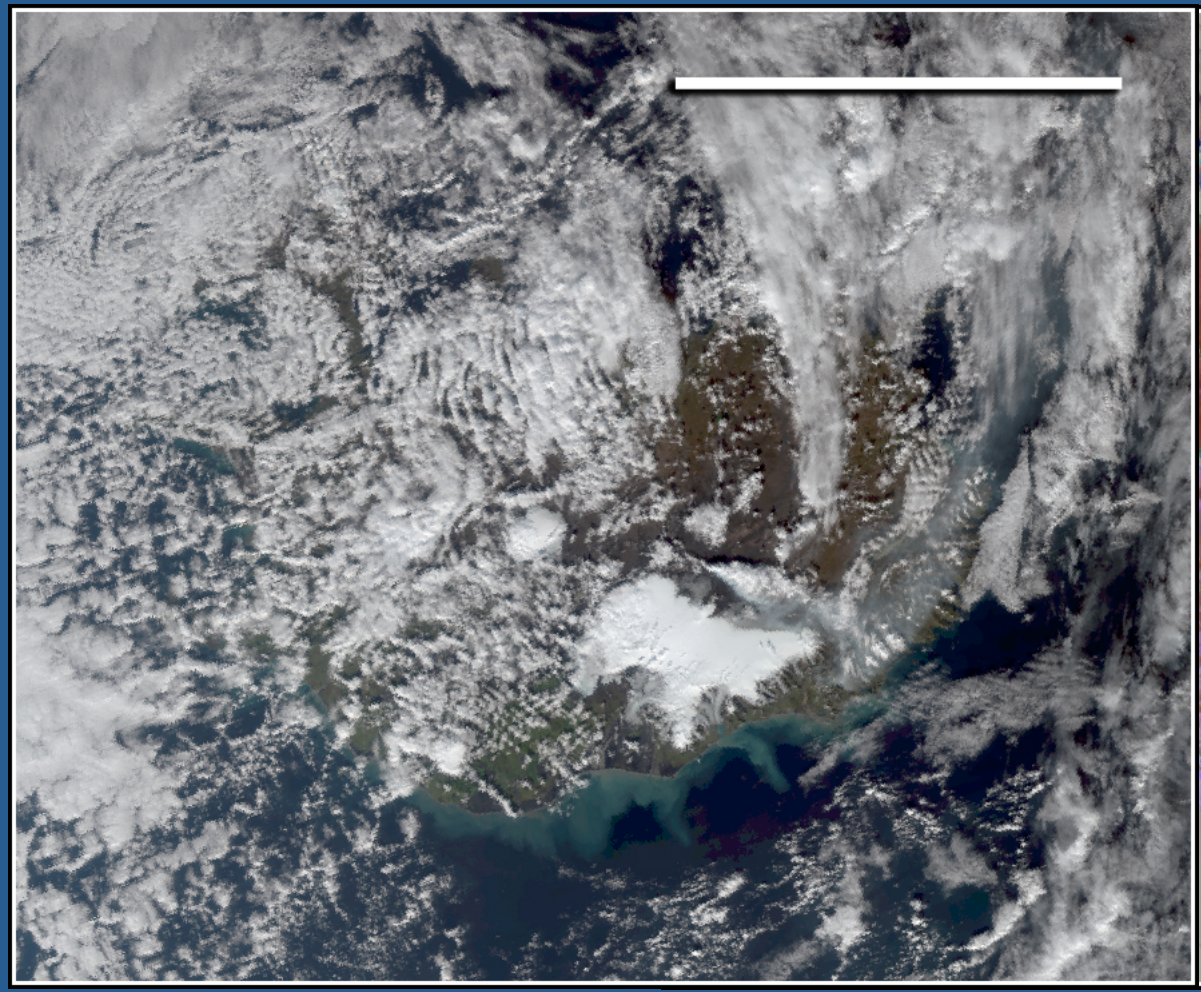

ASTER VNIR Color Composite

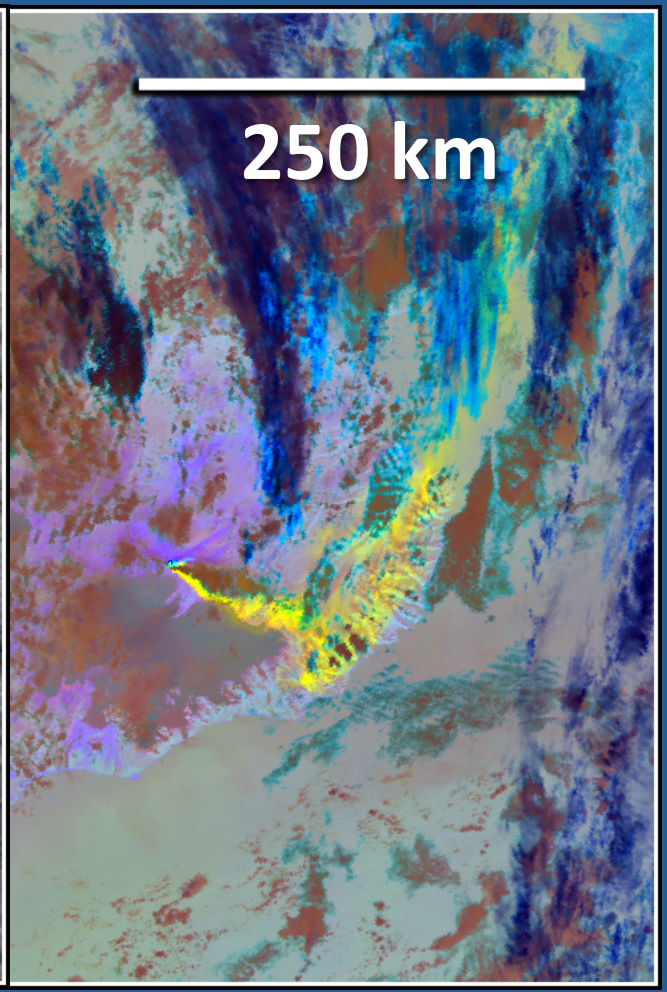



ASTER TIR Color Composite



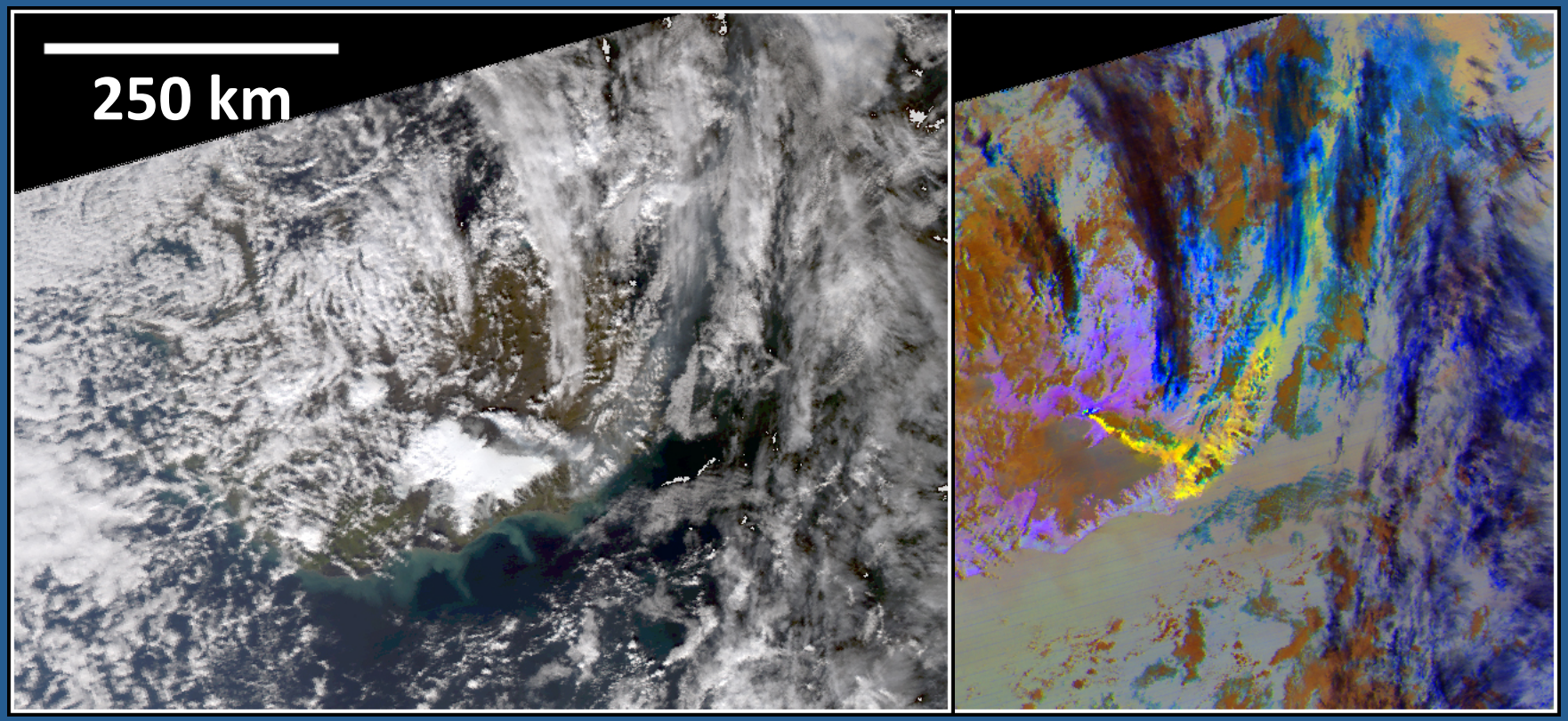





RGB Color Composite

TIR Color Composite

VIIRS
2014-09-23
12:30 UTC



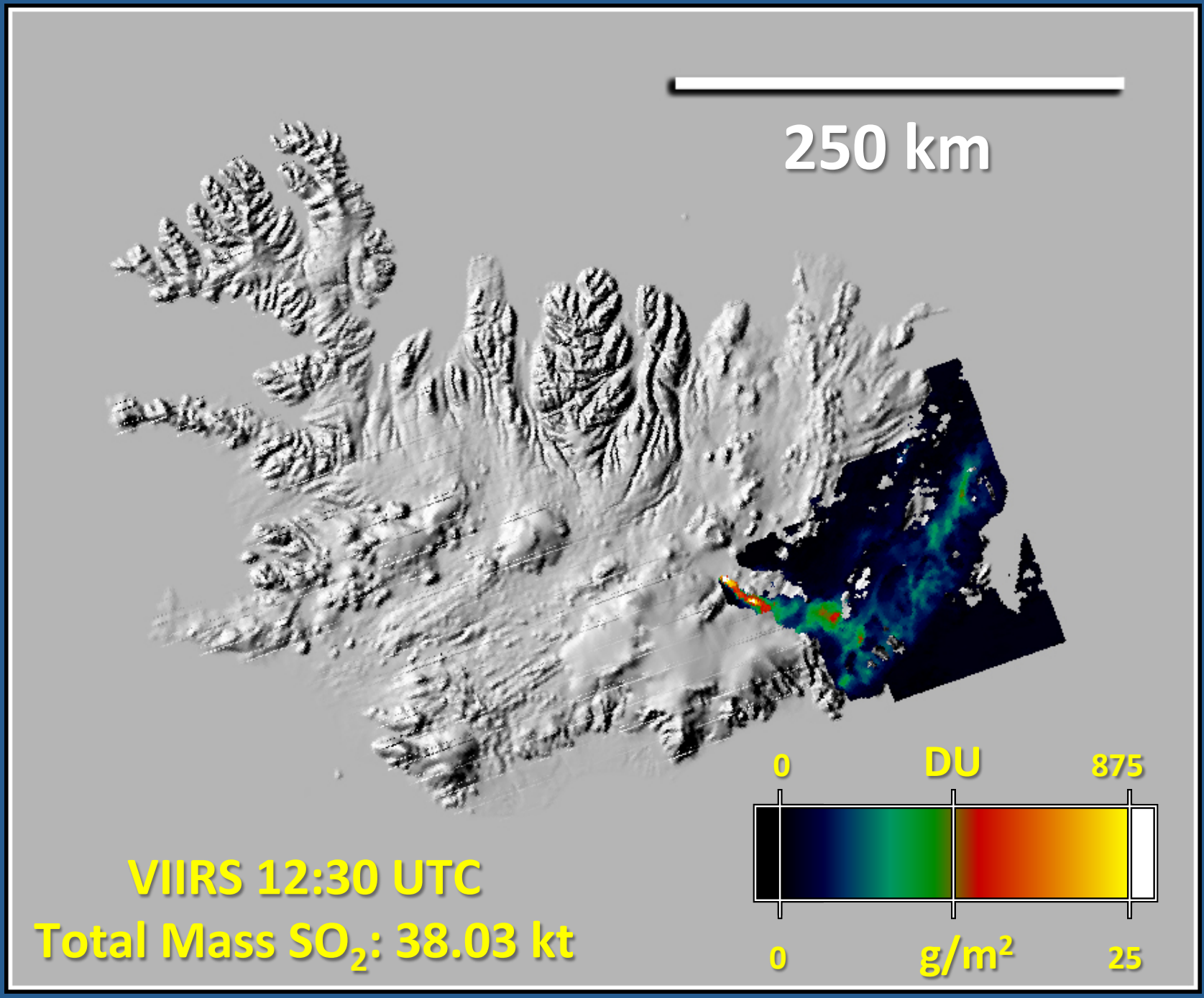

RGB Color Composite

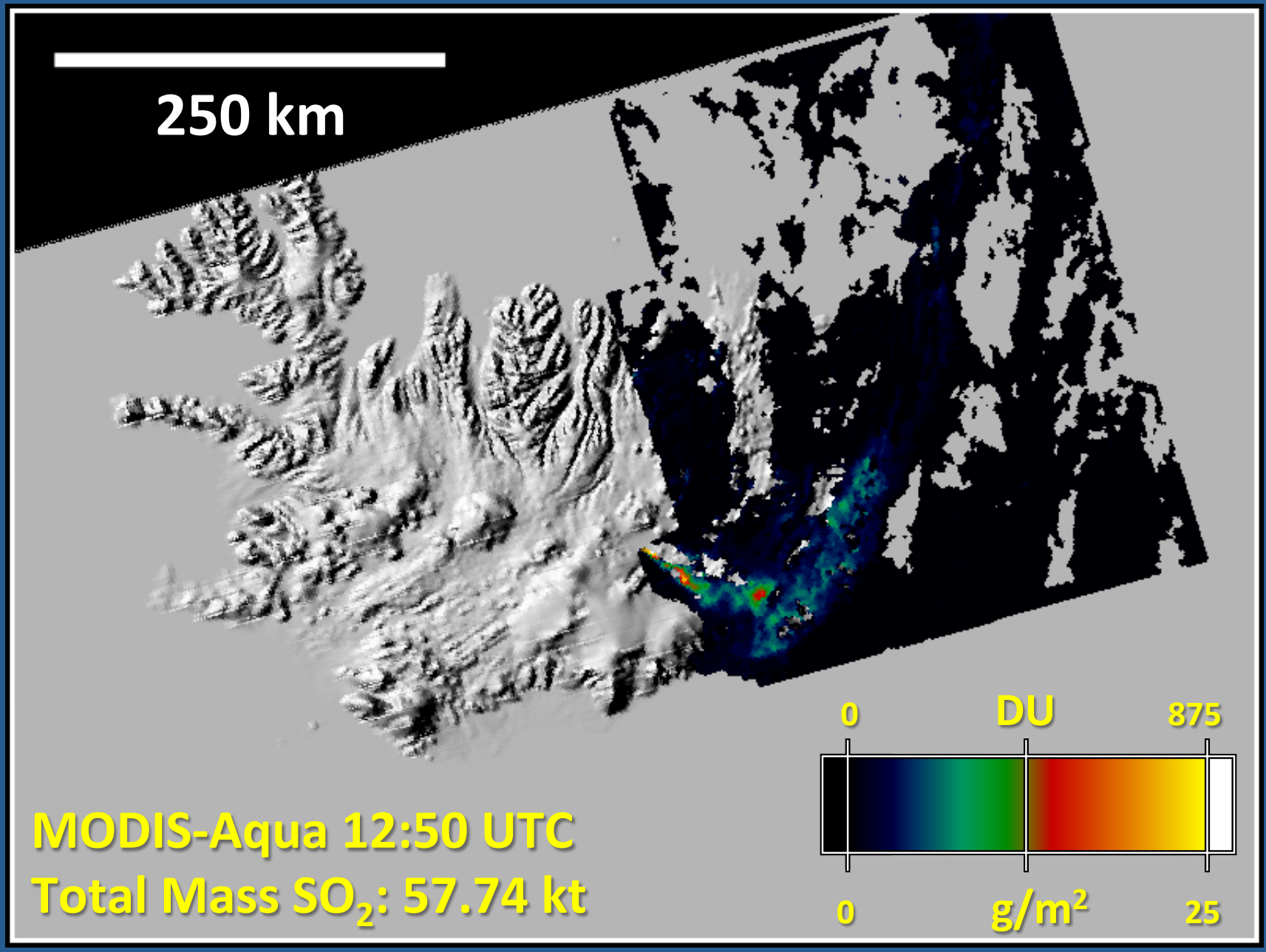
TIR Color Composite

MODIS-Aqua

2014-09-23

12:50 UTC


250 km
0
DU
875
0
g/m²
25
VIIRS 12:30 UTC
Total Mass SO2: 38.03 kt

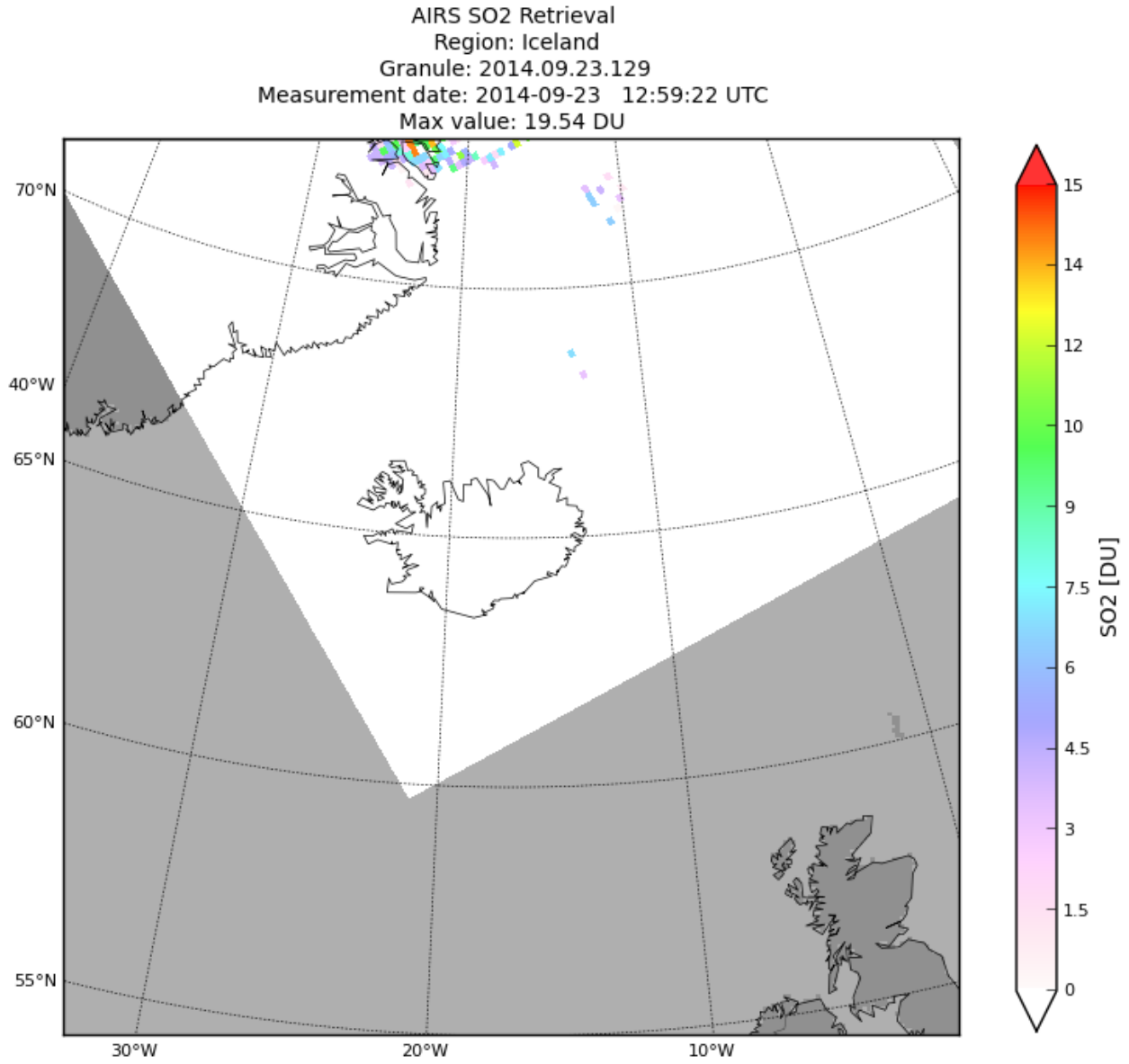

250 km
0
DU
875
0
g/m²
25
MODIS-Aqua 12:50 UTC
Total Mass SO2: 57.74 kt

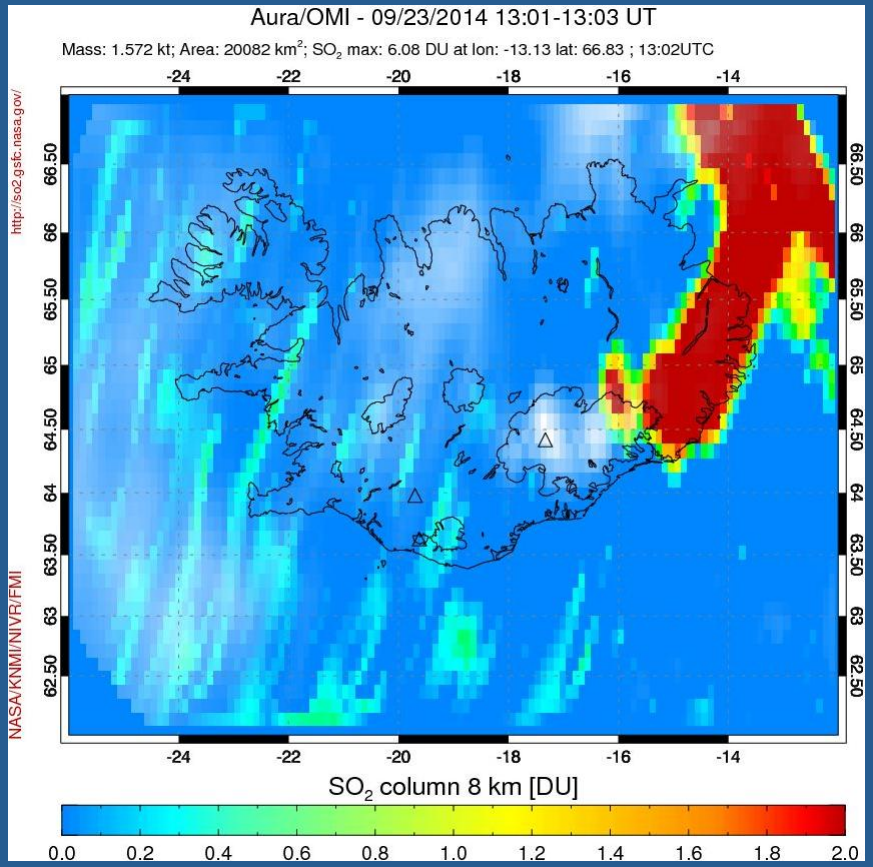
# Bardarbunga Volcano

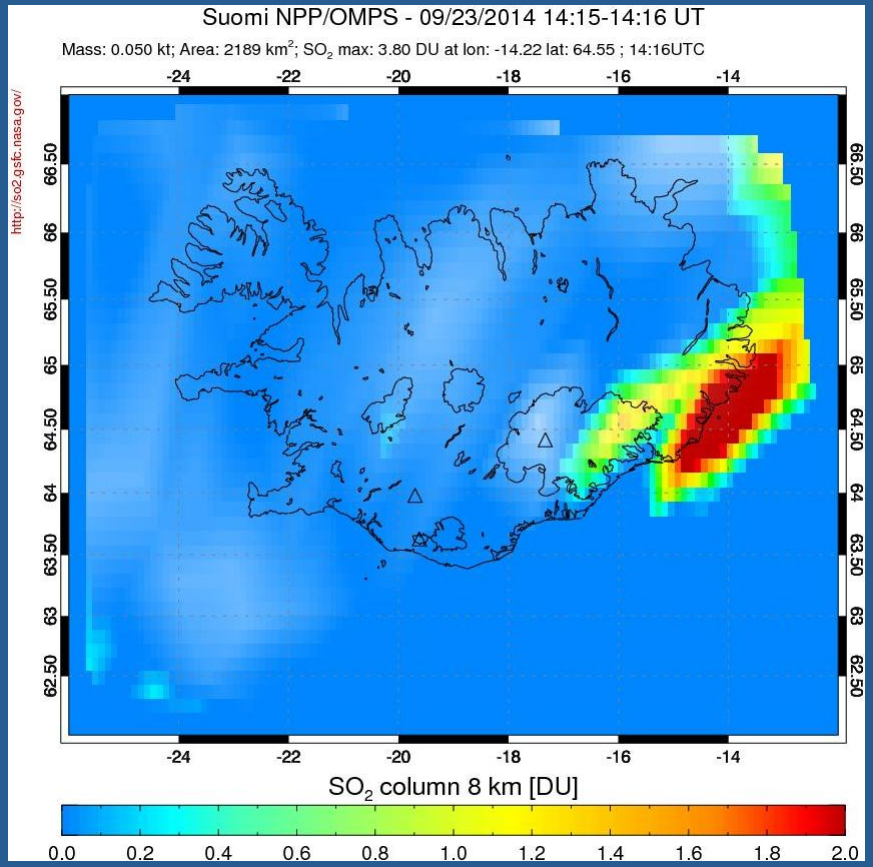
## AIRS Operational $SO_2$ Retrieval

## 2014-09-23 12:59 UTC

## No $SO_2$ Detected at Holuhraun Fissure





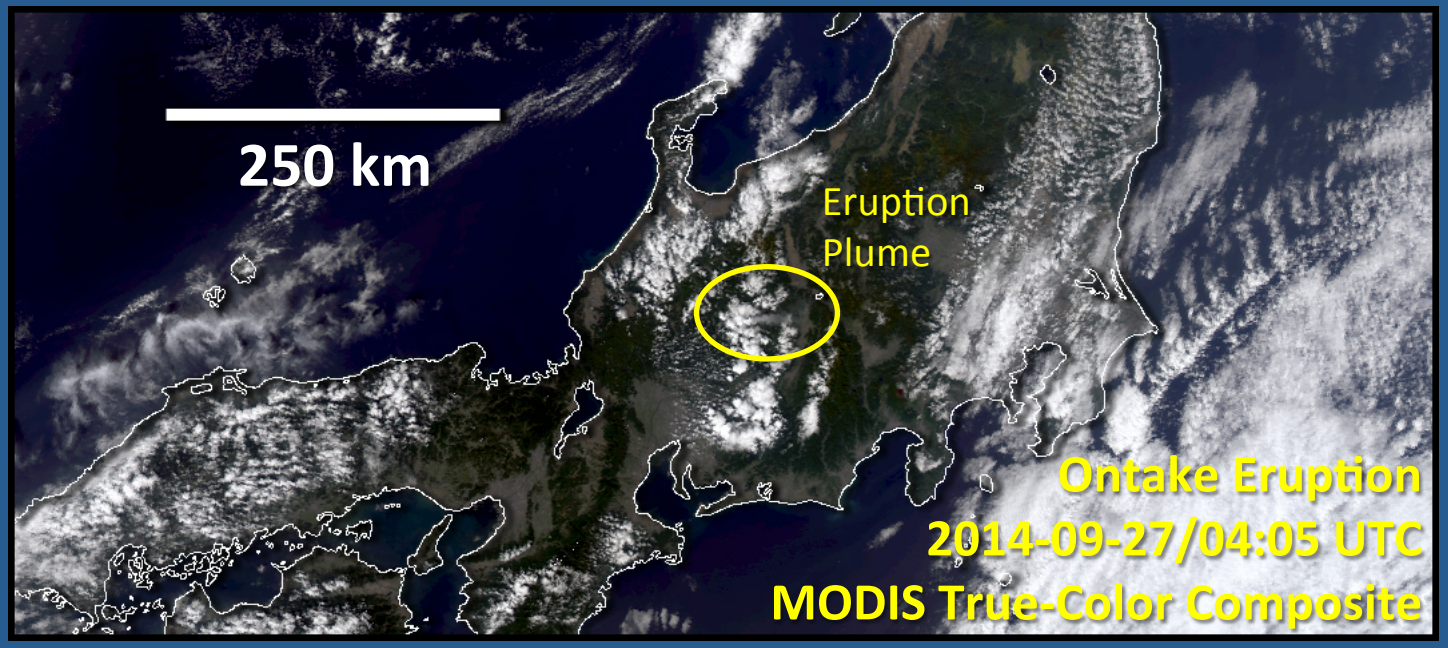

**OMI $SO_2$ Map**
**13:01 – 13:03 UTC**
**Total Mass $SO_2$: 1.572 kt**

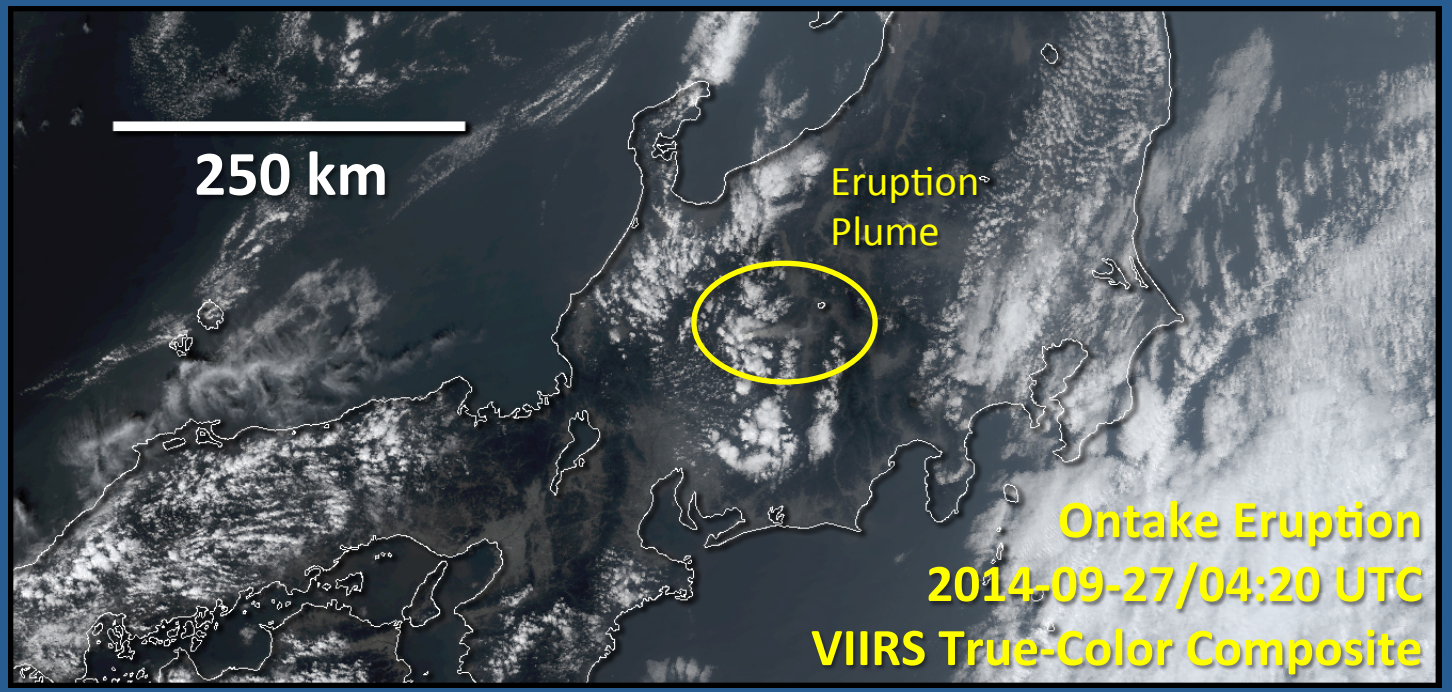
**OMPS $SO_2$ Map**
**14:15 – 14:16 UTC**
**Total Mass $SO_2$: 0.05 kt**

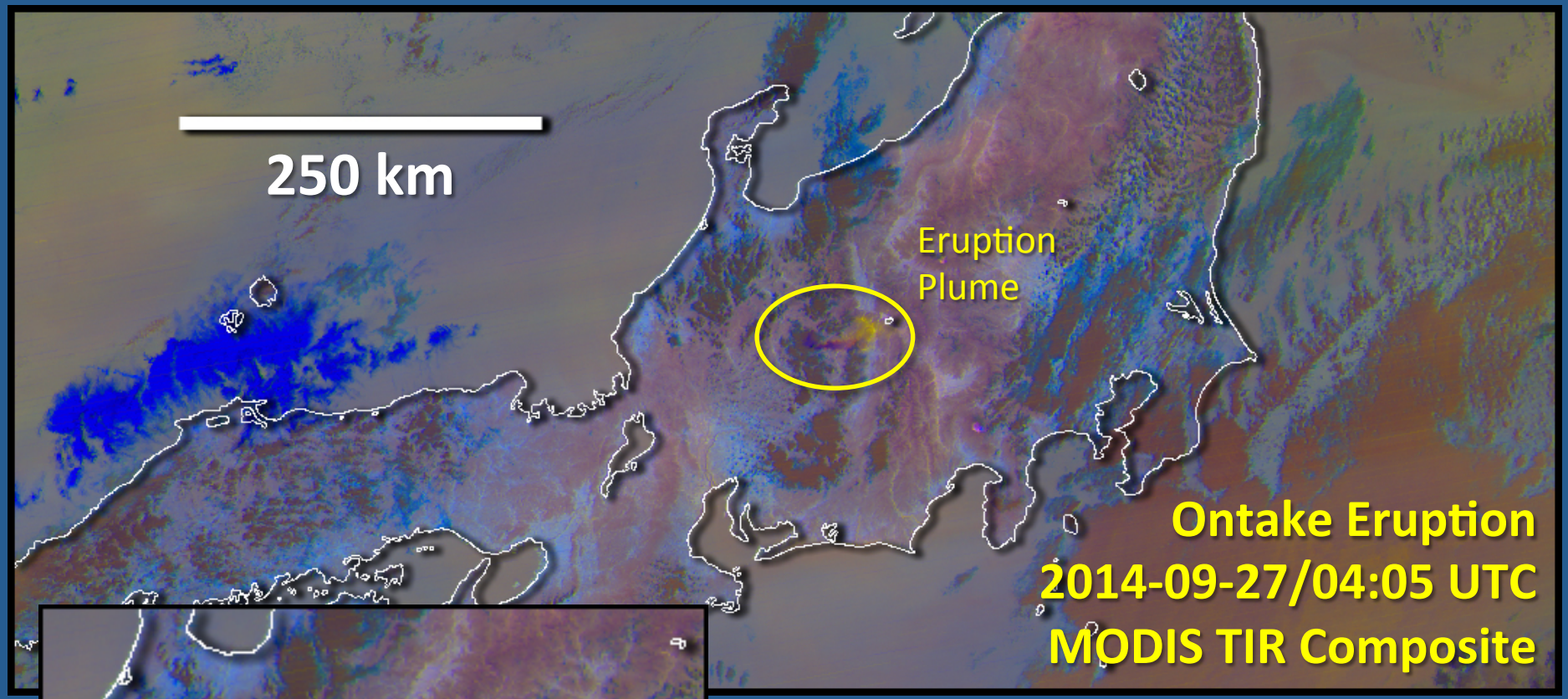


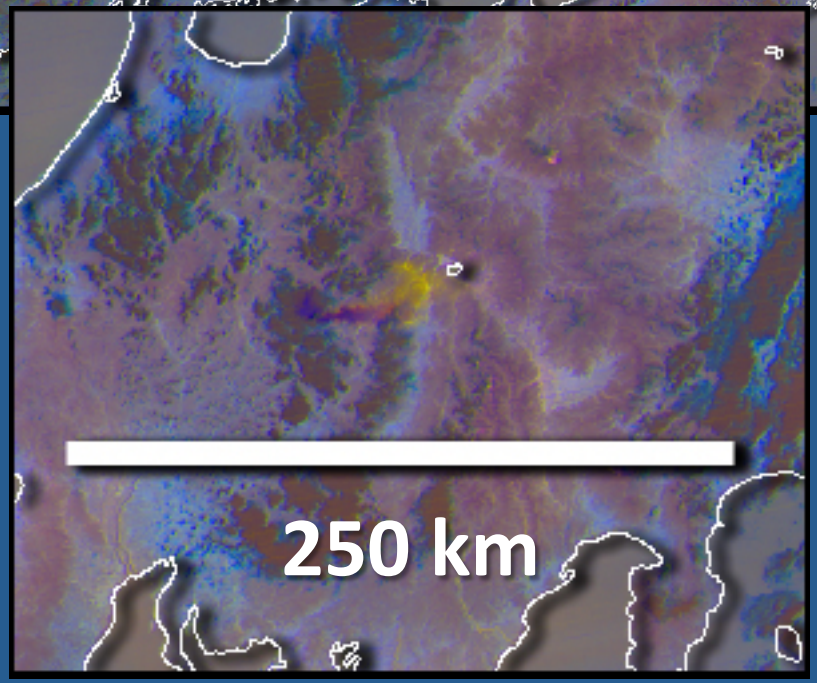
**Ontake-san Eruption, Japan**
**2014-09-27**

- Phreatic Eruption: Interaction of Magma with Water
- Highly-Explosive - Generate Large Volumes of Ash
- 55 Fatalities (as of October 7)


250 km
Eruption
Plume
Ontake Eruption
2014-09-27/04:05 UTC
MODIS True-Color Composite

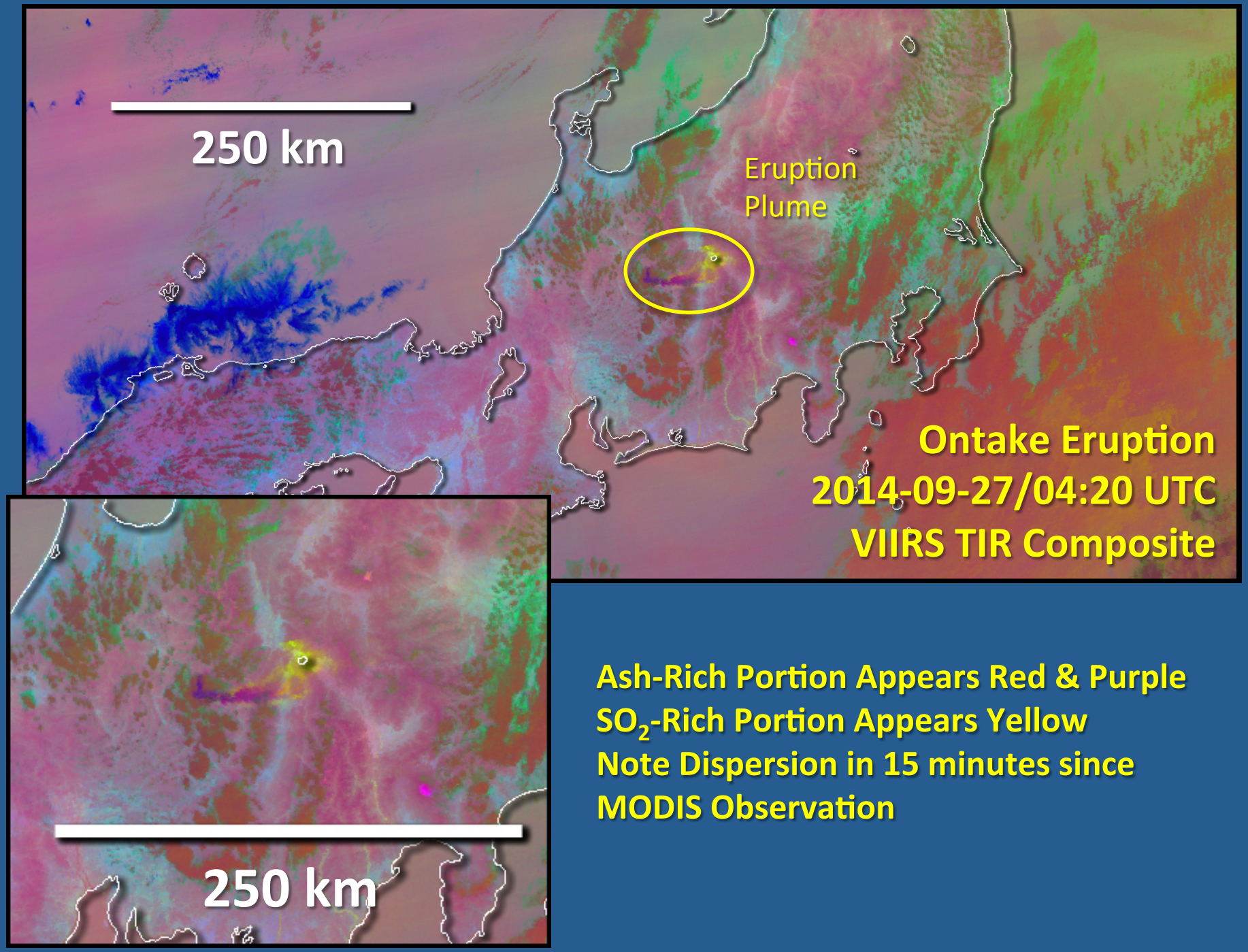

250 km
Eruption
Plume
Ontake Eruption
2014-09-27/04:20 UTC
VIIRS True-Color Composite




Ash-Rich Portion Appears Red & Purple

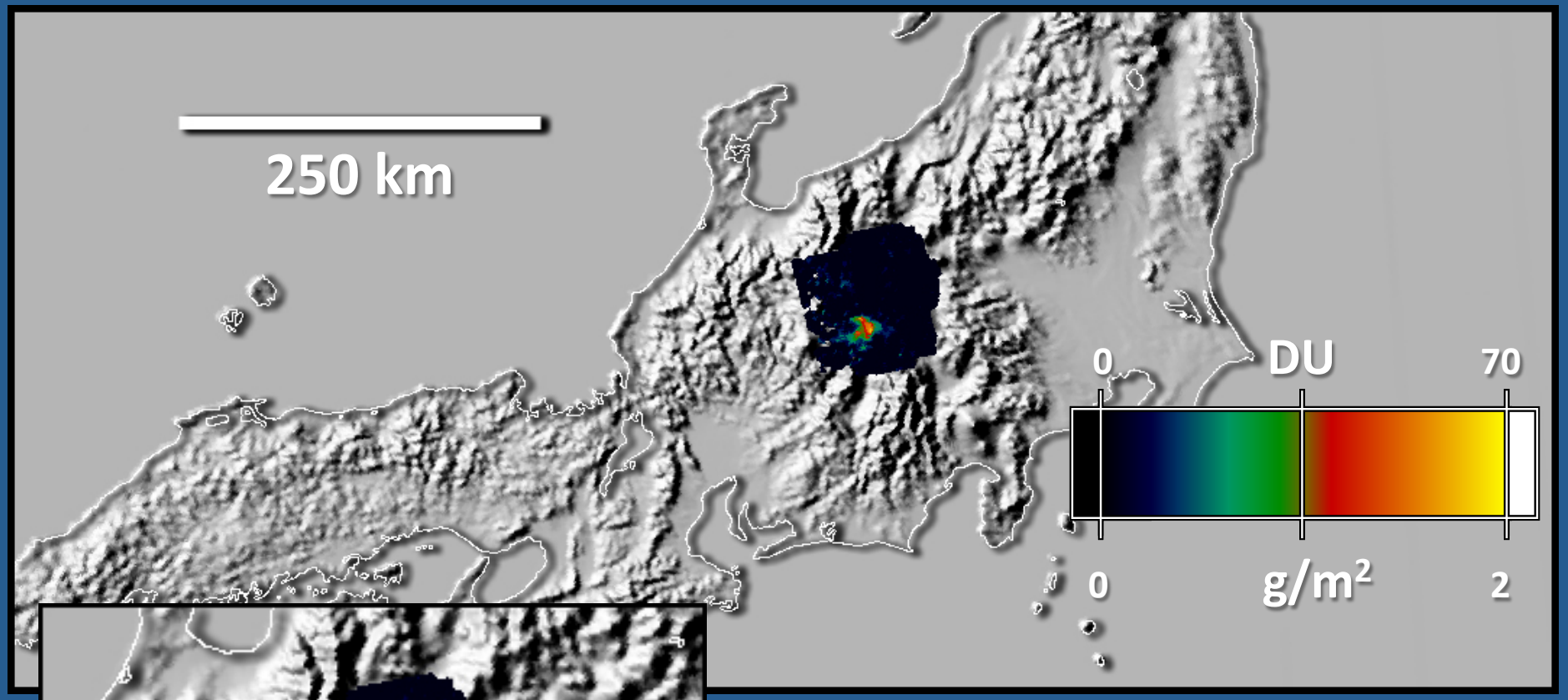
$SO_2$-Rich Portion Appears Yellow

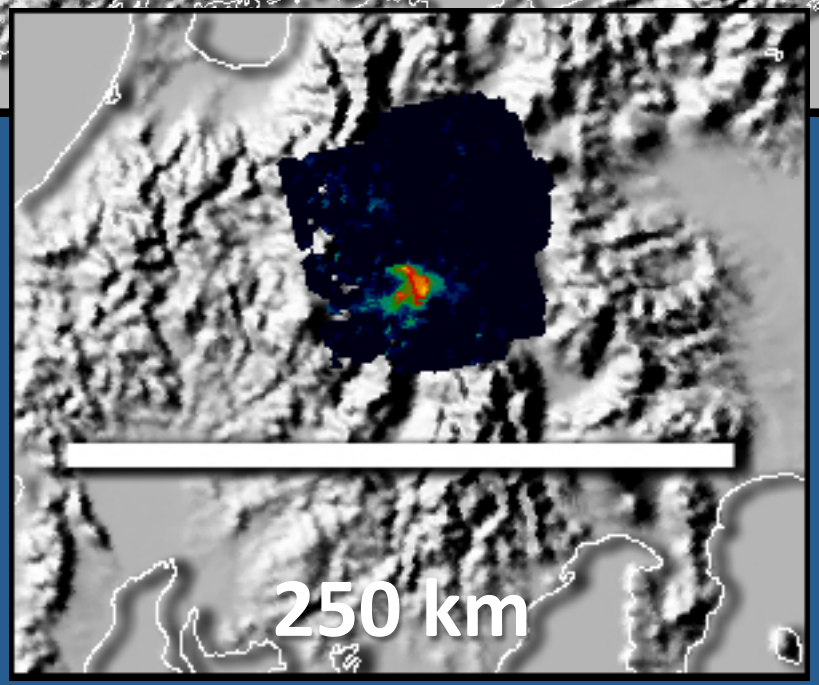



Ash-Rich Portion Appears Red & Purple

$SO_2$-Rich Portion Appears Yellow

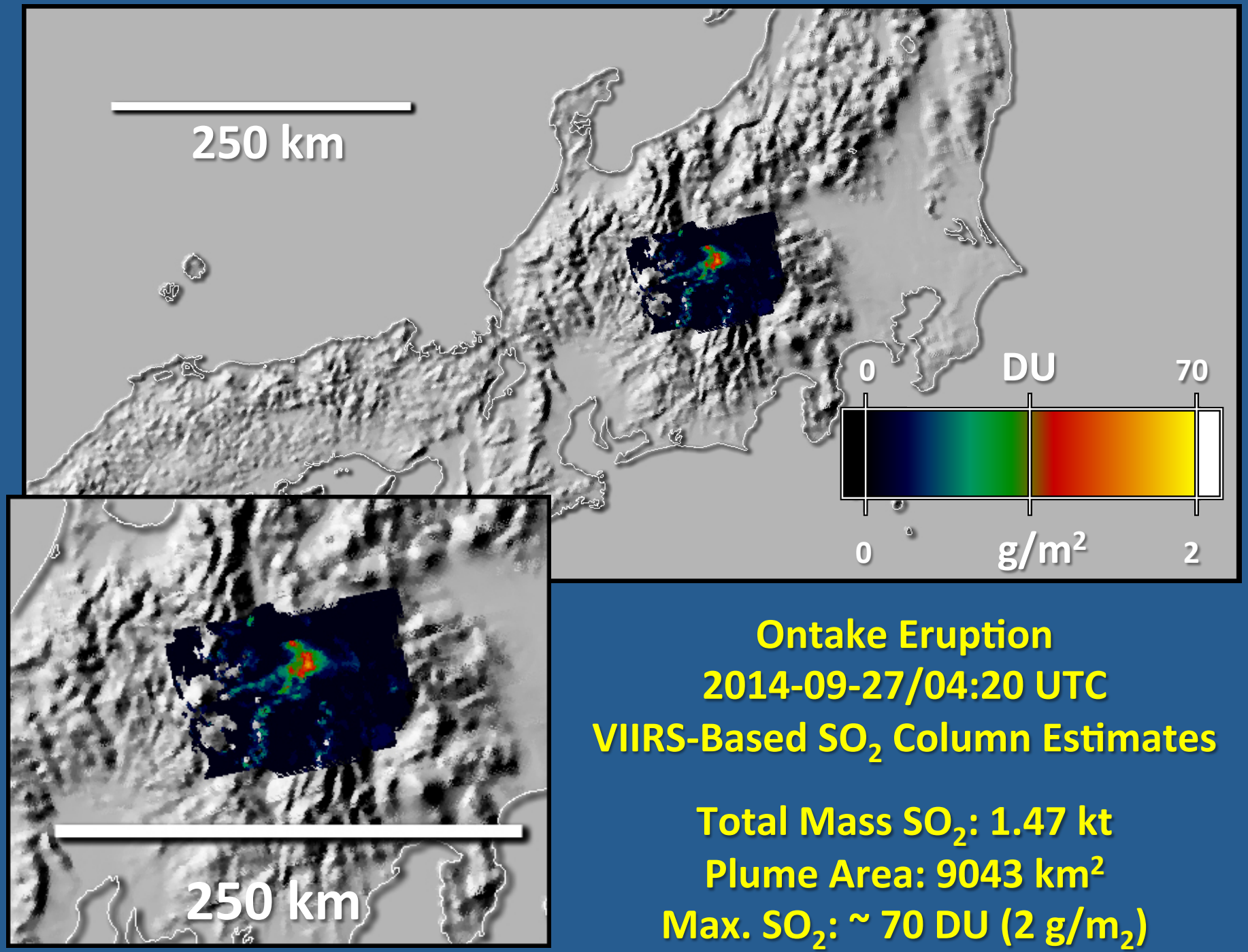
Note Dispersion in 15 minutes since MODIS Observation




**Ontake Eruption**
**2014-09-27/04:05 UTC**
**MODIS-Based $SO_2$ Column Estimates**

**Total Mass $SO_2$: 1.074 kt**
**Plume Area: 8077 $km^2$**
**Max. $SO_2$: ~ 70 DU (2 $g/m^2$)**

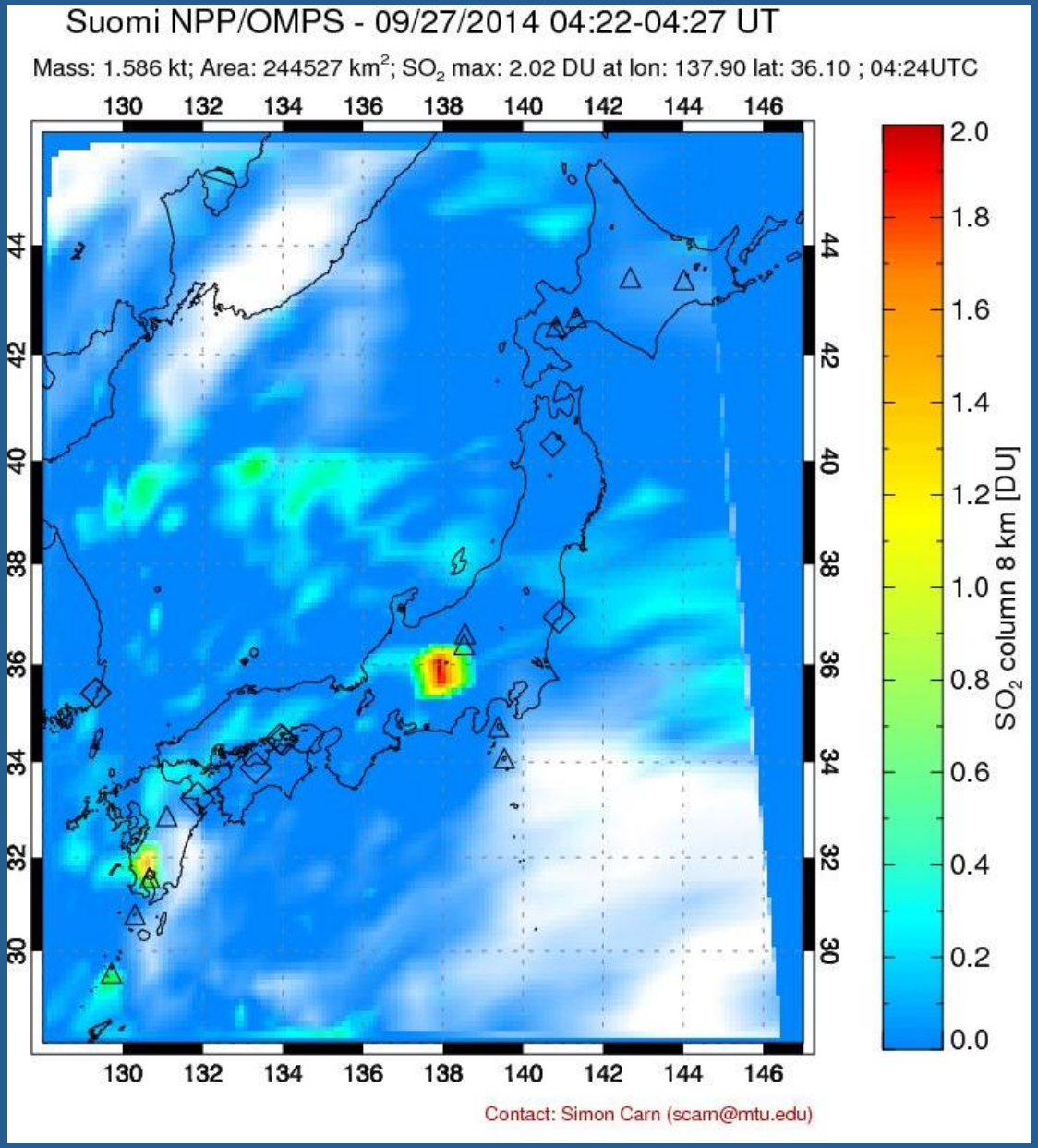



**Ontake Eruption**
**2014-09-27/04:20 UTC**
**VIIRS-Based $SO_2$ Column Estimates**

**Total Mass $SO_2$: 1.47 kt**
**Plume Area: 9043 $km^2$**
**Max. $SO_2$: ~ 70 DU (2 $g/m_2$)**

**Ontake Eruption**
**2014-09-27/04:24 UTC**
**OMPS-Based $SO_2$ Column Estimates**

**Total Mass $SO_2$: 1.586 kt**
**Plume Area: 244,527 $km^2$**
**Max. $SO_2$: 2.02 DU**



| Bardarbunga | 2014-09-05 | |
|---|---|---|
| MODIS-Aqua | 248.5 kt | 03:25 UTC |
| VIIRS | 177.3 kt* | 04:55 UTC |
| | | |
| Bardarbunga | 2014-09-23 | |
| VIIRS | 38.03 kt | 12:30 UTC |
| MODIS-Aqua | 57.74 kt | 12:50 UTC |
| OMI | 1.572 kt | 13:02 UTC |
| OMPS | 0.05 kt | 14:14 UTC |
| | | |
| Ontake | 2014-09-27 | |
| MODIS-Aqua | 1.074 kt | 04:25 UTC |
| VIIRS | 1.47 kt | 04:20 UTC |
| OMPS | 1.59 kt | 04:24 UTC |

**High-Altitude Plumes (e.g. Ontake) are Advantageous for Both UV- and TIR-Based Retrieval Procedures!**

**Thanks for Your Attention.**

**Any Questions?**