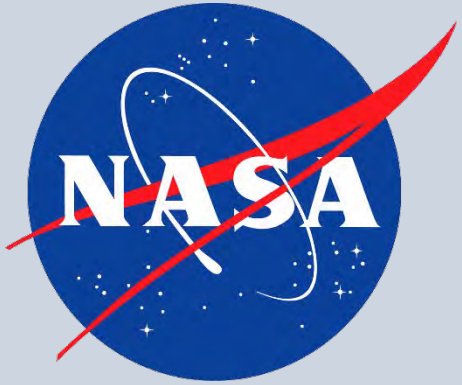
# TIR-Based Volcanic $SO_2$ Science Products for Terra, Aqua, and Suomi NPP

Vincent J. Realmuto,
Jet Propulsion Laboratory,
California Institute of Technology



## Objectives

- Develop a prototype system for the automated detection and mapping of volcanic $SO_2$ plumes based on multispectral TIR image data
- Validate system and data products through analysis of MODIS, VIIRS, and ASTER data records for the long-lived (29 August 2014 – 27 February 2015) eruption of Bardarbunga Volcano, Iceland
- Prepare and submit Algorithm Theoretical Basis Documents (ATBD) to MODIS, VIIRS, and ASTER Projects for future inclusion of plume detection and mapping system in corresponding Product Generation Systems (PGS)

## Input Data Products

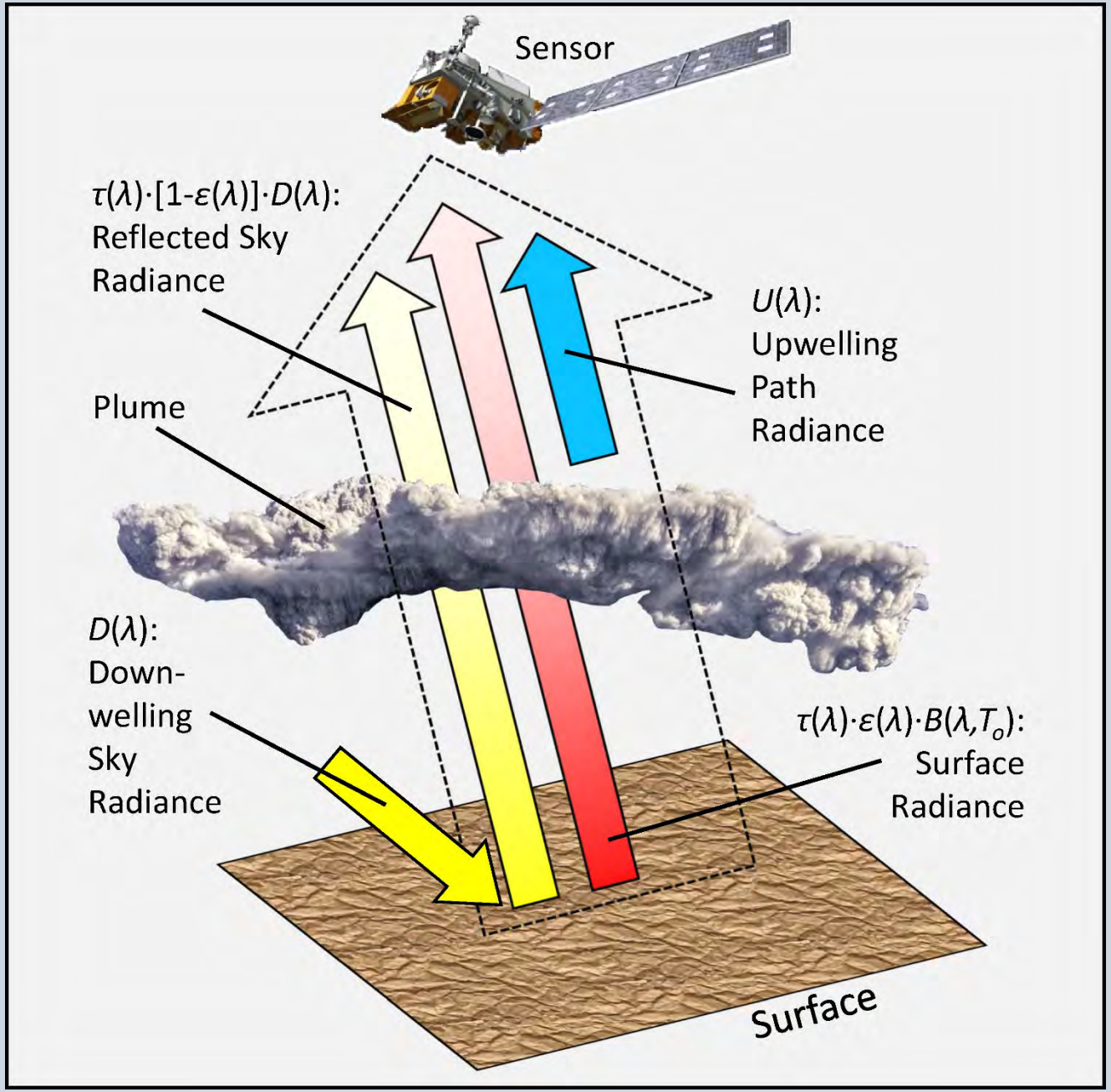
- L1 radiance data from MODIS, SNPP-VIIRS, and ASTER
- Emissivity data base (ASTER GED, MODIS MOD21, VIIRS VNP21)
- Atmospheric profiles (radiosonde, AIRS, MODIS, NCEP, MERRA-2)
- Digital Elevation Models
- Future Access to NOAA-20 VIIRS

# TIR Remote Sensing of Volcanic Plumes

**Detect plumes through transmission [t(λ)] - the attenuation of surface radiance passing through the plume enroute to the sensor**

**The observed radiance (outlined arrow) includes the surface radiance (red arrow), reflected sky radiance (yellow arrow), and upwelling path radiance (blue arrow)**

**Transmission, sky radiance [D(λ)], and path radiance [U(λ)] are estimated through radiative transfer (RT) modeling**

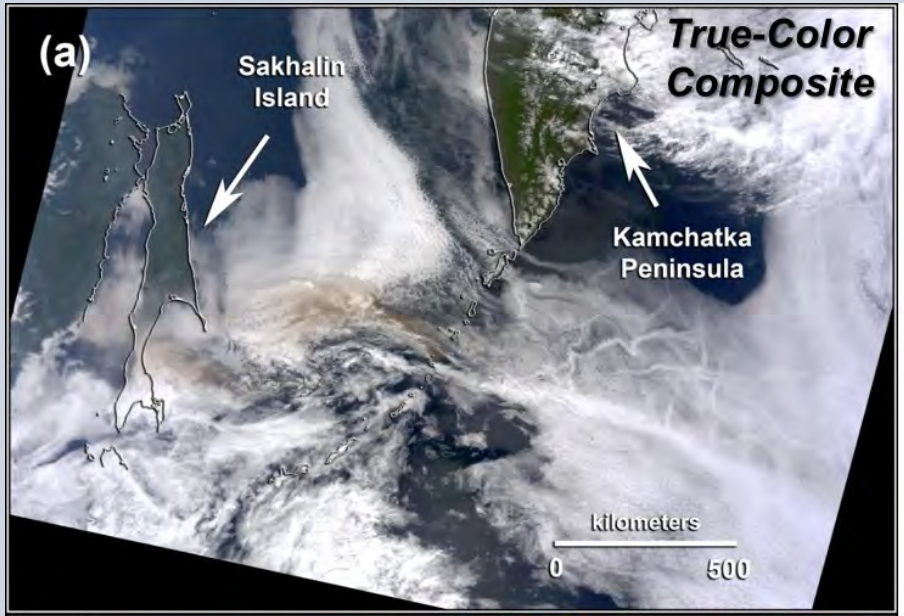


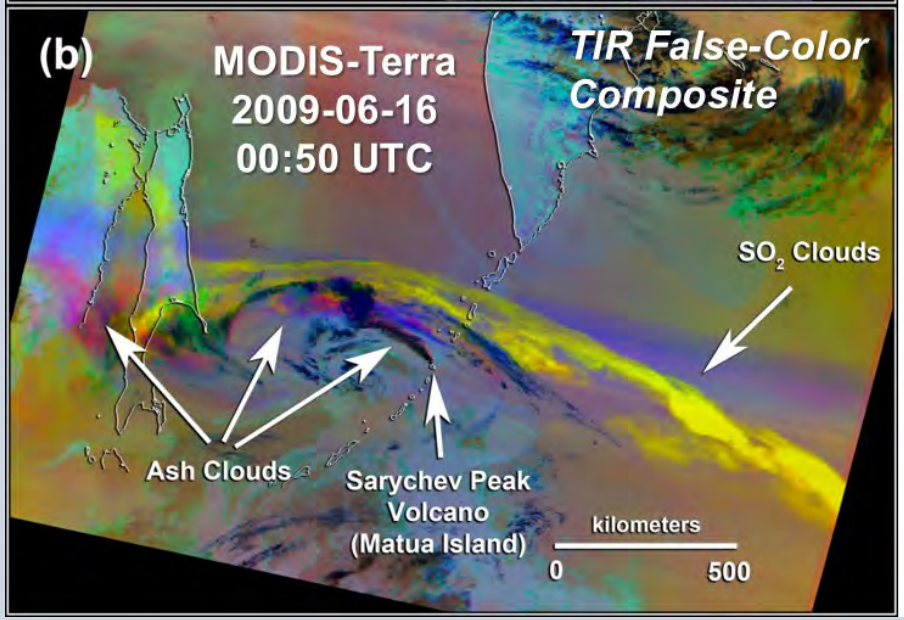
# MODIS-Terra
# Sarychev Peak Volcano
# 16 June 2009 (00:50 UTC)

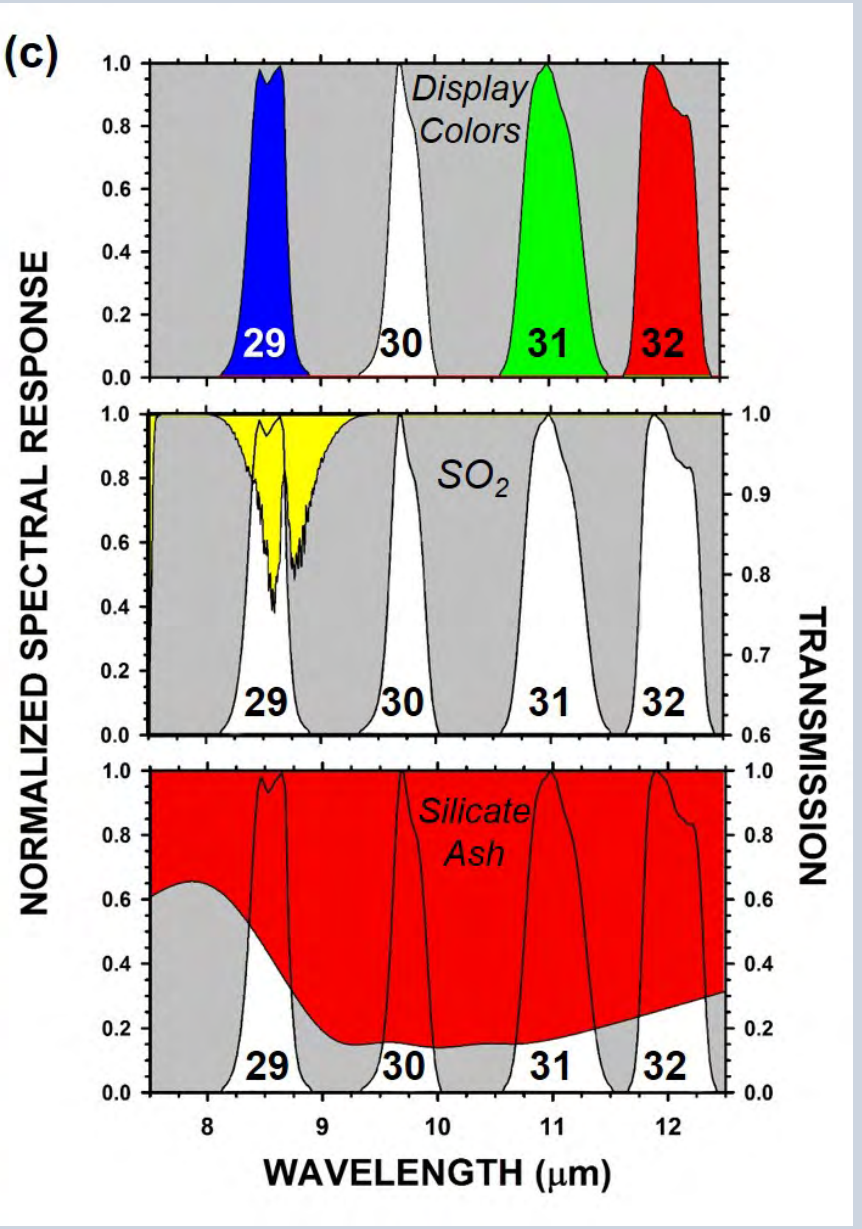
(a) True-color composite. Volcanic plumes and meteor-ological clouds have similar appearance at visible wavelengths

(b) False-color composite of TIR data from Channels 32, 31, and 29, displayed in red, green, and blue. $SO_2$ plumes appear yellow, while the display colors of ash plumes range between red and magenta

(c) Transmission spectra of $SO_2$ (middle) and silicate ash (bottom), superimposed on the spectral response of MODIS Channels 29, 30, 31, and 32



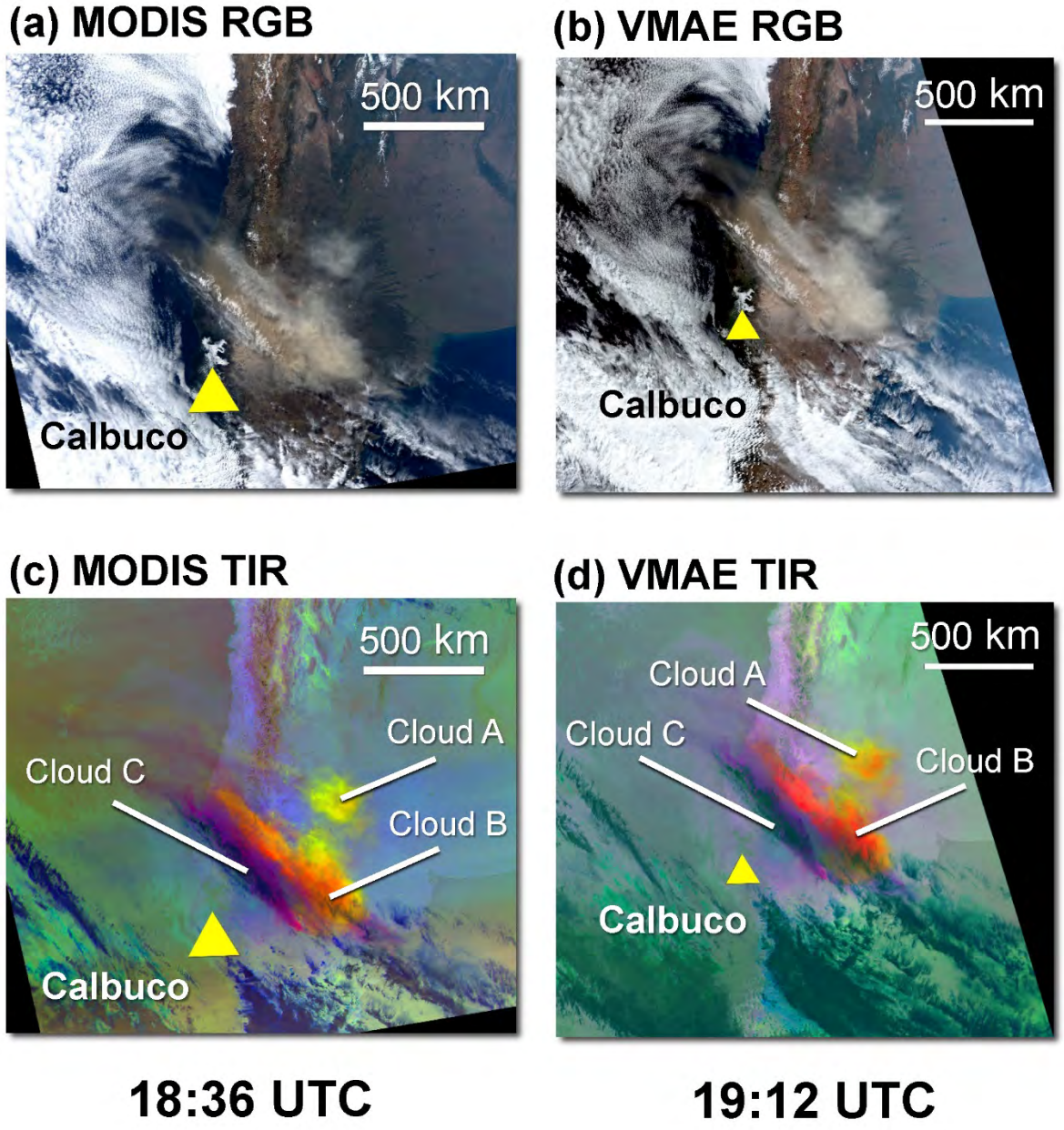
# Calbuco Volcano (Chile): 2015-04-23
# 18:35 UTC (Aqua) / 19:12 UTC (SNPP)

**MODIS/VMAE TIR provides spatial context + coarse spectral information:**

- **Cloud A - Dominated by $SO_2$ (yellow display color)**
- **Cloud B - Mixture of $SO_2$ and ash (orange display color)**
- **Cloud C – Mixture of ash and ice crystals (purple display color)**

**AIRS/CRIS Spectroscopy provides fine spectral information:**

- **Enables unique identification of plume components**
- **Ash features highlighted in red**
- **$SO_2$ features highlighted in yellow**



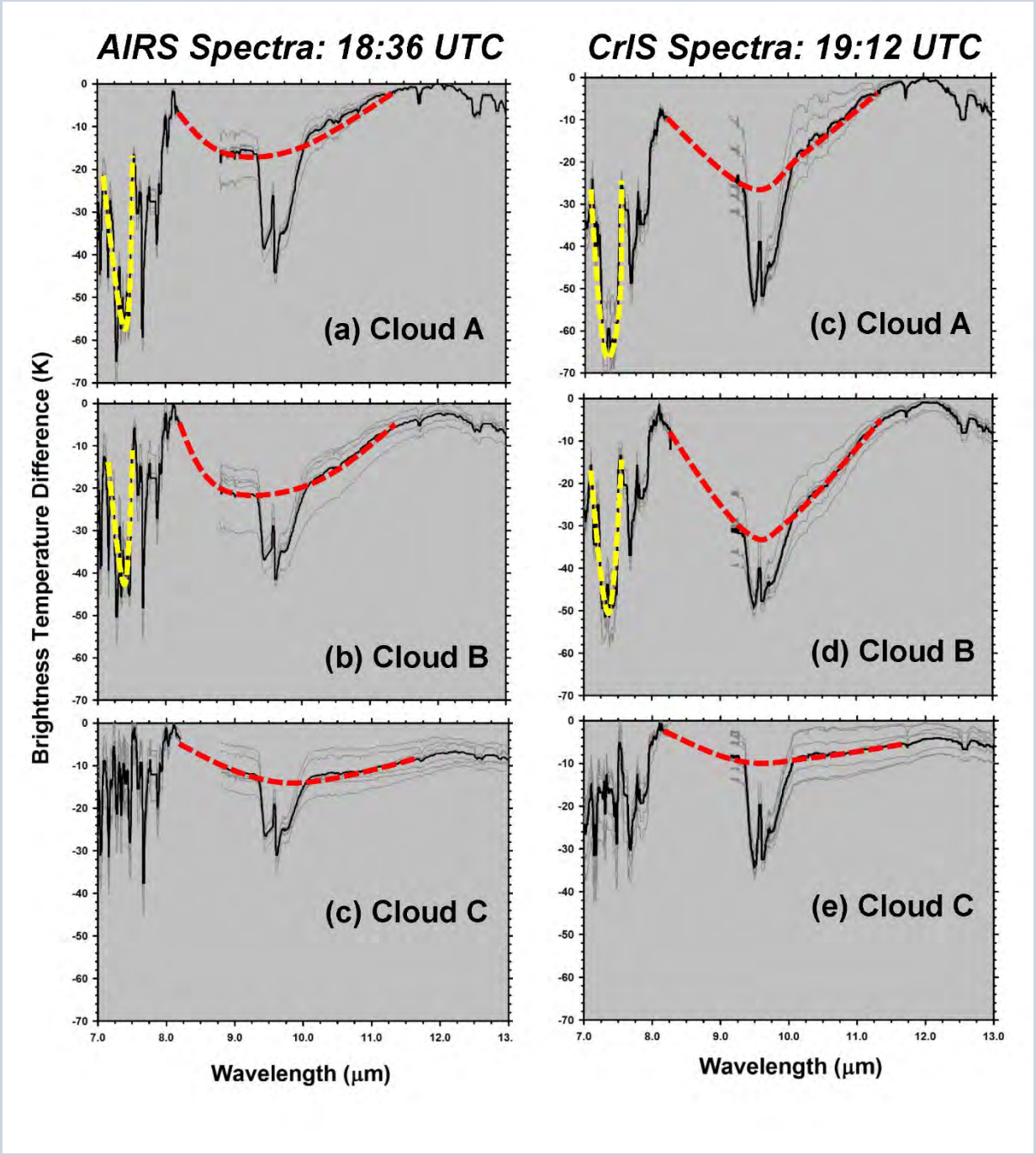
# Calbuco Volcano (Chile): 2015-04-23 18:35 UTC (Aqua) / 19:12 UTC (SNPP)

**MODIS/VMAE TIR provides spatial context + coarse spectral information:**

- **Cloud A - Dominated by $SO_2$ (yellow display color)**
- **Cloud B - Mixture of $SO_2$ and ash (orange display color)**
- **Cloud C – Mixture of ash and ice crystals (purple display color)**

**AIRS/CRIS Spectroscopy provides fine spectral information:**

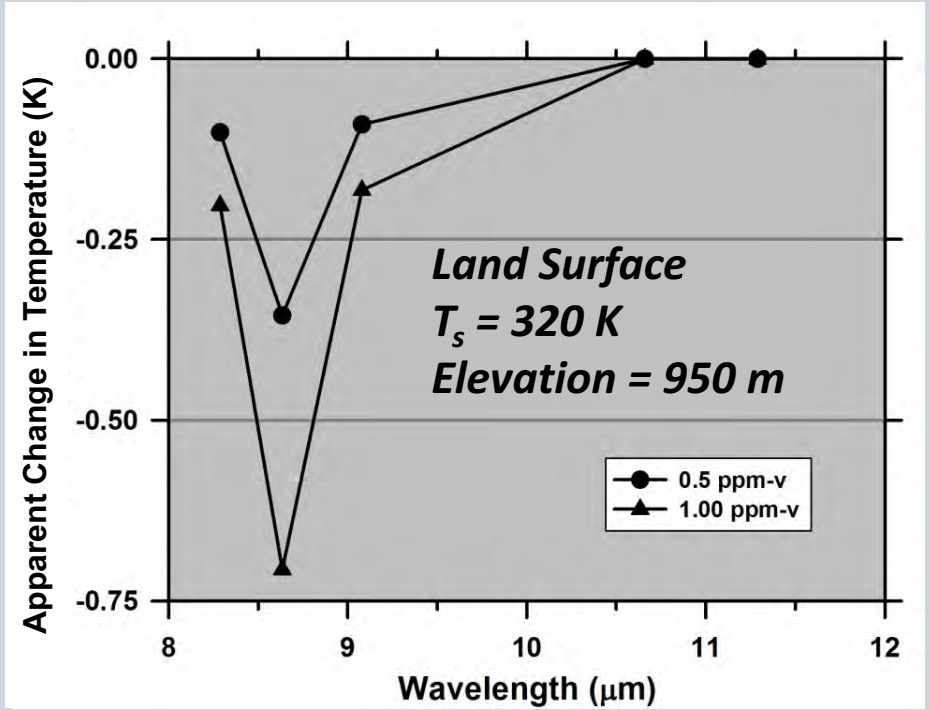
- **Enables unique identification of plume components**
- **Ash features highlighted in red**
- **$SO_2$ features highlighted in yellow**

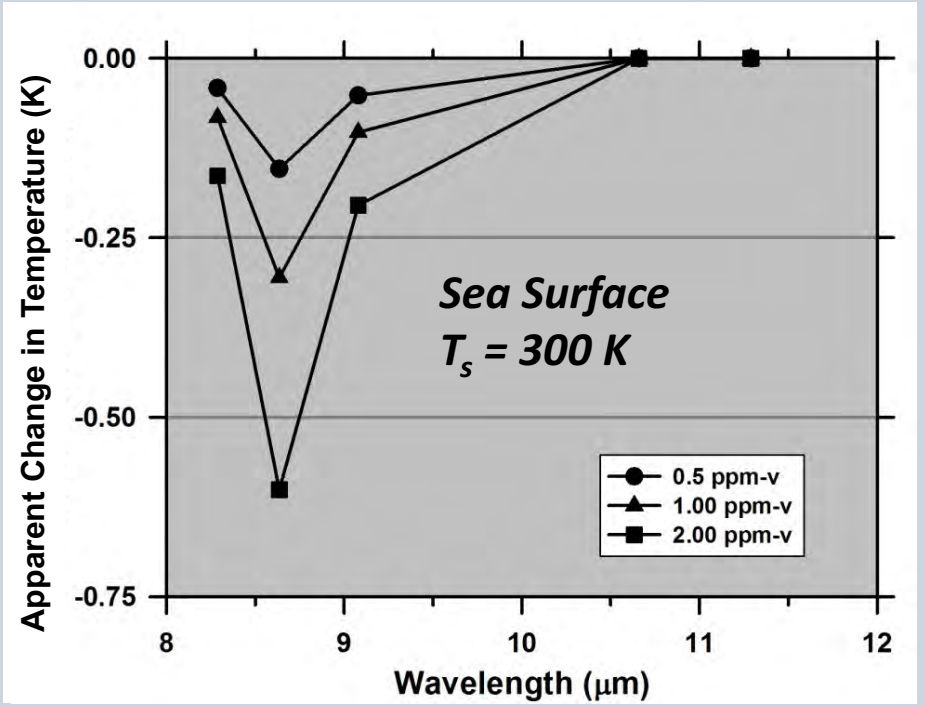


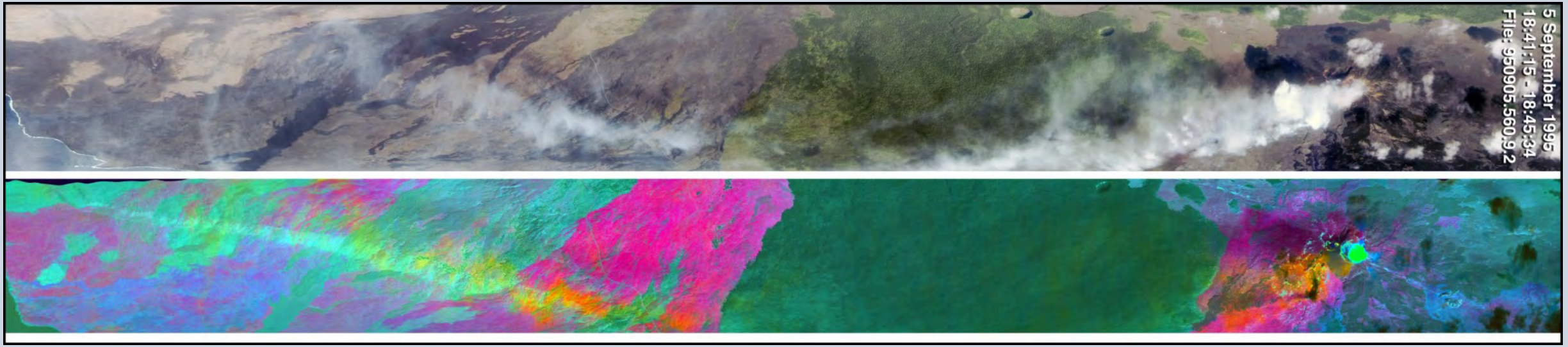
# Effects of Temperature and Emissivity

# Sensitivity to Gas vs. Temperature Contrast

- **Detection Threshold: Apparent Change in Temperature Must Exceed NE∆T of Instrument**
- **0.5 K: Realistic In-Flight NE∆T for ASTER or MODIS**
- **Land vs. Sea Surface: 20 K Decrease in Surface Temperature = 2X Increase in Detection Threshold**



# Retrieval of Surface Temperature and Gas Concentration

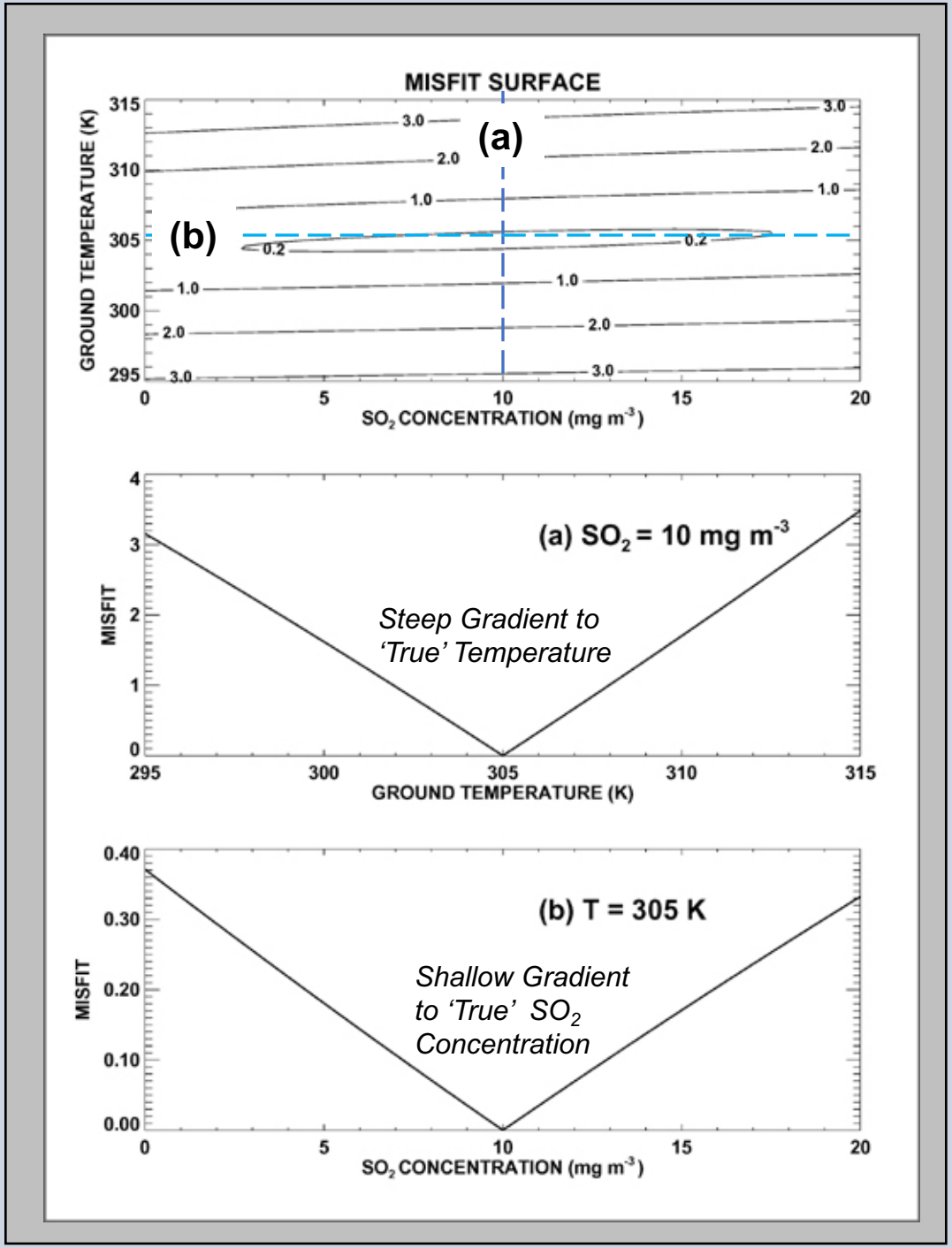
**Temperature is Well-Constrained by TIR Radiance Measurements, Relative to the Constraint on Gas Concentration**

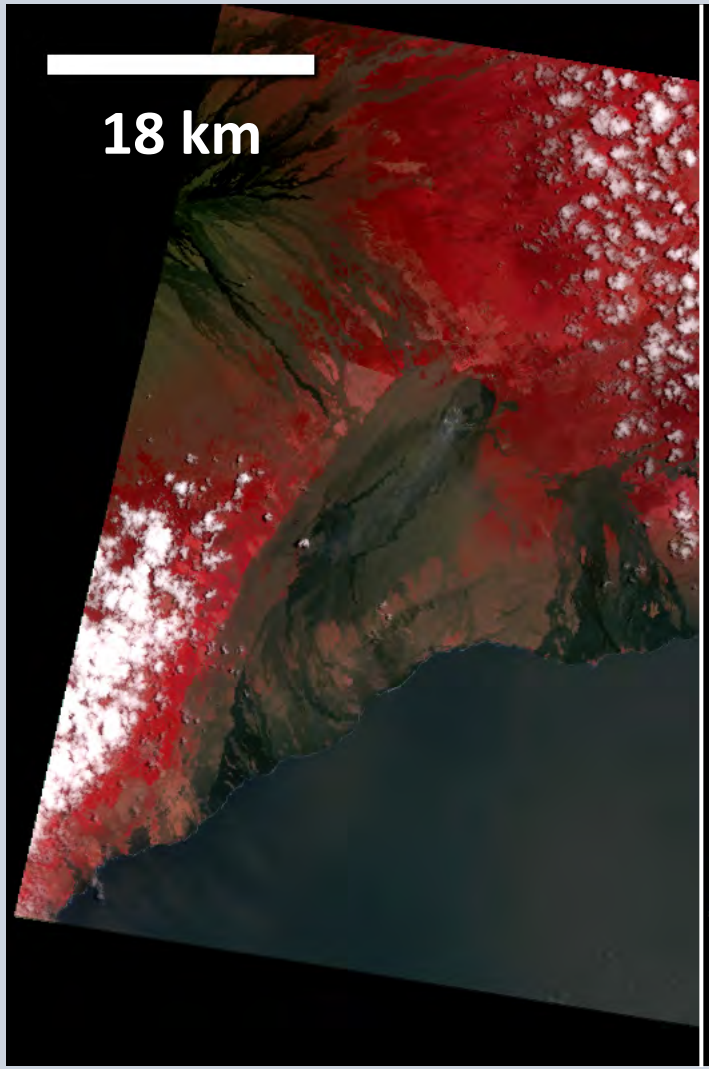
**Simultaneous Retrieval of Temperature and Gas Concentration is Difficult:**

- **Misfit Surface Resembles Broad Valley ("Hard Taco Shell")**
- **Rapid Convergence on Temperature Estimate**
- **Little to No Convergence on Concentration Estimate**

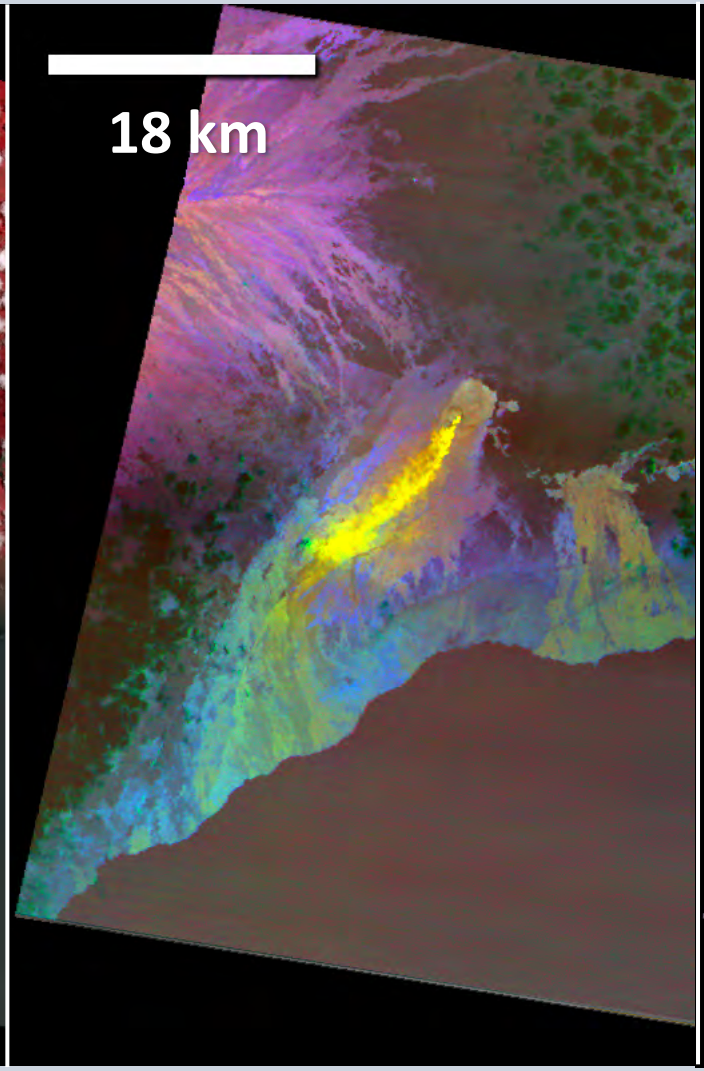
**Cascading (Serial) Retrieval is a Better Approach**

- **Estimate Surface Temperature**
- **Estimate Gas Concentration**

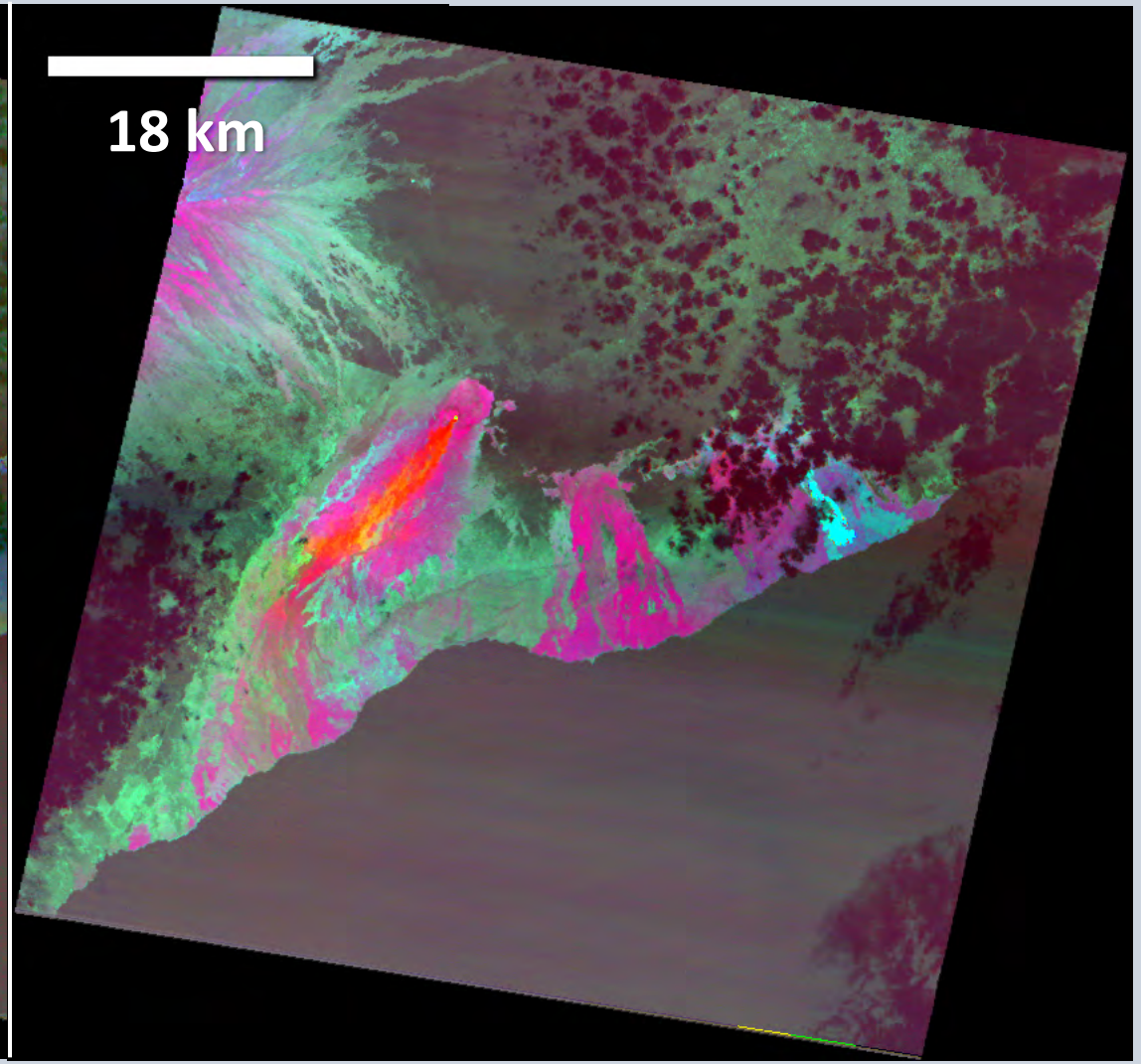





a) False-color composite of ASTER VNIR data




b) False-color composite of TIR data designed to detect $SO_2$ absorption. $SO_2$ plume appears in yellow




c) False-color composite of TIR data designed to accentuate emissivity variations within lava flows. The spectral variations in emissivity overlap the $SO_2$ absorption

# Surface Emissivity is a Confounding Factor for $SO_2$ Detection

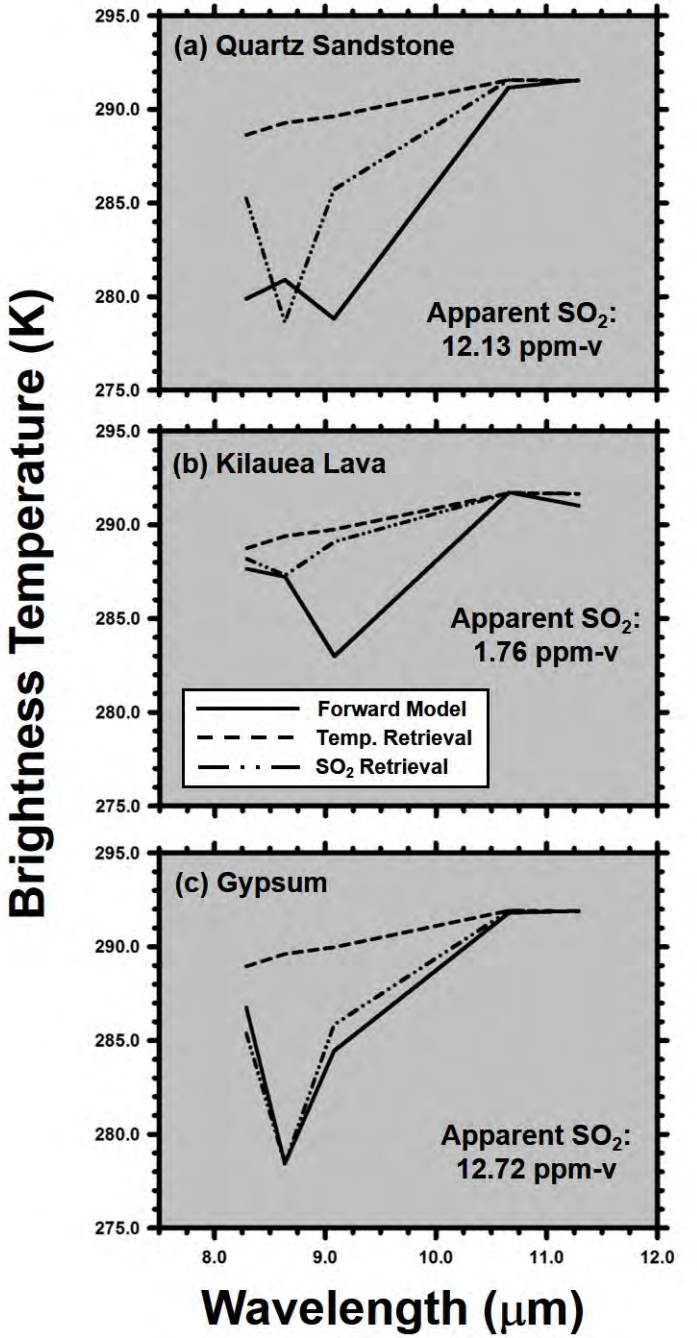
As a rule, the assumption of Blackbody emissivity for exposed (non-vegetated) surfaces will lead to false detections of $SO_2$

Solid Lines: Model spectra generated for $SO_2$-free atmospheric profiles over simulated surface compositions of (a) quartz sand-stone, (b) pahoehoe lava from Kilauea Volcano, and (c) gypsum

Dashed Lines: Attempts to fit the model spectra, assuming the surfaces are Blackbodies (emissivity = 1), by varying only surface temperature fail

Broken Lines: The fit improves if $SO_2$ is introduced as a free parameter, with the penalty of false, or apparent, $SO_2$ detections

The false detections are largest for sandstone and gypsum, due to the overlap between emissivity minima and $SO_2$ absorption



# Temperature and Gas Concentration Retrieval Procedures

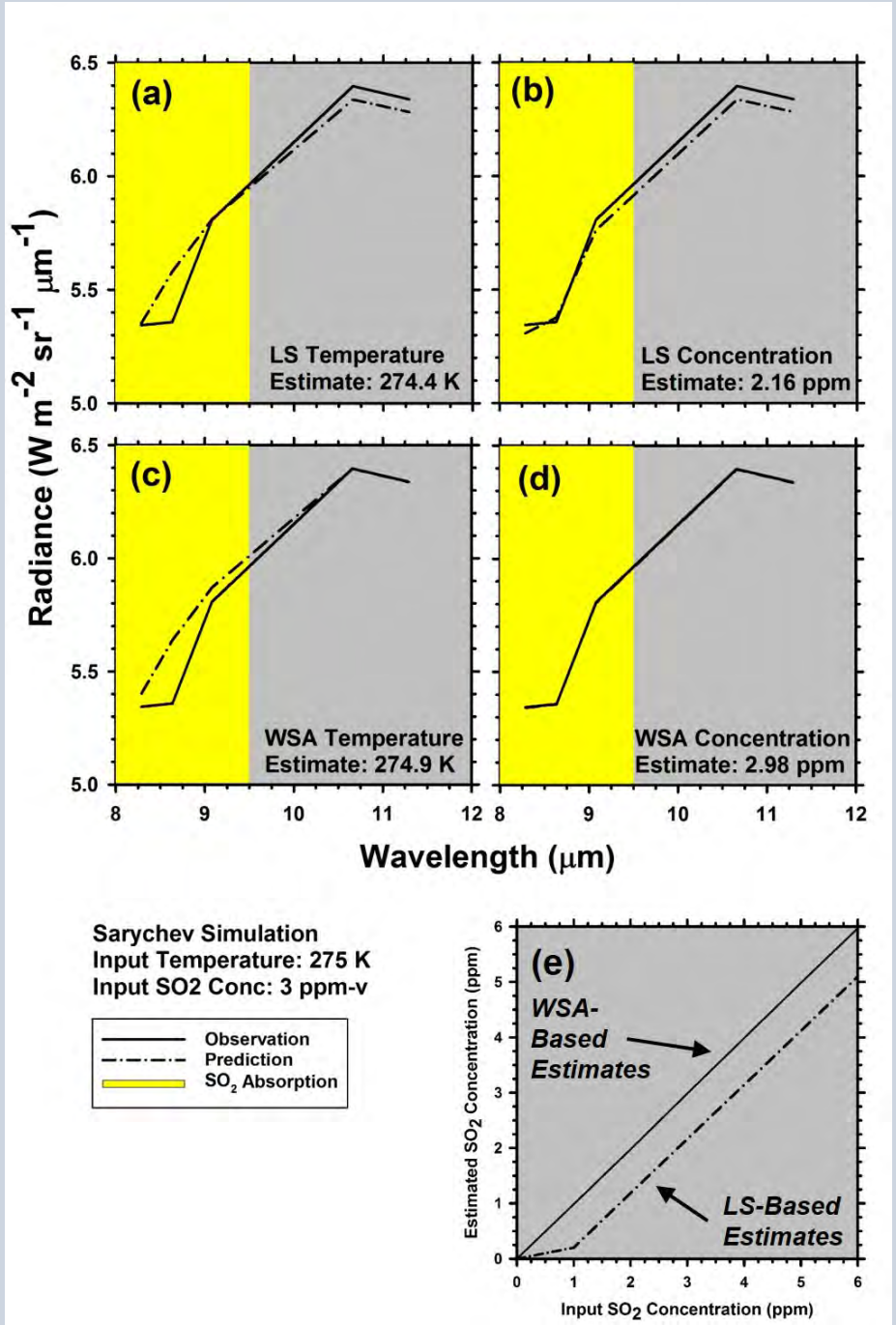
# Misfit Calculation: Least Squares vs. Weighted Spectral Angle

**Least Squares (LS):**

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

**Weighted Spectral Angle (WSA):**

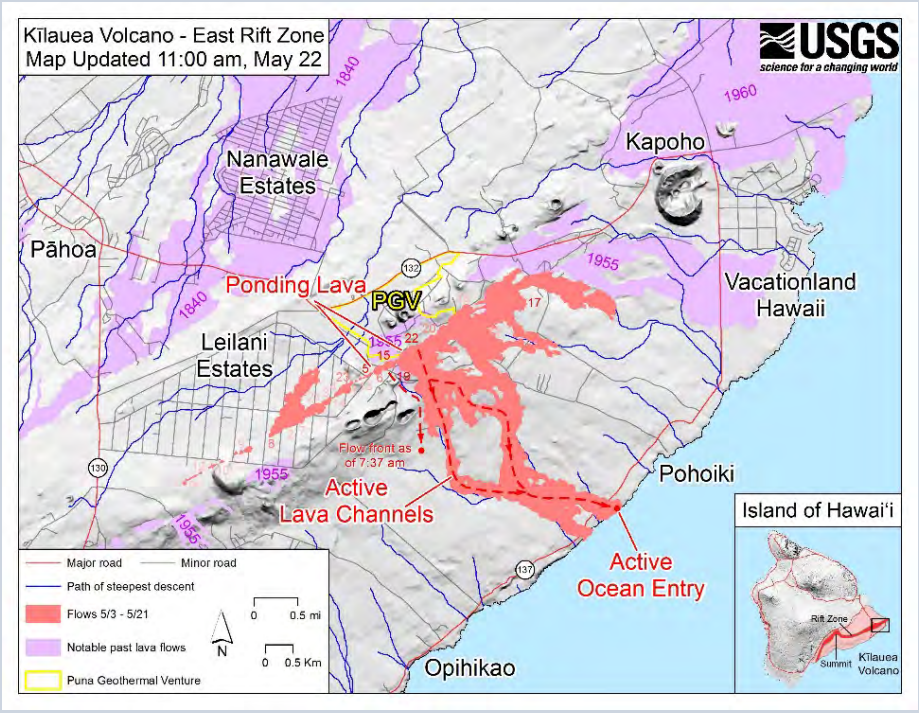
- Observed and Model Radiance Spectra Represented as Vectors in Data Space
- Minimize Angle Between Vectors (*Spectral Angle*)
- Minimization Weighted to Favor Solutions with Model Spectrum > Observed Spectrum
- Optimum Temperature Estimate Given Imperfect Knowledge of Atmospheric Composition

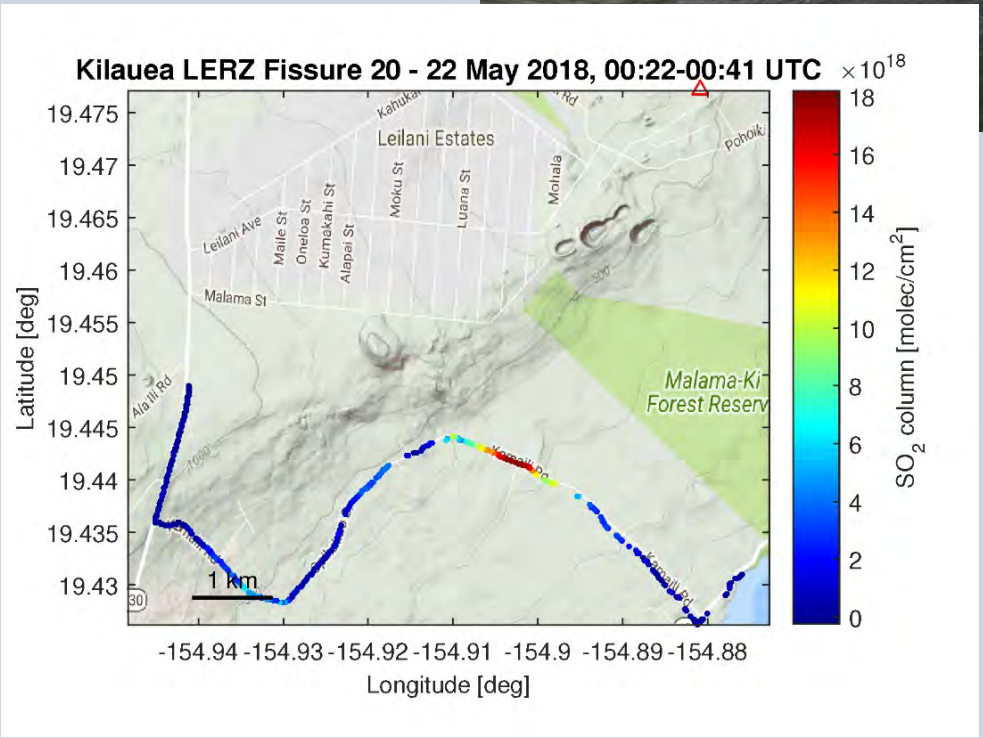


# Comparison with Field Measurements

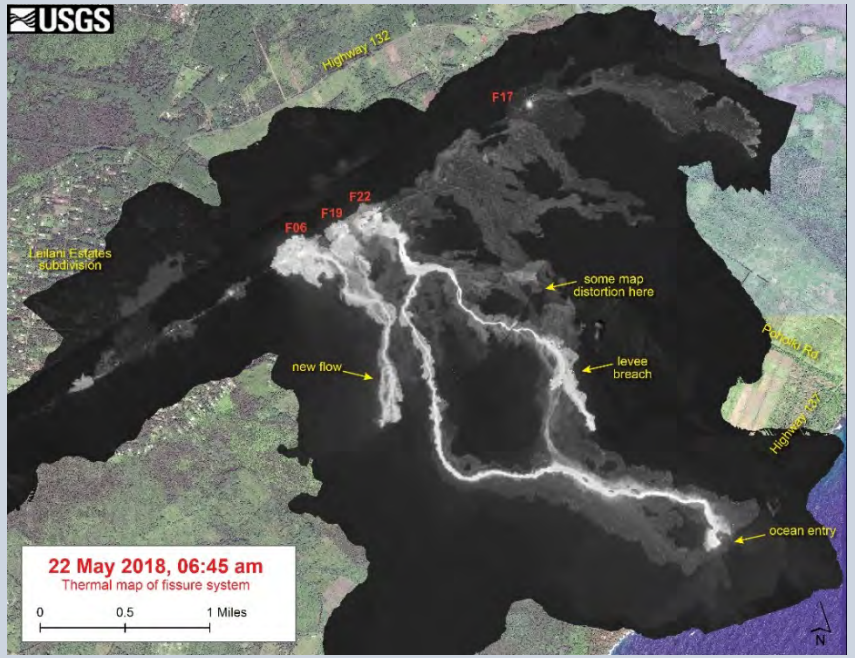
Kilauea Eruption

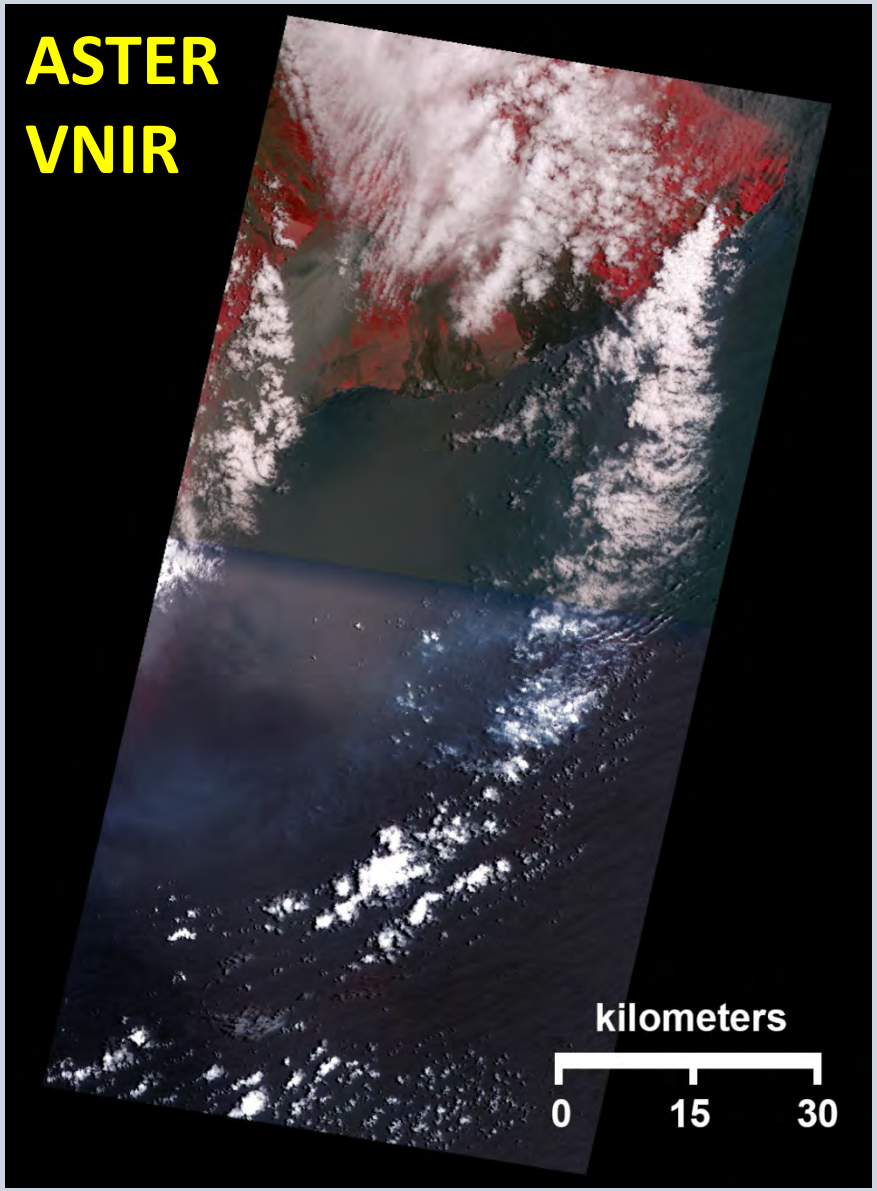
22 May 2018

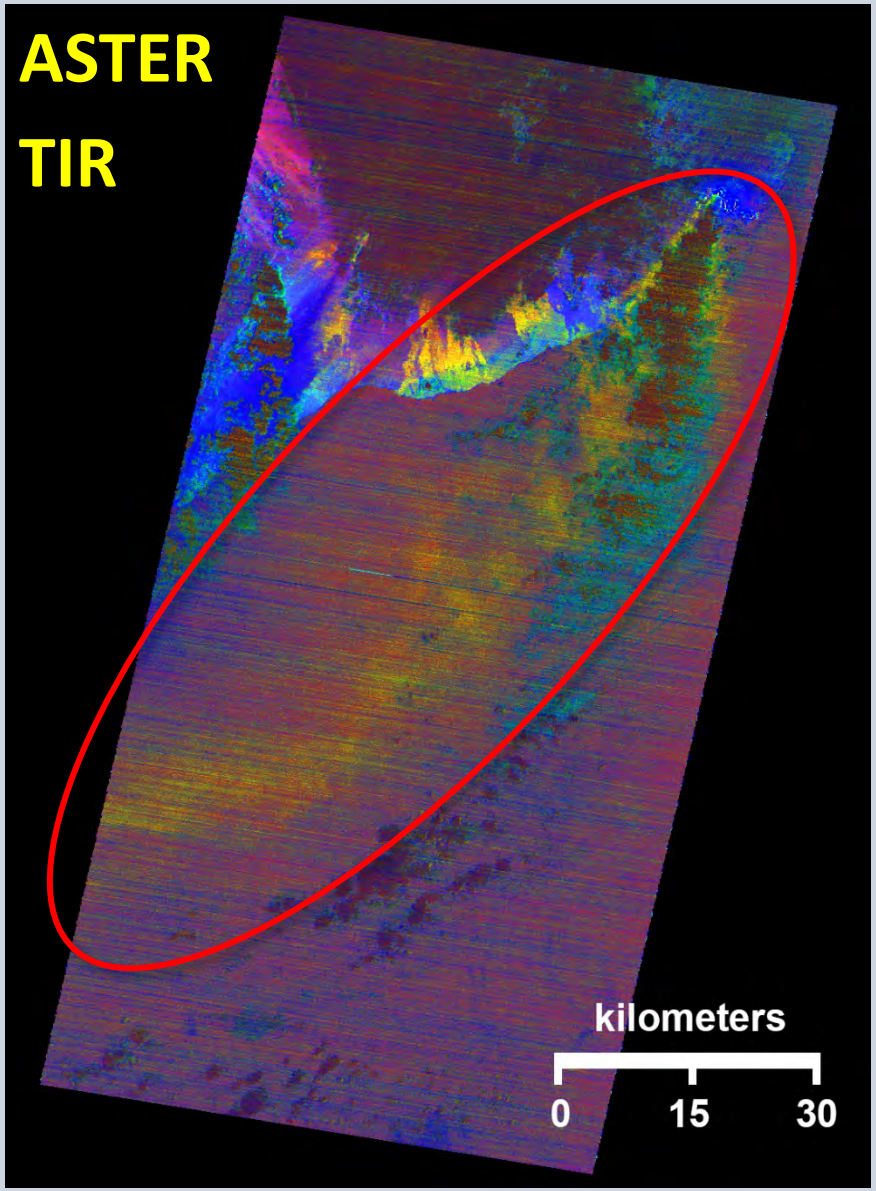


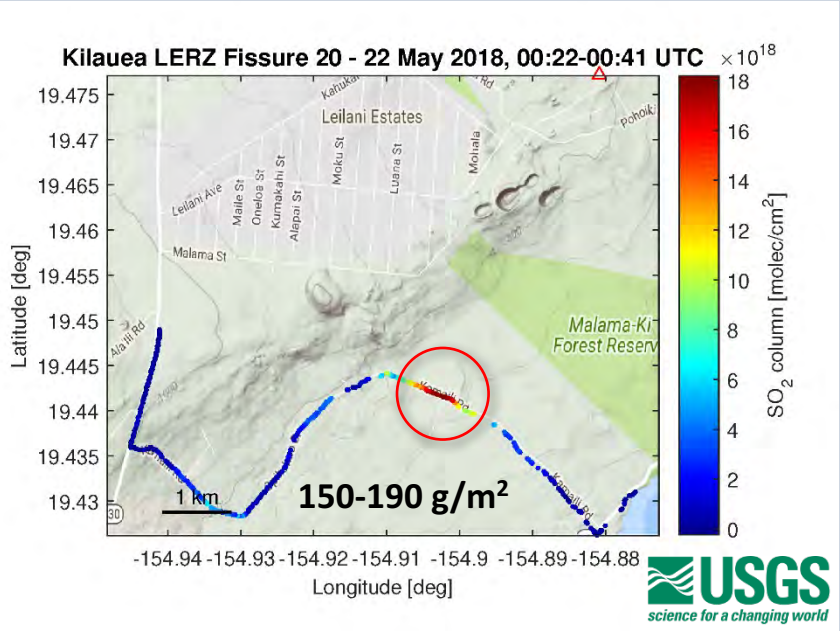

***Data courtesy of USGS/HVO.***
***Data analyses are preliminary, and not for distribution.***





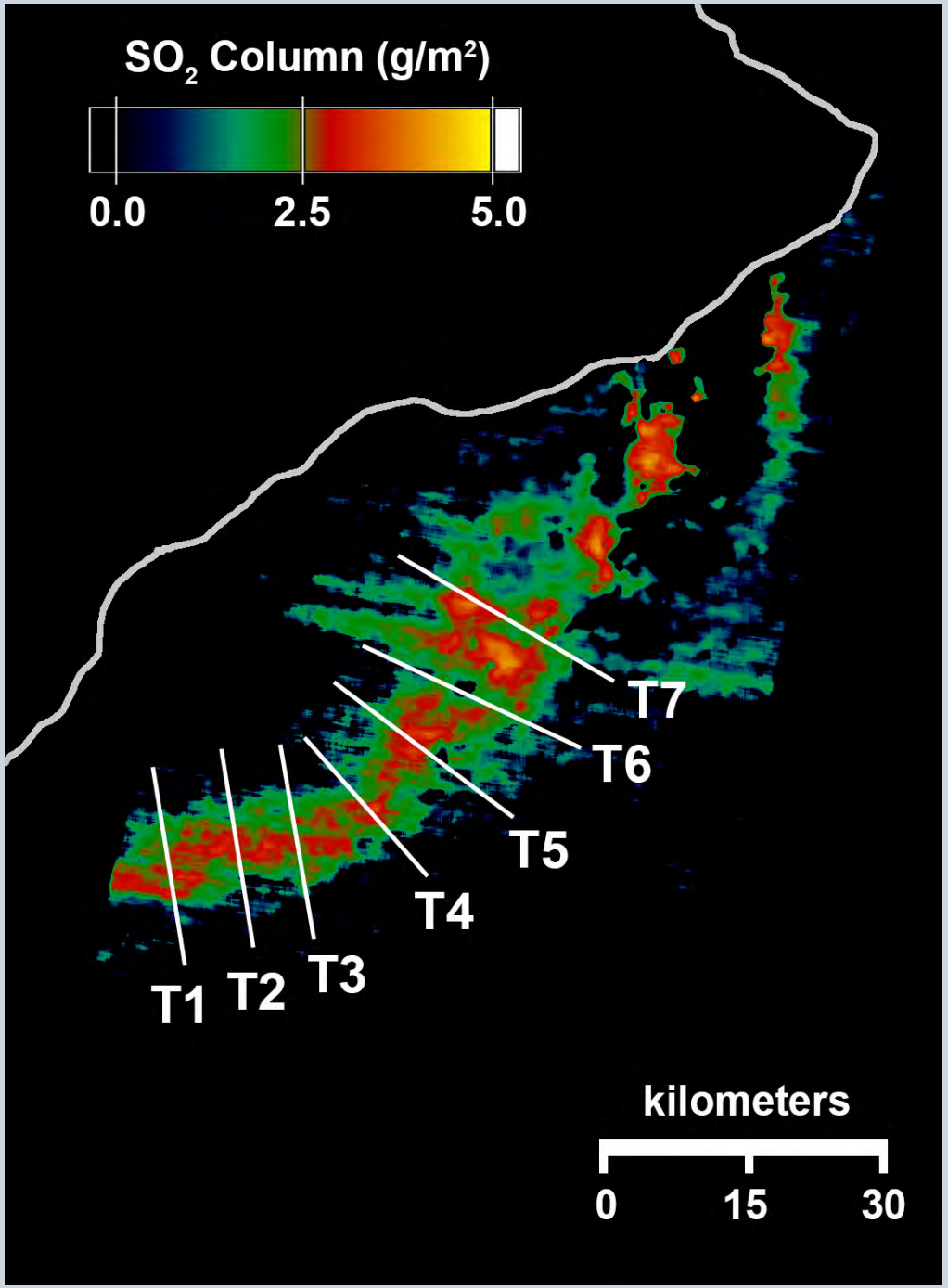




**2018-05-22 / 21:01 UTC**

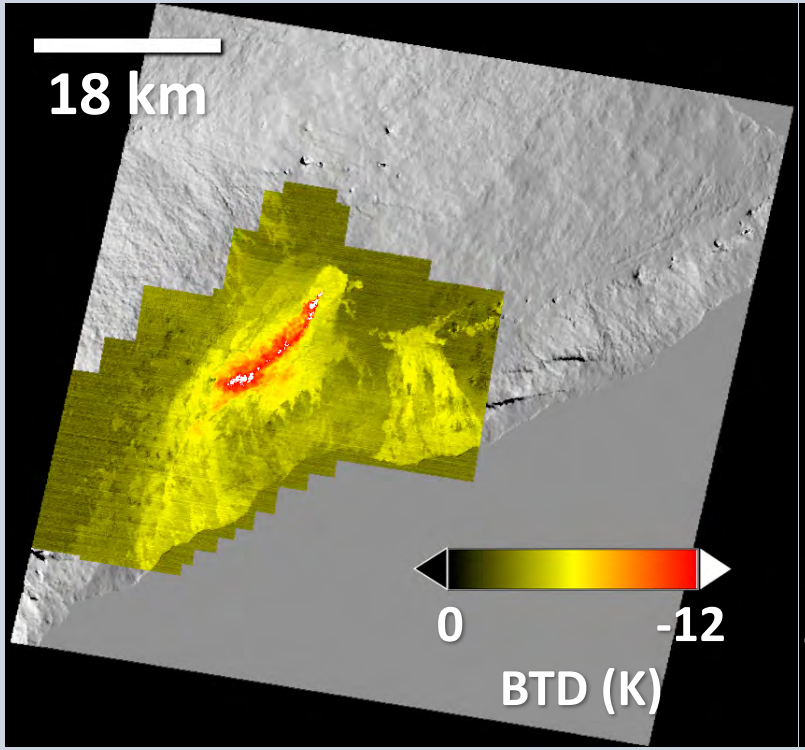


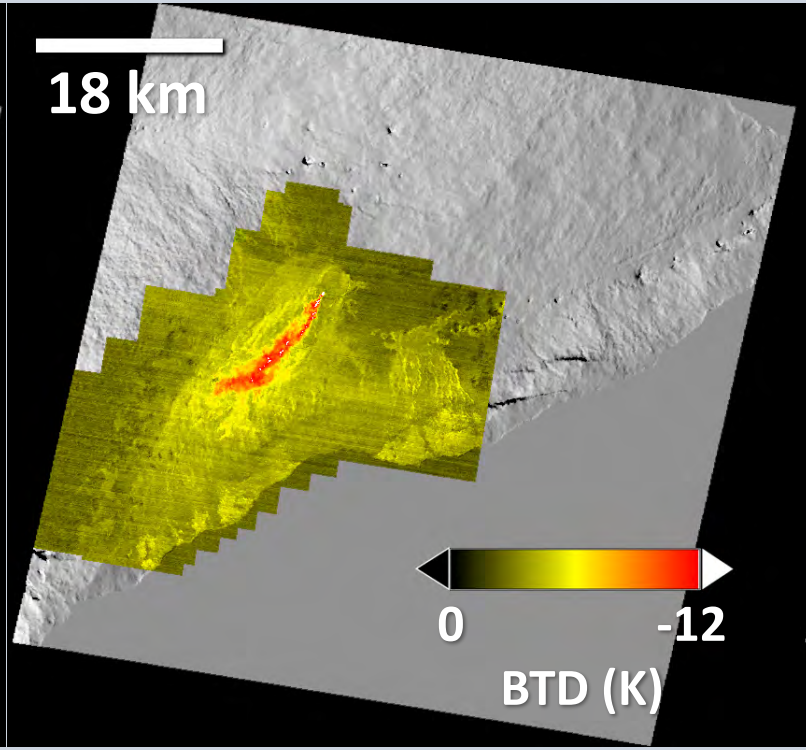

| HVO Integrated Transects (kg/m)* | ASTER Integrated Transects (kg/m) |
|---|---|
| 37.52 | T1: 25.37 |
| 30.34 | T2: 20.75 |
| 45.03 | T3: 24.20 |
| 38.10 | T4: 19.94 |
| Ave: 37.75 ± 5.2 | T5: 25.90 |
| | T6: 23.98 |
| | T7: 41.00 |
| | Ave: 25.88 ± 6.5 |

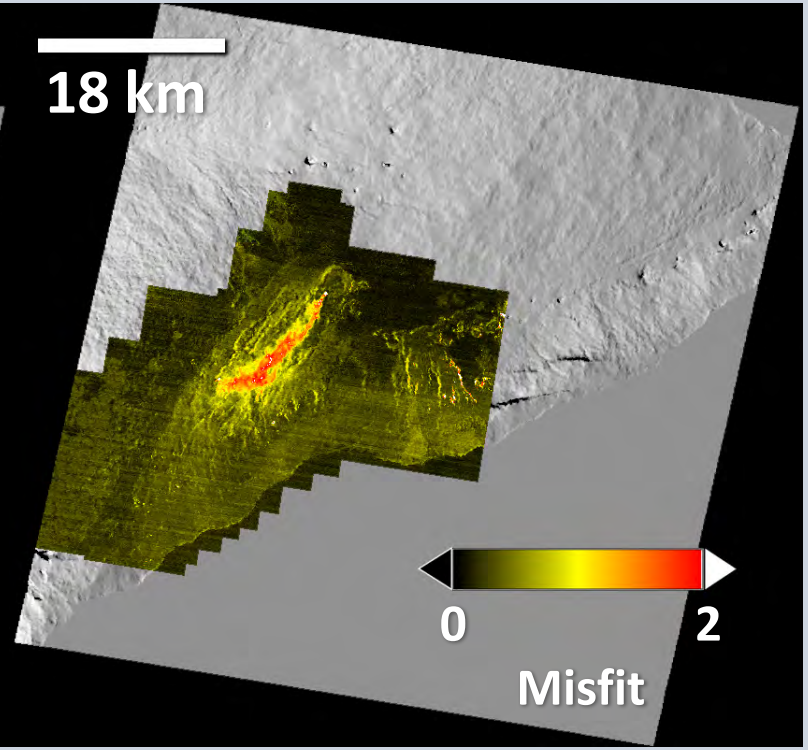
**USGS/HVO data analyses are preliminary, and not for distribution*

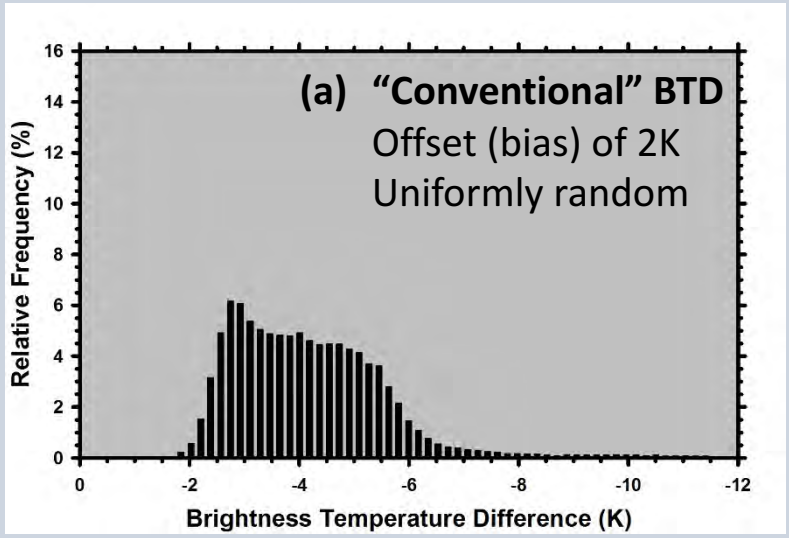


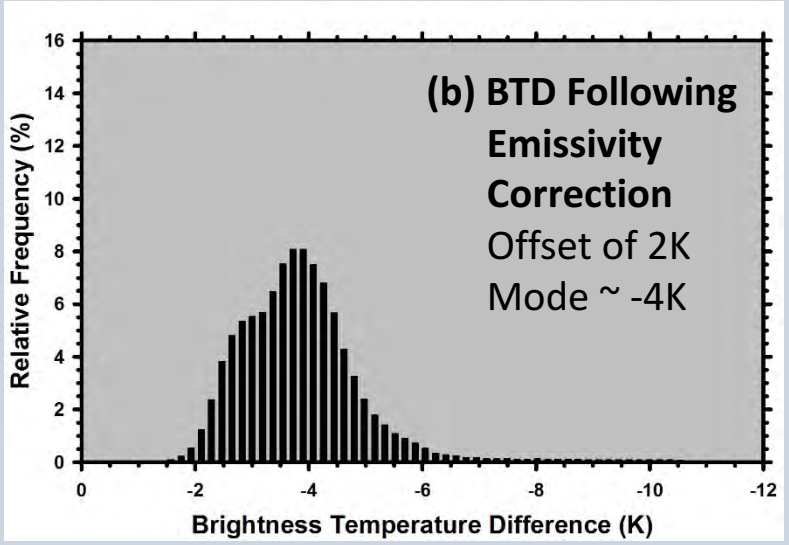
# Towards an Automated Plume Detection and Mapping System

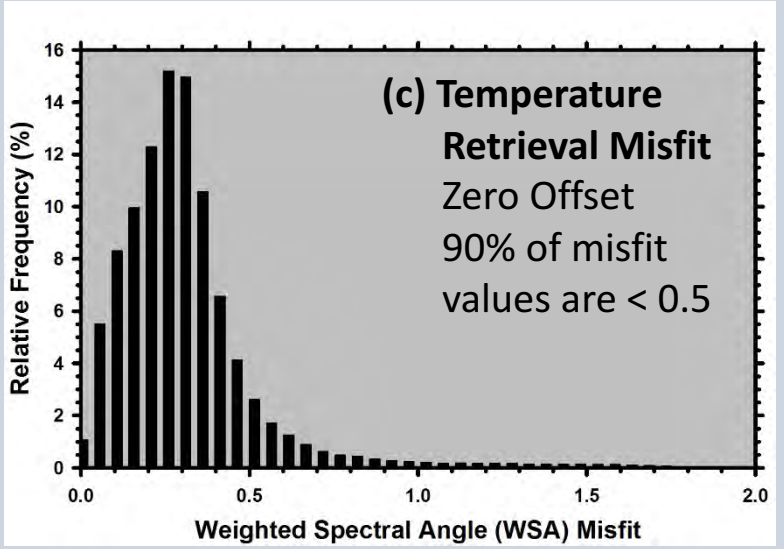

18 km
0
-12
BTD (K)


18 km
0
-12
BTD (K)

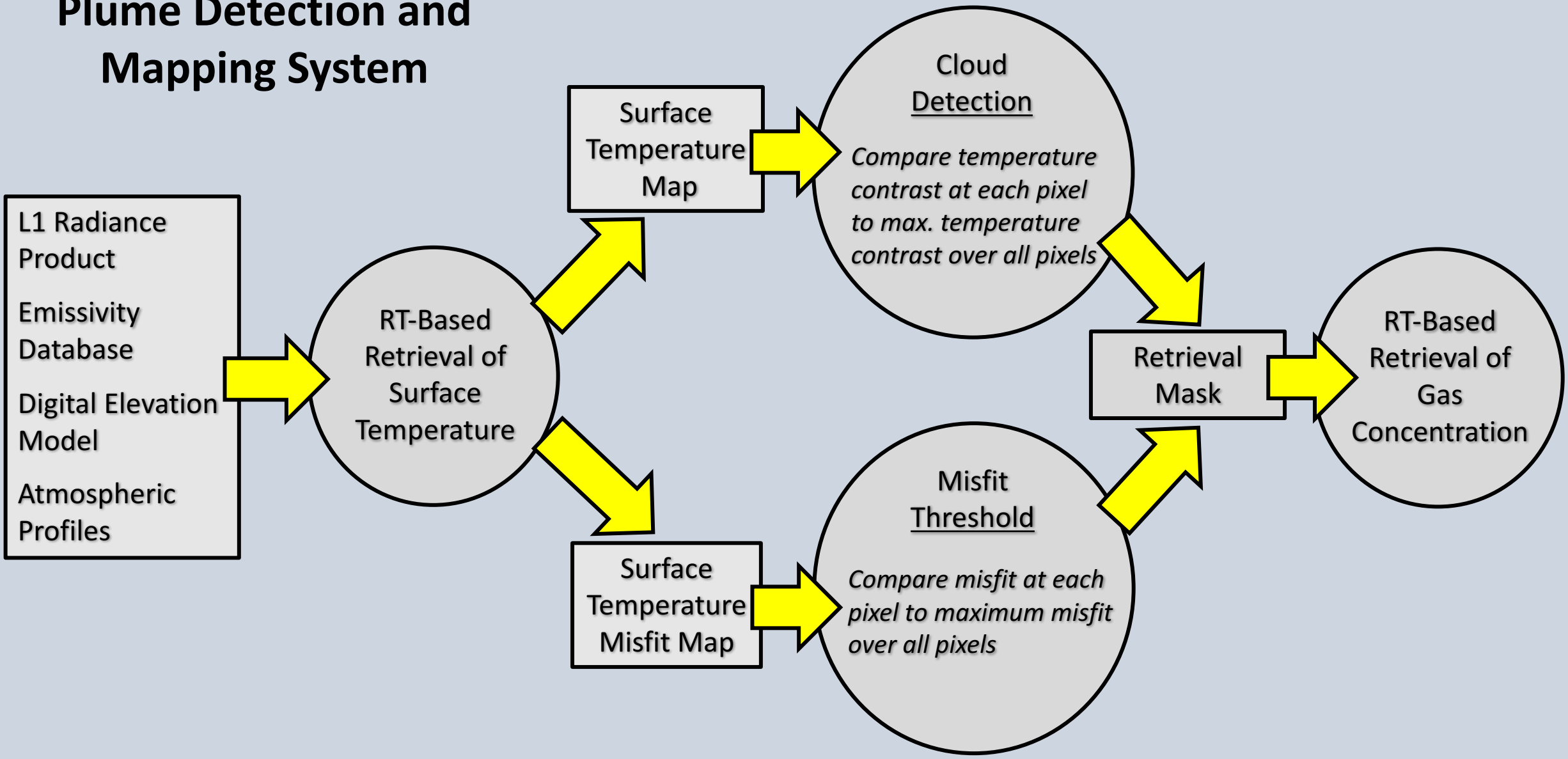

18 km
0
2
Misfit


(a) "Conventional" BTD
Offset (bias) of 2K
Uniformly random
Relative Frequency (%)
Brightness Temperature Difference (K)


(b) BTD Following Emissivity Correction
Offset of 2K
Mode ~ -4K
Relative Frequency (%)
Brightness Temperature Difference (K)

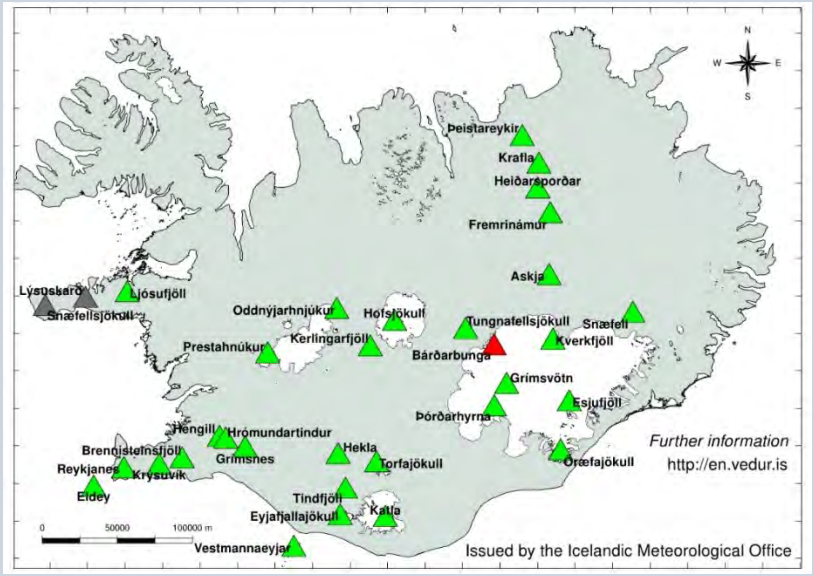

(c) Temperature Retrieval Misfit
Zero Offset
90% of misfit values are < 0.5
Relative Frequency (%)
Weighted Spectral Angle (WSA) Misfit

# Flow Chart for Automated Plume Detection and Mapping System



# Holuhraun Fissure Eruption, Bardarbunga Volcano, Iceland

- Active between 29 August 2014 and 27 February 2015
- $SO_2$ emission rates estimated at ~105 Mg/day based on SEVIRI (geostationary), OMI, and IASI





# Bardarbunga Volcano (Iceland) / VIIRS-VMAE / 2014-09-05

a) Surface temperature estimation does not consider volcanic plumes or met. clouds

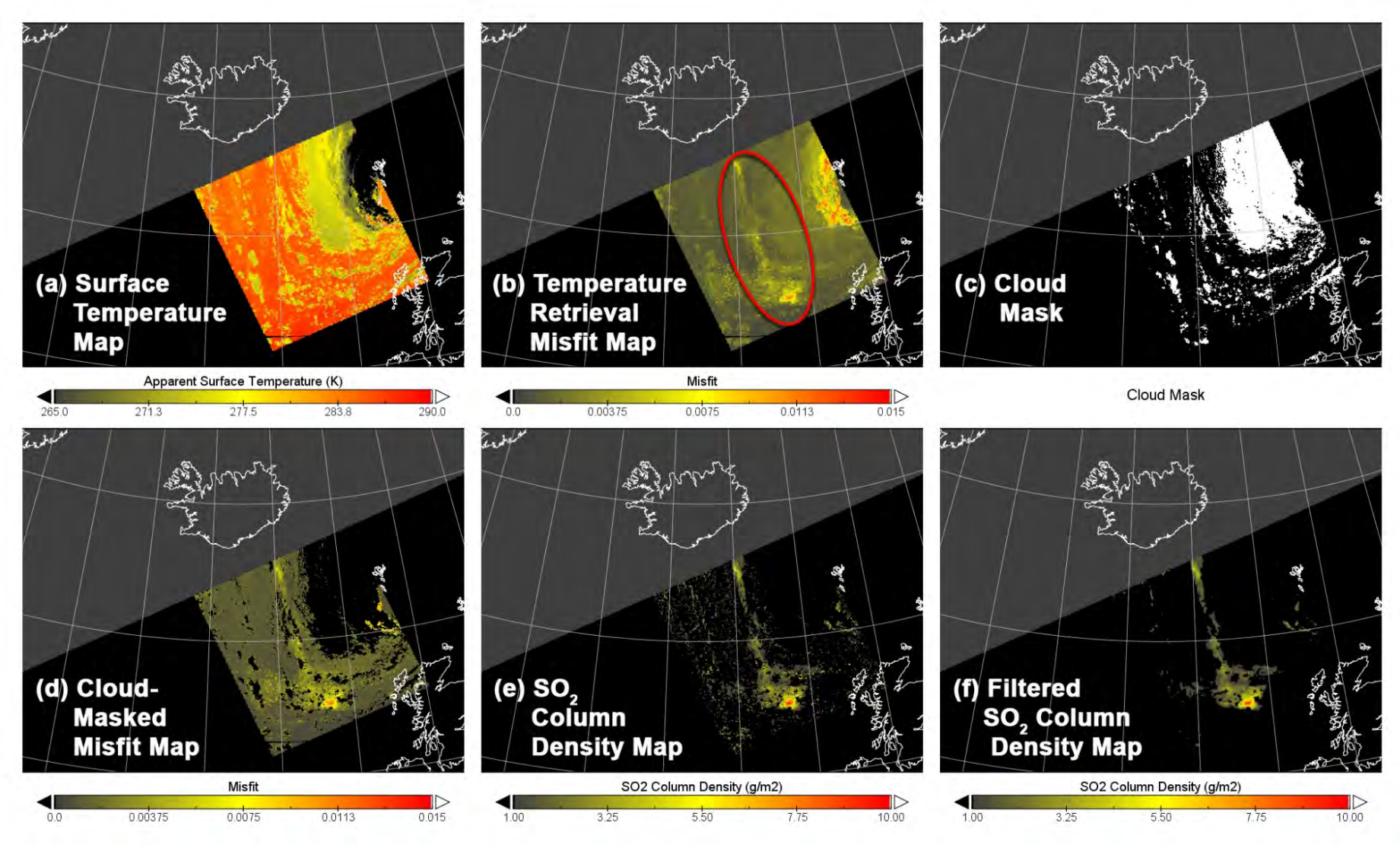
b) Misfit map shows the locations of plumes (red oval) and met clouds

c) Met clouds are identified by comparing apparent surface temperature with air temperature at plume altitude

d) Combination of cloud mask and misfit map improves the detection of volcanic plumes

e) Estimation of $SO_2$ column density is confined to the locations identified by the masked misfit map

f) $SO_2$ map is filtered to minimize the "holes" corresponding to the locations of met clouds.

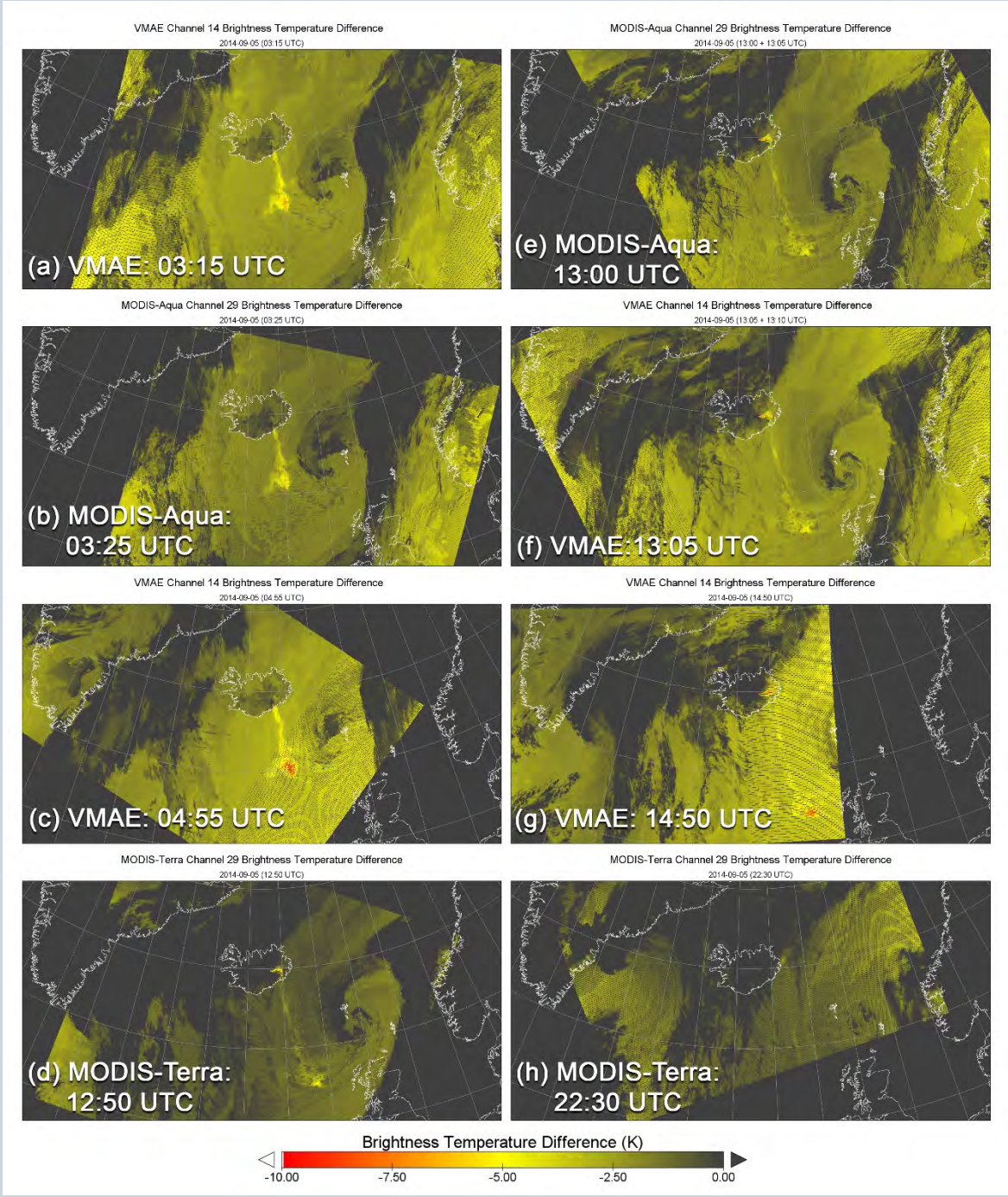


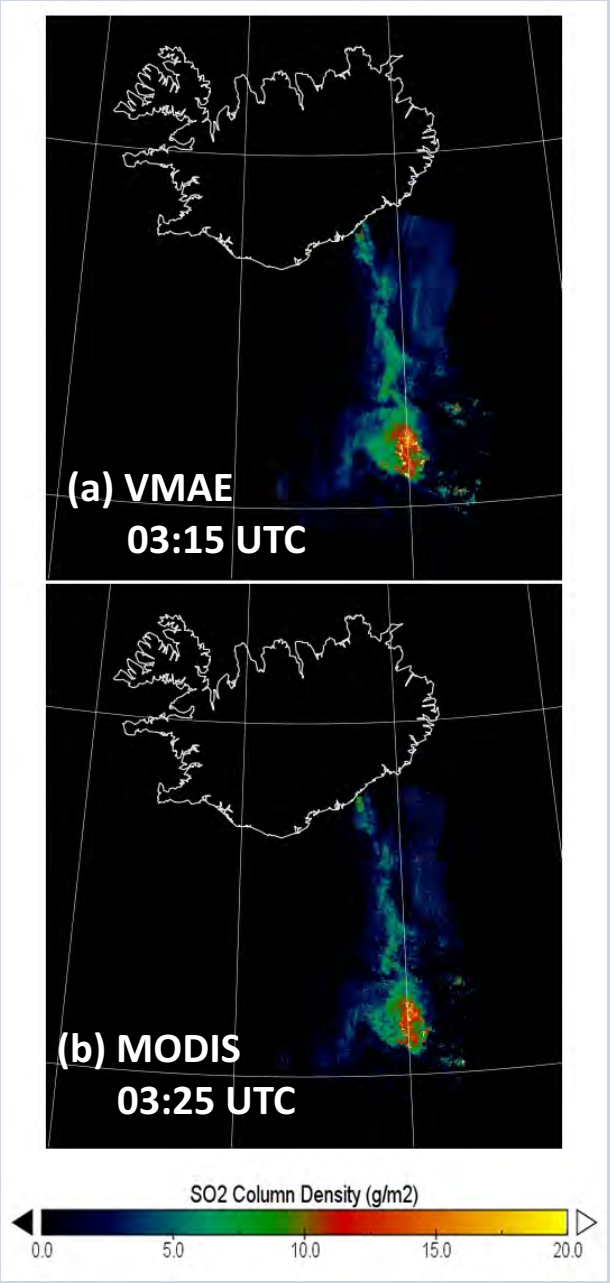
# Bardarbunga Eruption Plumes 2014-09-05

**Investigation will focus on the combined EOS and SNPP data records for the Bardarbunga (Iceland) Eruption**

**MODIS and VMAE nadir observations of Bardarbunga plumes provide a unique combination of spatial and temporal resolutions:**

- **Eight nadir observations acquired on 2014-09-05**
- **Documents plume dispersion on time scales from minutes to hours**

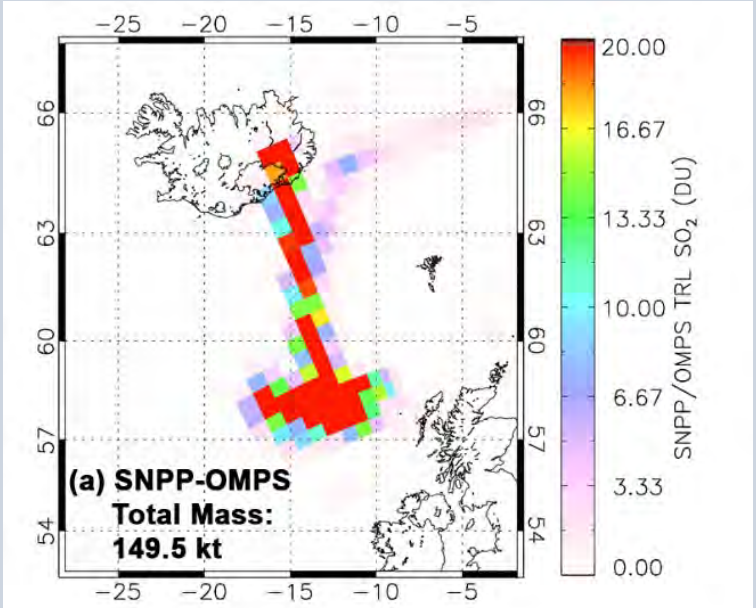


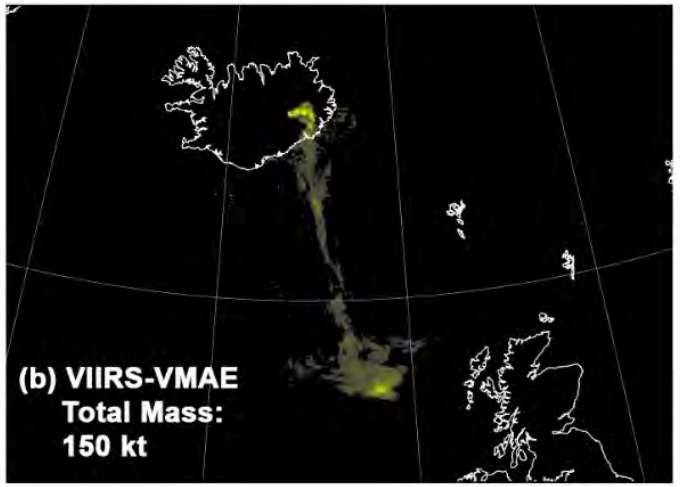


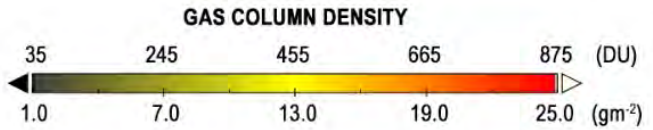

## 2014-09-05 03:15/03:25 UTC (Night-time)

$SO_2$ retrievals based on (a) VMAE and (b) MODIS-Aqua observations are virtually identical

Validates the use of VMAE data to augment and extend MODIS-based data records




## 2014-09-05 13:06 UTC (Daytime)

OMPS (UV) and VIIRS (TIR) Collocated on S-NPP and NOAA-20 Platforms

Contemporaneous Retrievals of Total $SO_2$ Mass from S-NPP are in Excellent Agreement (149.5 vs. 150 kt)

# Thank You for Your Attention…