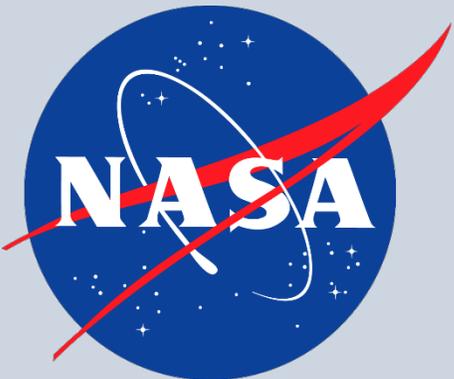


Plume Spectroscopy: Spectral Analysis of the Composition of Heterogeneous Volcanic Plumes

Vincent J. Realmuto

Paulo Penteado

**Jet Propulsion Laboratory,
California Institute of Technology**



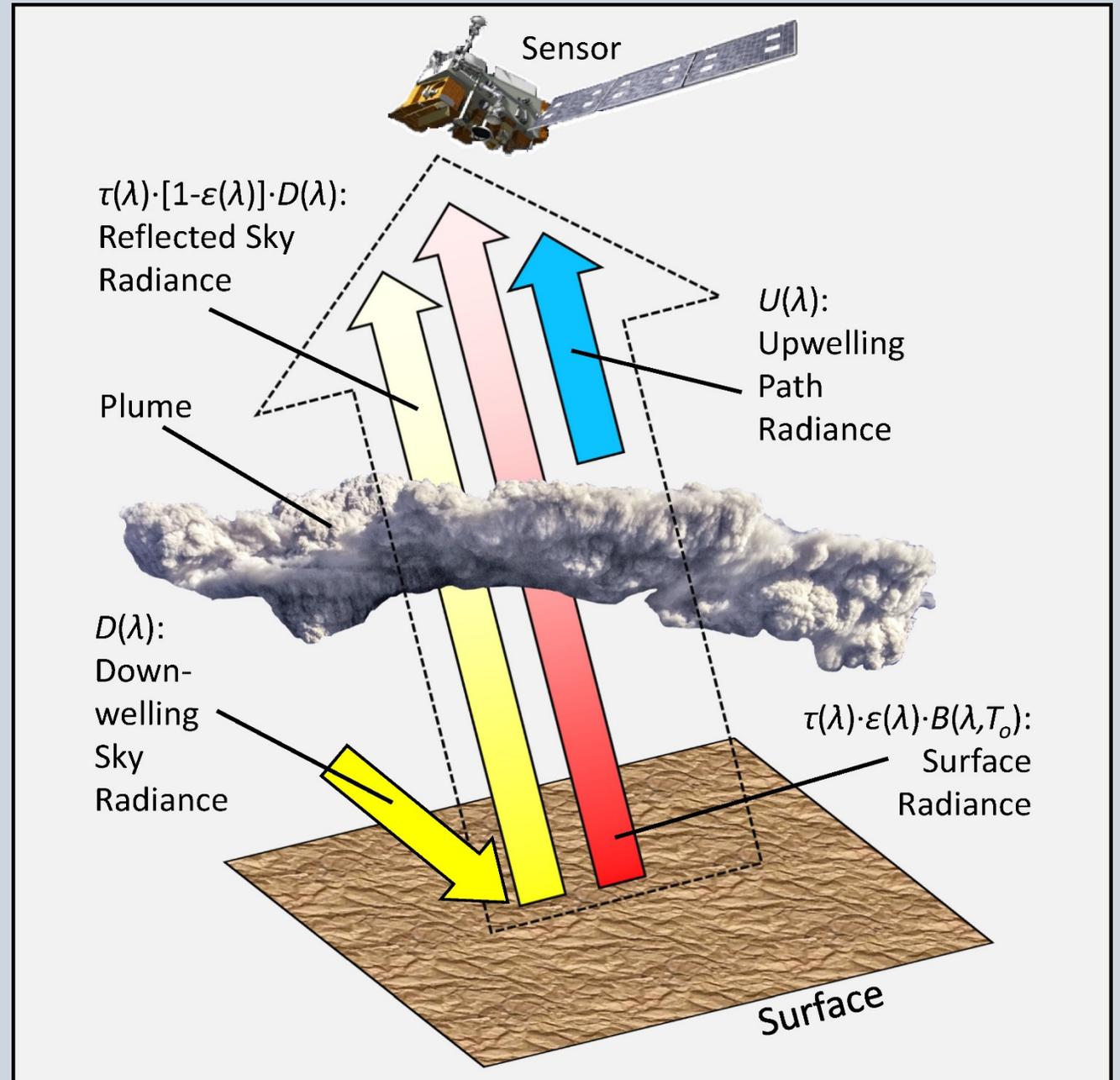
*© 2019, California Institute of Technology.
Government sponsorship acknowledged.*

TIR Remote Sensing of Volcanic Plumes

Detect plumes through transmission $[t(\lambda)]$ - the attenuation of surface radiance passing through the plume en route 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 $[D(\lambda)]$, and path radiance $[U(\lambda)]$ are estimated through radiative transfer (RT) modeling



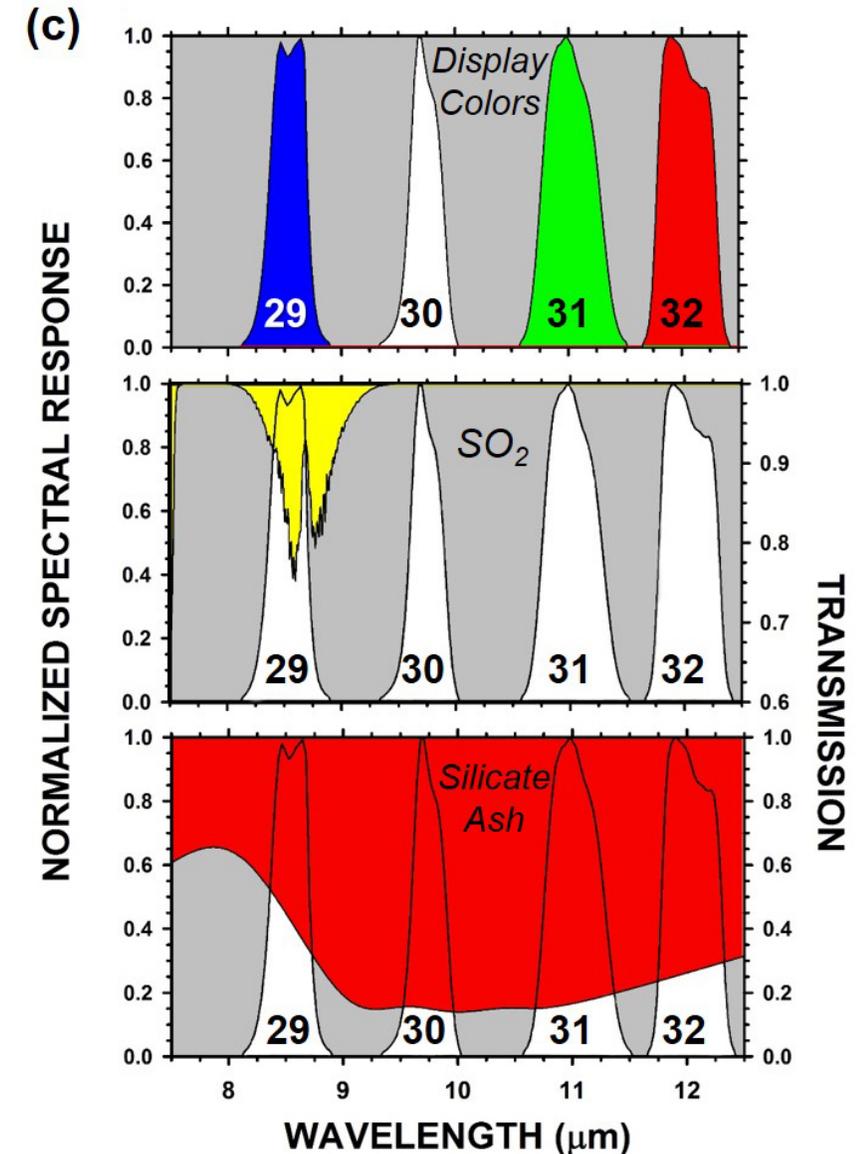
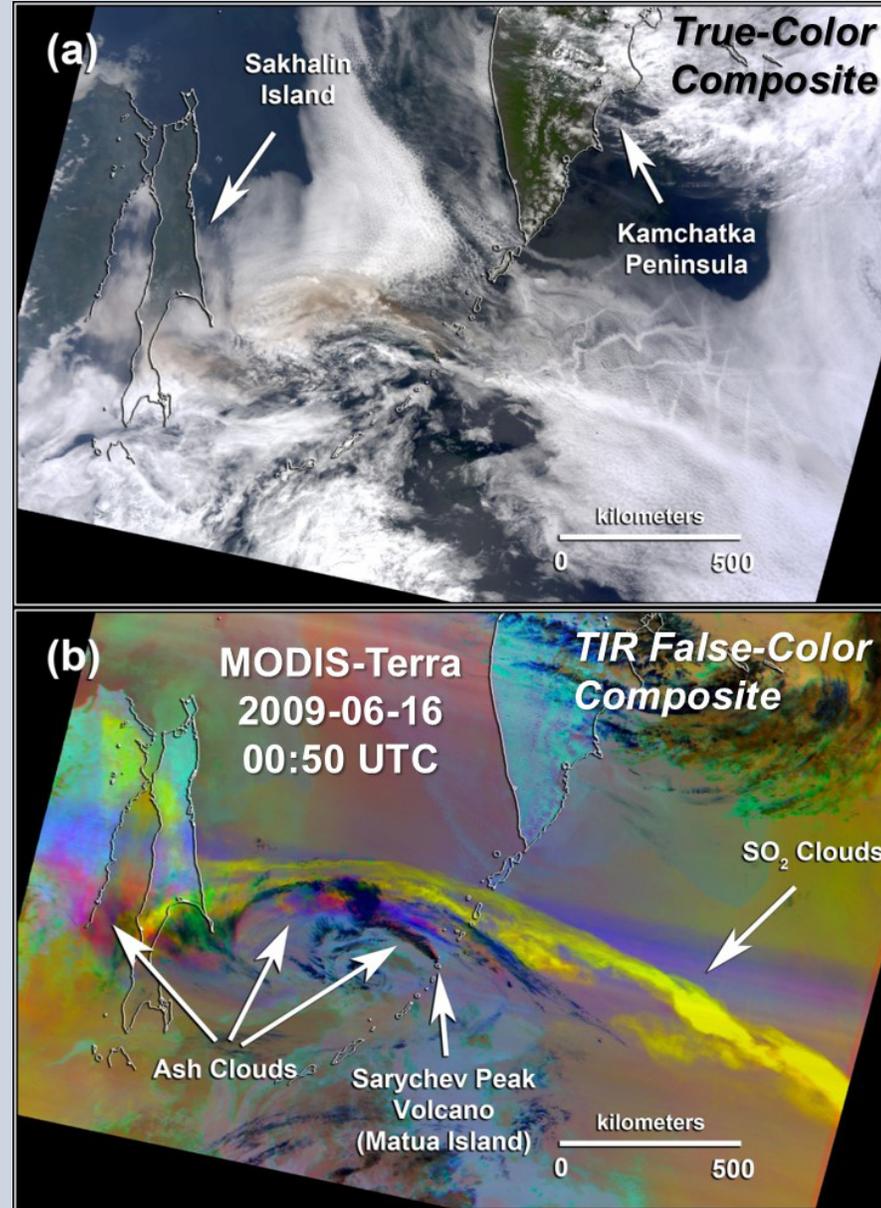
MODIS-Terra

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

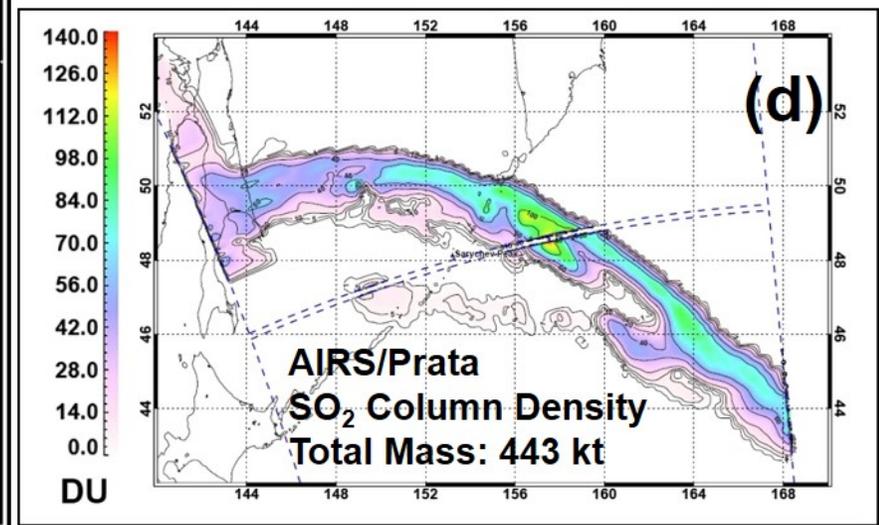
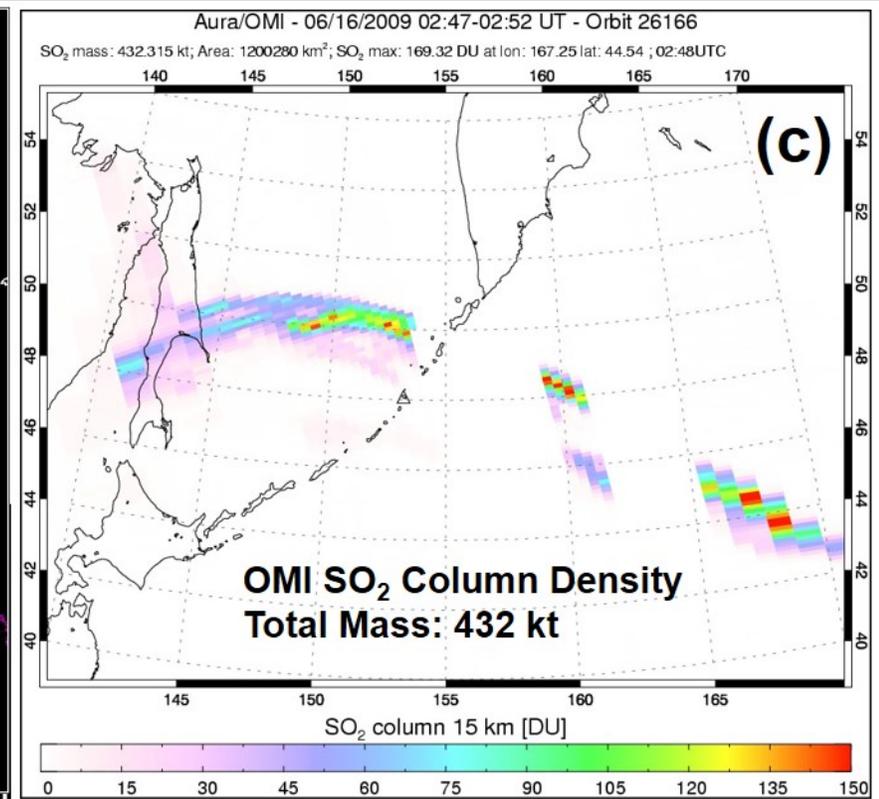
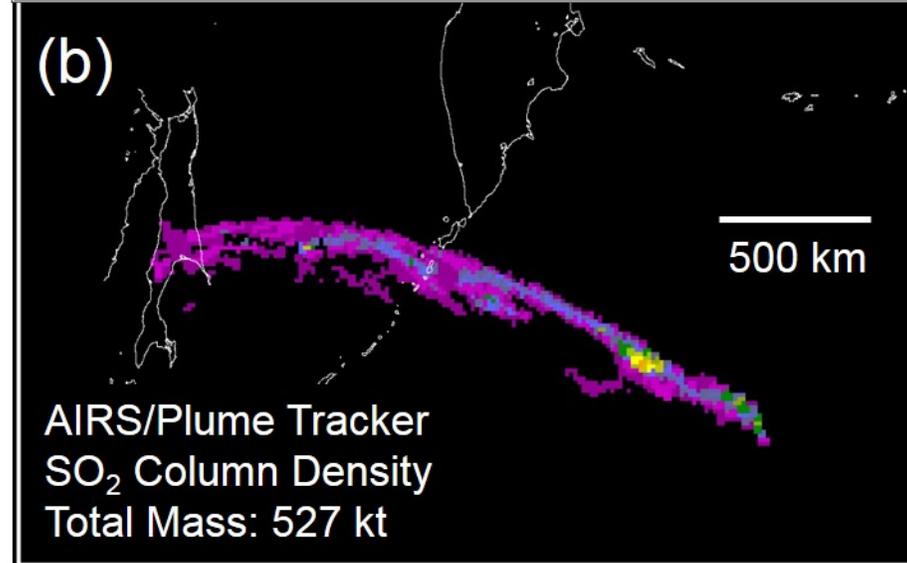
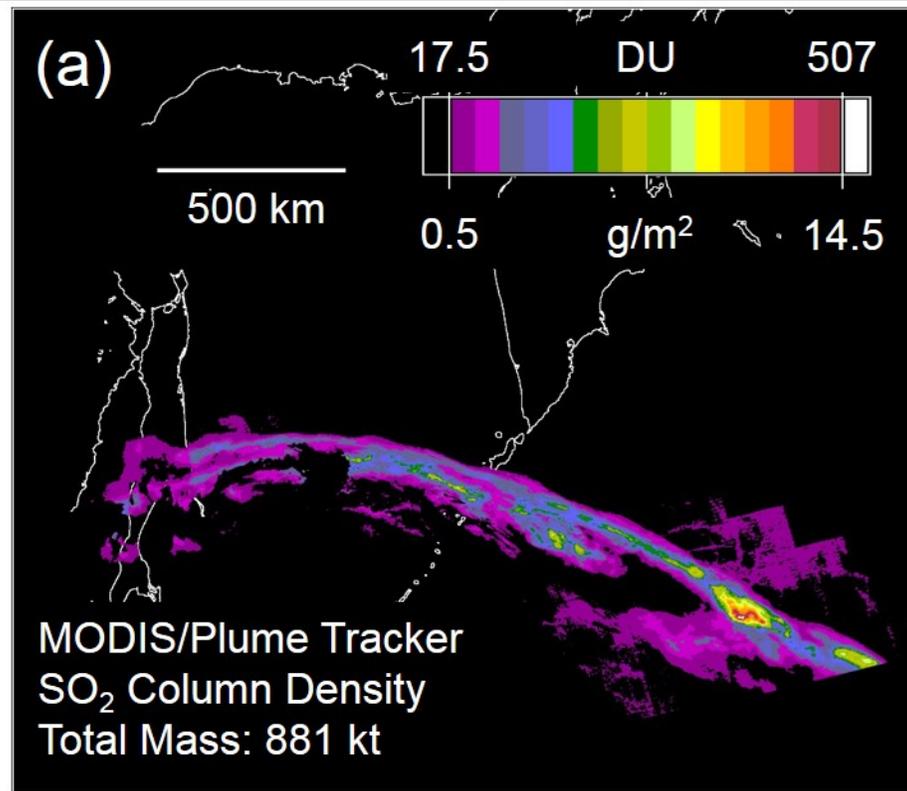
(b) False-color composite of TIR data from Channels 32, 31, and 29, displayed in red, green, and blue. SO₂ plumes appear yellow, while the display colors of ash plumes range between red and magenta

(c) Transmission spectra of SO₂ (middle) and silicate ash (bottom), superimposed on the spectral response of MODIS Channels 29, 30, 31, and 32



Comparison of AIRS, MODIS, and OMI-Based SO₂ Retrievals Sarychev Peak Eruption, 2009-06-16

- The Favorable Agreement between the AIRS and MODIS-based Estimates Indicates that the Distribution of SO₂ was Uniform at the Scale of an AIRS IFOV
- The Stronger Absorption of SO₂ at 7.3 μm (AIRS) vs. 8.7 μm (MODIS) Offsets the Differences in Spatial Resolution between AIRS and MODIS (13.7 vs. 1 km at nadir)



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

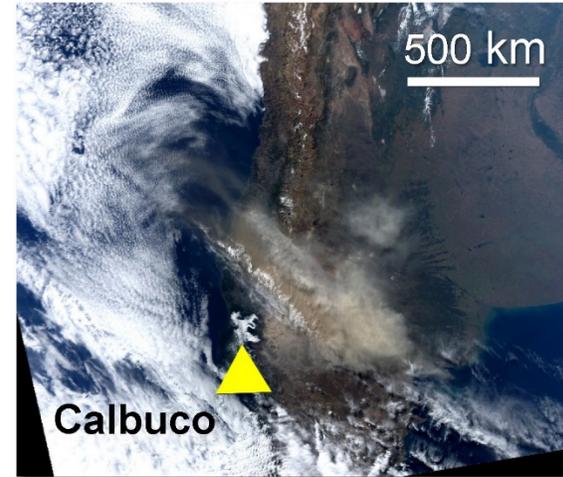
MODIS/VMAE TIR provides spatial context + coarse spectral information:

- Cloud A - Dominated by SO₂ (yellow display color)
- Cloud B - Mixture of SO₂ and ash (orange display color)
- Cloud C – Mixture of ash and ice crystals (purple display color)

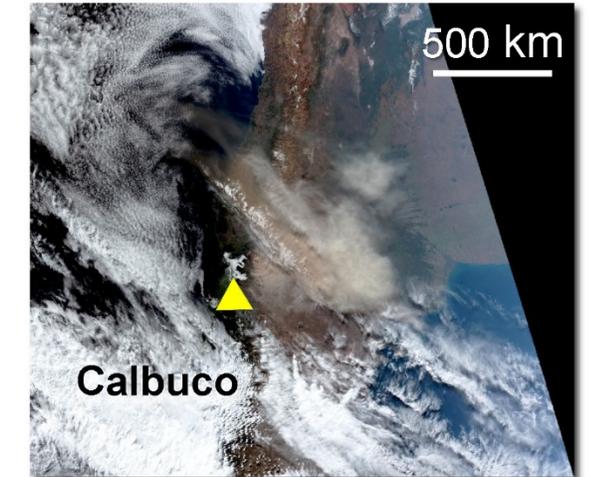
AIRS/CRIS Spectroscopy provides fine spectral information:

- Enables unique identification of plume components
- Ash features highlighted in red
- SO₂ features highlighted in yellow

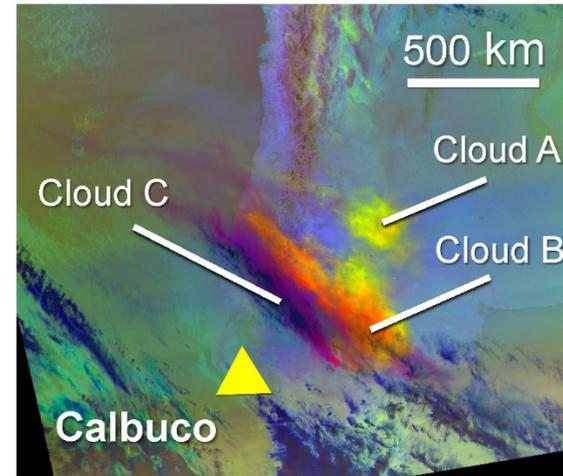
(a) MODIS RGB



(b) VMAE RGB

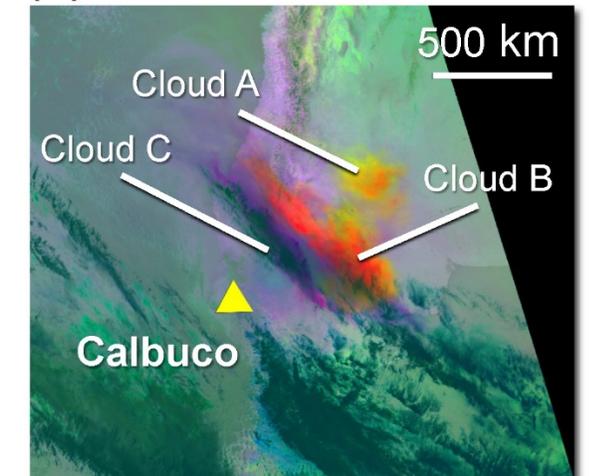


(c) MODIS TIR



18:36 UTC

(d) VMAE TIR



19:12 UTC

Calbuco Volcano (Chile): 2015-04-23

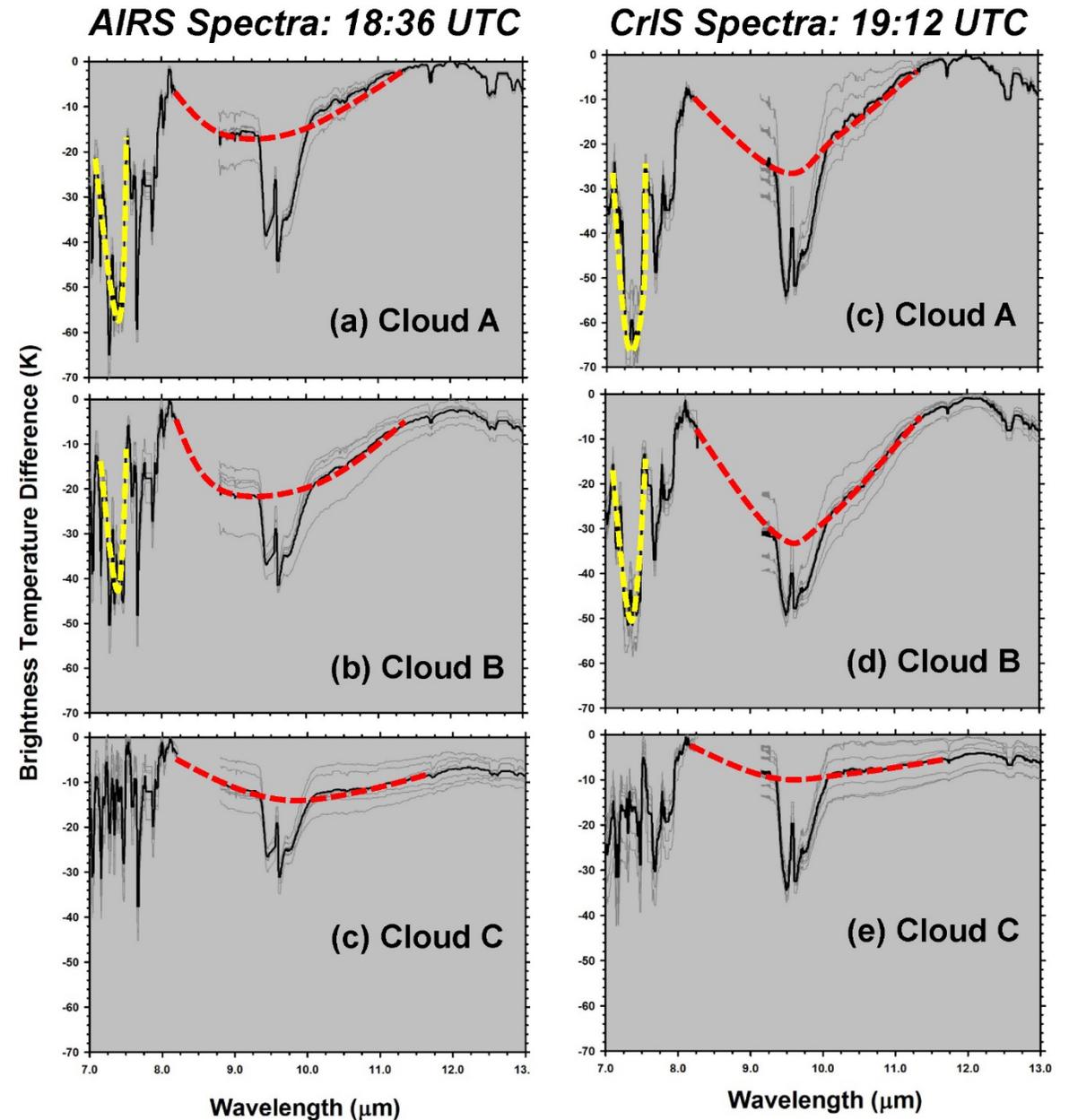
18:35 UTC (Aqua) / 19:12 UTC (SNPP)

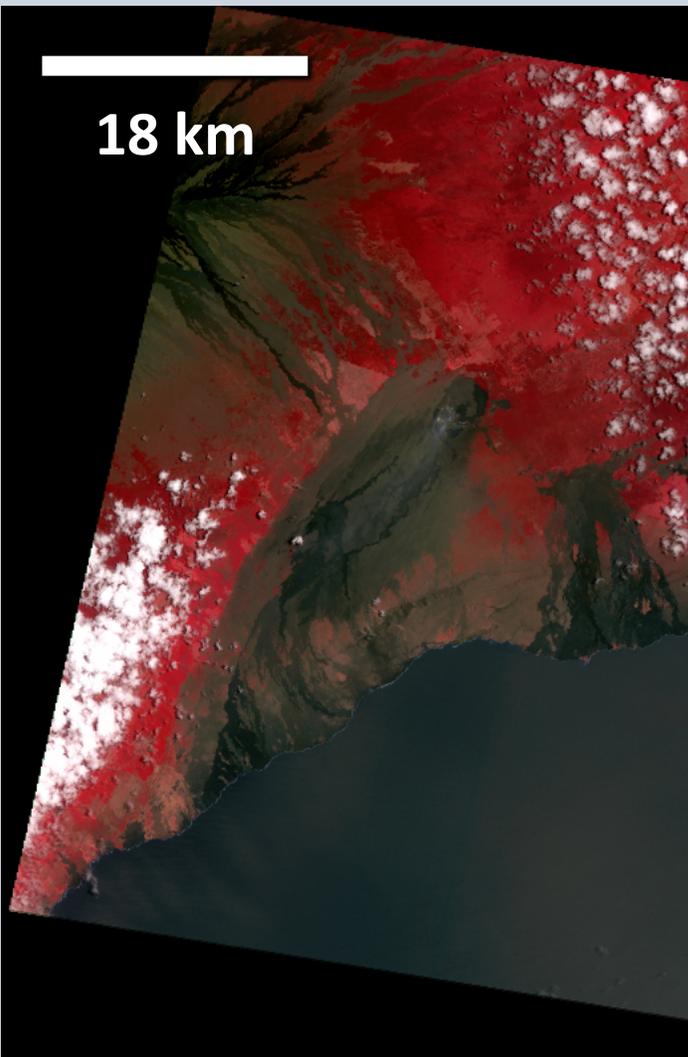
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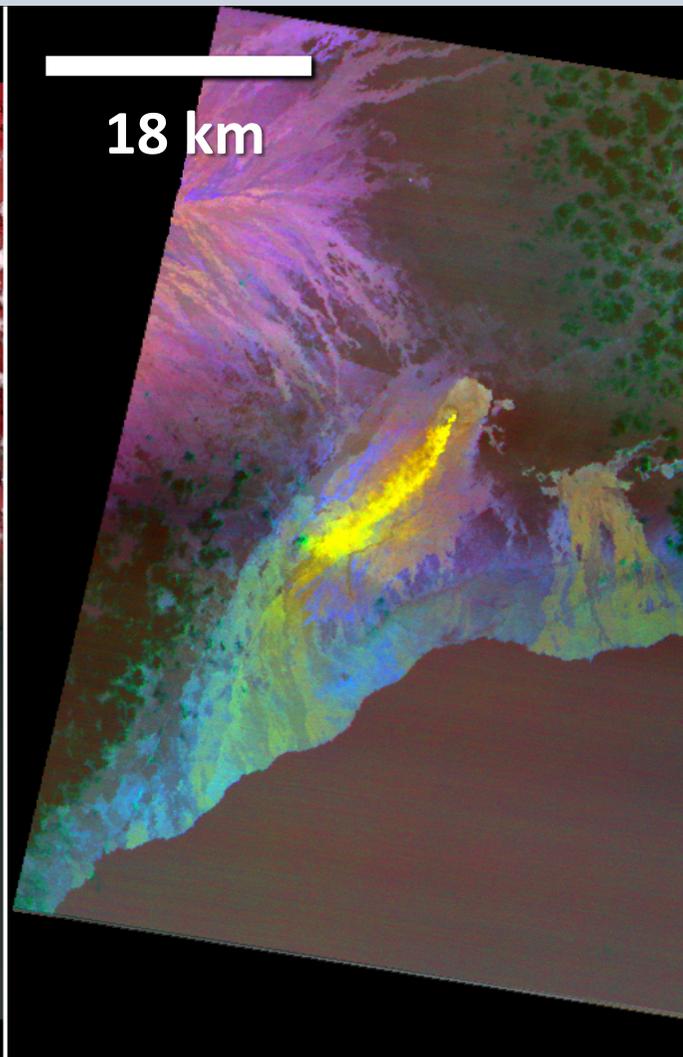
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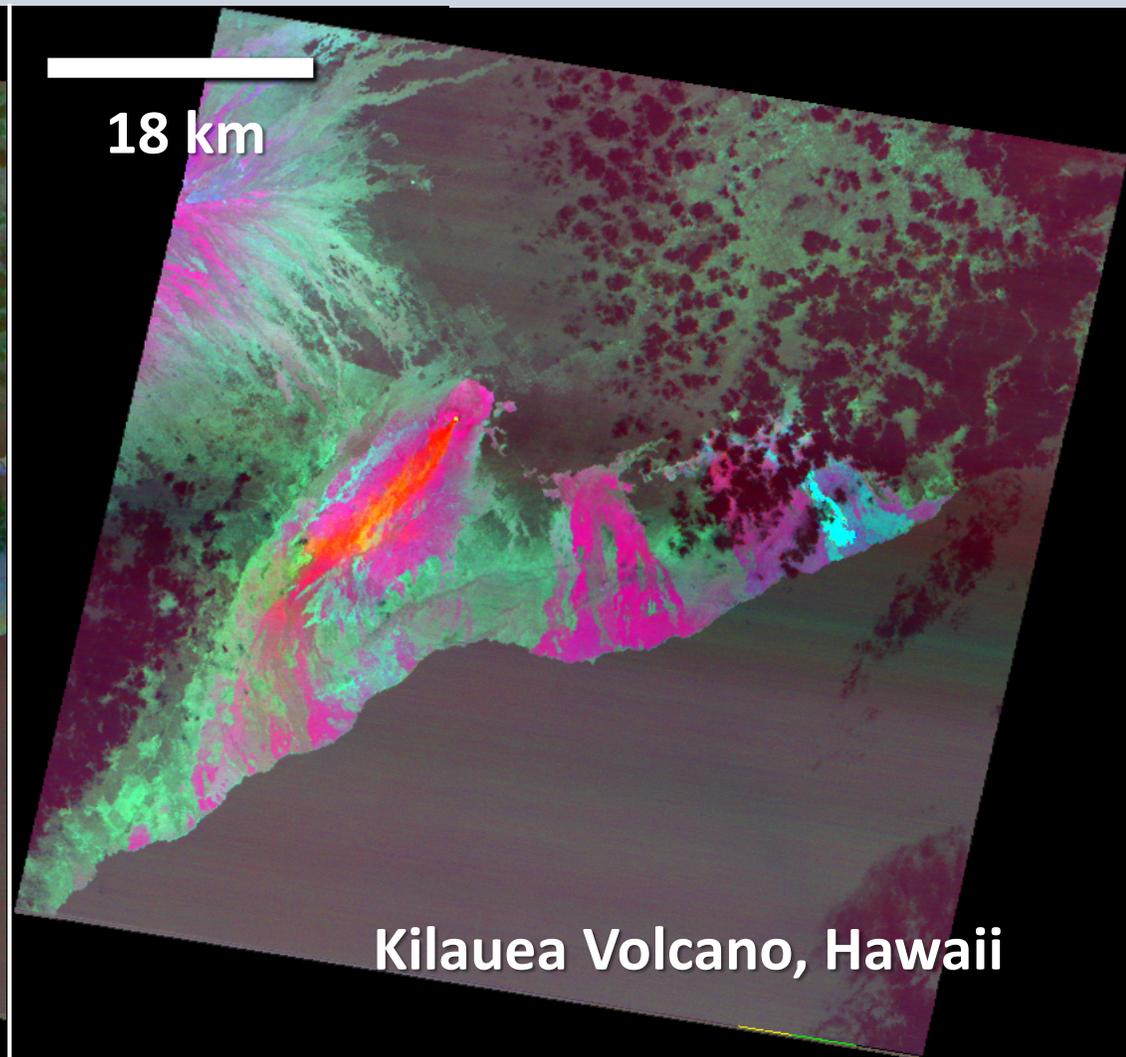




a) False-color composite of ASTER VNIR data



b) False-color composite of TIR data designed to detect SO₂ absorption. SO₂ 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 SO₂ absorption

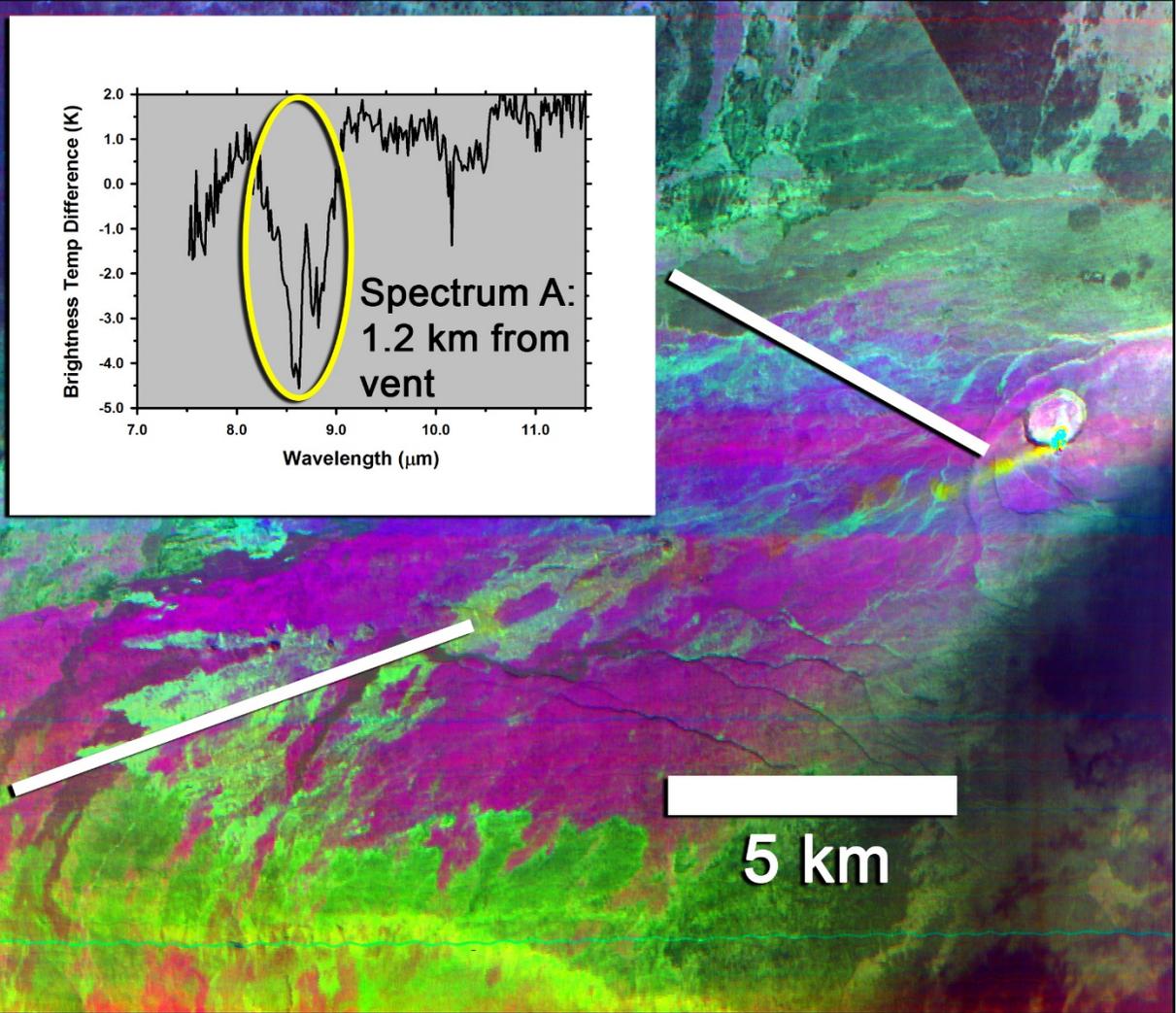
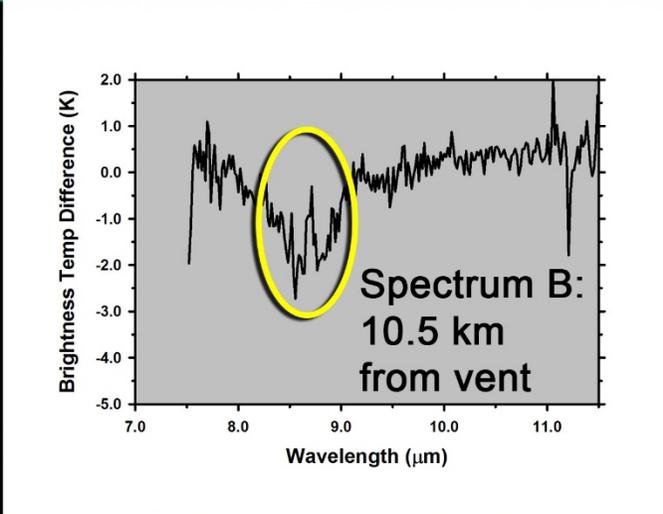
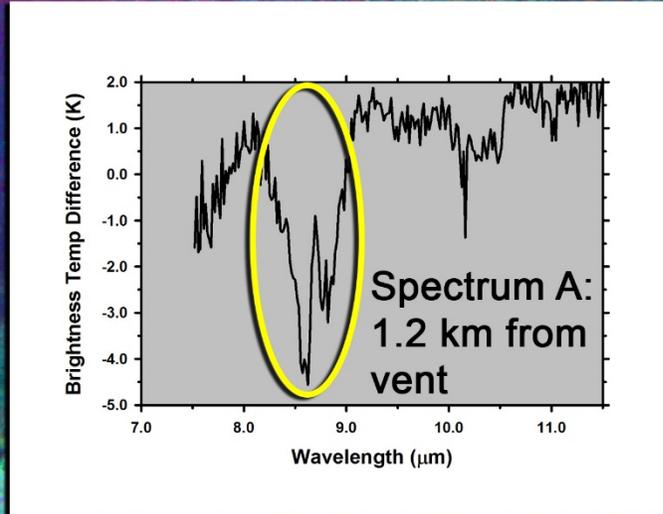
Imaging Spectroscopy:
Fine spectral resolution
of HyTES ($0.02 \mu\text{m}/2 \text{cm}^{-1}$)
enables unique
identification of SO_2

**Spectrum A indicates
stronger SO_2 absorption
than Spectrum B**

**Absence of SO_4 Spectral
Features - Decrease in
 SO_2 result of dispersion,
rather than conversion of
 SO_2 gas to SO_4 aerosols
(conversion rate of
 $\sim 8\% / \text{hr}$)**

HyTES Brightness Temperature Difference Spectra

**Kilauea Volcano
2018-01-18
21:15 UTC (11:15 HST)**

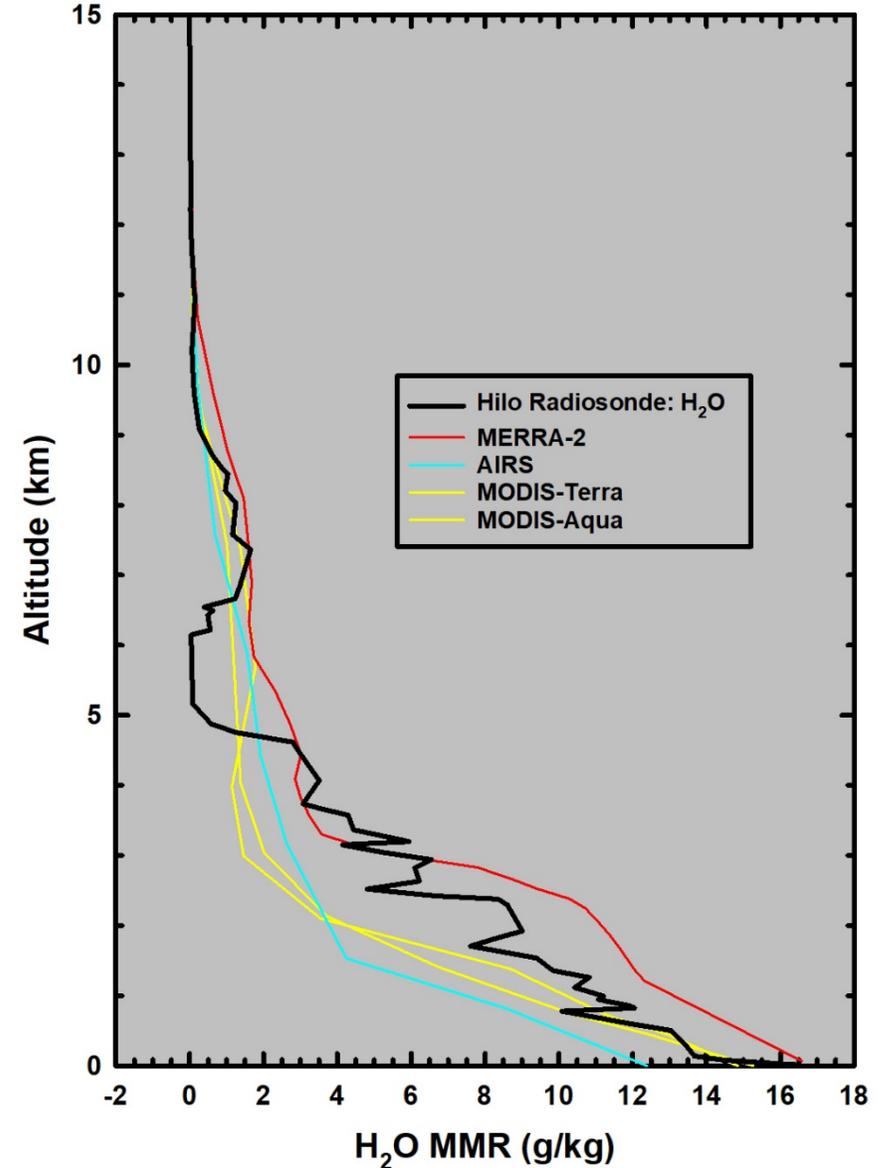
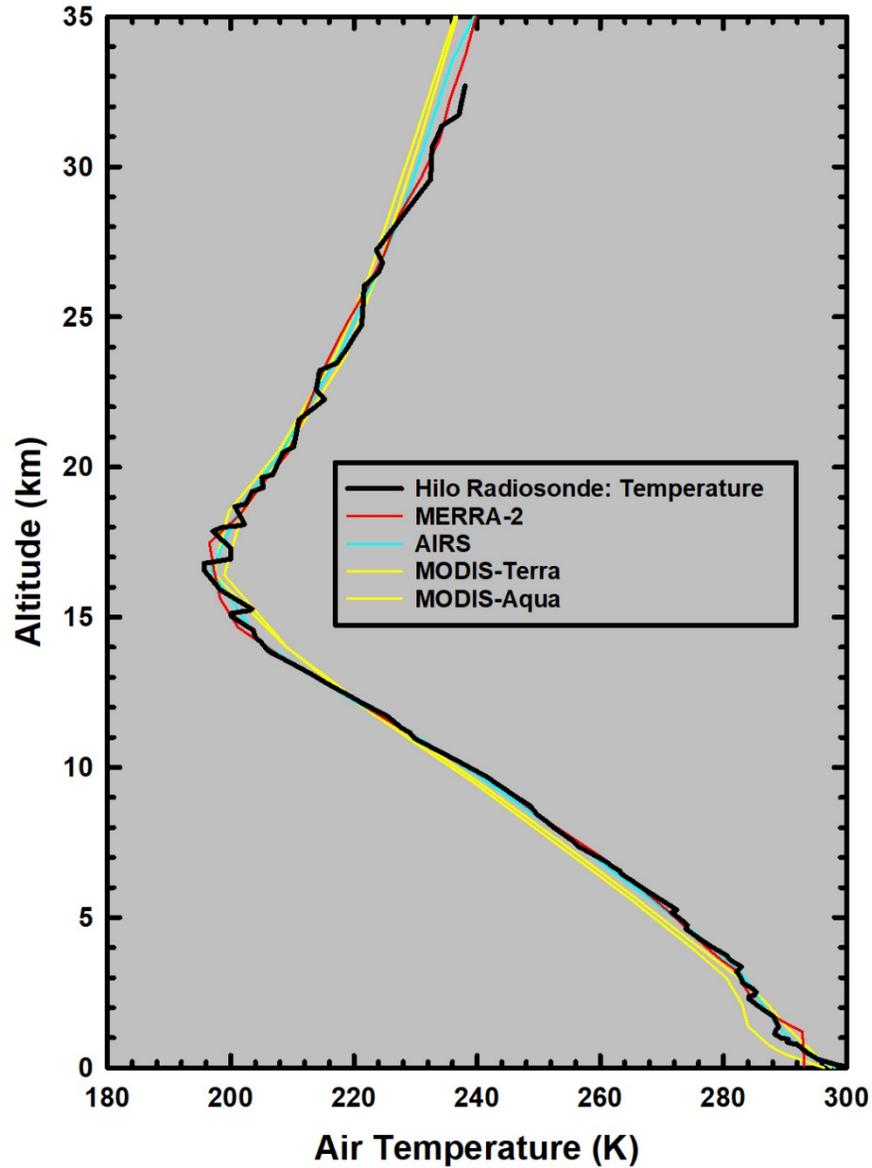


**We Require
Accurate
Knowledge of
Atmospheric
Temperature and
Water Vapor**

**Temperature
Profiles Generally
Well-Constrained
by Retrievals or
Reanalysis**

**Water Vapor
Profiles are More
Difficult to
Constrain:
Distribution of
Water Vapor is
Variable in Three
Dimensions**

Hilo (Hawaii) Radiosonde: 2018-05-06 (Local Time)



Retrieval of Surface Temperature and Gas Concentration

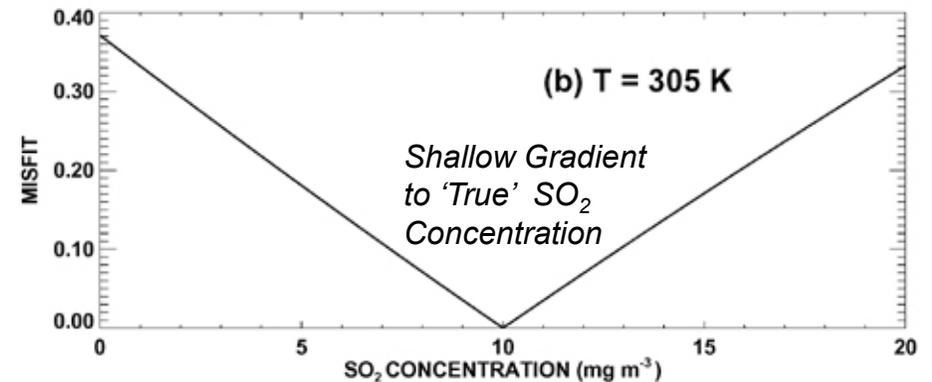
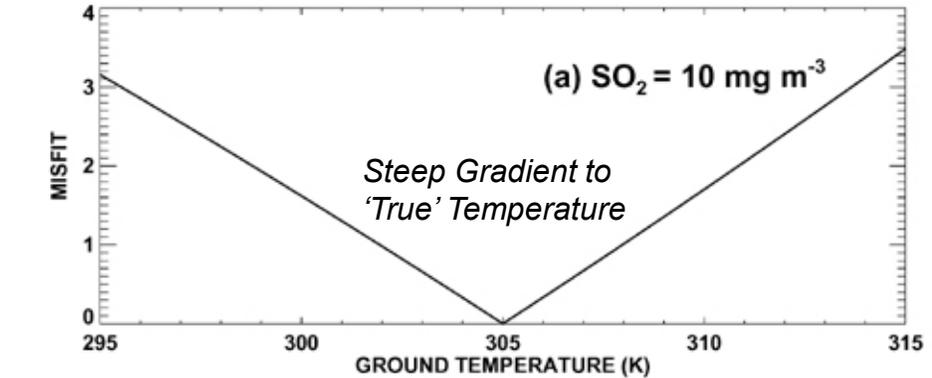
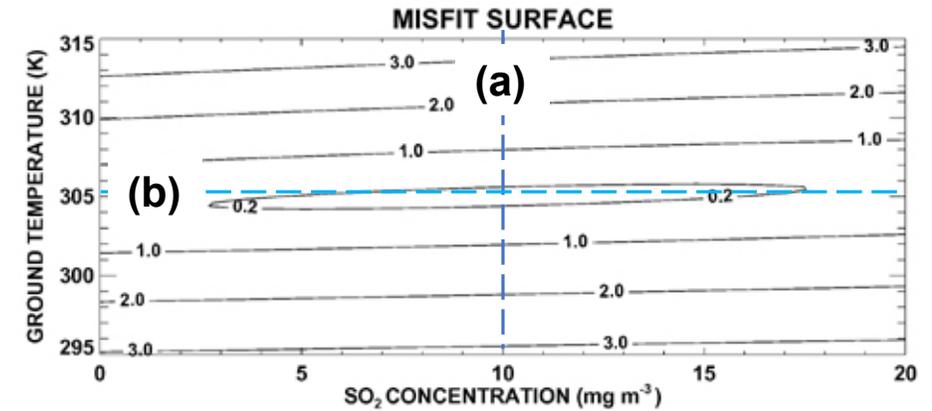
Temperature is Well-Constrained by TIR Radiance Measurements, Relative to the Constraint on Gas Concentration

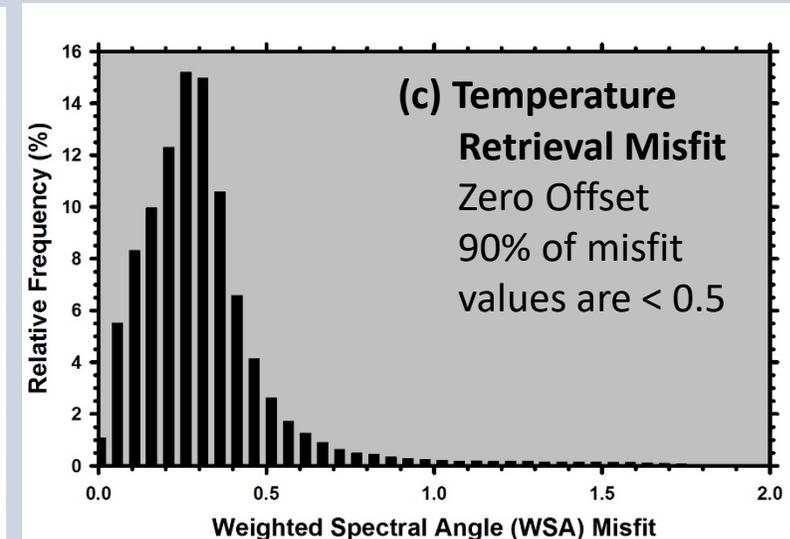
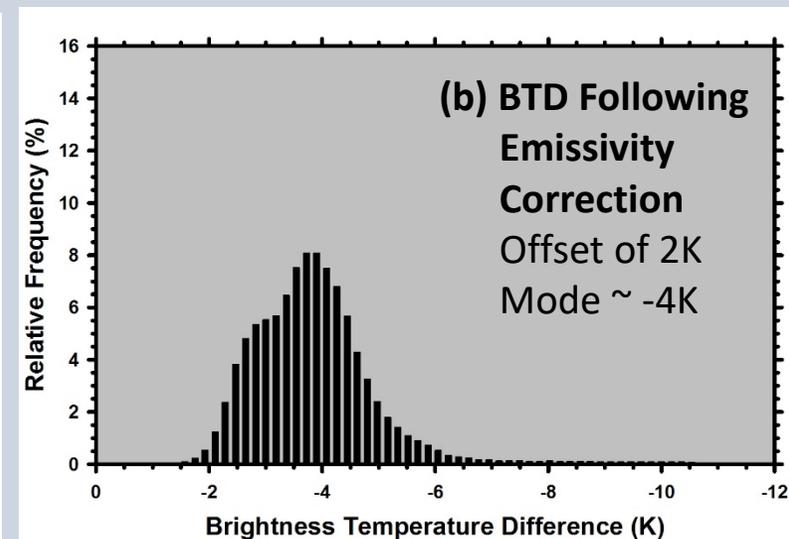
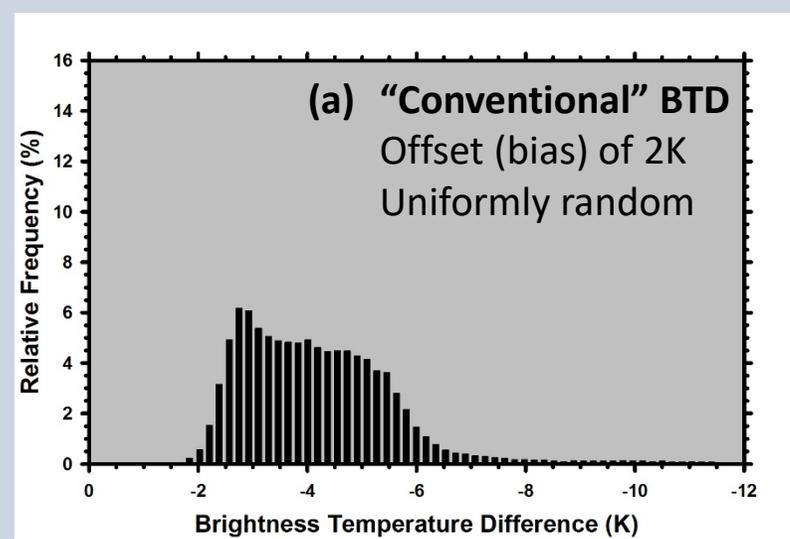
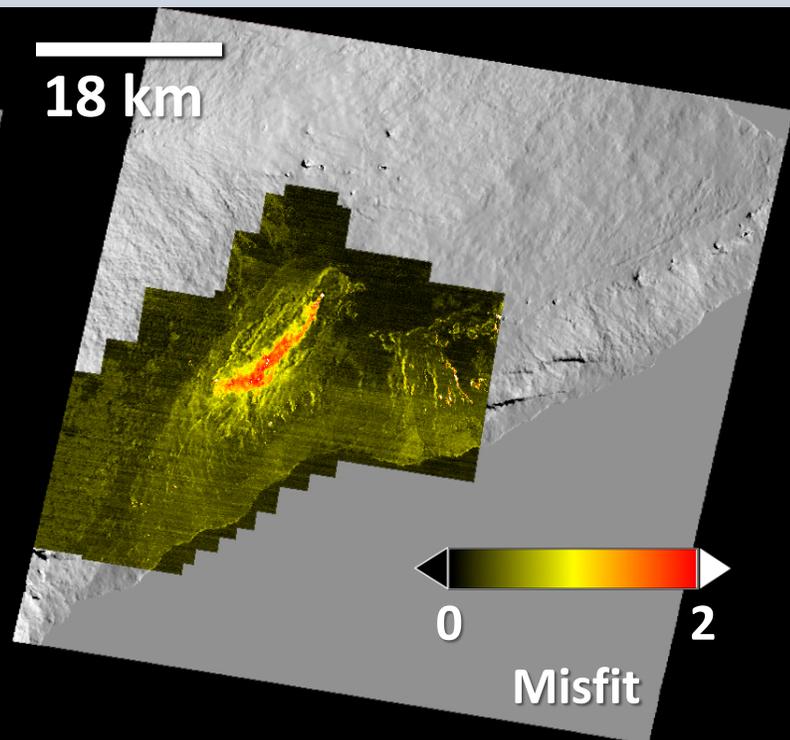
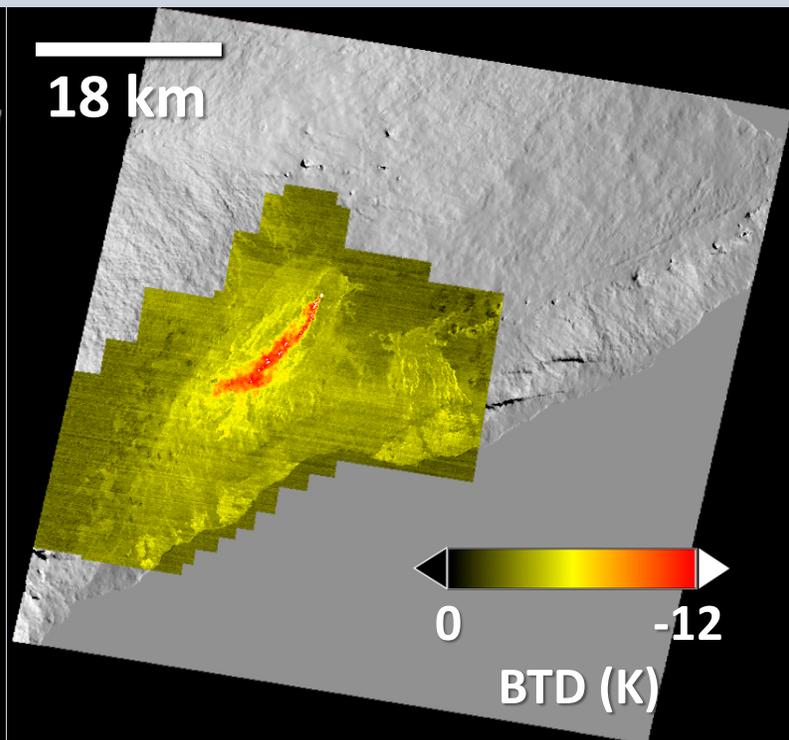
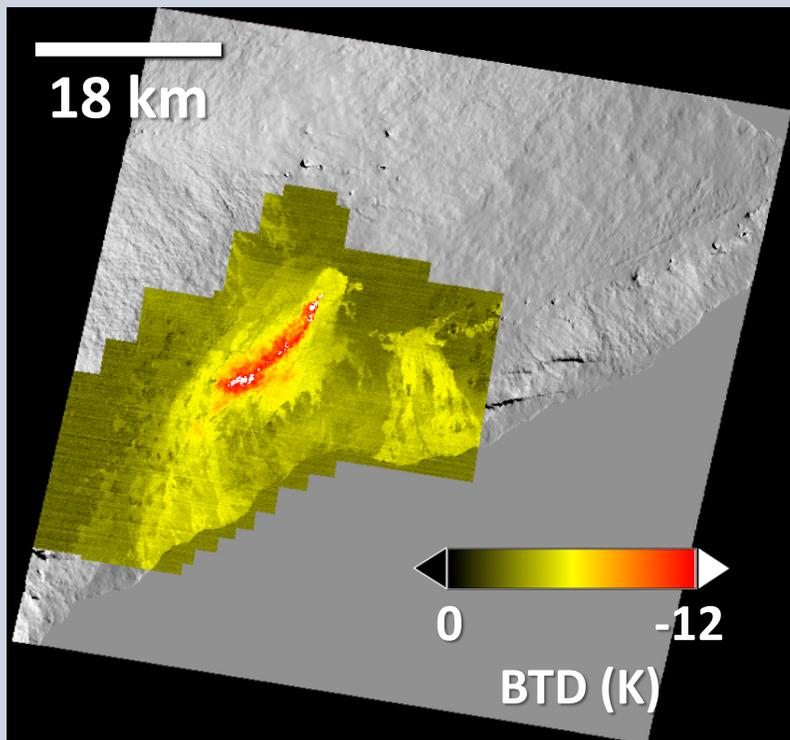
Simultaneous Retrieval of Temperature and Gas Concentration is Difficult:

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

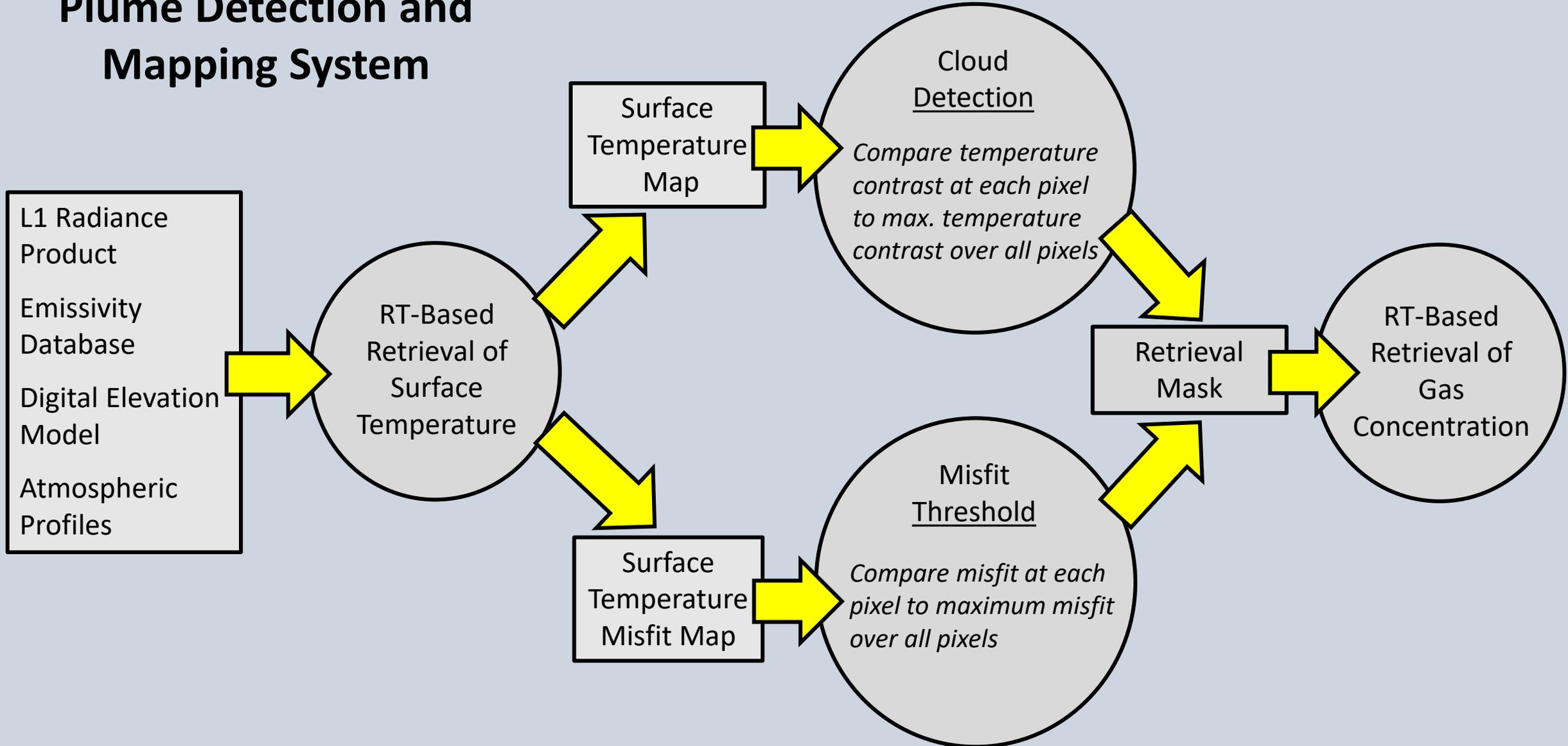
Cascading (Serial) Retrieval is a Better Approach

- Estimate Surface Temperature
- Estimate Gas Concentration



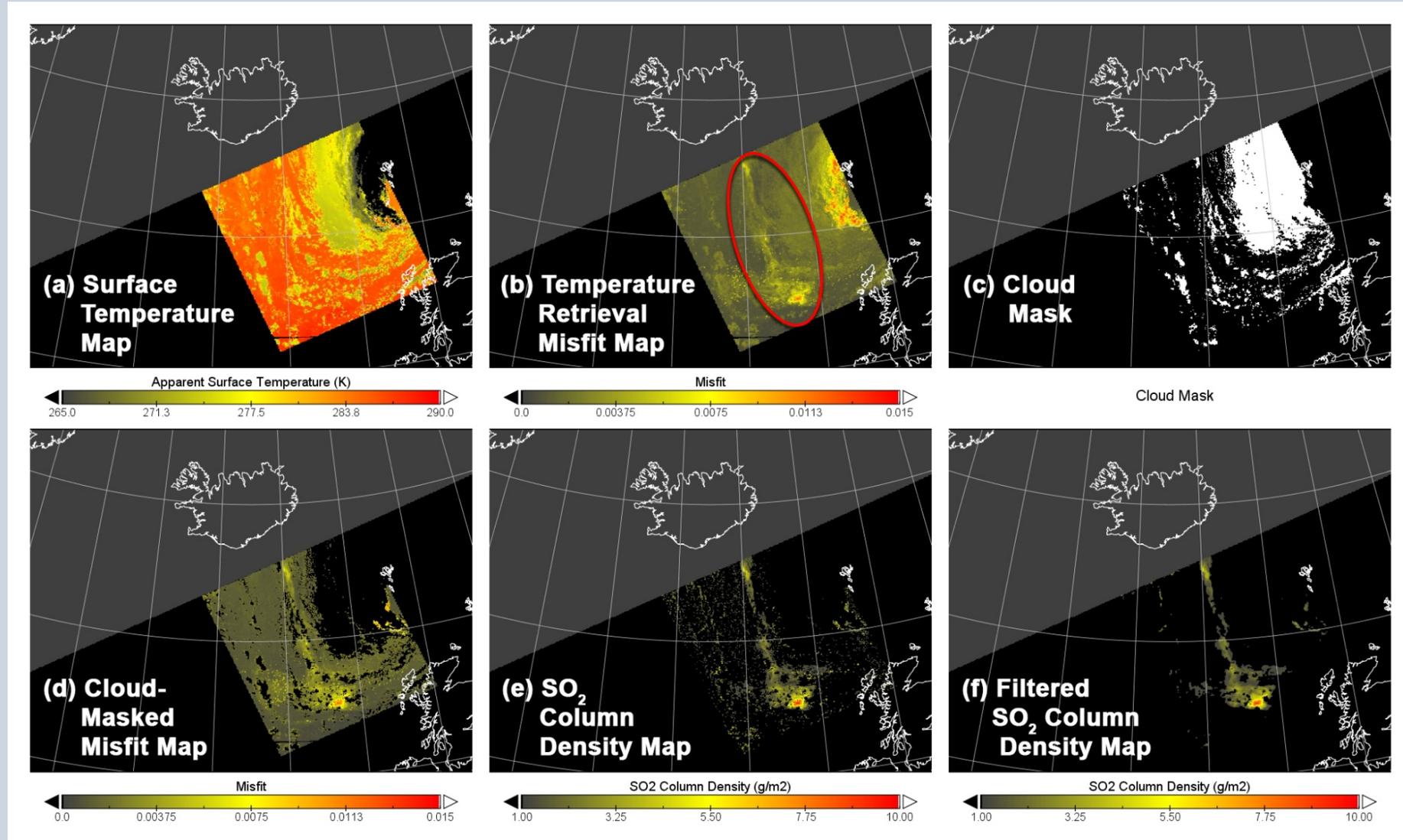


Flow Chart for Automated Plume Detection and Mapping System



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

- Surface temperature estimation does not consider volcanic plumes or met. clouds
- Misfit map shows the locations of plumes (red oval) and met clouds
- Met clouds are identified by comparing apparent surface temperature with air temperature at plume altitude
- Combination of cloud mask and misfit map improves the detection of volcanic plumes
- Estimation of SO_2 column density is confined to the locations identified by the masked misfit map
- SO_2 map is filtered to minimize the “holes” corresponding to the locations of met clouds.



Live Demonstration of Retrieval Procedures