A Multi-Sensor Approach to the Remote Sensing of Volcanic Emissions

Vincent J. Realmuto

Visualization and Scientific Animation Group

Modeling and Data Management Systems Section

Jet Propulsion Laboratory

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OBJECTIVES

Track Changes in SO_2 Emission Rate

Detect Passive Emissions Before an Eruption Occurs

Eruptions May be Preceded by Changes in Emission Rate

Few Volcanoes are Monitored with Necessary Frequency to Establish Baseline Emission Rates

Satellite Remote Sensing –> Facilitate Monitoring

Study the Fate of SO_2 in Atmosphere

Conversion to Sulfate Aerosols

Local/Regional Hazard to Respiratory Health

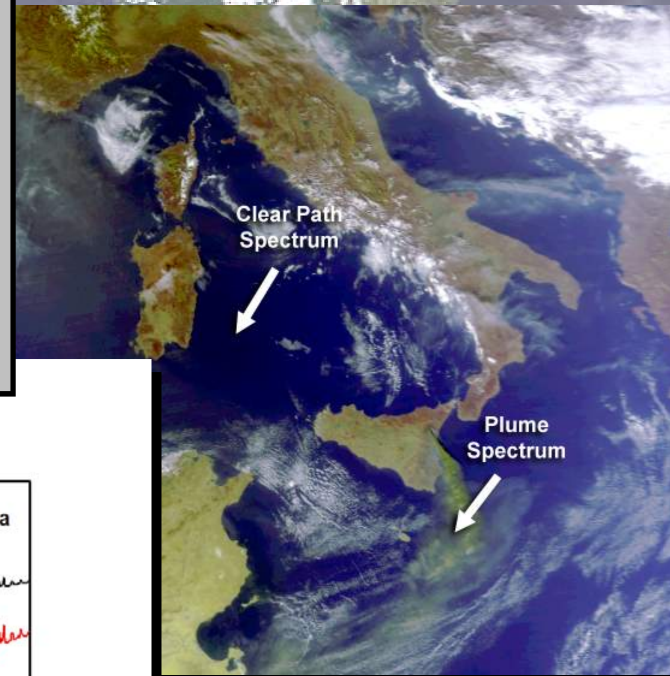
Regional/Global Climate Forcing

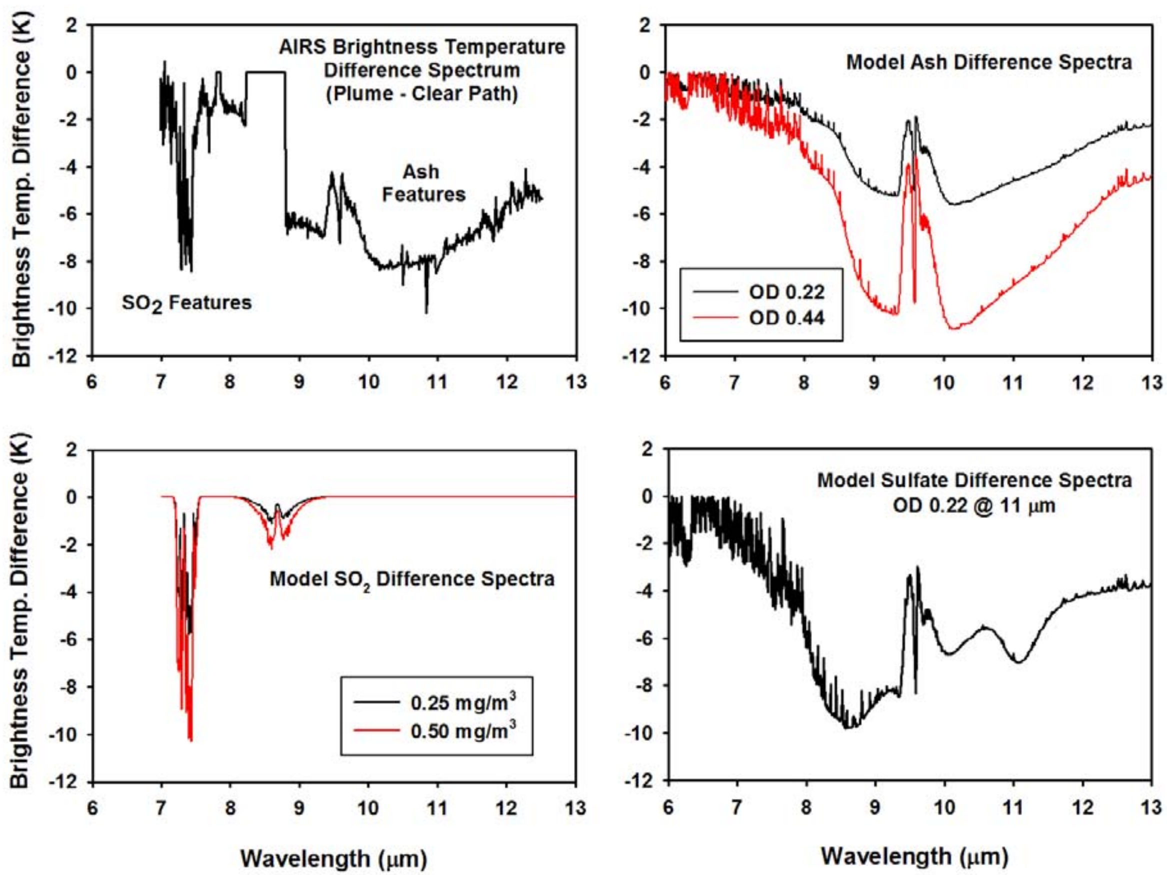
Nucleation Sites for Polar Stratospheric Clouds -> Catalysts for Ozone Depletion

AIRS Data Acquired over Mount Etna Eruption Plume: 28 October 2002

Constituents of Volcanic Plumes Amenable to Satellite Remote Sensing: SO_2, Silicate Ash, Sulfate Aerosol

Rare in "Normal" Atmosphere - Relatively Low Concentrations Can Be Detected in the Thermal IR (TIR)





Forward Modeling Results

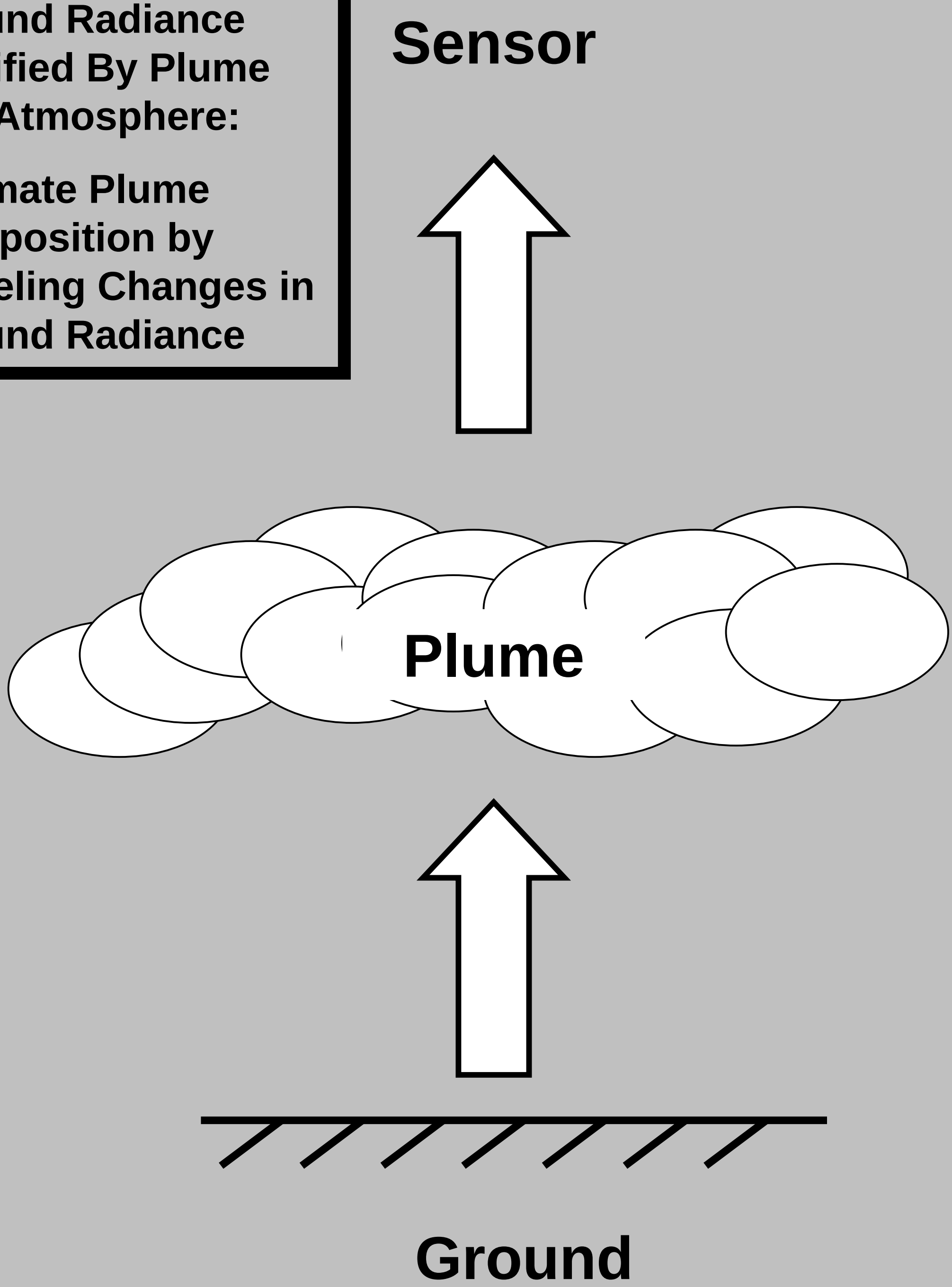
MODTRAN, CHARTS, LBLTran run at 1 cm^{-1} resolution

SO_2 concentrations between 0.25 – 0.50 mg/m^3

Silicate Ash Loading >> Sulfate Aerosol Loading

Ground Radiance Modified By Plume and Atmosphere:

Estimate Plume Composition by Modeling Changes in Ground Radiance



3-Slab Radiative <u>Transfer Model</u>

$\alpha_3(\lambda, x_3)\, B(\lambda, T_3) +$

$\tau_3(\lambda)$[Plume Radiance]

$\alpha_2(\lambda, x_2)\, B(\lambda, T_2) +$

$\tau_2(\lambda)$[Slab 1 Radiance]

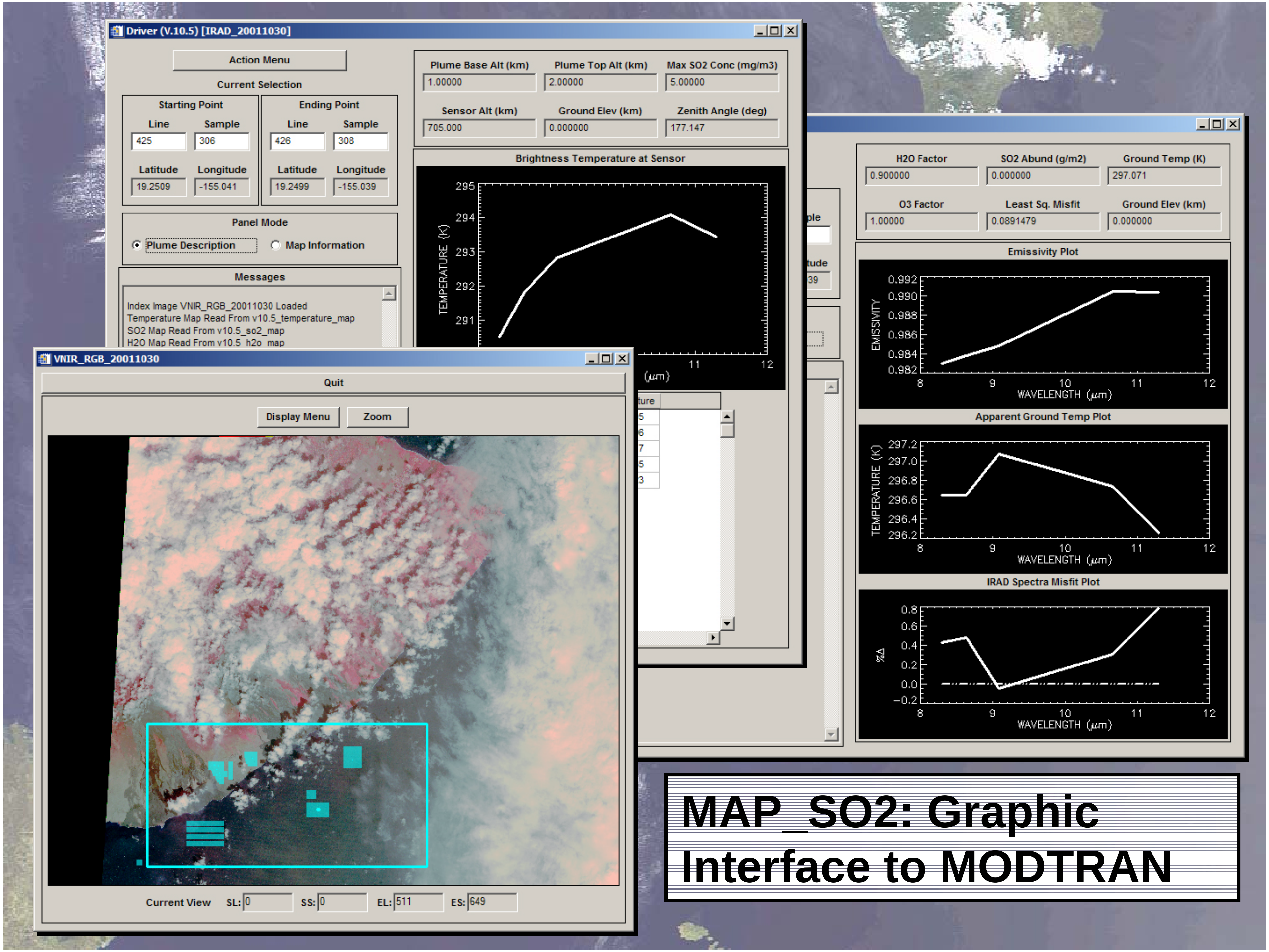
$\alpha_1(\lambda, x_1)\, B(\lambda, T_1) +$

$\tau_1(\lambda)$[Ground Radiance]

$\varepsilon_o(\lambda)\, B(\lambda, T_o) +$

$[1 - \varepsilon_o(\lambda)]\, \alpha_1(\lambda, x_1)\, B(\lambda, T_1)$

MAP_SO2: Graphic Interface to MODTRAN



Radiance at the Sensor

$$L(\lambda,T_o) = \{\varepsilon(\lambda)B(\lambda,T_o) + [1 - \varepsilon(\lambda)]L_d(\lambda,T_a,x)\}\ \tau(\lambda,x) + L_u(\lambda,T_a,x)$$

Where:

T_o = Surface Temperature

$\varepsilon(\lambda)B(\lambda,T_o)$ = Radiance at the Surface

x = Atmospheric Composition

$\tau(\lambda,x)$ = Atmospheric Transmission

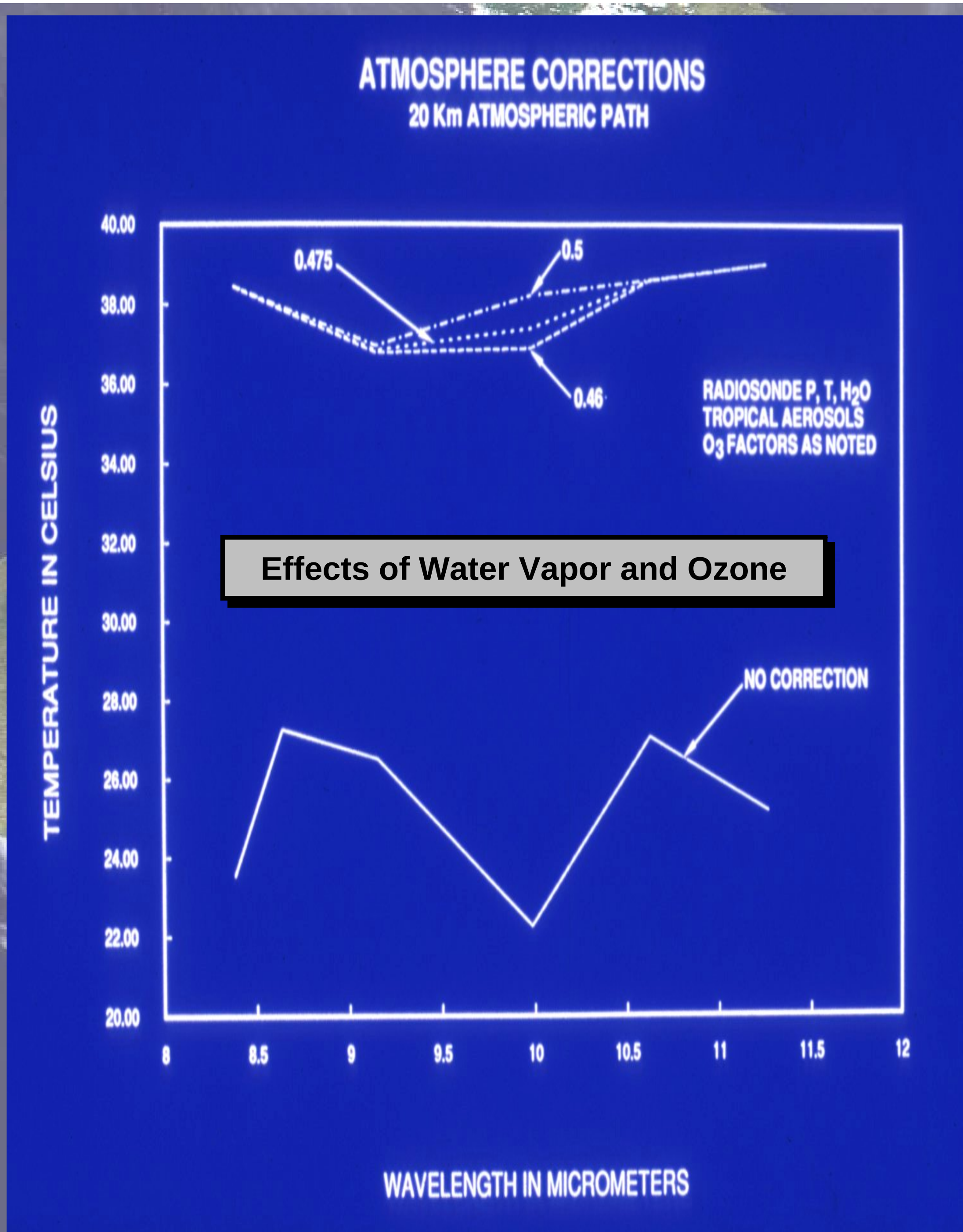
T_a = Atmospheric Temperature

$L_d(\lambda,T_a,x)$ = Downwelling Atmospheric Radiance (Sky Radiance)

$L_u(\lambda,T_a,x)$ = Upwelling Atmospheric Radiance (Path Radiance)

Note:

The Atmosphere is Both a Source and Sink Of Radiation

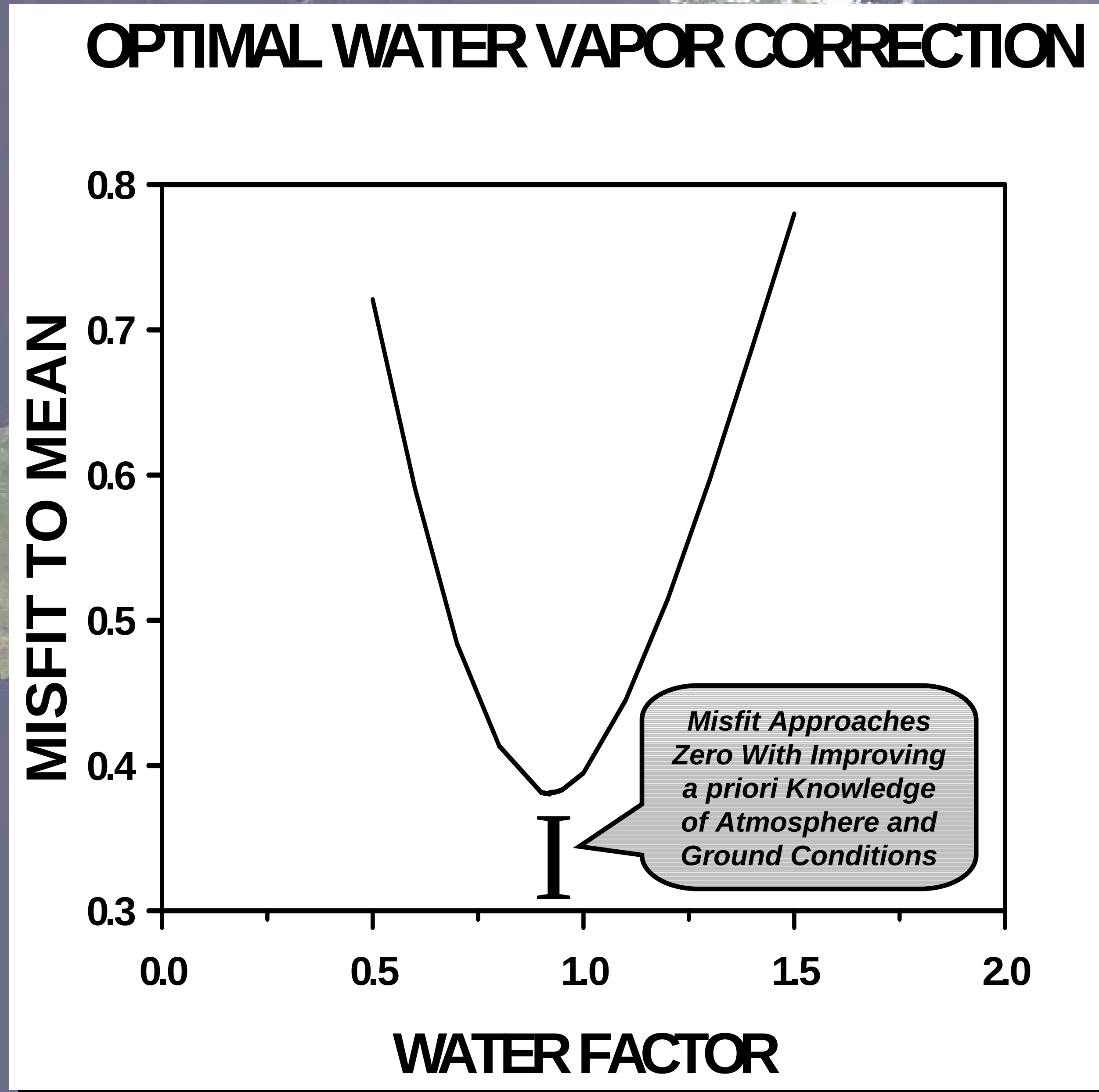


Spatially-Variable Optimal Water Vapor Correction

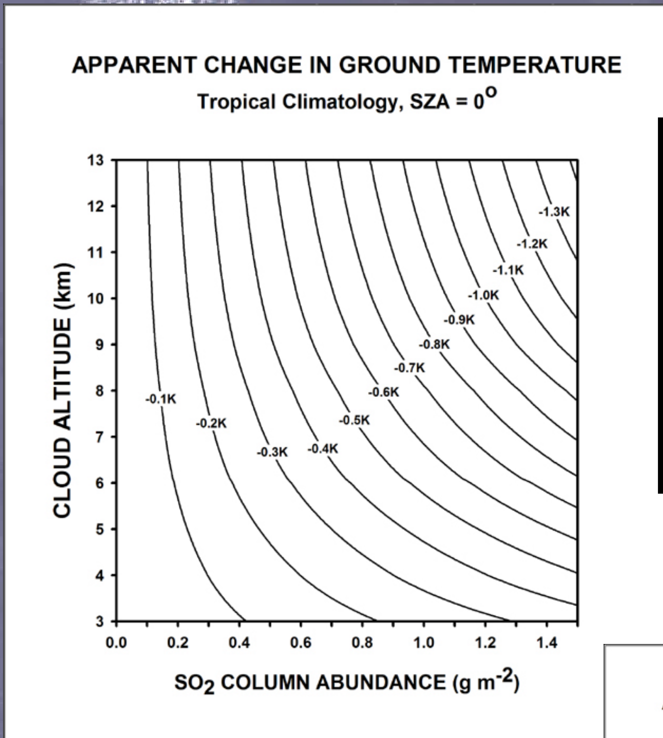
Ground Temperature is Independent of Wavelength – "Spectrum" Should be Flat Following Atmosphere and Emissivity Correction

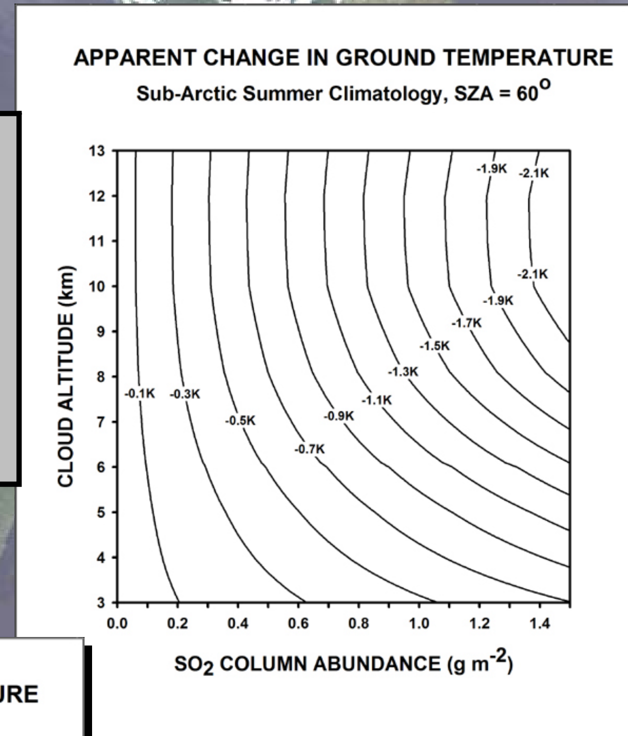
Iterate on Water Vapor Concentration Until "Flattest" Ground Temperature Spectrum is Achieved

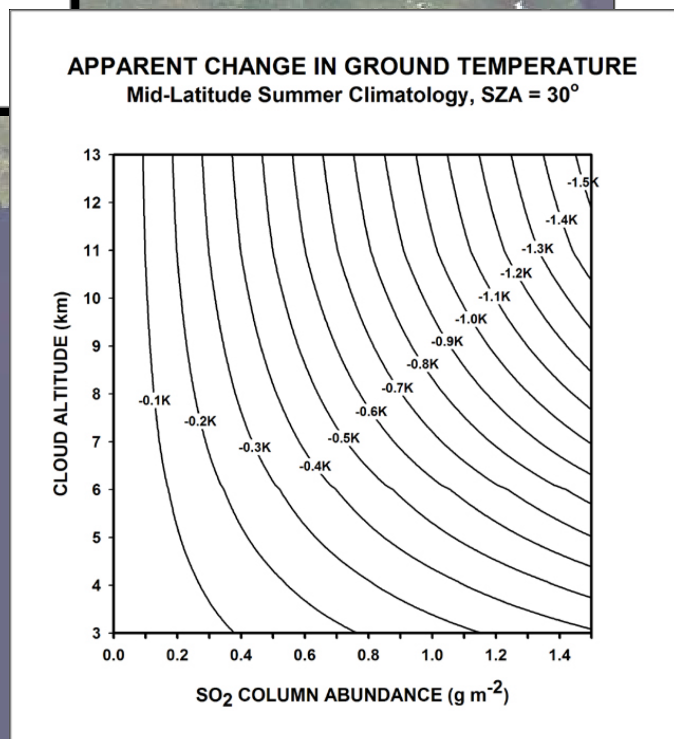
Technique Provides Best Possible Correction Given Uncertainty Regarding Atmospheric and Ground Conditions



Sensitivity of Instrument Defined by Noise Equivalent Change in Temperature (NE∆T): 0.5 (C or K)







Detection Limits Under Various Atmospheric Conditions

General Trends:

Increasing Cloud Altitude (i.e. Increasing Temperature Contrast) Improves Detection

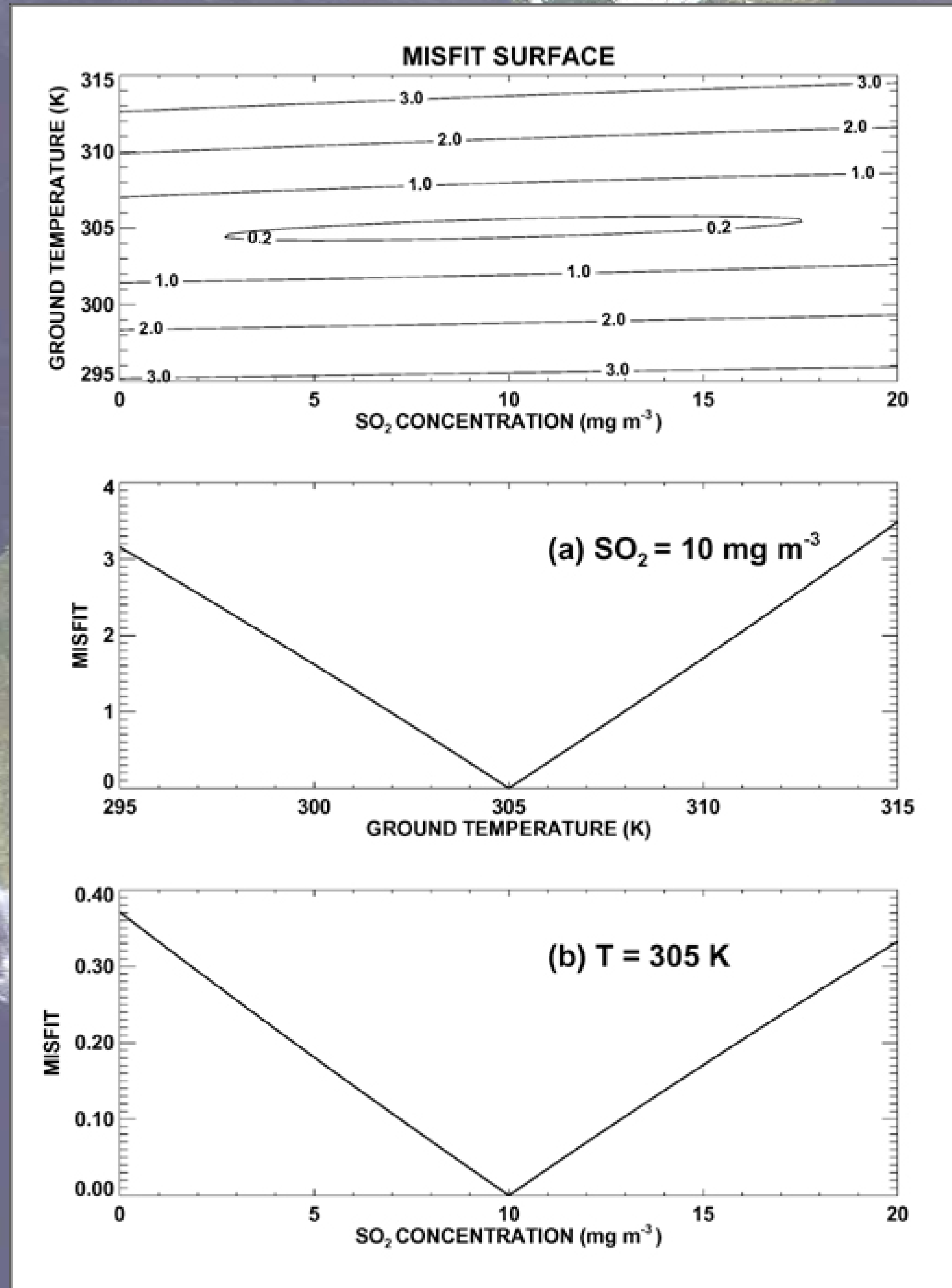
Increasing SZA Improves Detection

Sensitivity Analysis: Ground Temperature vs. SO_2 Concentration

Ground Temperature and SO_2 Concentration are Free Parameters

Ground Temperature has Stronger Influence Than SO_2 Concentration

Simultaneous Retrieval of Temperature and SO_2 is Difficult



Mapping Passive SO_2 Emissions from Space

Pu'u O'o Plume Map Derived from ASTER 90m TIR Data

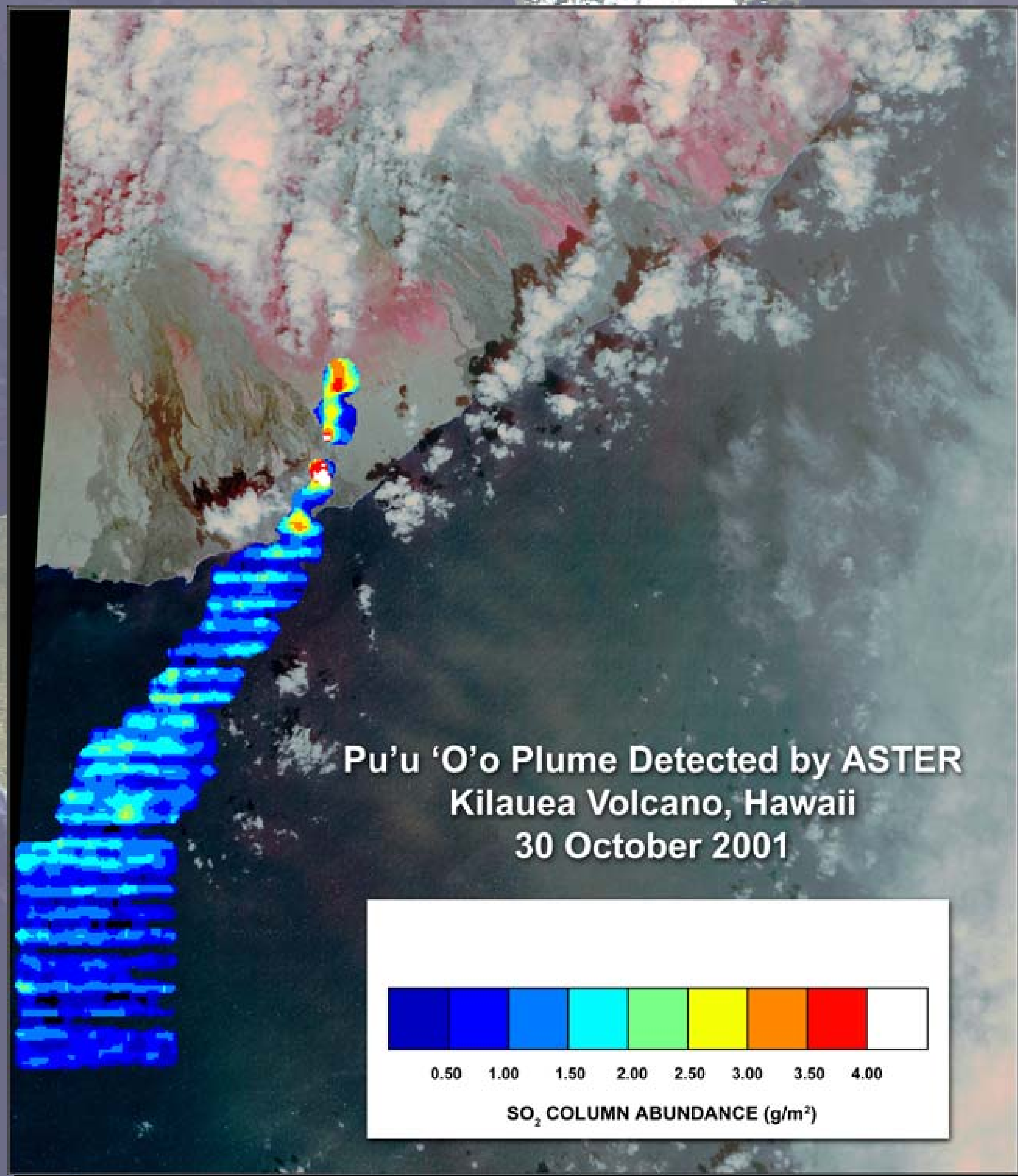
High Spatial Resolution => Greater Sensitivity to Low Levels of SO_2

Mitigating Factors

Small Plume: typically 1 km in thickness and width

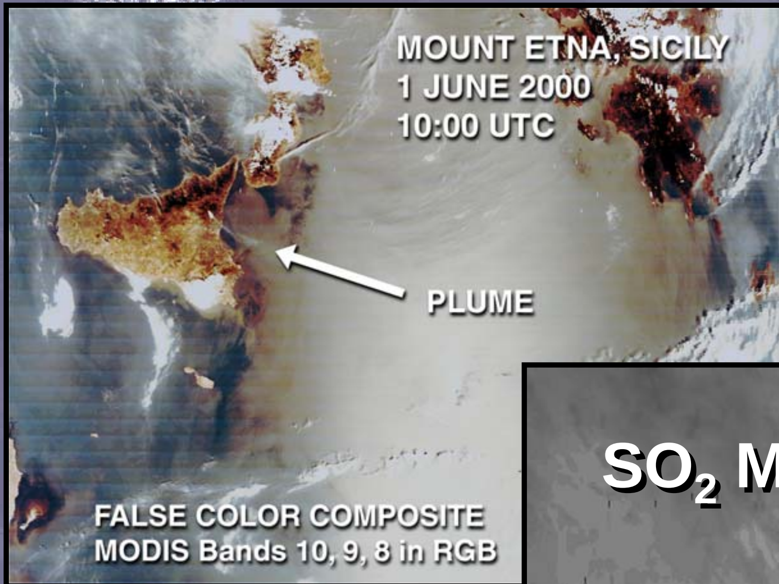
Low Altitude (typically 1.5 km asl): Low Temperature Contrast

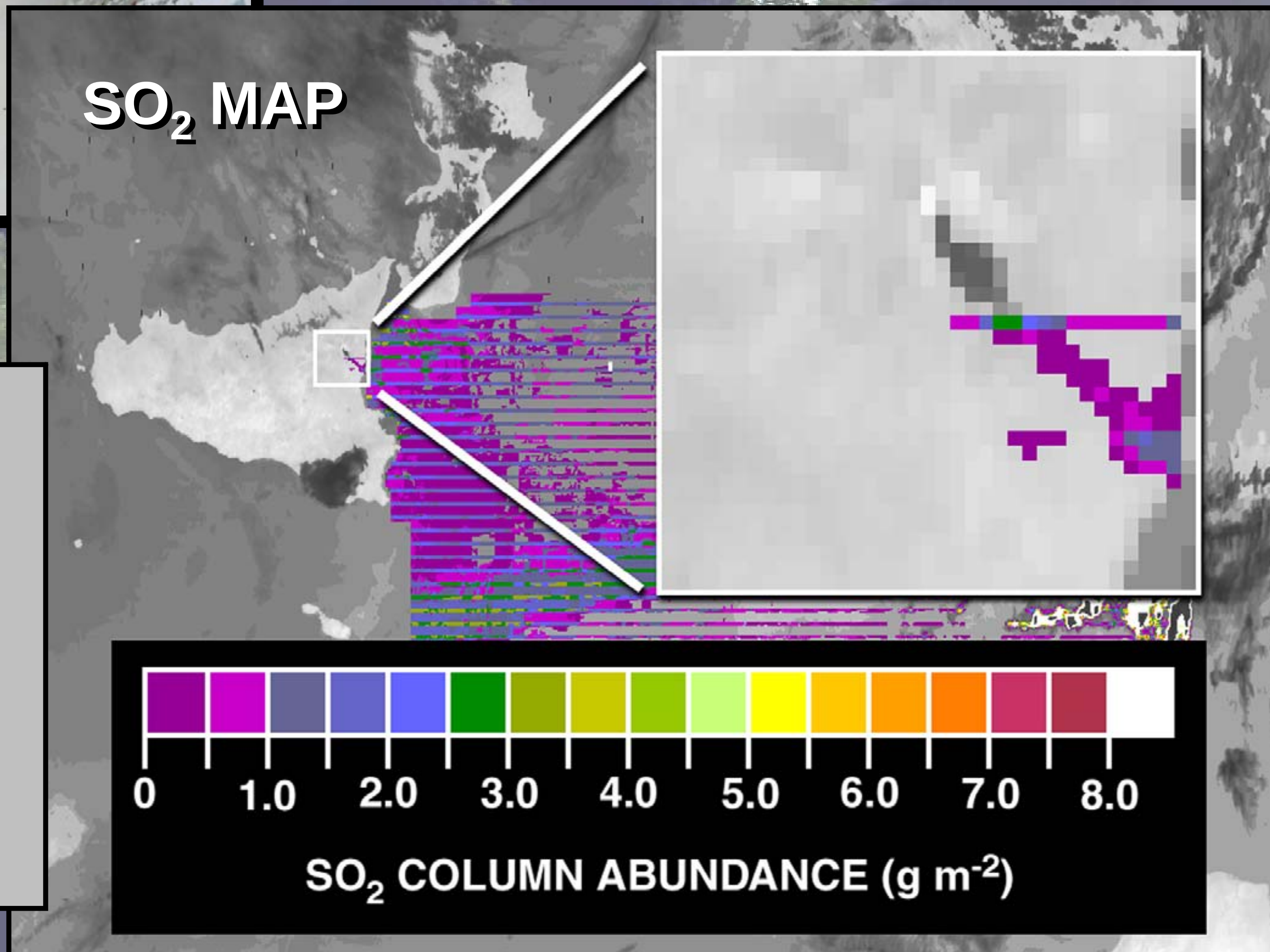
Warm, Humid Tropical Atmosphere: Decreased Temperature Contrast, Increased Atmospheric Absorption and Emission



Mapping Passive SO_2 Emissions From Space:

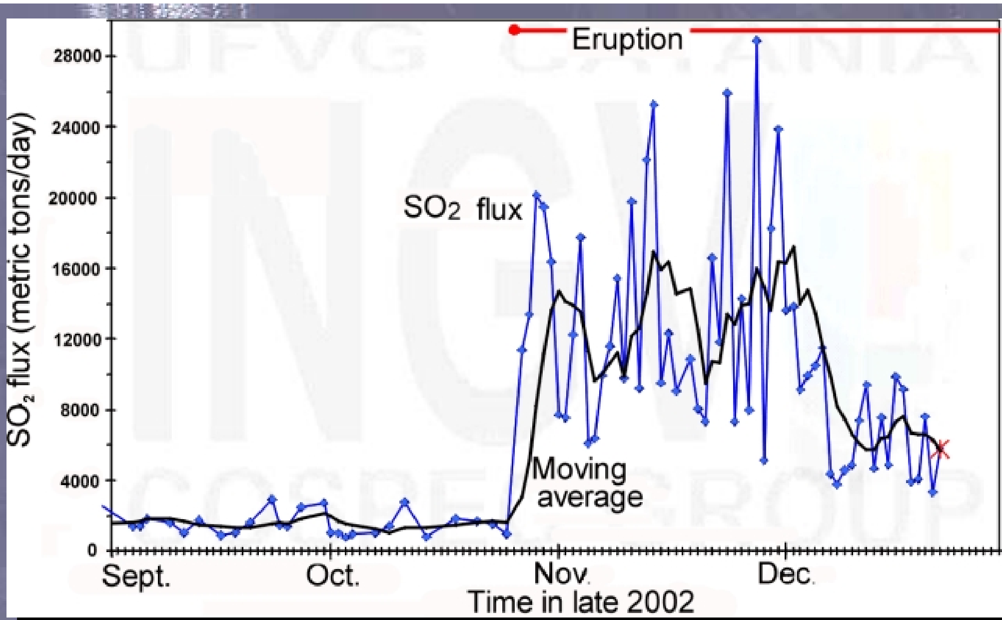
Etna Plume Map Derived From 1 km MODIS TIR Data





Higher Temperature Contrast Over Land: Increased Sensitivity to SO_2

Lower Temperature Contrast Over Water: Retrievals Dominated by Scan-Line Noise



2002-2003 Eruption Of Mount Etna

<u>27 Oct 2002 – 29 Jan 2003</u>

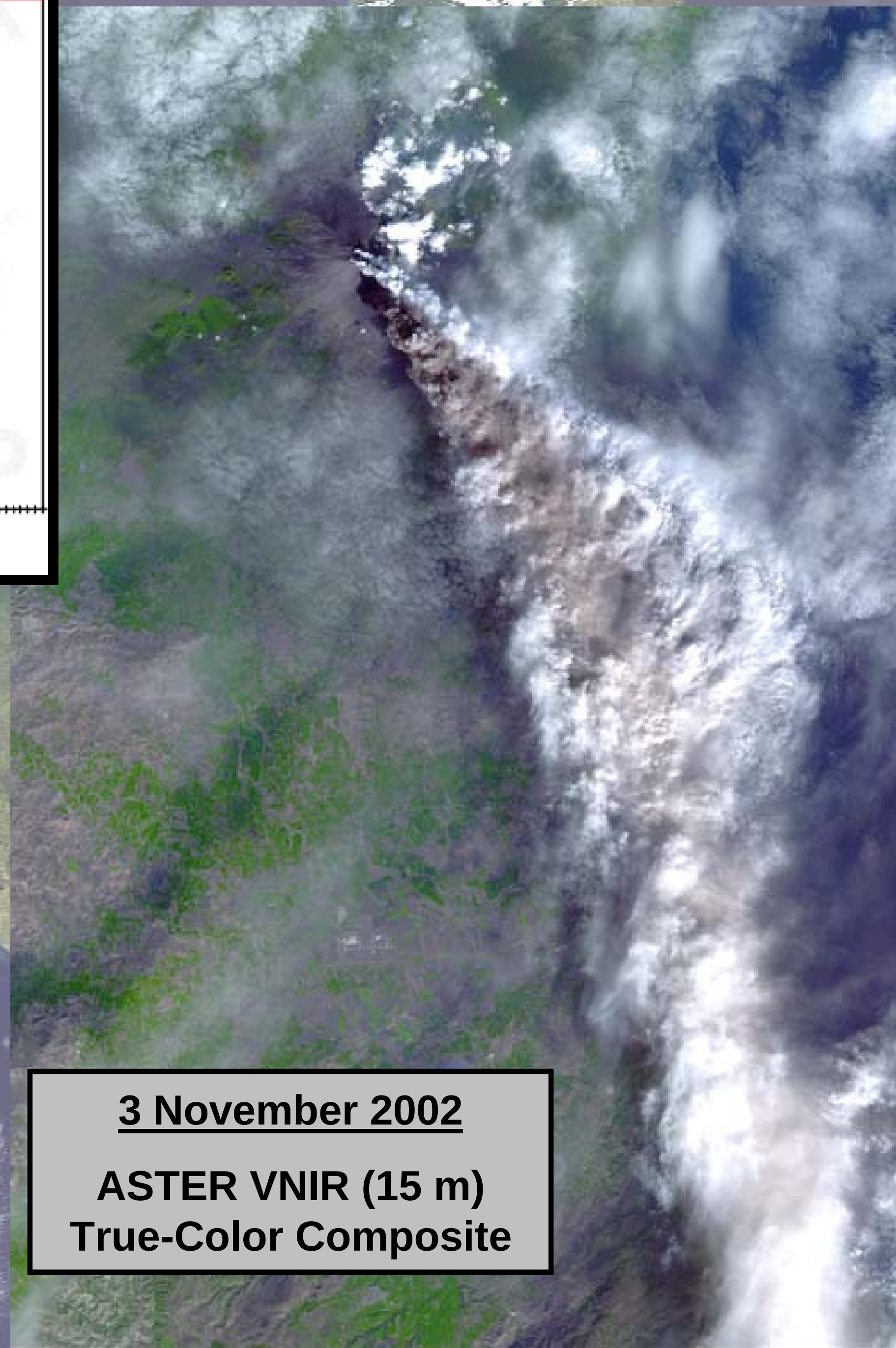
Terra/Aqua Record:

At least one daytime MODIS overpass per day

At least one daytime AIRS overpass every 2 days

Two MISR overpasses (one day apart) every 16 days

90 ASTER acquisitions between June and December 2002



<u>3 November 2002</u>

ASTER VNIR (15 m) True-Color Composite

Synergy Between Measurements

ASTER (Terra)

SO_2, aerosols, ash at concentrations below detection limits of MODIS or AIRS

MISR (Terra)

Plume Altitude, Wind Velocity, fine ash and aerosols

Measurements are Coincident with MODIS-Terra

MODIS (Terra/Aqua)

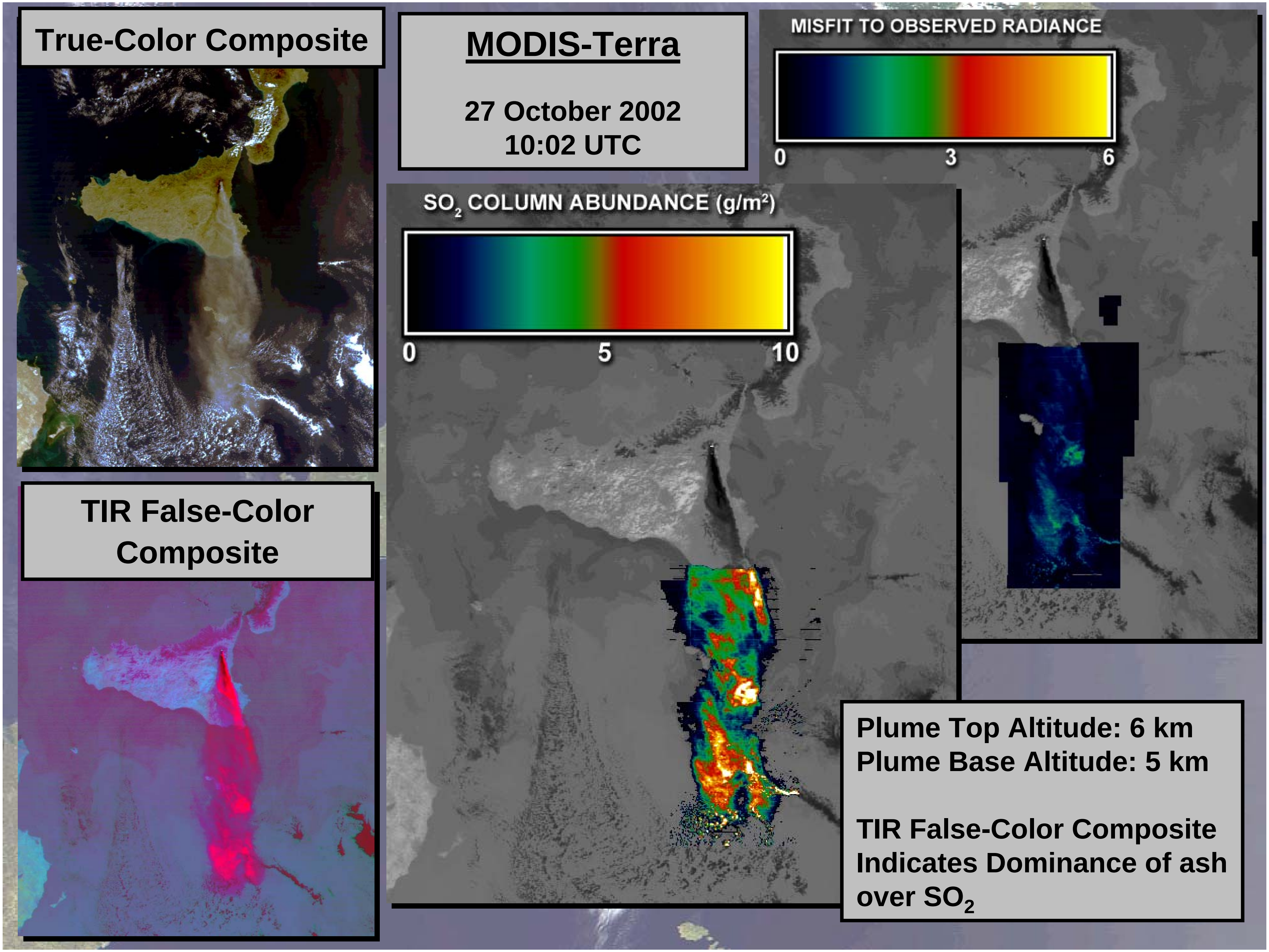
SO_2, aerosols, ash at concentrations below detection limits of AIRS

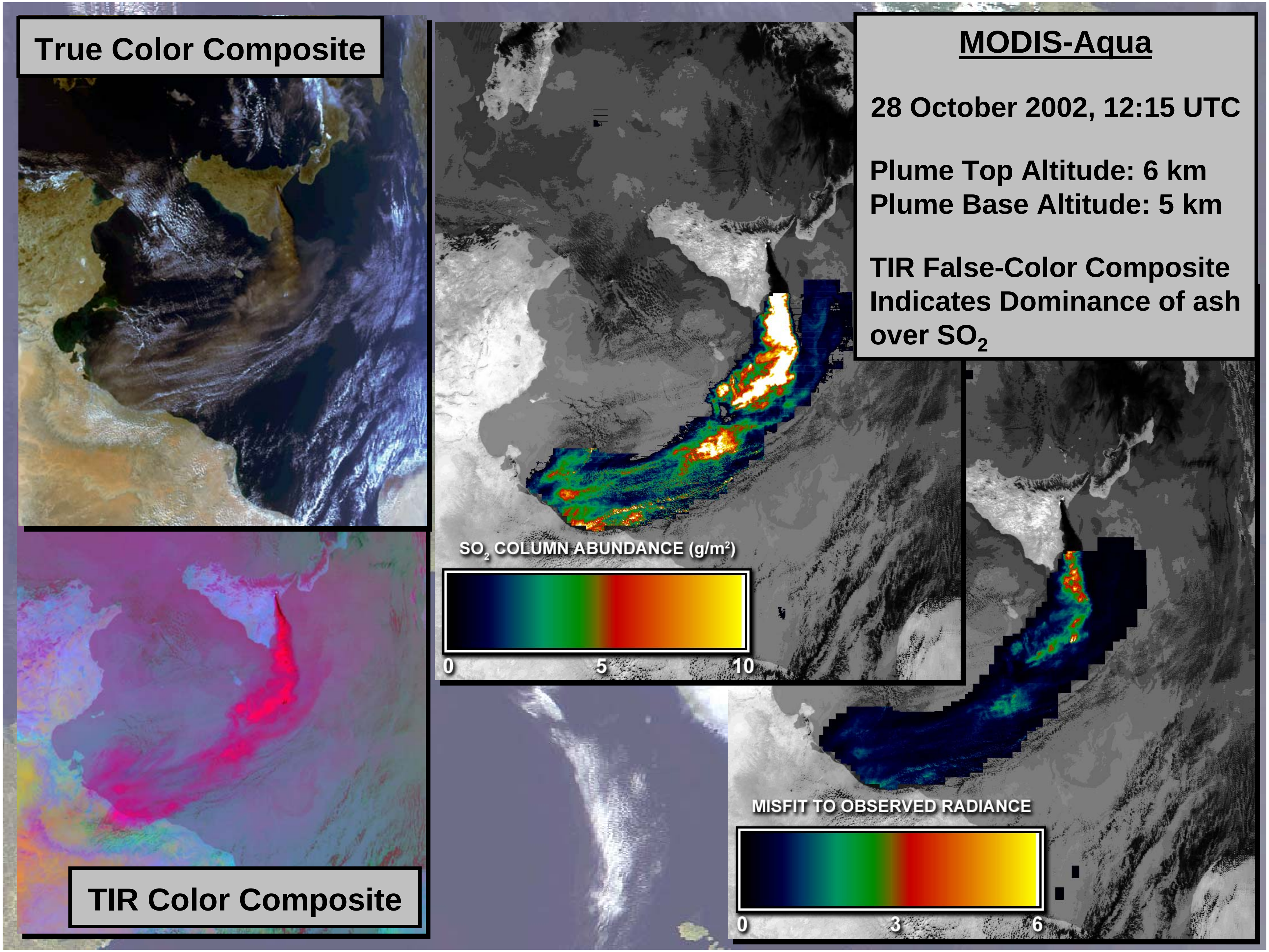
Measurements are Coincident with MISR (Terra) and AIRS (Aqua)

AIRS (Aqua)

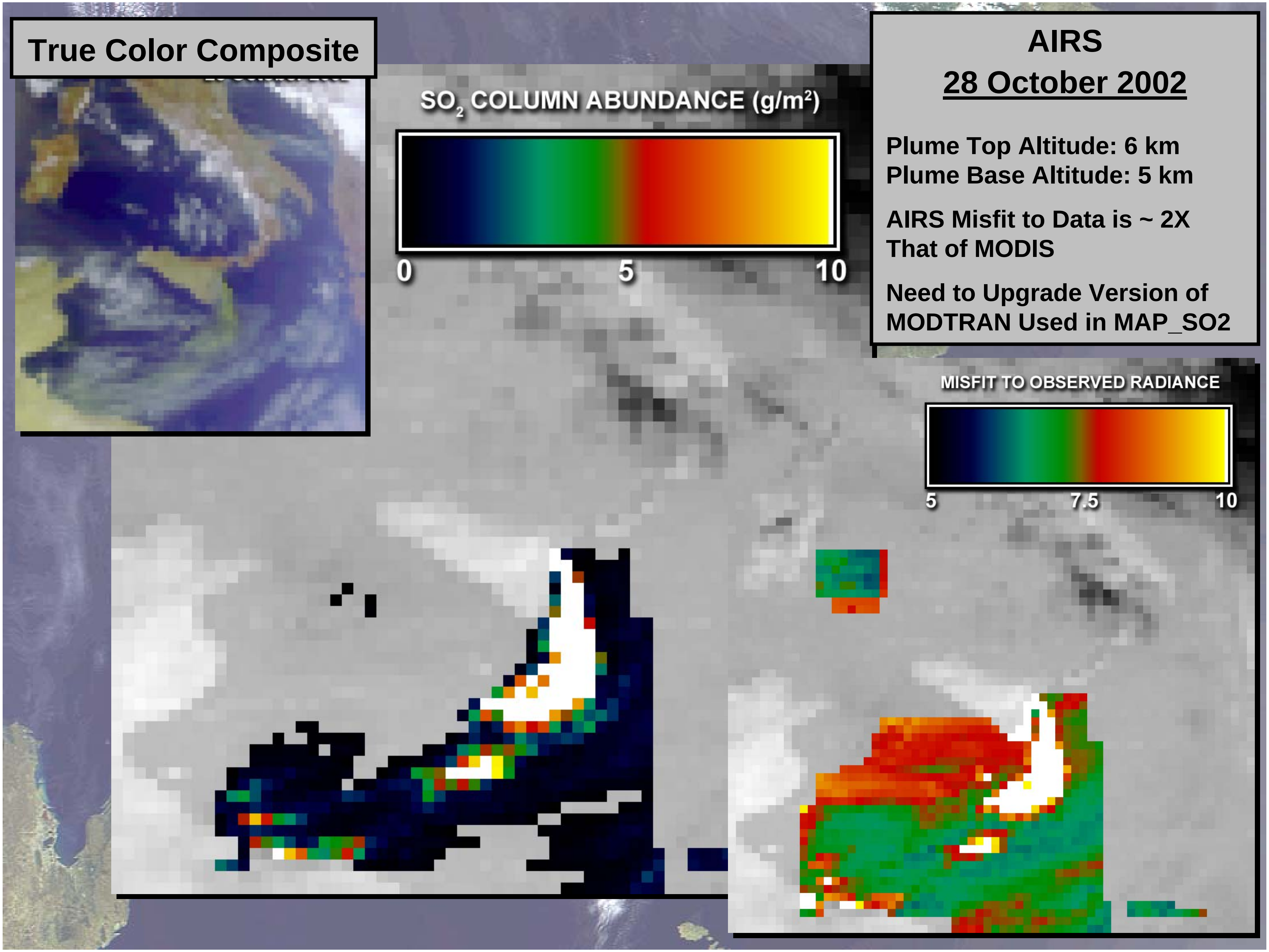
SO_2, aerosols, ash; unambiguous identification of constituents

Measurements are Coincident with MODIS-Aqua


True-Color Composite
MODIS-Terra
27 October 2002
10:02 UTC
MISFIT TO OBSERVED RADIANCE
0
3
6
SO2 COLUMN ABUNDANCE (g/m2)
0
5
10
TIR False-Color Composite
Plume Top Altitude: 6 km
Plume Base Altitude: 5 km
TIR False-Color Composite Indicates Dominance of ash over SO2

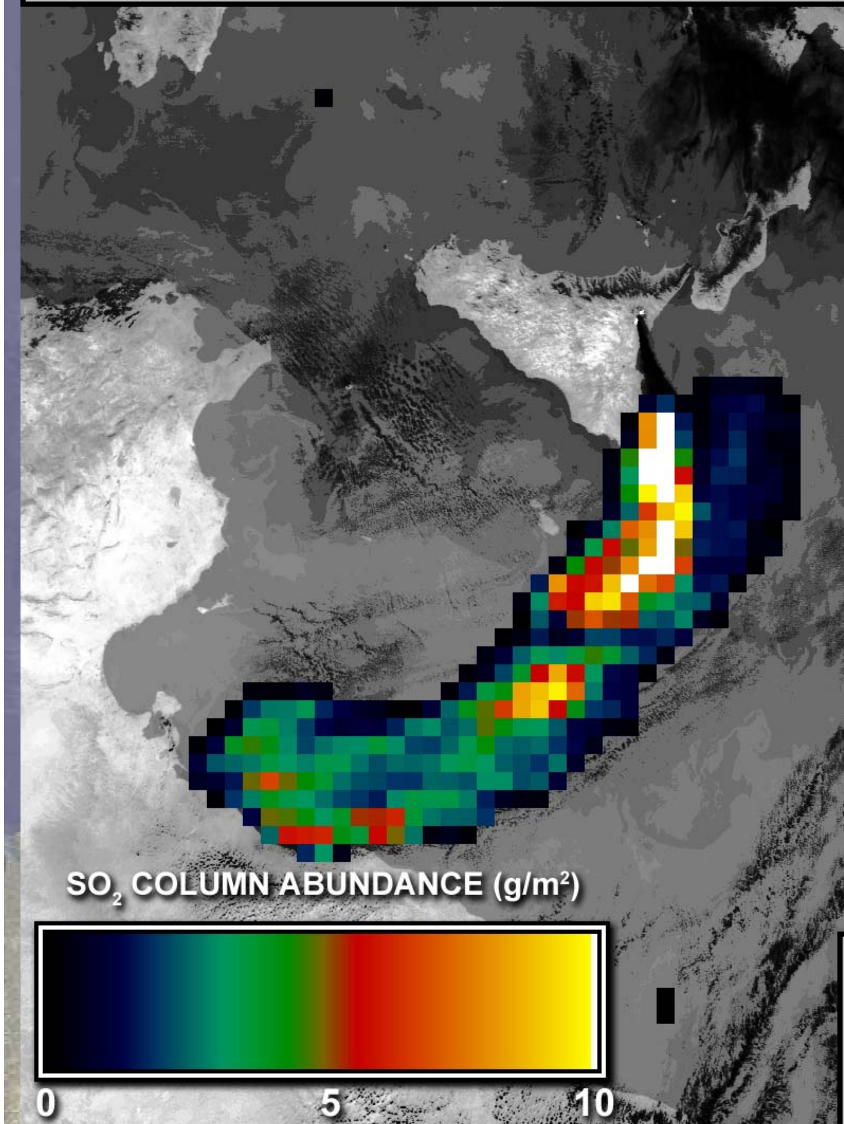


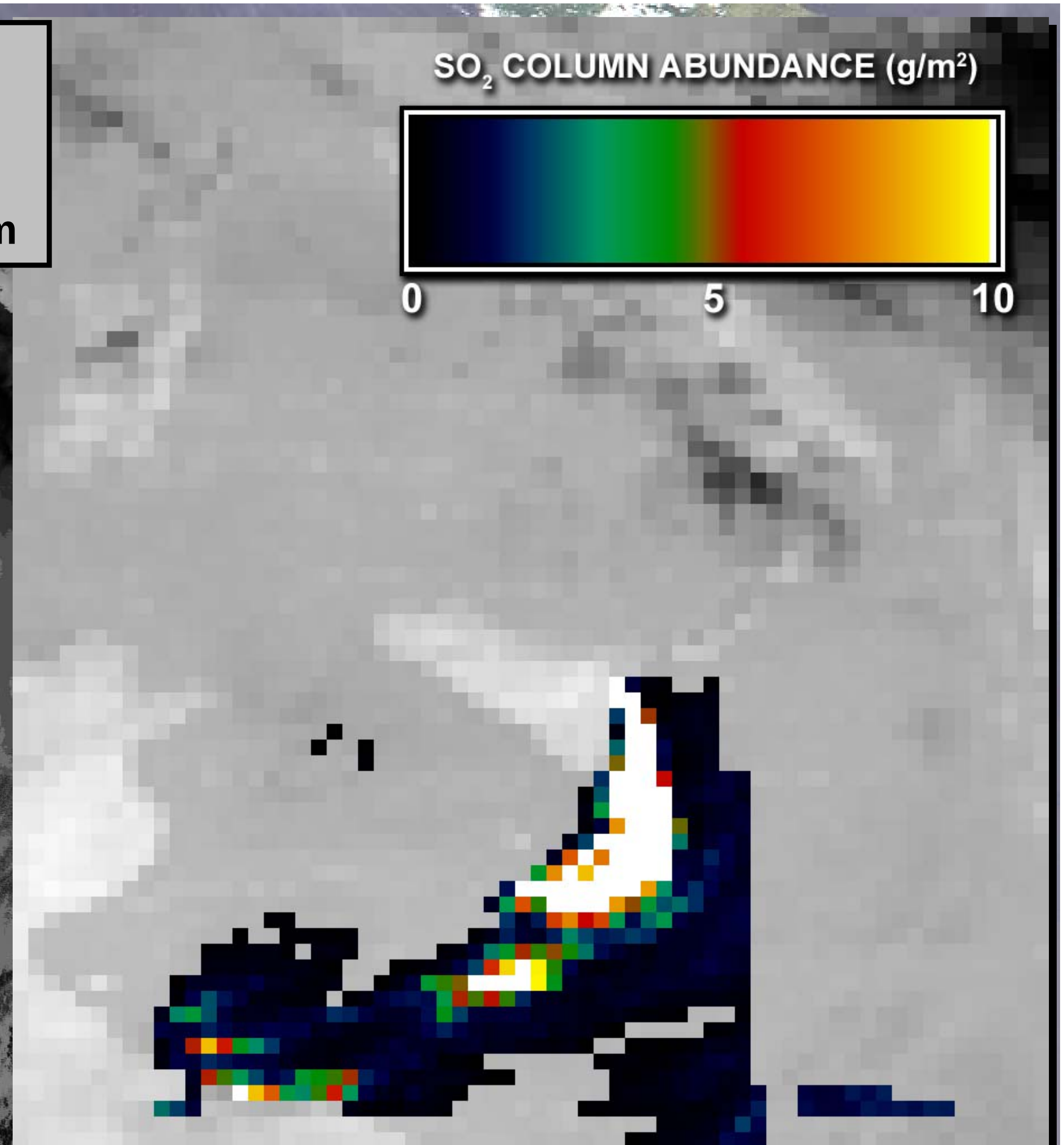
True Color Composite
MODIS-Aqua
28 October 2002, 12:15 UTC
Plume Top Altitude: 6 km
Plume Base Altitude: 5 km
TIR False-Color Composite Indicates Dominance of ash over SO_2
SO_2 COLUMN ABUNDANCE (g/m^2)
0
5
10
TIR Color Composite
MISFIT TO OBSERVED RADIANCE
0
3
6


True Color Composite
SO$_2$ COLUMN ABUNDANCE (g/m^2)
0
5
10
AIRS
28 October 2002
Plume Top Altitude: 6 km
Plume Base Altitude: 5 km
AIRS Misfit to Data is ~ 2X That of MODIS
Need to Upgrade Version of MODTRAN Used in MAP_SO2
MISFIT TO OBSERVED RADIANCE
5
7.5
10

MODIS-Aqua vs. AIRS
28 October 2002

MODIS SO_2 Map Re-Sampled to ~ 17 km





Lower Spatial Resolution of AIRS Results in Less Sensitivity to Small (~ 3 g/m²) Changes in SO_2 Burden

MODTRAN Upgrade will Improve the Sensitivity of AIRS-Based SO_2 Retrievals

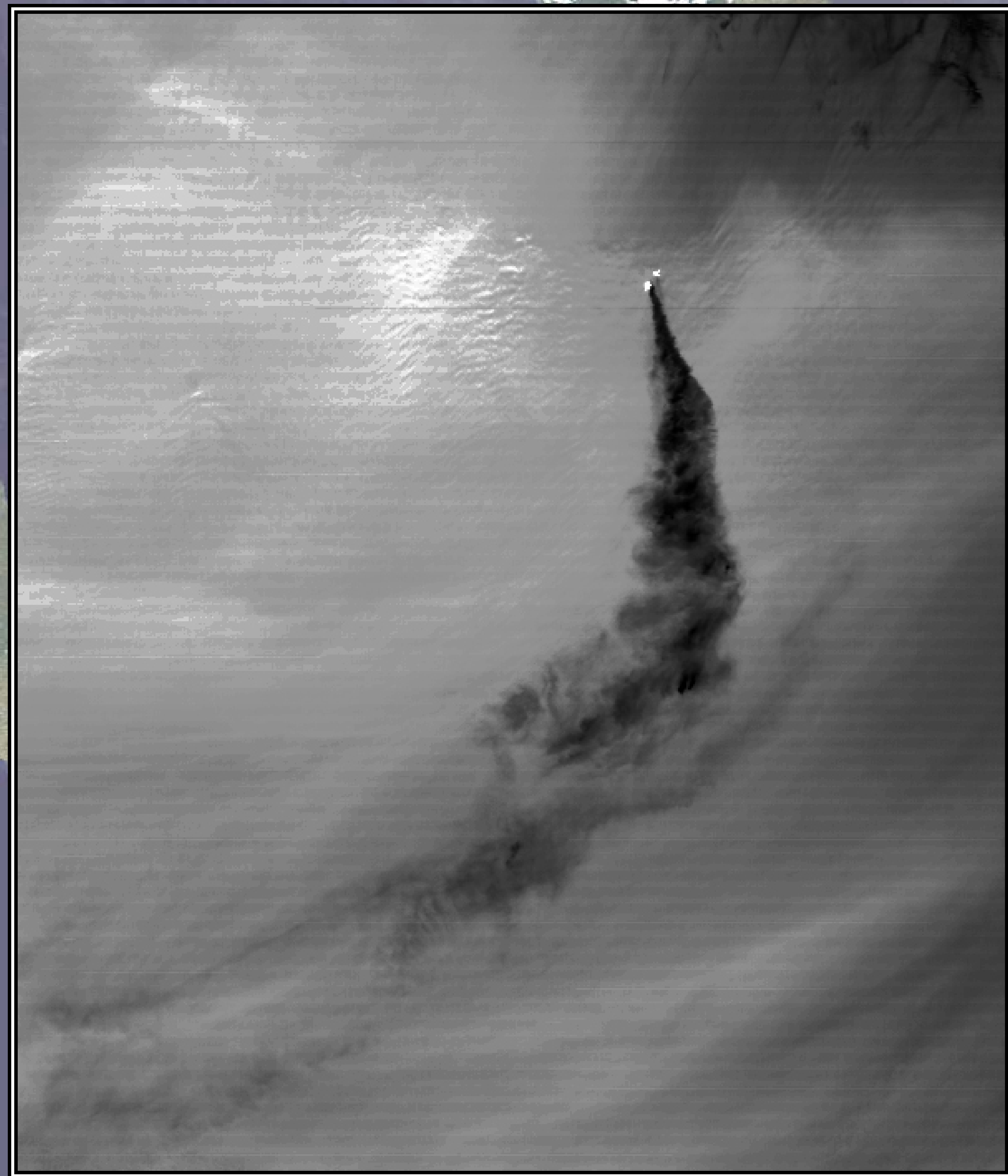
MODIS Band 28: Water Vapor Channel

Centered near 7.5 μm

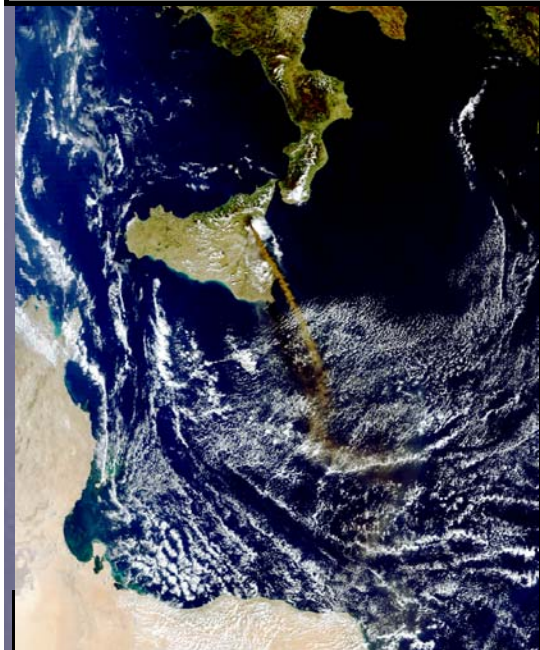
Most of Atmospheric Water Vapor is within Five Kilometers of Surface

Much of Etna Eruption Plume is Above Water Vapor

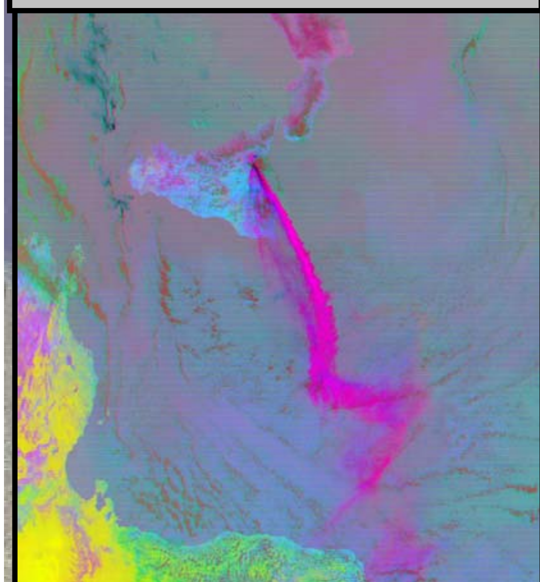
Ground is Obscured, Difficult to Model Temperature Contrast Between Plume and Background

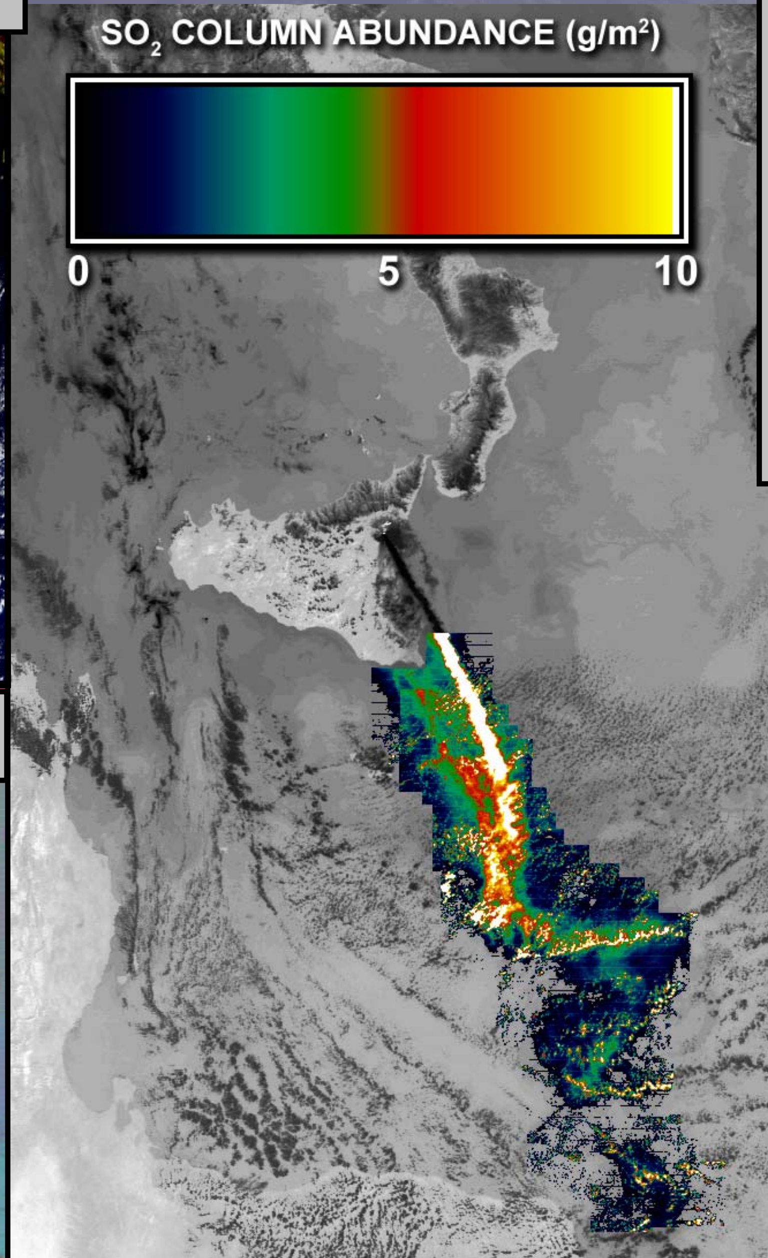


True Color Composite



TIR Color Composite



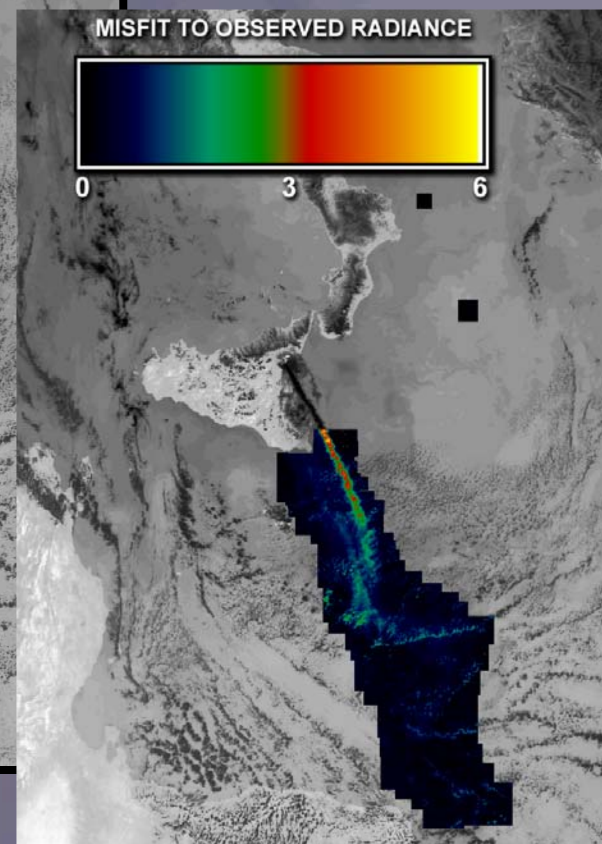


MODIS-Terra

29 October 2002, 09:45 UTC

Plume Top Altitude: 6 km
Plume Base Altitude: 5 km

TIR False-Color Composite Indicates Dominance of Ash over SO_2

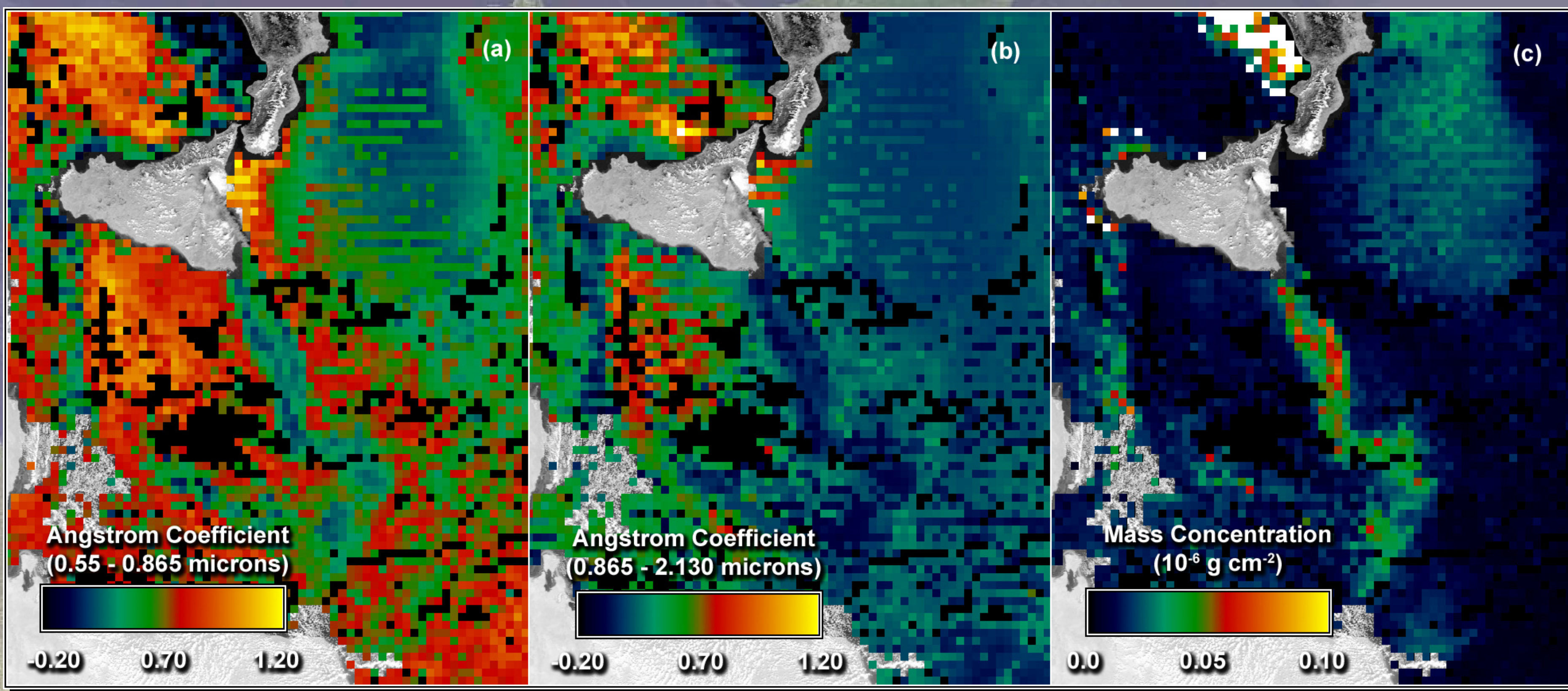


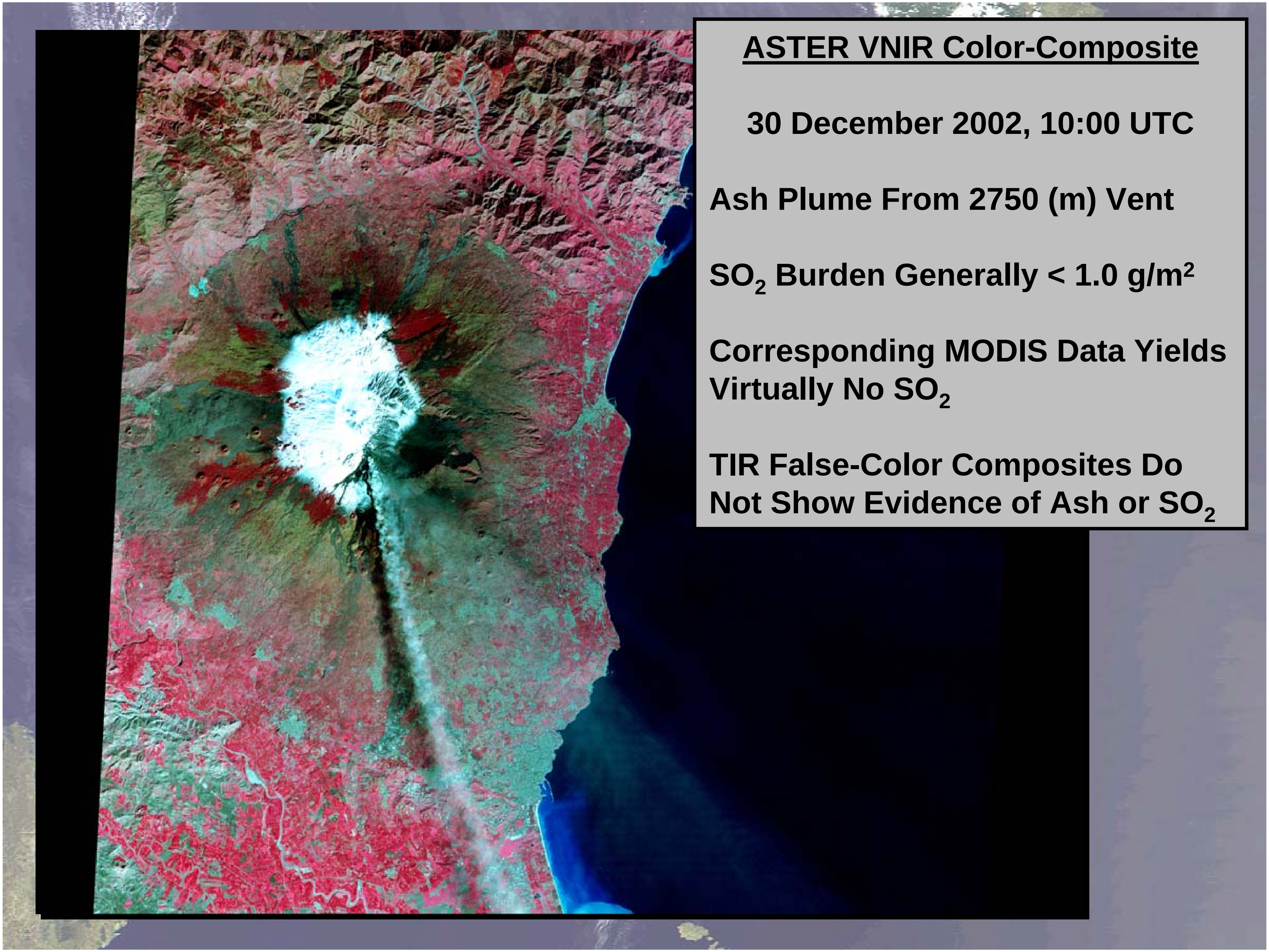
MODIS Aerosol Products

<u>Mount Etna Eruption Plume, 29 October 2002</u>

Standard Aerosol Products are Generated at Spatial Resolution of 10 km

Angstrom Coefficient: Smaller Values Indicate Coarser Aerosols





ASTER VNIR Color-Composite

30 December 2002, 10:00 UTC

Ash Plume From 2750 (m) Vent

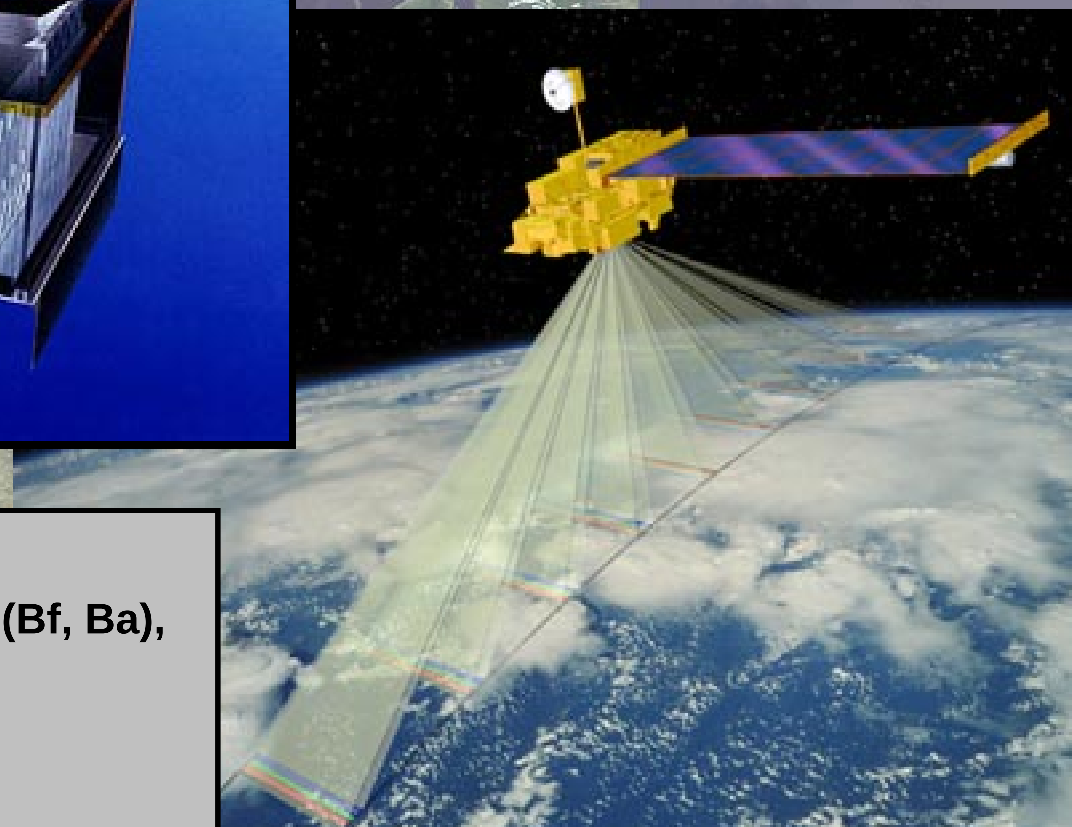
SO_2 Burden Generally < 1.0 g/m^2

Corresponding MODIS Data Yields Virtually No SO_2

TIR False-Color Composites Do Not Show Evidence of Ash or SO_2

MISR

Multi-Angle Imaging Spectro-Radiometer



9 Cameras

Nadir (An), $\pm 26.1^{o}$ (Af, Aa), $\pm 45.6^{o}$ (Bf, Ba),

$\pm 60^{o}$ (Cf, Ca), $\pm 70.5^{o}$ (Df, Da)

4 Spectral Channels

Blue (446.4 nm), Green (557.5 nm),

Red, (671.7 nm), and NIR (866.4 nm)

Disparities (Displacements) Resulting from Height and Wind

Along-Track Disparity for Any Features Above or Below Reference Elevation

Ellipsoid-Projected Radiance: $\Delta y = \pm h \tan \Theta$

7-Minute Delay Between Df and Da Images Results in Wind-Induced Disparities

Cross Track Disparity: $\Delta x = \pm V_x \, \Delta t$, Along-Track Disparity: $\Delta y = \pm V_y \, \Delta t$

Both Types of Disparity Used to Estimate Cloud Height and Wind Speed

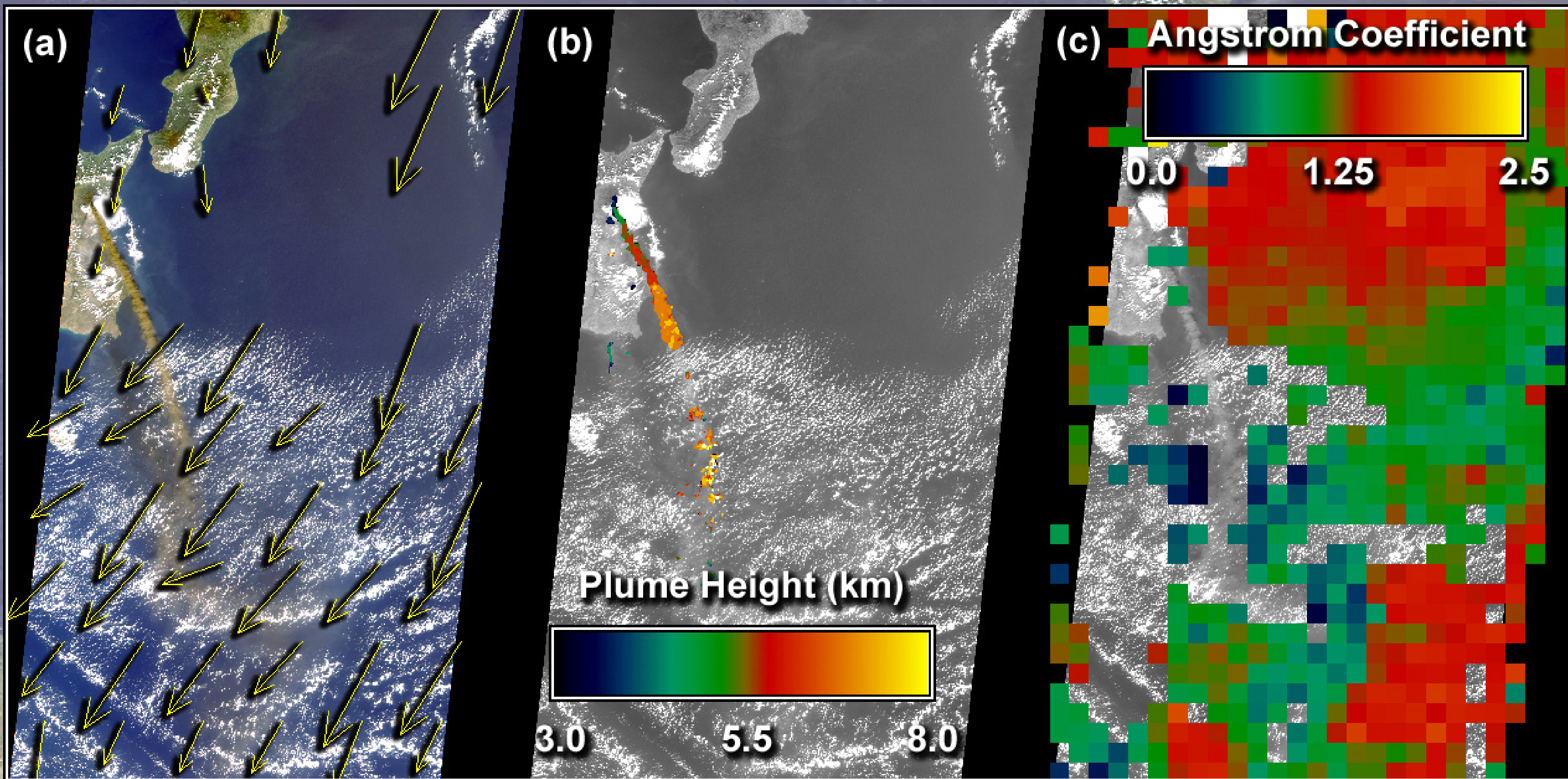
von Karman Vortices, Jan Mayen Island, Norway

MISR

MISR Data Products

Mount Etna Eruption Plume

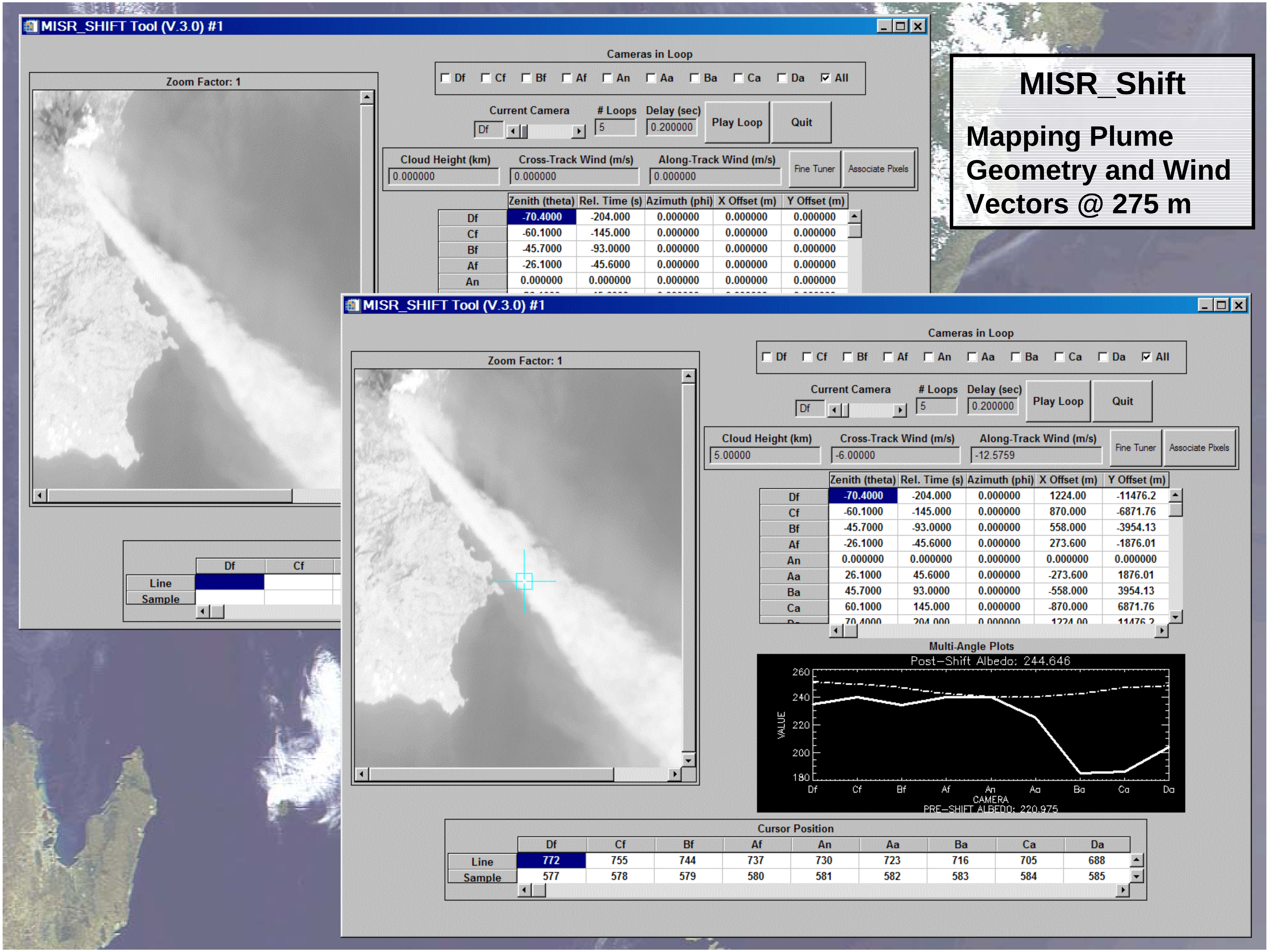
29 October 2002



Wind Velocity Range: 2 – 20 m/s

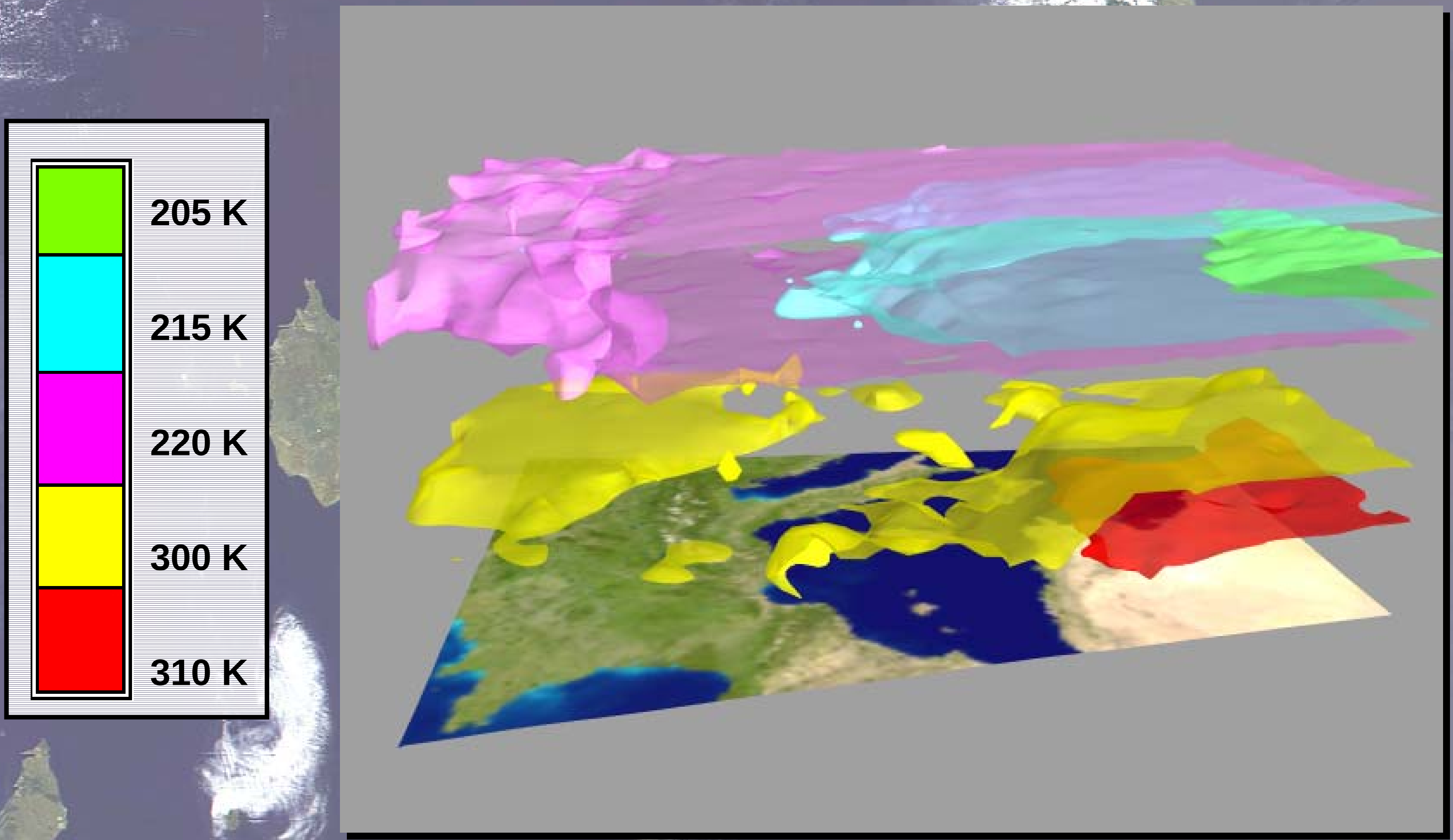
MISR_Shift

Mapping Plume Geometry and Wind Vectors @ 275 m



AIRS Level 2 Temperature Retrievals

8 September 2002



CONCLUDING REMARKS…

Retrievals Appear to be Consistent

Three Days of Activity; Three Instruments

MAP_SO2 Does Not Introduce Systematic Bias

AIRS-Based Retrievals in General Agreement with MODIS-Based Retrievals

Future Efforts

Focus on Days with Terra and Aqua Overpasses (eg. 27 Oct 2002)

Begin ASTER Processing (30 December 2002)

Incorporation of MISR-Based Plume Geometry

MODTRAN Upgrade

Incorporation of AIRS-Based Atmospheric Profiles