

Mapping Volcanic Emissions with Interactive RT Modeling

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Government sponsorship acknowledged.*

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

Facilitates Analysis of Data from Multiple Instruments, with Ancillary Data from Multiple Sources

Graphic User Interface

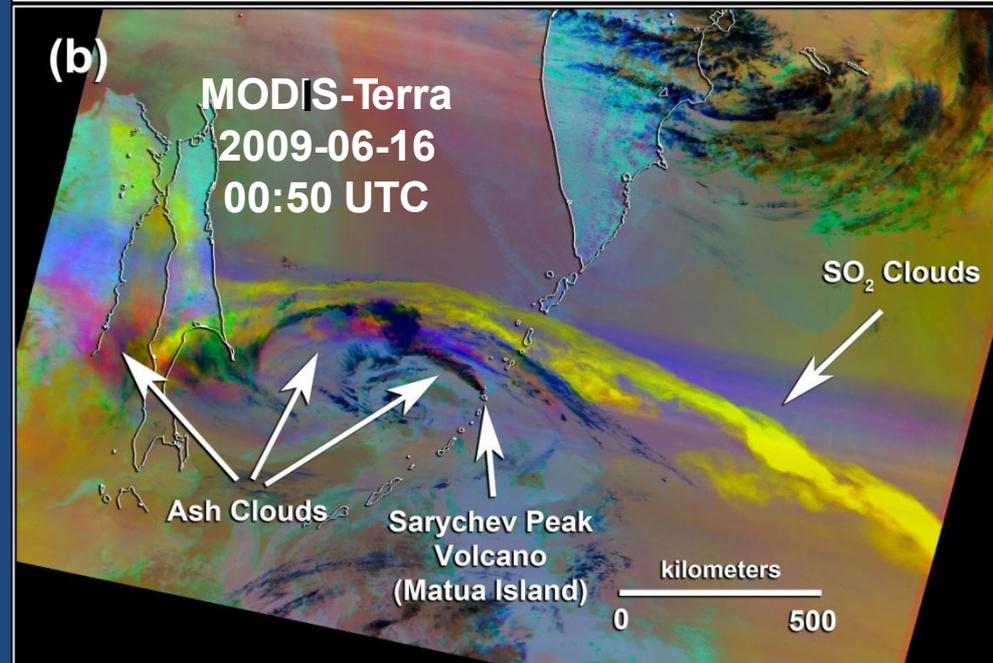
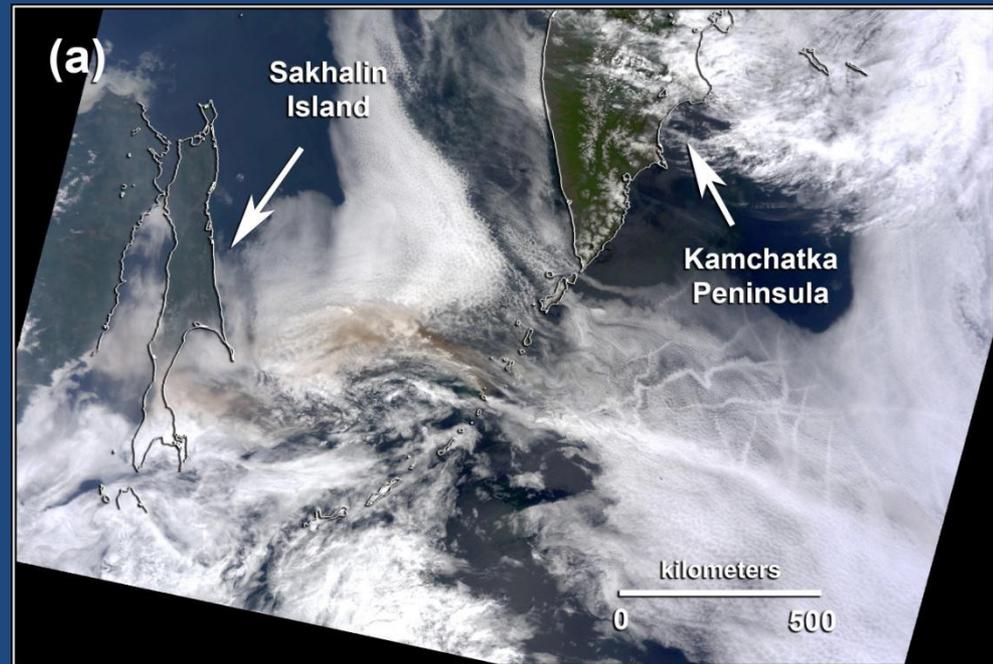
- Import Image and Ancillary Data
- Identify Regions-of-Interest for Mapping
- Visualize Input Data and Retrieval Results

Radiative Transfer Model Based on MODTRAN 3.5

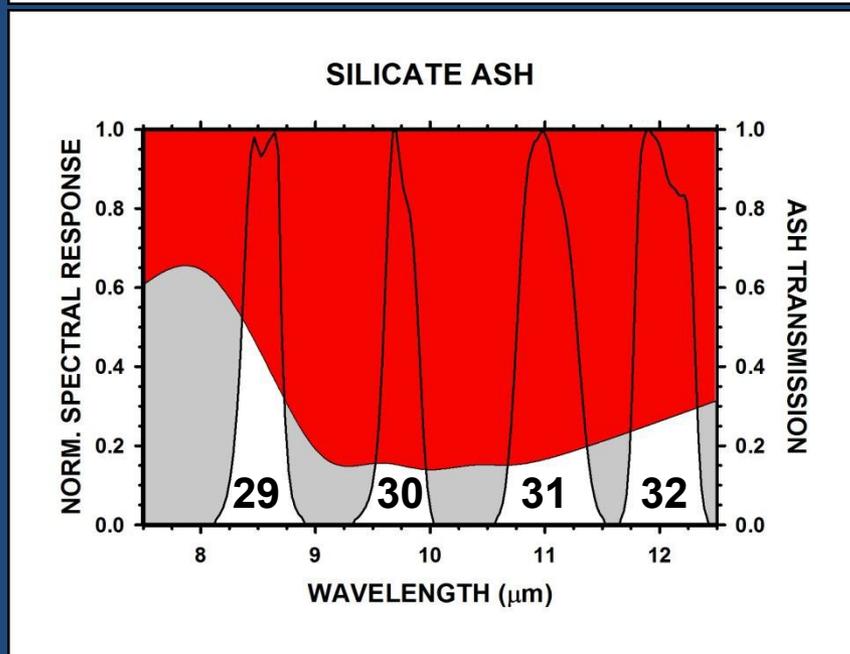
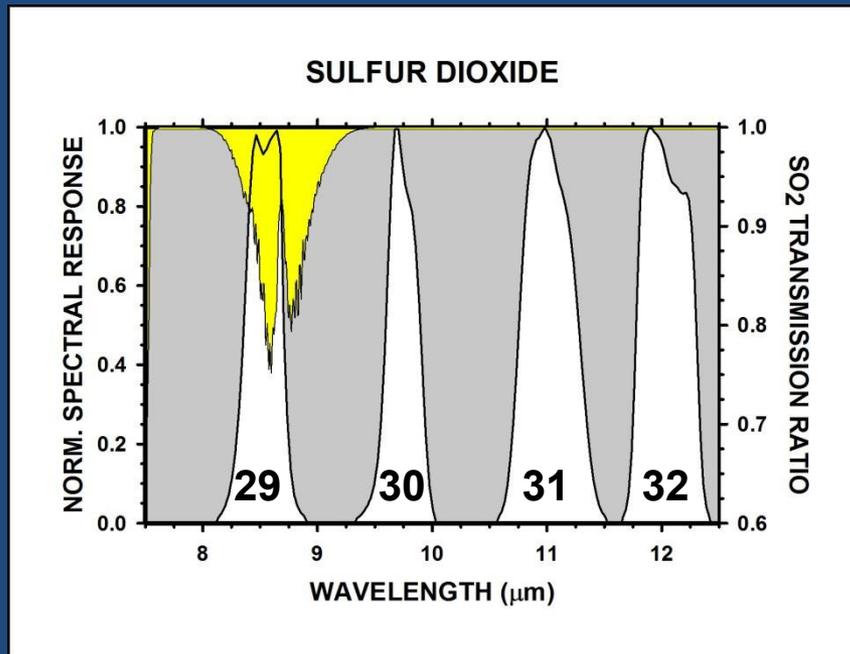
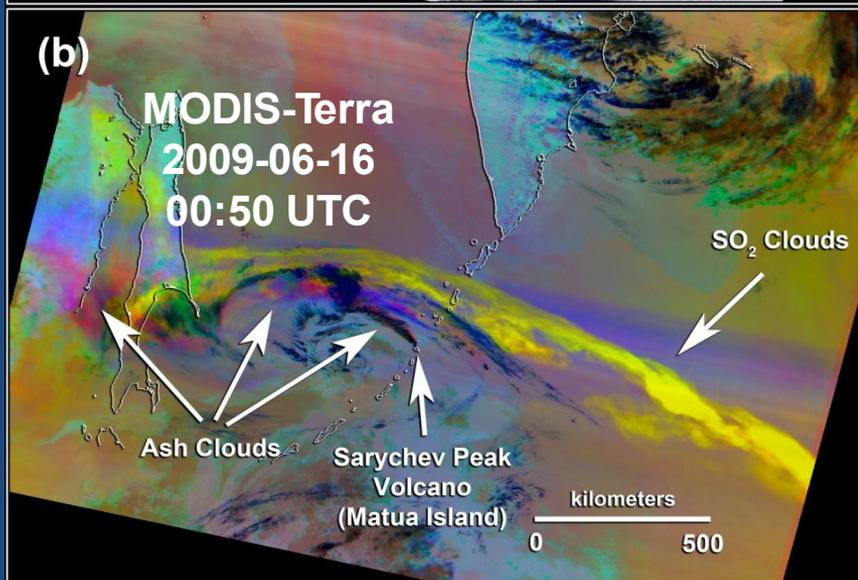
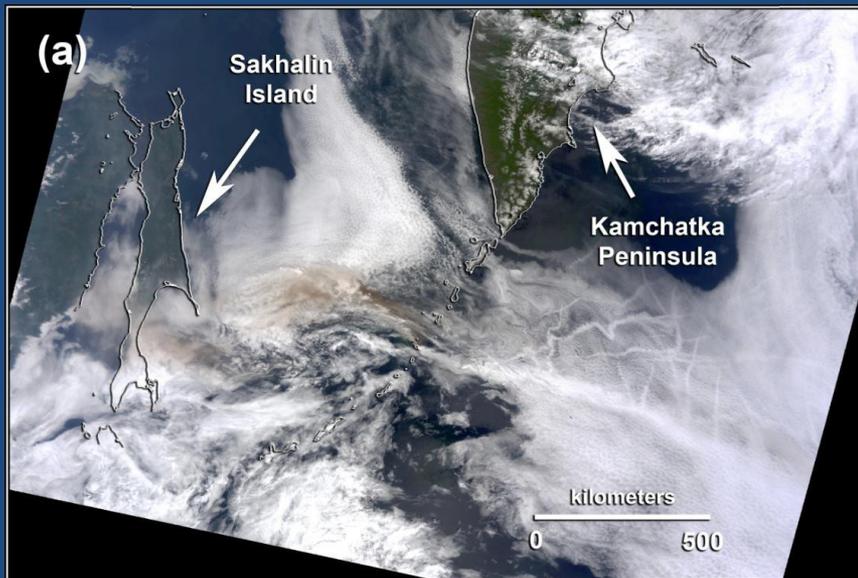
- Component Architecture
- Custom Formatting of Input Parameters for RT Model
- Communicate with Components via Interface Description Language (IDL)

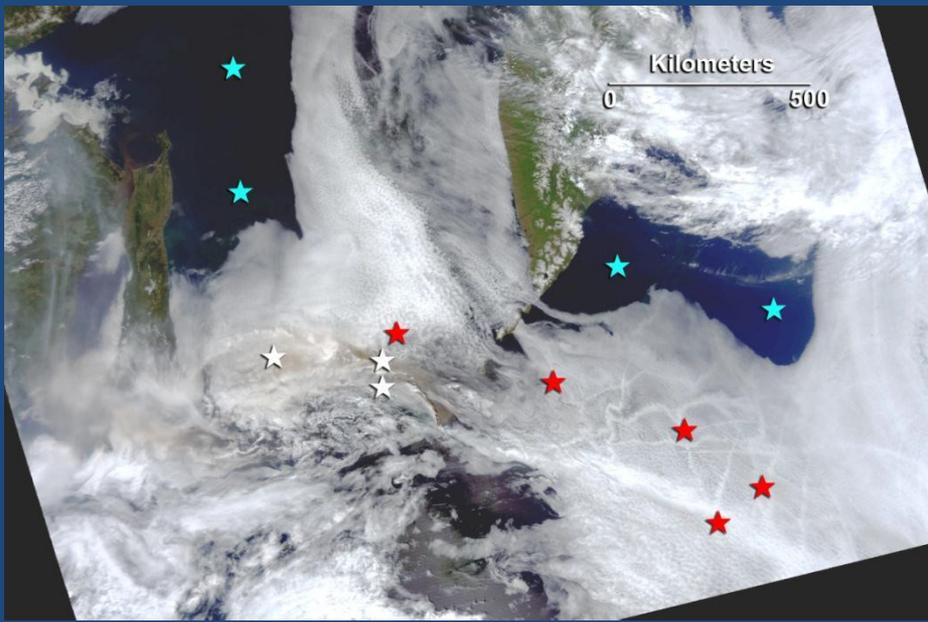
Retrieval Procedures

- Surface Emissivity
- Surface Temperature, SO₂, H₂O Vapor, and O₃
- Column Abundance/Total Column Retrievals
- Optimized for 2-Component Retrievals

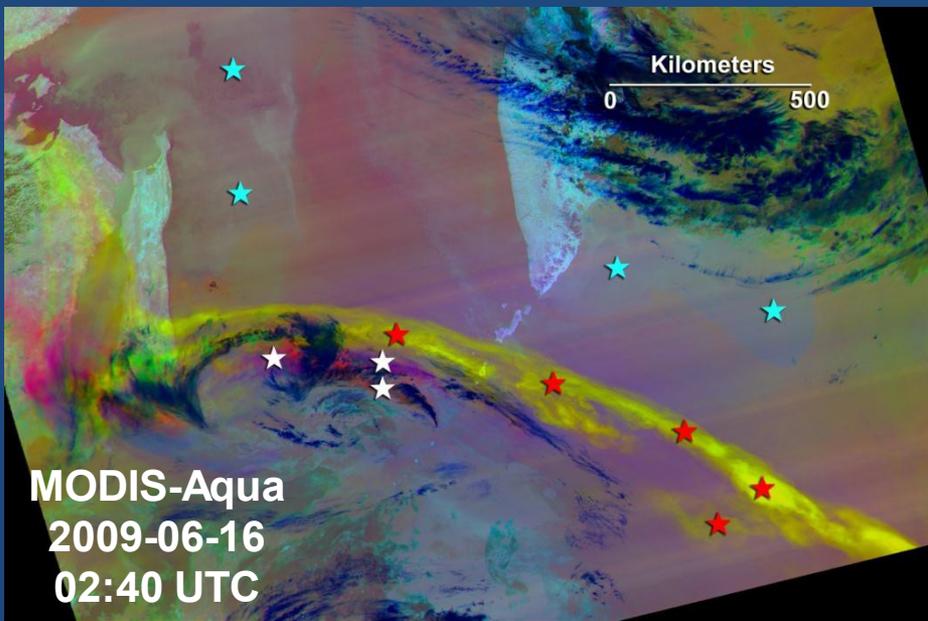


Detection of Volcanic Plumes in the Thermal Infrared (TIR)

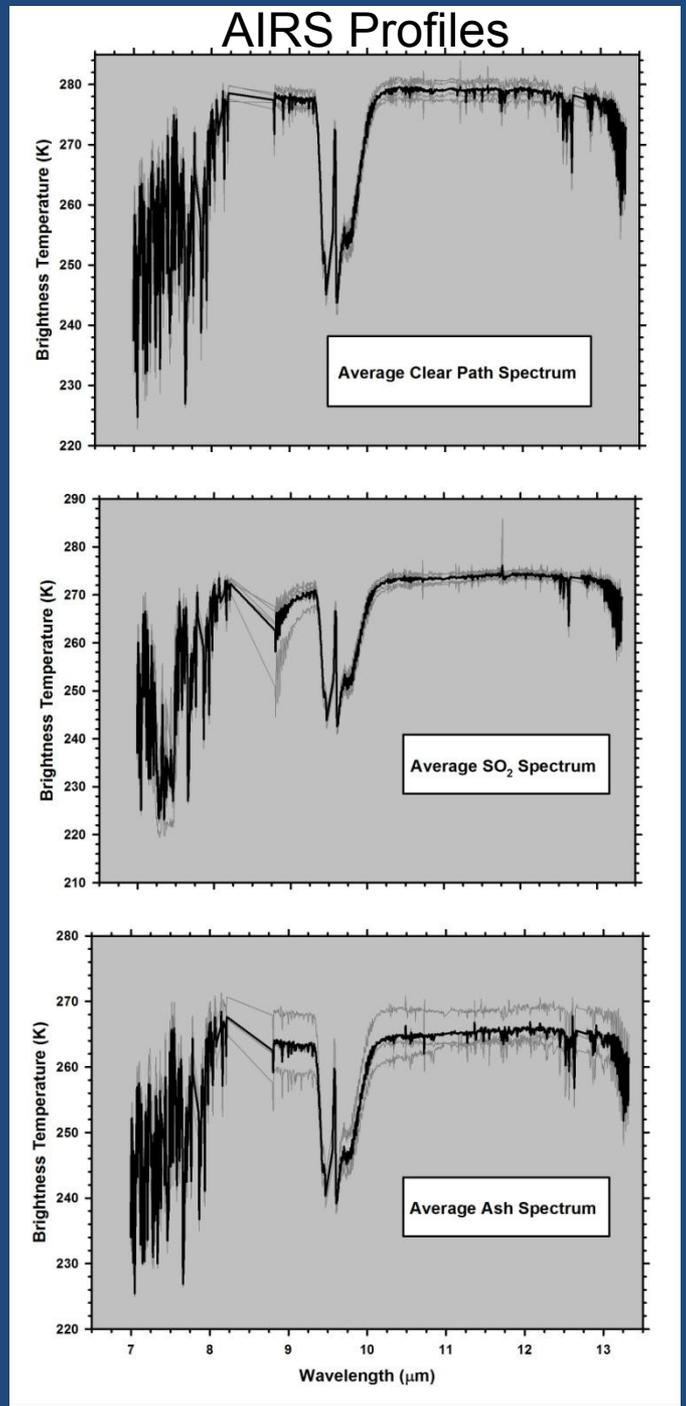


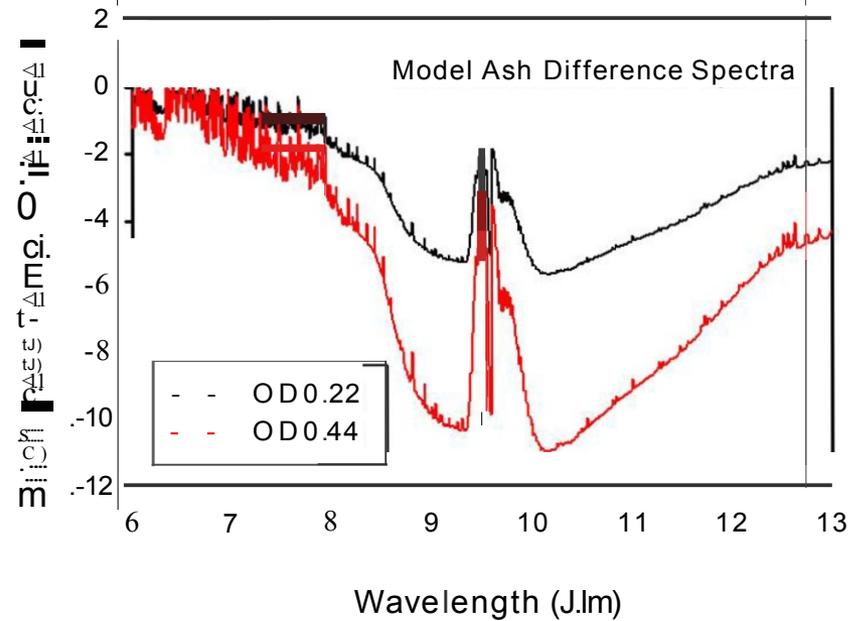
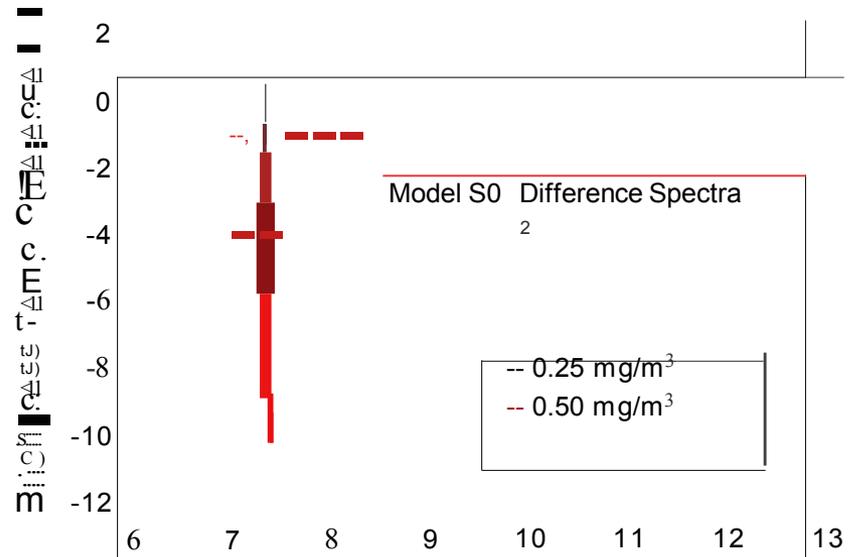
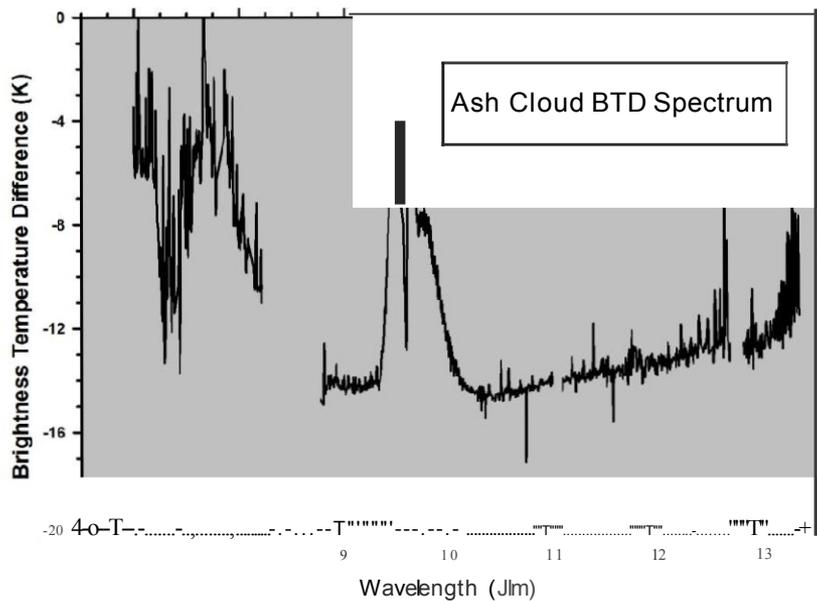
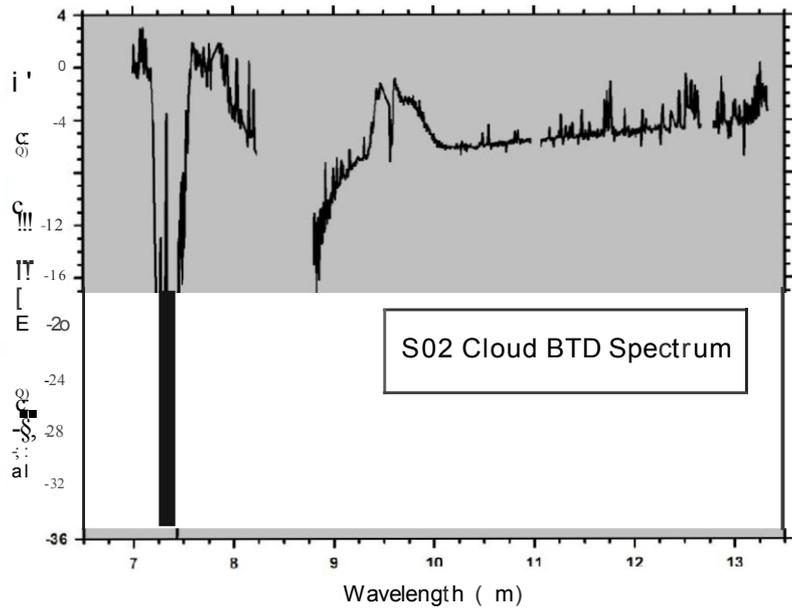


KEY



MODIS-Aqua
2009-06-16
02:40 UTC



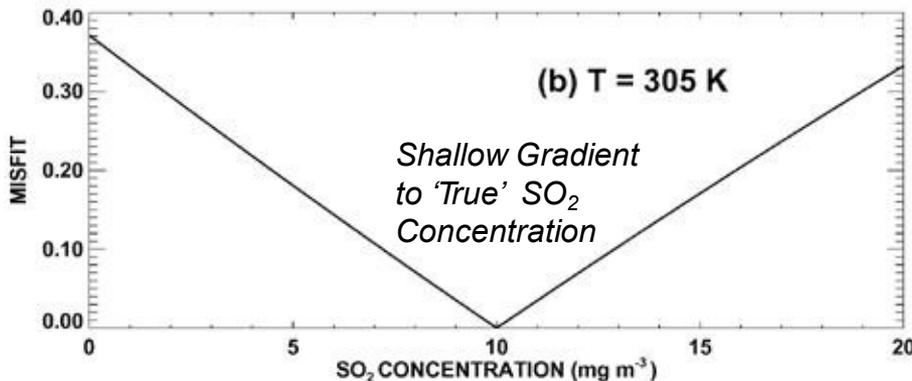
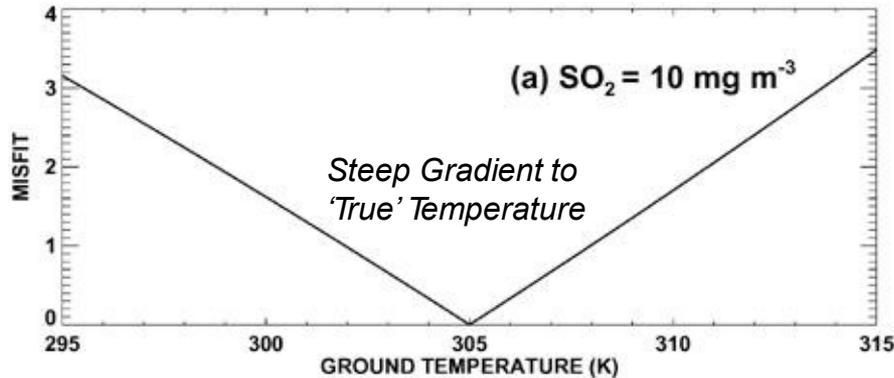
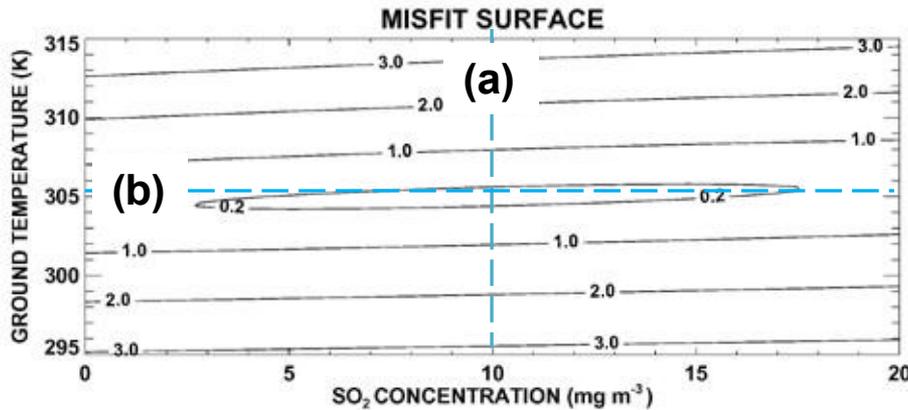
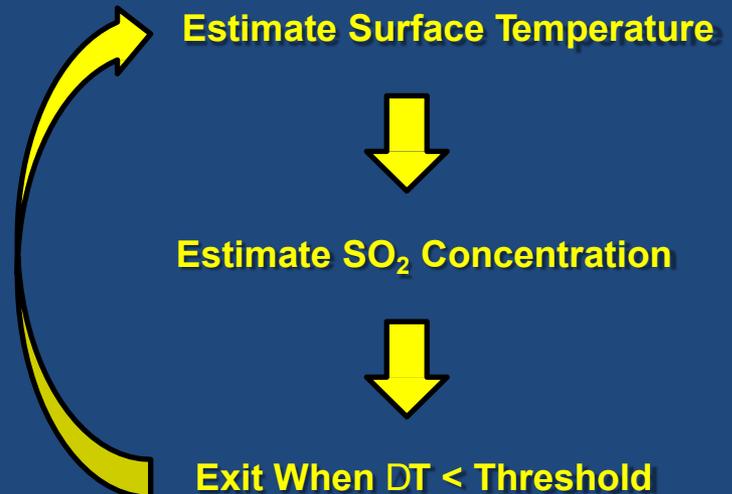


Retrieval of Surface Temperature and SO₂ Concentration

Temperature is Well-Constrained by Radiance Measurements but SO₂ is Poorly-Constrained

Simultaneous Retrieval of Temperature and SO₂ is Difficult

Cascading (Serial) Retrieval is a Better Option:



Hash Table (Associative Array): Acceleration of Retrieval Algorithm

Key(1)	MODTRAN Spectrum(1)
Key(2)	MODTRAN Spectrum(2)
Key(3)	MODTRAN Spectrum(3)
Key(4)	MODTRAN Spectrum(4)
...	...



Key(i) = [scan angle][surface elevation][surface T]
[H₂O factor][O₃ factor][SO₂ factor]

Scan Hash Table for Matches to Existing Keys

Associated Spectrum used for Matching Keys

New Table Entry for Unique Keys

Without Hash Table: ~ 12 sec/pixel (> 180 MODTRAN runs/pix)

With Hash Table: ~ 0.6 sec/pixel

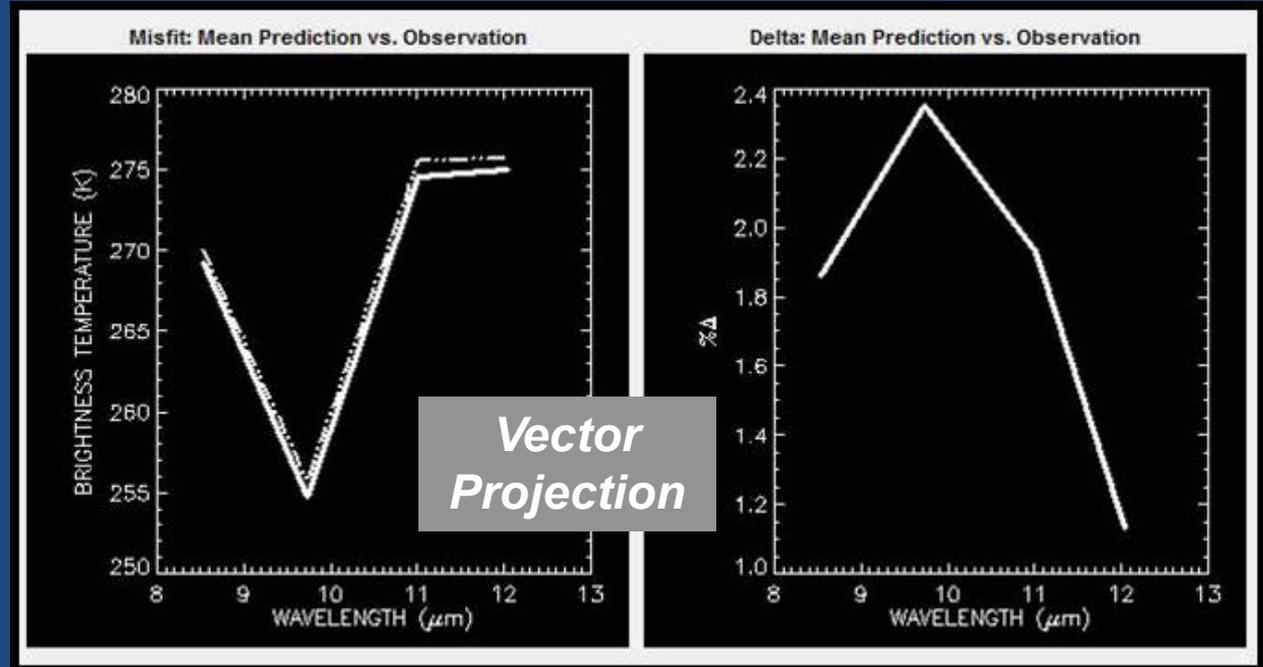
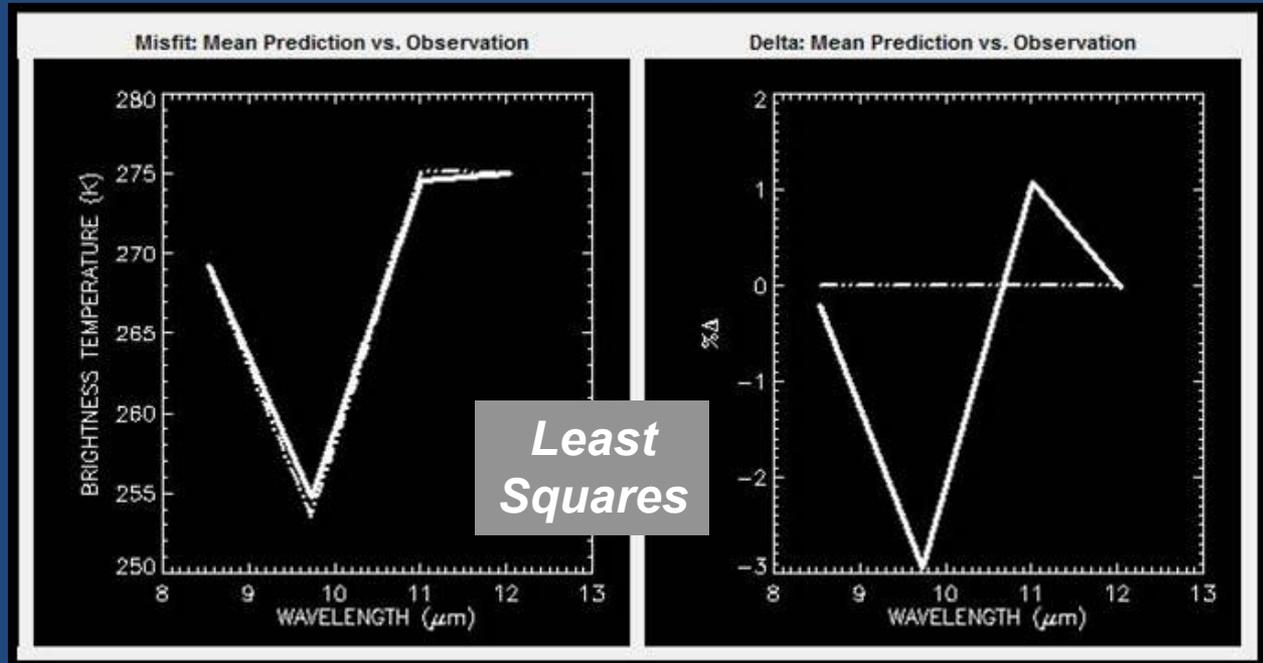
Misfit Calculation: Vector Projection vs. Least Squares

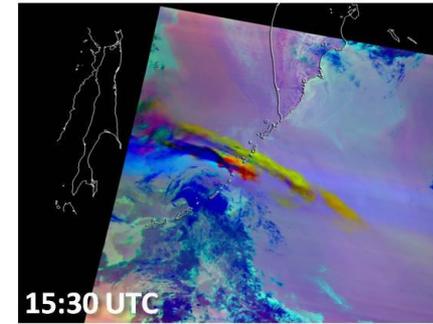
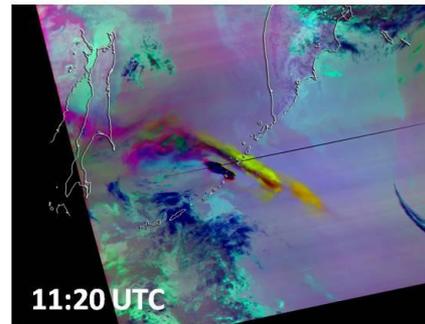
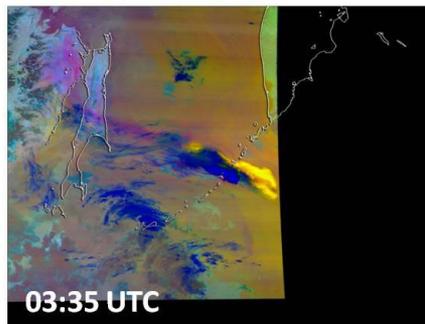
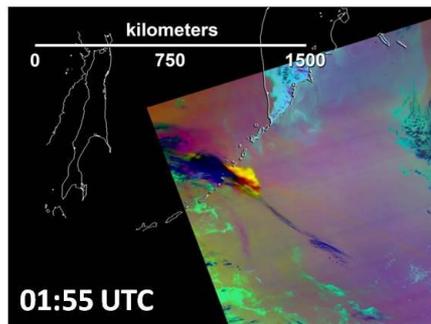
Least Squares:

- Optimal Fit to “Noisy” Data
- Equal Weight to all “Outliers”

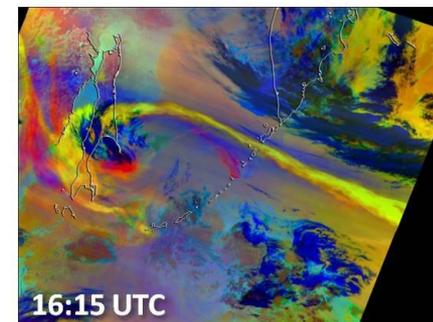
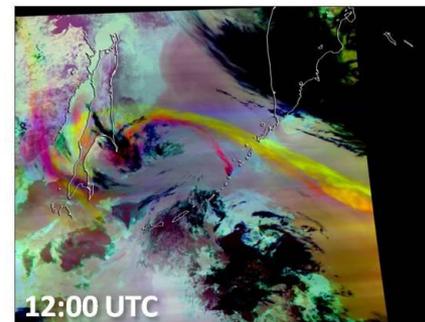
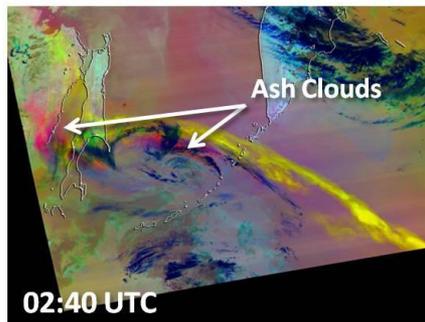
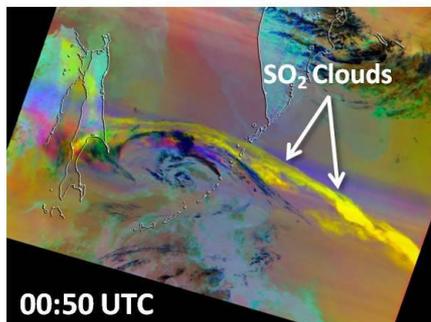
Vector Projection:

- “Spectral Angle Mapping:” Dot Product between Two n-Dimensional Unit Vectors
- Minimize Angle Between Vectors





(a) 2009-06-15



(b) 2009-06-16

[Rybin et al., 2011]

1509-06-15: Cloud Formation

Six Explosive Eruptions, with Five Injections into the Stratosphere (Altitude > 12 km)

15:30 (UTC): Leading Edge of Cloud Band was 14.5 hrs. old; Trailing Edge was 4.5 hrs. old

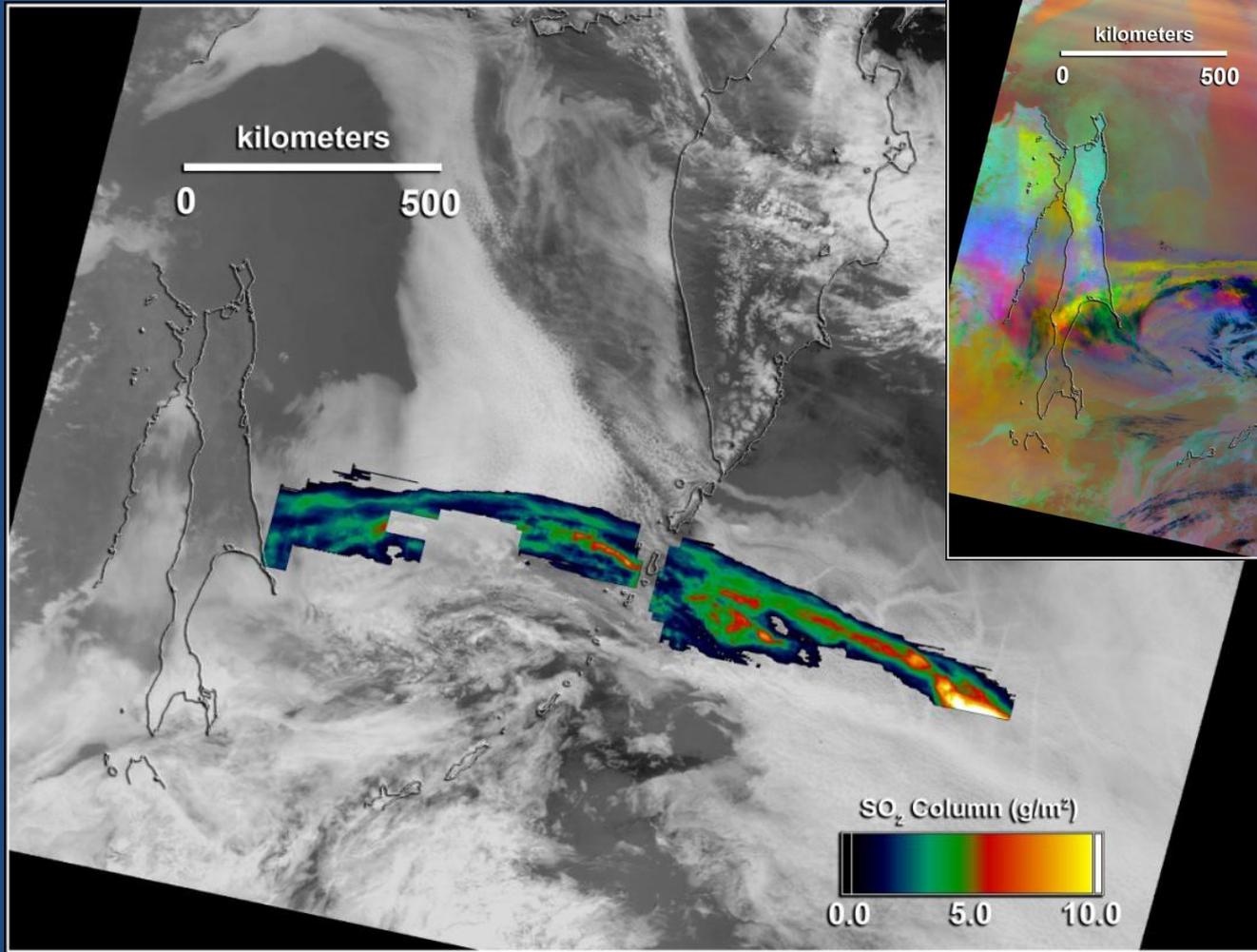
Major Explosion @ 16:55 UTC: Eruption Column to Altitude of 18 km

1609-06-16: Cloud Dispersion

No New Explosions Between 00:50 and 16:15 UTC

Time-Series Shows Transport and Dispersal of 2009-06-15 Clouds

Long-Lived Clouds: By 16:15 UTC the Youngest Clouds > 23 hrs old



MODIS-Terra Overpass

2009-06-16
00:50 UTC

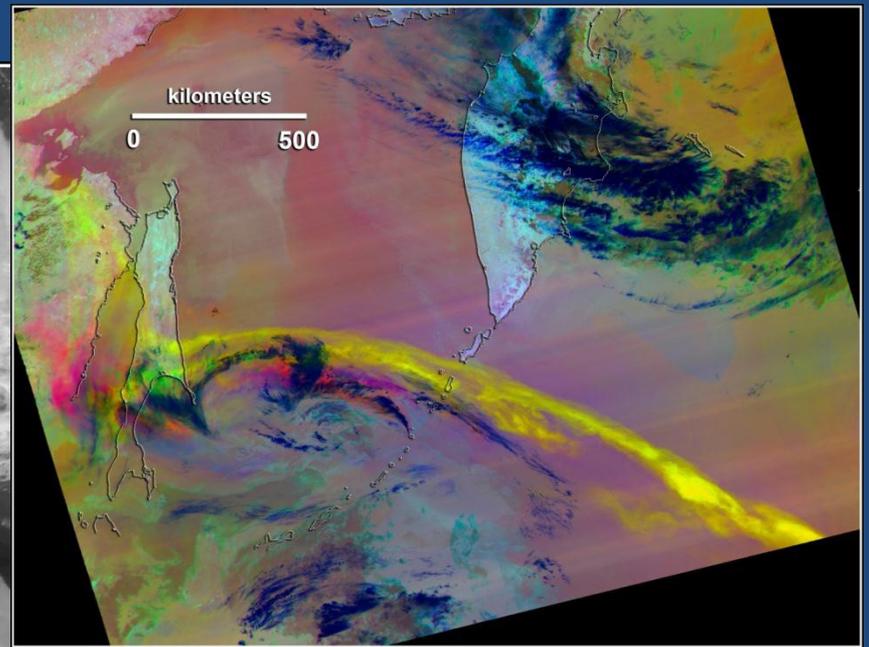
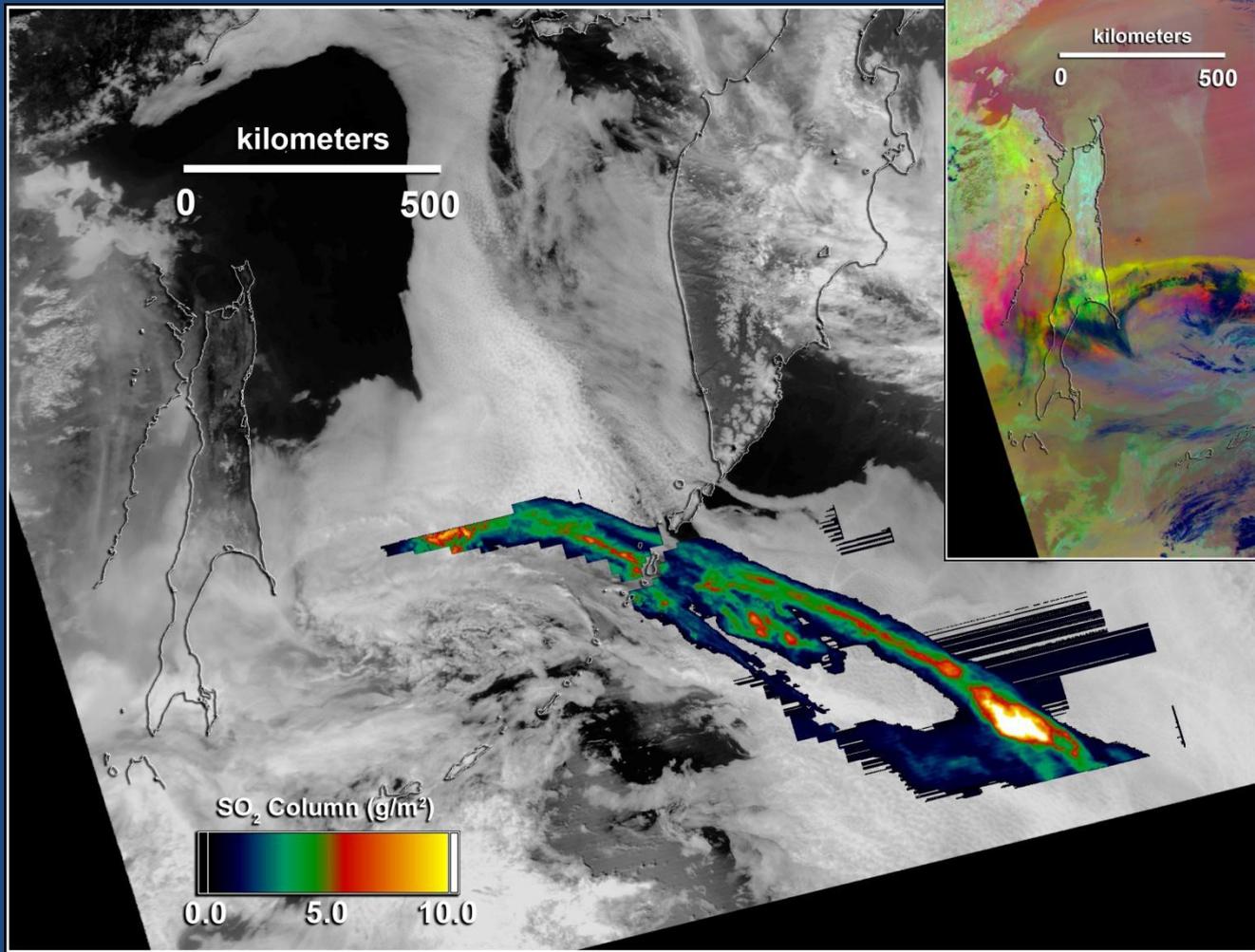
Elapsed Time Since Explosion

2009-06-15	00:57 UTC	+ 24 hr
2009-06-15	10:55 UTC	+ 14 hr
2009-06-15	16:55 UTC	+ 8 hr

Leading and Trailing Edges of Cloud Band had
Similar Concentrations of SO₂ Despite 16 hr.

Difference in Age

- Negligible Rate of SO₂ Depletion?
- Over-Printing by 16:55 (UTC) Eruption?



MODIS-Aqua Overpass

2009-06-16
02:40 UTC

Elapsed Time Since Explosion

2009-06-15	00:57 UTC	+ 27 hr
2009-06-15	10:55 UTC	+ 17 hr
2009-06-15	16:55 UTC	+ 11 hr

- Little Change in Concentration or Position of Cloud Bands Since Terra Overpass (+ 3 hrs)
- Results Suggest that 16:55 (UTC) Eruption Did Not Over-Print the Older Clouds
- Slow Rates of SO₂ Depletion in Stratosphere

AIRS-Based SO₂ Retrievals

1420 Channels Between 7 – 14 μm

- Gap in Spectral Coverage Excludes the 8.5 μm SO₂ Feature

High Spectral Resolution Allows Unique Identification of Plume Constituents

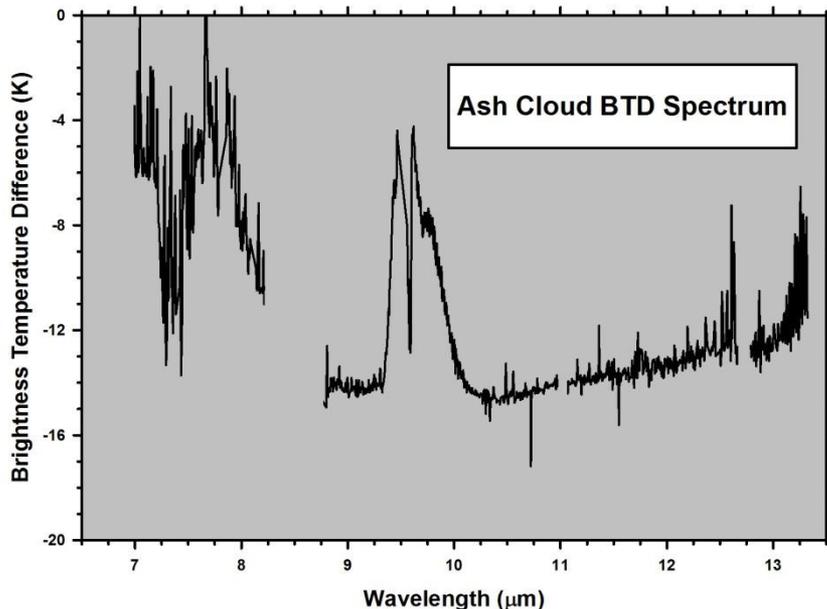
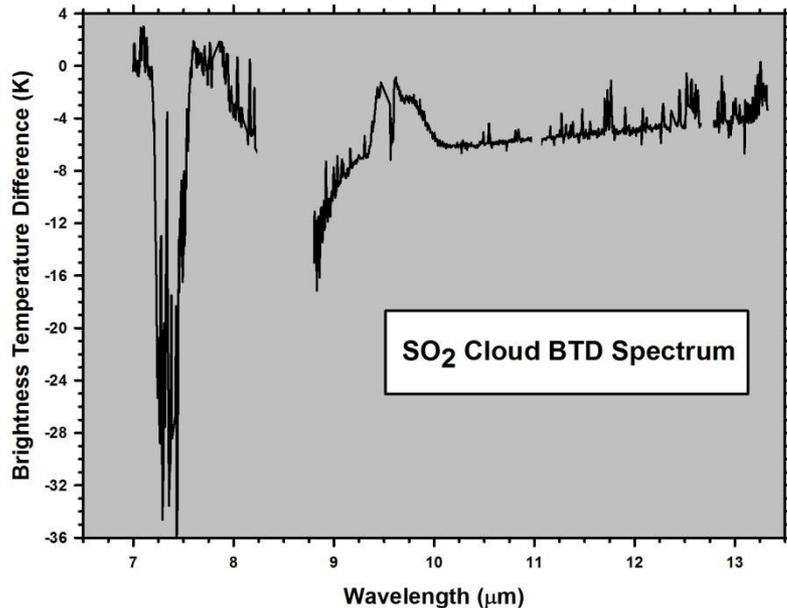
Standard (L2) Products include Profiles of Atmospheric Temperature, Water Vapor, and Ozone

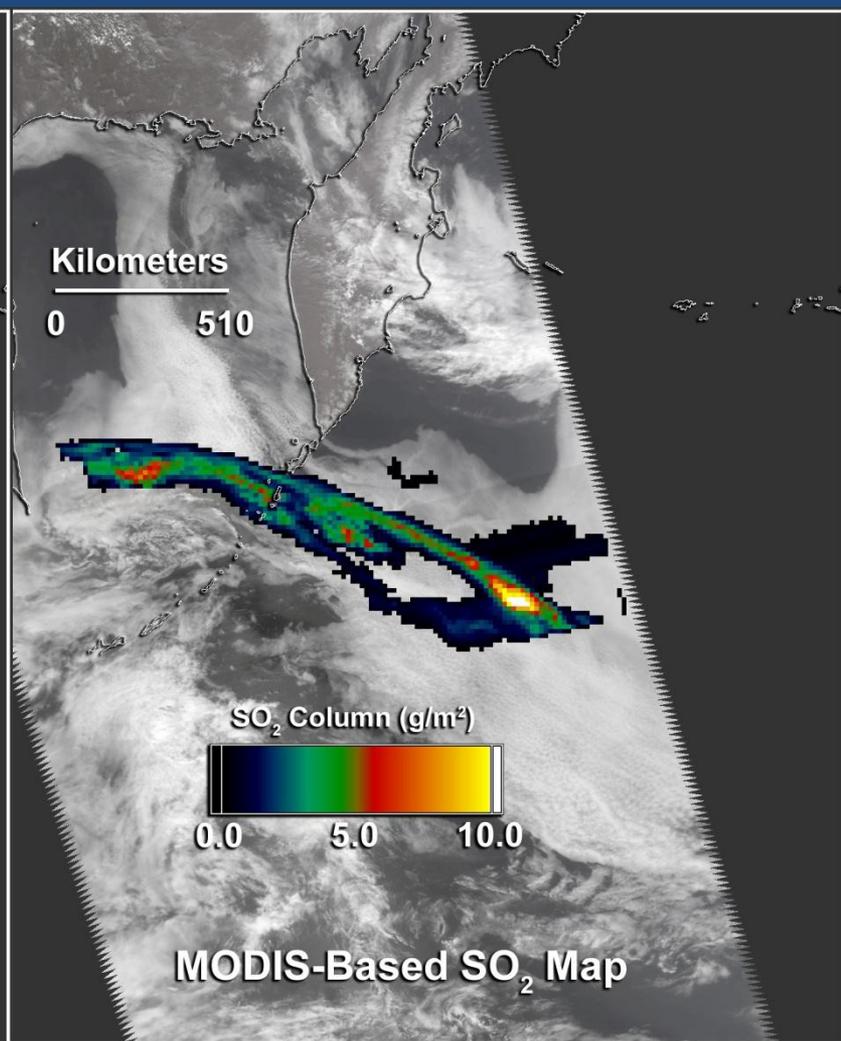
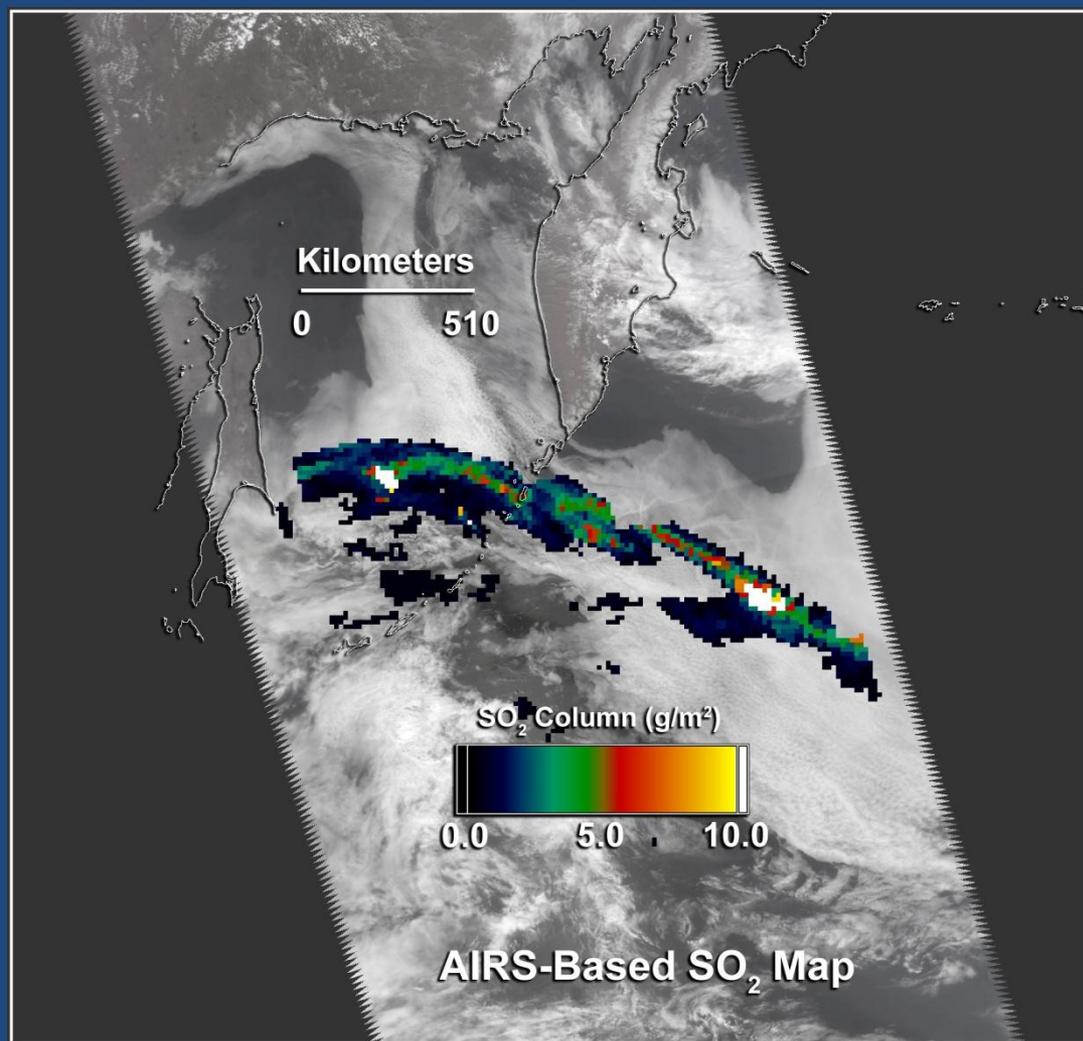
Data Acquisition is Coincident with MODIS-Aqua

Low Spatial Resolution: ~14 km @ nadir

- MODIS: 1 km @ nadir
- ASTER : 90 m

Spatial Resolution of L2 Products ~ 40 km @ nadir





Comparison of AIRS- and MODIS-Based SO₂ Retrievals

MODIS Results Re-Sampled to Spatial Resolution of AIRS

Excellent Agreement Between AIRS and MODIS Results:

AIRS Saturates for High Concentrations of SO₂ (7.3 nm vs. 8.5 nm Absorption)

AIRS Processing Time << MODIS Processing Time (10² pixels vs. 10⁵ pixels)

ASTER-Based SO₂ Retrievals

Co-Incident with MODIS-Terra Acquisition
(2009-06-16 @ 00:50 UTC)

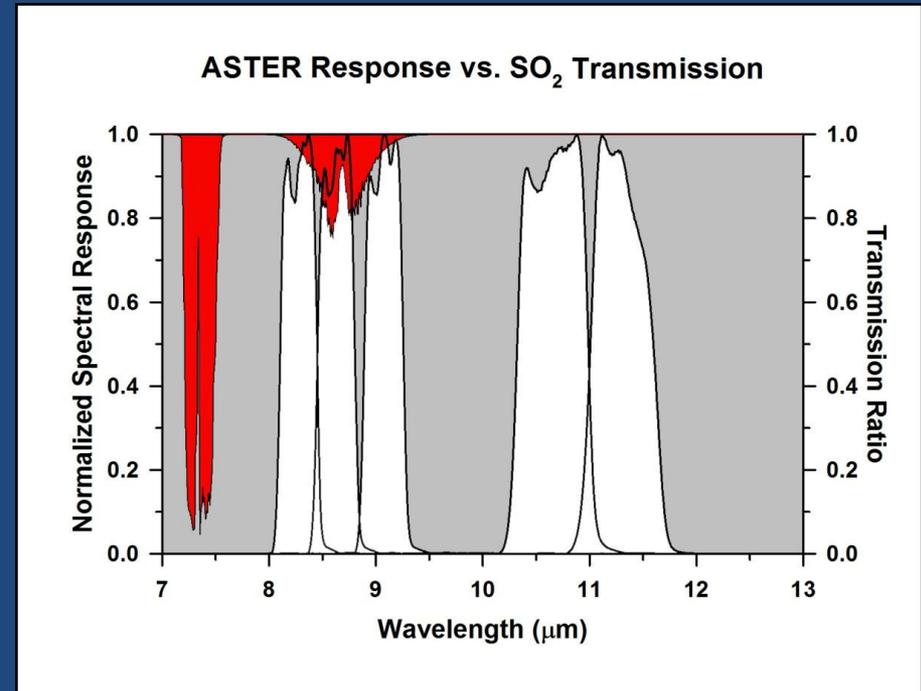
High Spatial Resolution (90 m) Allows Us
to Map SO₂ Concentration Near Source

Continuous Emission of Ash

- Plume Opaque in the TIR
- Map SO₂ in the Margins of Plume

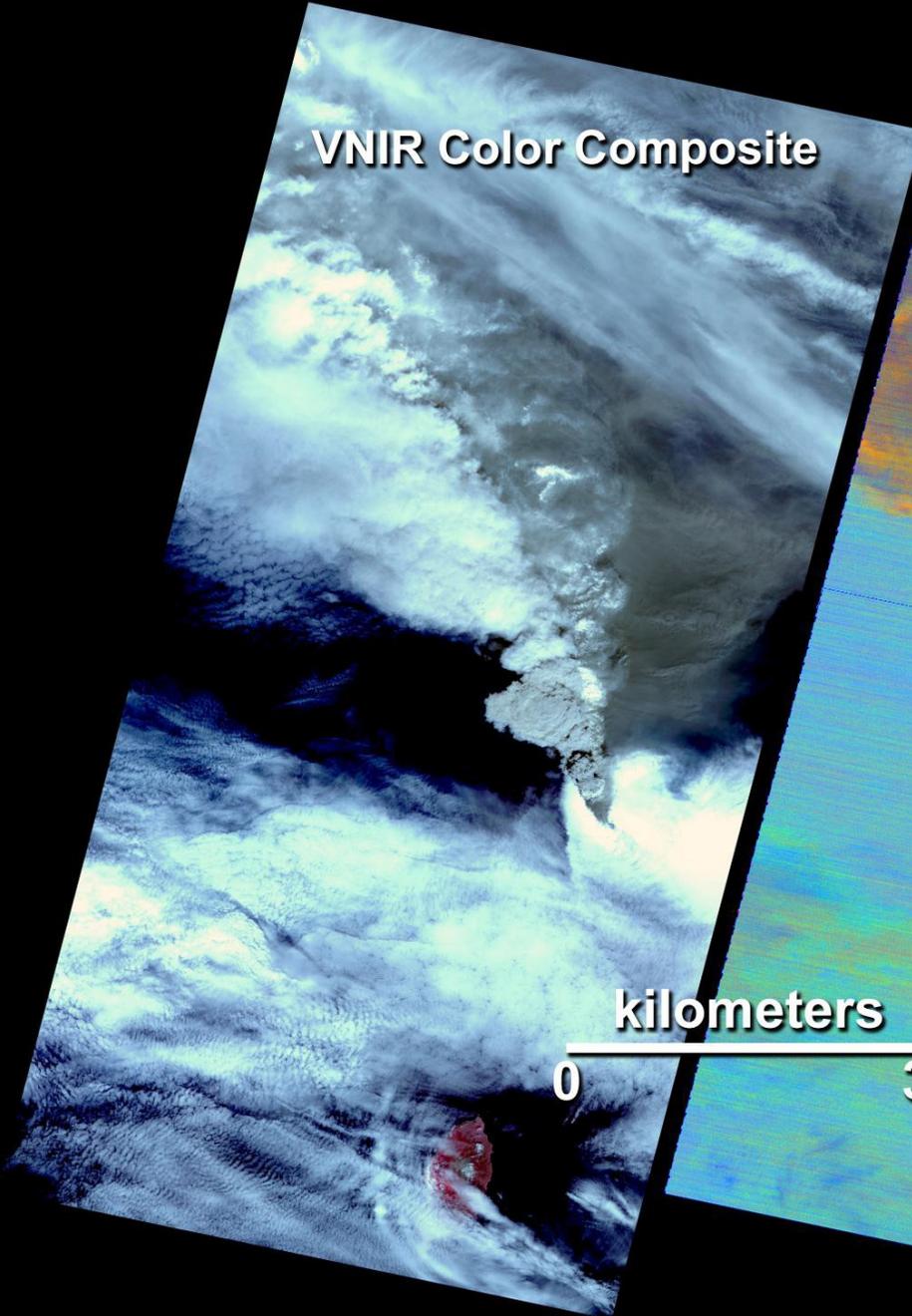
SO₂ Concentrations in Plume Margin
Similar to Those in Body of Stratospheric
Cloud Bands

- Further Evidence for Slow Rates of
SO₂ Depletion?



VNIR Color Composite

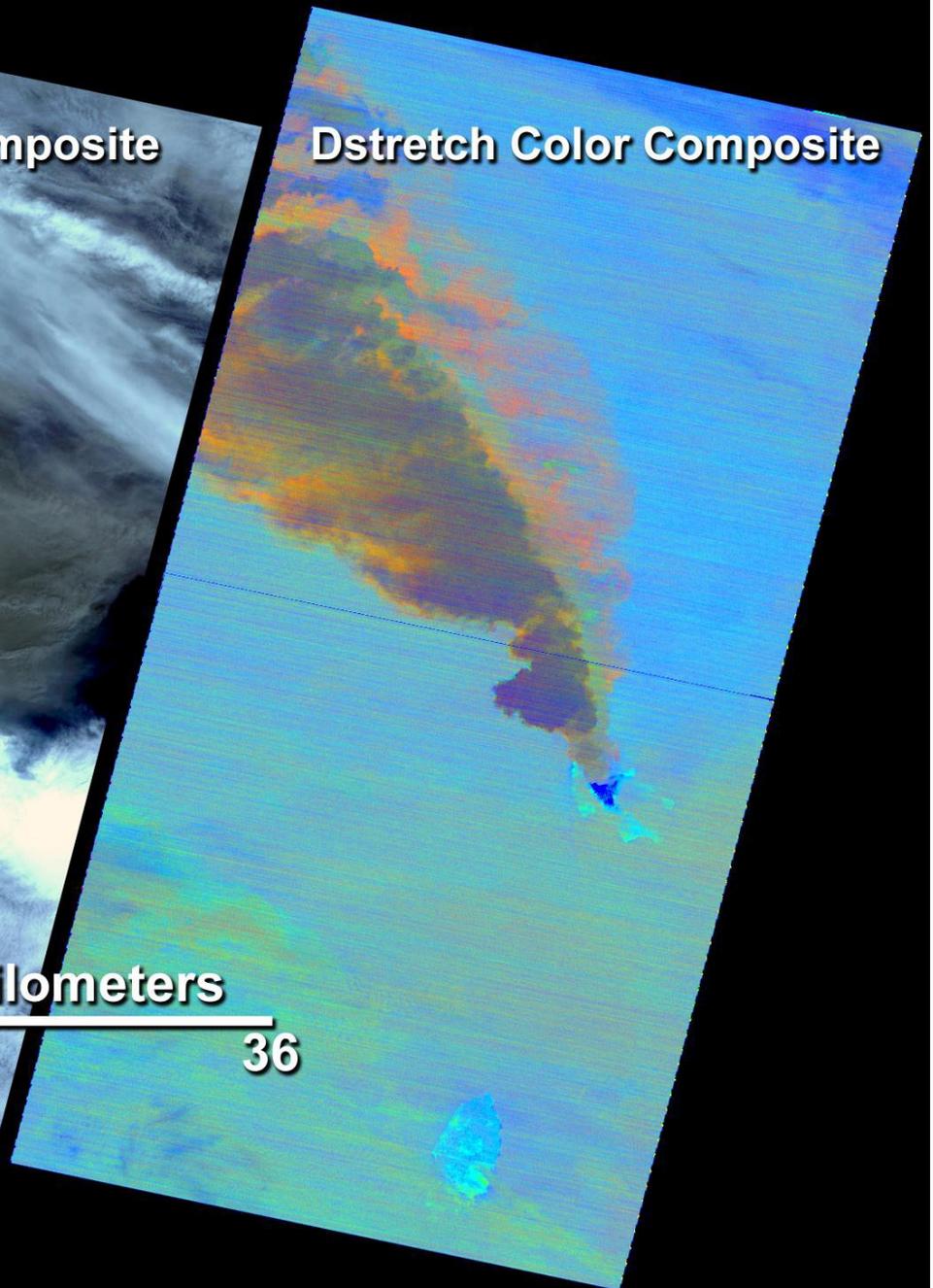
Dstretch Color Composite



kilometers

0

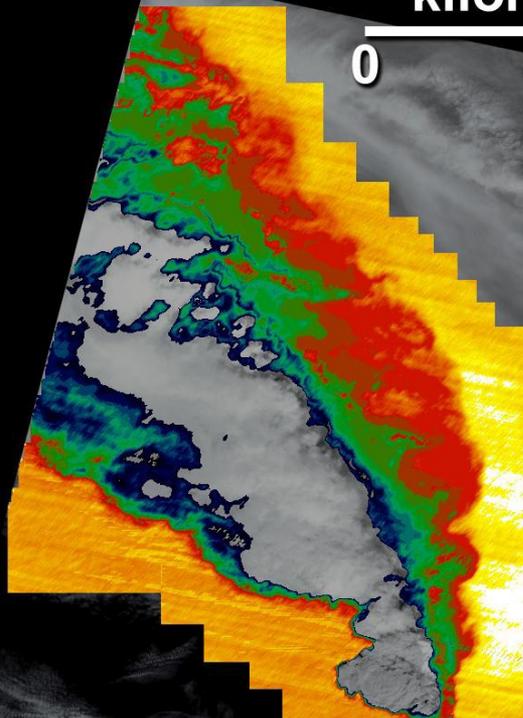
36



kilometers

0

36



Apparent Surface Temp (K)



250

265

280

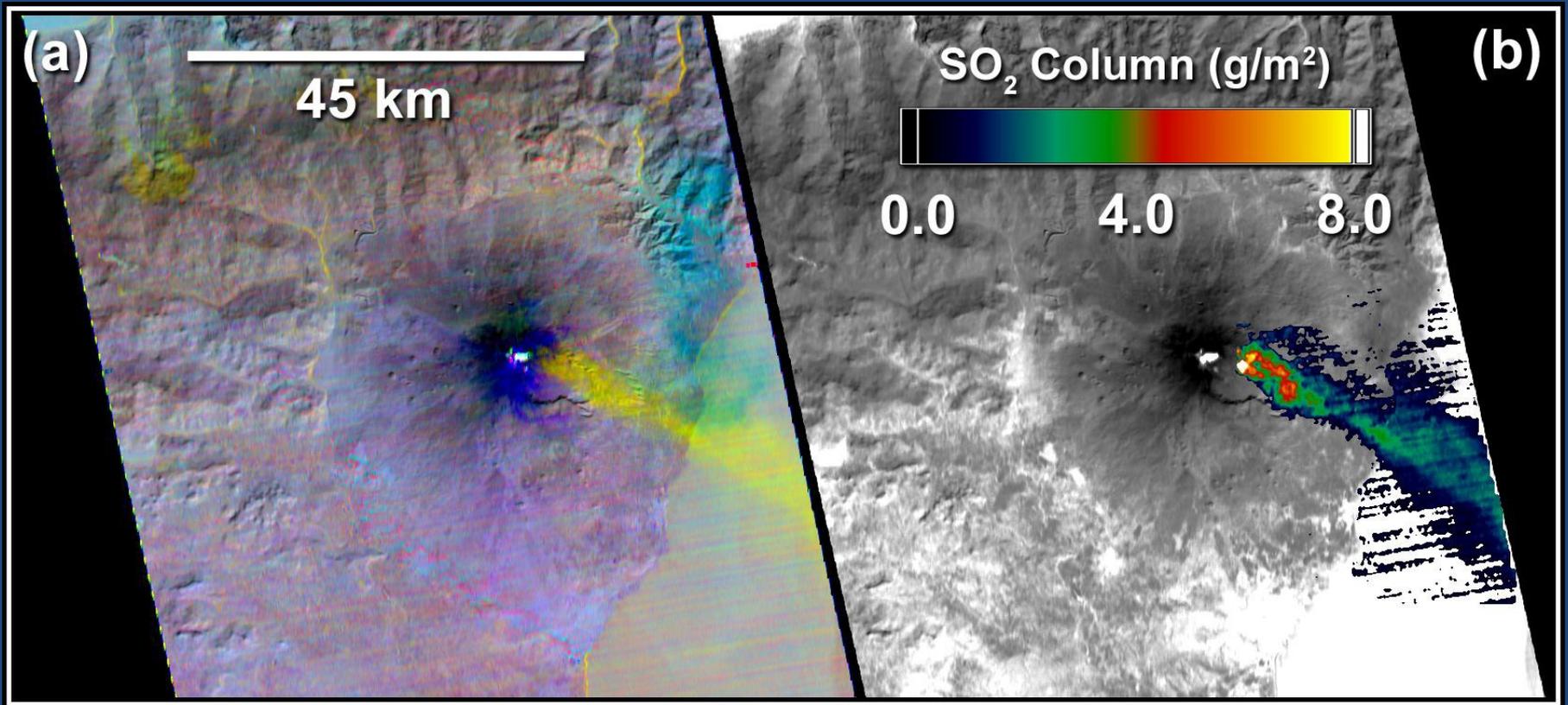
SO₂ Column (g/m²)



0.0

5.0

10.0

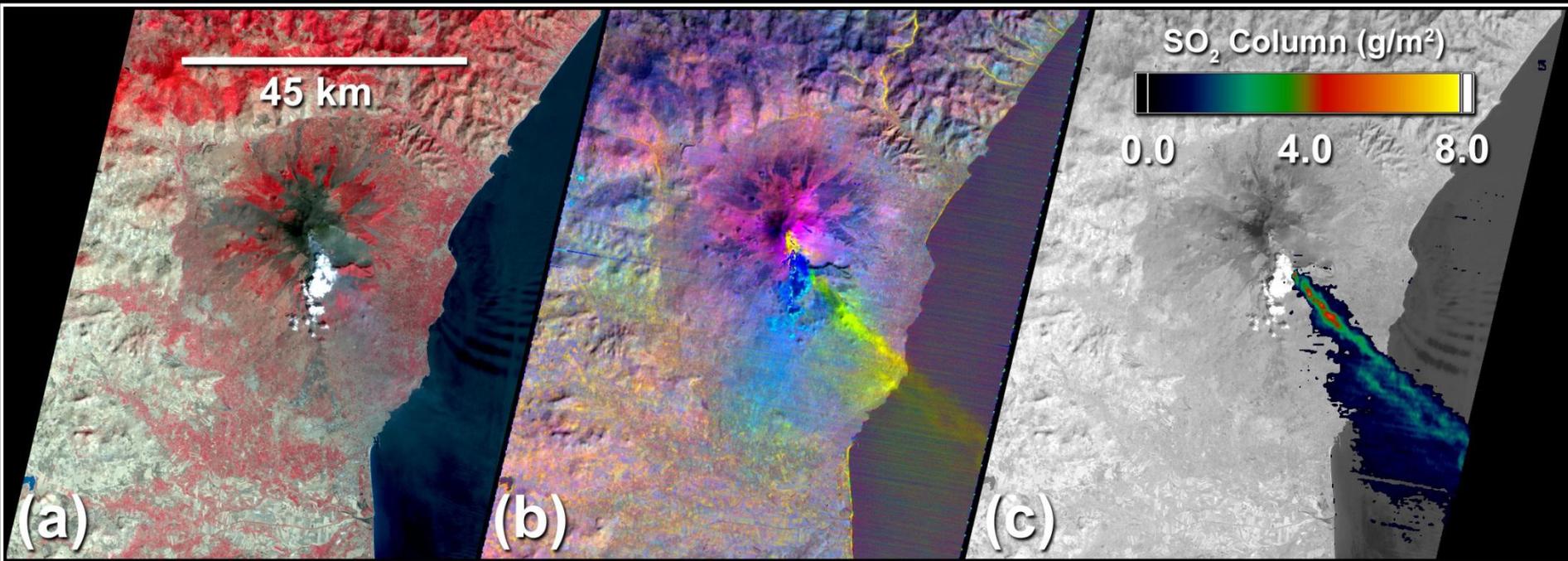


Mount Etna: 6 June 2000

Night-Time ASTER Data Acquisition (21:25 UTC)

Near Conclusion of Long-Lived Eruption Episode: 26 Jan – 24 June

Lava-Fountaining Event on 5 June 2000: Strong Gas Emissions



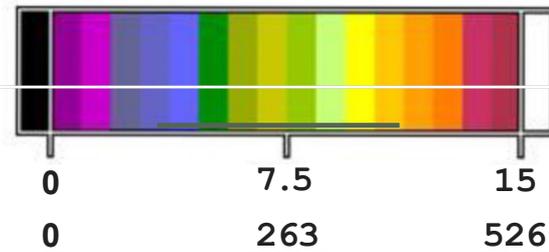
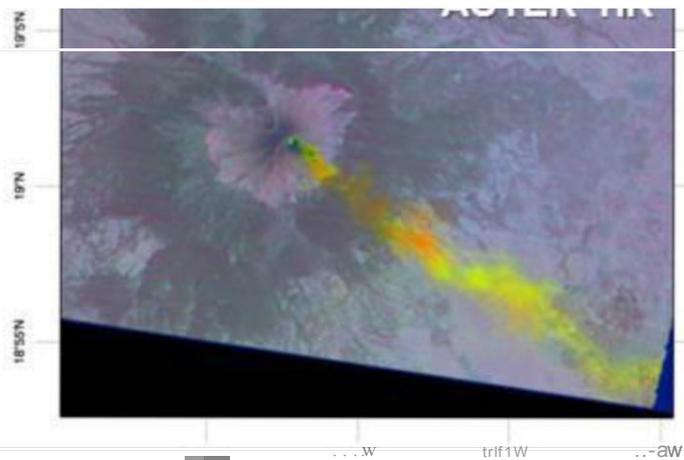
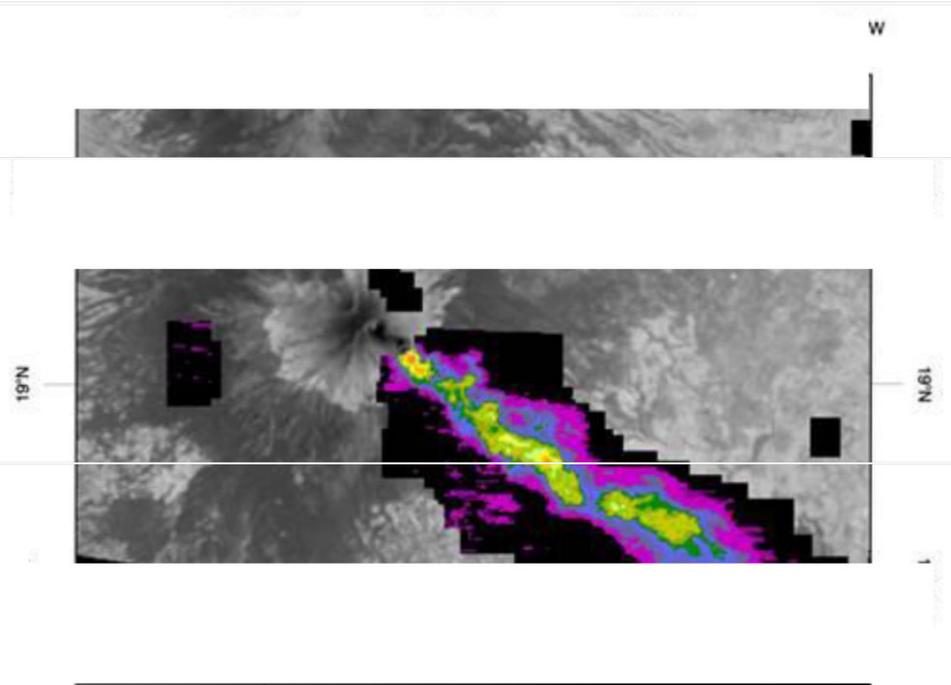
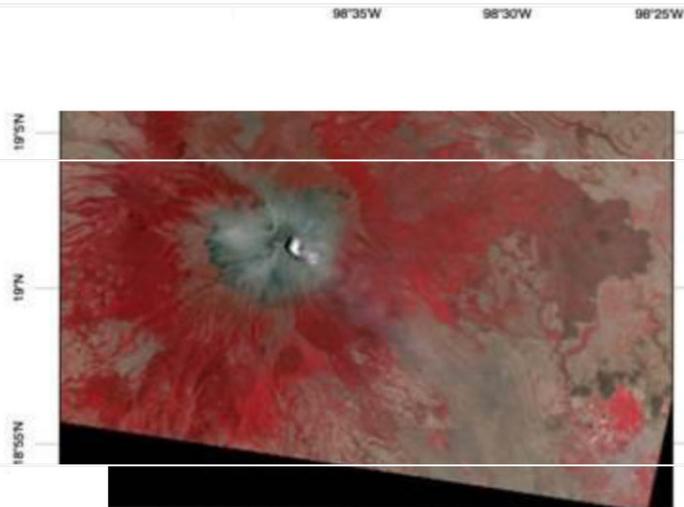
Mount Etna: 29 July 2001

Daytime ASTER Data Acquisition (10:01 UTC)

Fissure Eruption started on 17 July 2001

On-going Strombolian Explosions at Time of Overpass

Shearing of the Plume at Coast by On-Shore Winds



g/m^2
DU

Summary Remarks: Plume Tracker

Plume Tracker Facilitates the Interactive Analysis of Data from Multiple Instruments w// Ancillary Data from Multiple Sources

Image (Radiance) Data: MODIS, ASTER, AIRS

Ancillary Data:

Atmosphere Profiles from AIRS, MODIS, and NCEP

Digital Elevation Data from AIRS, MODIS, and GLOBE

Plume Height Estimates from MISR and Plume Dispersion Model

Emissivity Derived from Image Data and Imported from Spectral Libraries

Multi-Instrument Analyses = Multi-Resolution Analyses

Plume Tracker Workflow + Retrieval Procedures Accommodate Wide Ranges in Spatial and Spectral Resolution:

90 m ASTER Data → 14 km AIRS Data

5 Channels of ASTER/MODIS Data → 1000+ Channels of AIRS Data

Consistent Processing: Confidence that Changes in Retrievals Corresponding to Changes in Spatial/Spectral Resolution are Real

Future Plans

Integrate Plume Tracker into the Remote Sensing Program at Alaska Volcano Observatory

Upgrade RT Model To MODTRAN 5.2

Integrate SO₂ and Ash Retrievals

Implement RT Modeling on Graphics Processing Units (GPU)

H₂O Vapor vs. SO₂ Absorption

H₂O Vapor Absorption Affects the Entire 8-12 nm Atmospheric Window:

Add Channel Sensitive to H₂O to Facilitate Atm. "Corrections"

Considerable Variation in H₂O Within a Scene

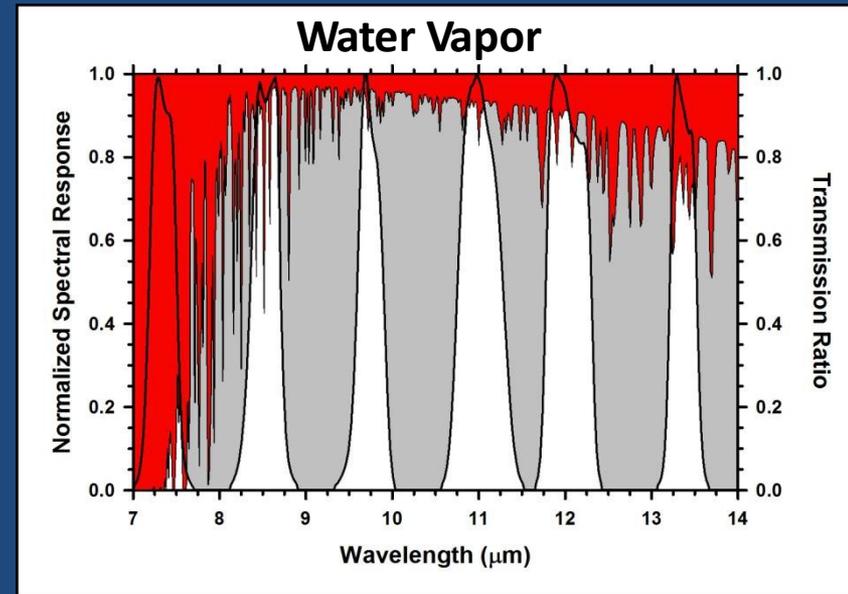
Very Strong H₂O Vapor and SO₂ Absorption in MODIS Channel 28 (7.3 nm):

Difficult to Separate Effects of H₂O and SO₂

7.3 nm Not Suitable for Mapping Plumes Below 5 km [Prata et al., 2003]

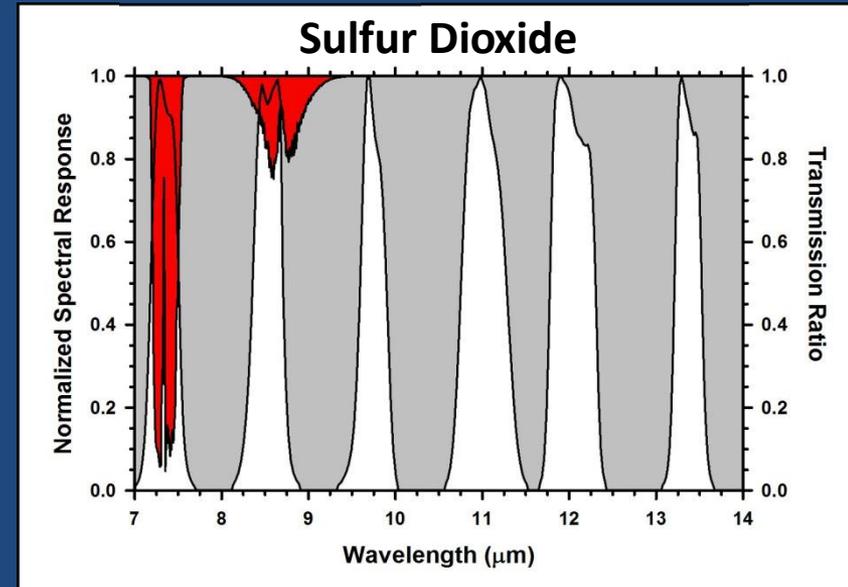
Moderate H₂O Absorption and Zero SO₂ Absorption in MODIS Channel 33 (13.5 μm)

Include Channel 33 in the SO₂ Retrieval Procedure



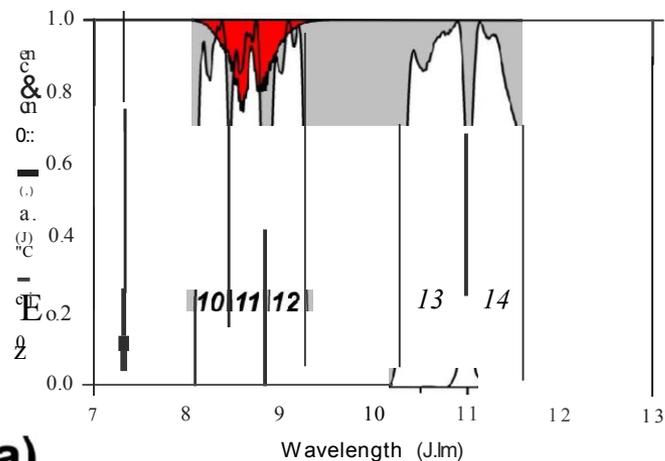
MODIS Channels

28 29 30 31 32 33



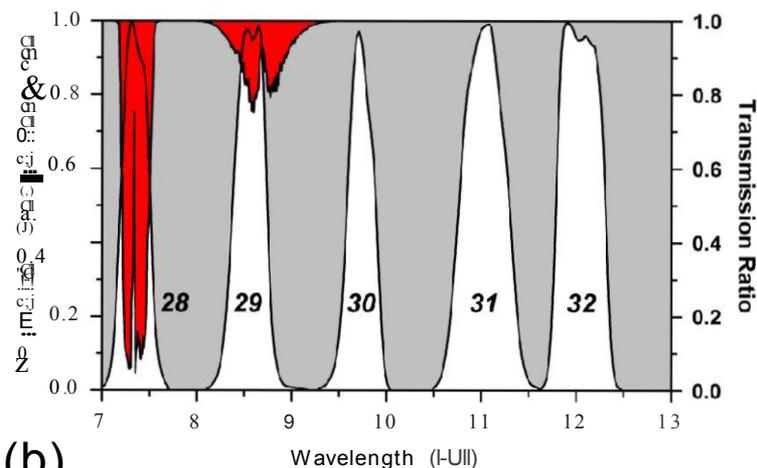
Heritage for HypSI-RI Spectral Response

ASTER Response vs. SO_2 Transmission



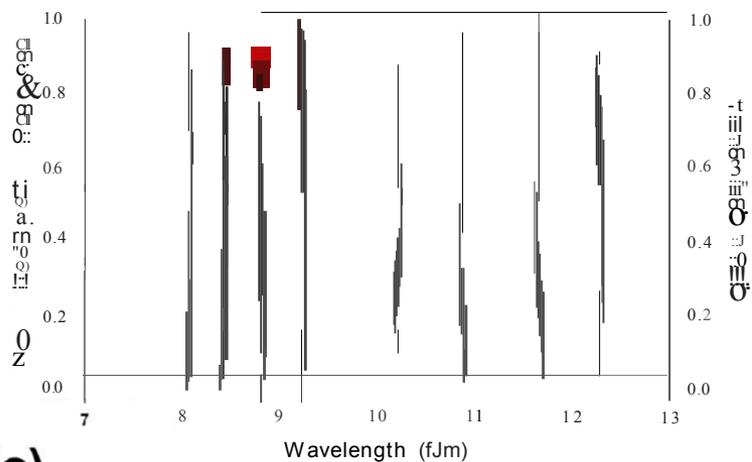
(a)

MODIS Response vs. SO_2 Transmission



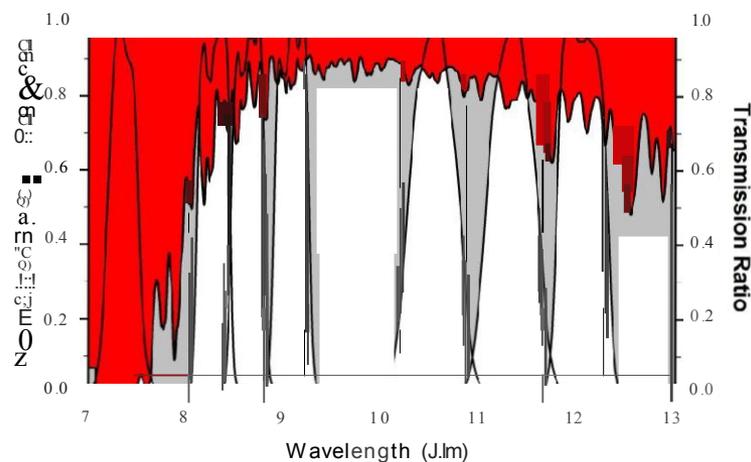
(b)

HypSI-RI-TIR Response vs. SO_2 Transmission



(c)

HypSI-RI-TIR Response vs. H_2O Vapor Transmission



(d)

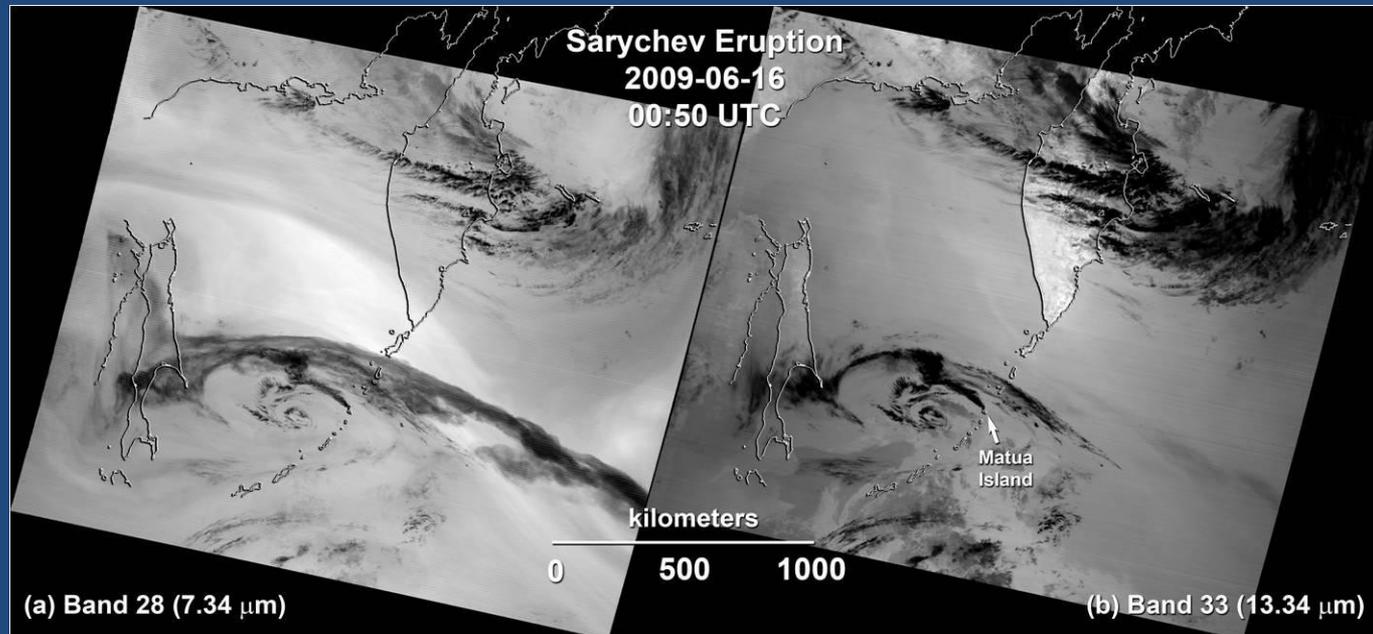
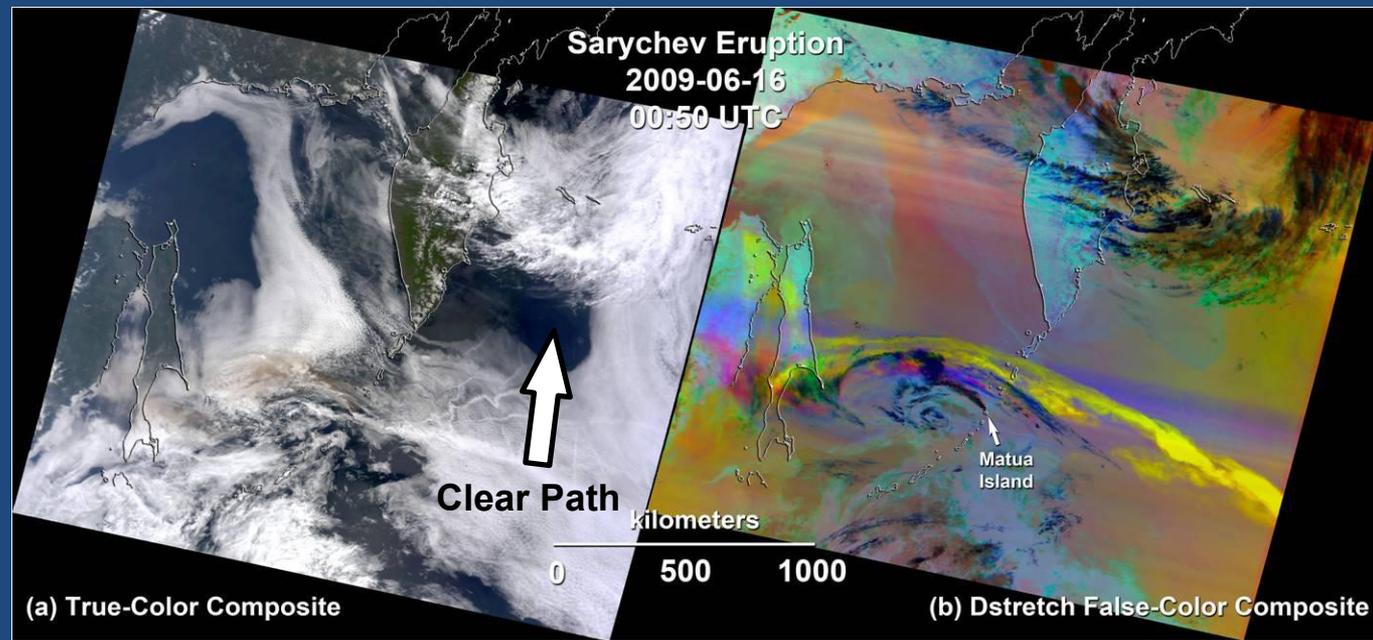
**Retrieval Procedure
Requires Profiles of
Atm. Temp, H₂O, and
O₃ as Input**

**Radiance Spectra from
Clear Path (Plume-Free)
Regions are used to
“Tune” the H₂O and O₃
Profiles**

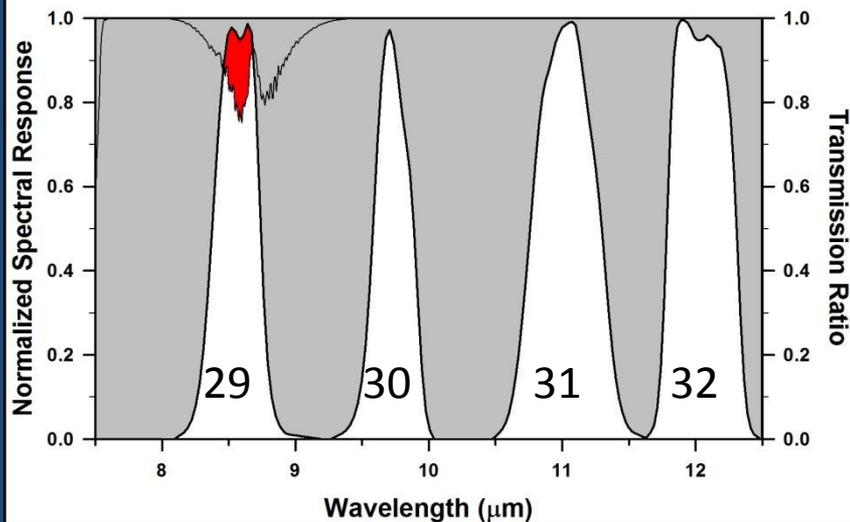
**Tuning is a Time-
Consuming Process:
Retrieval of H₂O is More
Efficient and a Better
Characterization of
Variations in H₂O**

**Strong H₂O Absorption in
MODIS 28 Obscures the
Surface**

**Moderate H₂O Absorption
in MODIS 33 Does Not
Obscure the Surface**



MODIS 29-32 Response vs. SO₂ Transmission



MODIS 29-32 Simulation Results

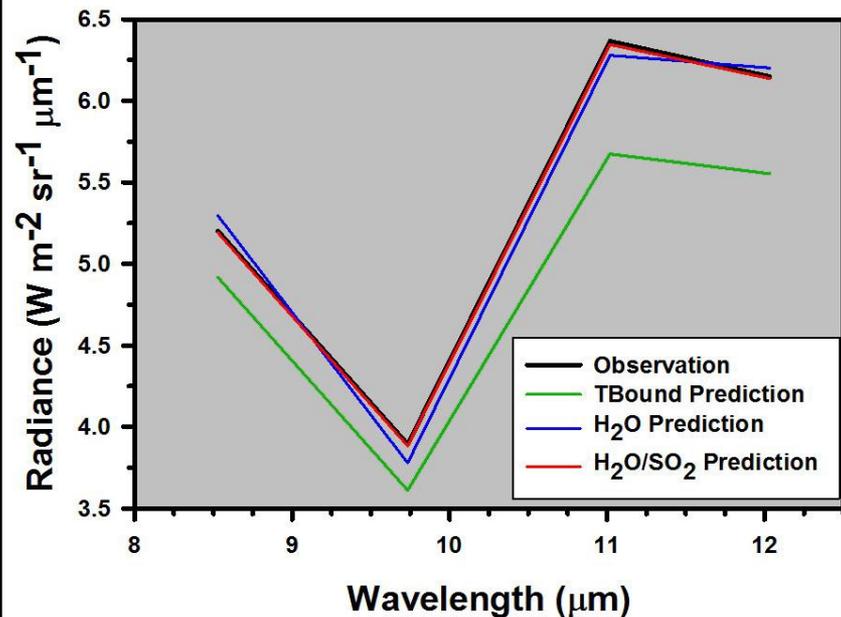
Temperature Under-Estimated, Misfit Spectrum Between 5 – 11%

H₂O: Misfit Within ±3%

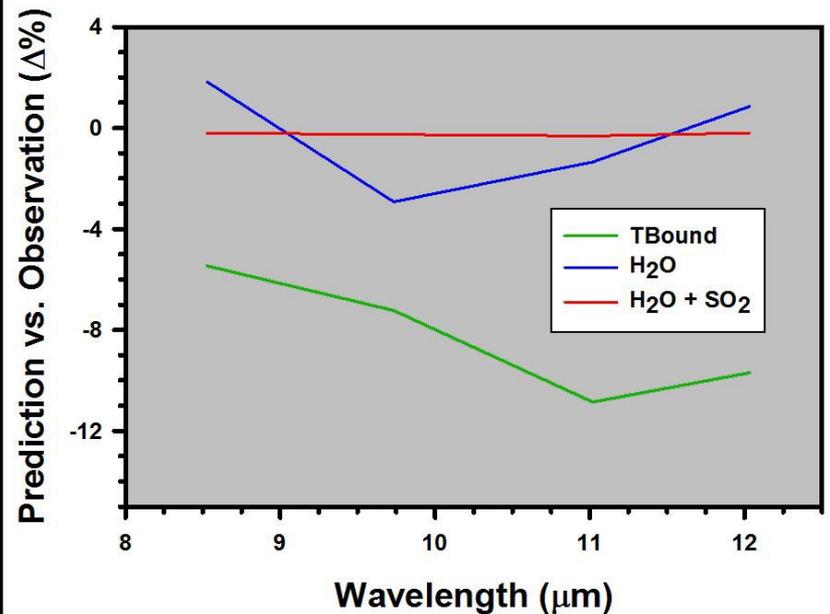
H₂O + SO₂: Misfit Spectrum < 1%

D% Axis Range = 19%

Simulated MOD29-32 Results



Simulated MOD29-32 Results



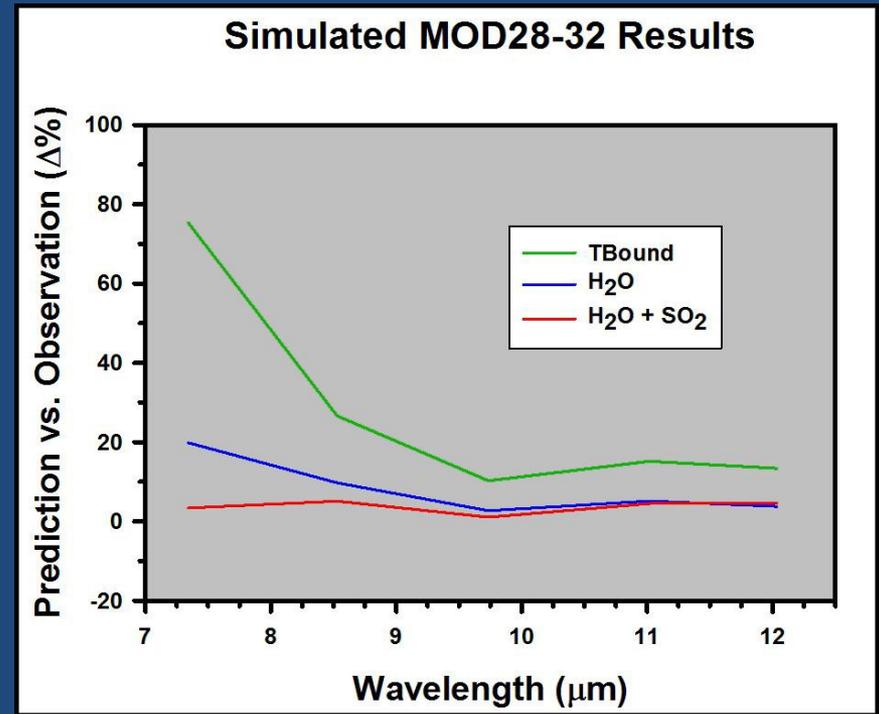
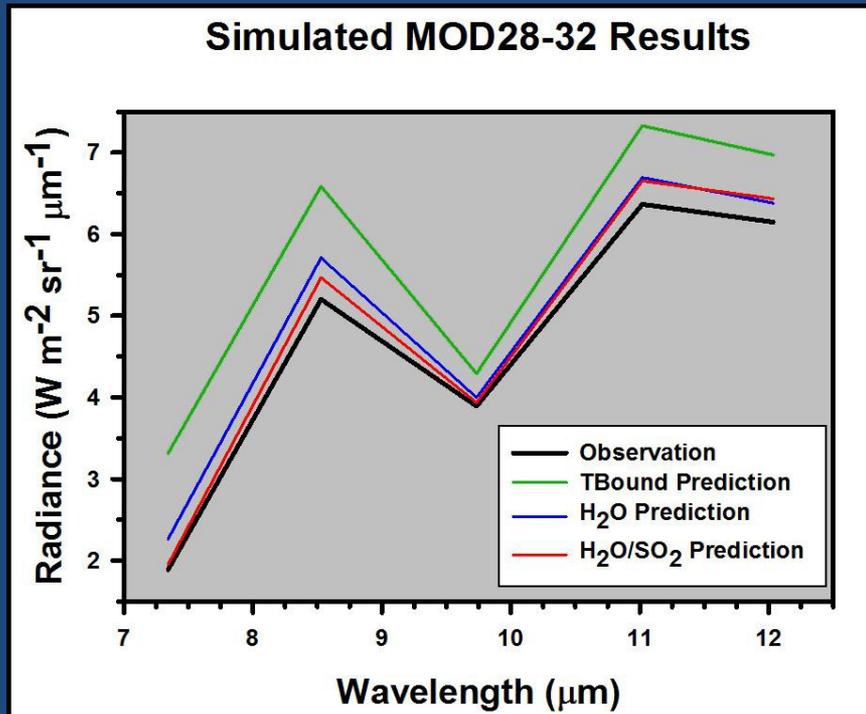
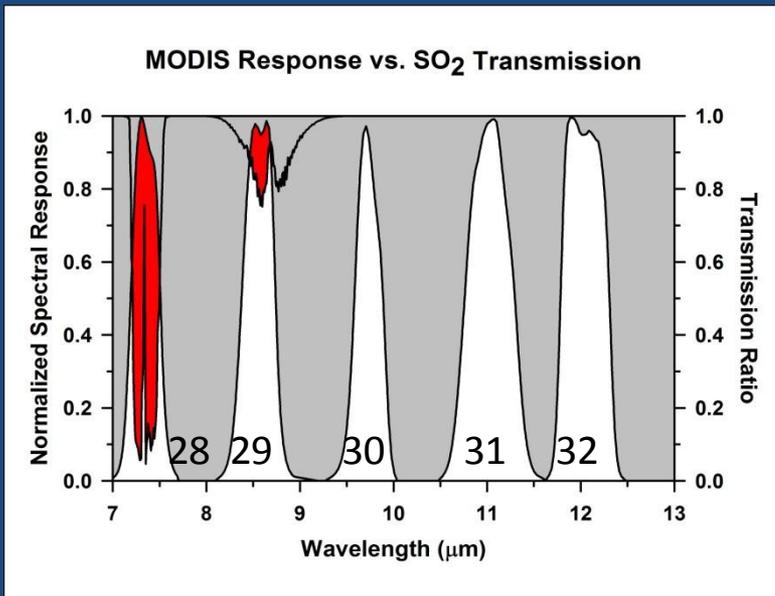
MODIS 28-32 Simulation Results

Temperature Over-Estimated, Misfit Spectrum ~80% at 7.3 μm

H₂O: Misfit ~20% at 7.3 μm

H₂O + SO₂: Misfit Spectrum < 10%

D%Axis Range = **120%**



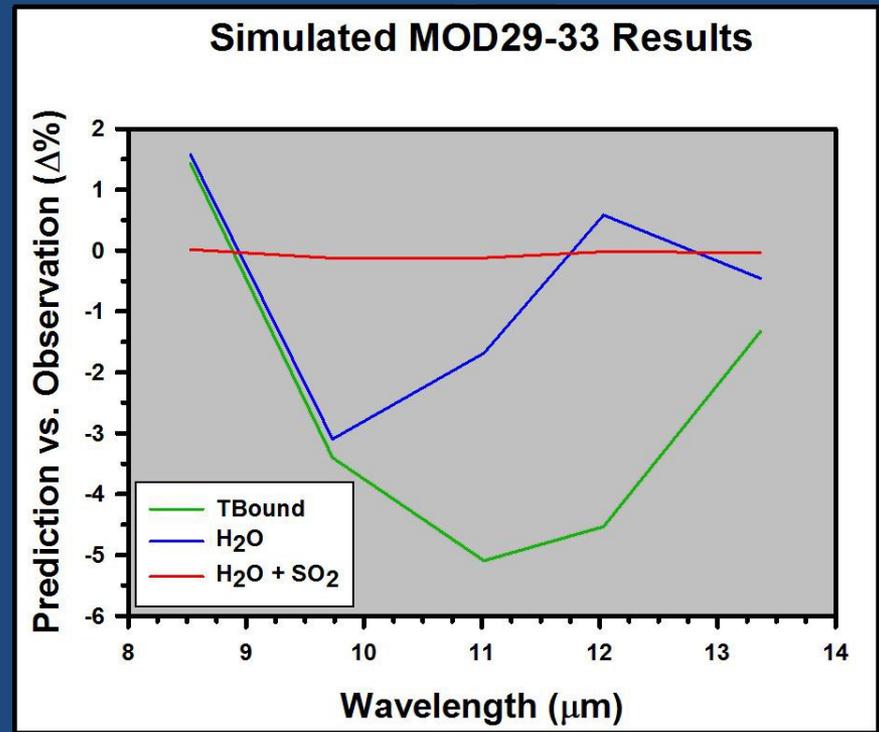
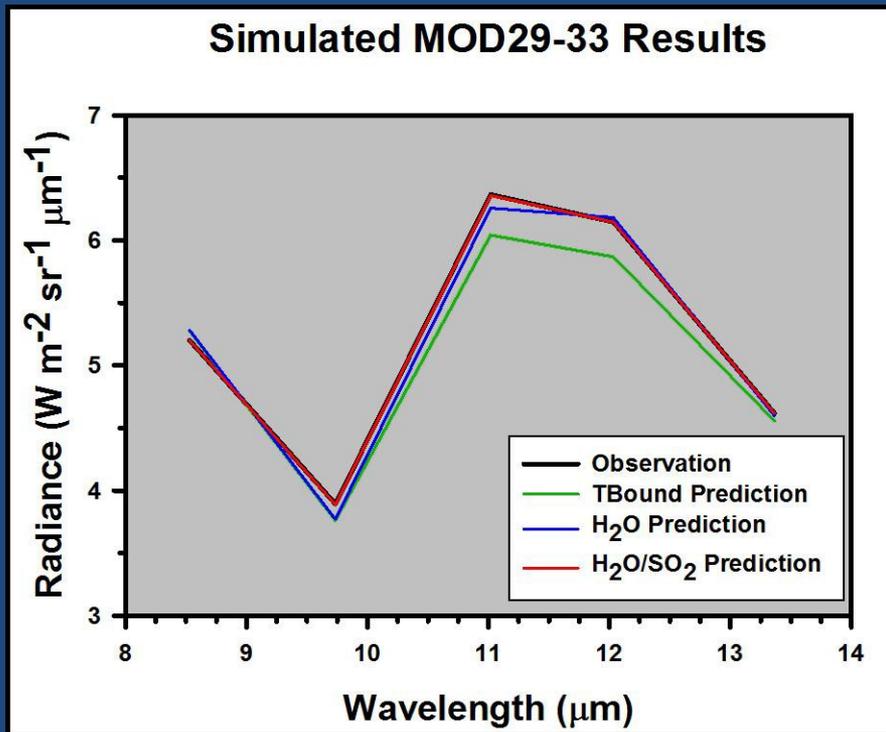
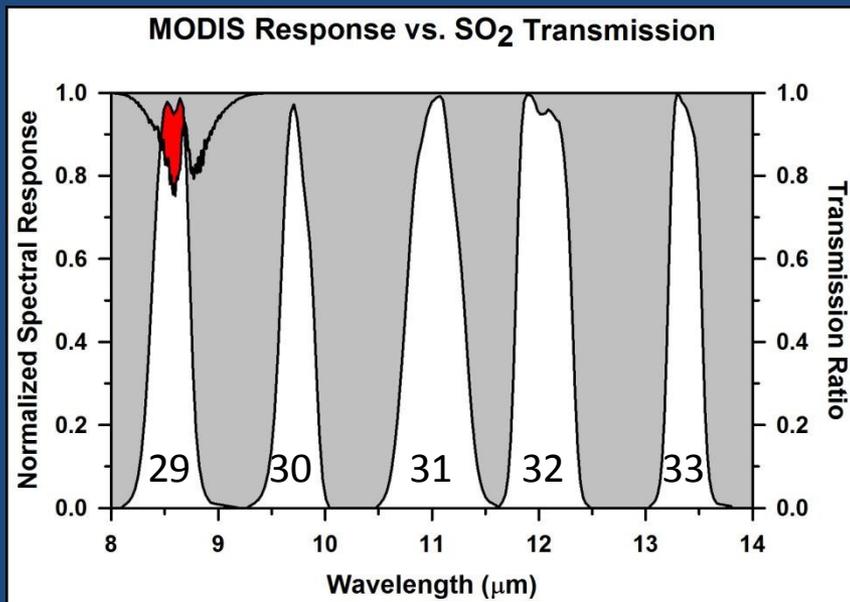
MODIS 29-33 Simulation Results

Temperature Under-Estimated, Misfit Spectrum < 6%

H₂O: Misfit < 3%

H₂O + SO₂: Misfit Spectrum < 1%

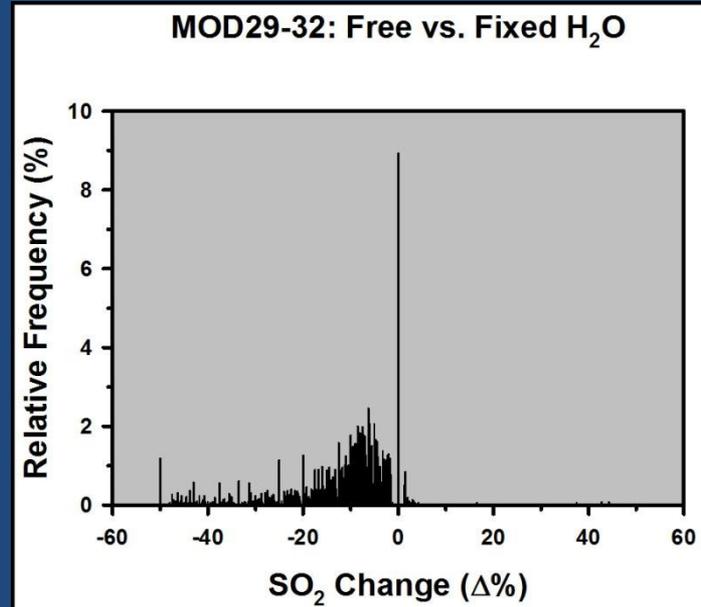
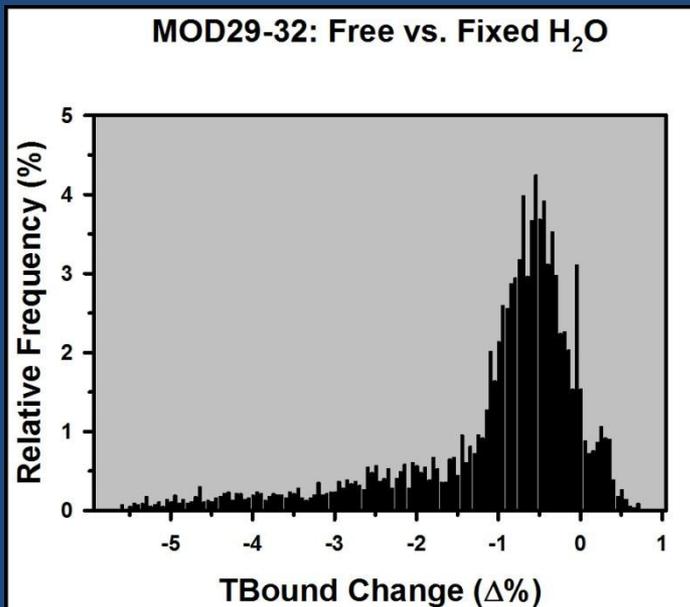
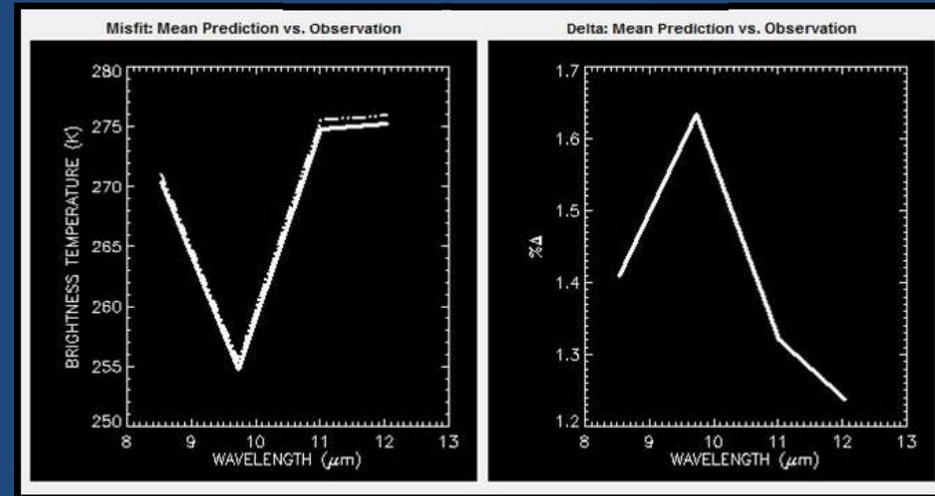
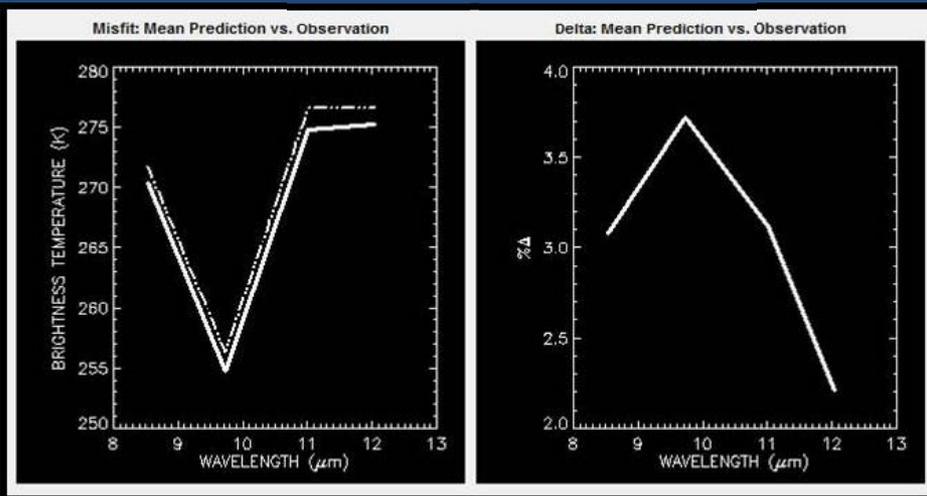
D%Axis Range = 8%



MODIS 29 – 32 Results

Fixed H₂O Factor

Free H₂O Factor



**Improved Fit: D%
Range Reduced
from 2% to 0.5%**

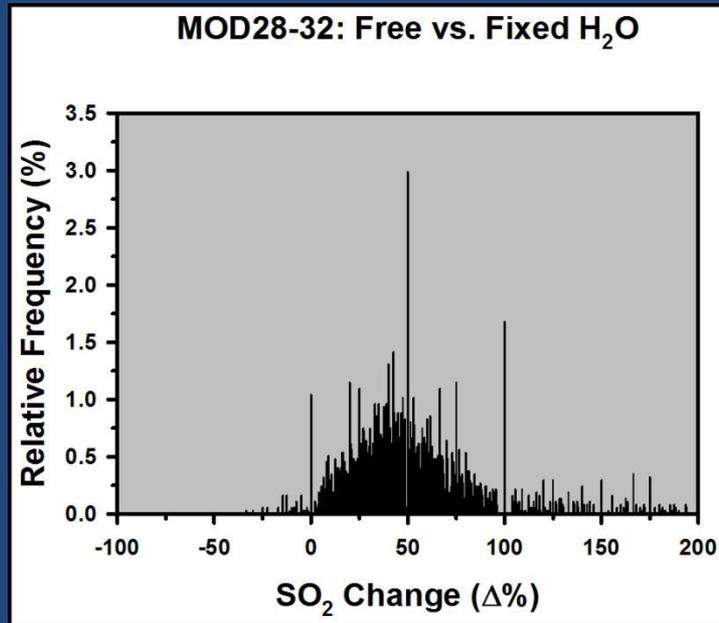
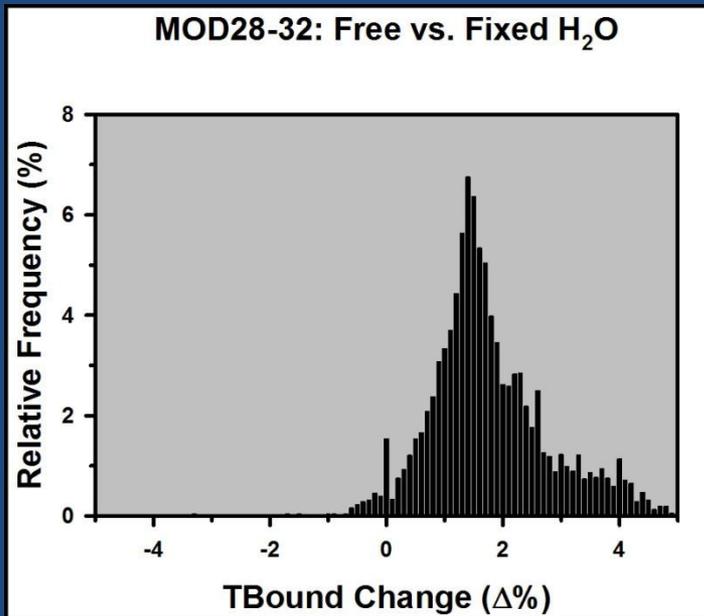
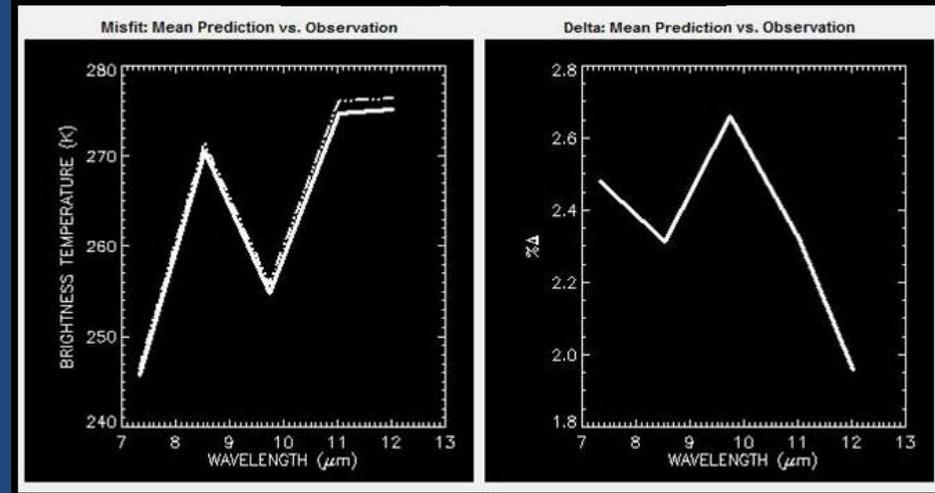
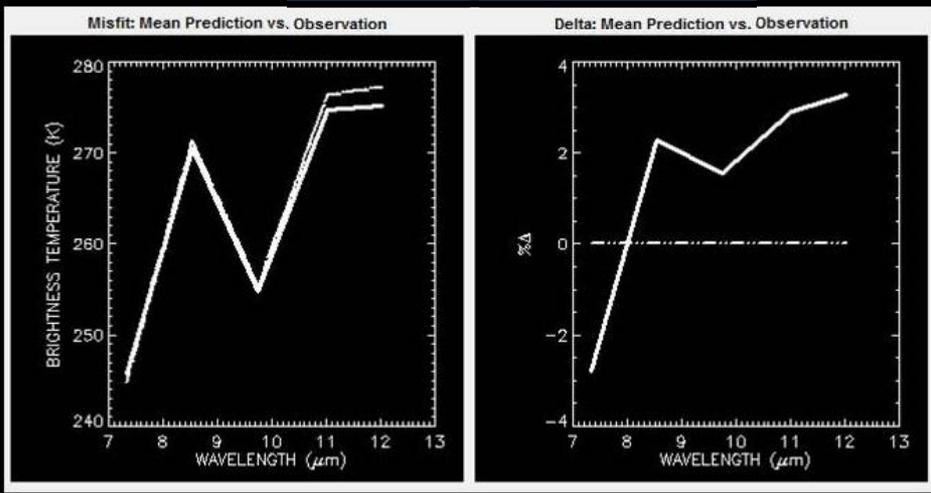
**TBound Estimates
Decreased ~0.5%**

**SO₂ Estimates
Decreased 5 –
10%**

MODIS 28 – 32 Results

Fixed H₂O Factor

Free H₂O Factor



Improved Fit: D%
Range Reduced
from 8% to 1%

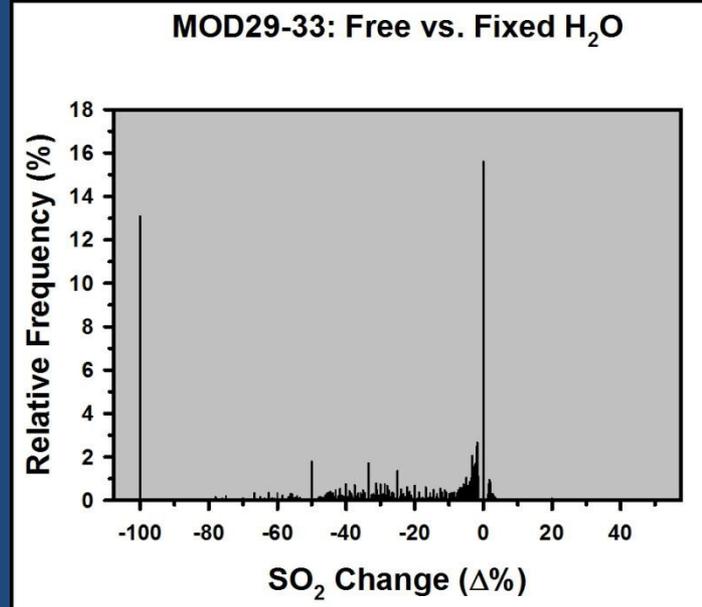
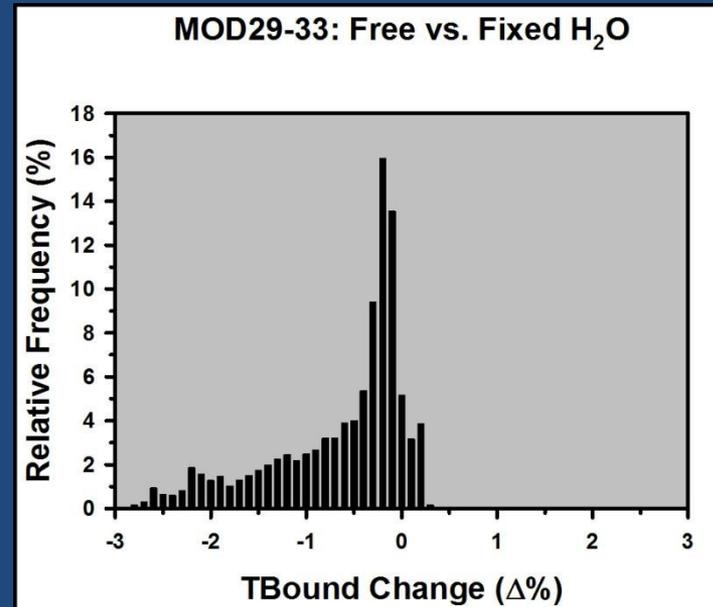
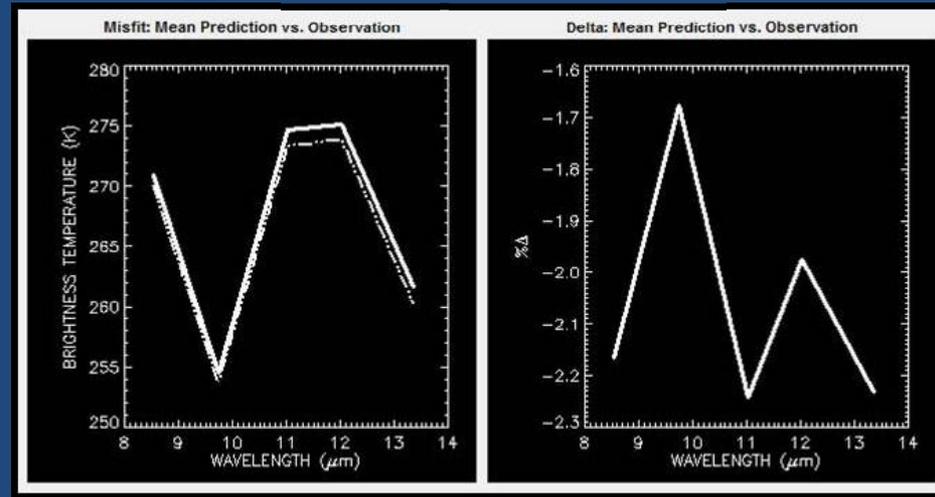
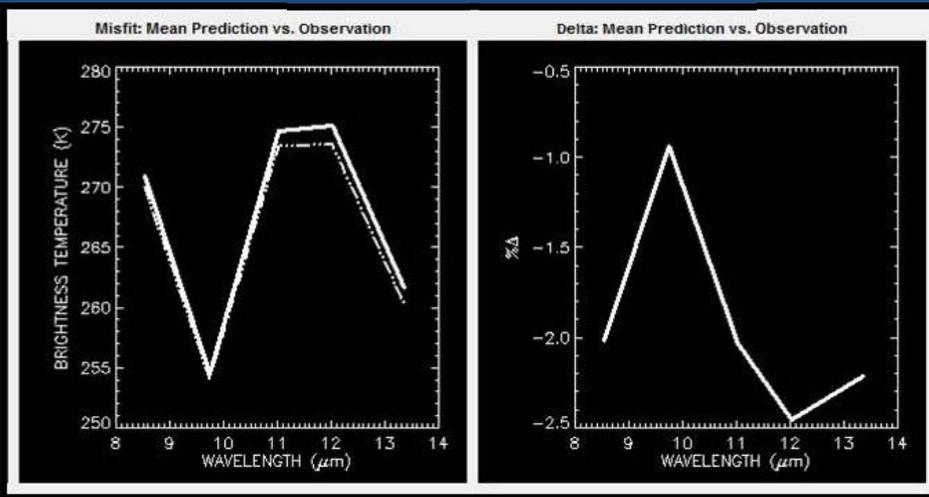
TBound Estimates
Increased ~1.5%

SO₂ Estimates
Increased ~ 50%

MODIS 29 – 33 Results

Fixed H₂O Factor

Free H₂O Factor



**Improved Fit: D%
Range Reduced from
3% to 0.7%**

**TBound Estimates
Decreased < 0.5%**

**Problematic
Interpretation of SO₂
Results:**

**Reduction in Estimates
< 10% ?**

**Spike @ -100% is
Significant!**

**Spike @ 0 Change
Significant?**

ASTER Simulation Results

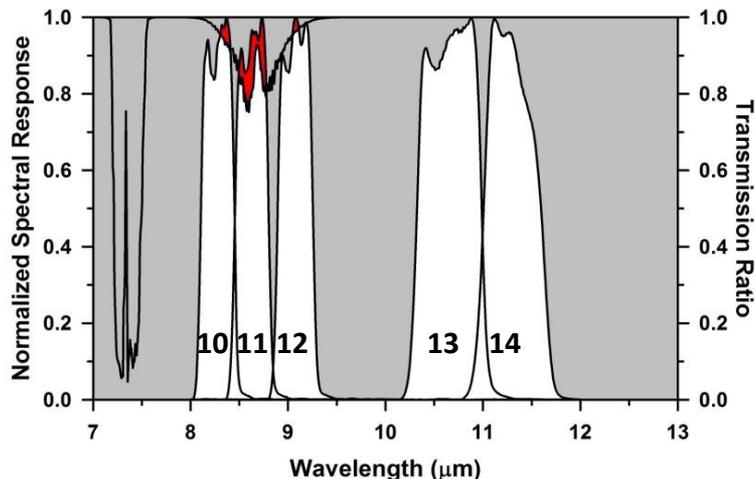
Temperature Under-Estimated, Misfit Spectrum 4 – 10%

H₂O: Misfit Spectrum < 6%

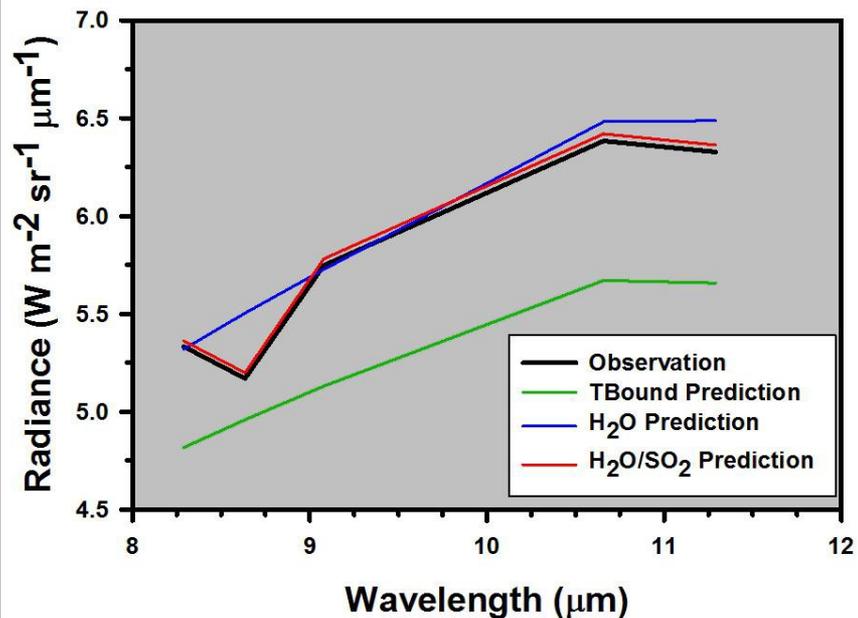
H₂O + SO₂: Misfit Spectrum < 2%

D% Axis Range = 24%

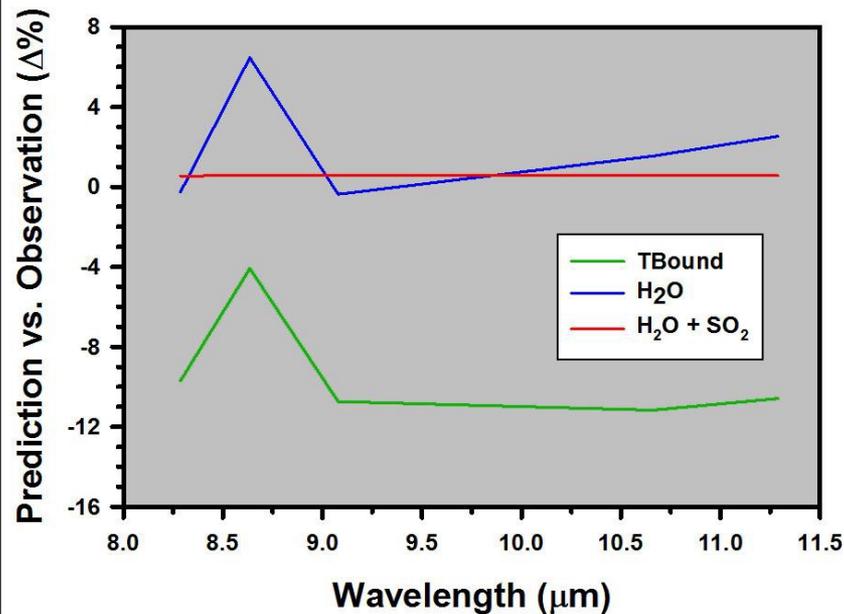
ASTER Response vs. SO₂ Transmission



Simulated ASTER Results



Simulated ASTER Results



HyspIRI Simulation Results

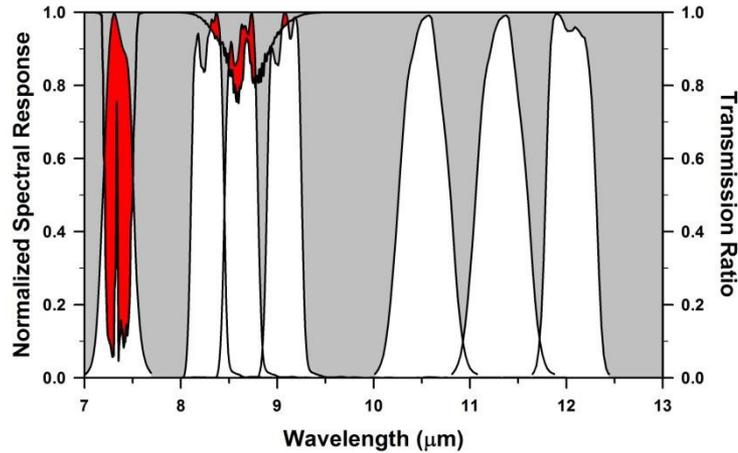
Temperature Over-Estimated, Misfit Spectrum ~75% at 7.3 μm

H₂O: Misfit ~20% at 7.3 μm

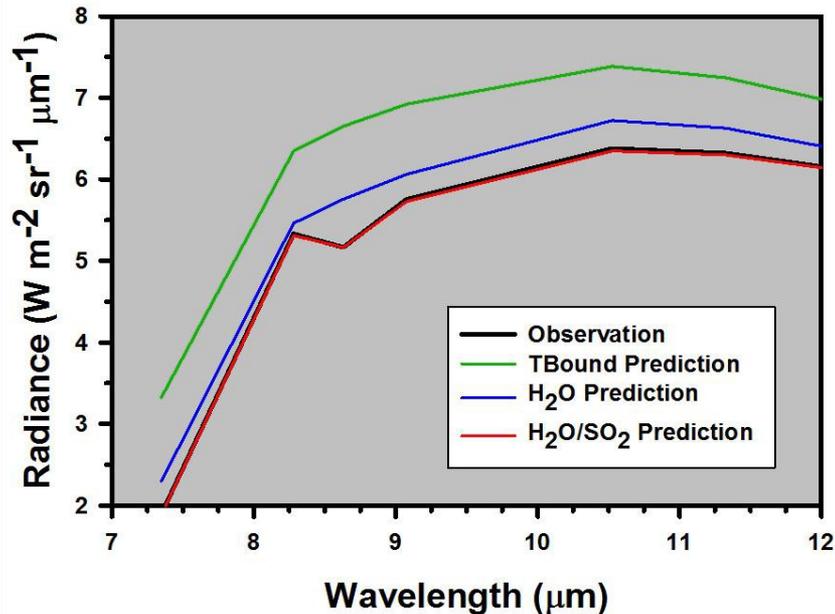
H₂O + SO₂: Misfit Spectrum < 2%

D% Axis Range = 100%

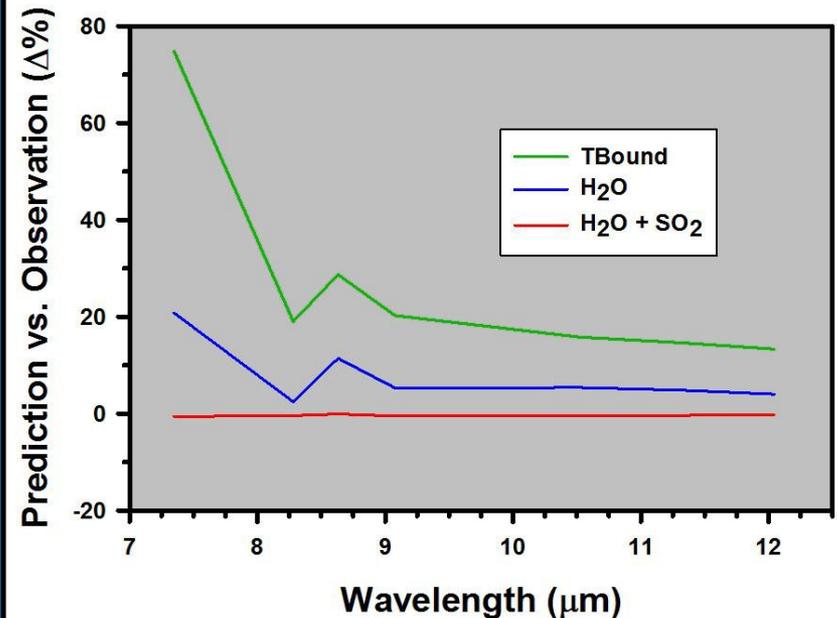
HyspIRI Response vs. SO₂ Transmission

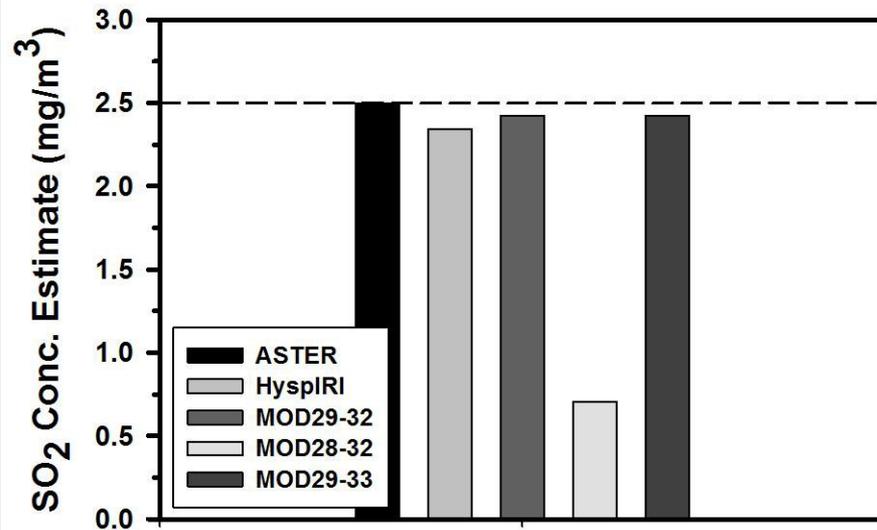
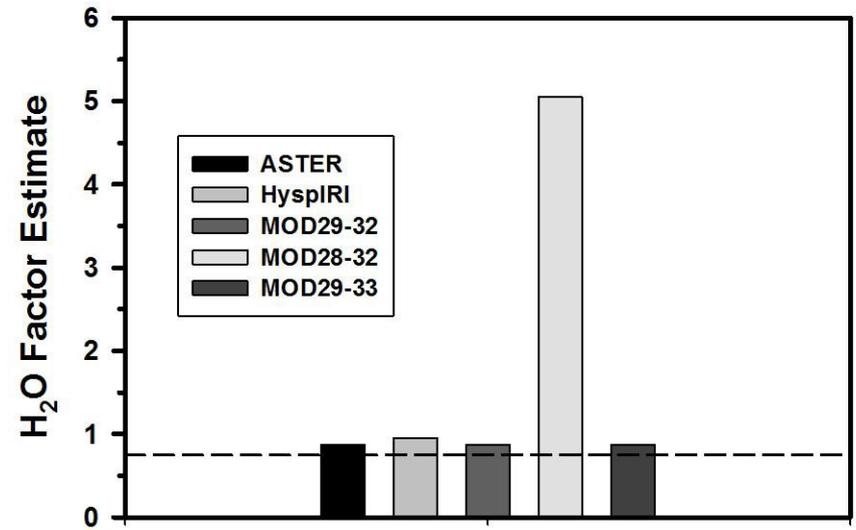
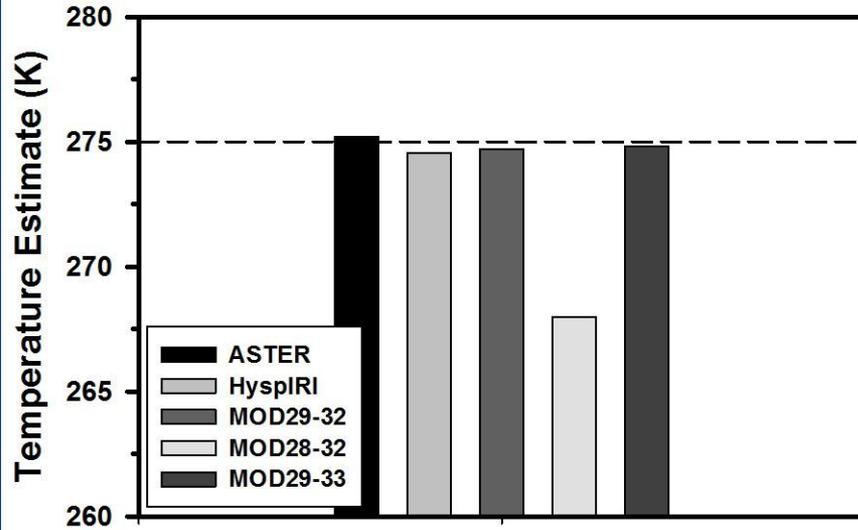


Simulated HyspIRI Results



Simulated HyspIRI Results





Retrieval Accuracy

ASTER: Best Overall Performance

MODIS 28-32: Worst Overall Performance

MODIS 29-32/MODIS 29-33: Roughly Equal Performance; Slightly Better Than HypsIRI

Presence of 7.3 nm Channel Degrades Performance

Note: All Configurations Produced Exact Retrievals in Traditional (TBound + SO₂) Mode

Summary Remarks: HypsIRI HypsIRI Channels Positions

Single Channel @ 7.3 μm Does Not Provide Sufficient Resolution to Separate the Effects of H_2O and SO_2

Characterizing Spatial Variations in H_2O Has Broader Science Impact than SO_2 Detection:

Shift 7.5 μm Channel to Longer Wavelength ($\sim 8.0 \mu\text{m}$)

Definitive Solution to Channel Position Requires HyTES Data

Adopting 13.3 μm Channel (MOD 33) for MODIS-Based Plume Mapping

Not Necessary for HypsIRI Due to High Spectral Resolution Between 8 and 9 μm

