

Multispectral Remote Sensing

Lectures in Monteponi
September 2008

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UW/CIMSS/AOS

Applications with Multispectral Remote Sensing Data

Satellite Remote Sensing

Energy Balance

VIS, IR, and MW Radiative Transfer

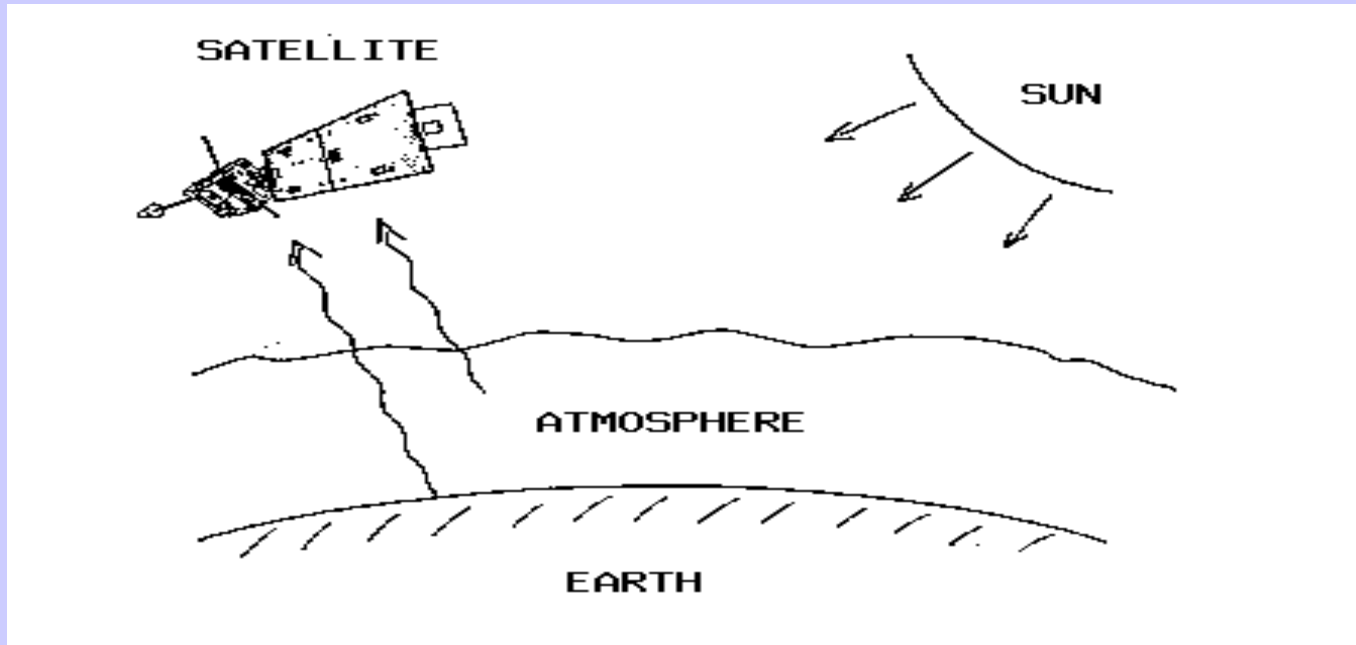
EOS Terra & Aqua MODIS

Multispectral Signatures

*(Ocean Color, Snow/Ice, Vegetation, Aerosols,
Clouds, Moisture, Fires, Volcanic Ash)*

Detecting Climate Trends

Satellite remote sensing of the Earth-atmosphere



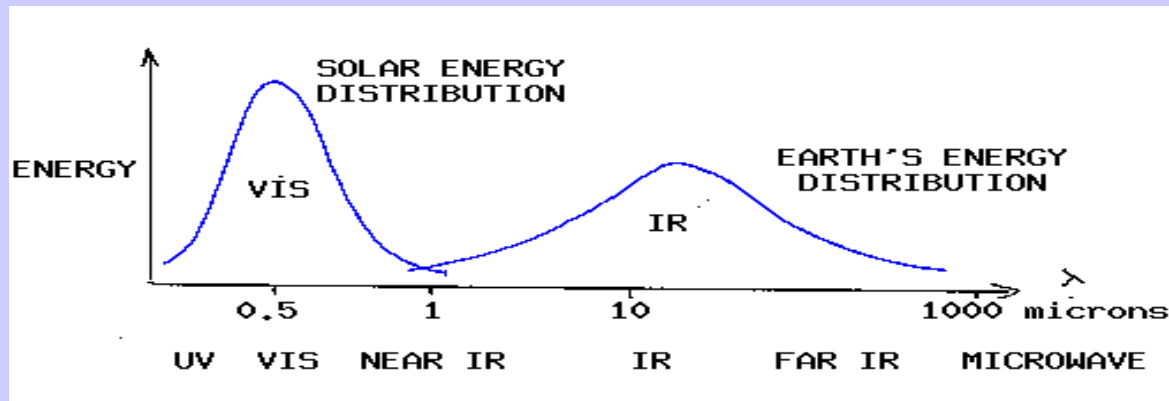
Observations depend on

- telescope characteristics (resolving power, diffraction)
- detector characteristics (signal to noise)
- communications bandwidth (bit depth)
- spectral intervals (window, absorption band)
- time of day (daylight visible)
- atmospheric state (T, Q, clouds)
- earth surface (Ts, vegetation cover)

Remote Sensing Advantages

- * provides a regional view
- * enables one to observe & measure the causes & effects of climate & environmental changes (both natural & human-induced)
- * provides repetitive geo-referenced looks at the same area
- * covers a broader portion of the spectrum than the human eye
- * can focus in on a very specific bandwidth in an image
- * can also look at a number of bandwidths simultaneously
- * operates in all seasons, at night, and in bad weather

Solar (visible) and Earth emitted (infrared) energy



Incoming solar radiation (mostly visible) drives the earth-atmosphere (which emits infrared).

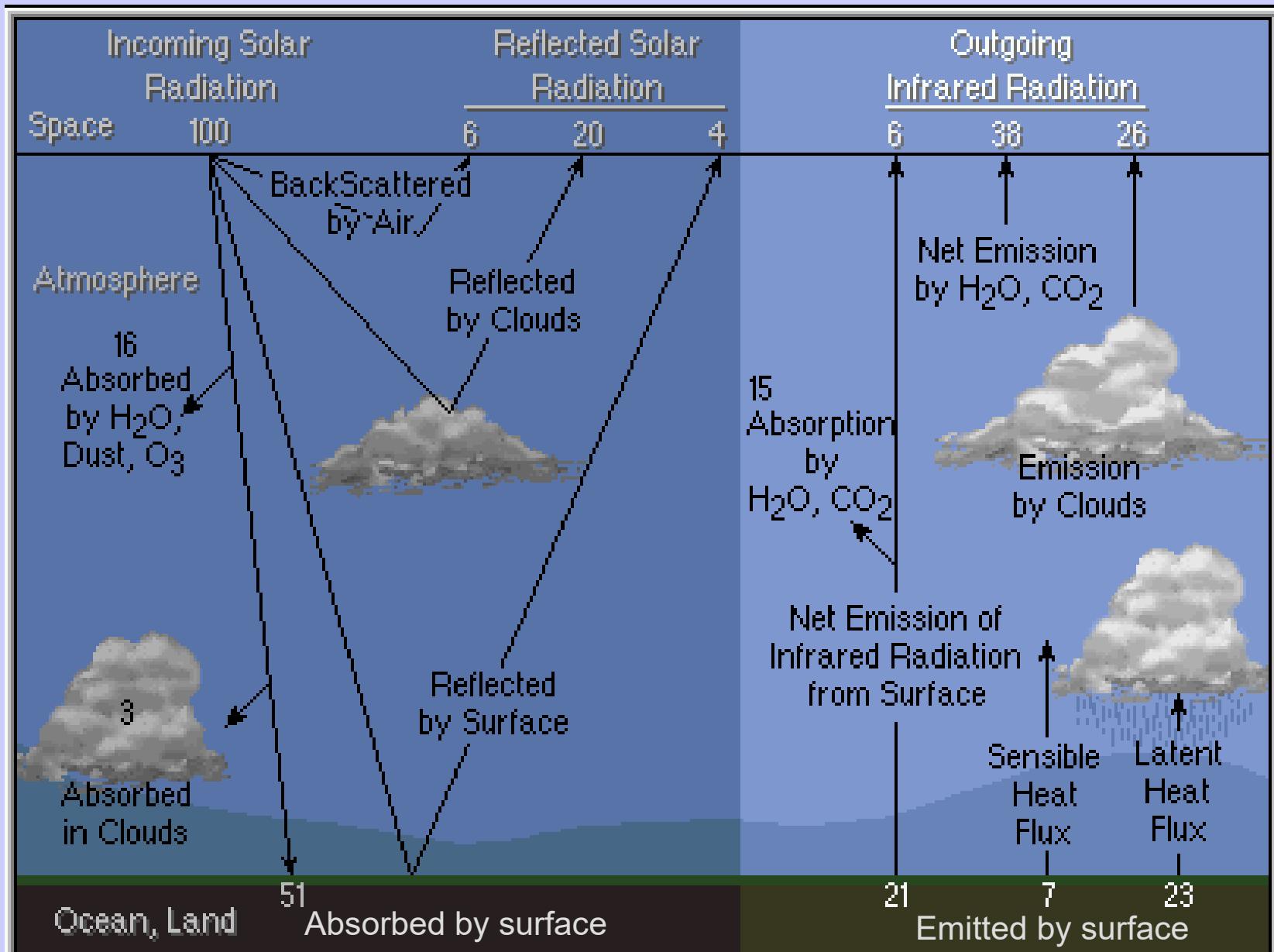
Over the annual cycle, the incoming solar energy that makes it to the earth surface (about 50 %) is balanced by the outgoing thermal infrared energy emitted through the atmosphere.

The atmosphere transmits, absorbs (by H₂O, O₂, O₃, dust) reflects (by clouds), and scatters (by aerosols) incoming visible; the earth surface absorbs and reflects the transmitted visible. Atmospheric H₂O, CO₂, and O₃ selectively transmit or absorb the outgoing infrared radiation. The outgoing microwave is primarily affected by H₂O and O₂.

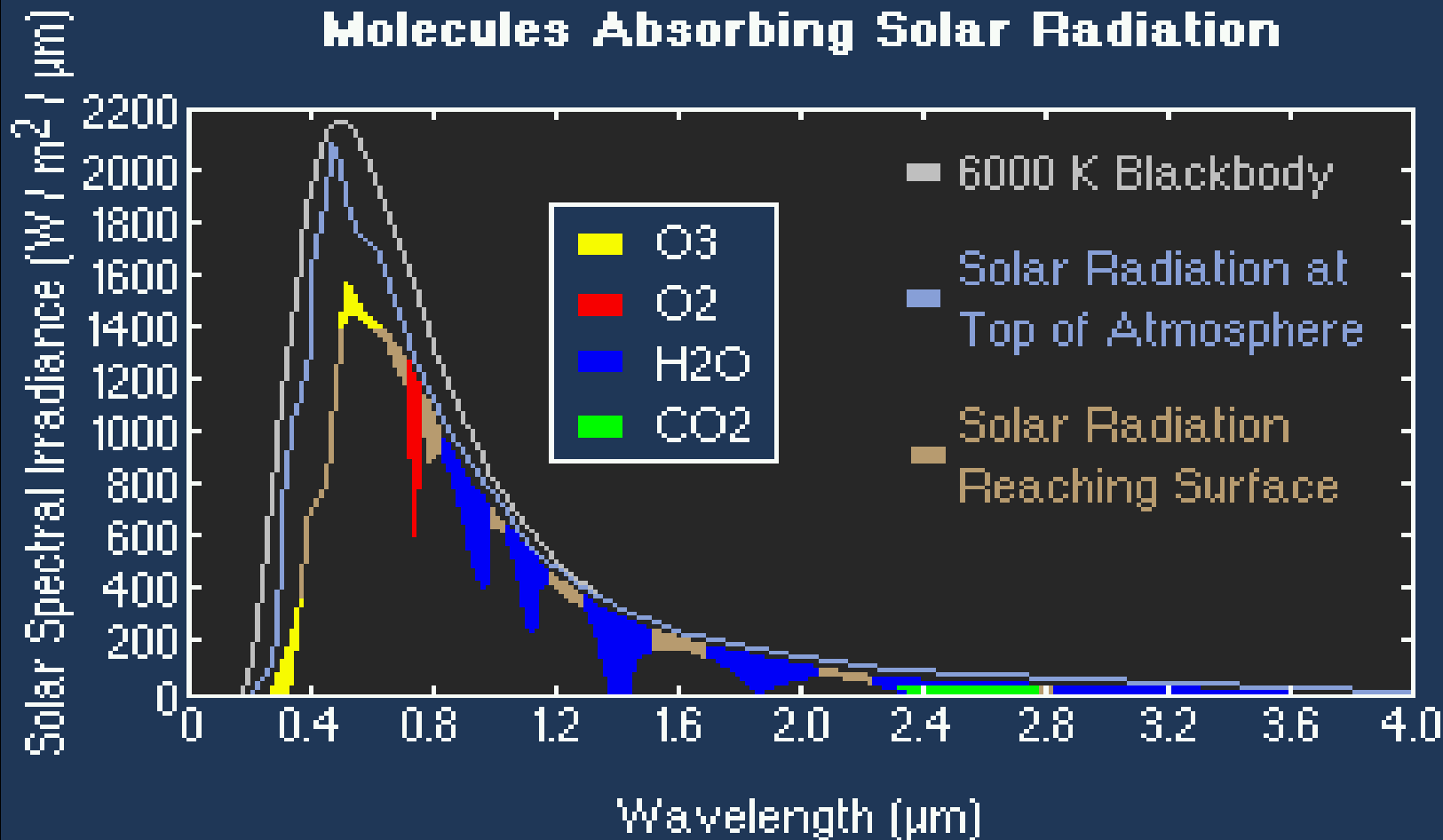
Key Areas of Uncertainty **in Understanding Climate & Global Change**

- * Earth's radiation balance and the influence of clouds on radiation and the hydrologic cycle
- * Oceanic productivity, circulation and air-sea exchange
- * Transformation of greenhouse gases in the lower atmosphere, with emphasis on the carbon cycle
- * Changes in land use, land cover and primary productivity, including deforestation
- * Sea level variability and impacts of ice sheet volume
- * Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone
- * Volcanic eruptions and their role in climate change

Radiative Energy Balance

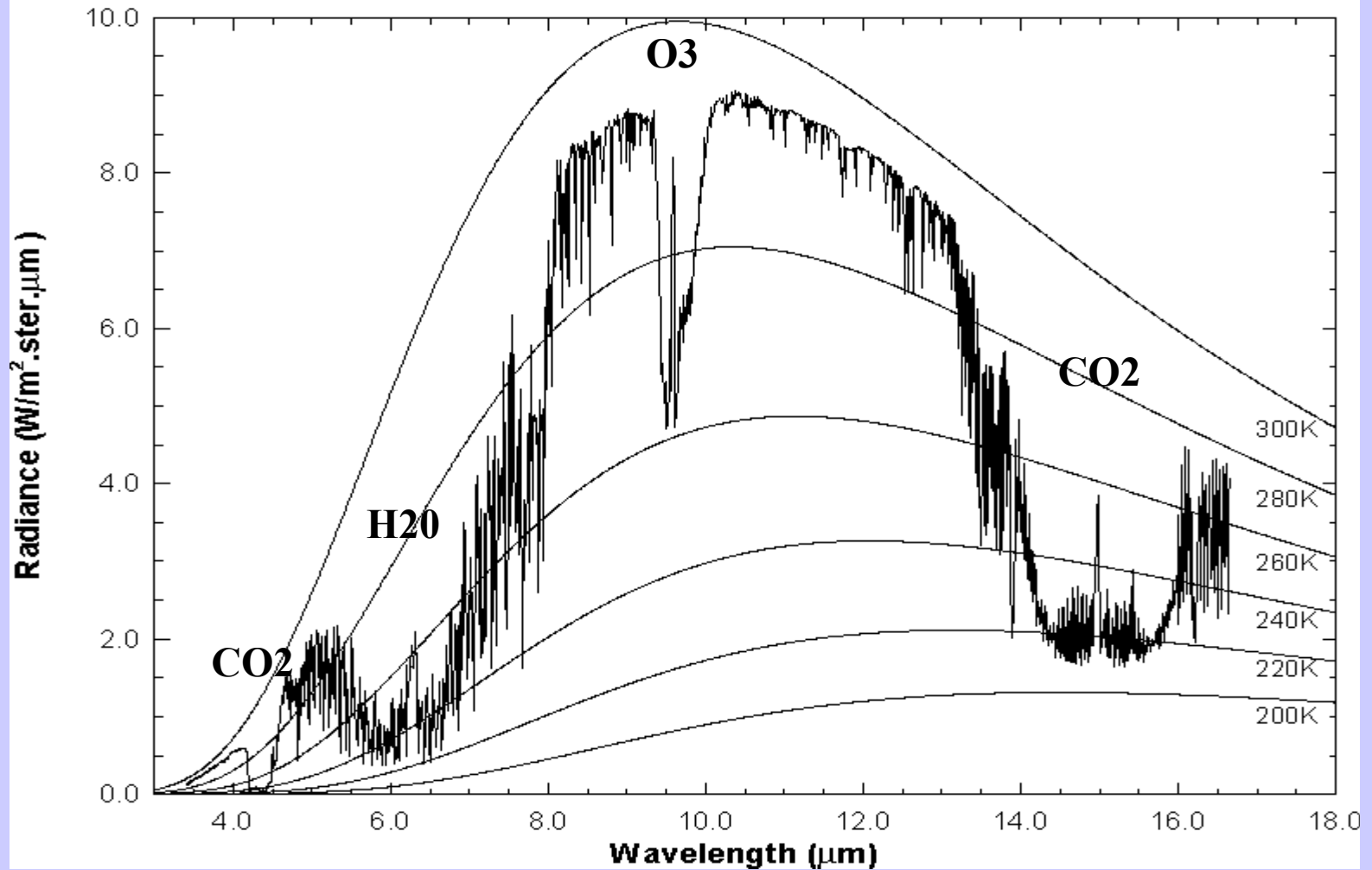


Solar Spectrum

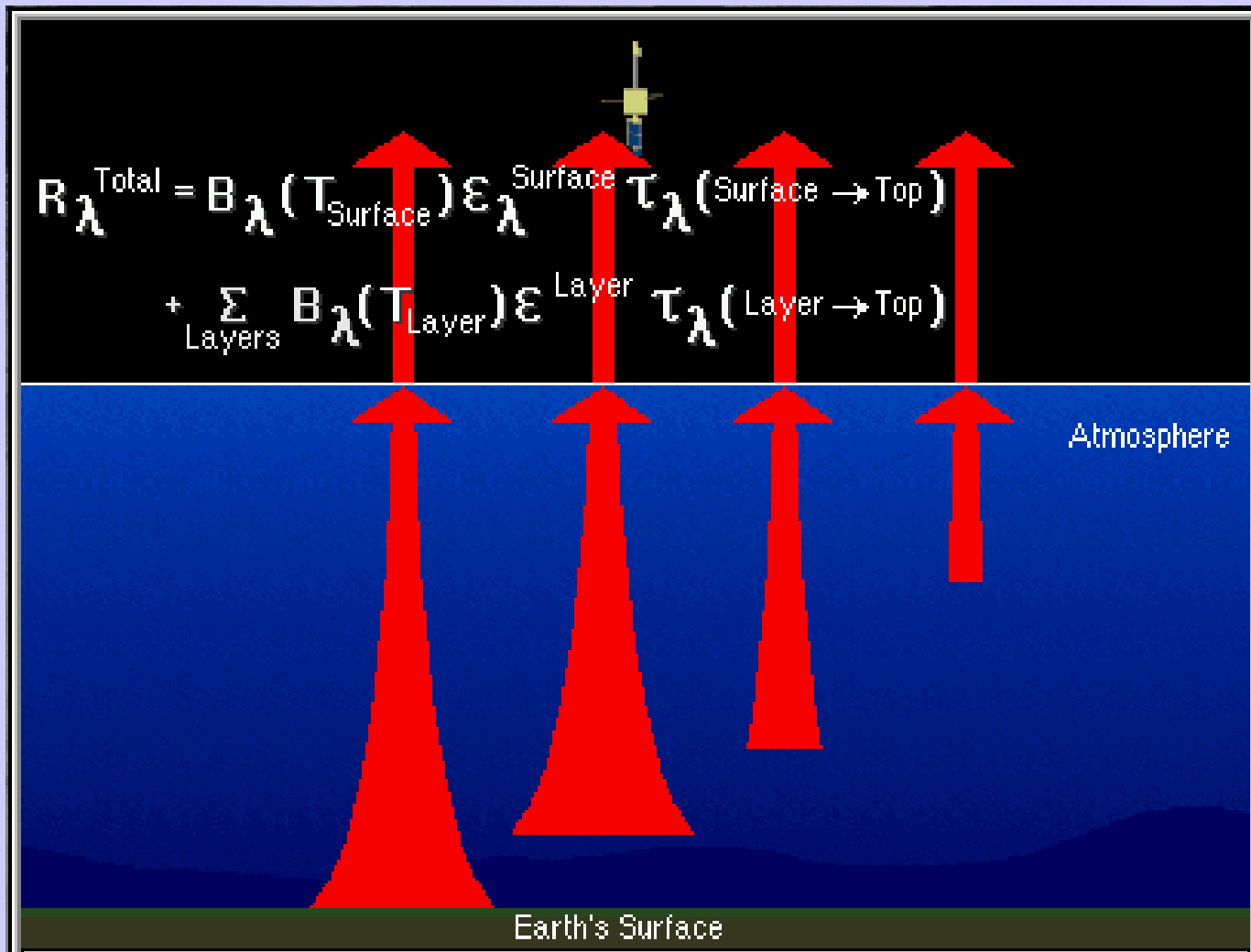


Earth emitted spectra overlaid on Planck function envelopes

High resolution atmospheric absorption spectrum and comparative blackbody curves.



Radiative Transfer through the Atmosphere



When reflection from the earth surface is also considered, the Radiative Transfer Equation for infrared radiation can be written

$$I_{\lambda} = \varepsilon_{\lambda}^{\text{sfc}} B_{\lambda}(T_s) \tau_{\lambda}(p_s) + \int_{p_s}^0 B_{\lambda}(T(p)) F_{\lambda}(p) [d\tau_{\lambda}(p) / dp] dp$$

where

$$F_{\lambda}(p) = \{ 1 + (1 - \varepsilon_{\lambda}) [\tau_{\lambda}(p_s) / \tau_{\lambda}(p)]^2 \}$$

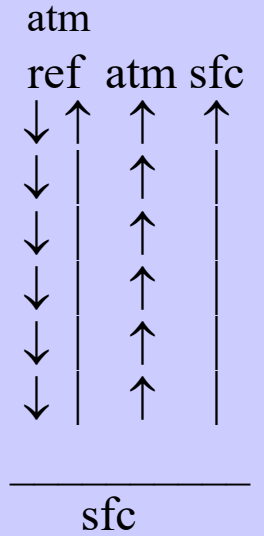
The first term is the spectral radiance emitted by the surface and attenuated by the atmosphere, often called the boundary term and the second term is the spectral radiance emitted to space by the atmosphere directly or by reflection from the earth surface.

The atmospheric contribution is the weighted sum of the Planck radiance contribution from each layer, where the weighting function is $[d\tau_{\lambda}(p) / dp]$. This weighting function is an indication of where in the atmosphere the majority of the radiation for a given spectral band comes from.

Including surface emissivity

$$I_{\lambda}^{\text{sfc}} = \varepsilon_{\lambda} B_{\lambda}(T_s) \tau_{\lambda}(p_s) + (1-\varepsilon_{\lambda}) \tau_{\lambda}(p_s) \int_0^{p_s} B_{\lambda}(T(p)) \frac{\partial \tau'_{\lambda}(p)}{\partial \ln p} d \ln p$$

$$I_{\lambda} = \varepsilon_{\lambda} B_{\lambda}(T_s) \tau_{\lambda}(p_s) + (1-\varepsilon_{\lambda}) \tau_{\lambda}(p_s) \int_0^{p_s} B_{\lambda}(T(p)) \frac{\partial \tau'_{\lambda}(p)}{\partial \ln p} d \ln p + \int_{p_s}^0 B_{\lambda}(T(p)) \frac{\partial \tau_{\lambda}(p)}{\partial \ln p} d \ln p$$



using $\tau'_{\lambda}(p) = \tau_{\lambda}(p_s) / \tau_{\lambda}(p)$ then.

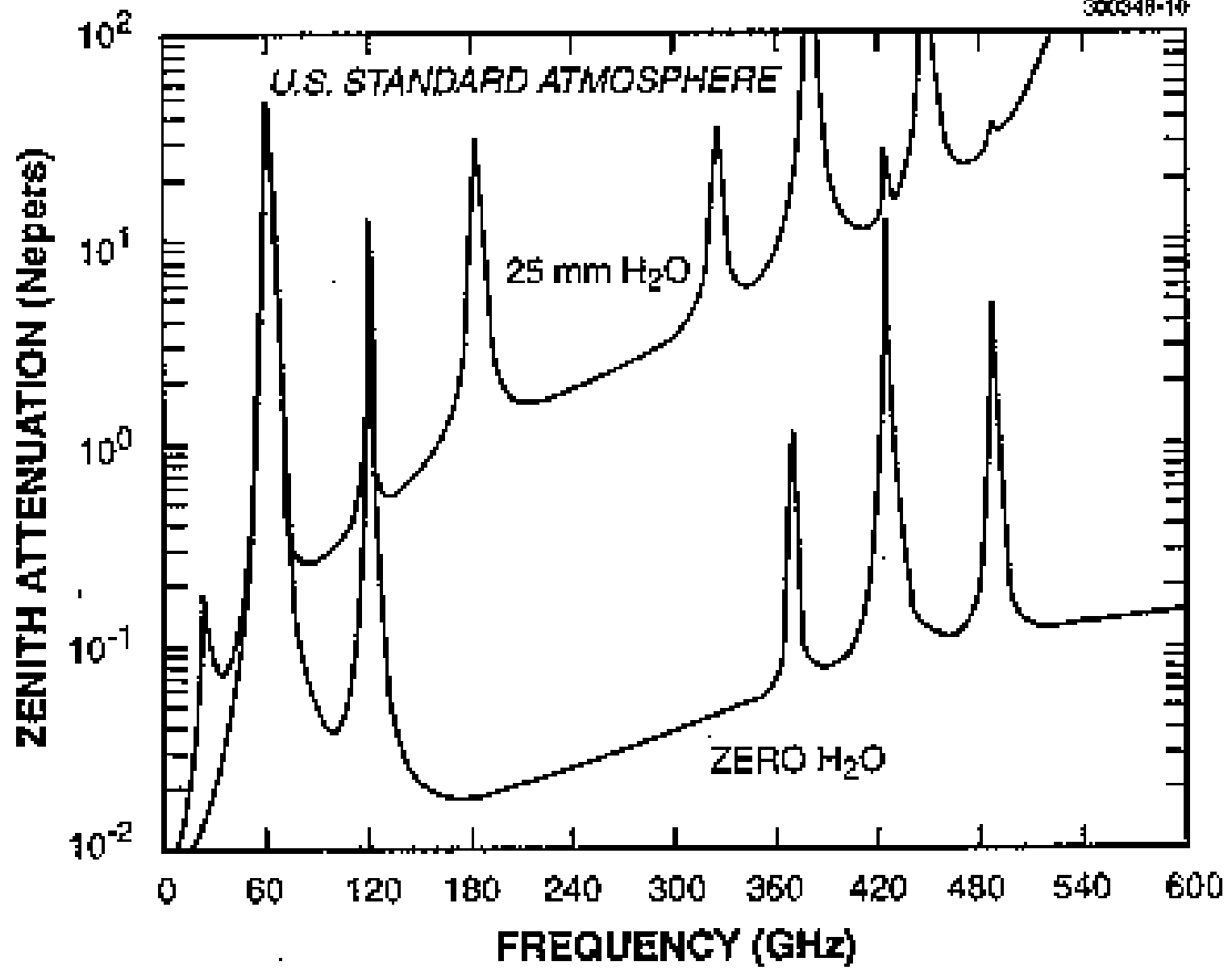
$$\frac{\partial \tau'_{\lambda}(p)}{\partial \ln p} = - \frac{\tau_{\lambda}(p_s)}{(\tau_{\lambda}(p))^2} \frac{\partial \tau_{\lambda}(p)}{\partial \ln p}$$

Thus

$$I_{\lambda} = \varepsilon_{\lambda} B_{\lambda}(T(p_s)) \tau_{\lambda}(p_s) + \int_{p_s}^0 B_{\lambda}(T(p)) F_{\lambda}(p) \frac{\partial \tau_{\lambda}(p)}{\partial \ln p} d \ln p$$

where

$$F_{\lambda}(p) = \left\{ 1 + (1 - \varepsilon_{\lambda}) \left[\frac{\tau_{\lambda}(p_s)}{\tau_{\lambda}(p)} \right]^2 \right\} .$$



NOAA-J/14

for over 12 years of service to the Nation and the world!

Launched : **December 30, 1994**
 Deactivated : **May 23, 2007**
 Approximately **4,528 days** and **63,925 orbits**

Data visualizations are courtesy of the NASA/Goddard Scientific Visualization Studio including Sea Surface Temp/Anomalies, Sea Surface Temp/Heights and Fires and Aerosols, each created in part from NOAA J/14 data.

Joint Polar System

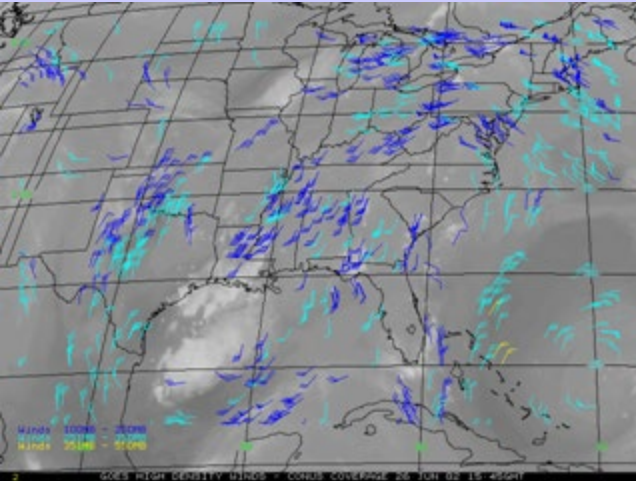
Welcome METOP

Congratulations ESA / EUMETSAT

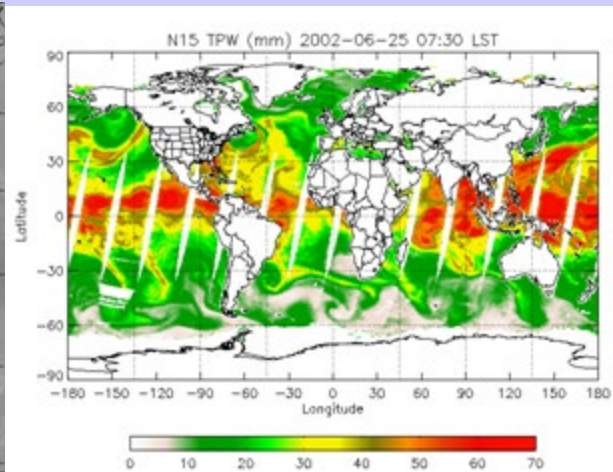
MetOp-A Launch on 19 October, 16h28 UTC
 Soyuz 2-1a, Baikonour

Atmospheric Products: Examples

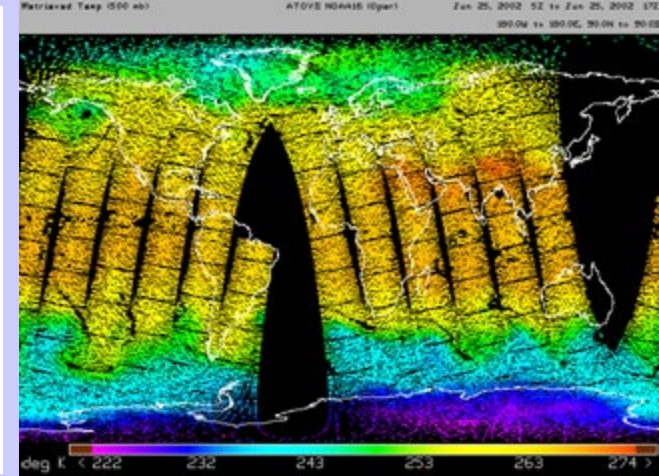
Winds



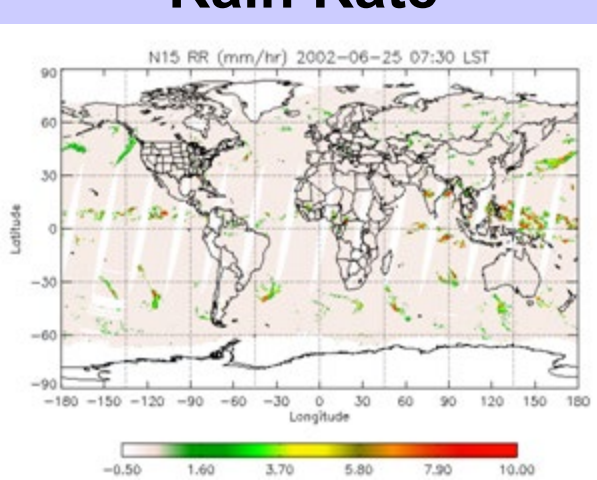
Total Water Vapor



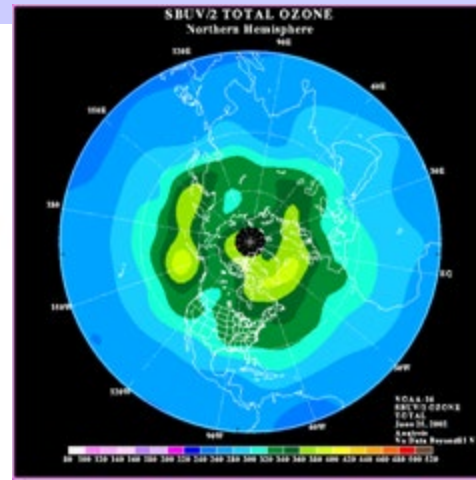
Temperature 500 mb



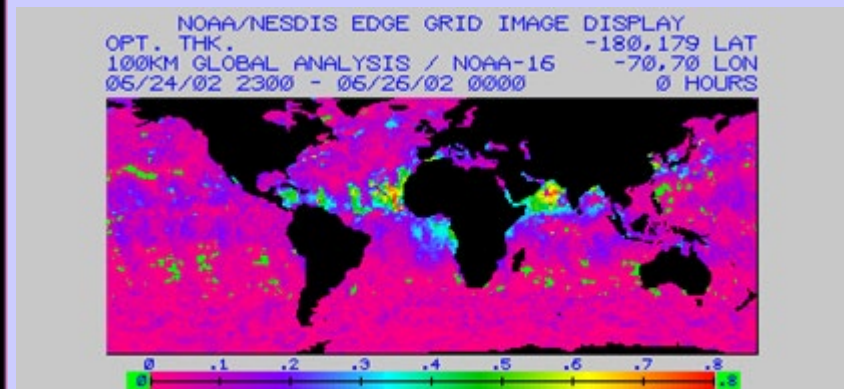
Rain Rate



Ozone

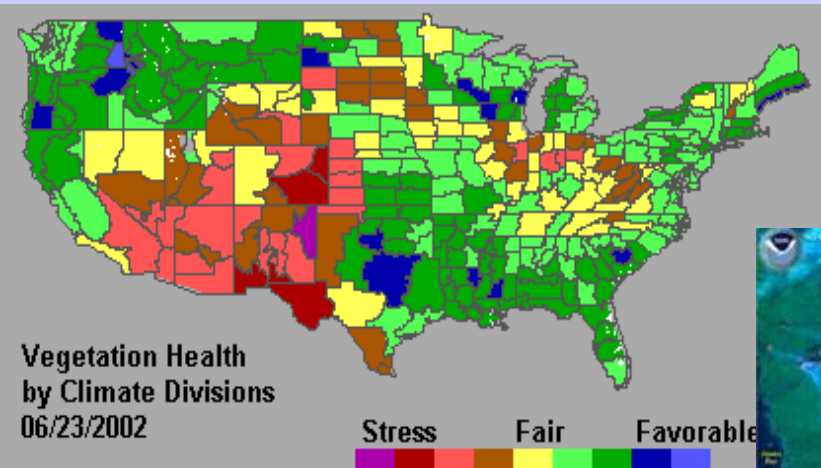


Aerosol Optical Thickness

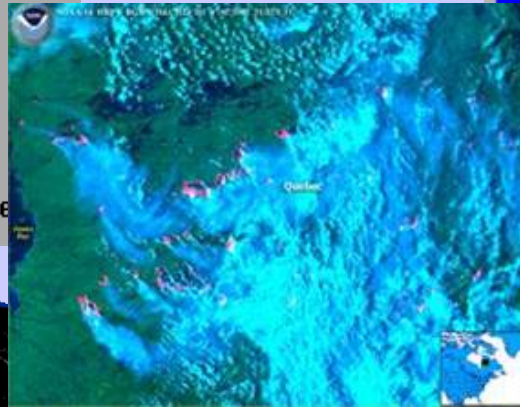


Land Surface Products: Examples

Vegetation Health



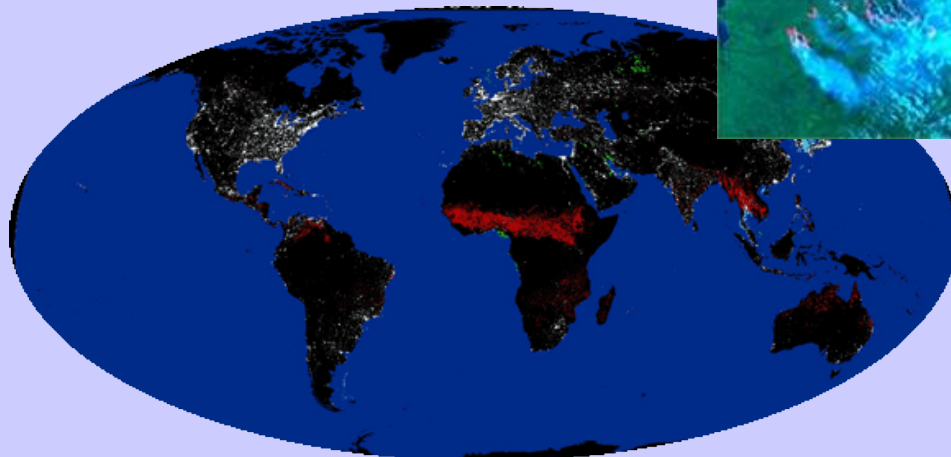
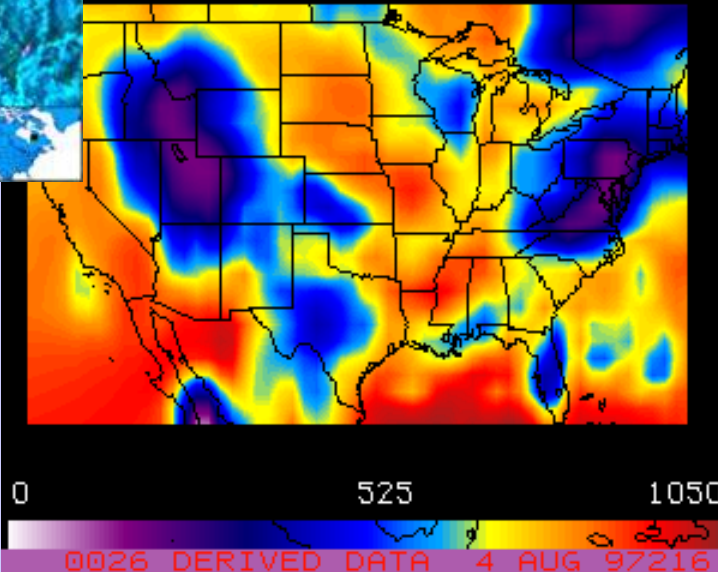
Quebec Fires/Smoke



Snow

Solar Radiation

RFACE DOWNWARD FLUX (W/M2)

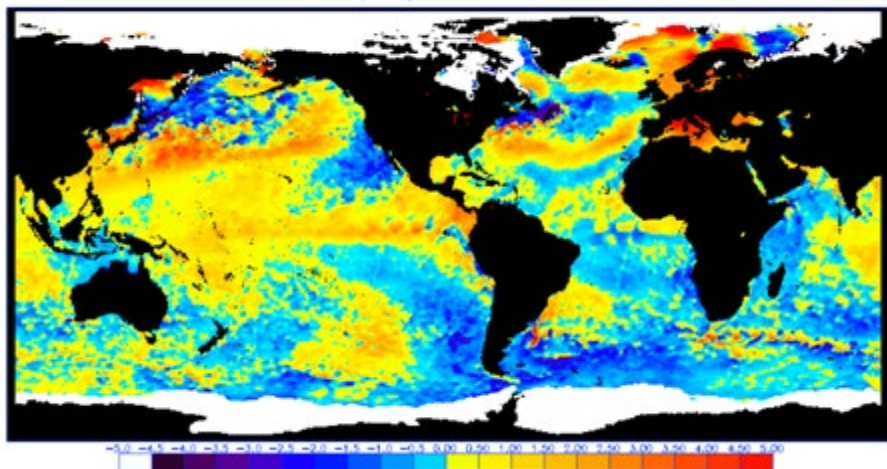


Global Lights/Fires

Ocean Products: Examples

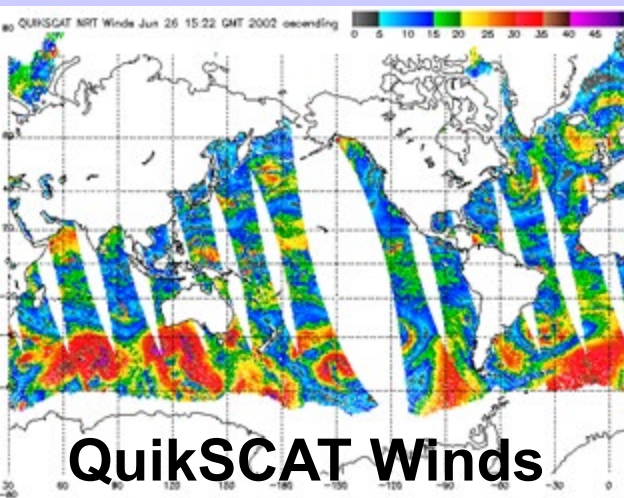
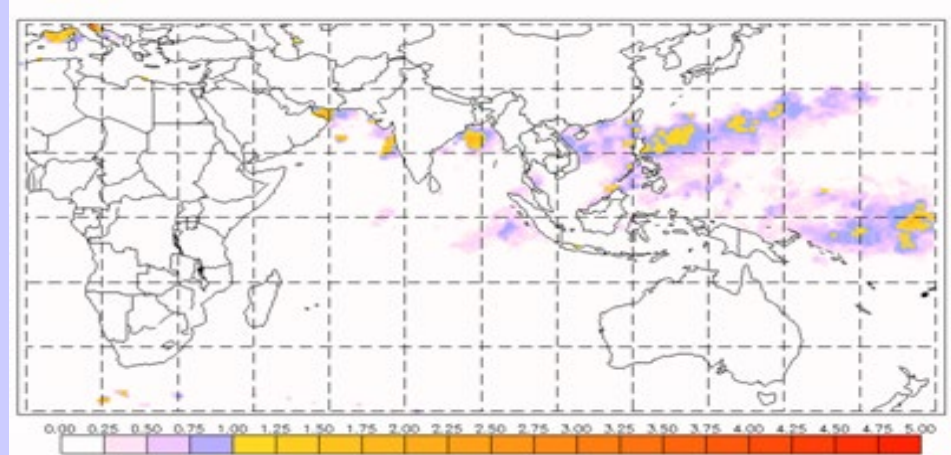
SST Anomalies

NOAA 50KM GLOBAL ANALYSIS: SST - Climatology (C), 6/24/2002
(white regions indicate sea-ice)

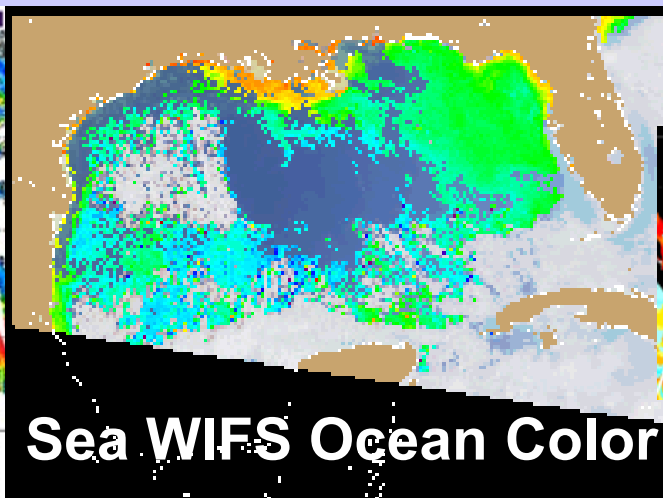


Hot Spots: Potential Coral Bleaching

NOAA/NESDIS 50km SST - Maximum Monthly Climatology (C), 6/24/2002

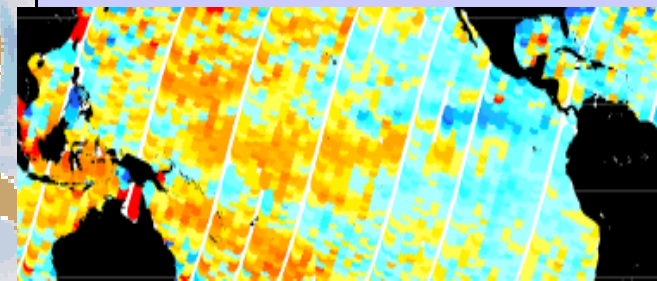


QuikSCAT Winds



SeaWiFS Ocean Color

TOPEX Sea Level



Applications with Multispectral Remote Sensing Data

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EOS Terra & Aqua MODIS

Multispectral Signatures

(Ocean Color, Snow/Ice, Vegetation, Aerosols, Clouds, Moisture, Fires, Volcanic Ash)

Detecting Climate Trends

Evolution of Leo Obs

**Terra was launched in 1999
and the EOS Era began**

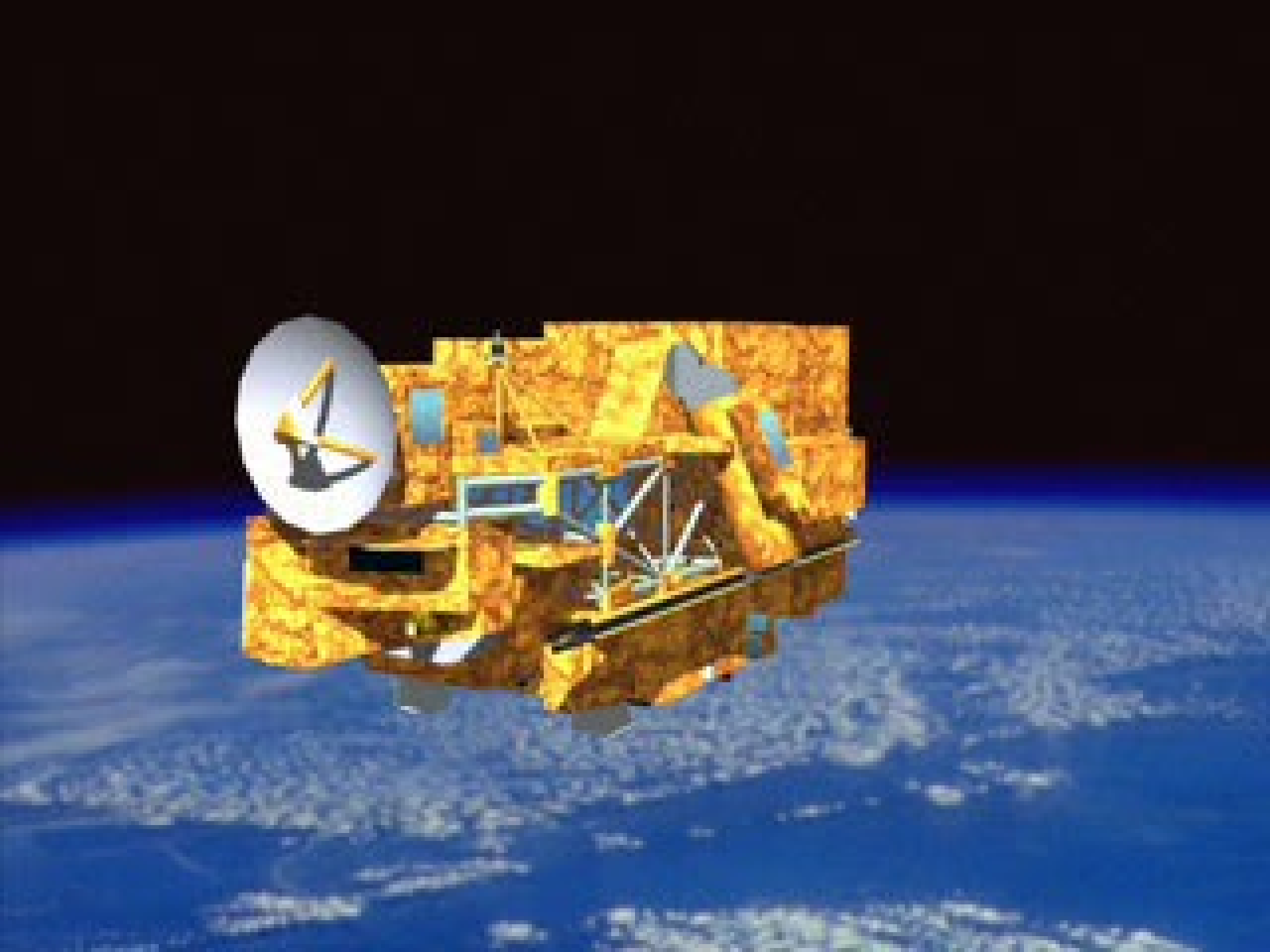
**MODIS, CERES, MOPITT,
ASTER, and MISR
reach polar orbit**

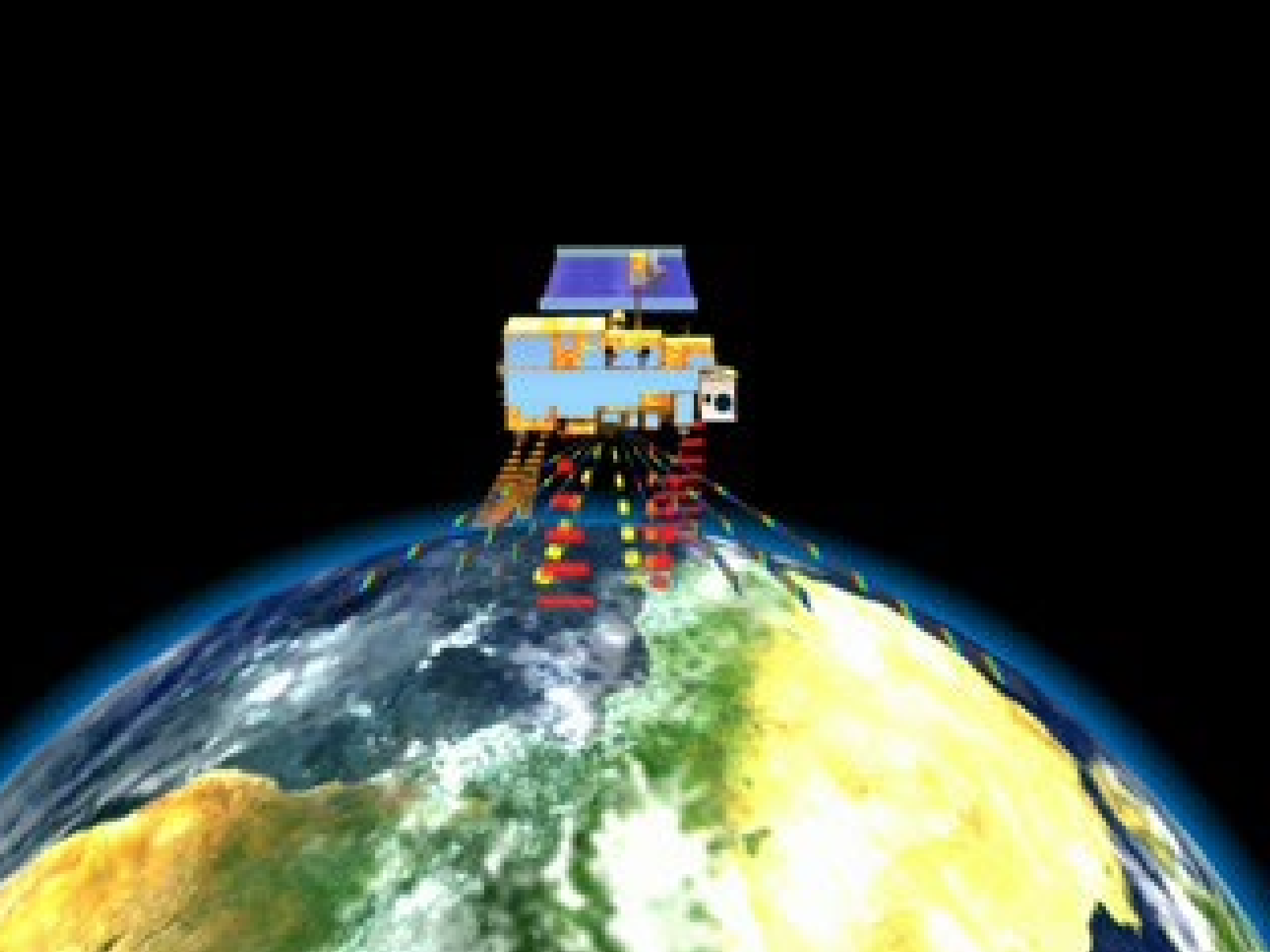
**Aqua and ENVISAT
followed in 2002**

**MODIS and MERIS
to be followed by VIIRS
AIRS and IASI
to be followed by CrIS
AMSU leading to ATMS**

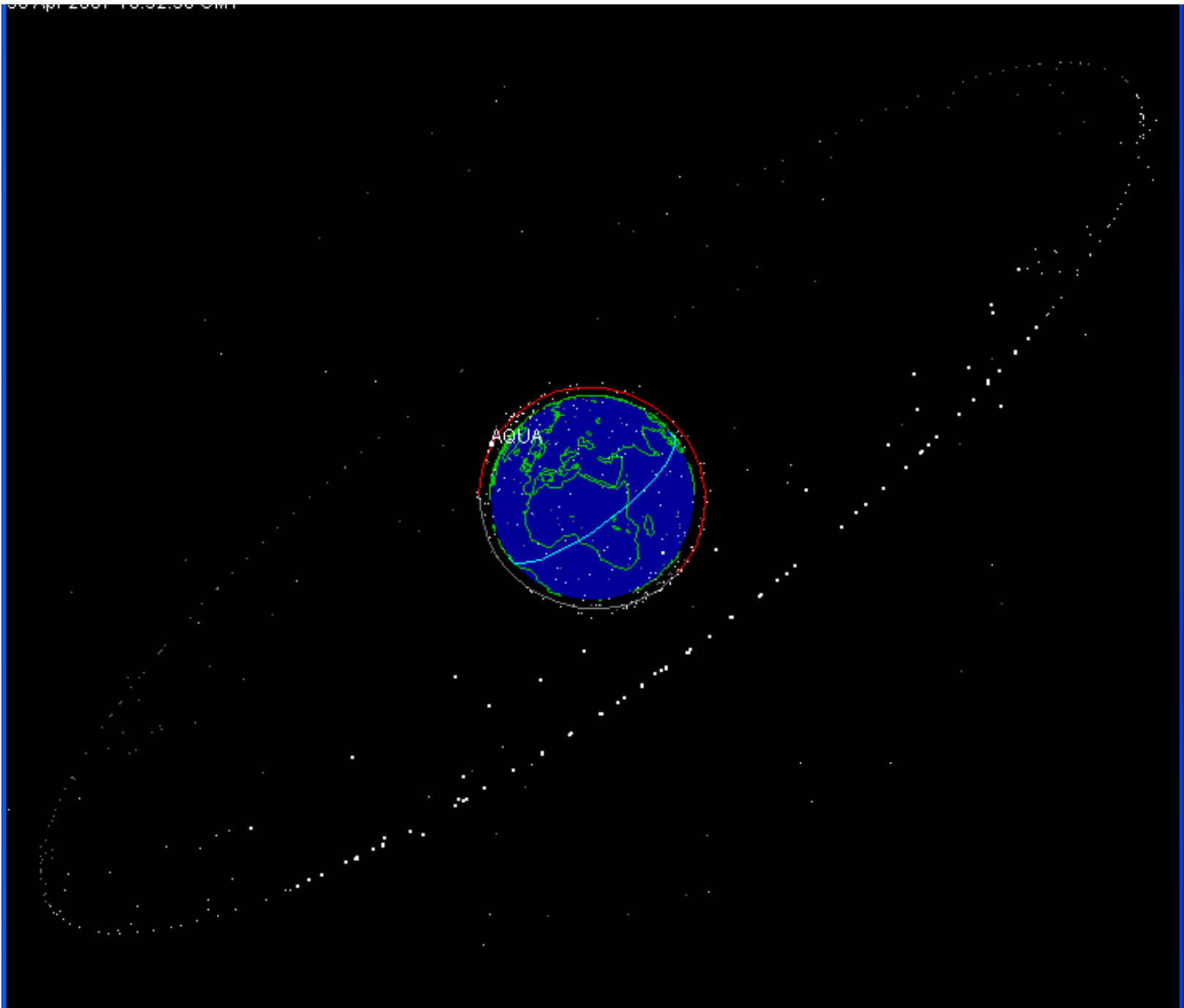






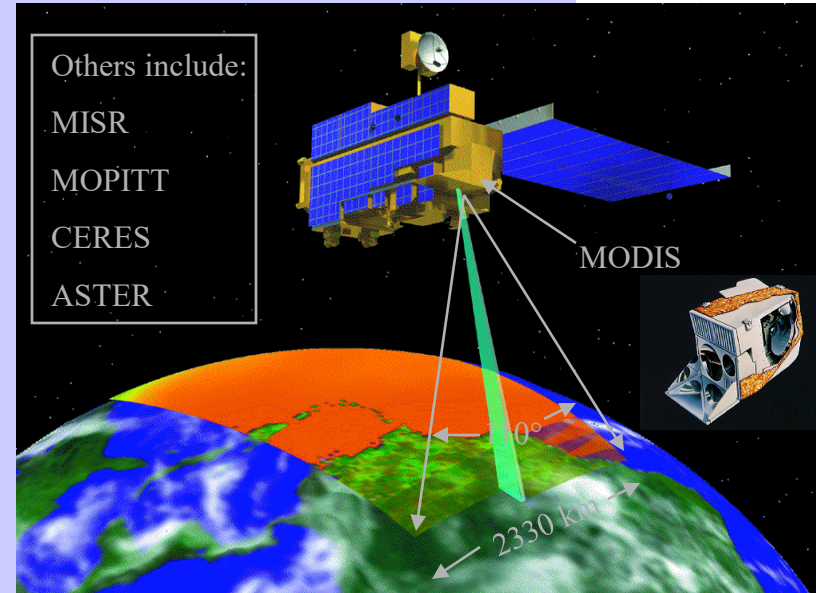


**All
Sats
on
NASA
J-track**





Launch of EOS-Terra (EOS-AM) Satellite - A New Era Begins



MODIS instrument Specifications:

Bands 1-2 (0.66, 0.86 μm): 250 m

Bands 3-7 (0.47, 0.55, 1.24, 1.64, 2.13 μm): 500 m

Bands 8-36: 1 km

Launch date: December 18, 1999, 1:57 PT
Earth viewdoor open date: February 24, 2001

Allen Chu/NASA GSFC

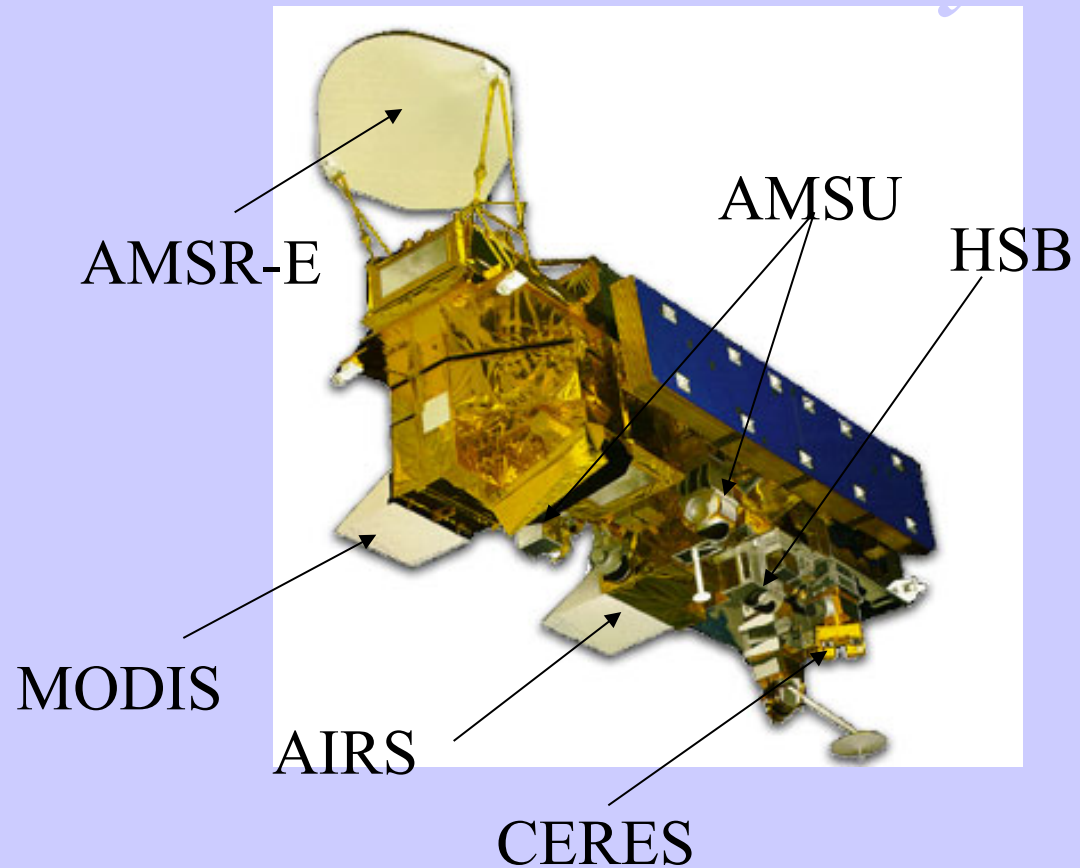


Followed by the launch of EOS-Aqua (EOS-PM) Satellite



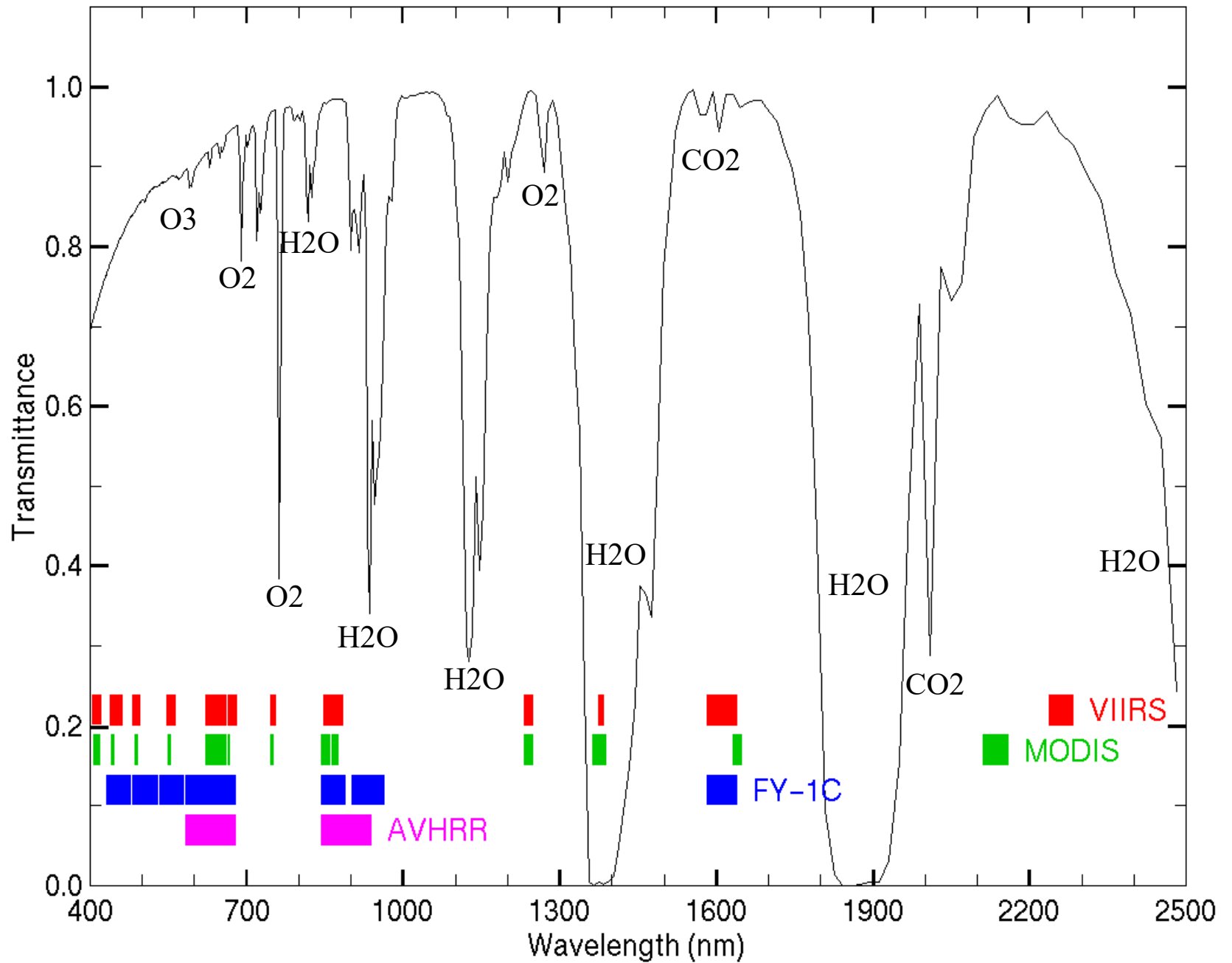
“

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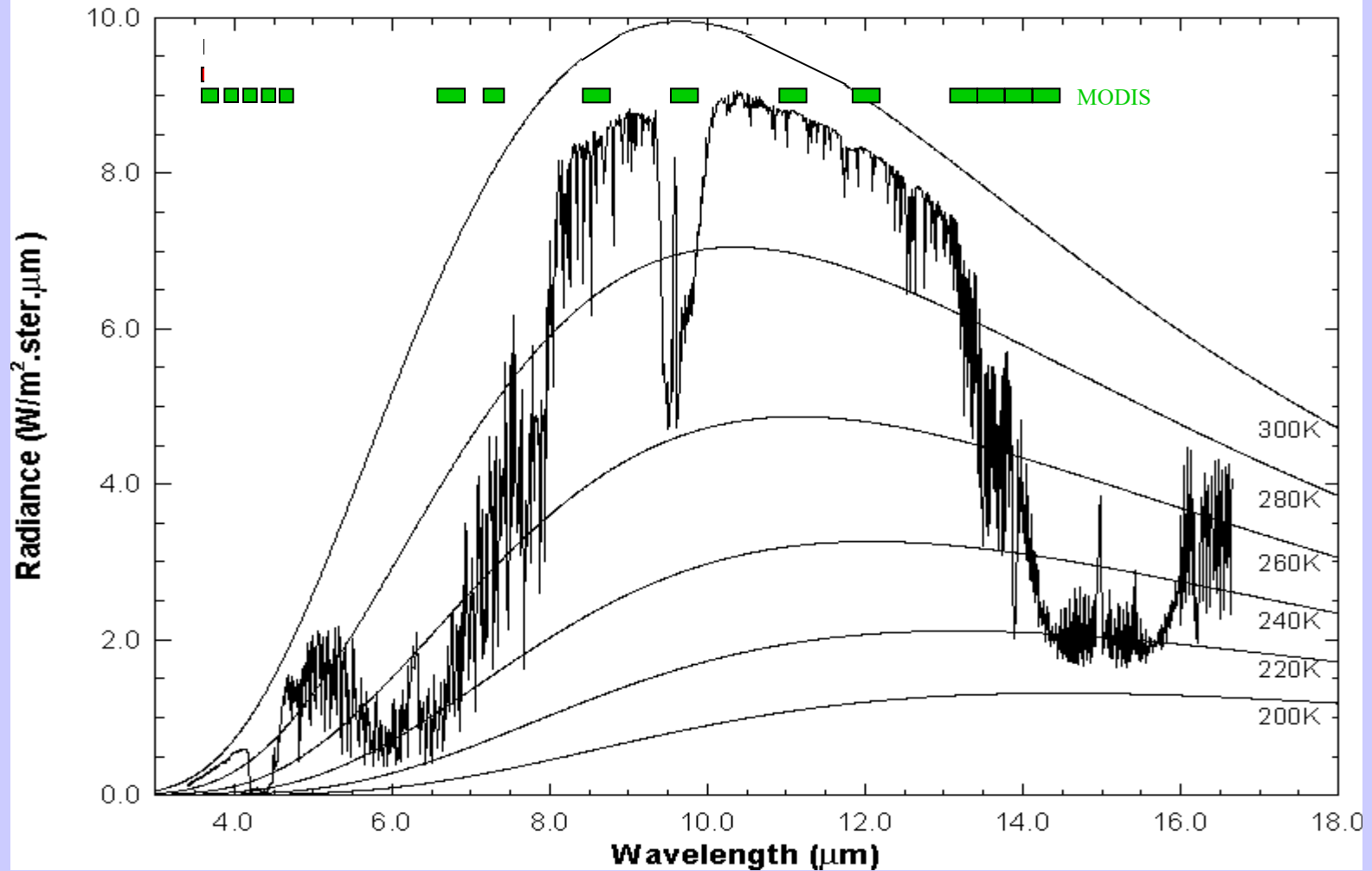
Launch date: May 4, 2002, 2:55 PDT
Earth view door open date: June 25, 2002

VIIRS, MODIS, FY-1C, AVHRR



MODIS IR Spectral Bands

High resolution atmospheric absorption spectrum and comparative blackbody curves.



Applications with Multispectral Remote Sensing Data

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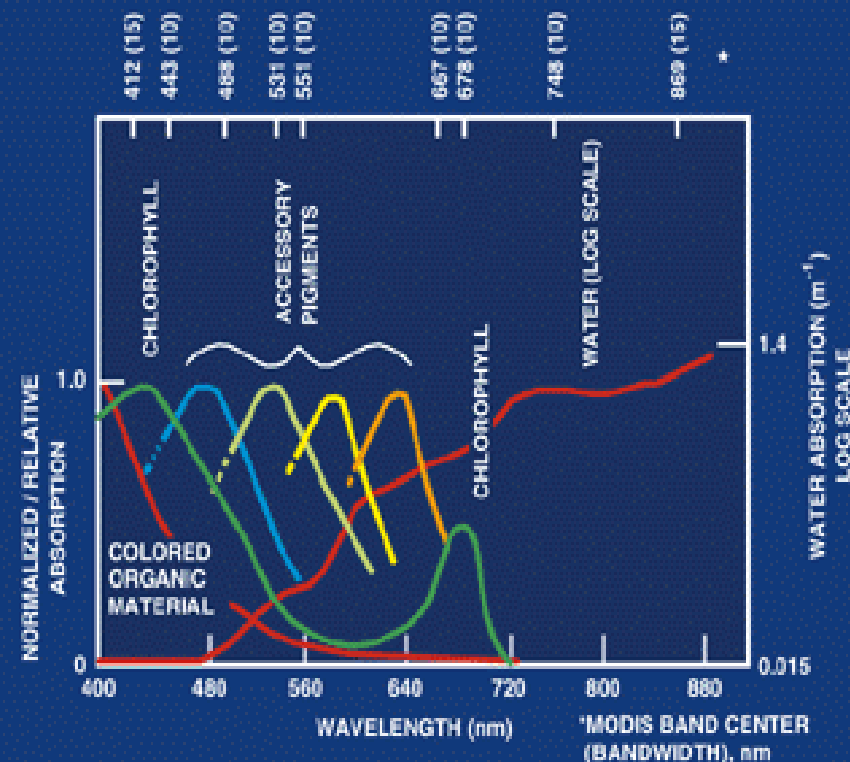
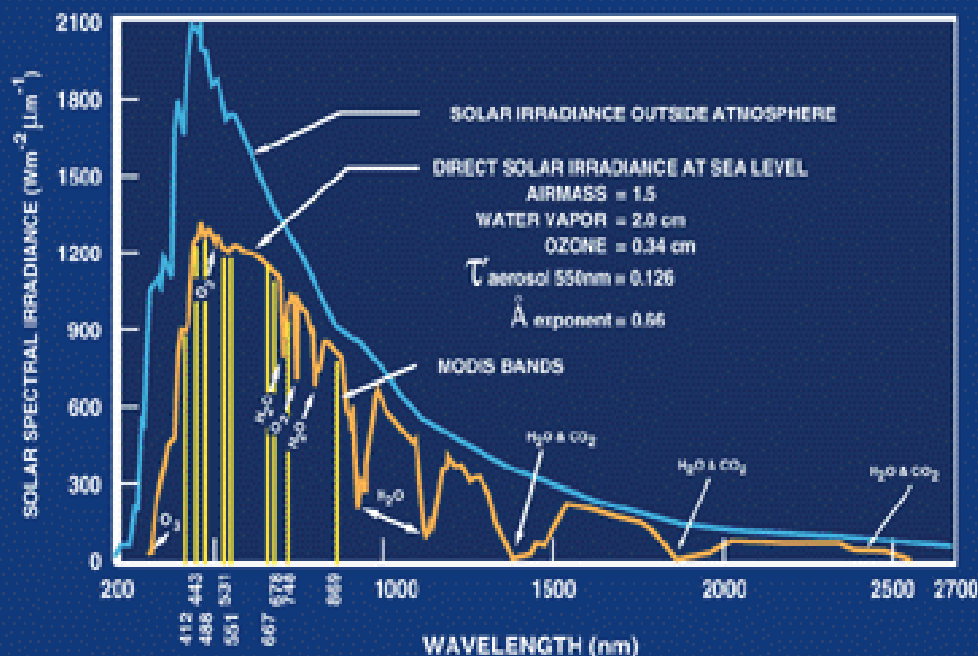
EOS Terra & Aqua MODIS

Multispectral Signatures

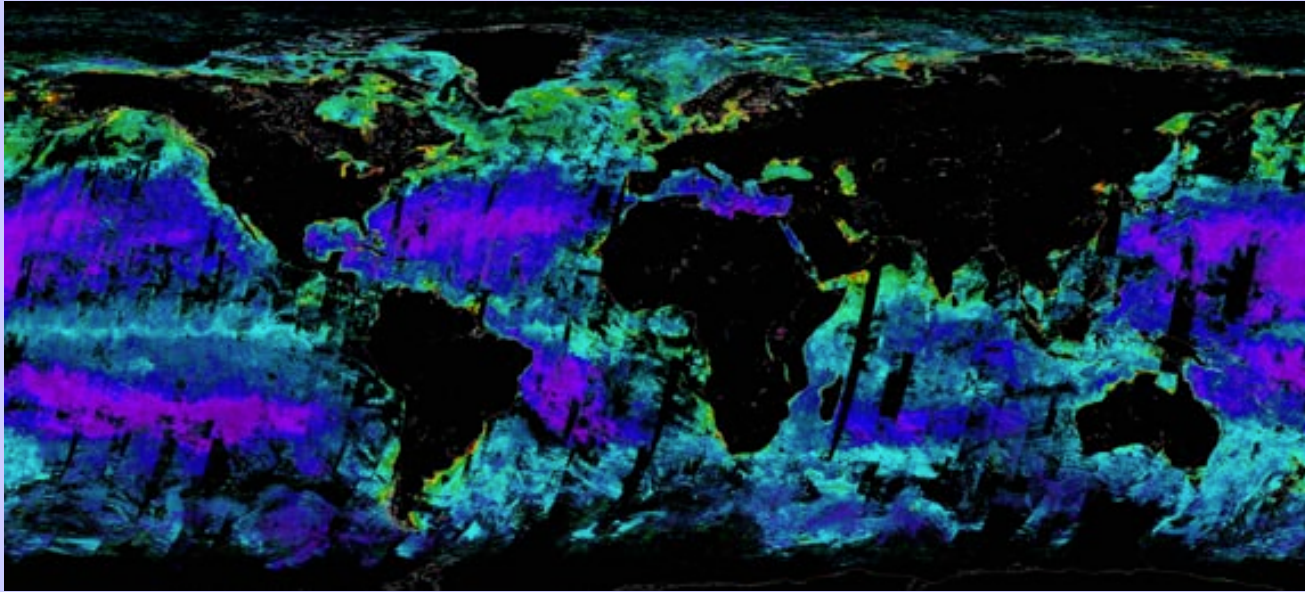
*(Ocean Color, SST, Snow/Ice, Vegetation,
Aerosols, Clouds, Moisture, Fires, Volcanic Ash)*

Detecting Climate Trends

OCEAN-SOLAR RADIATION



Chlorophyll - MODIS and SeaWiFS



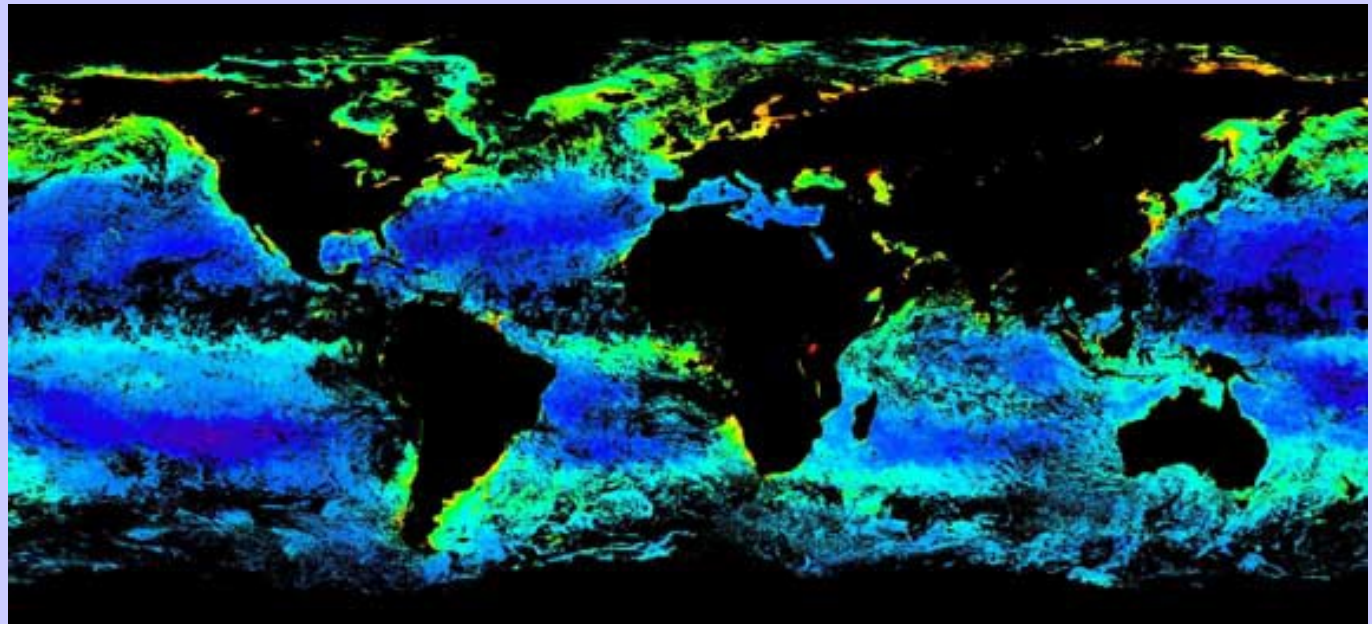
MODIS Chlor
243-250, 2000

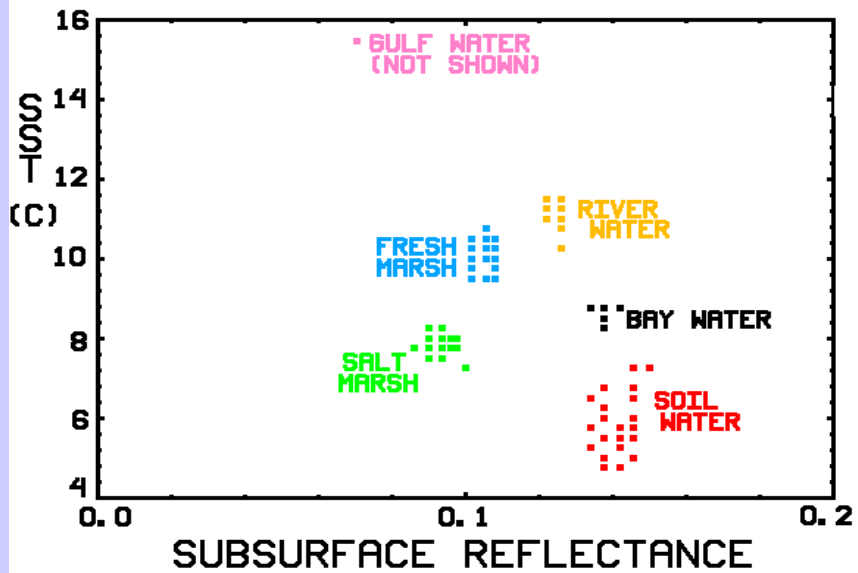
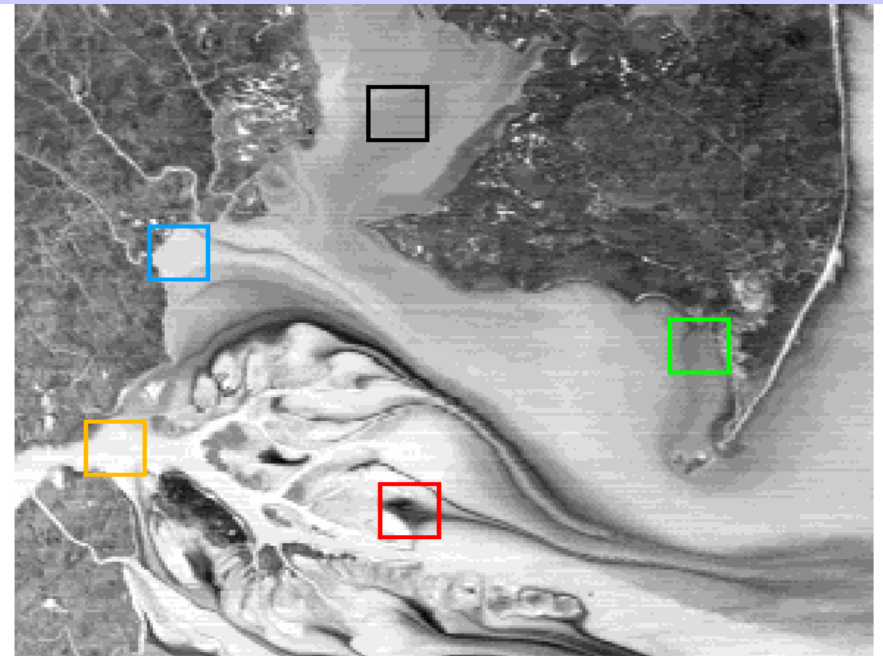
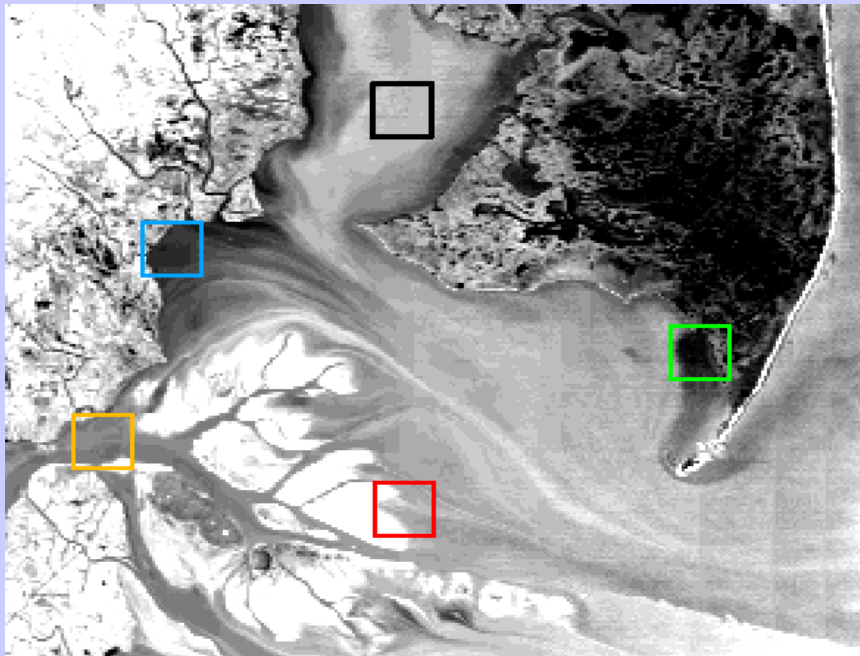
U. Miami



MODIS tropics coverage is greater (time of day + no tilt loss). MODIS reveals global fine structure. Color scales not identical, cal not final.

SeaWiFS Chlor
241-248, 2000
SeaWiFS Project





MAMS WATER TYPE ANALYSIS DEC 4 1990

SHOWN:

* .66 μ m REFLECTANCE (LEFT)

* SPLIT WINDOW SST (RIGHT)

First Order Estimation of SST

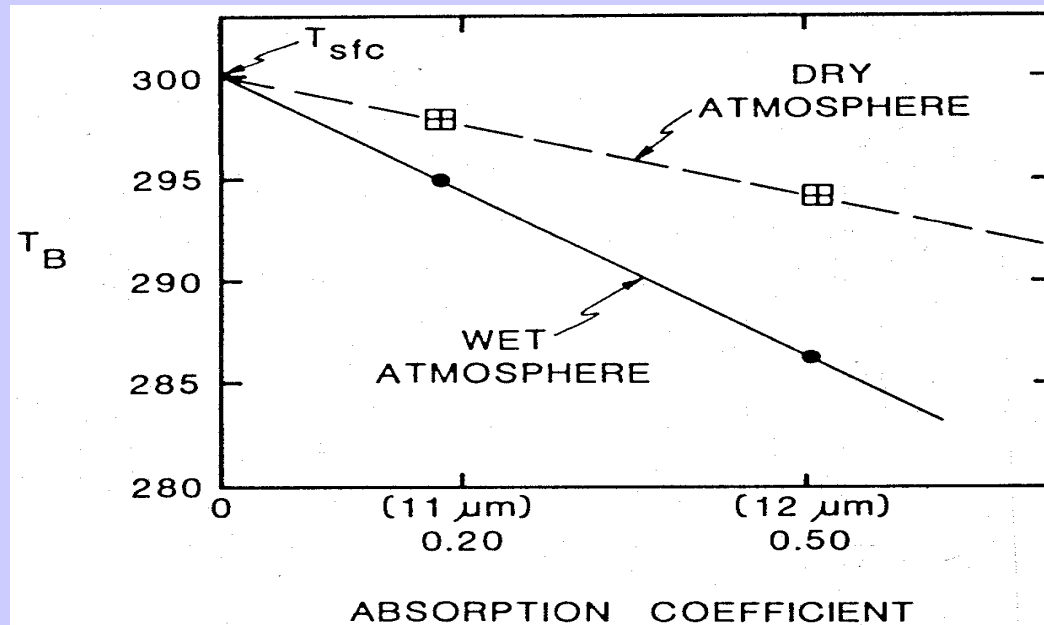
Moisture attenuation in atmospheric windows varies linearly with optical depth.

$$\tau_\lambda = e^{-k_\lambda u} \approx 1 - k_\lambda u$$

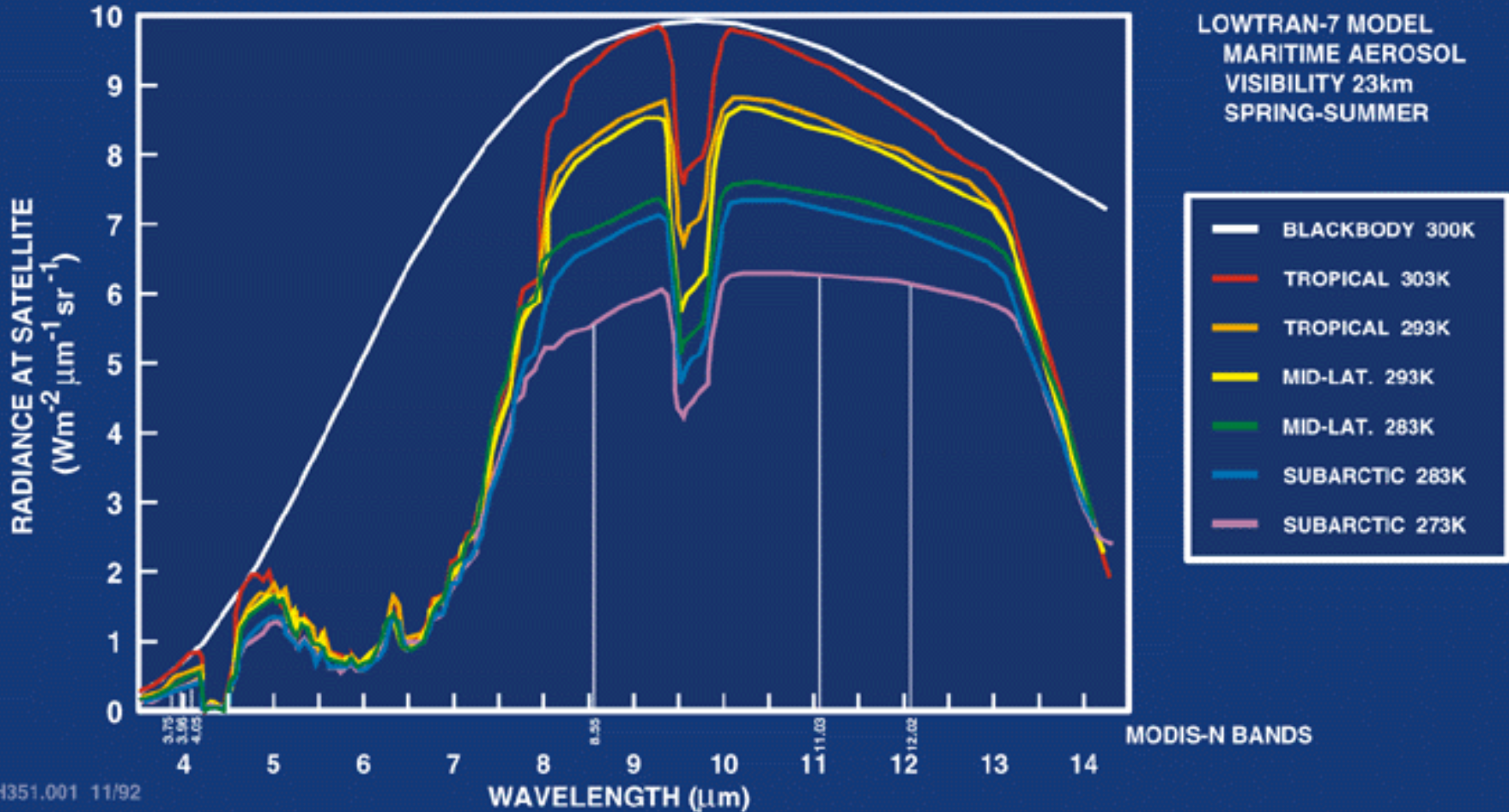
For same atmosphere, deviation of brightness temperature from surface temperature is a linear function of absorbing power. Thus moisture corrected SST can be inferred by using split window measurements and extrapolating to zero k_λ .

$$T_s = T_{bw1} + [k_{w1} / (k_{w2} - k_{w1})] [T_{bw1} - T_{bw2}] .$$

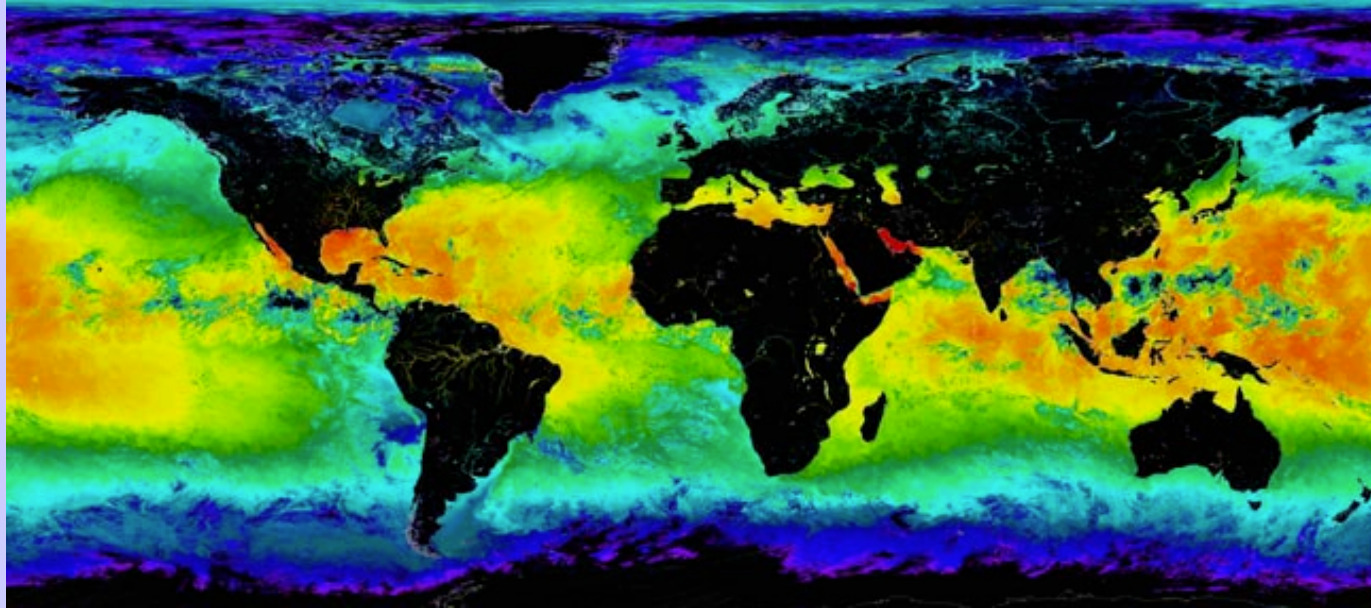
Moisture content of atmosphere inferred from slope of linear relation.



MODIS SEA SURFACE TEMPERATURE



SST - MODIS and AVHRR

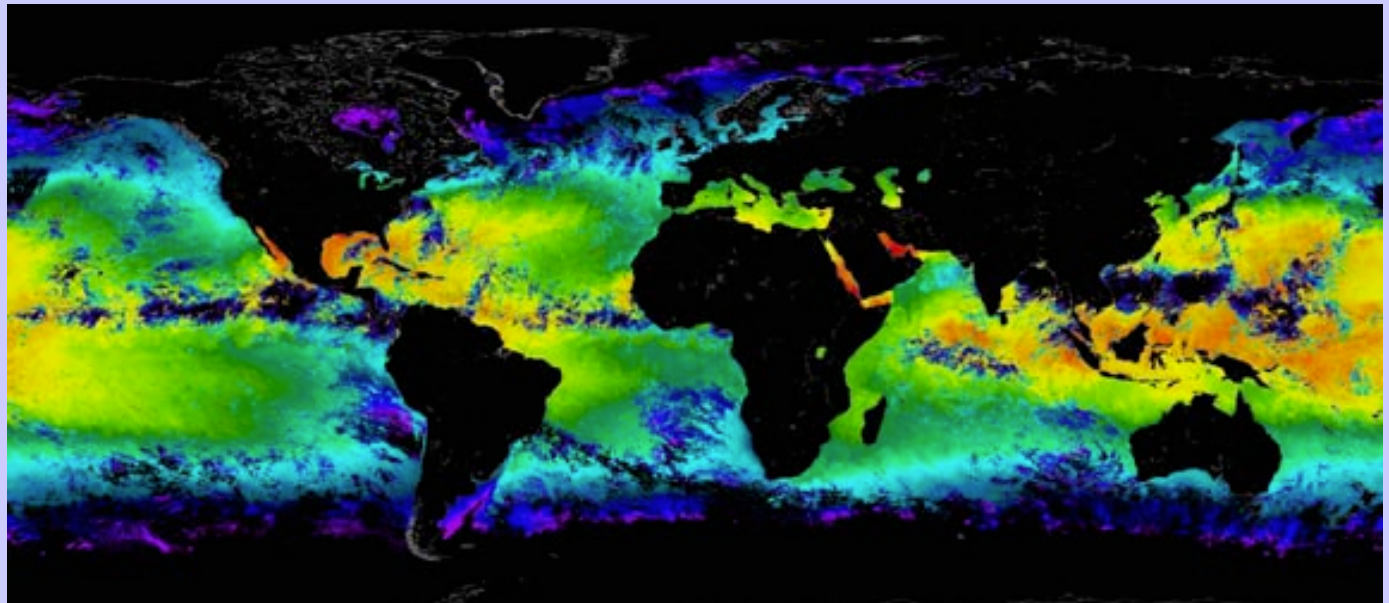


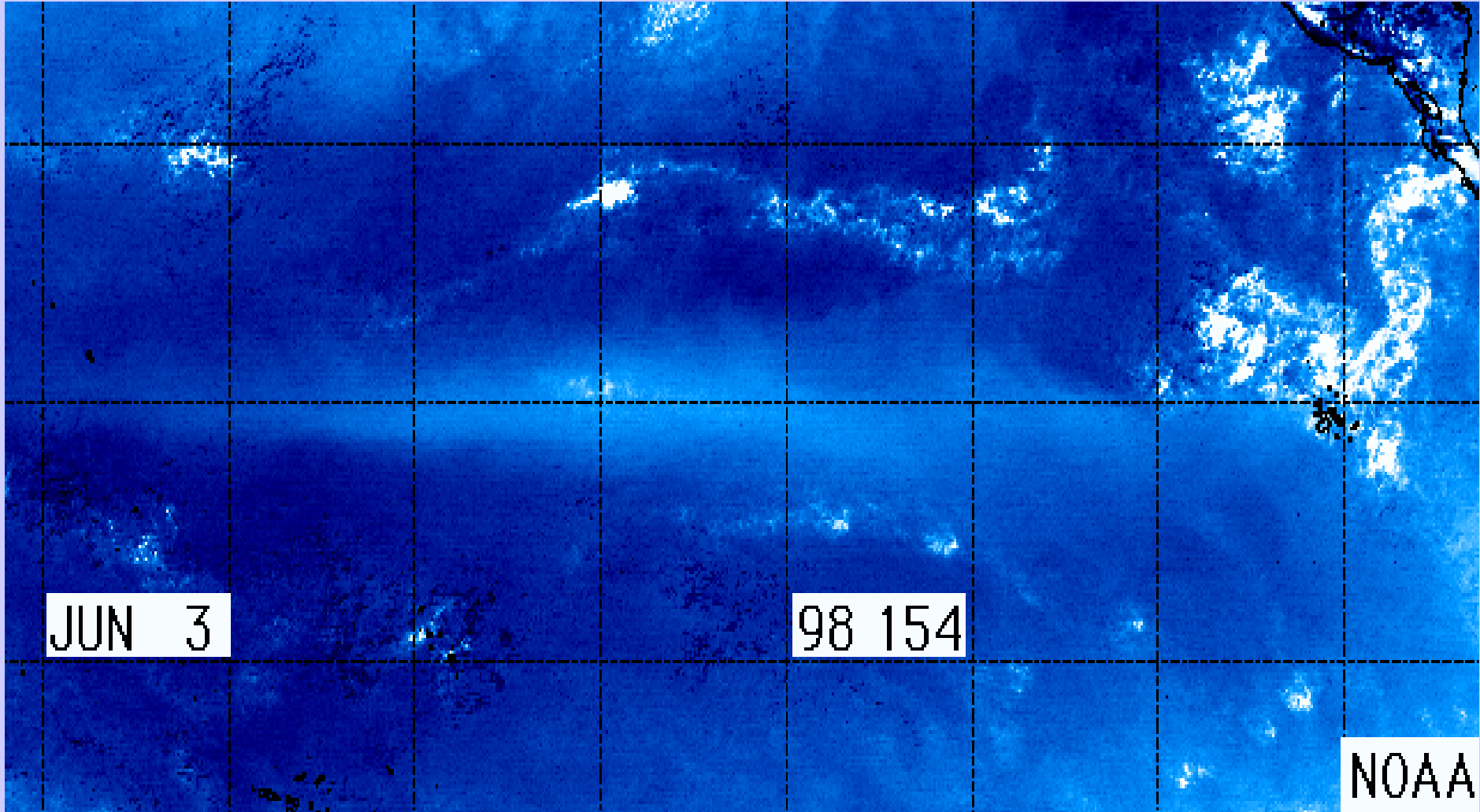
**MODIS 4 μm
Night SST**



Improved coverage in tropical regions. Color scales are not identical, cloud mask is not applied.

**AVHRR
Night SST**





SST Waves from Legeckis

Applications with Multispectral Remote Sensing Data

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VIS, IR, and MW Radiative Transfer

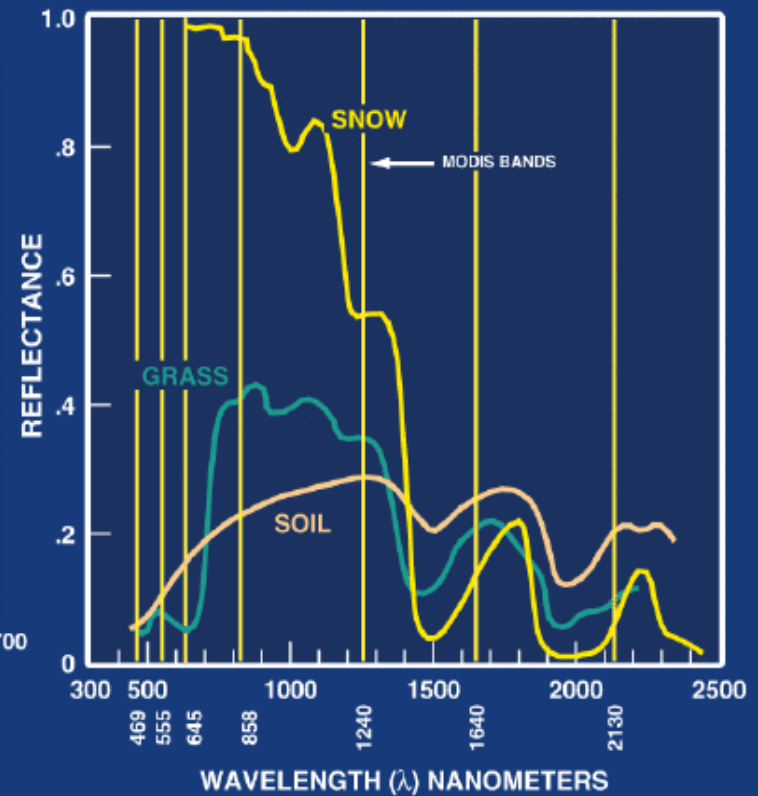
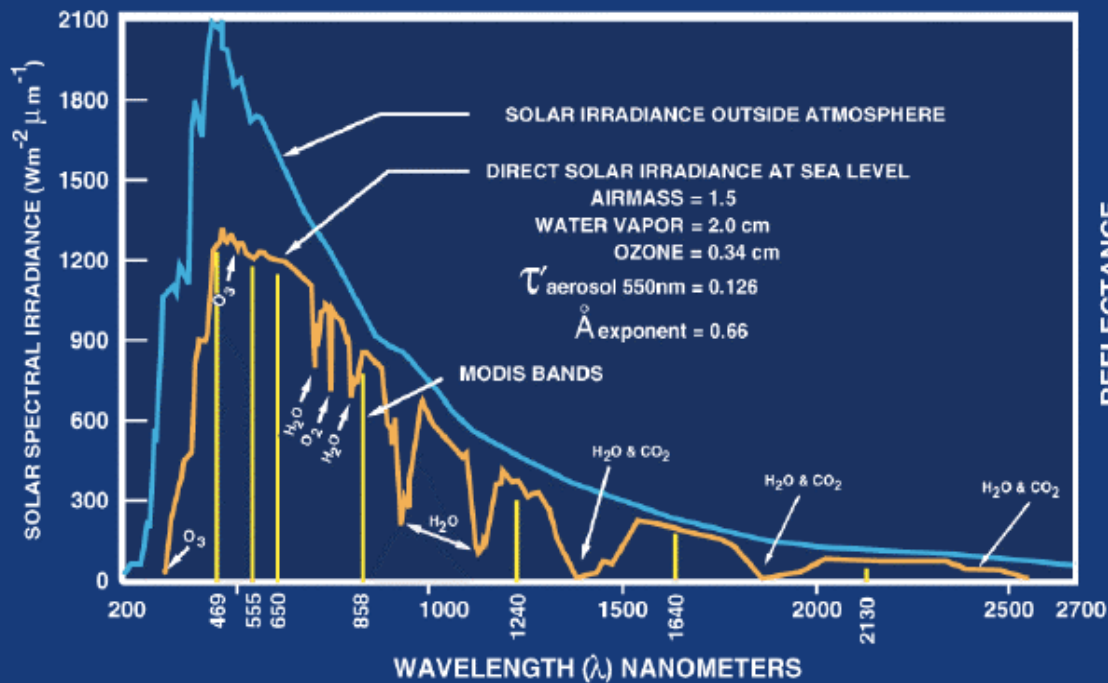
EOS Terra & Aqua MODIS

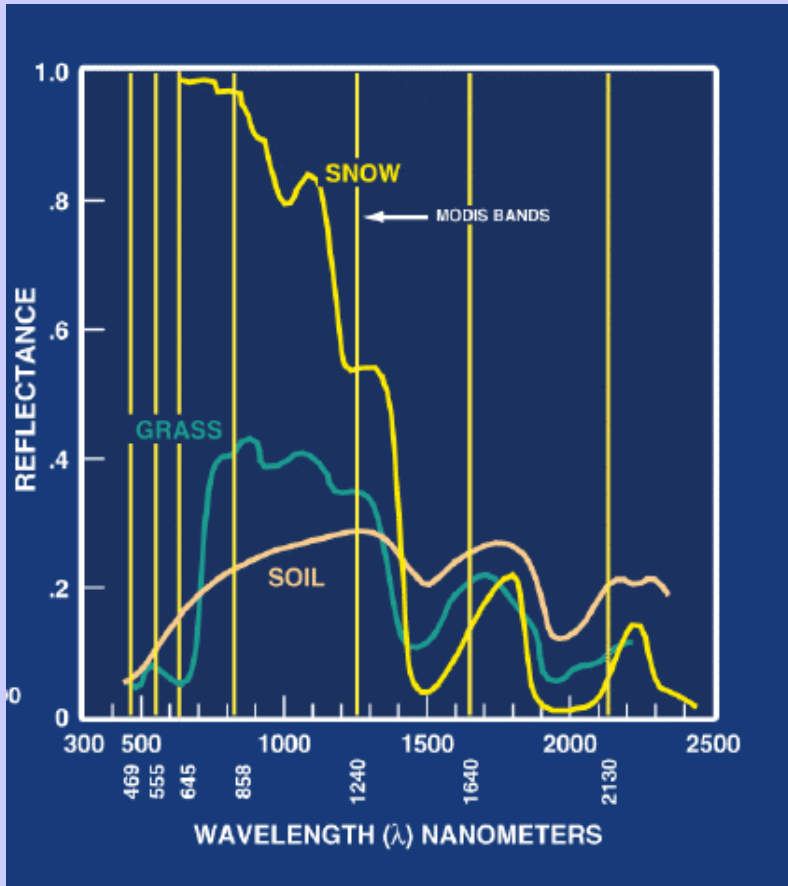
Multispectral Signatures

*(Ocean Color, SST, Snow/Ice, Vegetation,
Aerosols, Clouds, Moisture, Fires, Volcanic Ash)*

Detecting Climate Trends

LAND-SOLAR RADIATION



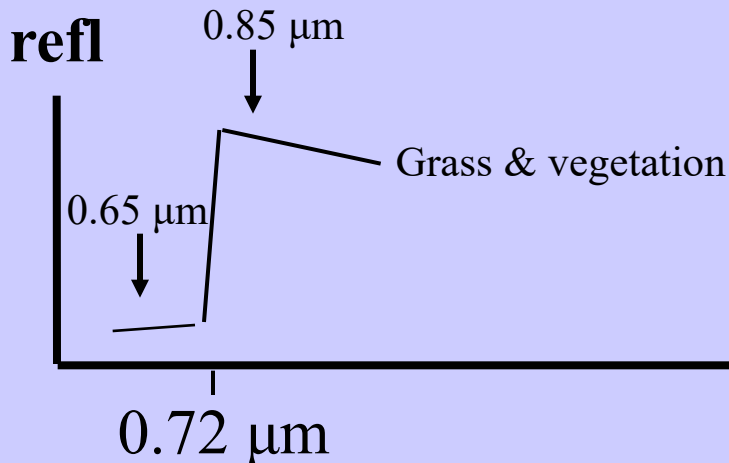


Investigating with Multi-spectral Combinations

Given the spectral response of a surface or atmospheric feature

Select a part of the spectrum where the reflectance or absorption changes with wavelength

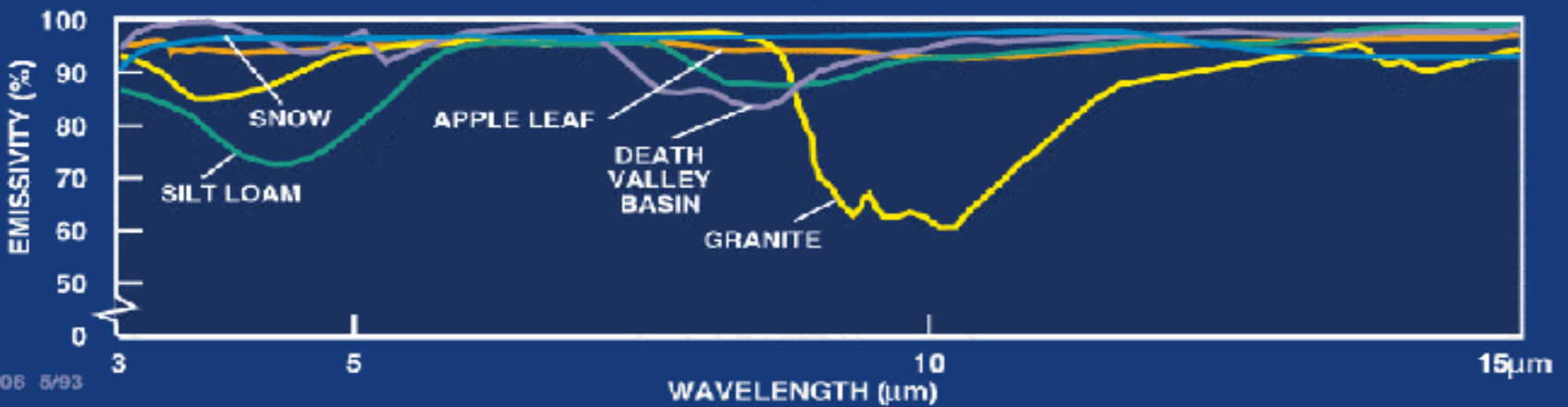
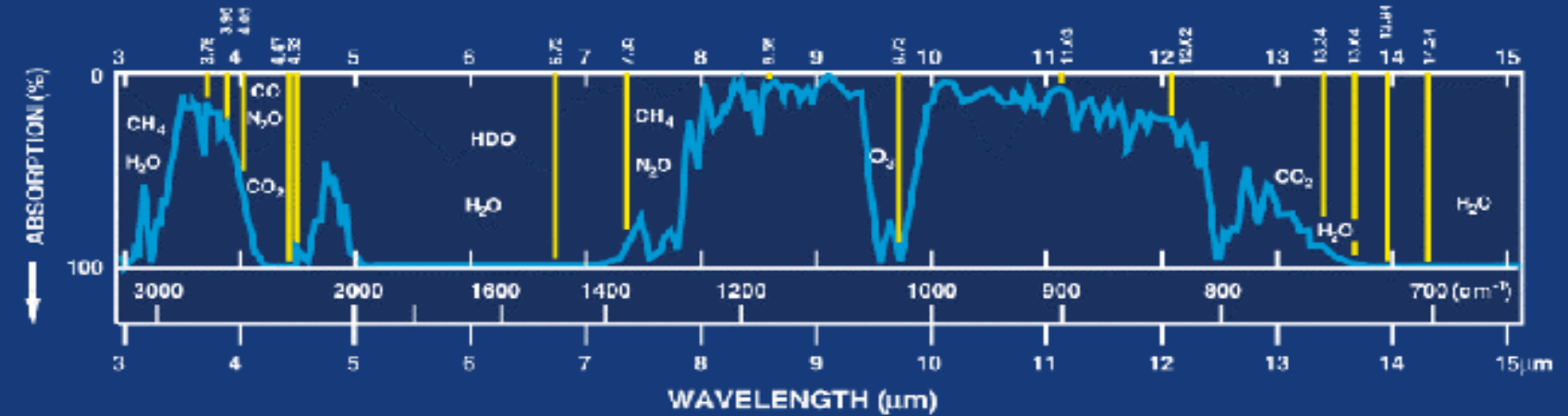
e.g. reflection from grass



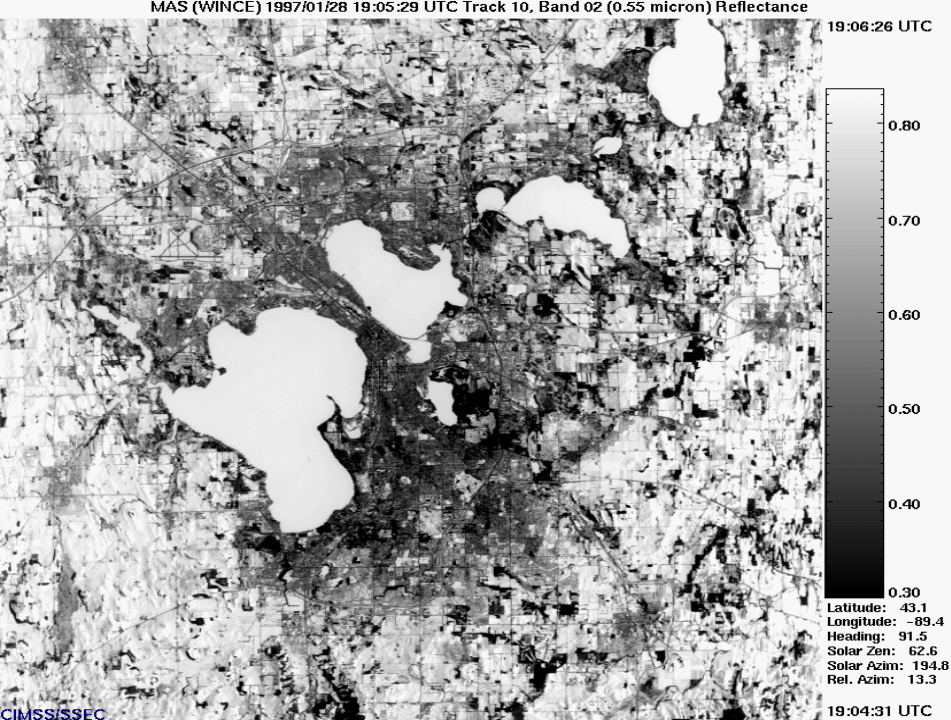
If 0.65 μm and 0.85 μm channels see the same reflectance than surface viewed is not grass;
 if 0.85 μm sees considerably higher reflectance than 0.65 μm then surface might be grass



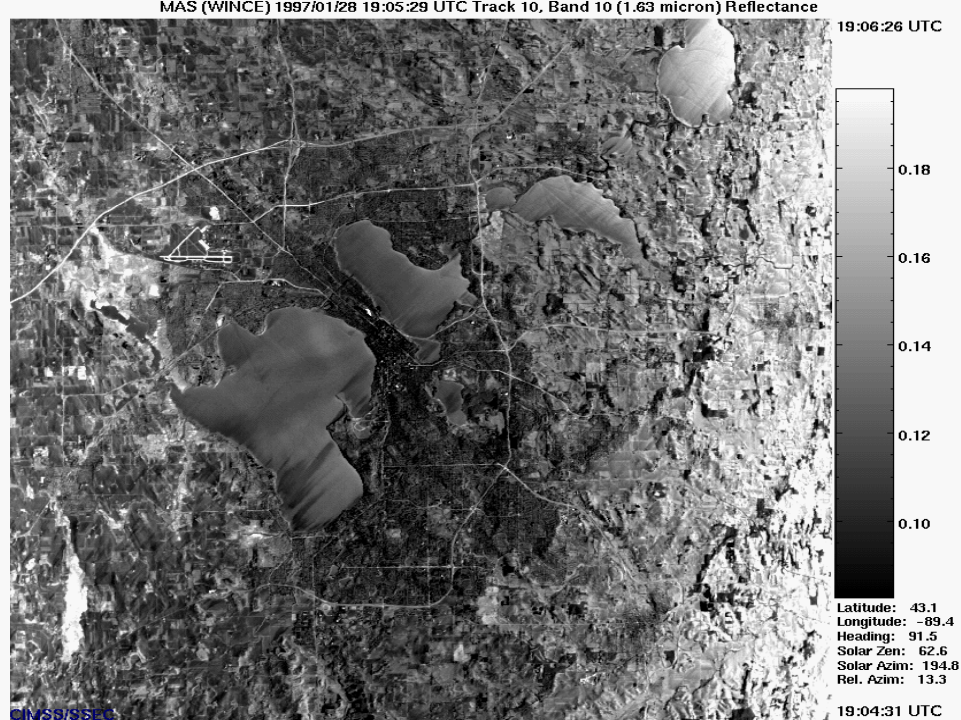
LAND - THERMAL RADIATION



MAS (WINCE) 1997/01/28 19:05:29 UTC Track 10, Band 02 (0.55 micron) Reflectance



MAS (WINCE) 1997/01/28 19:05:29 UTC Track 10, Band 10 (1.63 micron) Reflectance

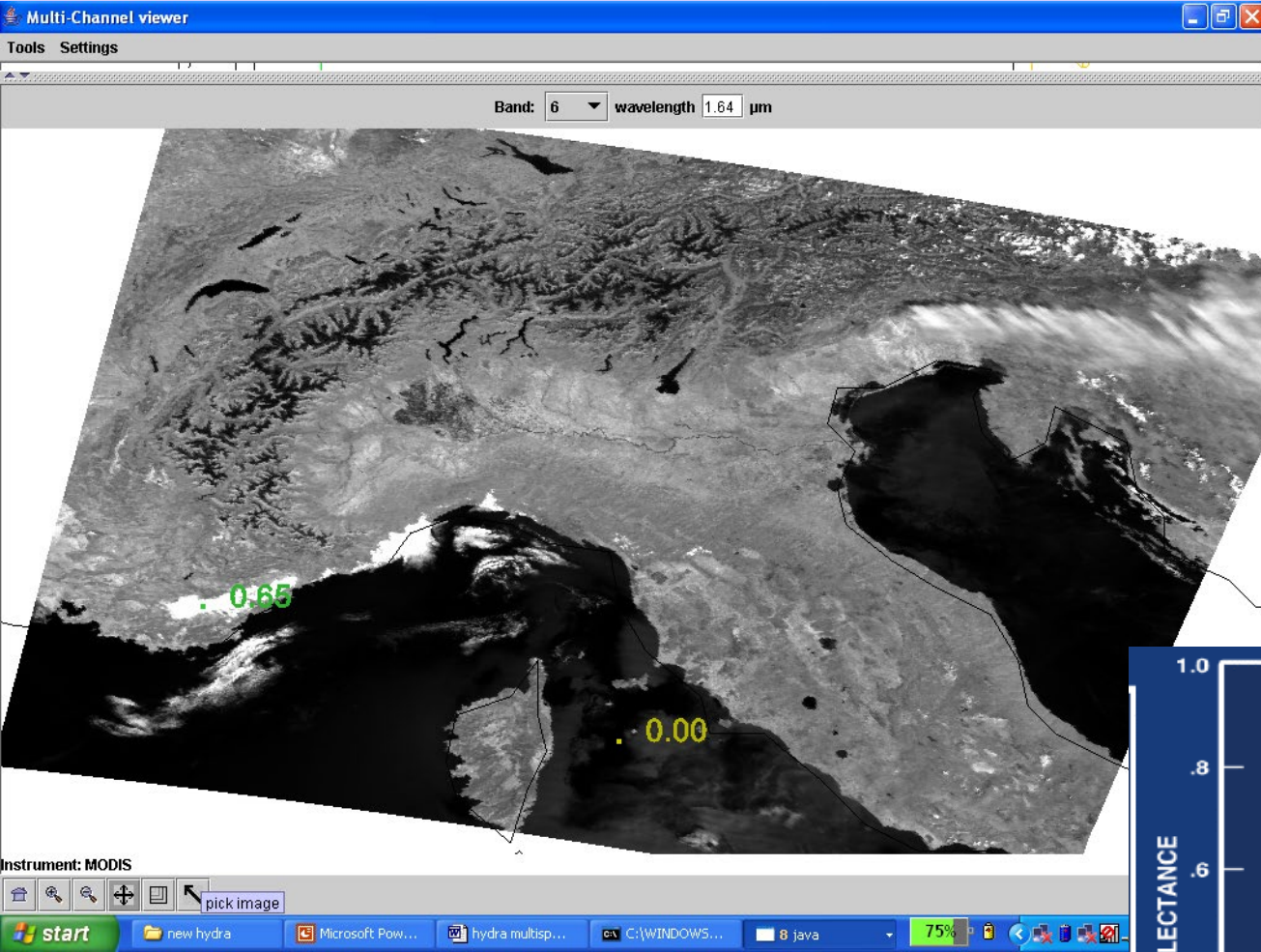


MAS (WINCE) 1997/01/28 19:05:29 UTC Track 10, Band 45 (10.97 micron) Brightness Temp. (K)

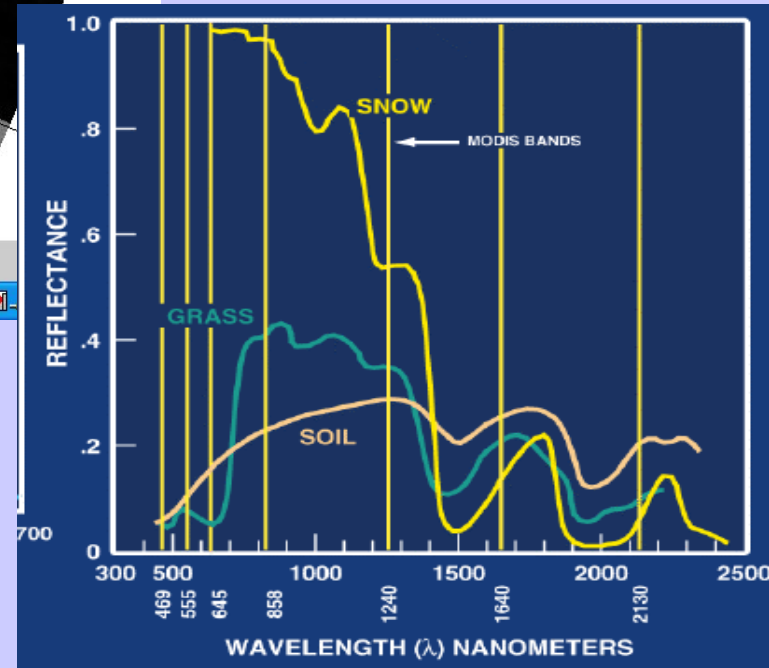


MODIS Airborne Simulator
(MAS)
0.6, 1.6, & 11.0 um data
over Madison in Jan 97

Example with MODIS

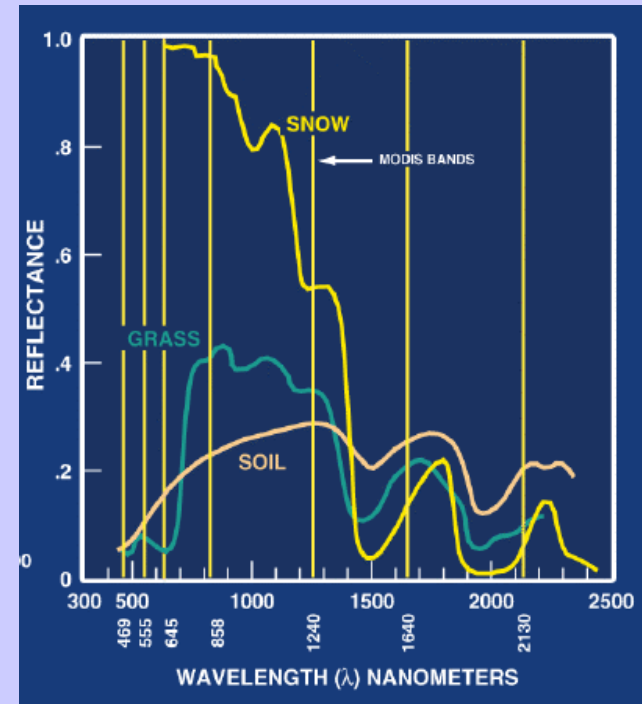


low refl at 1.6 μm from snow in mountains



NDVI versus EVI

EVI is a useful proxy for ‘greenness’ or photosynthetically active vegetation in optically dense canopies, as found throughout the Amazon (LAI= 4 -7), by relying on the more sensitive NIR canopy reflectance which is less prone to saturate

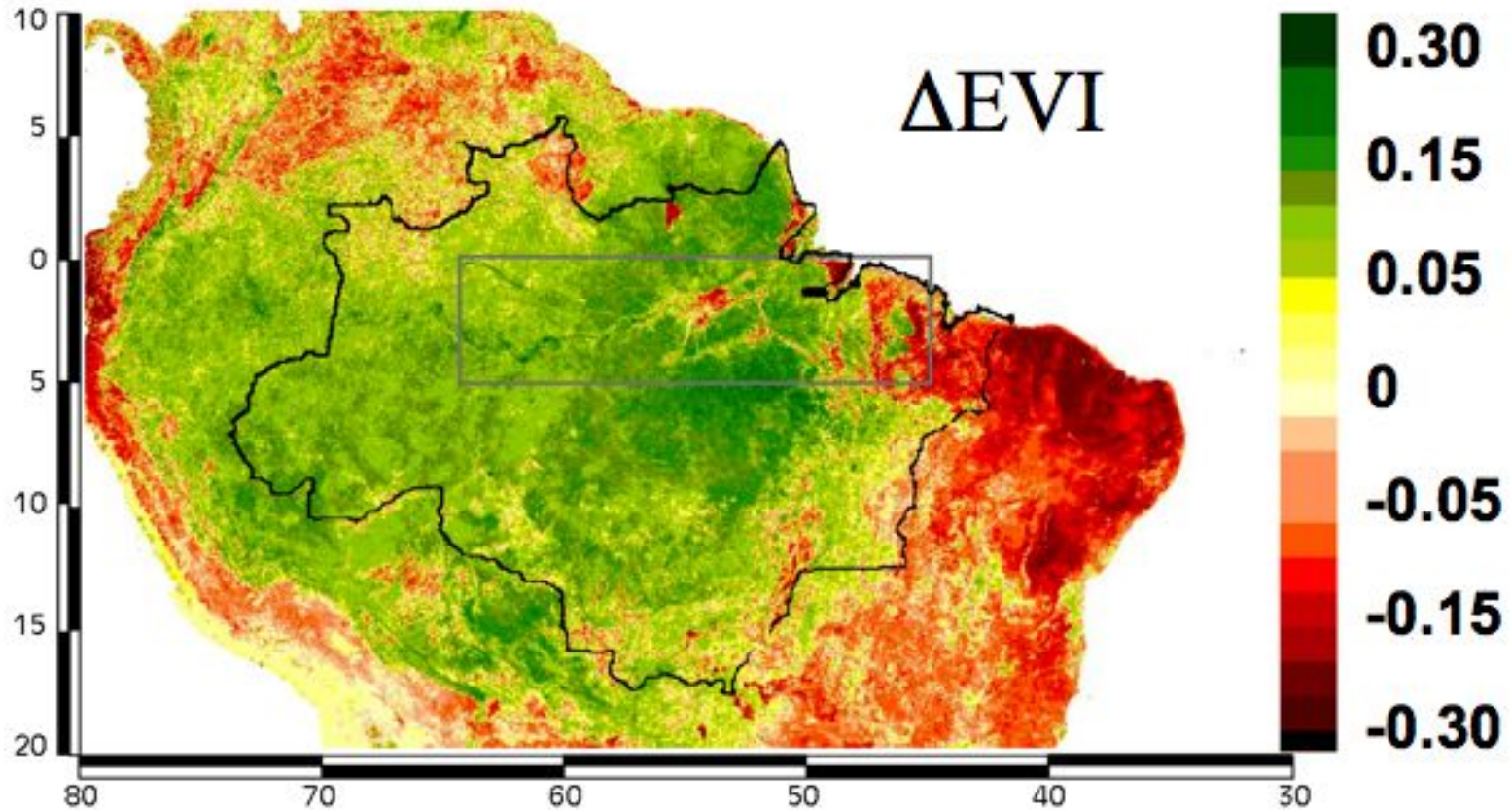


$$NDVI = (\rho_{0.8} - \rho_{0.6}) / (\rho_{0.8} + \rho_{0.6})$$

$$EVI = 2.5 \times \frac{\rho_{NIR} - \rho_{red}}{1 + \rho_{NIR} + (6 \times \rho_{red} - 7.5 \times \rho_{blue})}$$

Basin-wide greening in dry season

October EVI (dry) minus June EVI (wet season) CMG
from Huete et al



- green colors depict 'greening' and red colors depict 'browning' in the dry season

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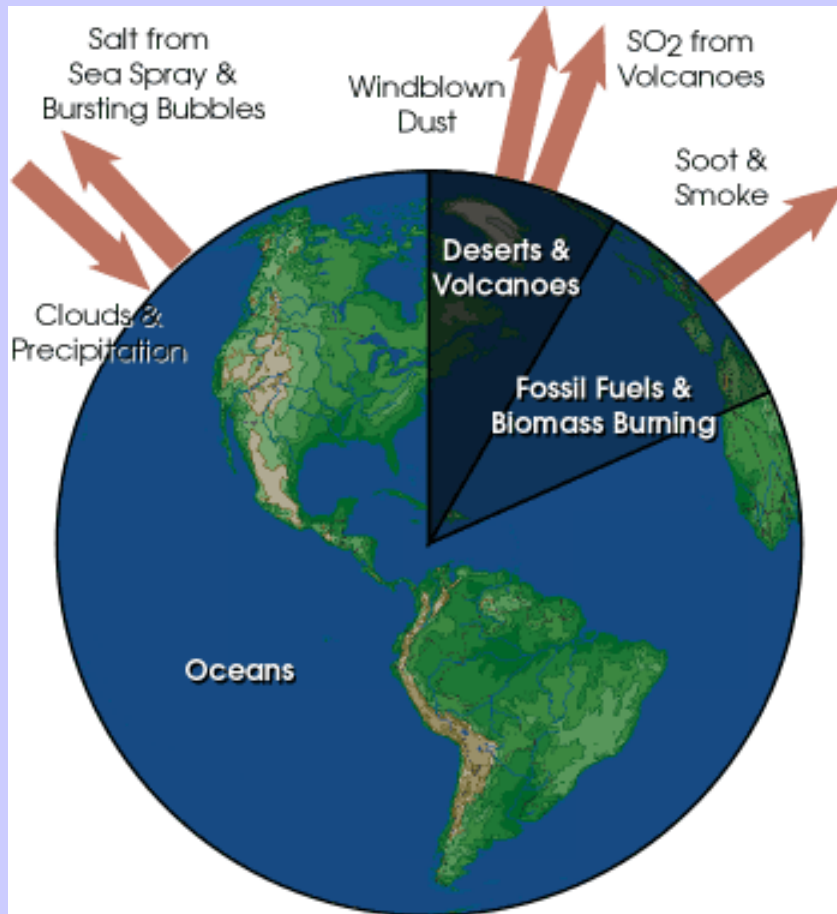
EOS Terra & Aqua MODIS

Multispectral Signatures

(Ocean Color, SST, Snow/Ice, Vegetation, Aerosols, Clouds, Moisture, Fires, Volcanic Ash)

Detecting Climate Trends

Aerosol Types and Origin



- Aerosol particles larger than about $1\ \mu\text{m}$ in size are produced by windblown dust and sea salt from sea spray and bursting bubbles
- Aerosols smaller than $1\ \mu\text{m}$ are mostly formed by condensation processes such as conversion of sulfur dioxide (SO_2) gas (released from volcanic eruptions) to sulfate particles and by formation of soot and smoke during burning processes.
- After formation, aerosols are mixed and transported by atmospheric motions and are primarily removed by clouds and precipitation.

Aerosol Size Distribution

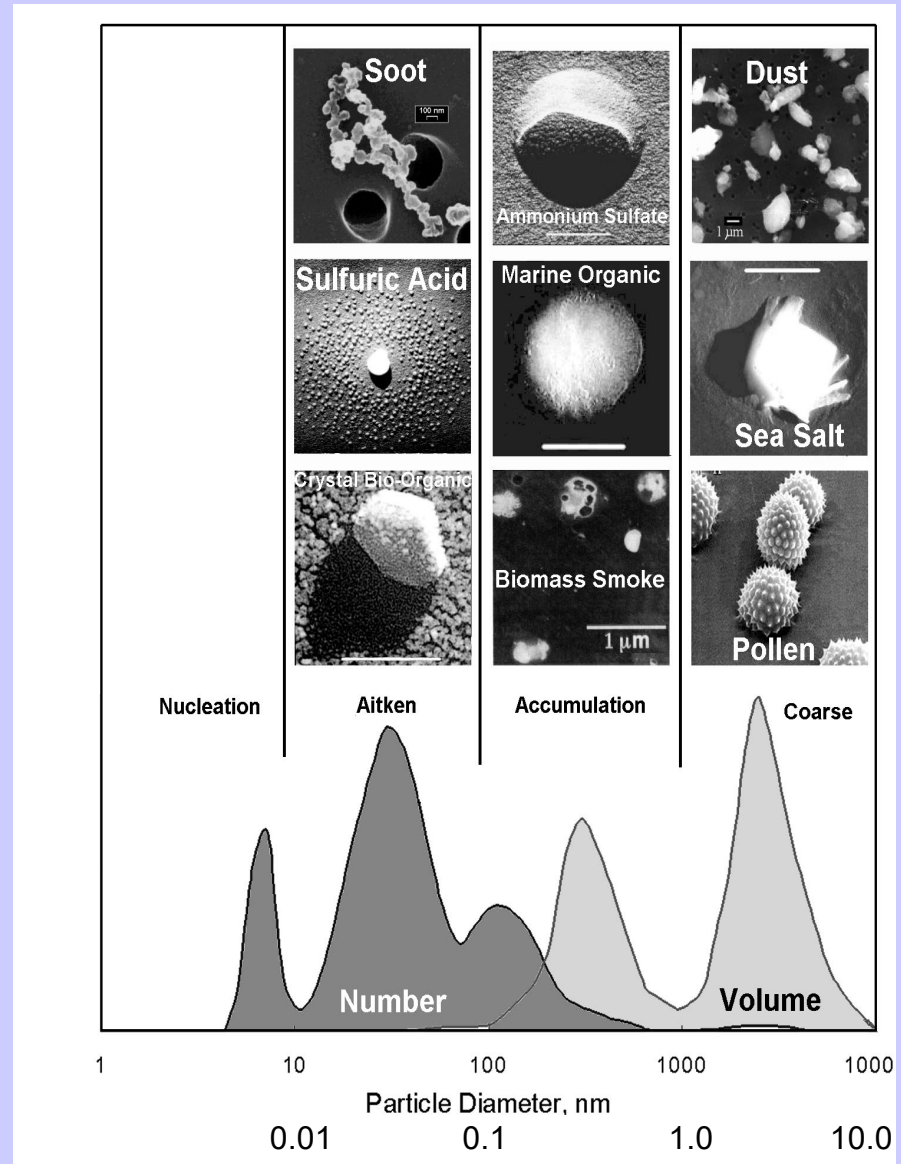
There are **3 modes** :

- « **nucleation** »: radius is between 0.002 and $0.05 \mu\text{m}$. They result from combustion processes, photo-chemical reactions, etc.

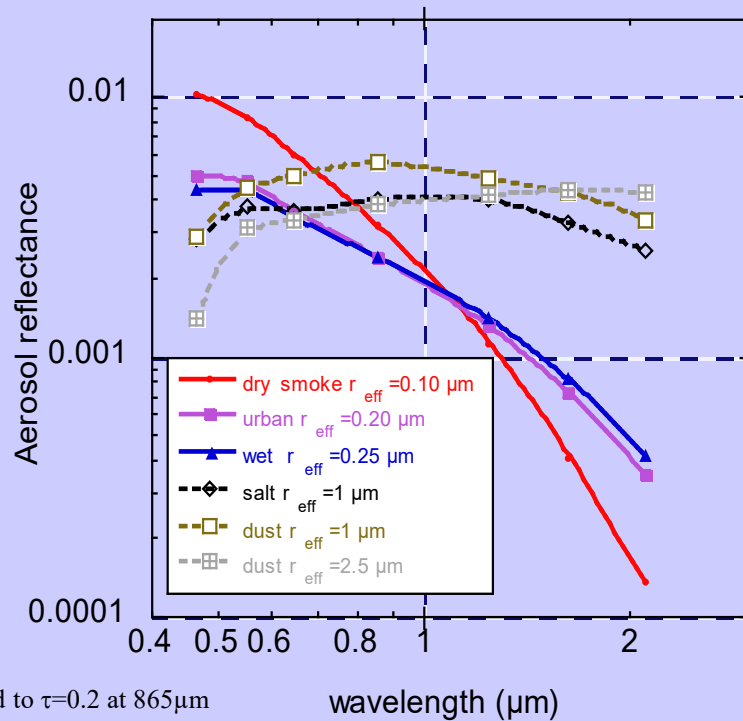
- « **accumulation** »: radius is between $0.05 \mu\text{m}$ and $0.5 \mu\text{m}$. Coagulation processes.

- « **coarse** »: larger than $1 \mu\text{m}$. From mechanical processes like aeolian erosion.

« **fine** » particles (nucleation and accumulation) result from anthropogenic activities, coarse particles come from natural processes.



Aerosols over Ocean



- Radiance data in 6 bands (550-2130nm).

- Spectral radiances (LUT) to derive the aerosol size distribution

- Two modes (accumulation 0.10-0.25 μm ; coarse 1.0-2.5 μm); ratio is a free parameter

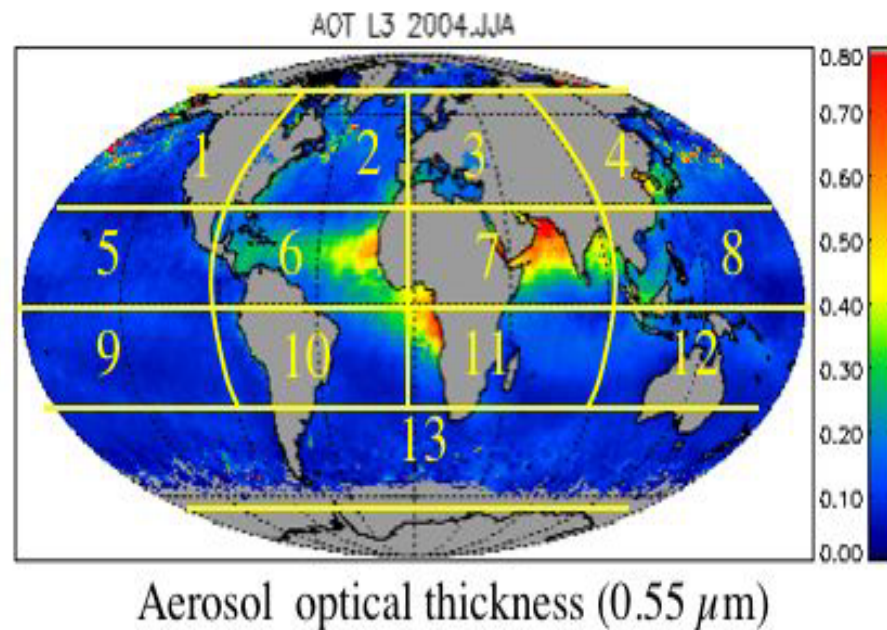
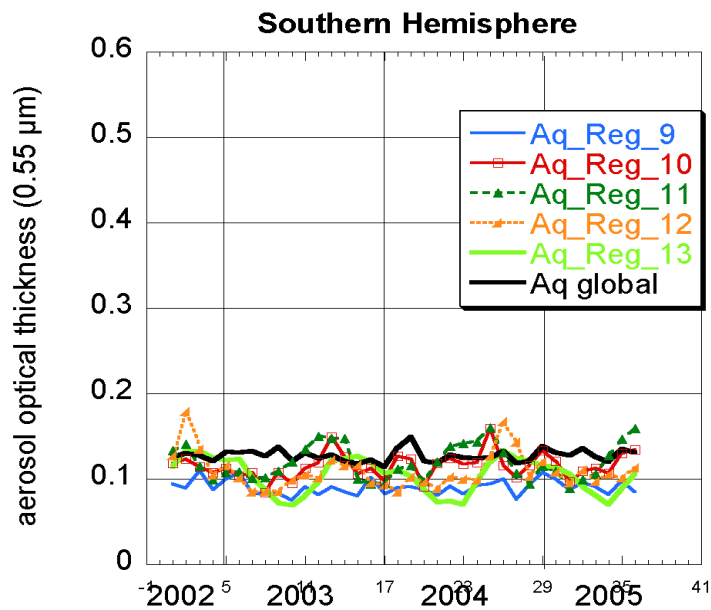
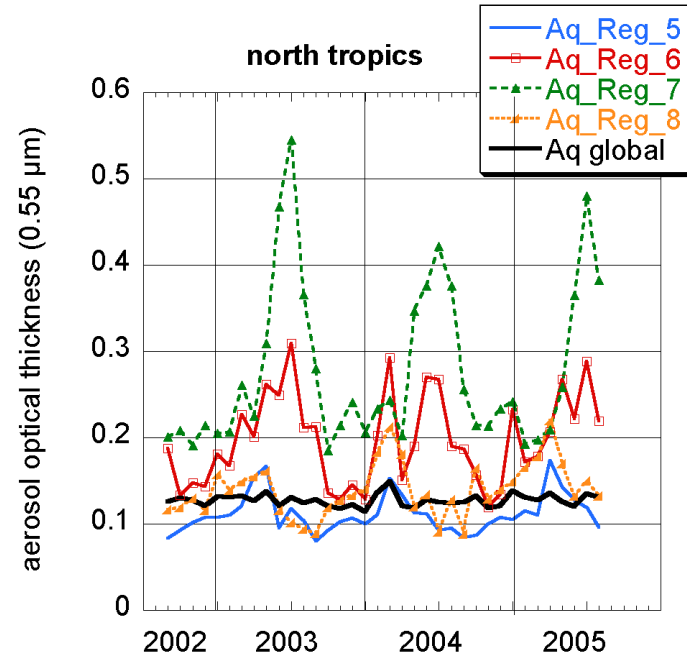
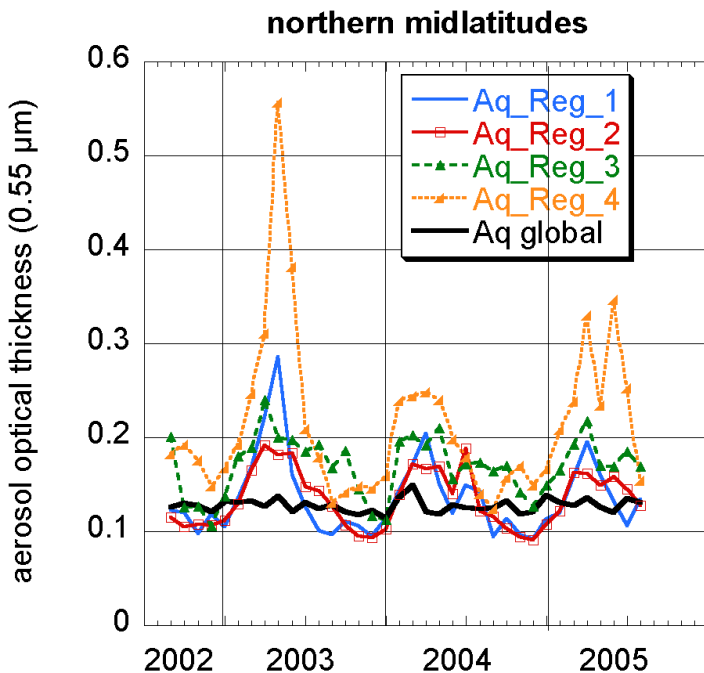
- Radiance at $865\mu\text{m}$ to derive τ

Ocean products :

- The total Spectral Optical thickness
- The effective radius
- The optical thickness of small & large modes/ratio between the 2 modes

Global aerosol AOT trends

Remer et al
2005



Aerosol effects on cloud cover

over the Atlantic Ocean -
several aerosol types
interact with clouds

June-Aug 2002

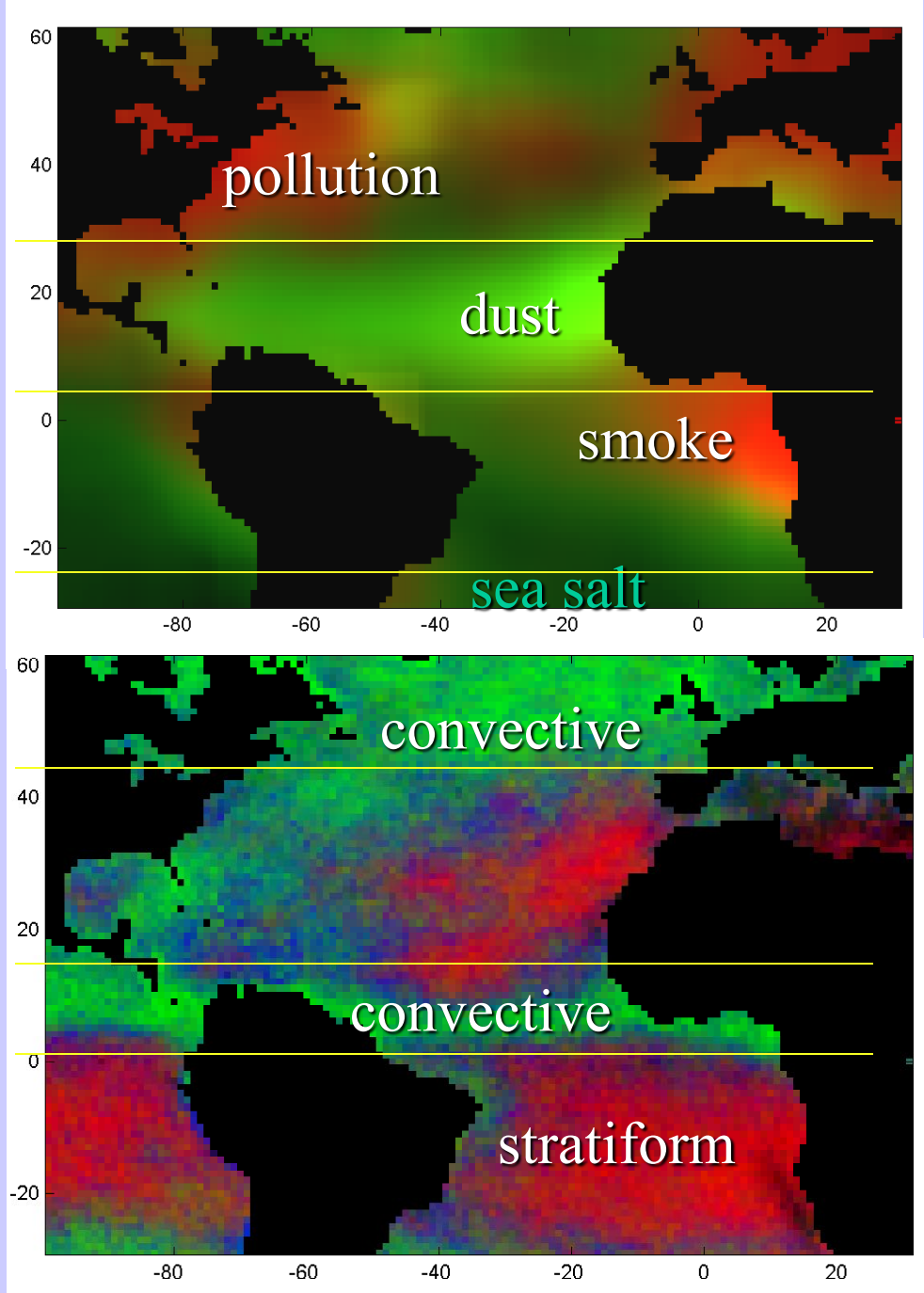
Pollution zone

Dust zone

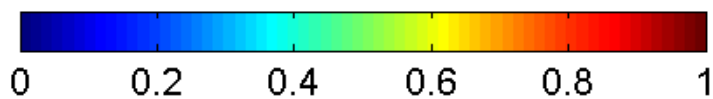
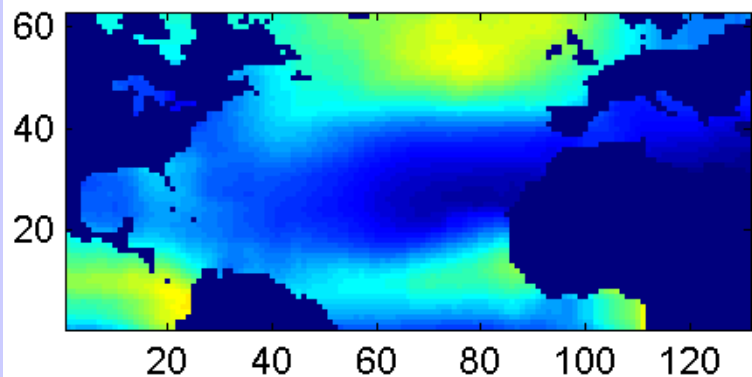
Smoke zone

Marine aerosol

aerosol forcing increased cloud cover 5% ($\sim 6 \text{ W/m}^2$) and height 40 hPa ($\sim 400 \text{ m}$) in June-Aug 02 over Atlantic Ocean

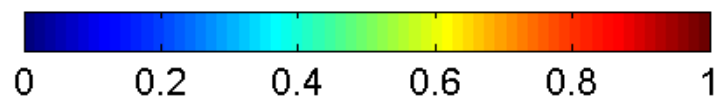
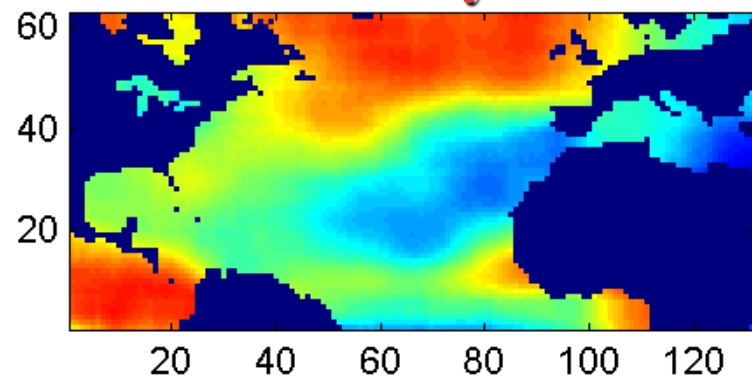


clean



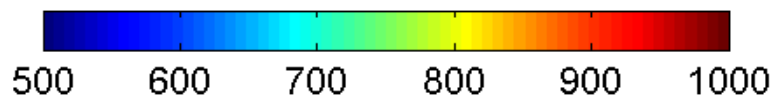
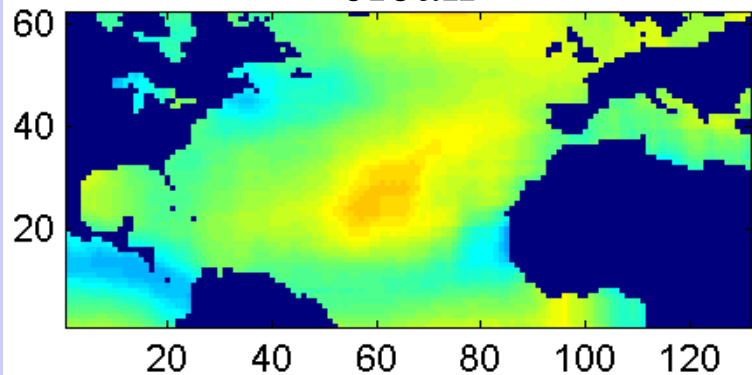
Cloud fraction

hazy



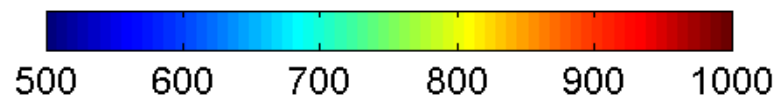
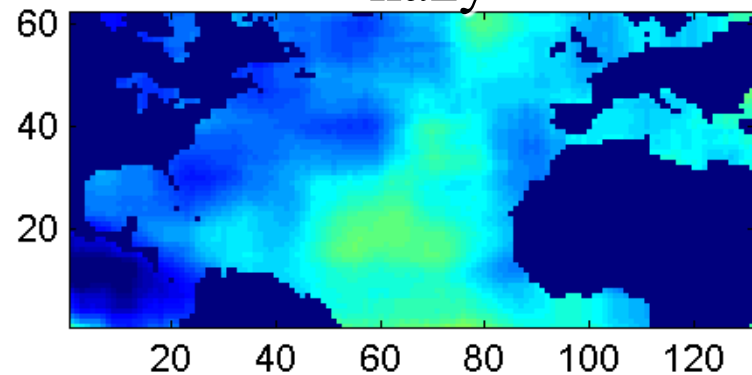
Cloud fraction

clean



Cloud top pressure

hazy



Cloud top pressure

Applications with Multispectral Remote Sensing Data

Satellite Remote Sensing

Energy Balance

VIS, IR, and MW Radiative Transfer

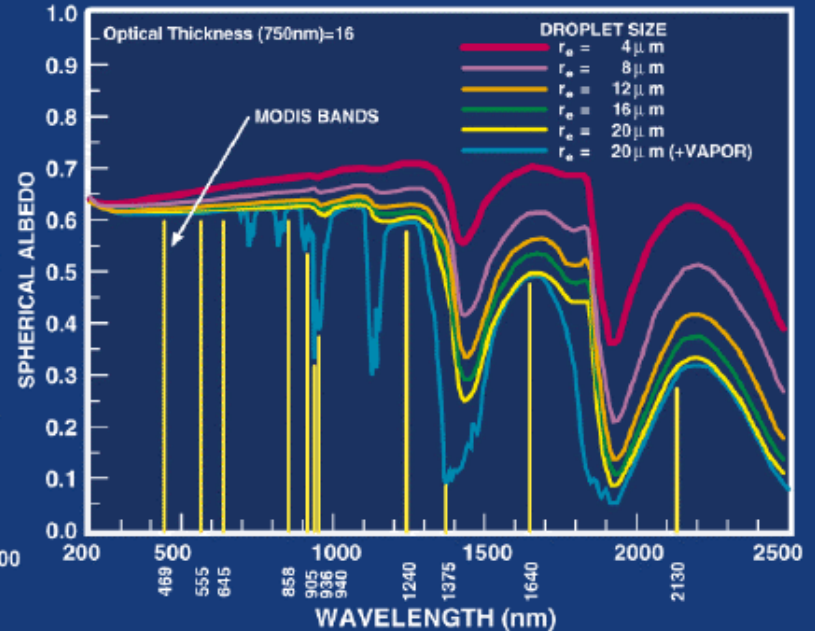
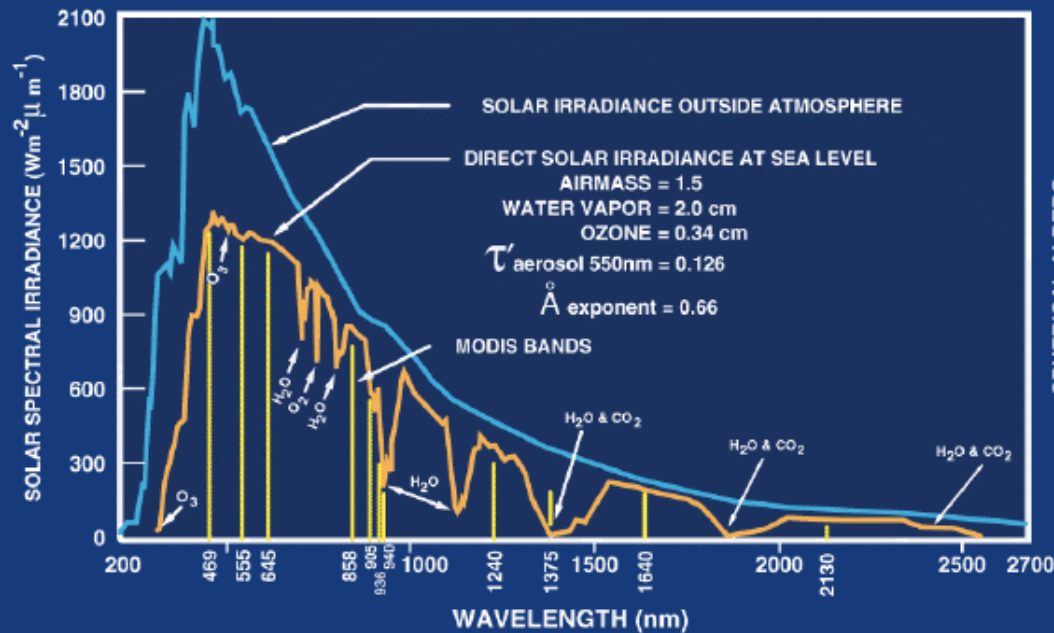
EOS Terra & Aqua MODIS

Multispectral Signatures

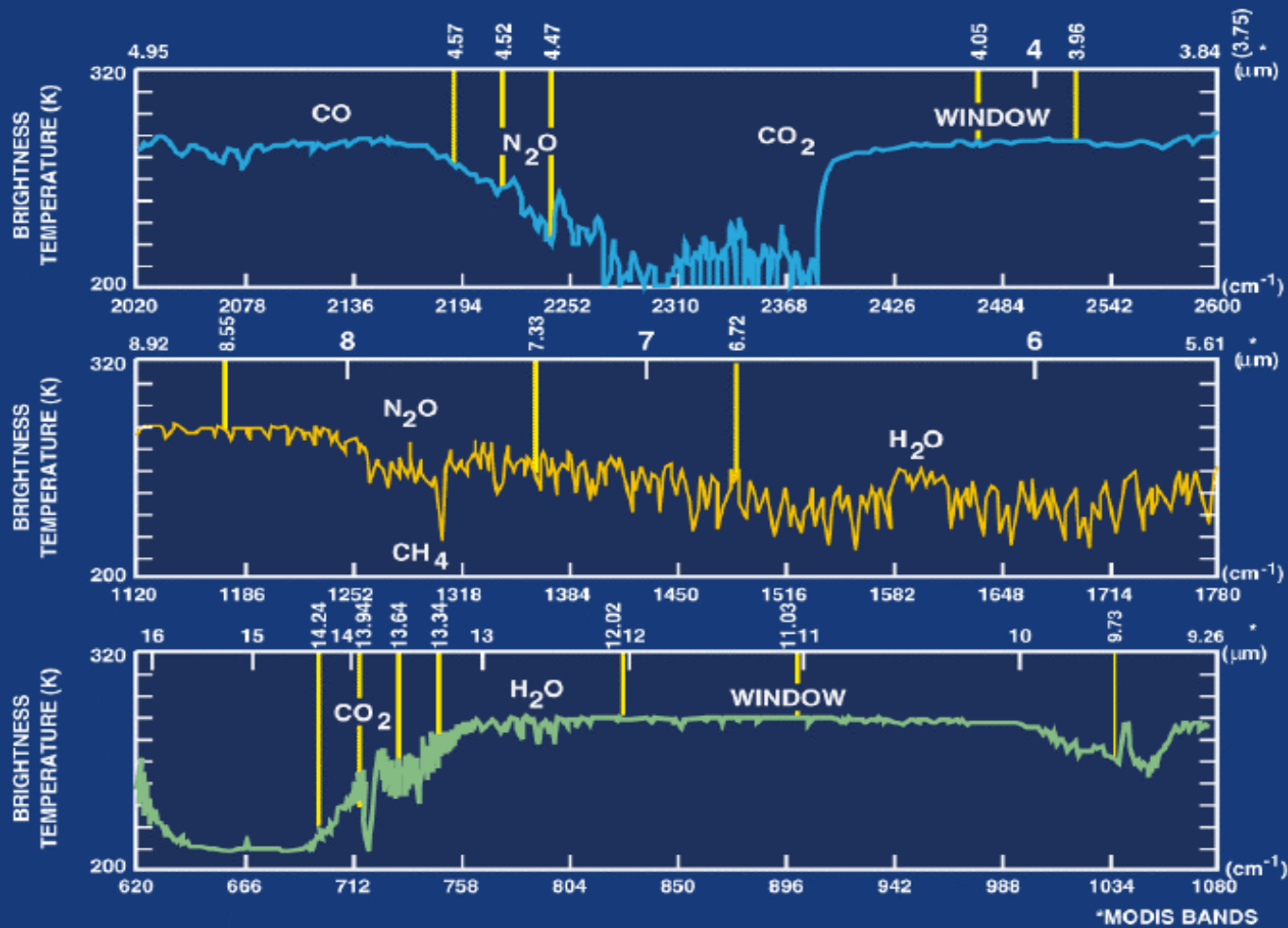
(Ocean Color, SST, Snow/Ice, Vegetation, Aerosols, Clouds, Moisture, Fires, Volcanic Ash)

Detecting Climate Trends

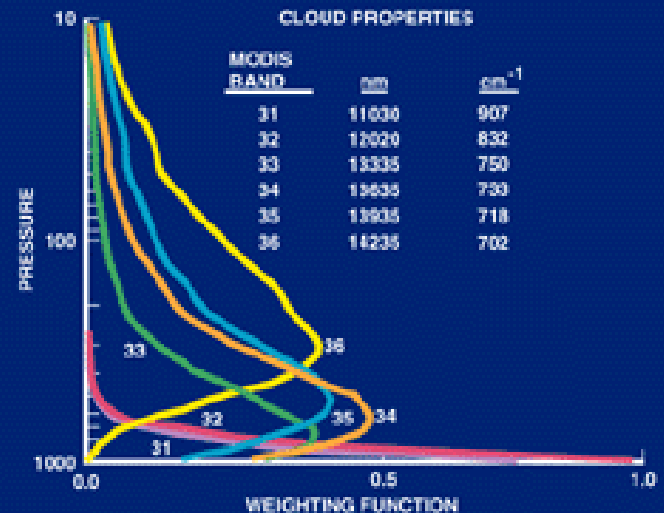
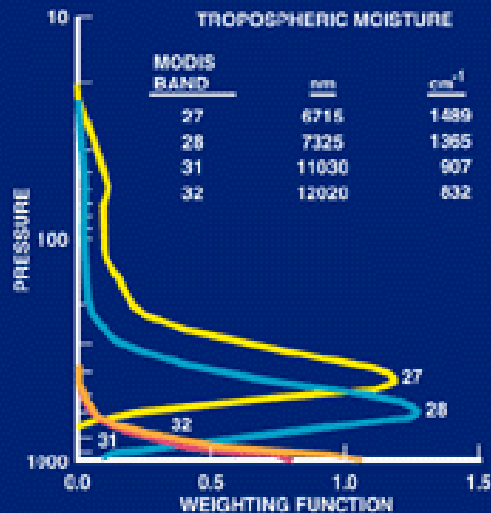
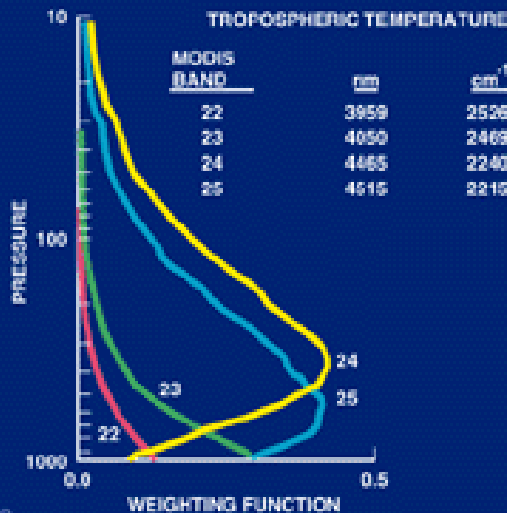
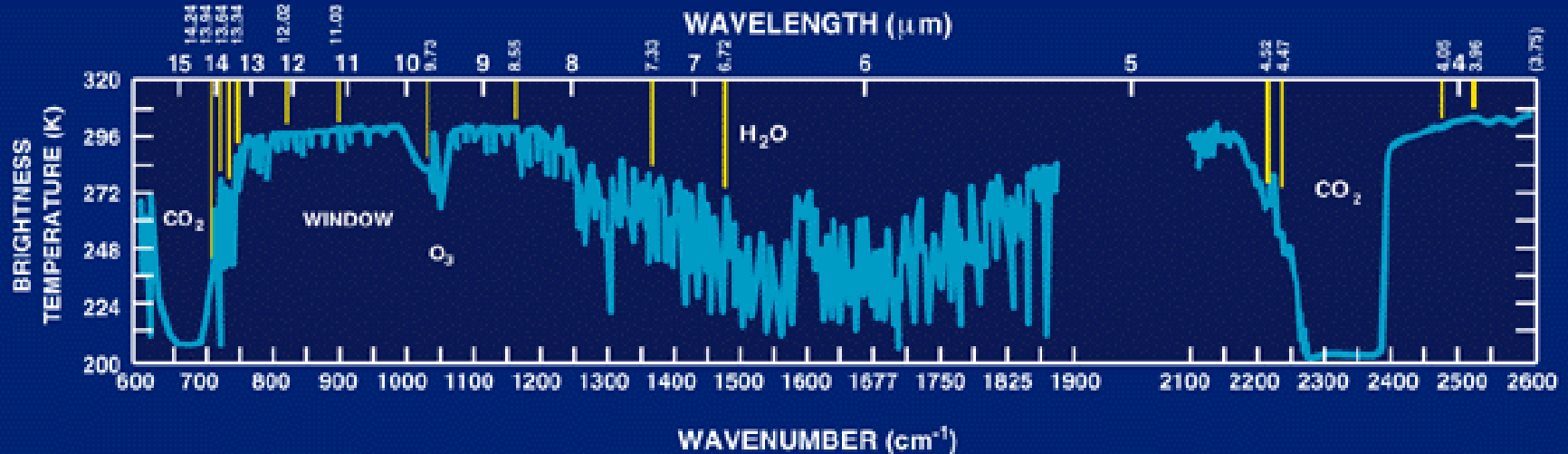
ATMOSPHERE-SOLAR RADIATION

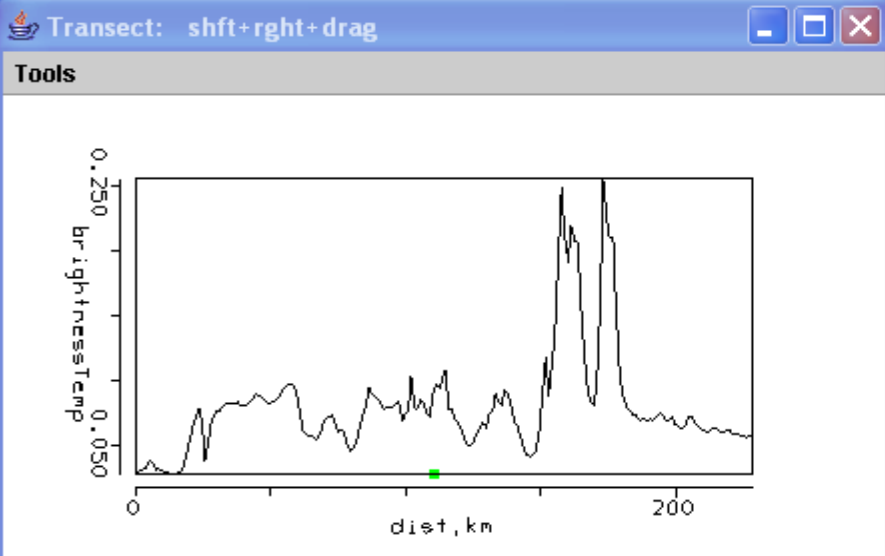
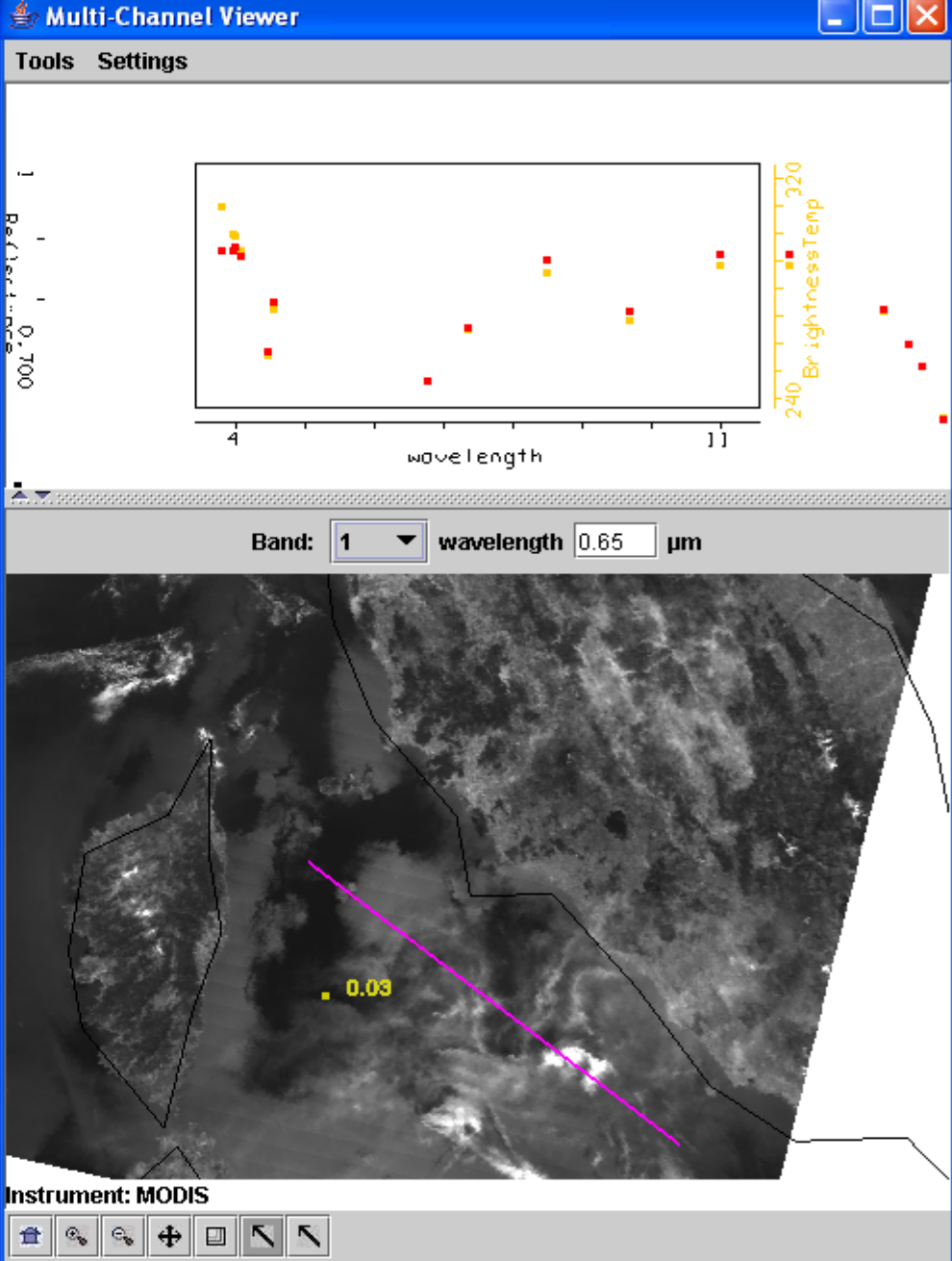
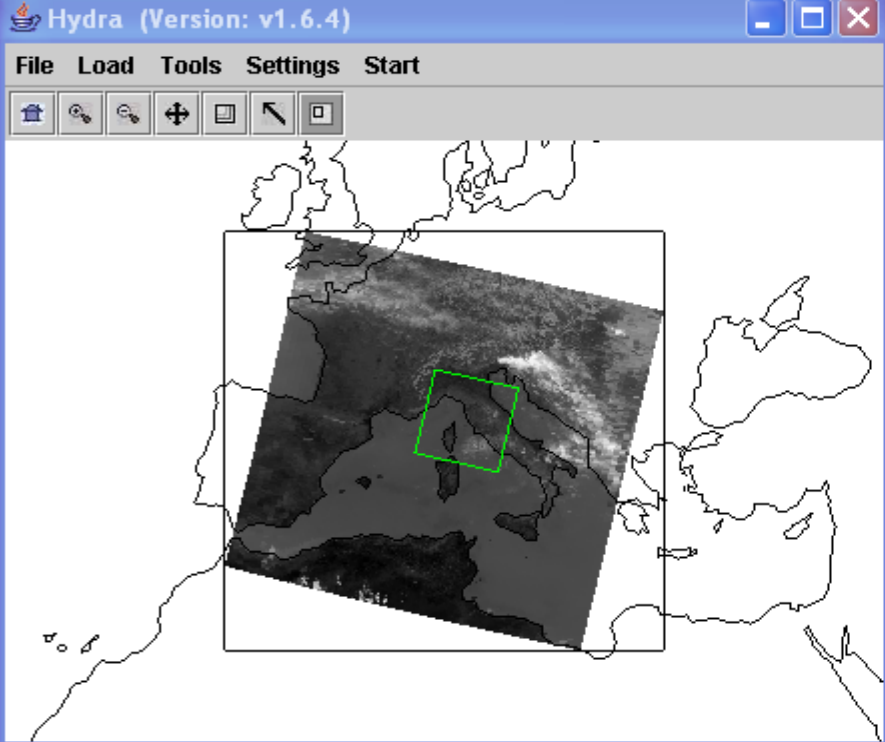


ATMOSPHERE - CLEAR SKY THERMAL EMISSION

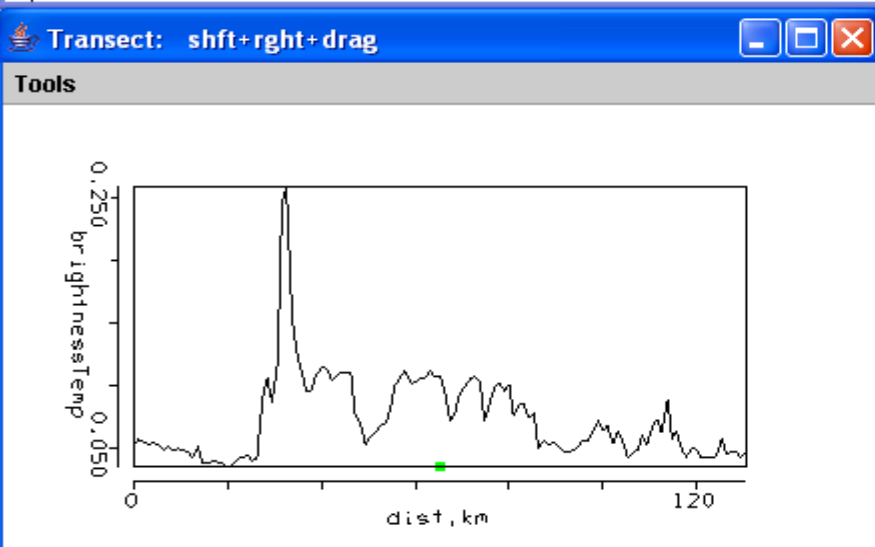
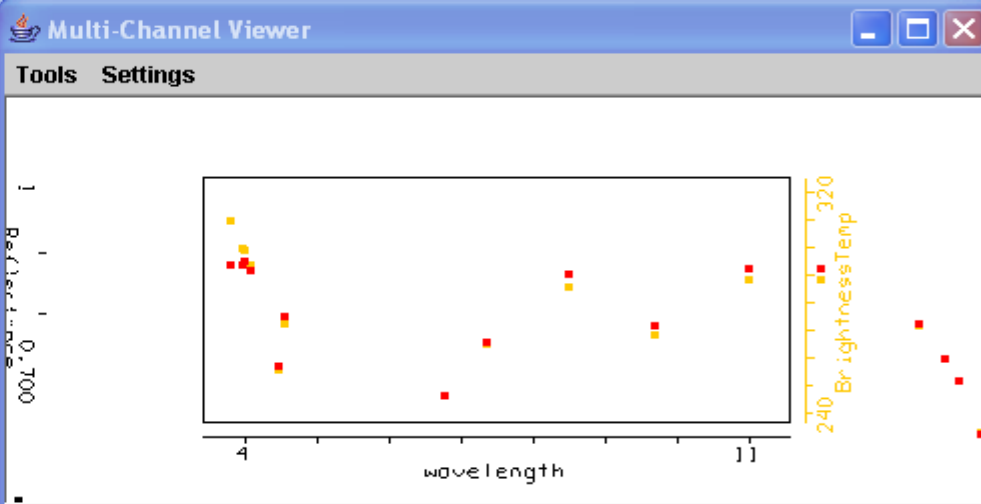
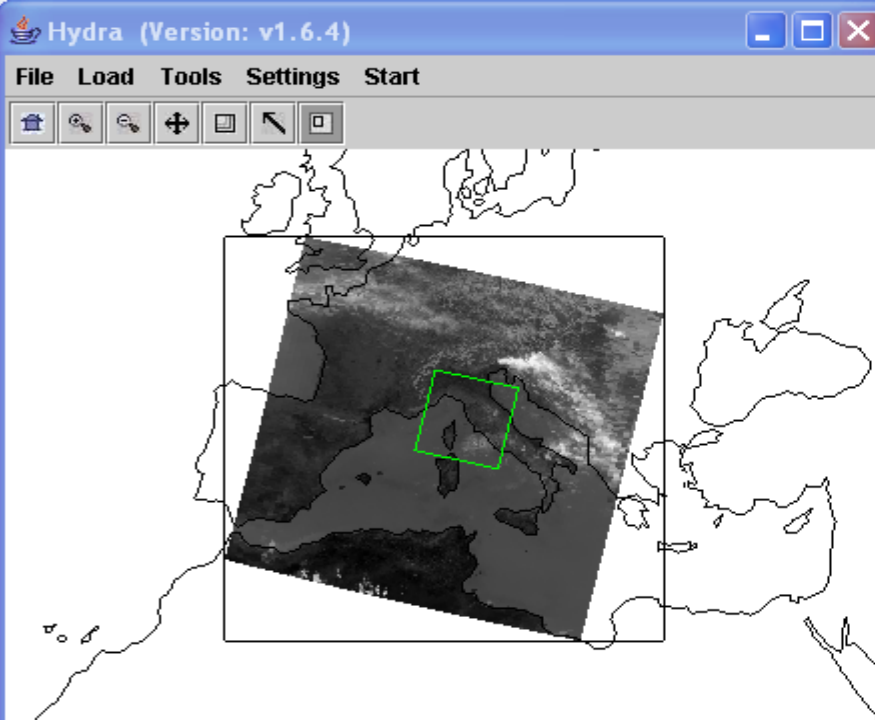


ATMOSPHERE - THERMAL RADIATION

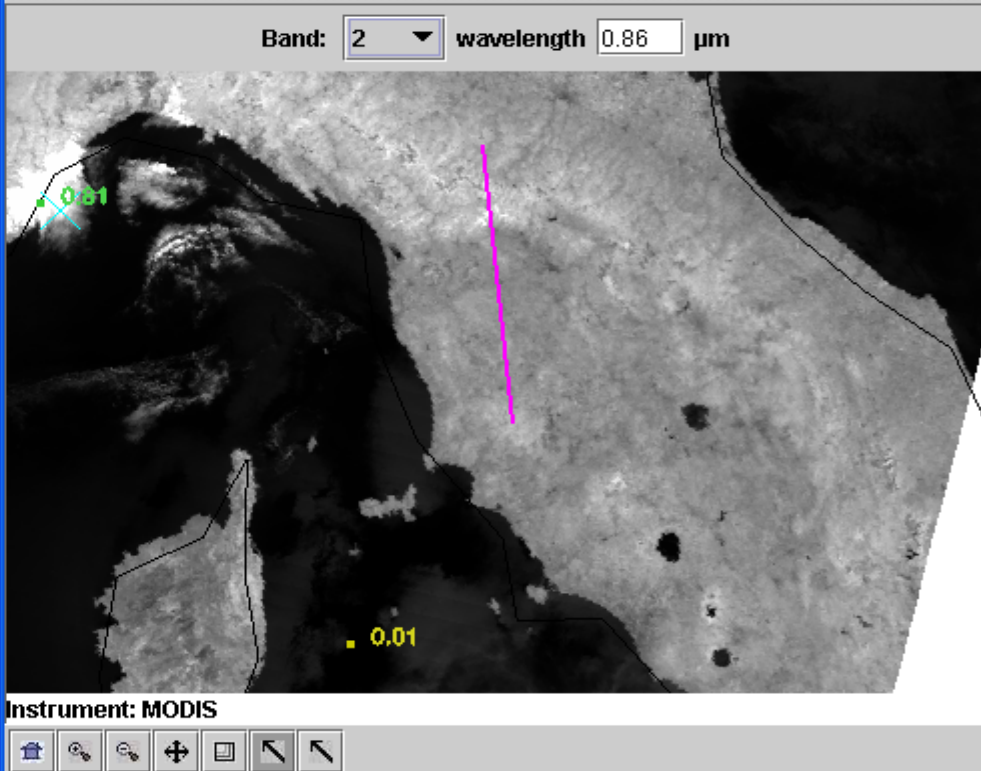
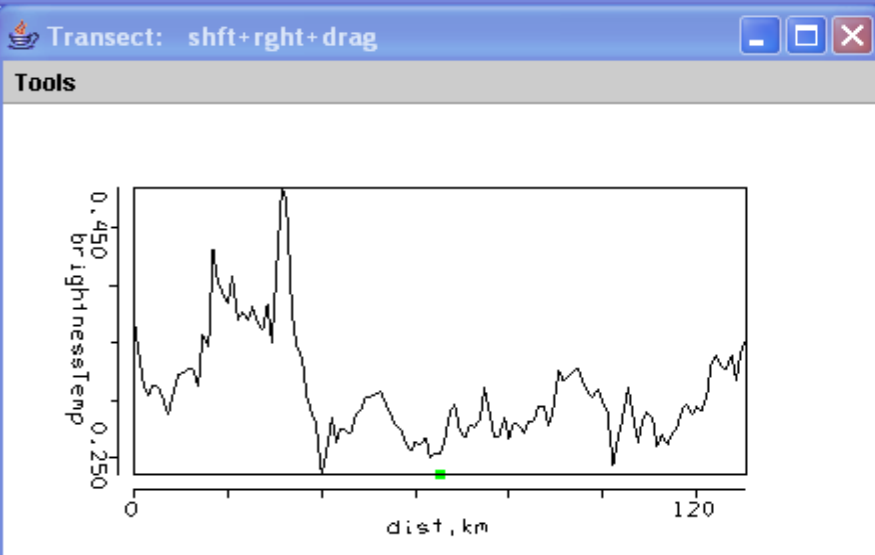
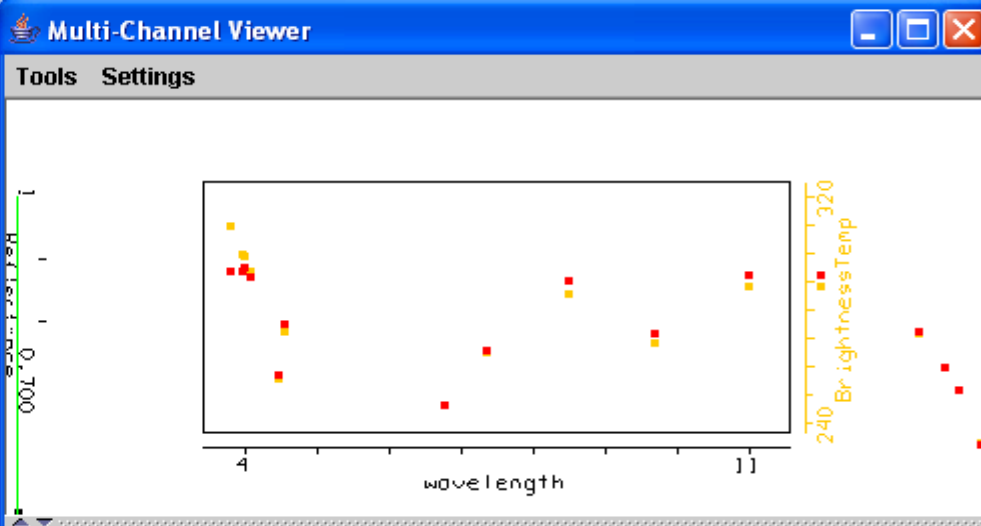
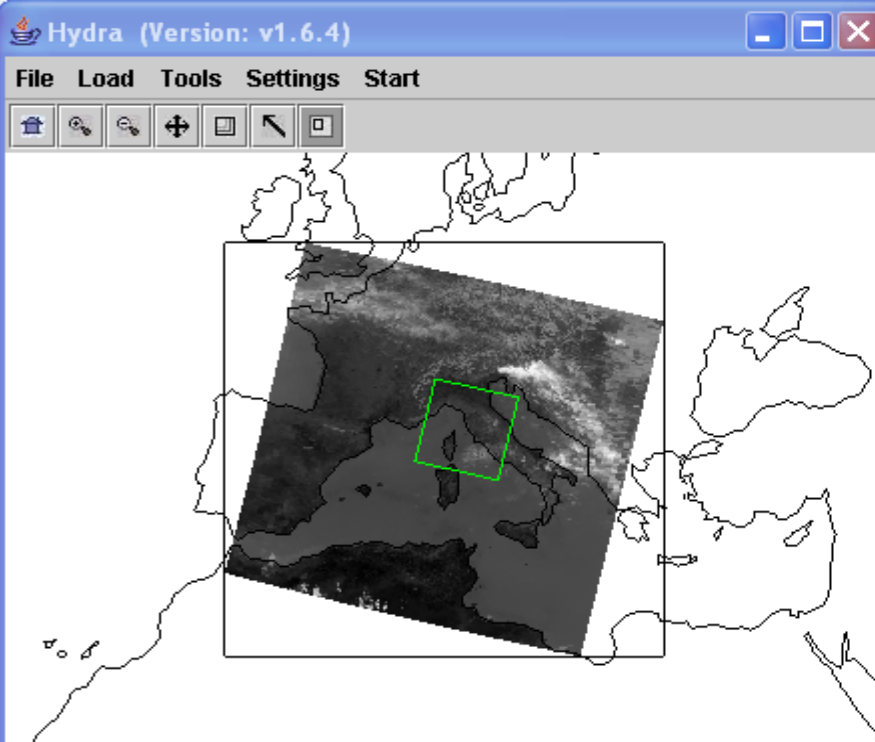




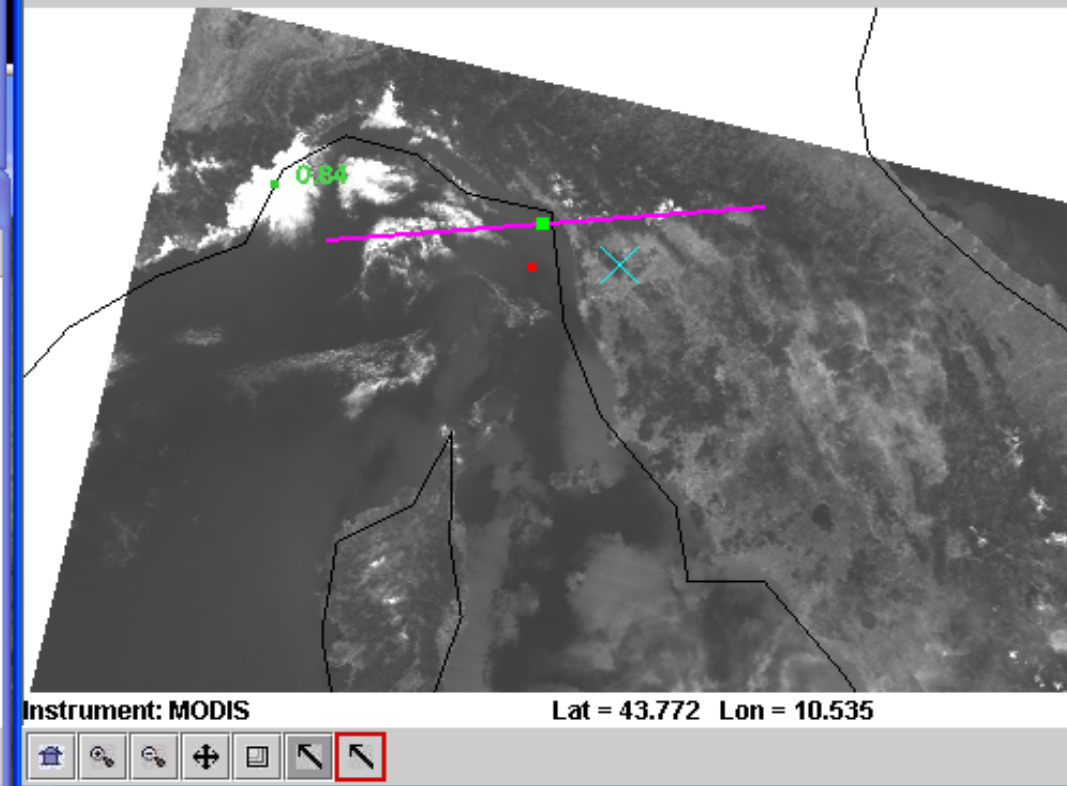
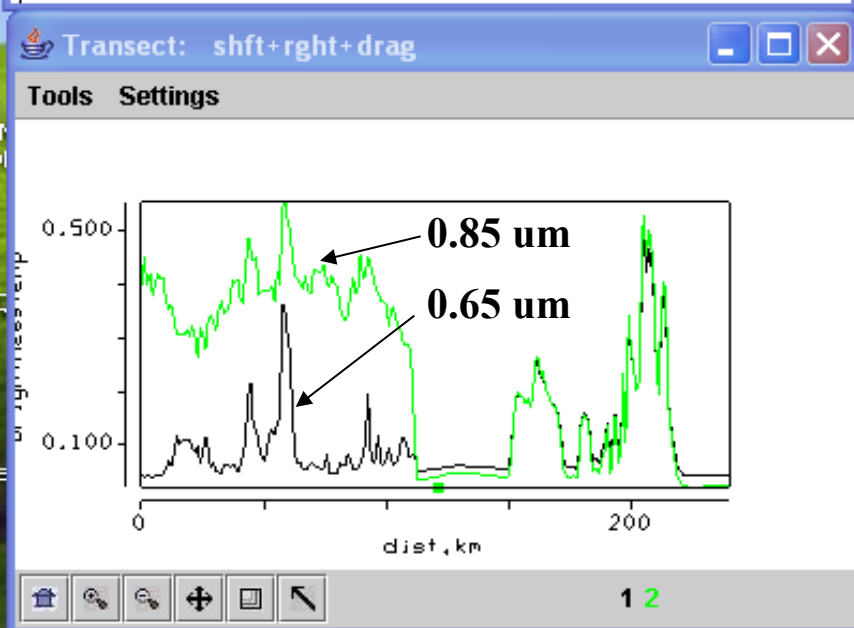
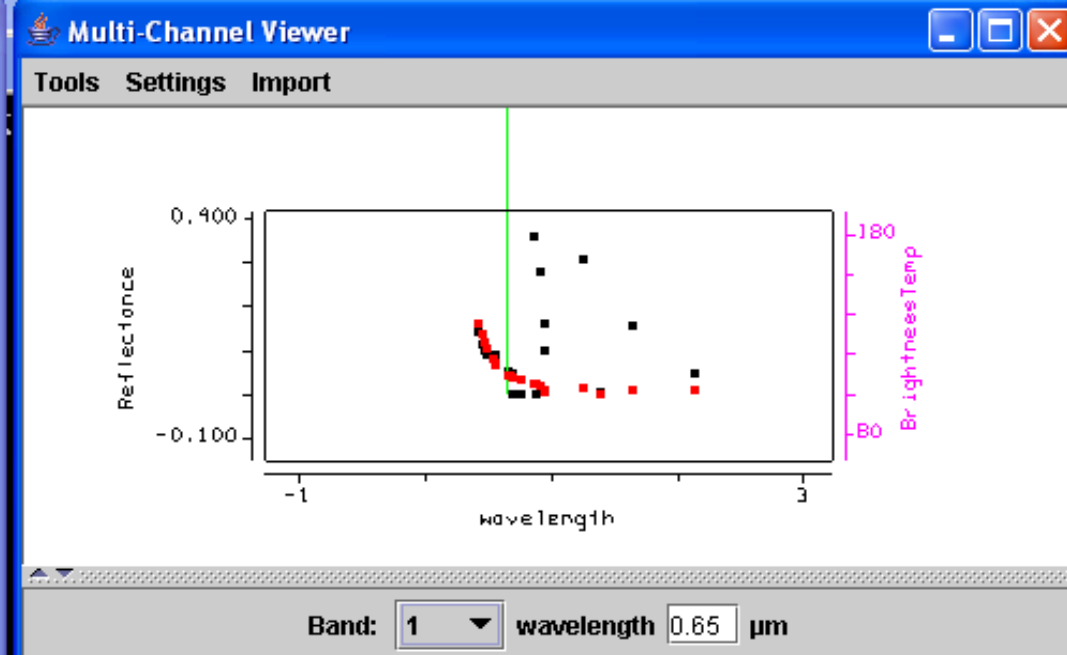
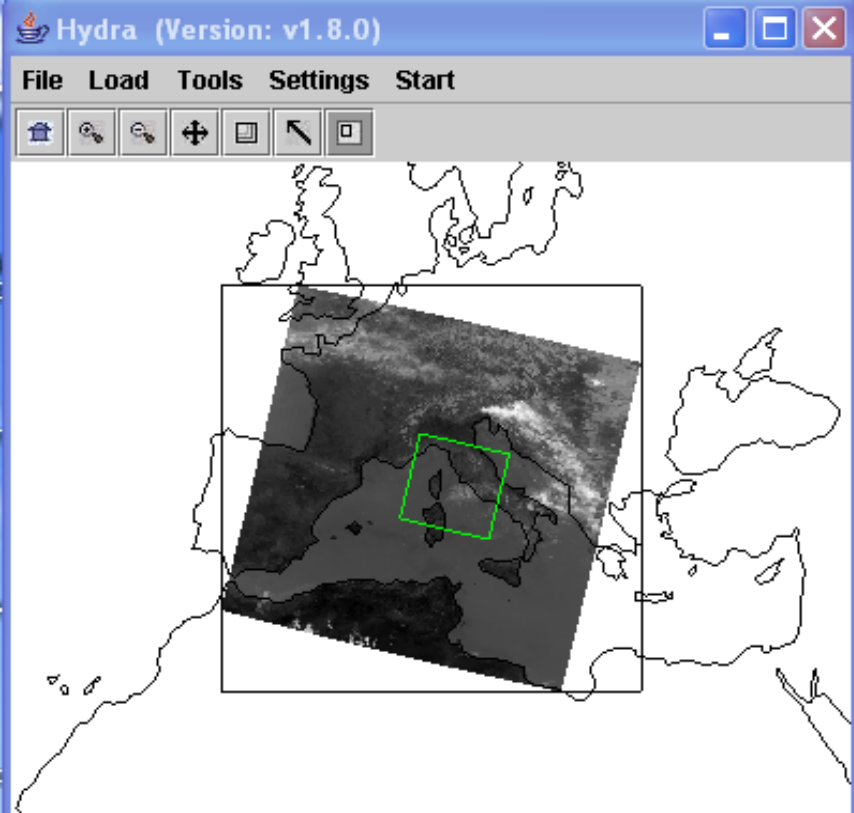
High clouds reflect more than surface at 0.65 μm

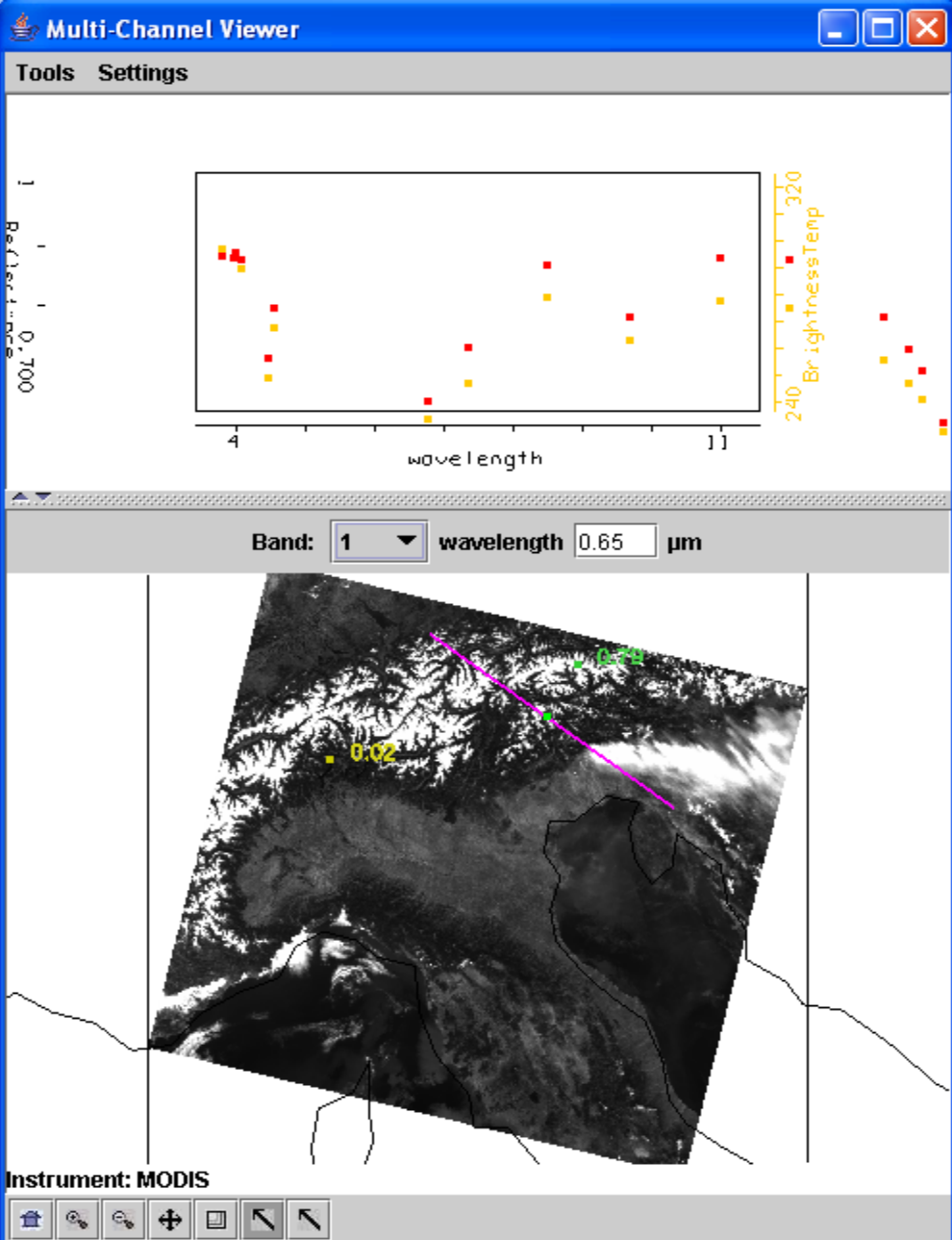
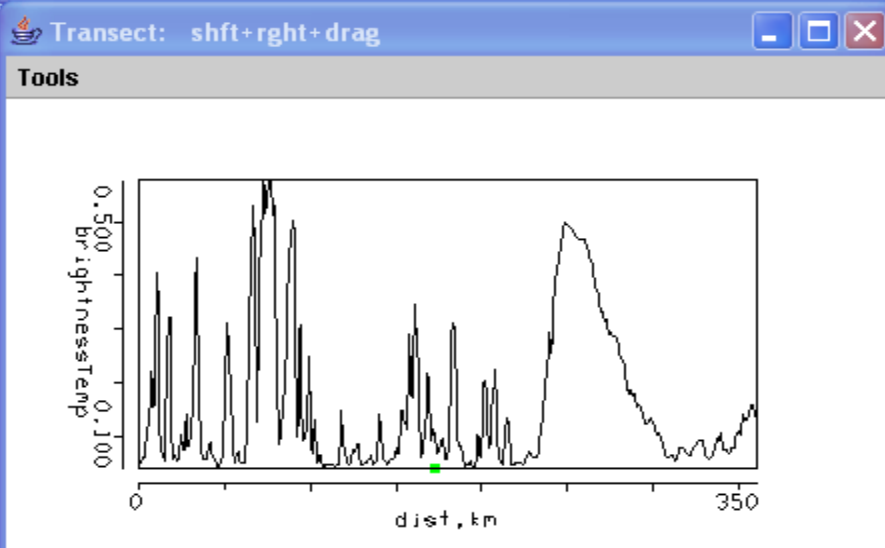
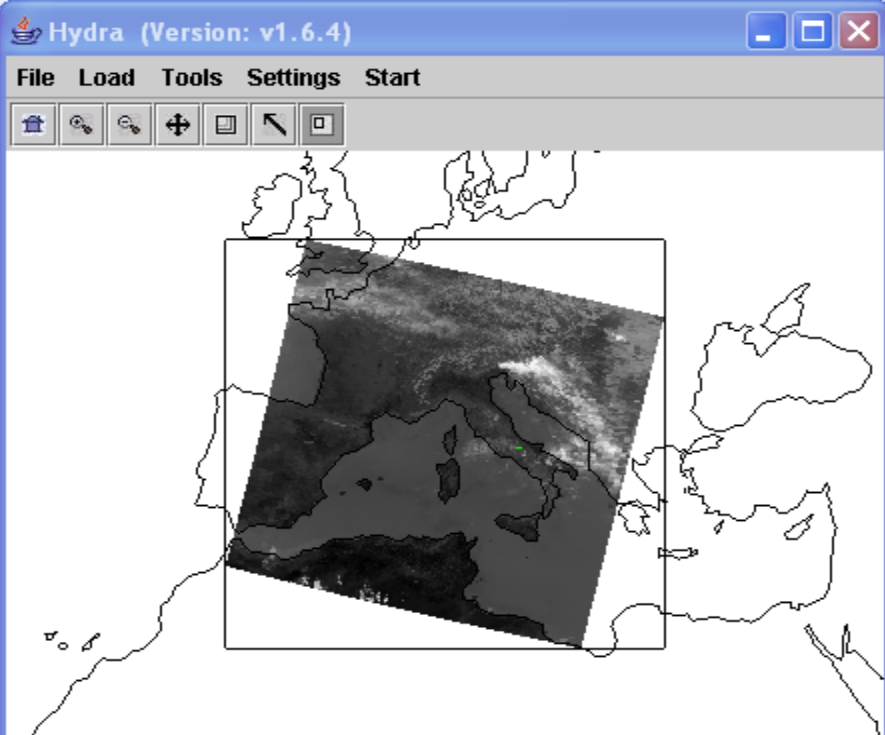


High clouds reflect more than surface at 0.65 μm, even over vegetation

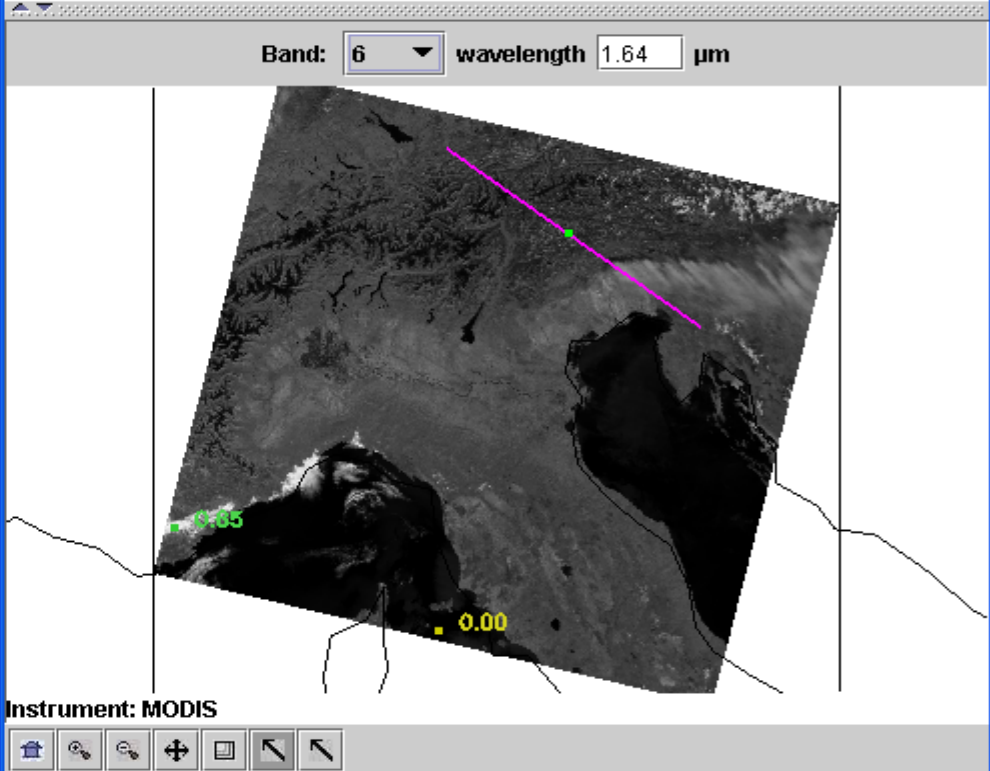
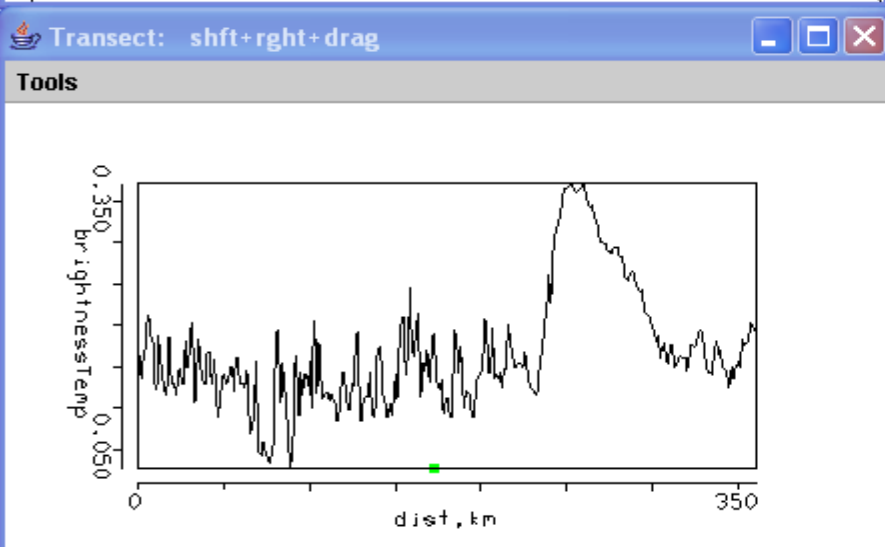
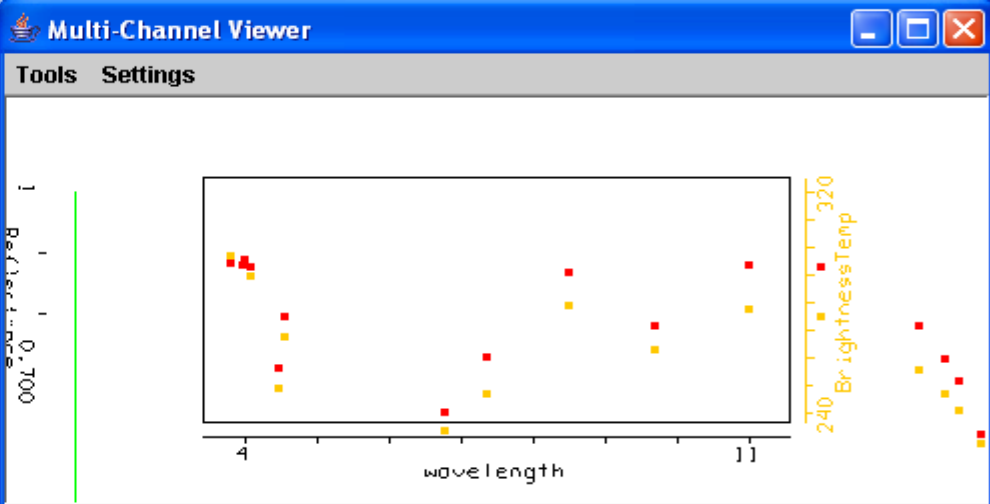
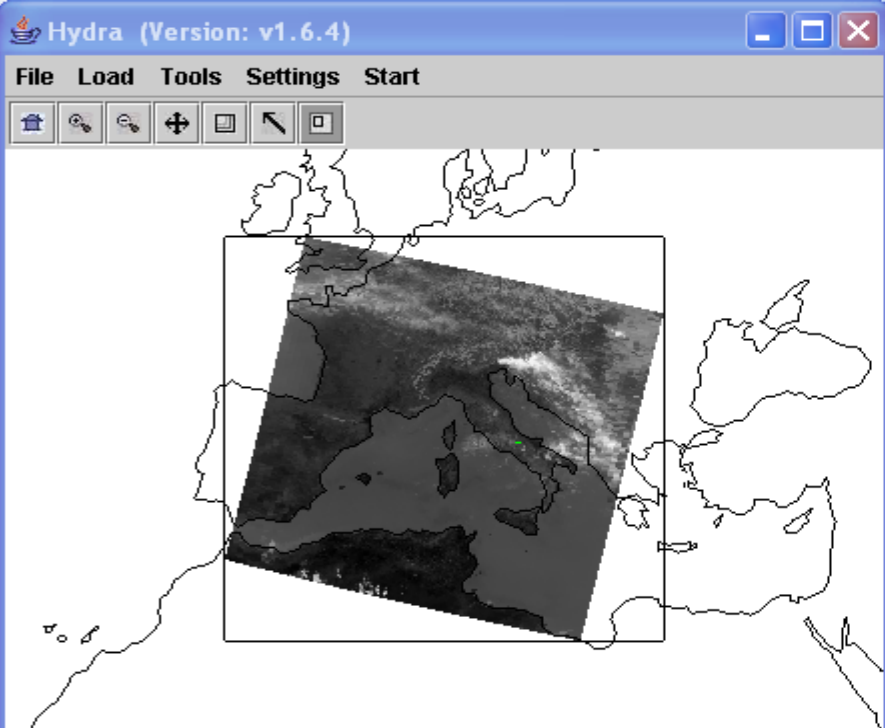


High clouds are more difficult to detect at 0.86 μm over vegetation

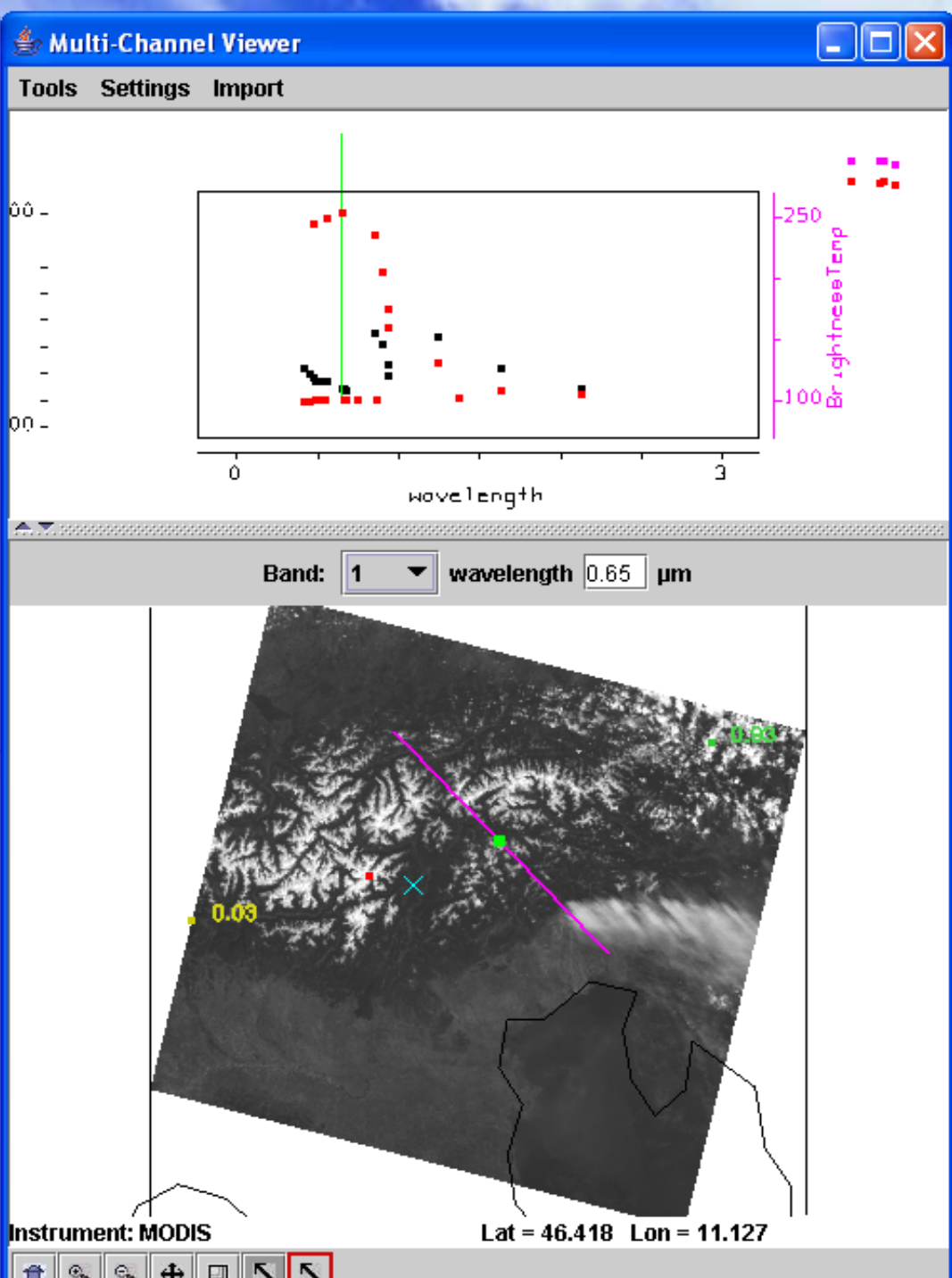
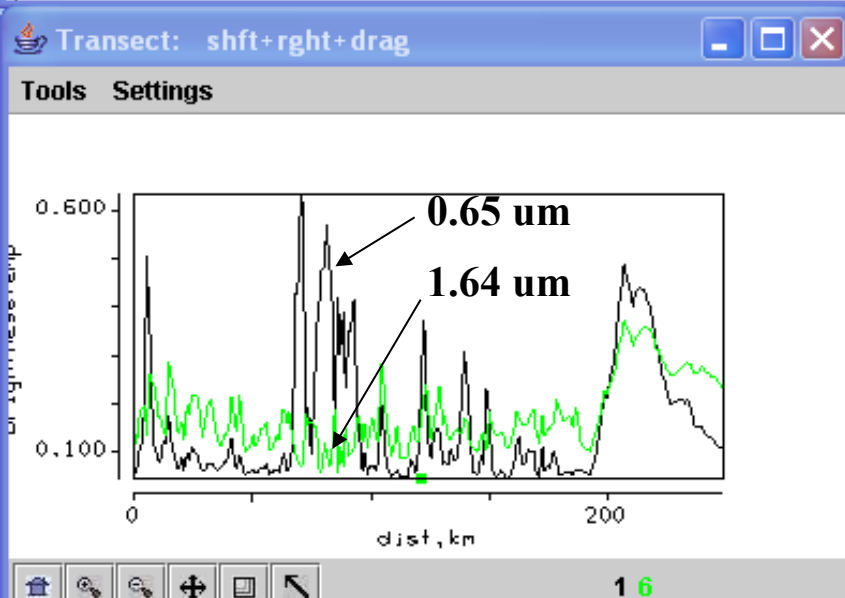
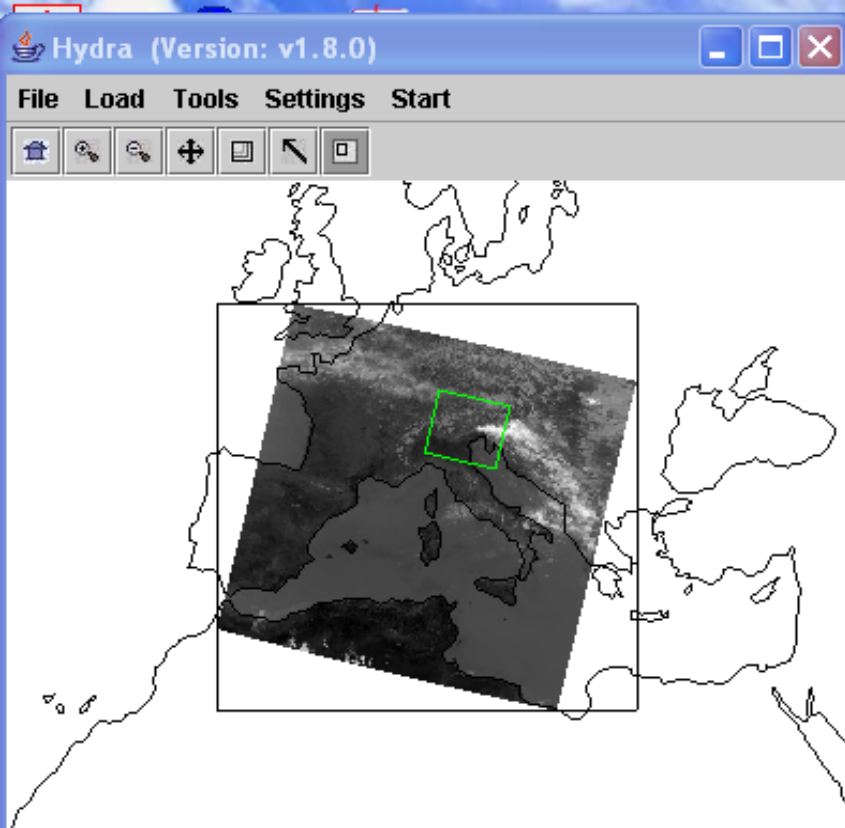


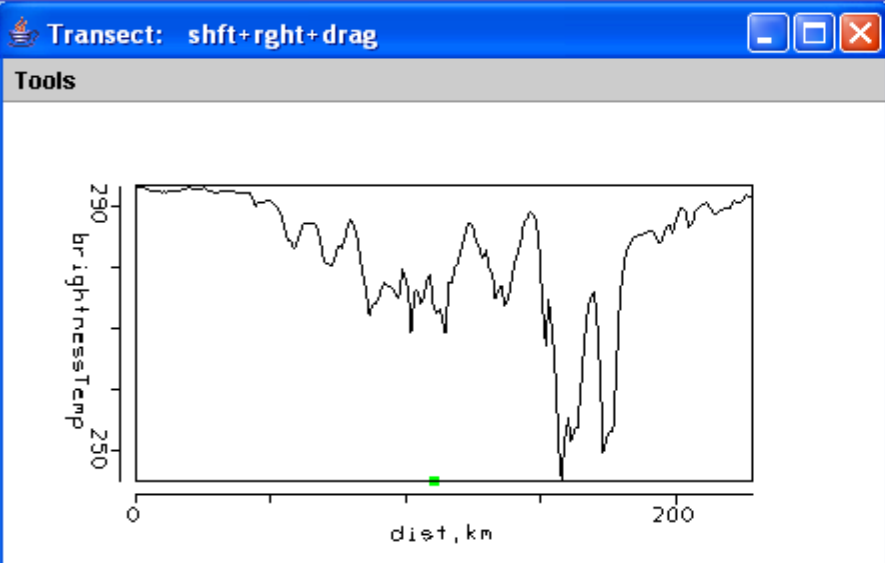
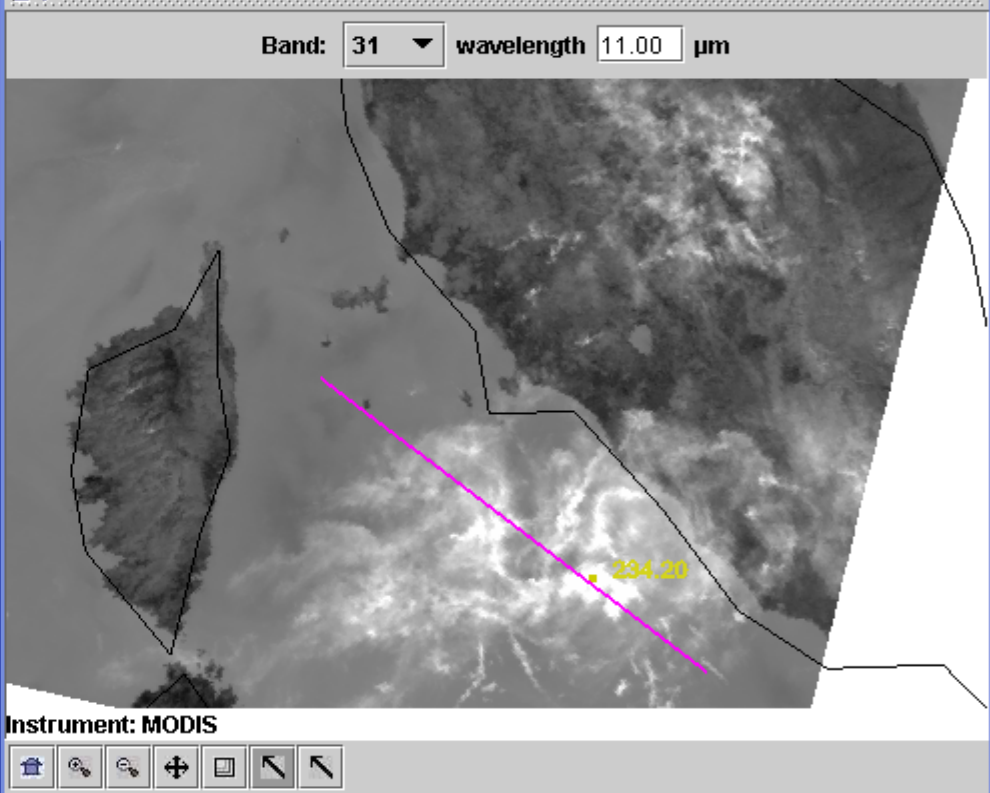
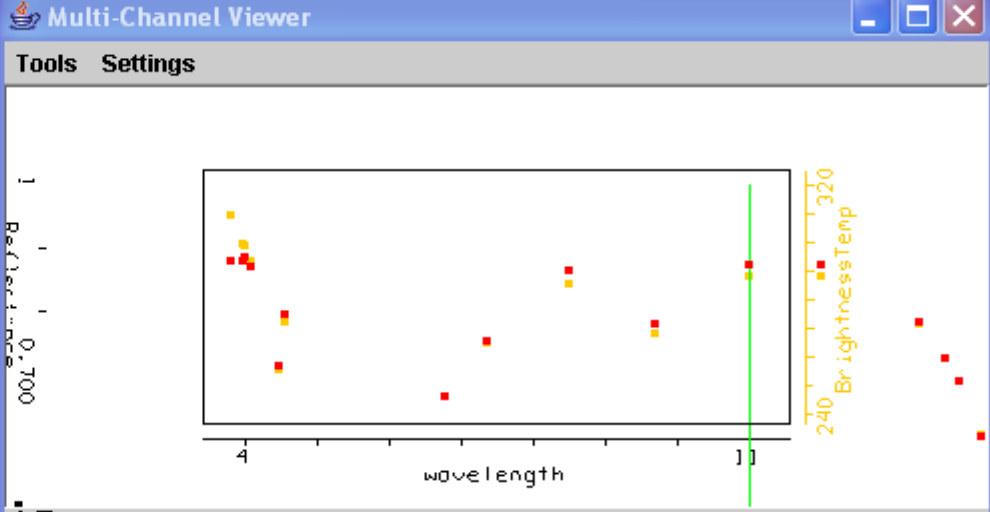
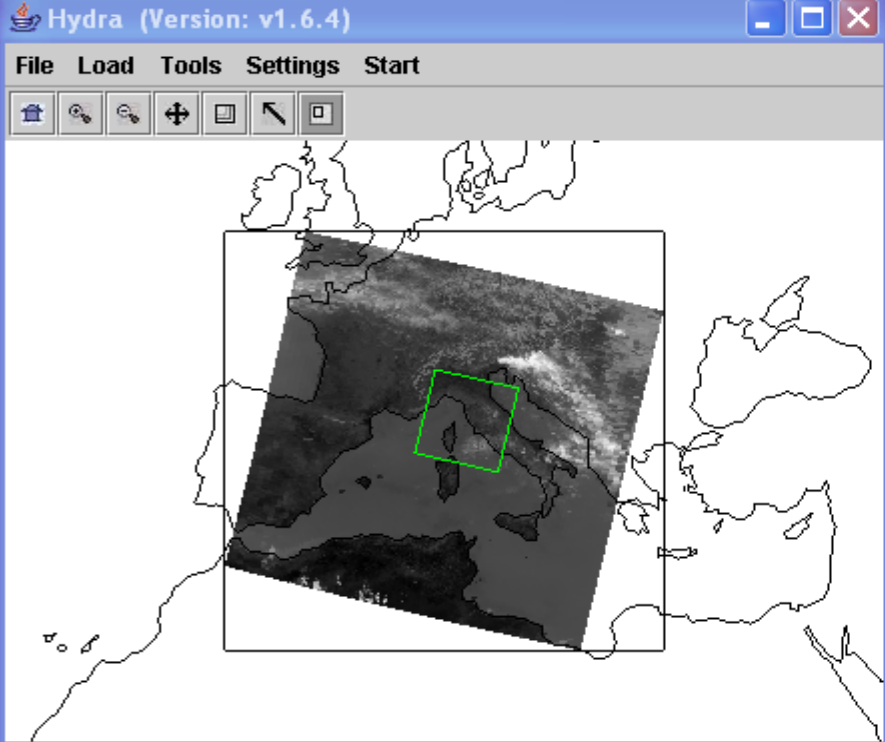


High clouds and snow both reflect a lot at 0.65 μm

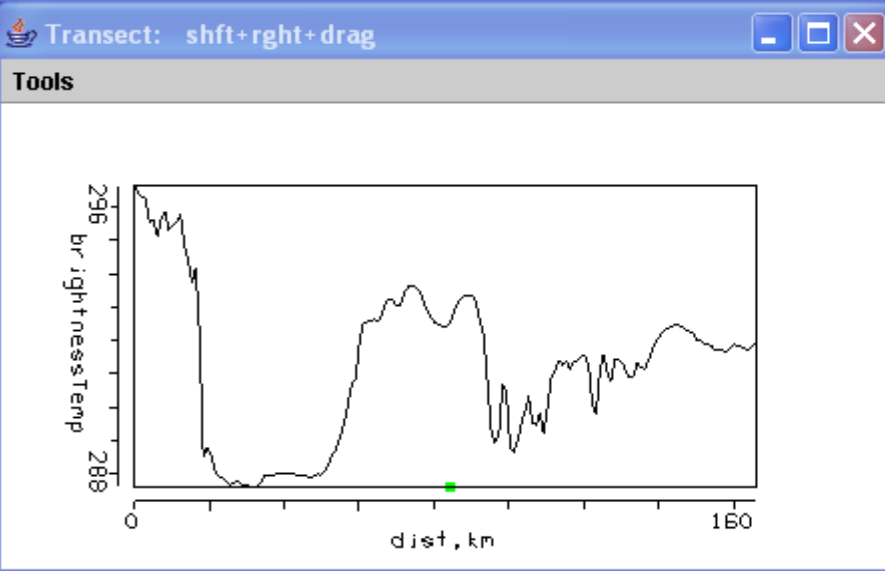
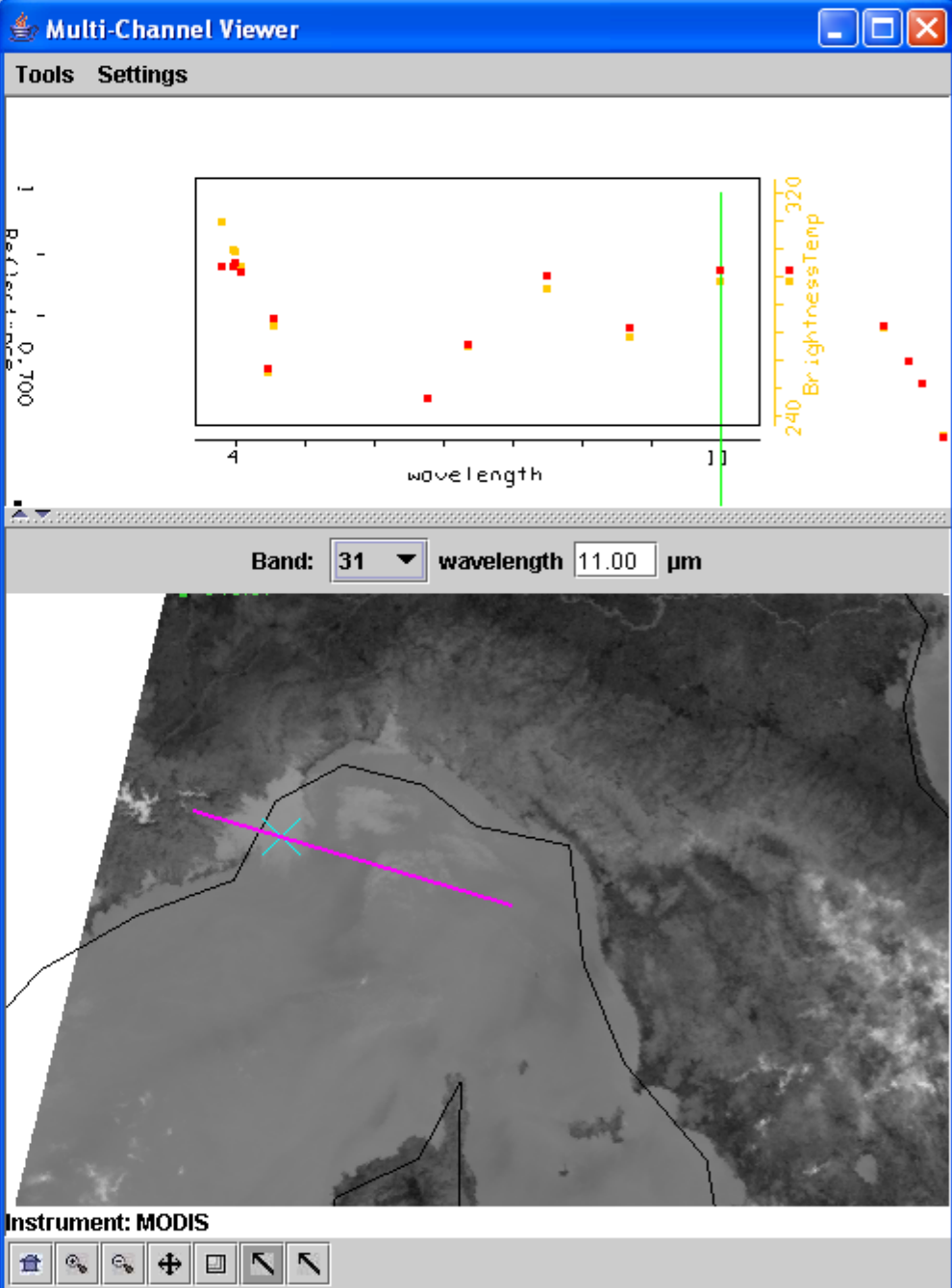
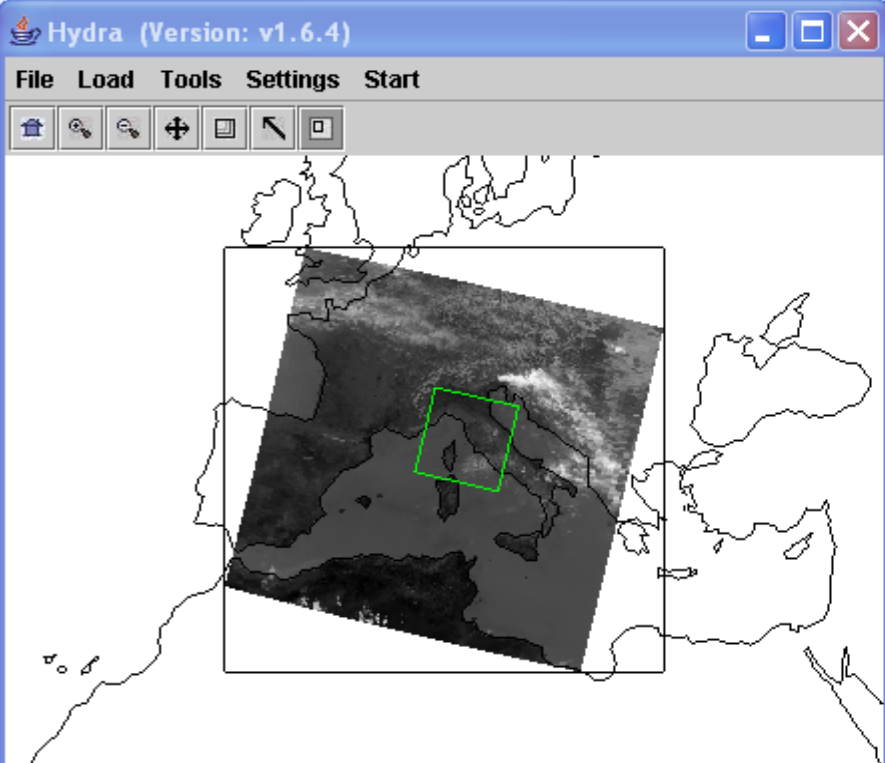


High clouds reflect but snow doesn't at 1.64 μm

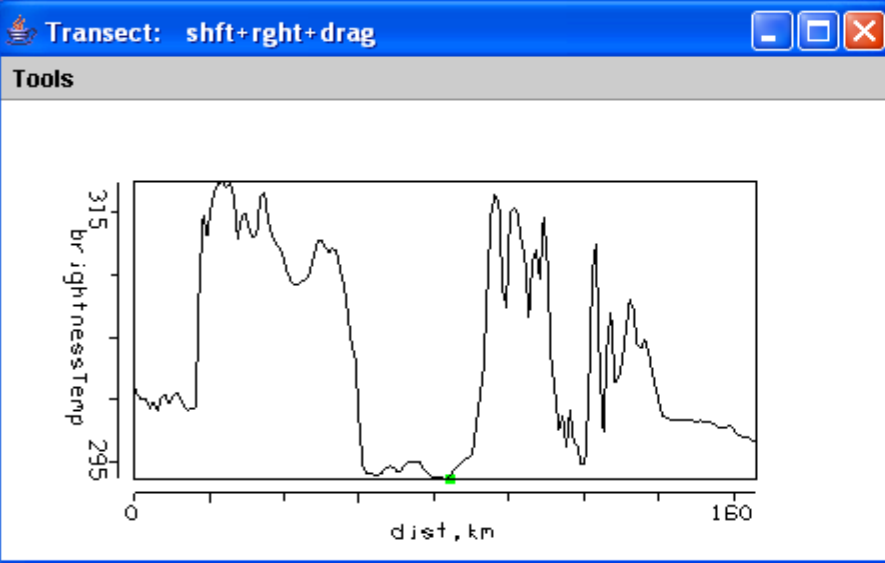
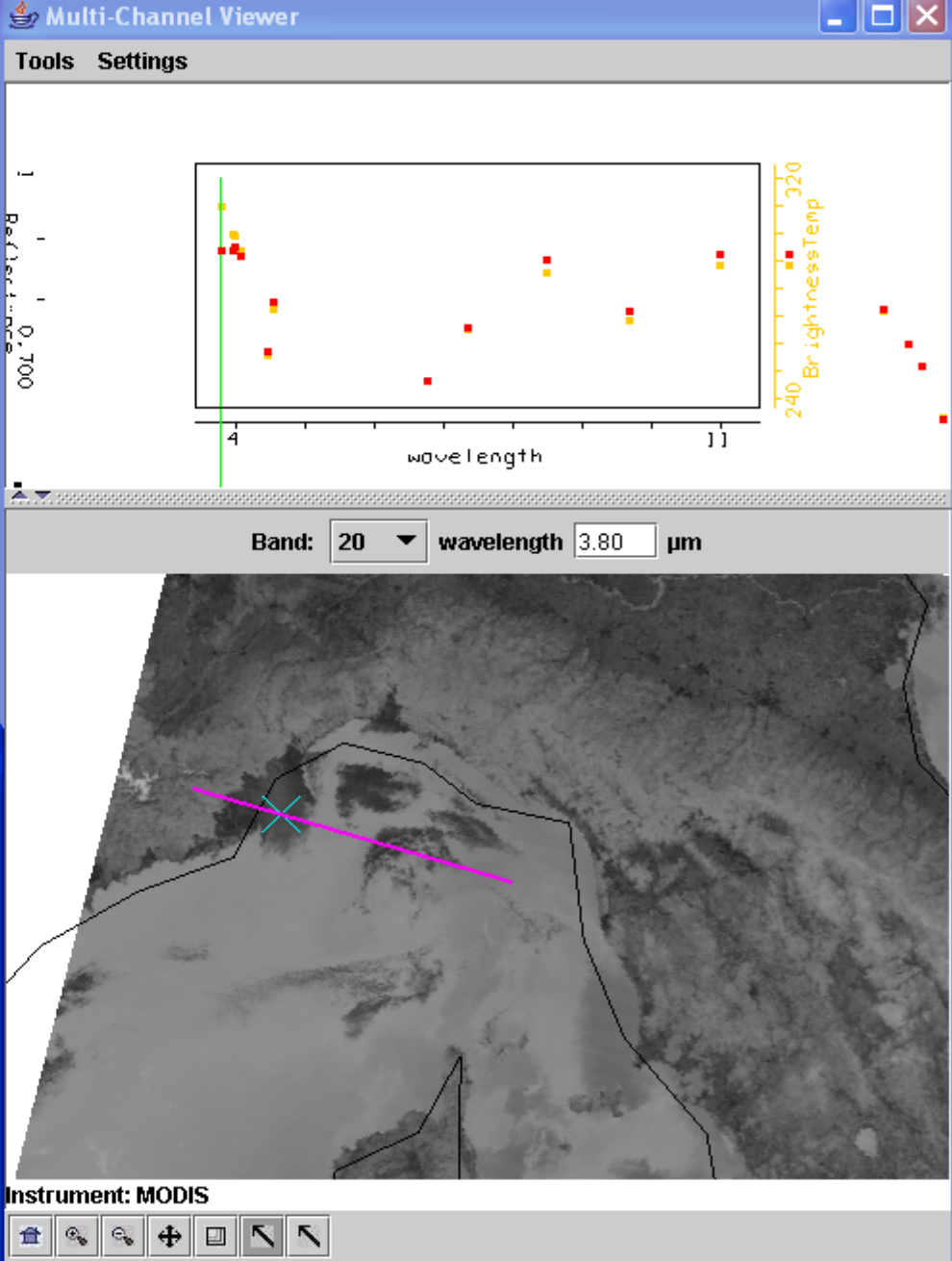
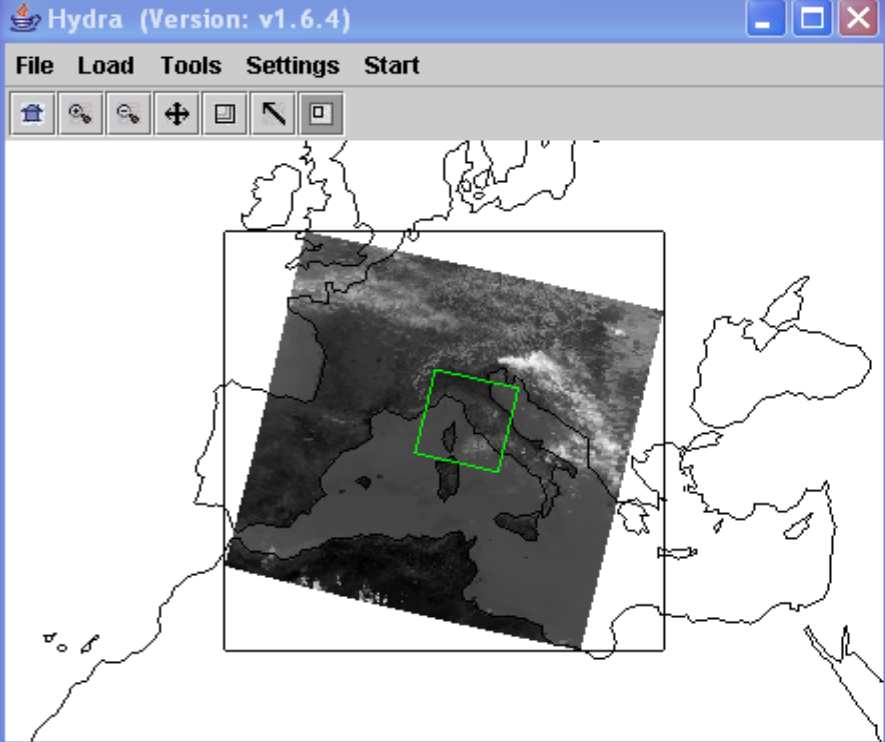




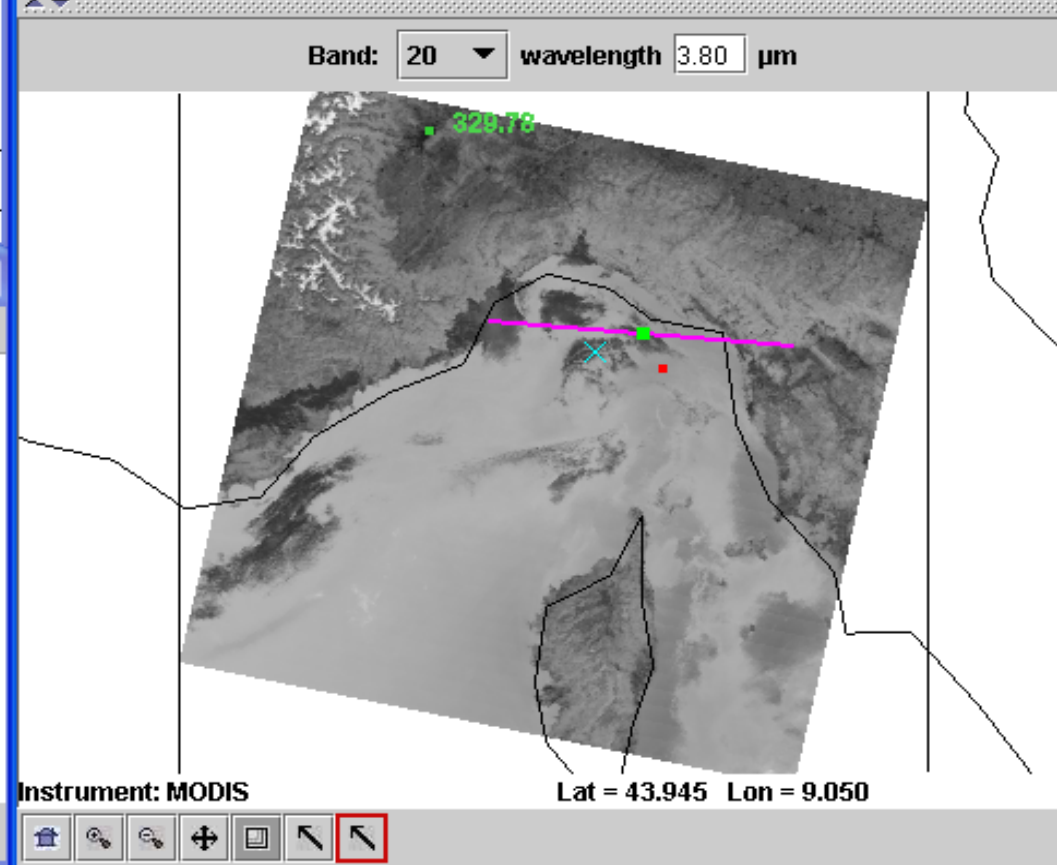
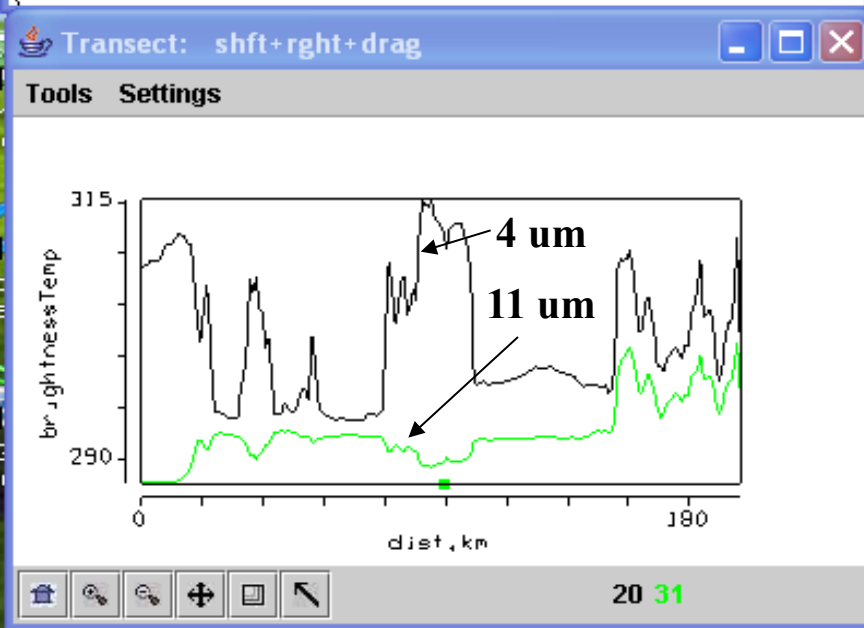
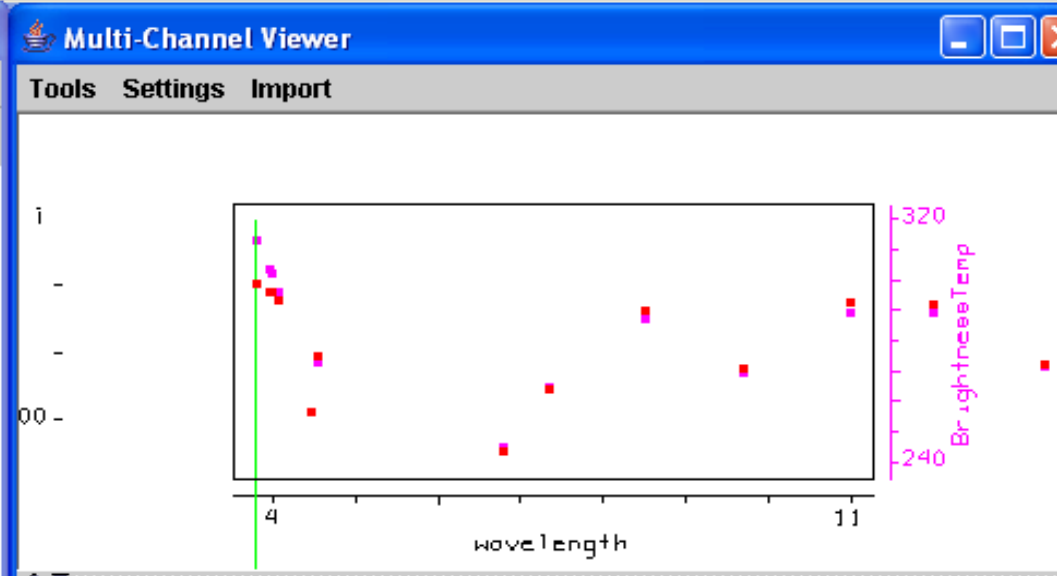
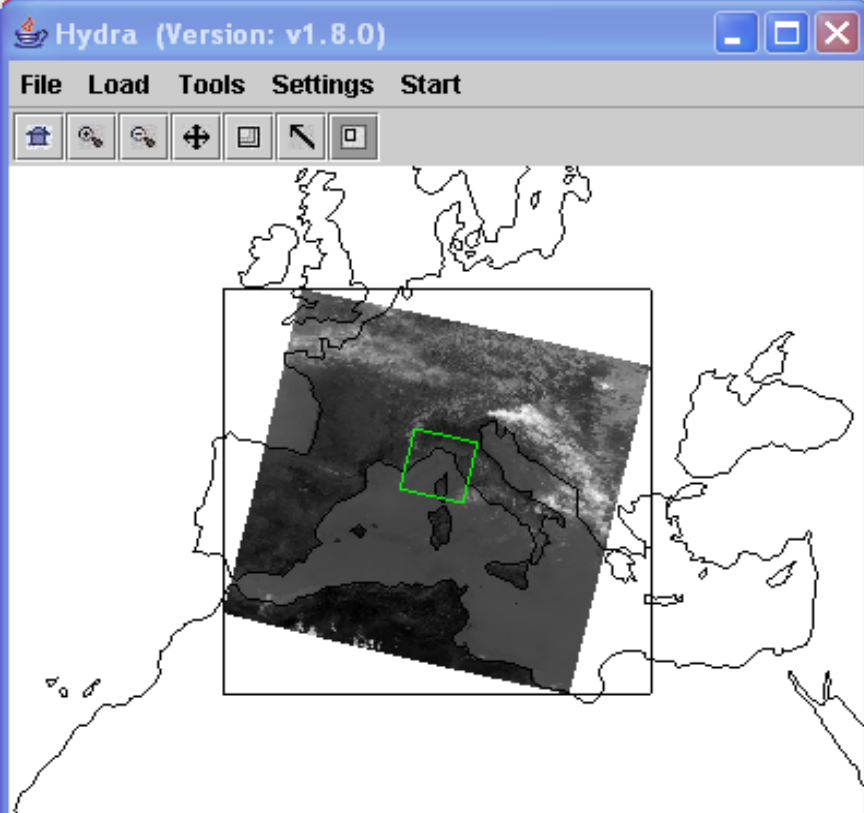
High clouds, cooler than surface, create lower 11 μm BTs

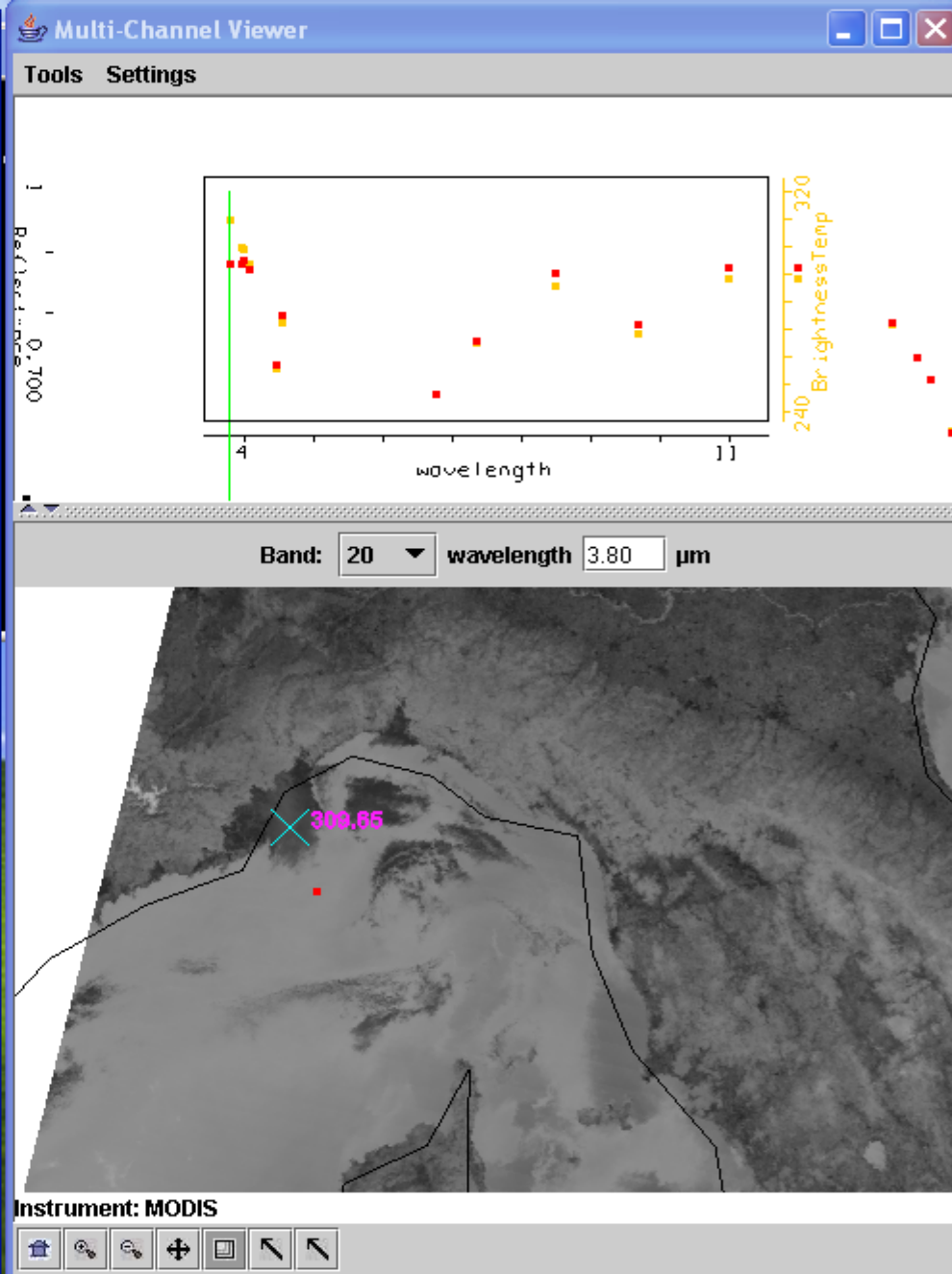
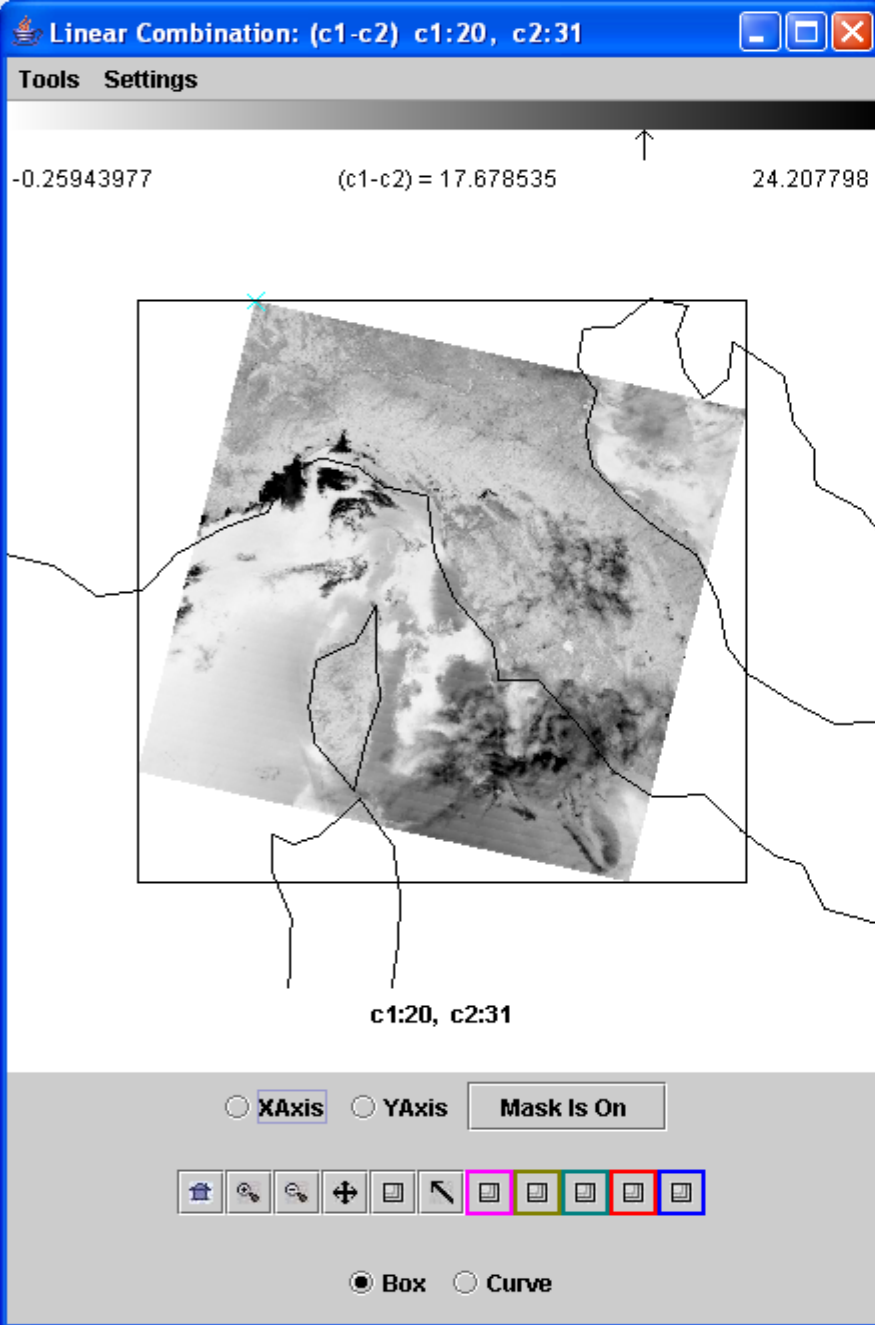


Low clouds, cooler than surface, create lower 11 μm BTs

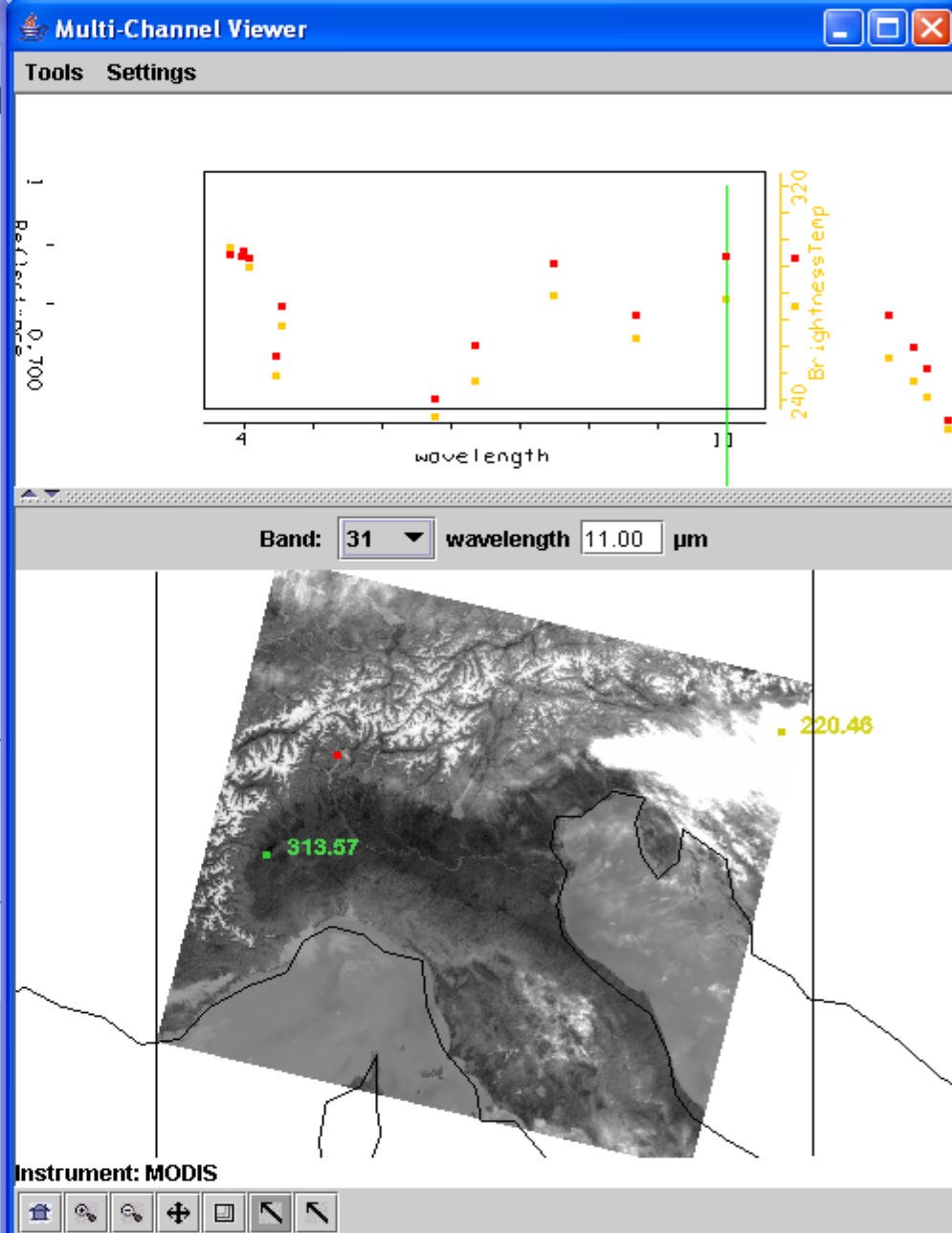
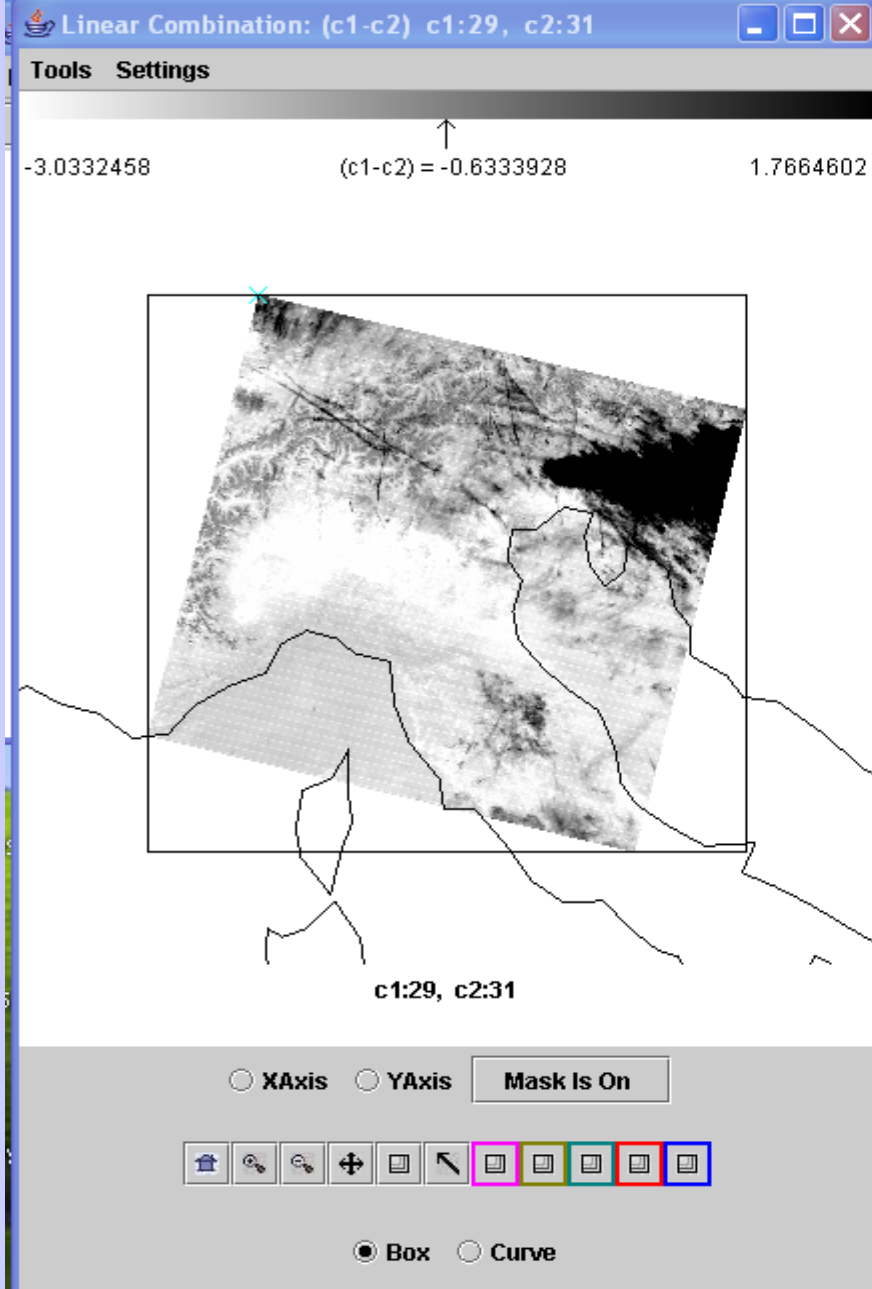


Low clouds reflecting create larger 4 μm brightness temperatures





Detecting low clouds in 4-11 μm brightness temperature differences



Detecting ice clouds in 8.6-11 μm brightness temperature differences

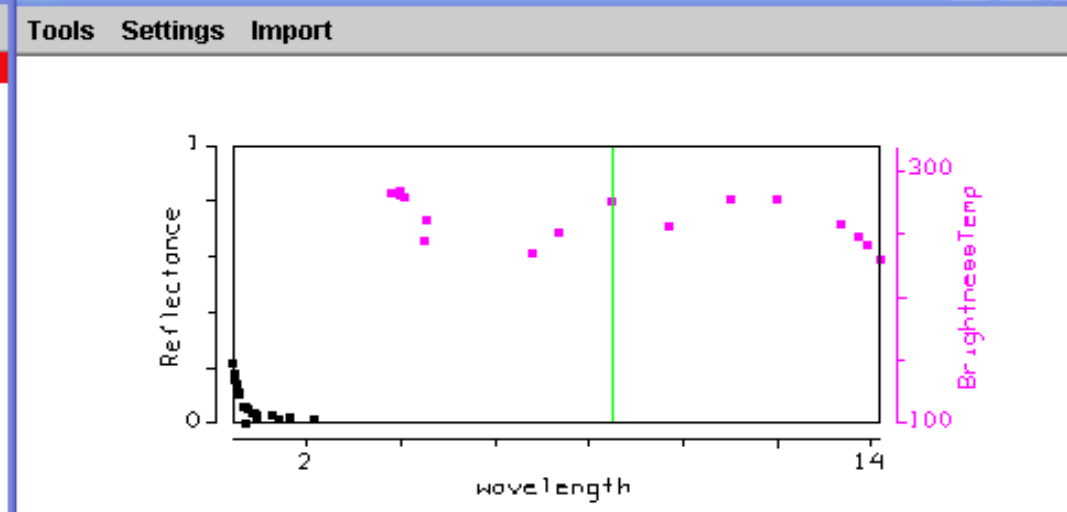
Tools Settings

-3.6338787 (c1-c2) = 0.5717621 4.330529

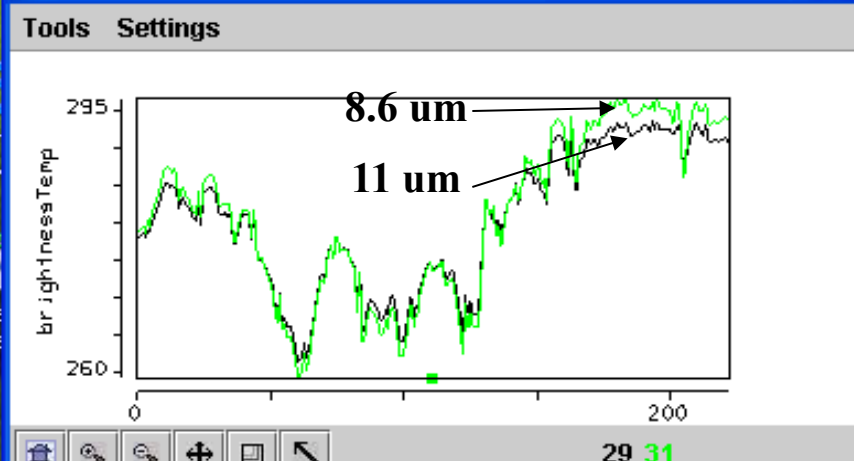
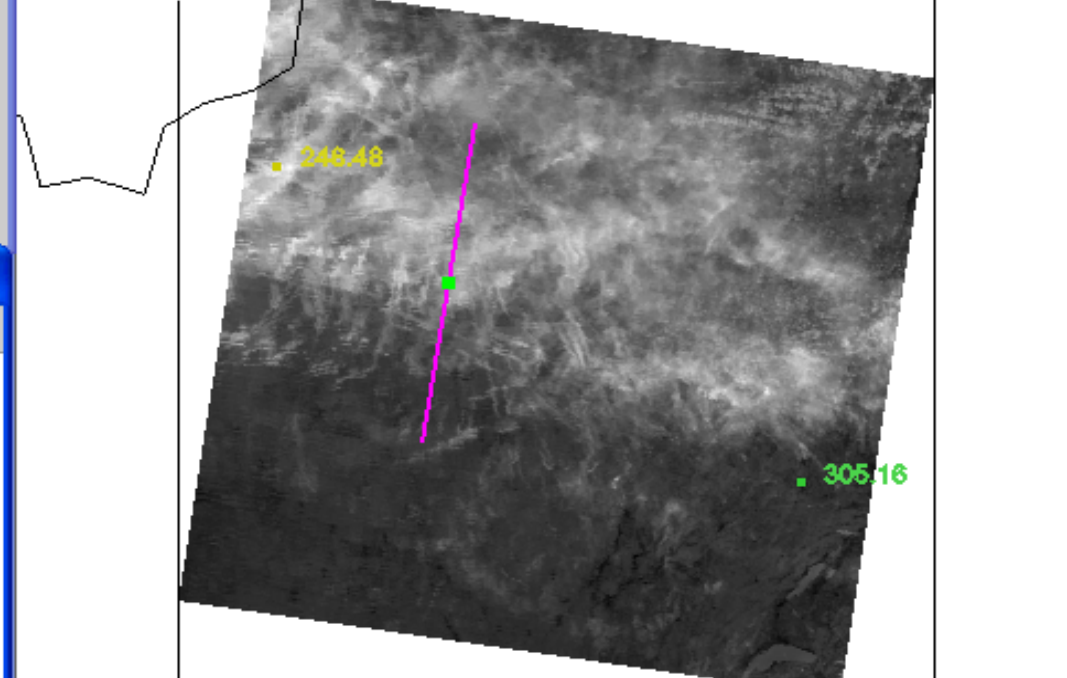
c1:29, c2:31

XAxis YAxis

Box Curve

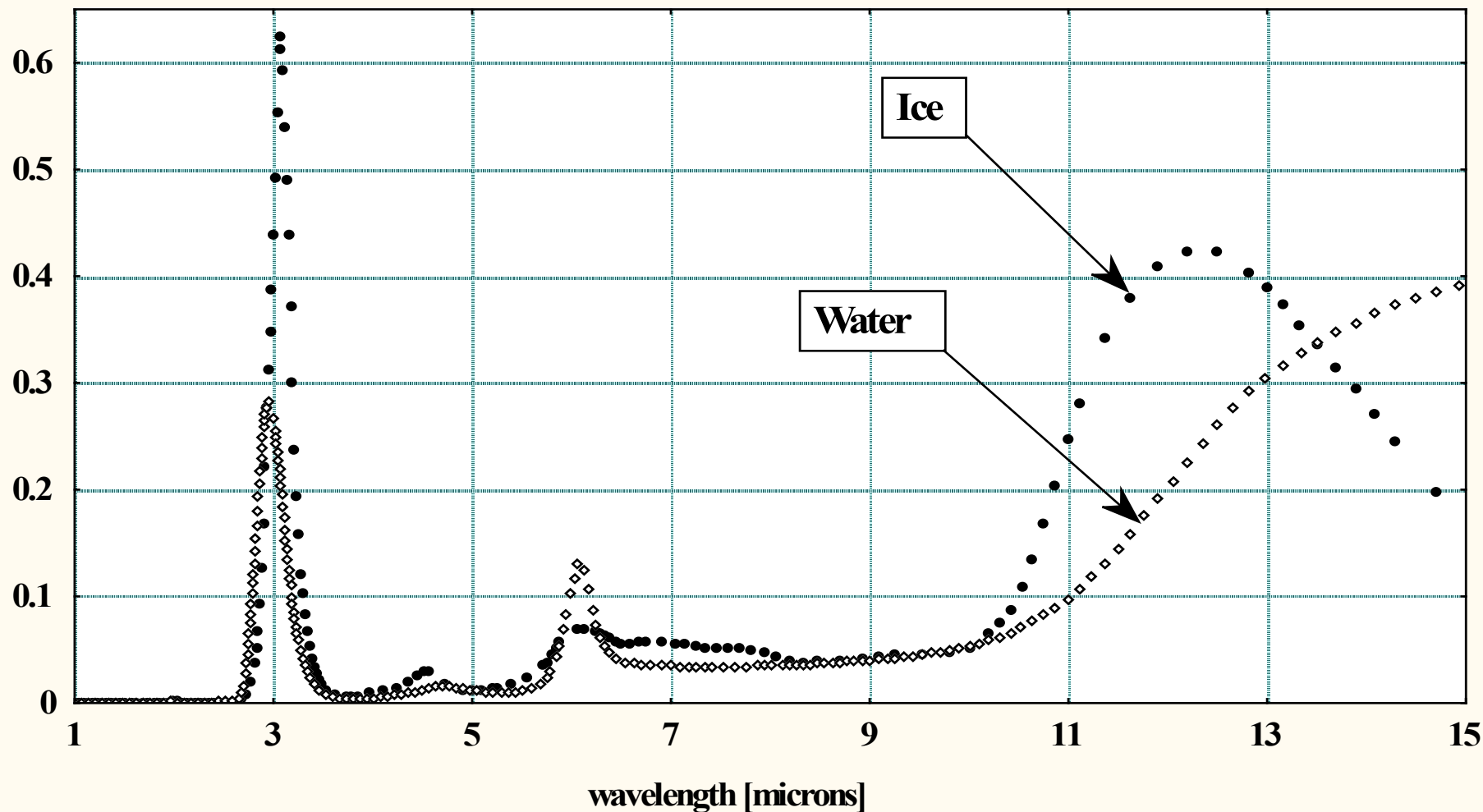


Band: 29 wavelength 8.50 μ m

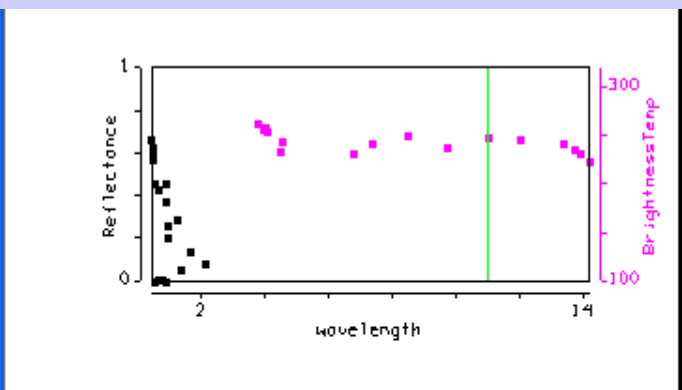
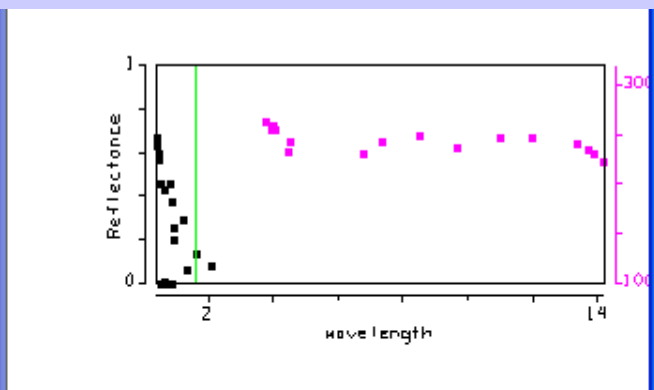
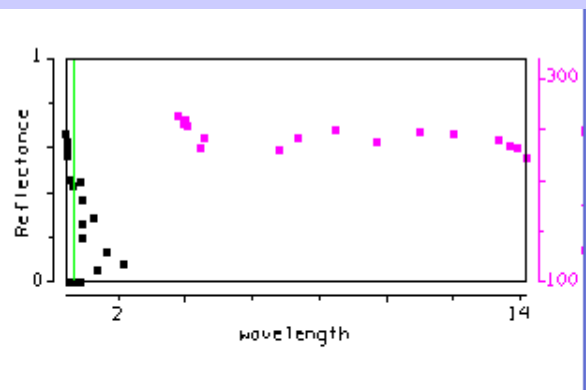


Optical properties of cloud particles: imaginary part of refractive index

Imaginary part of refractive index



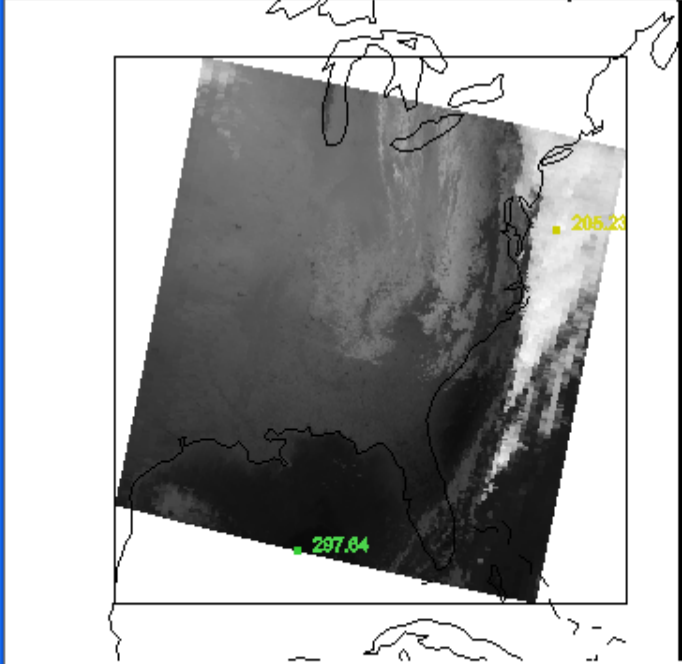
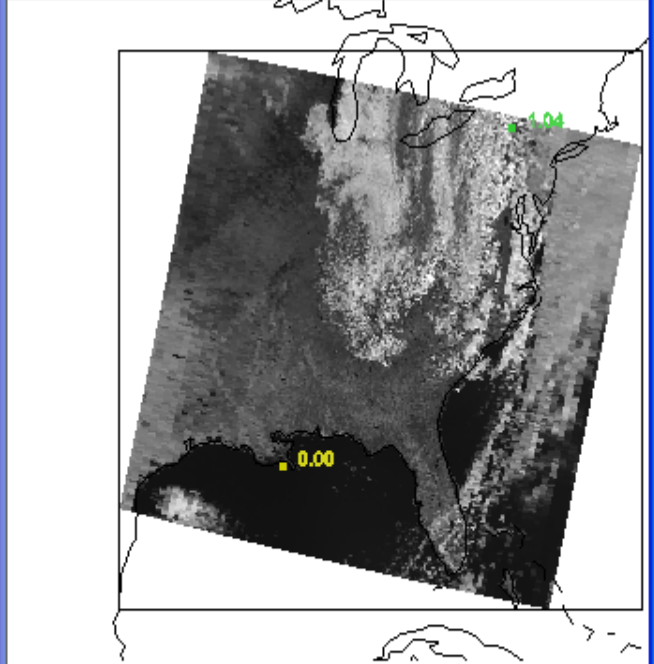
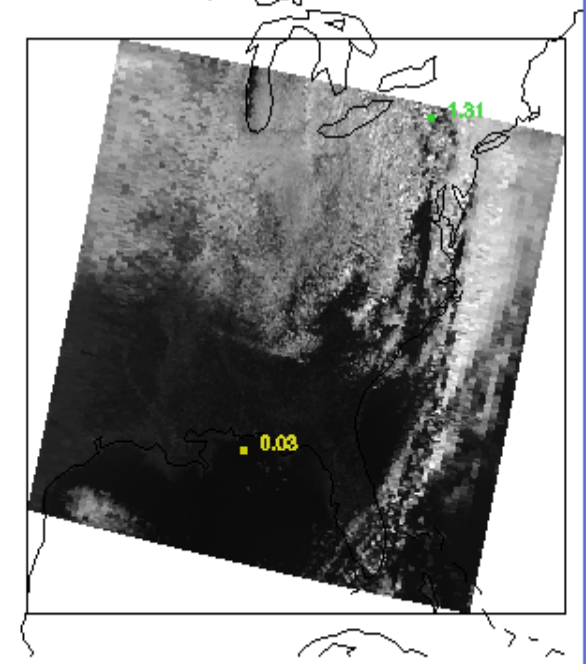
BT[8.6] – BT[11] will be positive for transmissive ice clouds



Band: 1 wavelength 0.65 μm

Band: 6 wavelength 1.64 μm

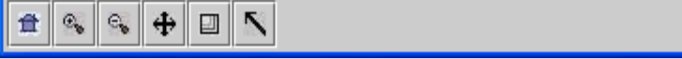
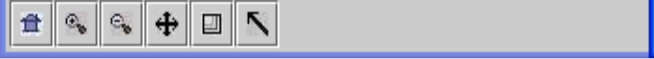
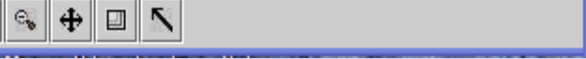
Band: 31 wavelength 11.00 μm



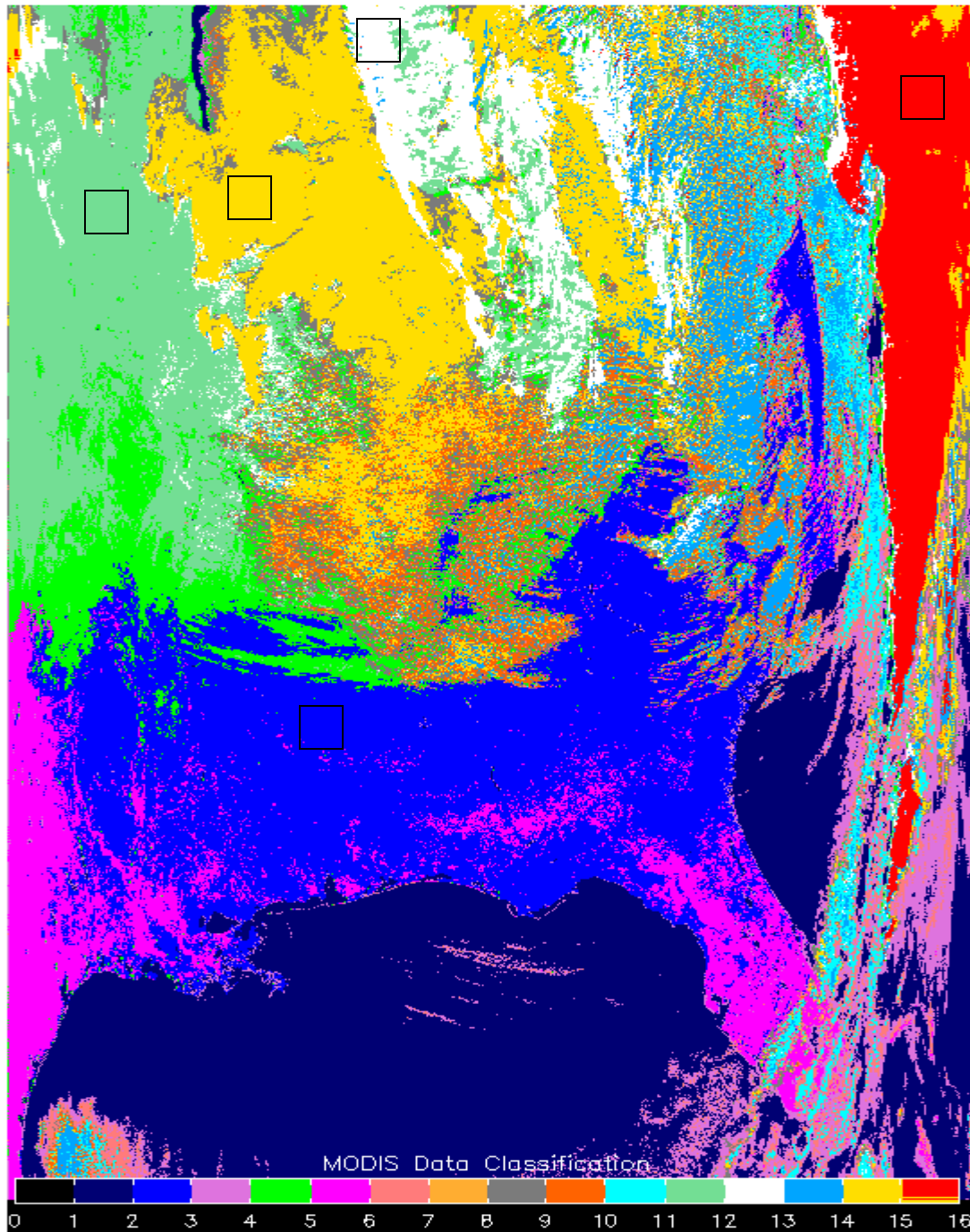
Instrument: MODIS Lat = 44.602 Lon = -96.026

Instrument: MODIS Lat = 44.602 Lon = -96.026

Instrument: MODIS Lat = 44.602 Lon = -96.026



**MODIS
identifies
cloud
classes**



Hi cld

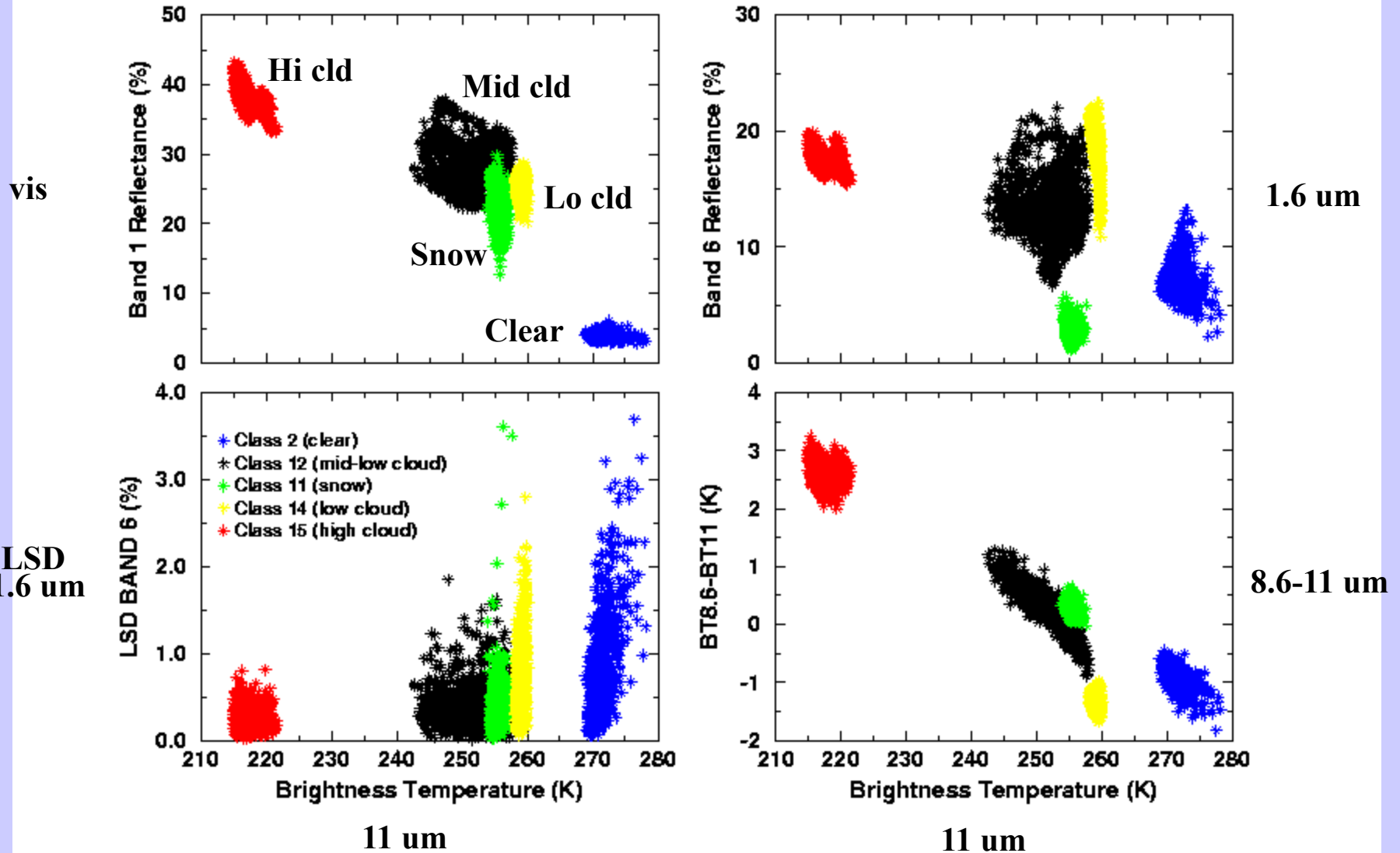
Mid cld

Lo cld

Snow

clr

Clouds separate into classes when multispectral radiance information is viewed



Cloud Mask Tests

- BT11 clouds over ocean
- BT13.9 high clouds
- BT6.7 high clouds
- BT3.9-BT11 broken or scattered clouds
- BT11-BT12 high clouds in tropics
- BT8.6-BT11 ice clouds
- BT6.7-BT11 or BT13.9-BT11 clouds in polar regions
- BT11+aPW(BT11-BT12) clouds over ocean
- r0.65 clouds over land
- r0.85 clouds over ocean
- r1.38 thin cirrus
- r1.6 clouds over snow, ice cloud
- r0.85/r0.65 or NDVI clouds over vegetation
- σ (BT11) clouds over ocean

Cloud Properties

True Color Image

Cloud Mask

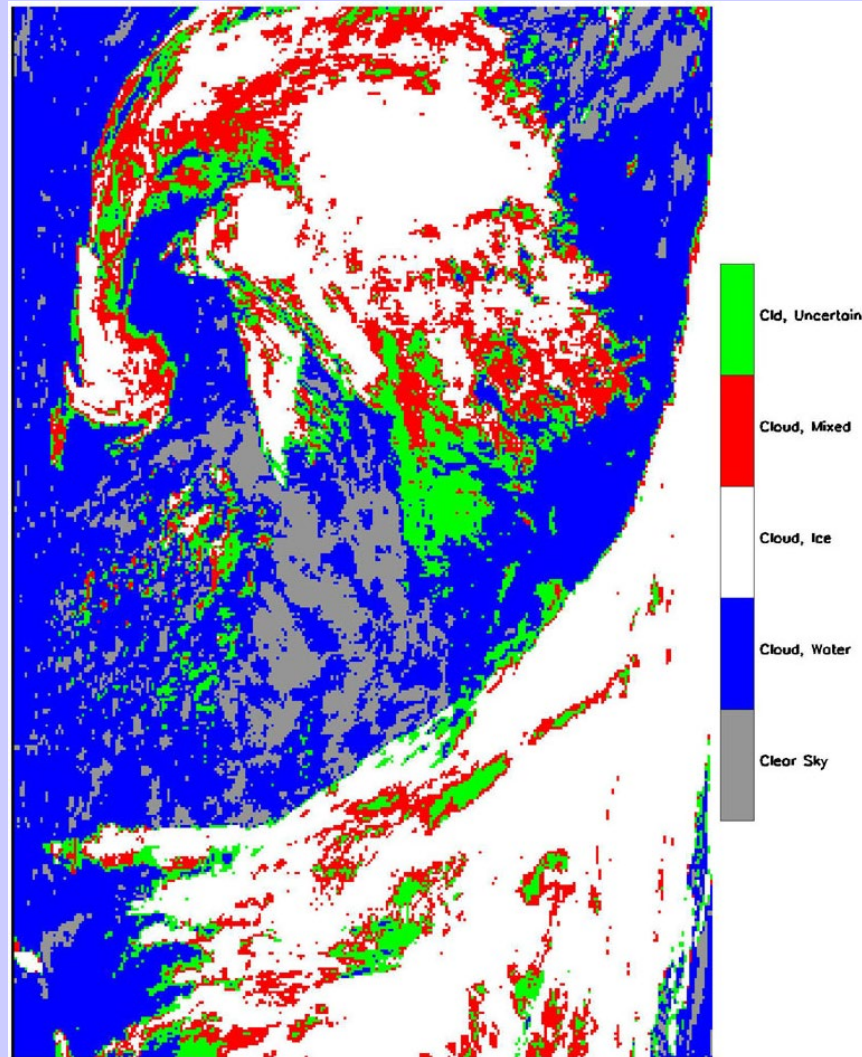
Land Classification

Cloud Opt Thickness

Cloud Eff Radius

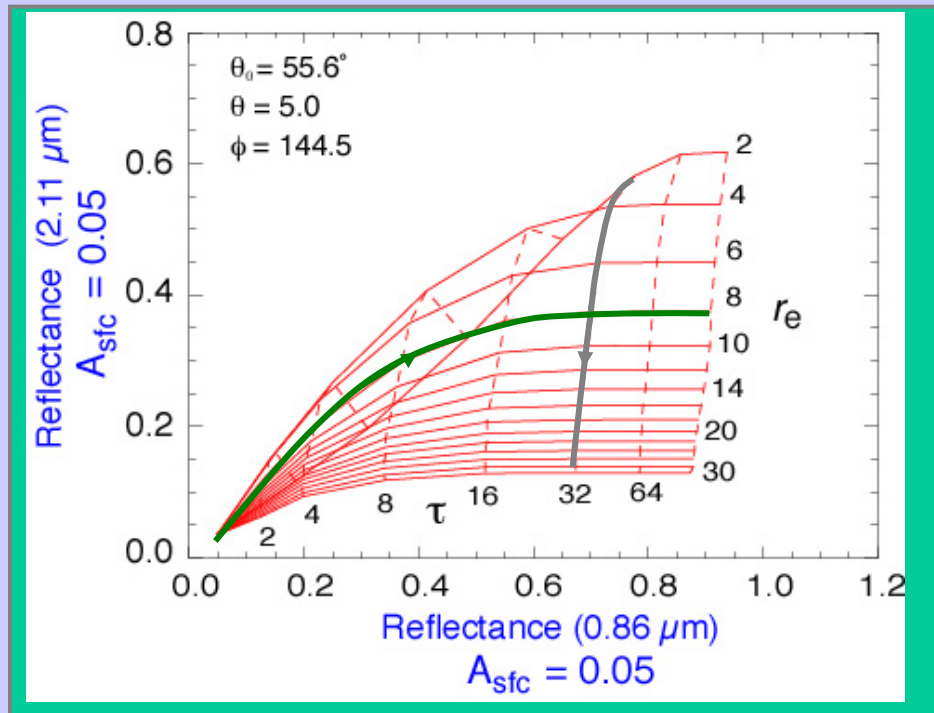
Cloud Top Temp

Bispectral Phase



October 1, 2001

Cloud optical, microphysical properties retrieval space example



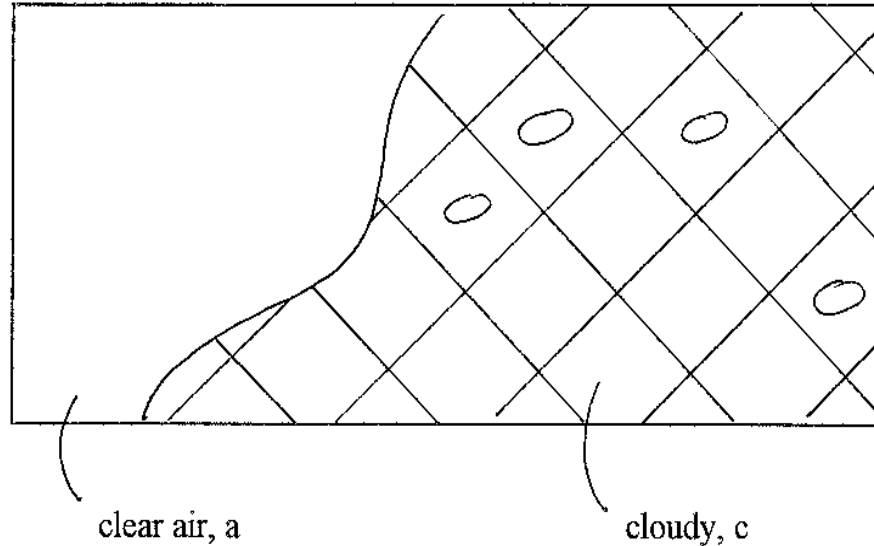
2.1 μm absorption increases with particle size,
little effect at 0.86 μm

2.1 μm reflectance reaches limiting values
with optical thickness

Liquid water cloud
ocean surface

Cloud Parameter Determinations from Satellite Measured Radiances
for a given field of view (FOV) partly clear and partly cloudy

**Radiance from a
partly cloudy FOV**



$$R = [1 - N] R_a + N R_c$$

but if b indicates opaque "black" cloud

$$R_c = [1 - \epsilon] R_a + \epsilon R_b(p_c)$$

so together

$$R = [1 - N\epsilon] R_a + N\epsilon R_b(p_c)$$

**Two unknowns, ϵ and P_c ,
require two measurements**

RTE in Cloudy Conditions

$$I_{\lambda} = \eta I_{\lambda}^{\text{cd}} + (1 - \eta) I_{\lambda}^{\text{clr}} \quad \text{where cd = cloud, clr = clear, } \eta = \text{cloud fraction}$$

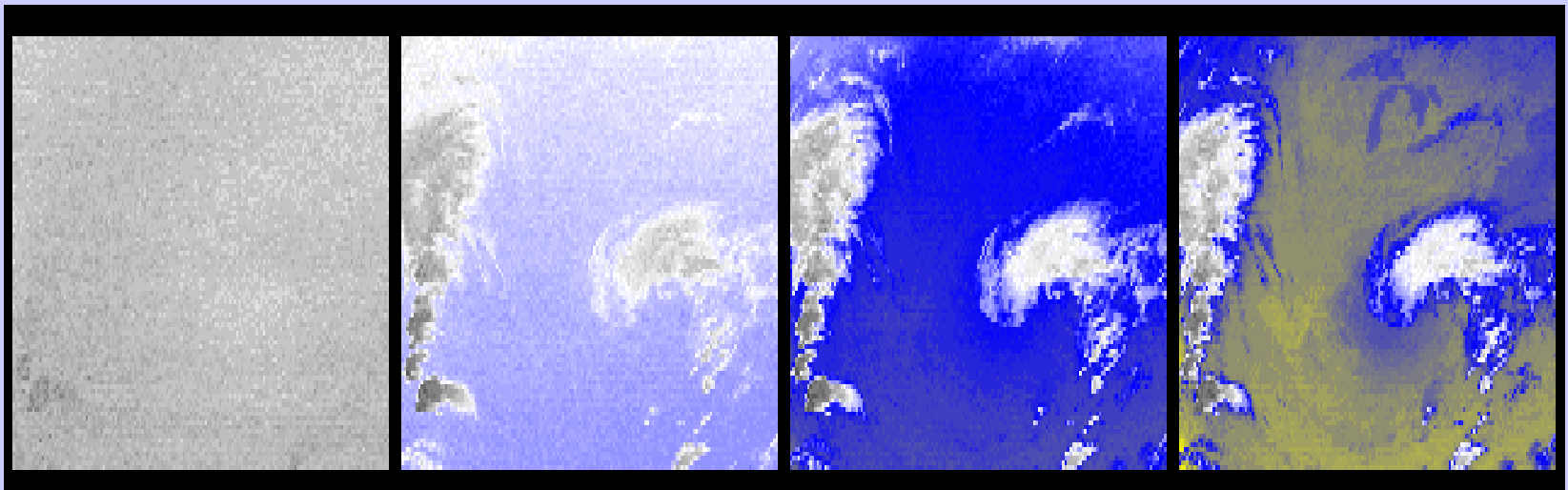
$$I_{\lambda}^{\text{clr}} = B_{\lambda}(T_s) \tau_{\lambda}(p_s) + \int_{p_s}^0 B_{\lambda}(T(p)) d\tau_{\lambda} .$$

$$I_{\lambda}^{\text{cd}} = (1 - \varepsilon_{\lambda}) B_{\lambda}(T_s) \tau_{\lambda}(p_s) + (1 - \varepsilon_{\lambda}) \int_{p_s}^{p_c} B_{\lambda}(T(p)) d\tau_{\lambda} \\ + \varepsilon_{\lambda} B_{\lambda}(T(p_c)) \tau_{\lambda}(p_c) + \int_{p_c}^0 B_{\lambda}(T(p)) d\tau_{\lambda}$$

ε_{λ} is emittance of cloud. First two terms are from below cloud, third term is cloud contribution, and fourth term is from above cloud. After rearranging

$$I_{\lambda} - I_{\lambda}^{\text{clr}} = \eta \varepsilon_{\lambda} \int_{p_s}^{p_c} \tau(p) \frac{dB_{\lambda}}{dp} dp .$$

CO2 channels see to different levels in the atmosphere



14.2 um

13.9 um

13.6 um

13.3 um

Cloud Properties from CO2 Slicing

RTE for cloudy conditions indicates dependence of cloud forcing (observed minus clear sky radiance) on cloud amount ($\eta\epsilon_\lambda$) and cloud top pressure (p_c)

$$(I_\lambda - I_\lambda^{\text{clr}}) = \eta\epsilon_\lambda \int_{p_s}^{p_c} \tau_\lambda dB_\lambda .$$

Higher colder cloud or greater cloud amount produces greater cloud forcing; dense low cloud can be confused for high thin cloud. Two unknowns require two equations.

p_c can be inferred from radiance measurements in two spectral bands where cloud emissivity is the same. $\eta\epsilon_\lambda$ is derived from the infrared window, once p_c is known.

Different ratios reveal cloud properties at different levels

hi - 14.2/13.9

mid - 13.9/13.6

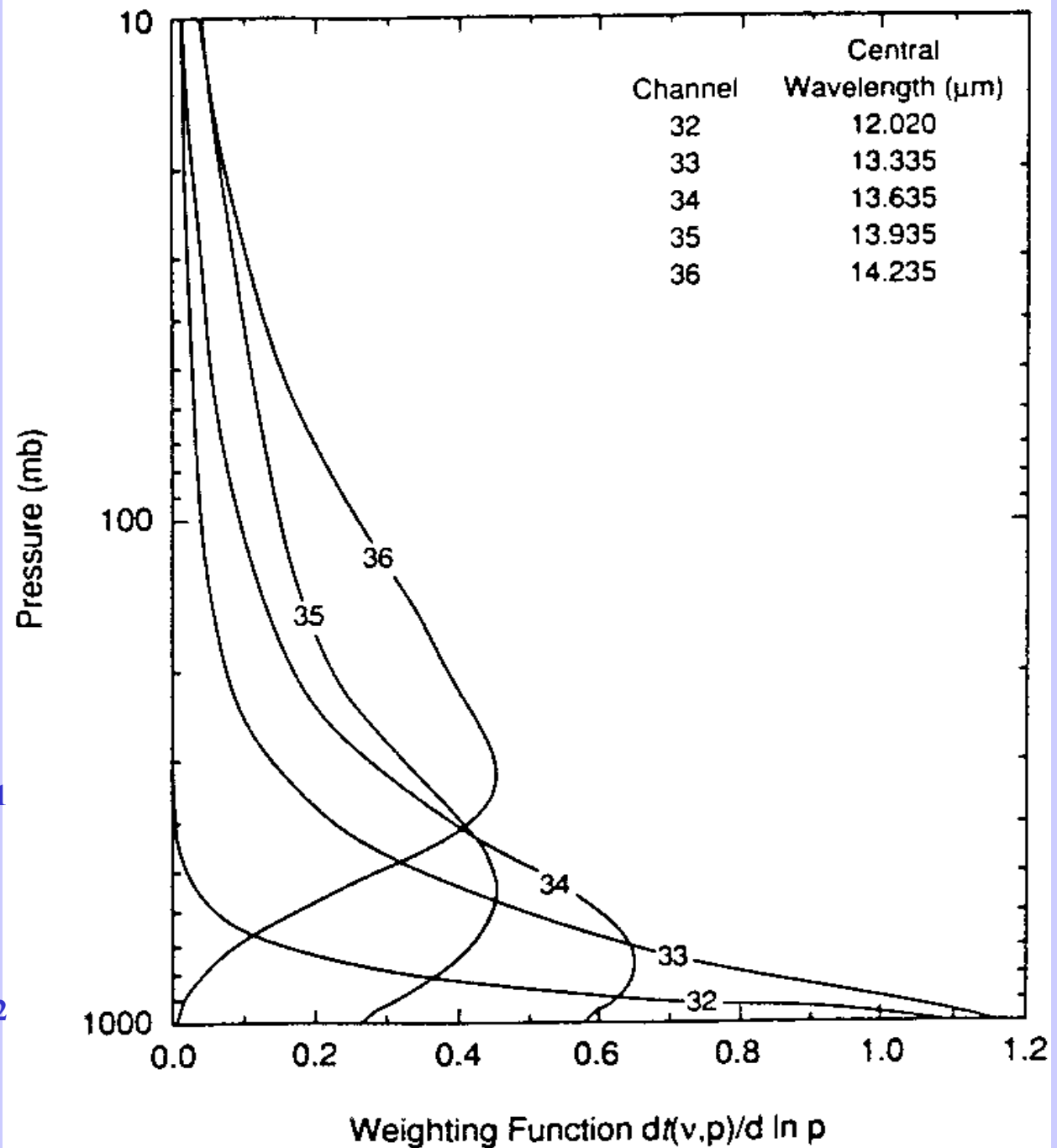
low - 13.6/13.3

Meas

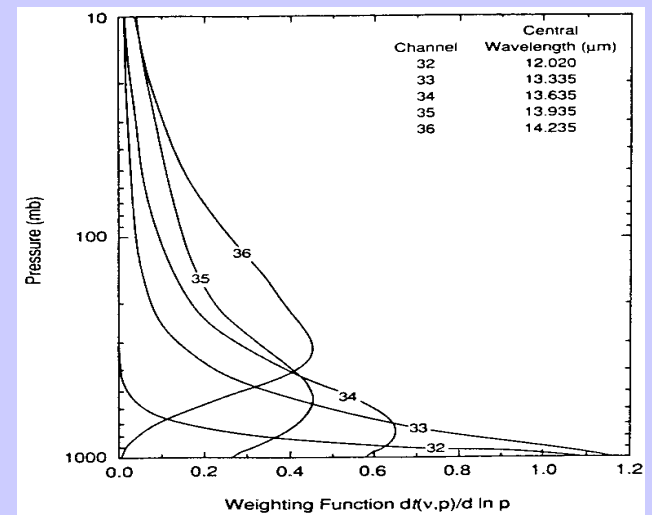
Calc

$$\frac{(I_{\lambda_1} - I_{\lambda_1}^{\text{clr}})}{p_s} = \frac{\eta \epsilon_{\lambda_1} \int_{p_c}^{p_s} \tau_{\lambda_1} dB_{\lambda_1}}{p_s}$$

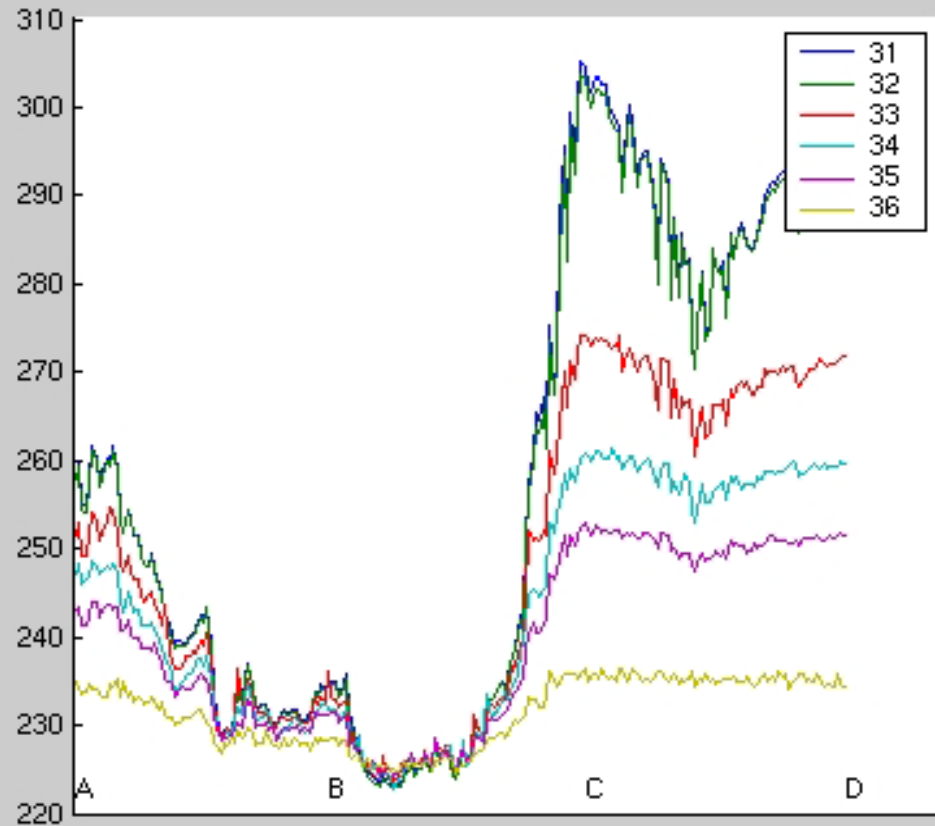
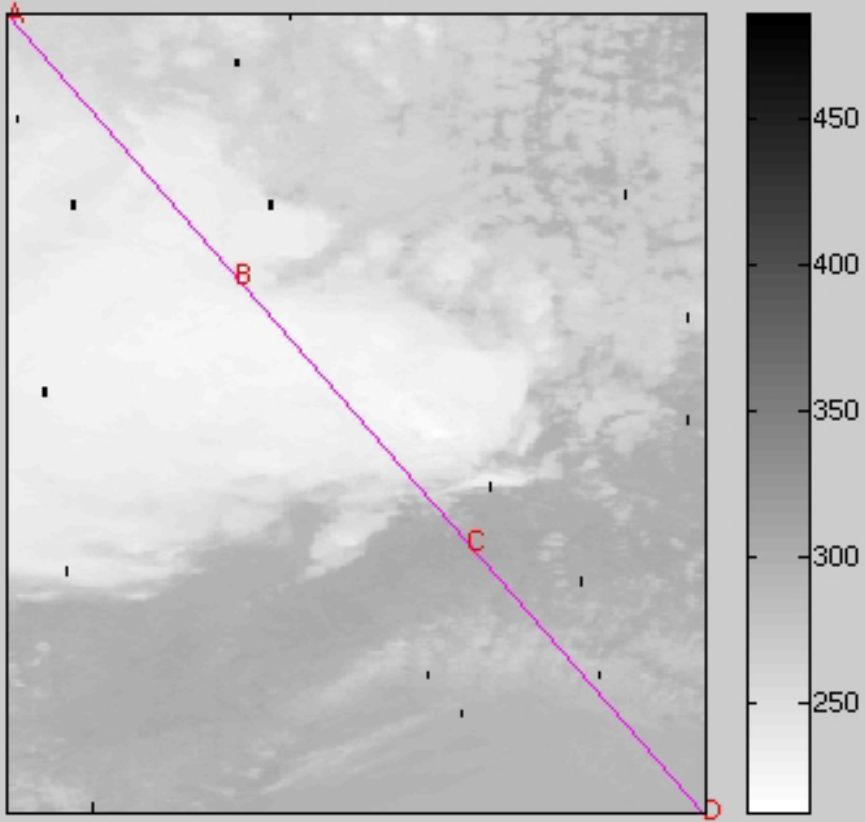
$$\frac{(I_{\lambda_2} - I_{\lambda_2}^{\text{clr}})}{p_s} = \frac{\eta \epsilon_{\lambda_2} \int_{p_c}^{p_s} \tau_{\lambda_2} dB_{\lambda_2}}{p_s}$$

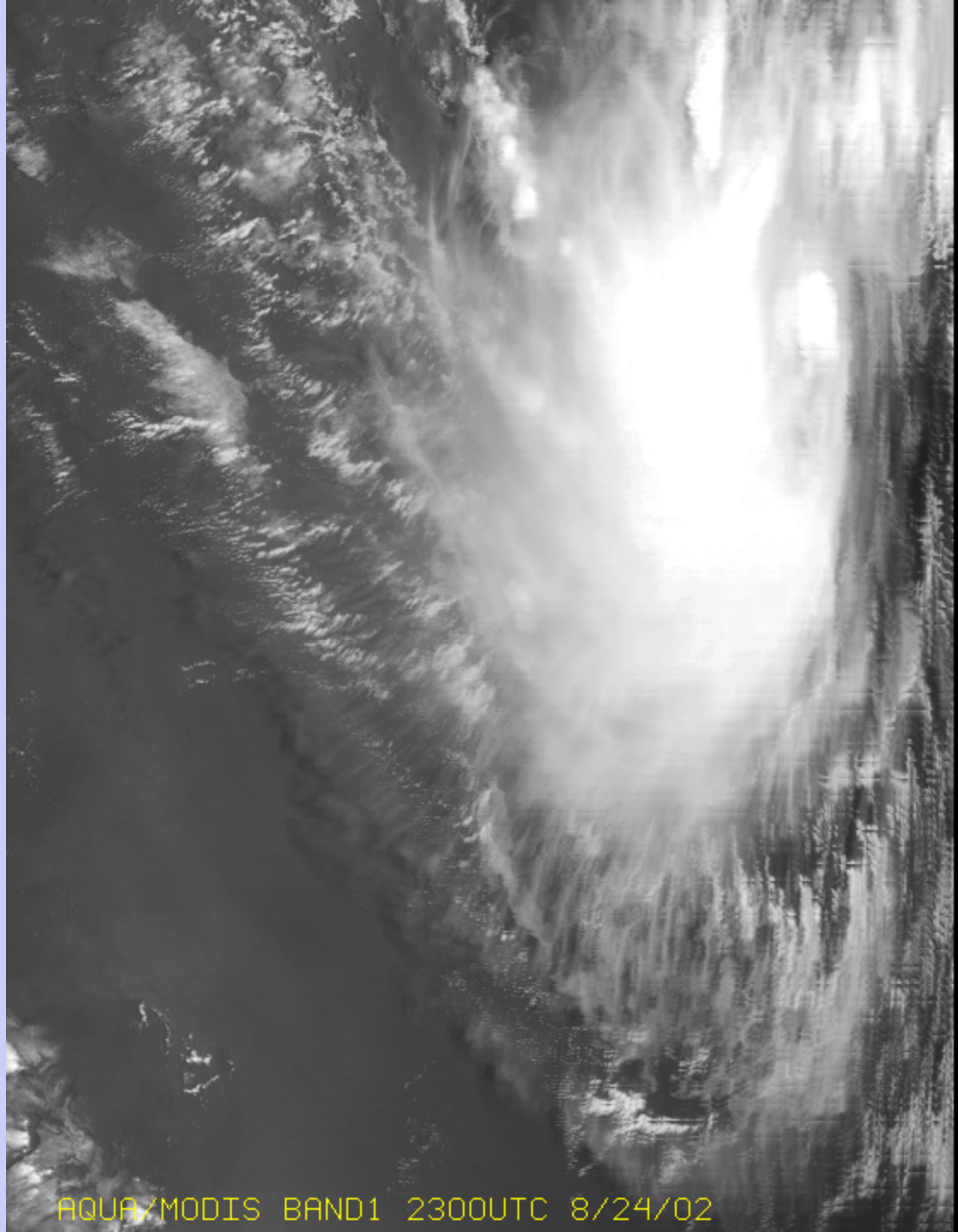


BTs in and out of clouds for MODIS CO₂ bands demonstrate weighting functions and cloud top algorithm

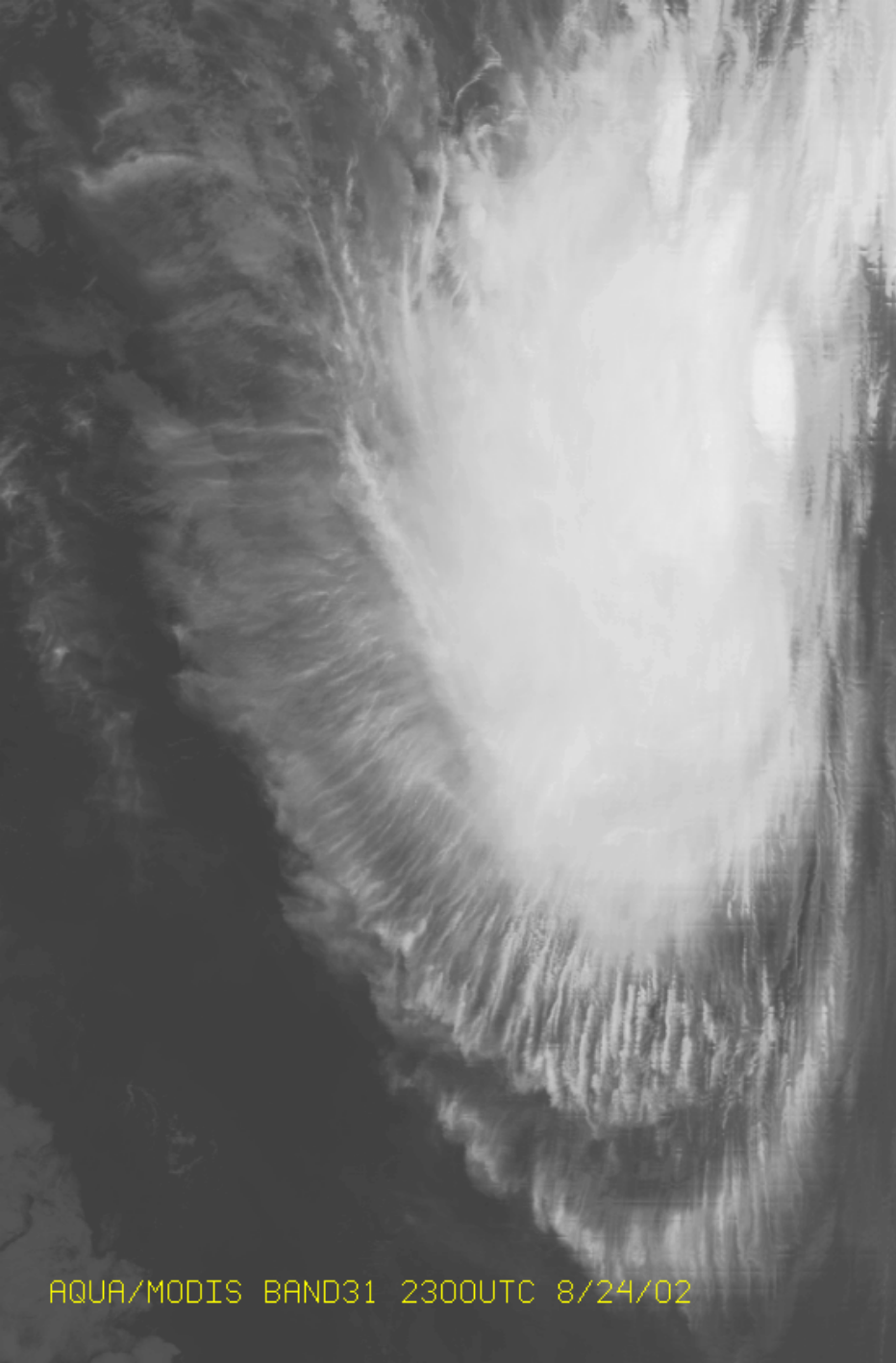


Channel 31

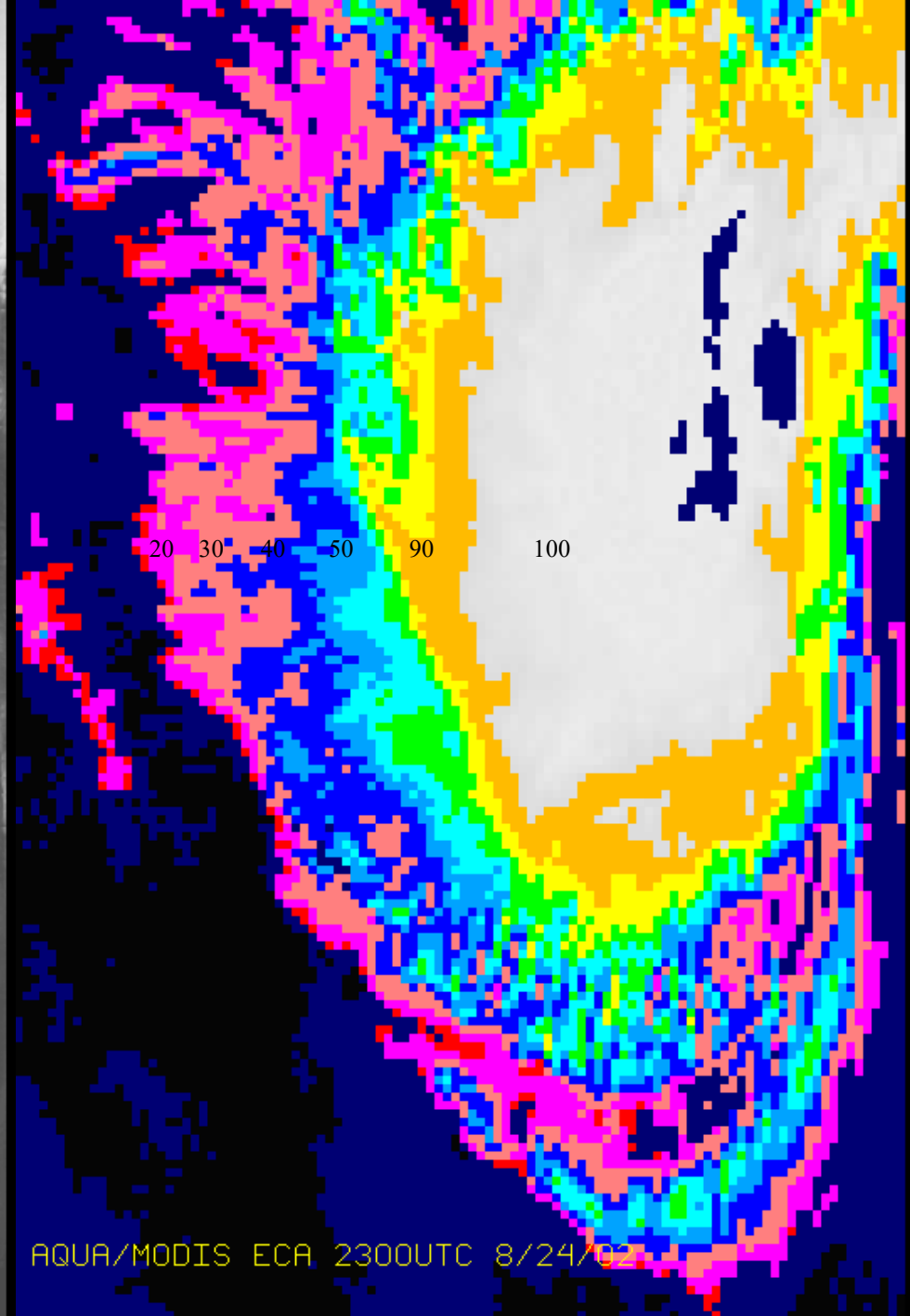




AQUA/MODIS BAND1 2300UTC 8/24/02

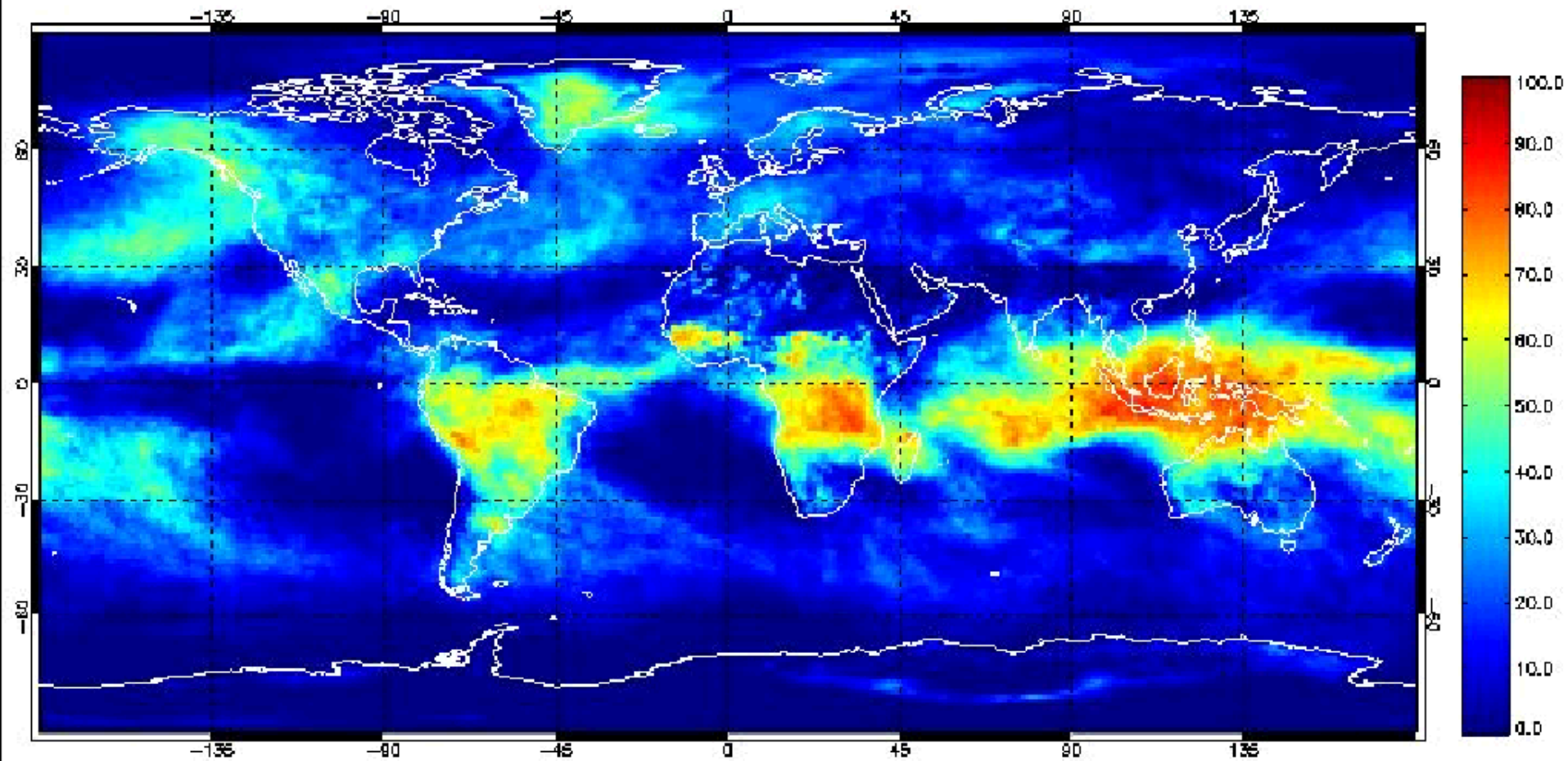


AQUA/MODIS BAND31 2300UTC 8/24/02



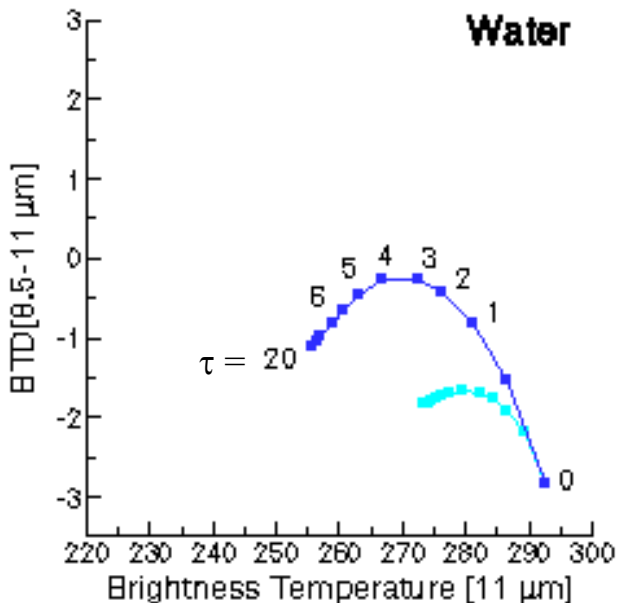
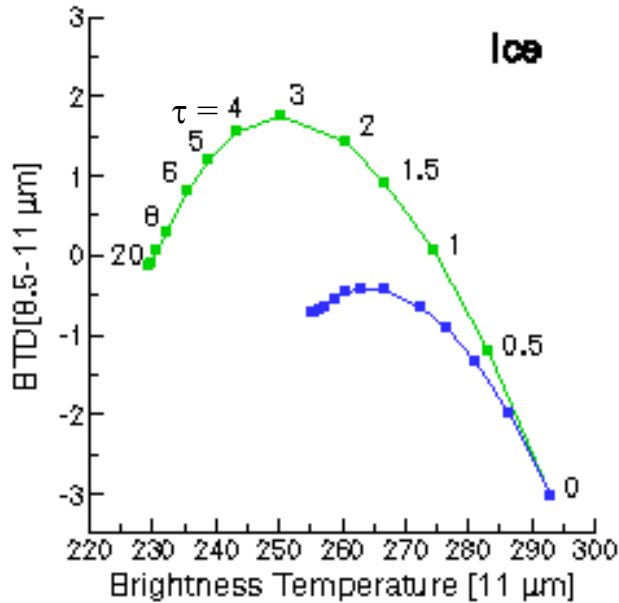
AQUA/MODIS ECA 2300UTC 8/24/02

January 2001: MODIS High Clouds (0-400 mb)



Simulations of Ice and Water Phase Clouds

8.5 - 11 μm BT Differences



High Ice clouds

- BT D[8.5-11] > 0 over a large range of optical thicknesses τ
- $T_{\text{cld}} = 228$ K

Midlevel clouds

- BT D[8.5-11] values are similar (i.e., negative) for both water and ice clouds
- $T_{\text{cld}} = 253$ K

Low-level, warm clouds

- BT D[8.5-11] values always negative
- $T_{\text{cld}} = 273$ K

Ice: Cirrus model derived from FIRE-I in-situ data (Nasiri et al, 2002)

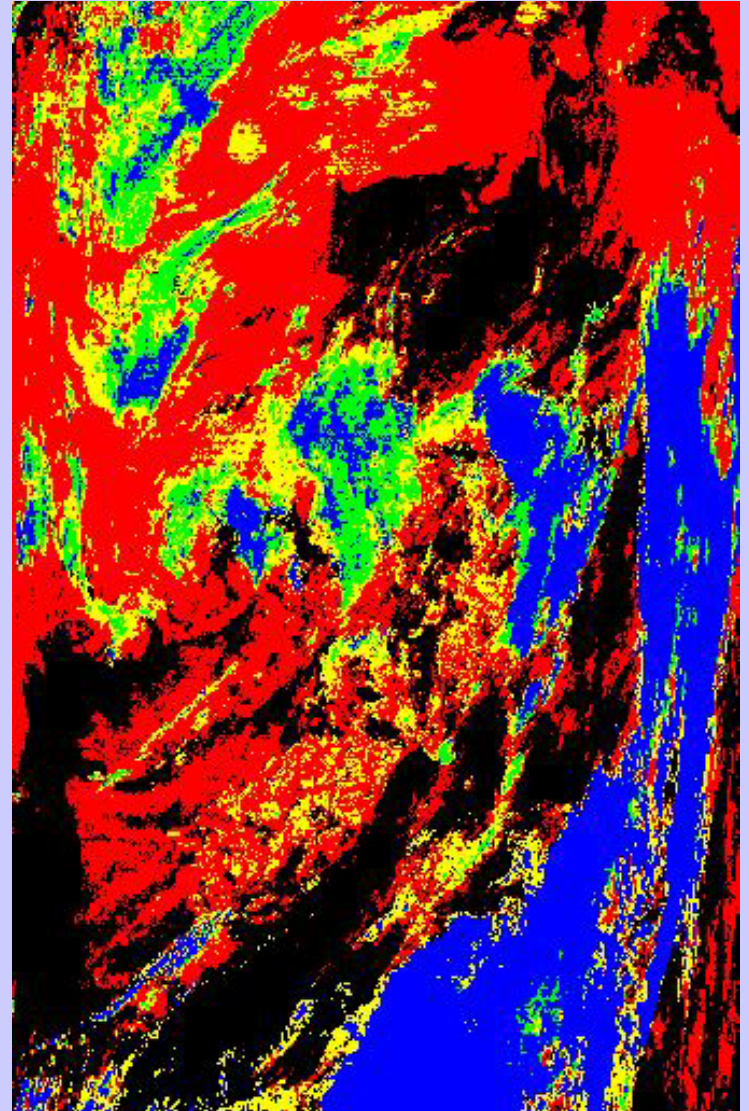
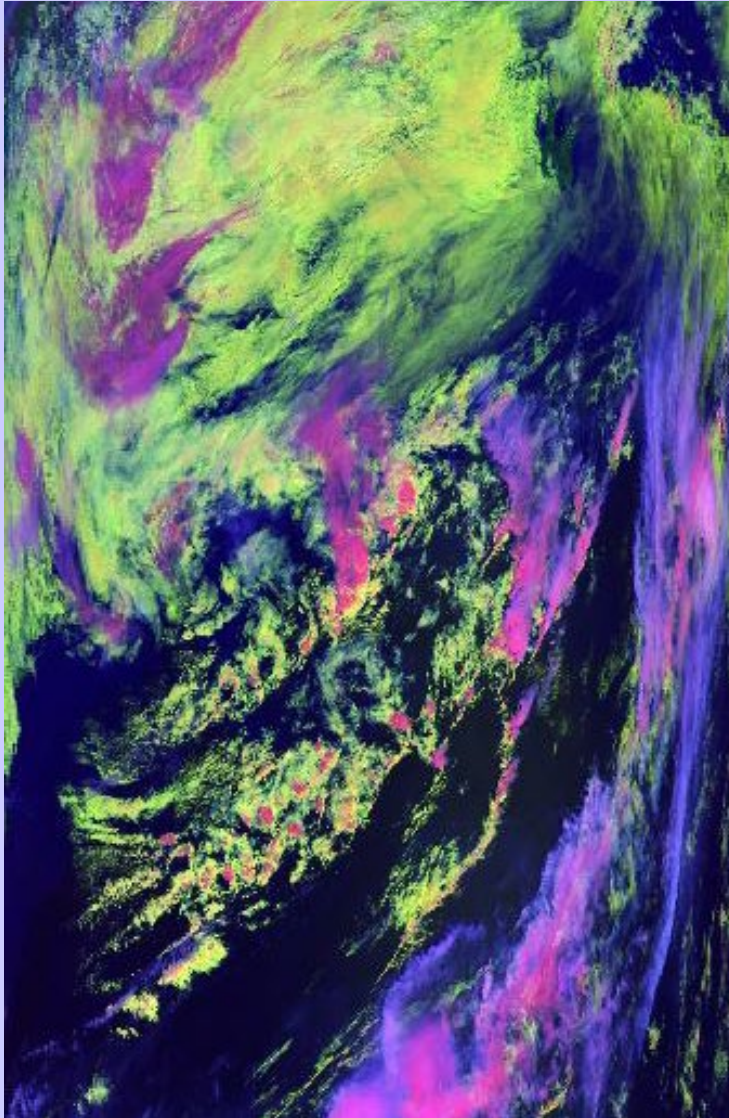
Water: $r_e = 10 \mu\text{m}$

Angles: $\theta_o = 45^\circ$, $\theta = 20^\circ$, and $\phi = 40^\circ$

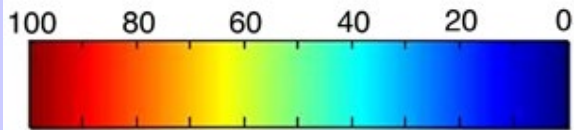
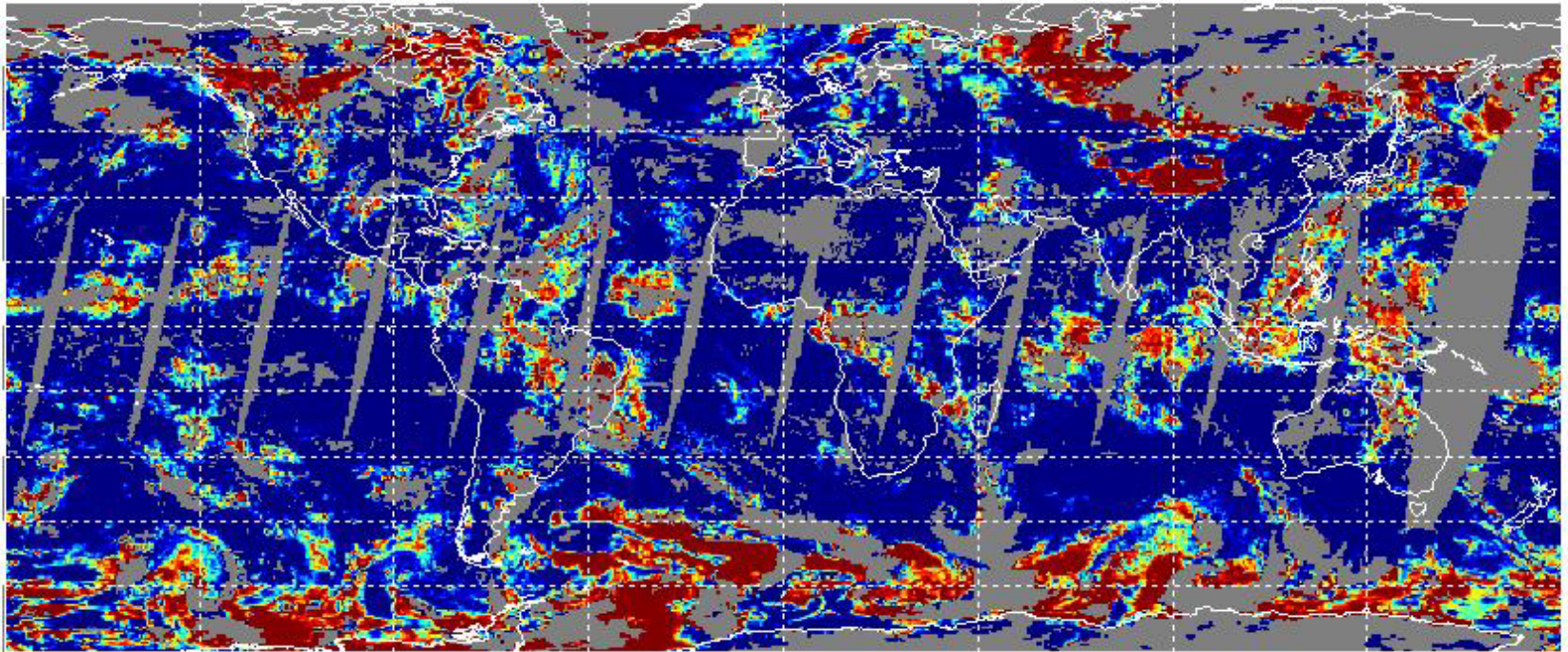
Profile: midlatitude summer

MODIS Direct Broadcast

May 14, 2003 at 1458 UTC (Terra)
1-km resolution

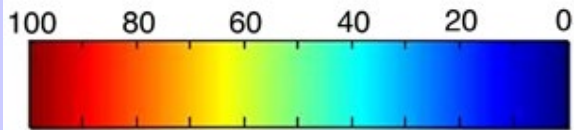
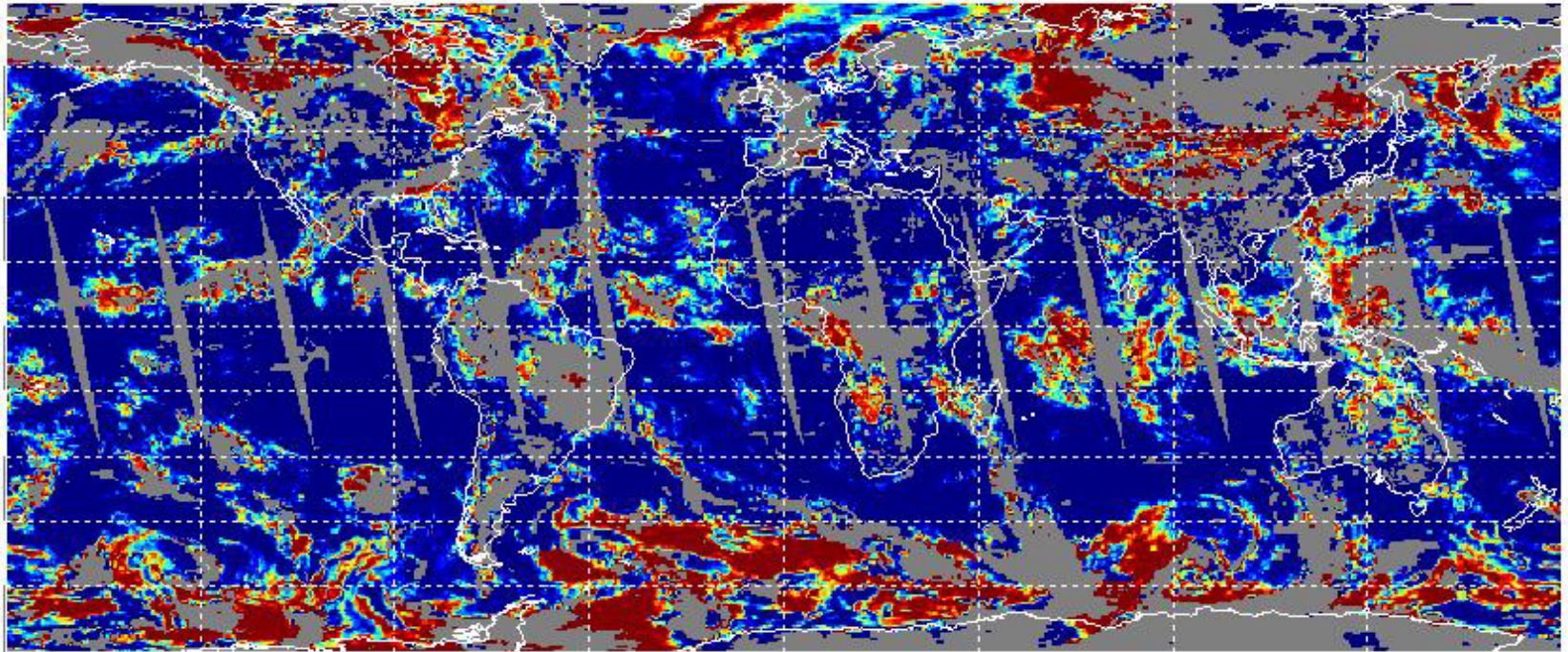


MODIS Frequency of Co-occurrence
Water Phase with $253 \text{ K} < T_{\text{cld}} < 268 \text{ K}$
05 Nov. 2000 - Daytime Only



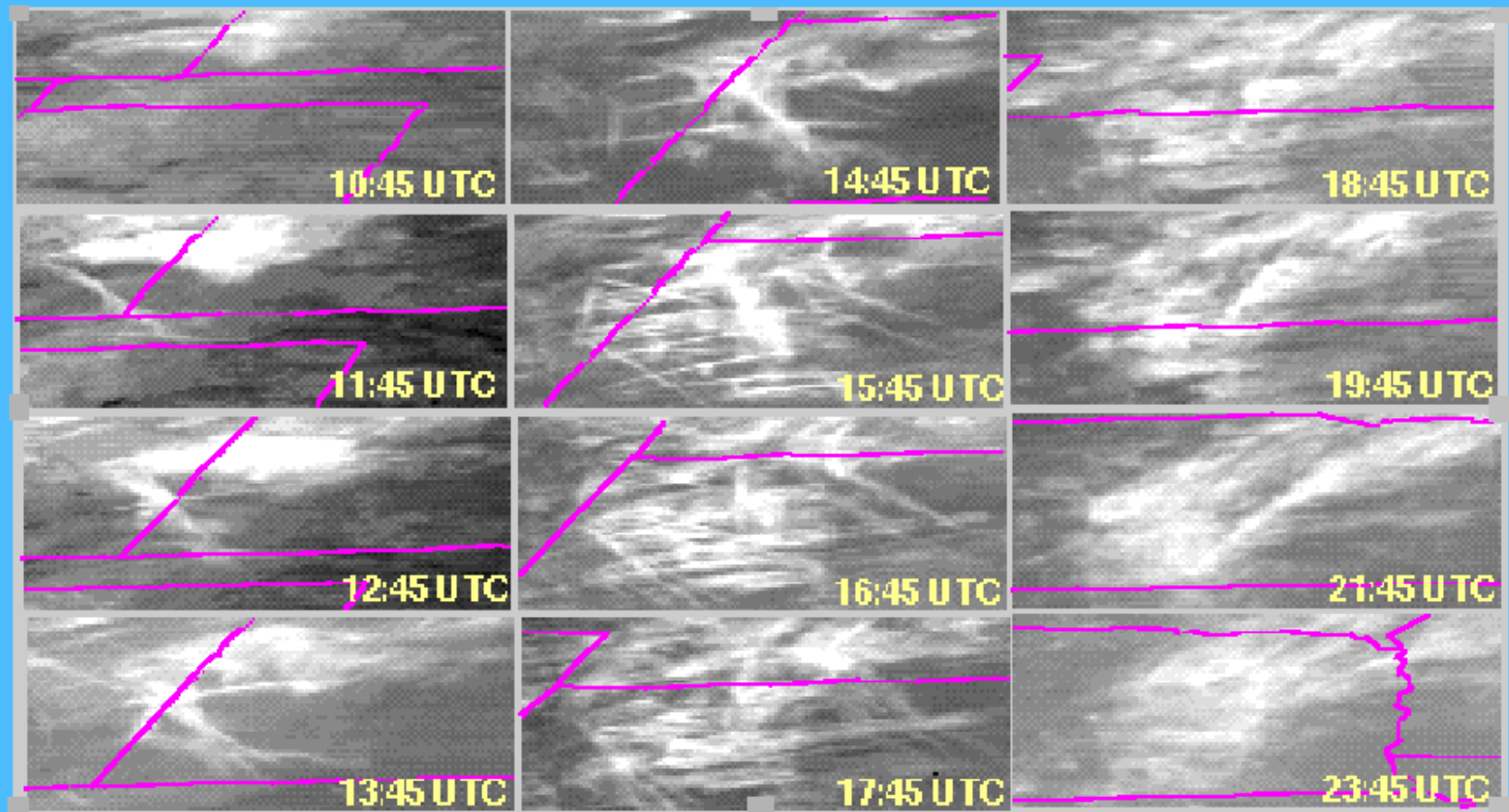
frequency of occurrence in percent (%)

MODIS Frequency of Co-occurrence
Water Phase with $253\text{ K} < T_{\text{cld}} < 268\text{ K}$
05 Nov. 2000 - Nighttime Only



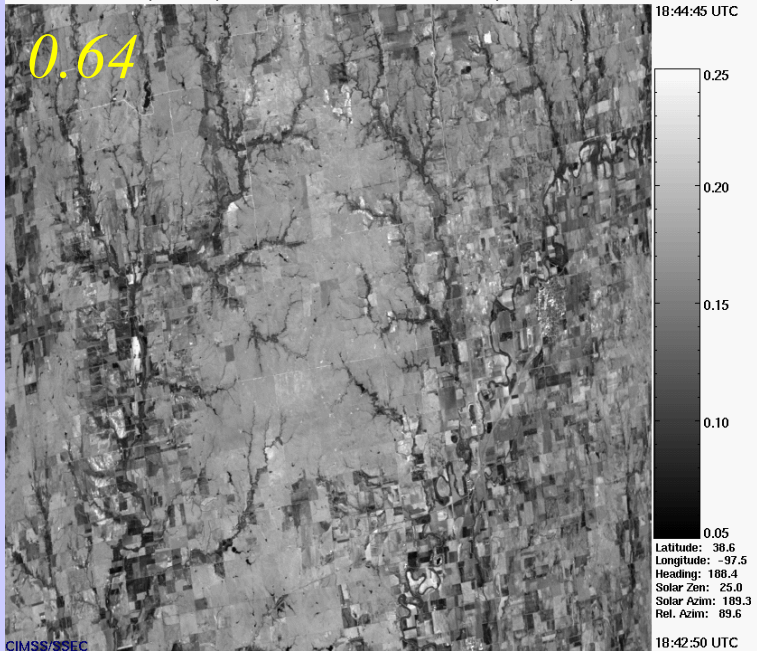
frequency of occurrence in percent (%)

CIRRUS FORMATION BY CONTRAILS OVER CENTRAL U.S. IN GOES-8 IR IMAGERY October 26, 1996

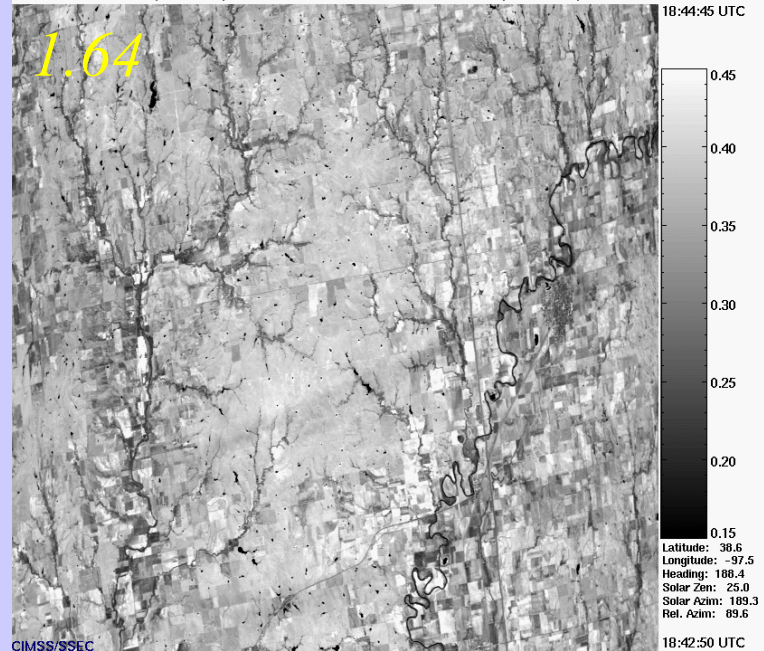


Minnis et al., *Science*, 1999

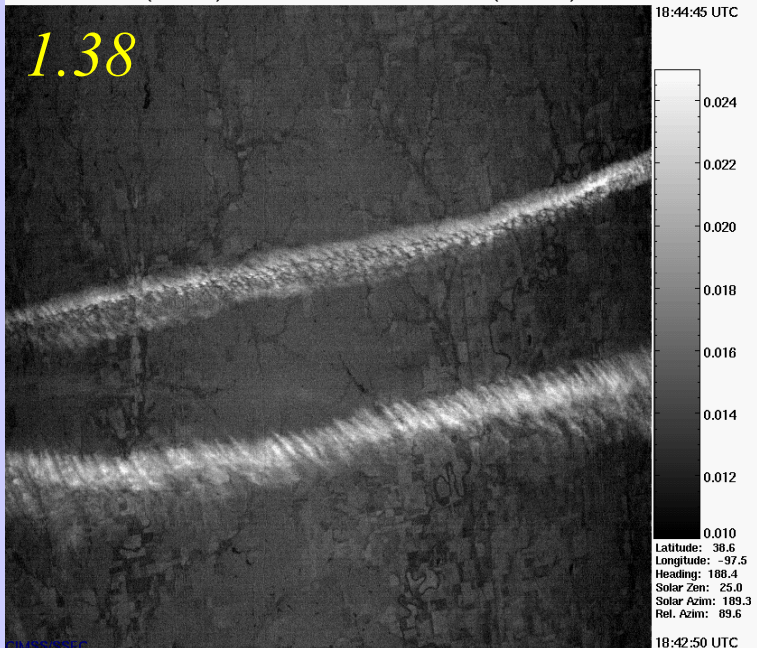
MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 02 (0.64 micron) Reflectance



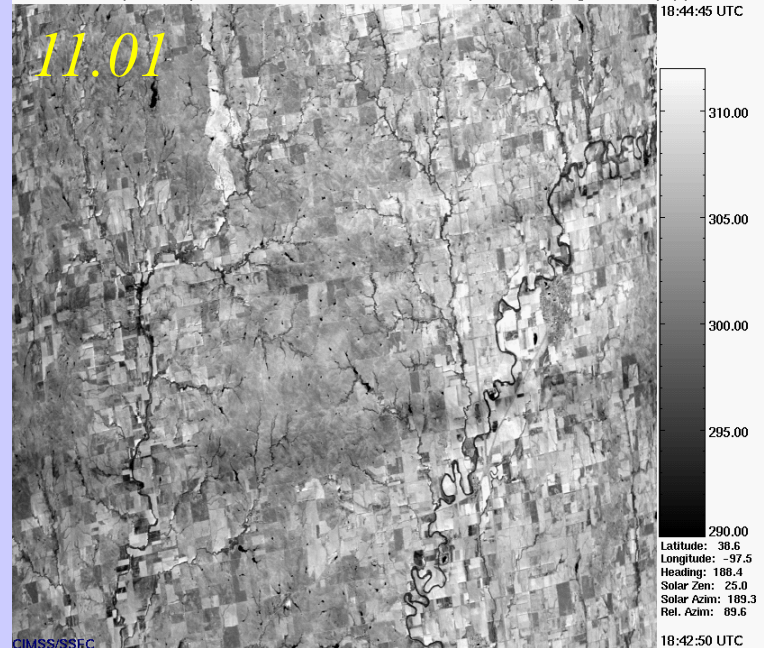
MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 10 (1.64 micron) Reflectance



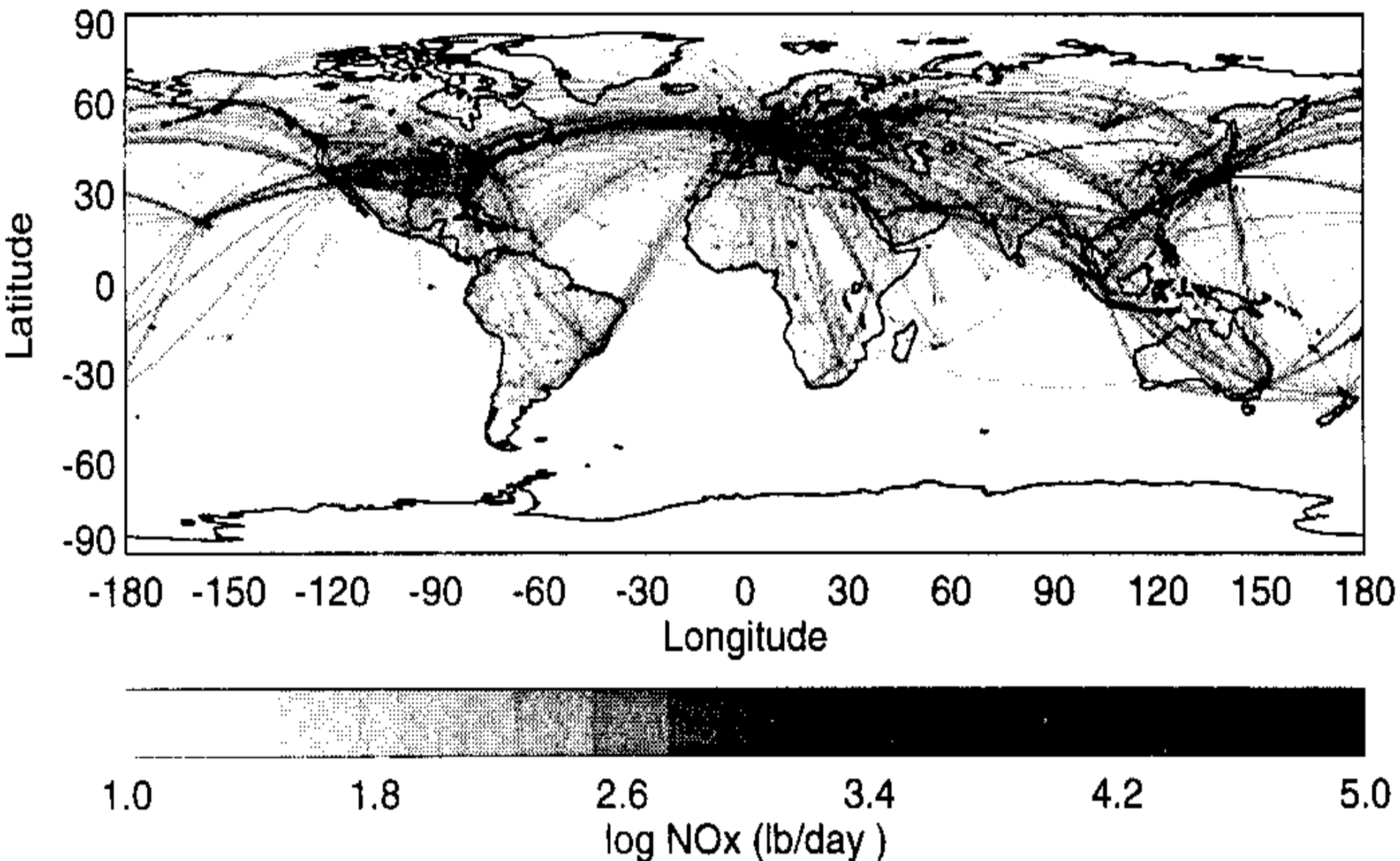
MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 15 (1.90 micron) Reflectance



MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 45 (11.01 micron) Brightness Temp. (K)



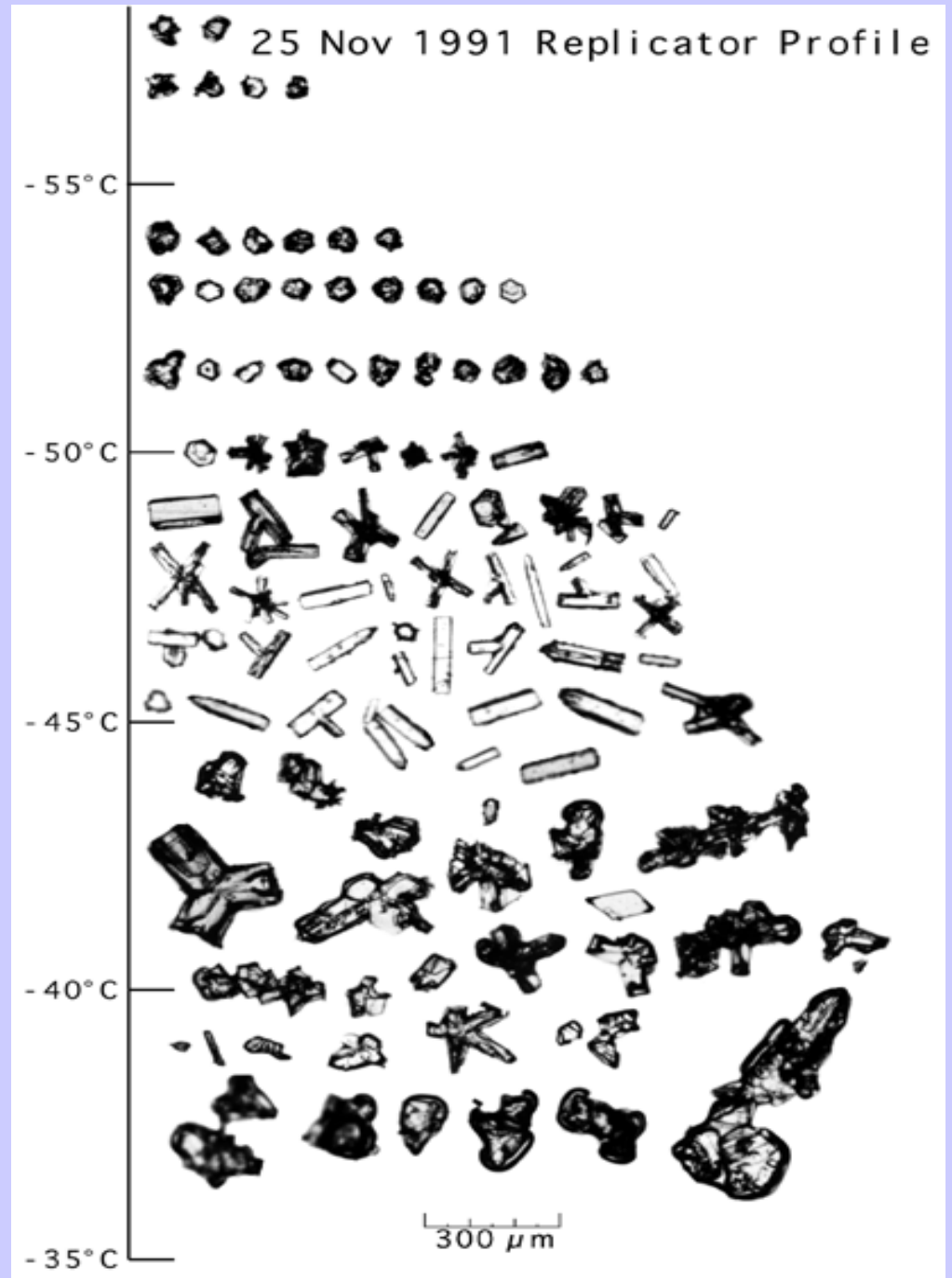
Is cirrus related to air traffic?



Ice Clouds have particles of many sizes and shapes

3 layer model

- *1 km 10 to 50 μm spheres
- *1 km 300 μm columns
- *2 km 150 μm aggregates and bullet rosettes.



MODIS detects ship tracks

Ship Tracks occur in marine stratocumulus regions of the globe

California, Azores,
Namibia, and Peru

Conditions for formation

High humidity

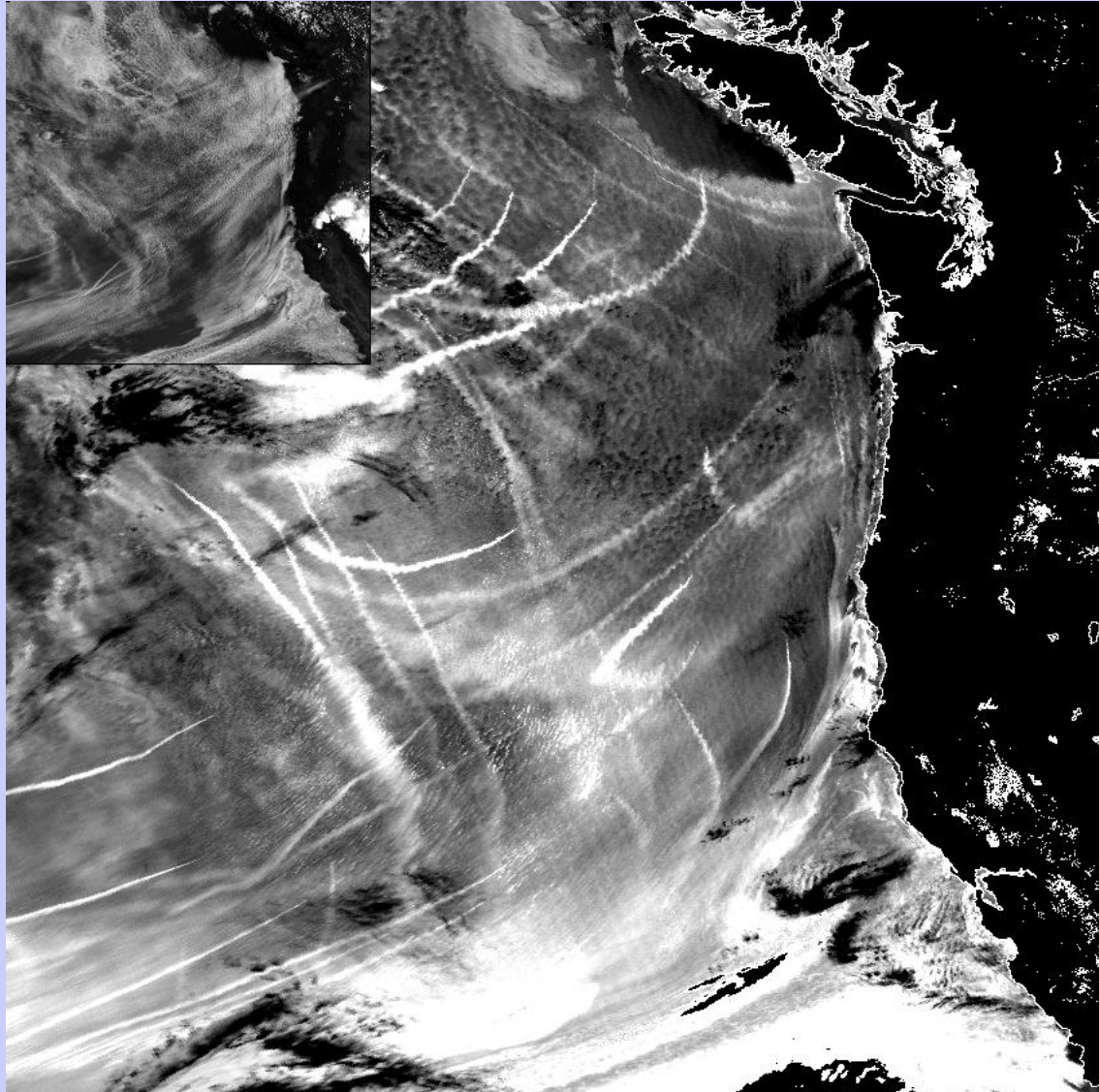
Small air-sea temperature
difference

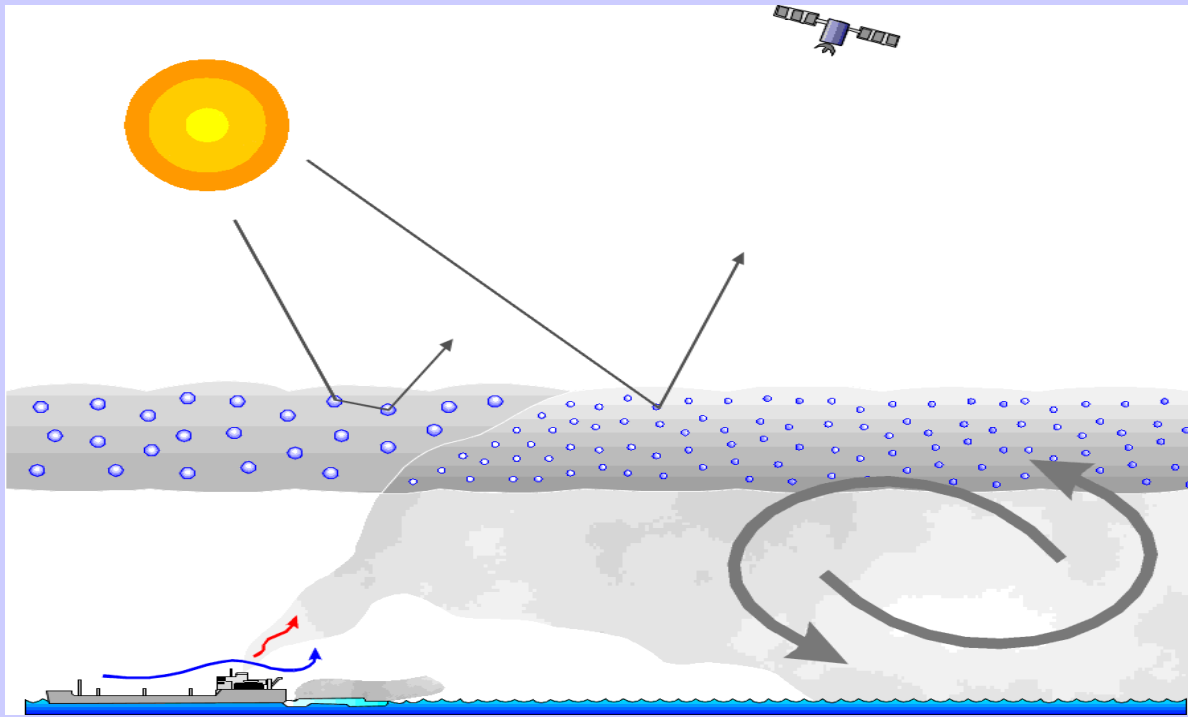
Low wind speed

Boundary layer between
300 and 750 m deep

Enhanced reflectance of clouds
at $3.7 \mu\text{m}$

Larger number of small
droplets arising from
particulate emission from
ships

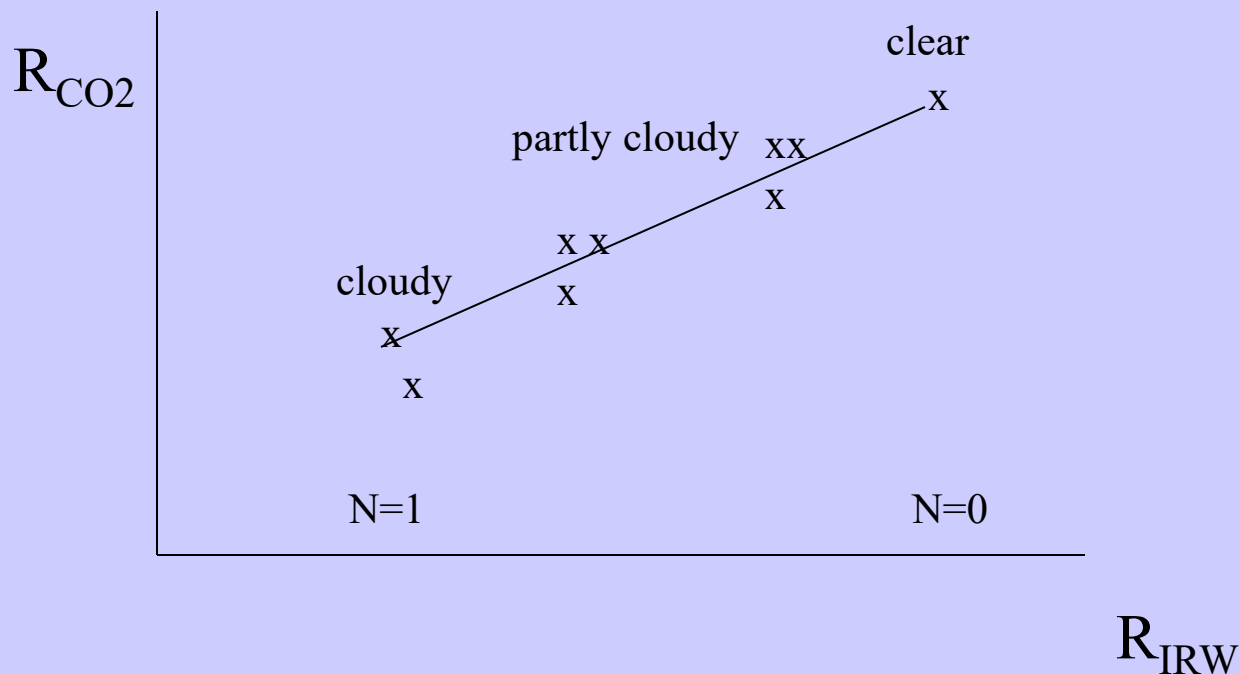




- * Particles emitted by ships increase concentration of cloud condensation nuclei (CCN) in the air
- * Increased CCN increase concentration of cloud droplets and reduce average size of the droplets
- * Increased concentration and smaller particles reduce production of drizzle (100 μm radius) droplets in clouds
- * Liquid water content increases because loss of drizzle particles is suppressed
- * Clouds are *optically thicker* and brighter along ship track

Cloud Clearing

For a single layer of clouds, radiances in one spectral band vary linearly with those of another as cloud amount varies from one field of view (fov) to another



Clear radiances can be inferred by extrapolating to cloud free conditions.

Paired field of view proceeds as follows. For a given wavelength λ , radiances from two spatially independent, but geographically close, fields of view are written

$$I_{\lambda,1} = \eta_1 I_{\lambda,1}^{\text{cd}} + (1 - \eta_1) I_{\lambda,1}^{\text{c}} \quad ,$$

$$I_{\lambda,2} = \eta_2 I_{\lambda,2}^{\text{cd}} + (1 - \eta_2) I_{\lambda,2}^{\text{c}} \quad ,$$

If clouds are at uniform altitude, and clear air radiance is in each FOV

$$I_{\lambda}^{\text{cd}} = I_{\lambda,1}^{\text{cd}} = I_{\lambda,2}^{\text{cd}}$$

$$I_{\lambda}^{\text{c}} = I_{\lambda,1}^{\text{c}} = I_{\lambda,2}^{\text{c}}$$

$$\frac{\eta_1 (I_{\lambda,1}^{\text{cd}} - I_{\lambda}^{\text{c}})}{\eta_2 (I_{\lambda,2}^{\text{cd}} - I_{\lambda}^{\text{c}})} = \frac{\eta_1}{\eta_2} = \eta^* = \frac{I_{\lambda,1} - I_{\lambda}^{\text{c}}}{I_{\lambda,2} - I_{\lambda}^{\text{c}}} \quad ,$$

where η^* is the ratio of the cloud amounts for the two geographically independent fields of view of the sounding radiometer. Therefore, the clear air radiance from an area possessing broken clouds at a uniform altitude is given by

$$I_{\lambda}^{\text{c}} = [I_{\lambda,1} - \eta^* I_{\lambda,2}] / [1 - \eta^*]$$

where η^* still needs to be determined. Given an independent measurement of surface temperature, T_s , and measurements $I_{w,1}$ and $I_{w,2}$ in a spectral window channel, then η^* can be determined by

$$\eta^* = [I_{w,1} - B_w(T_s)] / [I_{w,2} - B_w(T_s)]$$

and I_{λ}^{c} for different spectral channels can be solved.

Applications with Multispectral Remote Sensing Data

Satellite Remote Sensing

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VIS, IR, and MW Radiative Transfer

EOS Terra & Aqua MODIS

Multispectral Signatures

*(Ocean Color, SST, Snow/Ice, Vegetation, Aerosols,
Clouds, Moisture, Fires, Volcanic Ash)*

Detecting Climate Trends

Water vapour evaluated in multiple infrared window channels where absorption is weak, so that

$$\tau_w = \exp[-k_w u] \sim 1 - k_w u \text{ where } w \text{ denotes window channel}$$

and

$$d\tau_w = -k_w du$$

What little absorption exists is due to water vapour, therefore, u is a measure of precipitable water vapour. RTE in window region

$$I_w = B_{sw} (1 - k_w u_s) + k_w \int_0^{u_s} B_w du$$

u_s represents total atmospheric column absorption path length due to water vapour, and s denotes surface. Defining an atmospheric mean Planck radiance, then

$$I_w = B_{sw} (1 - k_w u_s) + k_w u_s \bar{B}_w \text{ with } \bar{B}_w = \frac{\int_0^{u_s} B_w du}{\int_0^{u_s} du}$$

Since B_{sw} is close to both I_w and B_w , first order Taylor expansion about the surface temperature T_s allows us to linearize the RTE with respect to temperature, so

$T_{bw} = T_s (1 - k_w u_s) + k_w u_s \bar{T}_w$, where T_w is mean atmospheric temperature corresponding to B_w .

For two window channels (11 and 12um) the following ratio can be determined.

$$\frac{T_s - T_{bw1}}{T_s - T_{bw2}} = \frac{k_{w1} u_s (T_s - \bar{T}_{w1})}{k_{w2} u_s (T_s - \bar{T}_{w2})} = \frac{k_{w1}}{k_{w2}}$$

where the mean atmospheric temperature measured in the one window region is assumed to be comparable to that measured in the other, $\bar{T}_{w1} \sim \bar{T}_{w2}$,

Thus it follows that

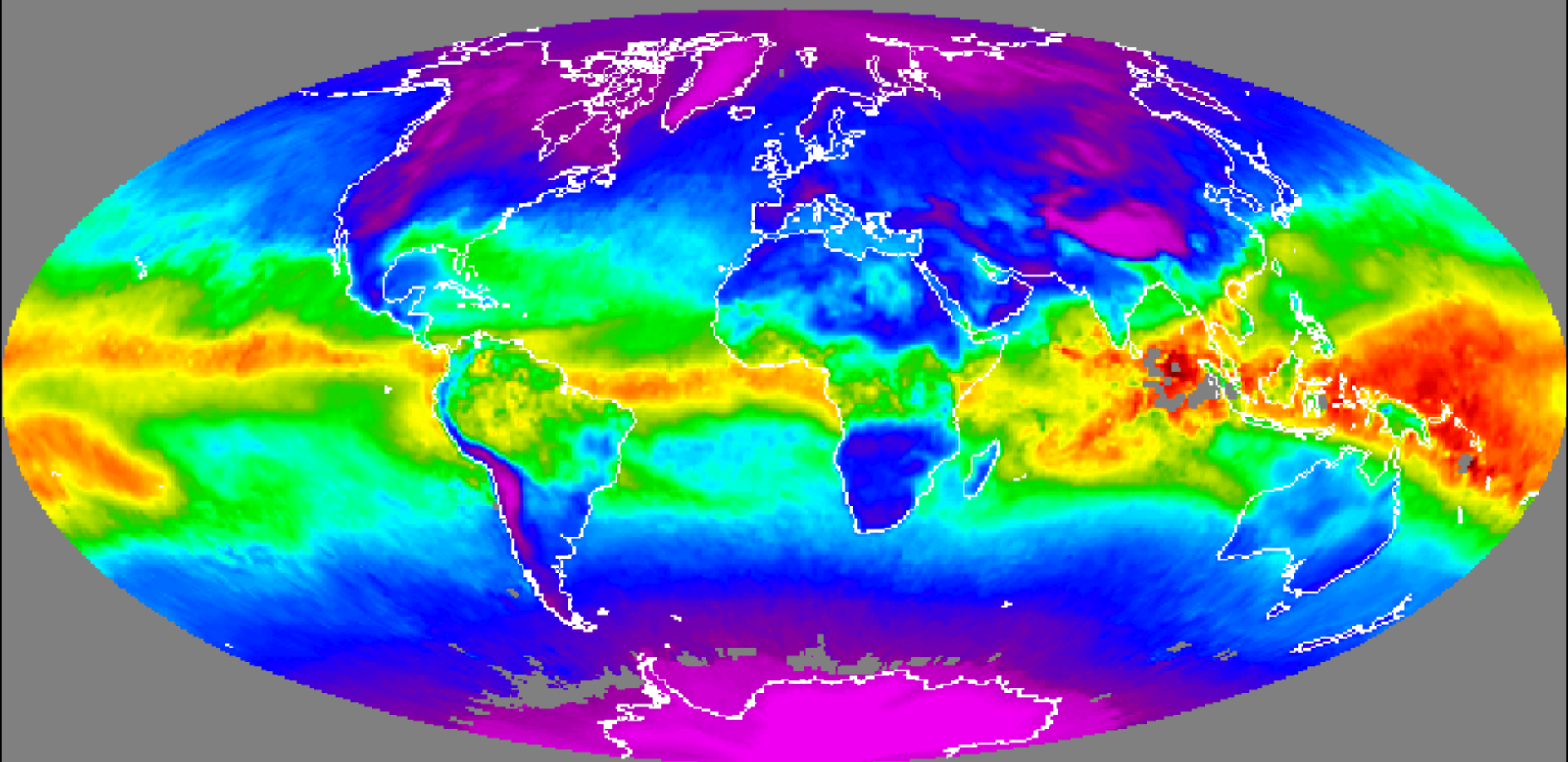
$$T_s = T_{bw1} + \frac{k_{w1}}{k_{w2} - k_{w1}} [T_{bw1} - T_{bw2}]$$

and

$$u_s = \frac{T_{bw} - T_s}{k_w (\bar{T}_w - T_s)} .$$

Obviously, the accuracy of the determination of the total water vapour concentration depends upon the contrast between the surface temperature, T_s , and

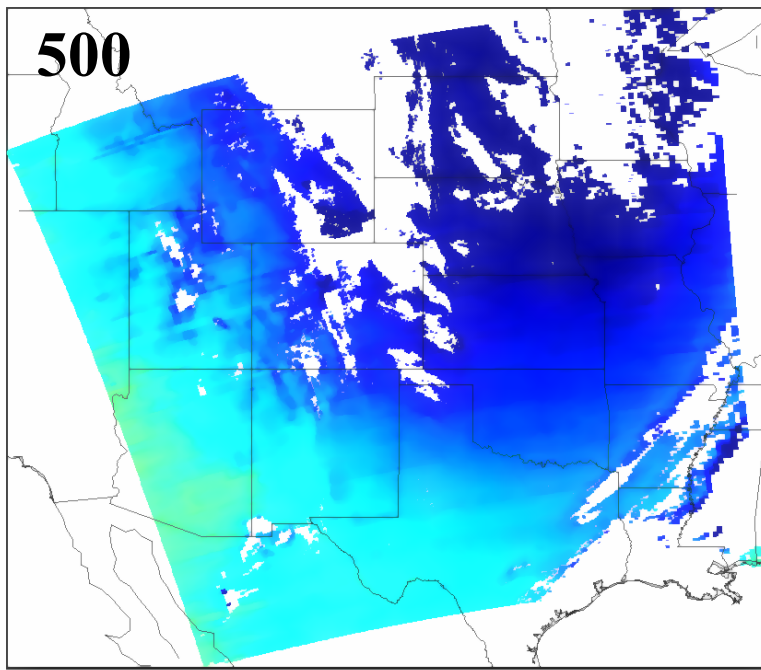
the effective temperature of the atmosphere \bar{T}_w



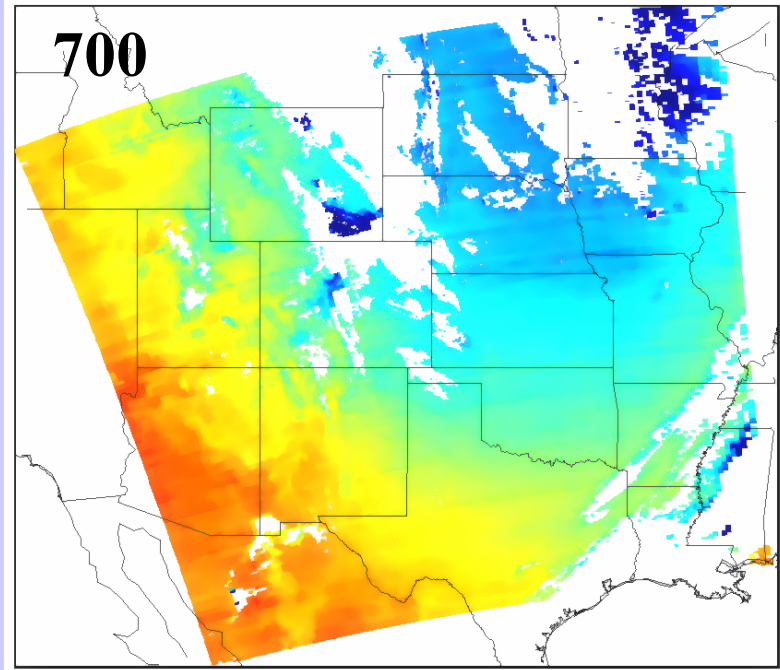
1 MAY 2002 **Global TPW from Seemann**

TPW_Terra_2002

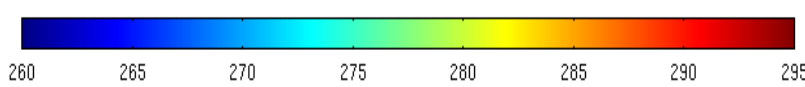
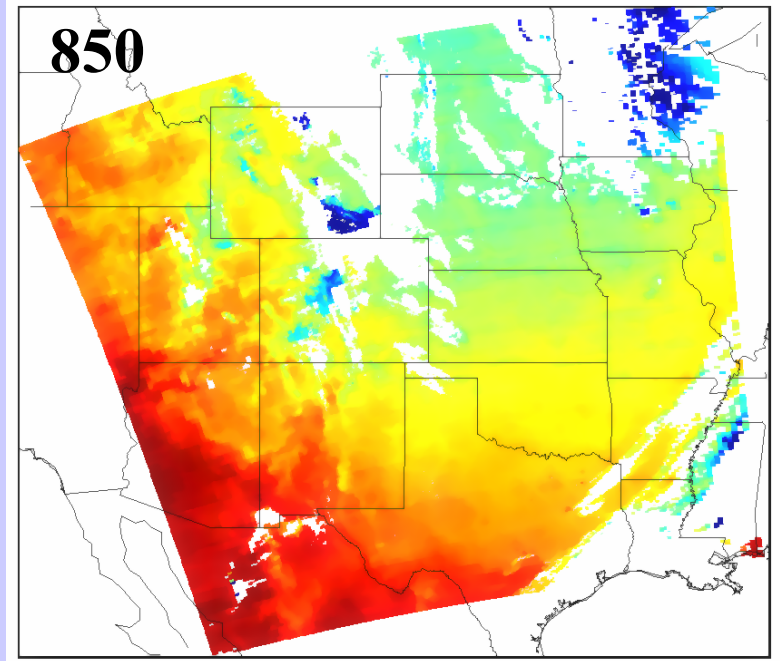
MODIS Temperature (°K) at 500hPa: 2001142.0500



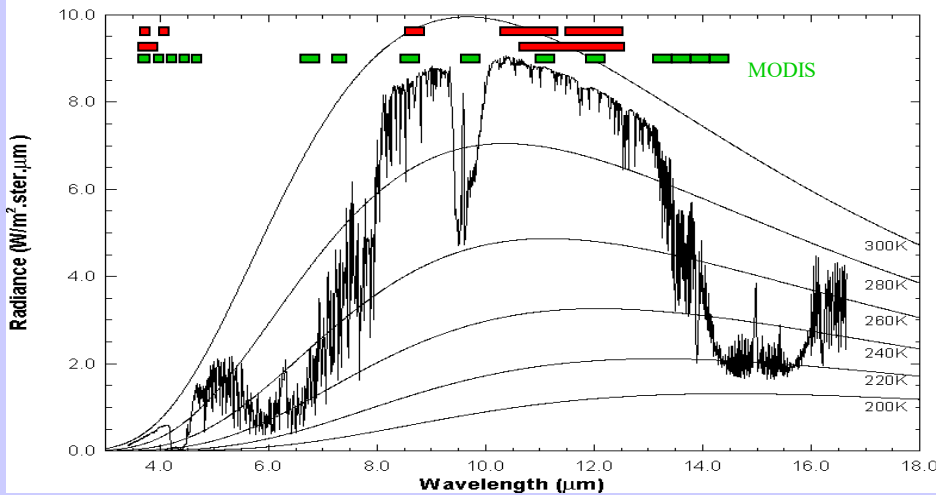
MODIS Temperature (°K) at 700hPa: 2001142.0500



MODIS Temperature (°K) at 850hPa: 2001142.0500

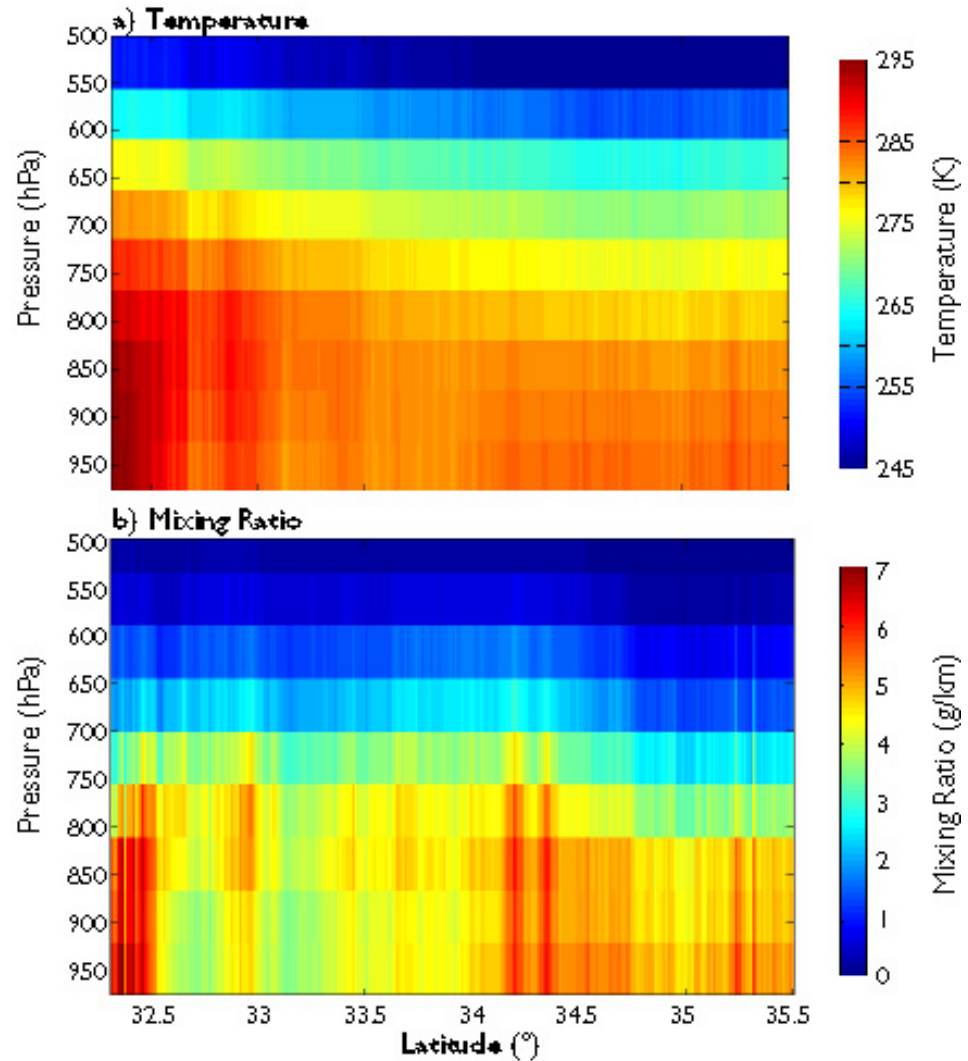
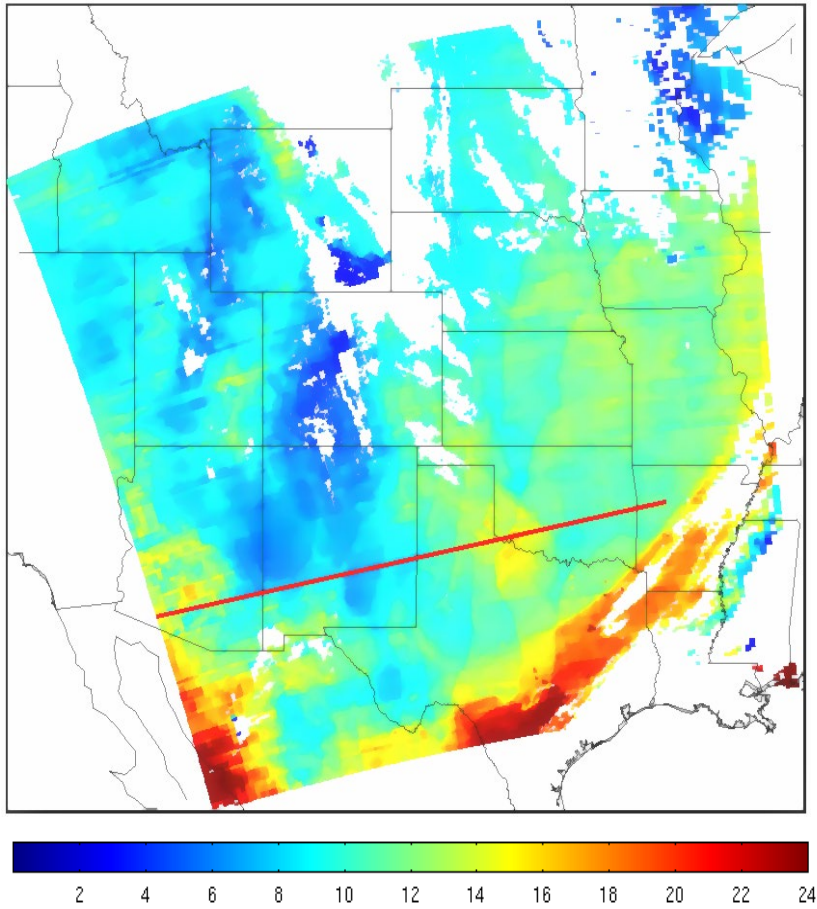


High resolution atmospheric absorption spectrum and comparative blackbody curves.



T(p)

MODIS TPW



Clear sky layers of temperature and moisture on 2 June 2001

Applications with Multispectral Remote Sensing Data

Satellite Remote Sensing

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VIS, IR, and MW Radiative Transfer

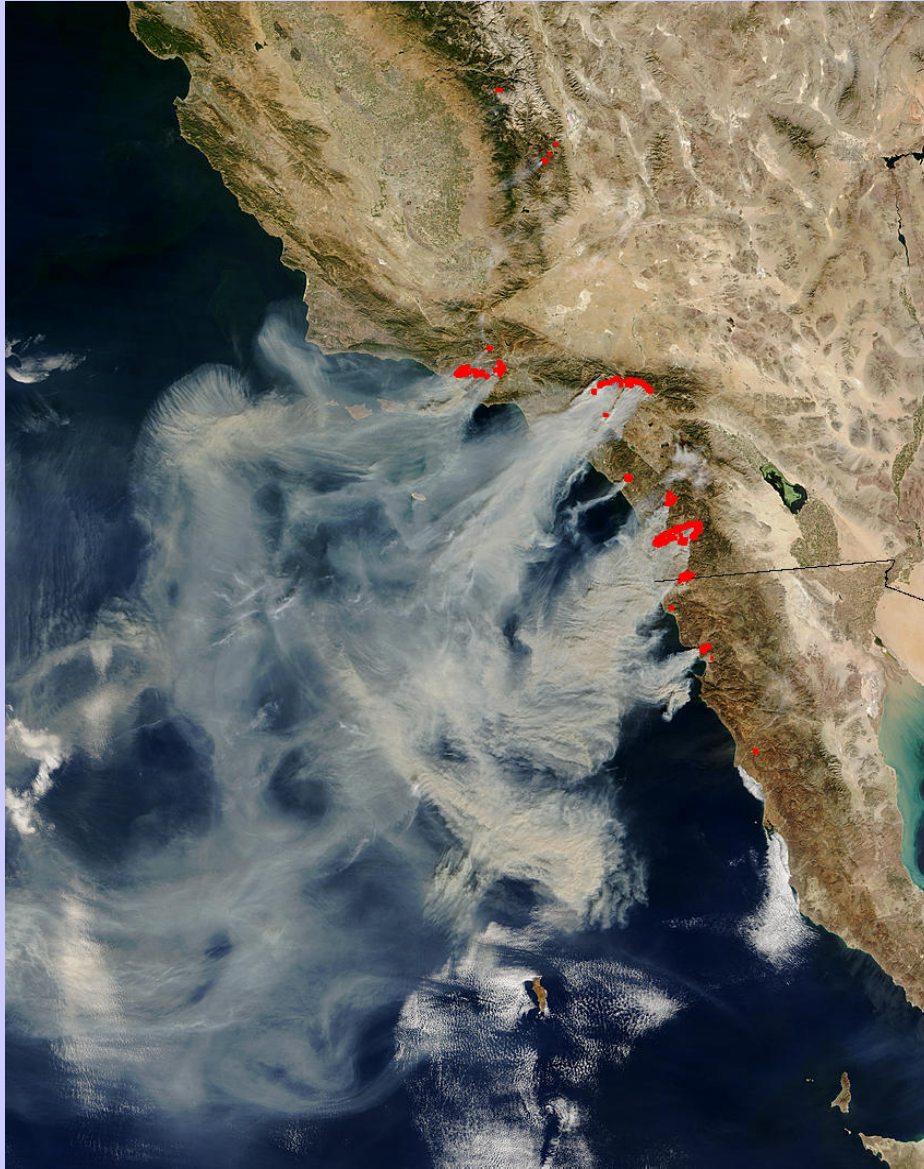
EOS Terra & Aqua MODIS

Multispectral Signatures

*(Ocean Color, SST, Snow/Ice, Vegetation, Aerosols,
Clouds, Moisture, Fires, Volcanic Ash)*

Detecting Climate Trends

Active Fire Detection



California - 10/26/03

- Same code as the "official" MOD14 thermal anomalies product
- Contextual algorithm (Giglio et al., 2003)
- The algorithm considers the spectral signature (in middle and thermal infrared) of each pixel and compares it to the non-burning surrounding pixels
- The natural variability of the surrounding background is taken into account
- Fewer false detections than traditional threshold-based algorithms
- Sensitive enough to detect small fires
- Current version: v4.3.2 (March 2003)

The fire extent and temperature within a field of view can be determined by considering the upwelling thermal radiance values obtained by both channels (Matson and Dozier, 1981; Dozier, 1981). For a given channel, λ , the radiative transfer equation indicates

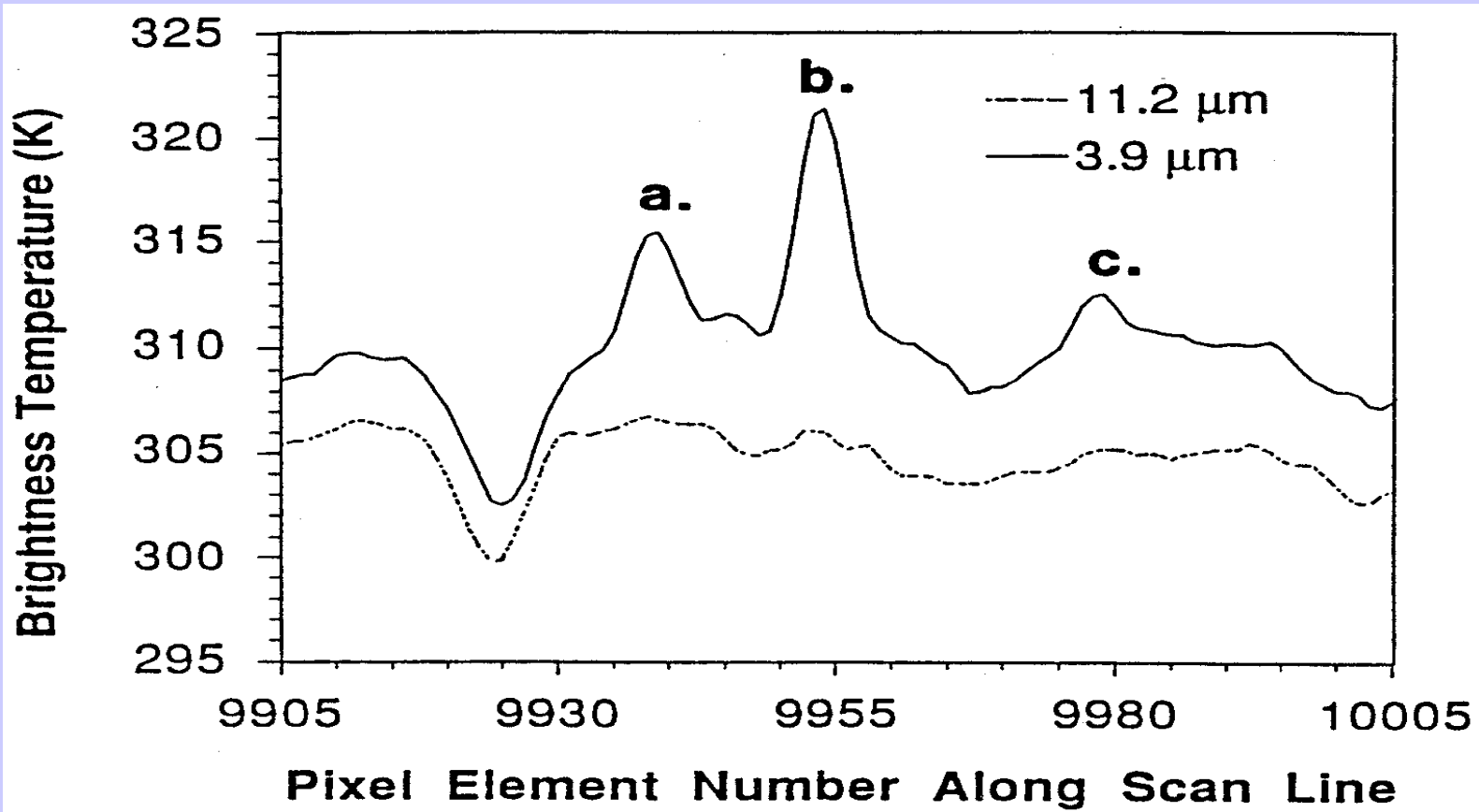
$$R_{\lambda}(T) = \varepsilon_{\lambda} B_{\lambda}(T_s) \tau_{\lambda}(s) + \int_0^1 B_{\lambda}(T) d\tau_{\lambda}$$

When the GOES radiometer senses radiance from a pixel containing a target of blackbody temperature T_t occupying a portion p (between zero and one) of the pixel and a background of blackbody temperature T_b occupying the remainder of the pixel $(1-p)$, the following equations represent the radiance sensed by the instrument at 4 and 11 micron.

$$R_4(T_4) = p R_4(T_t) + \varepsilon_4 (1-p) R_4(T_b) + (1-\varepsilon_4) \tau_4(s) R_4(\text{solar})$$

$$R_{11}(T_{11}) = p R_{11}(T_t) + \varepsilon_{11} (1-p) R_{11}(T_b)$$

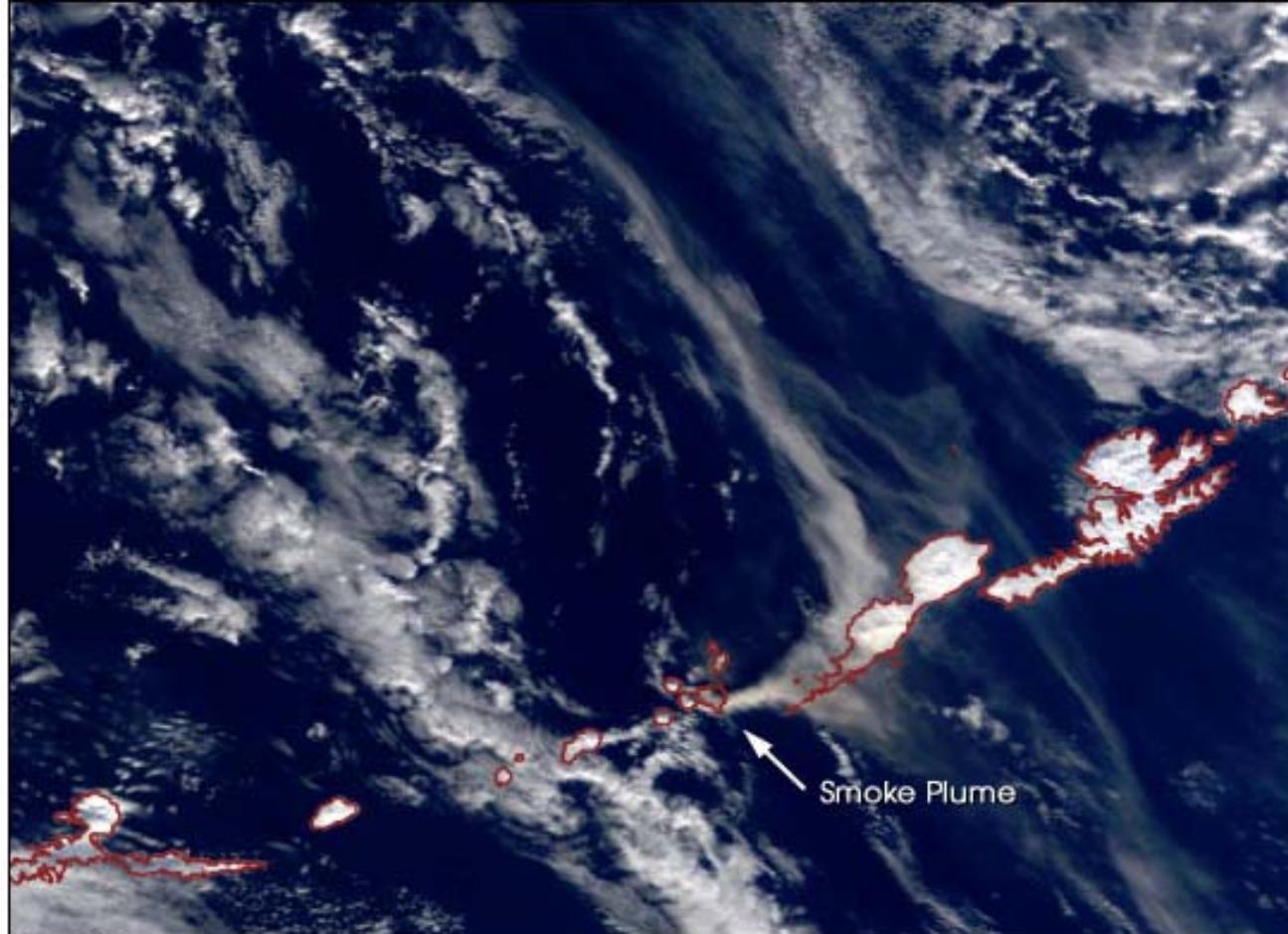
The observed short wave window radiance also contains contributions due to solar reflection that must be distinguished from the ground emitted radiances; solar reflection is estimated from differences in background temperatures in the 4 and 11 micron channels. Once T_b is estimated from nearby pixels, these two nonlinear equations can be solved for T_t and p . In this study, the solution to the set of equations is found by applying a globally convergent bisection technique followed by Newton's method.



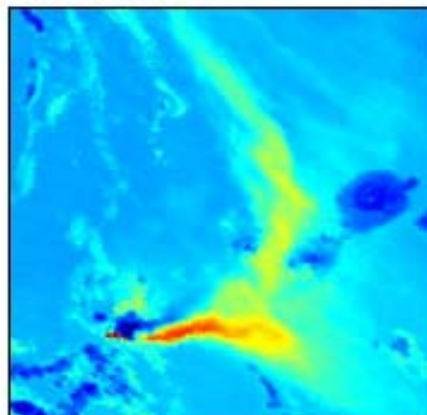
3.9 and 11.2 microns plotted for one scan line over grassland burning in South America; fires are likely at a, b, and c.

Ash Plume Detection

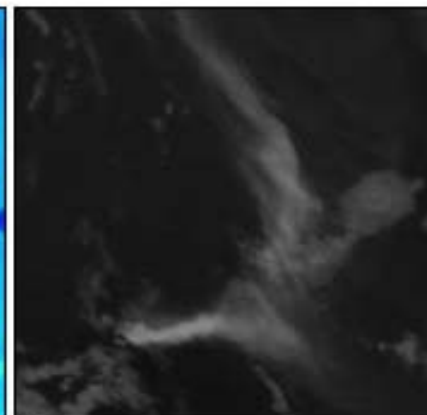
Mt. Cleveland
Eruption
19 Feb 2001



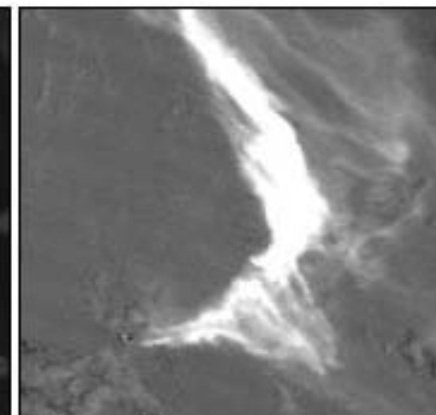
True Color



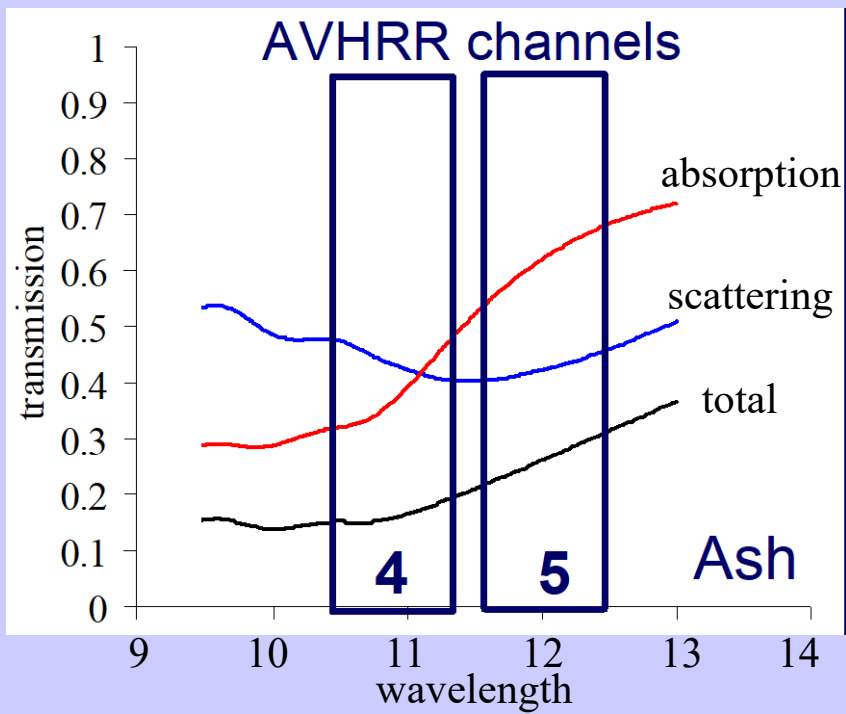
3.9µm



11µm



11µm - 12µm

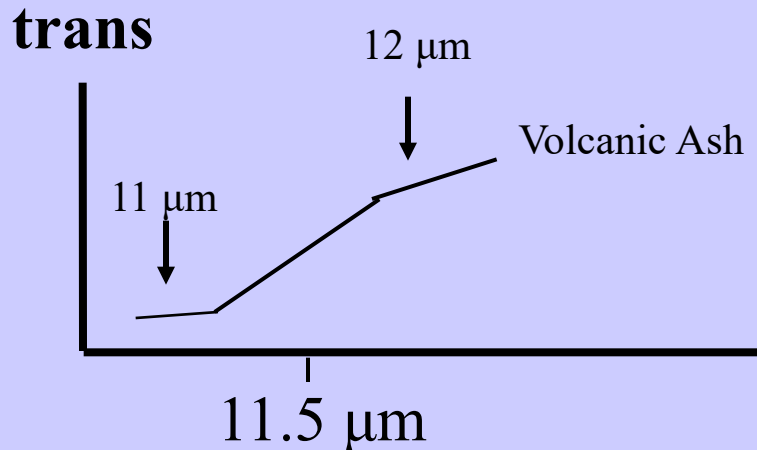


Investigating with Multi-spectral Combinations

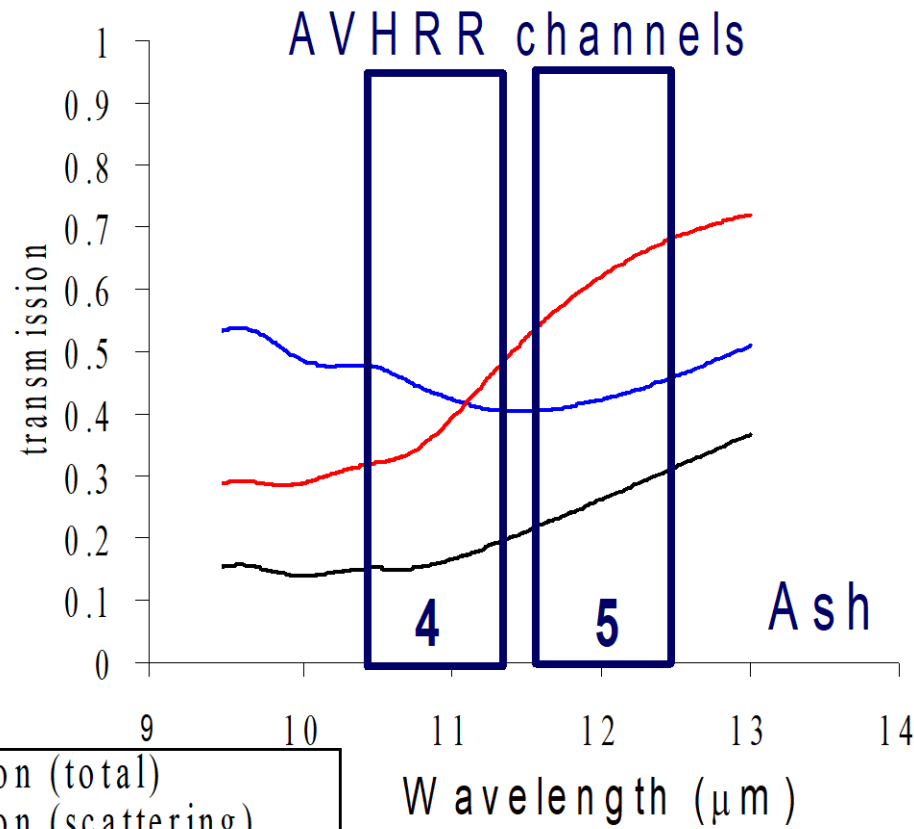
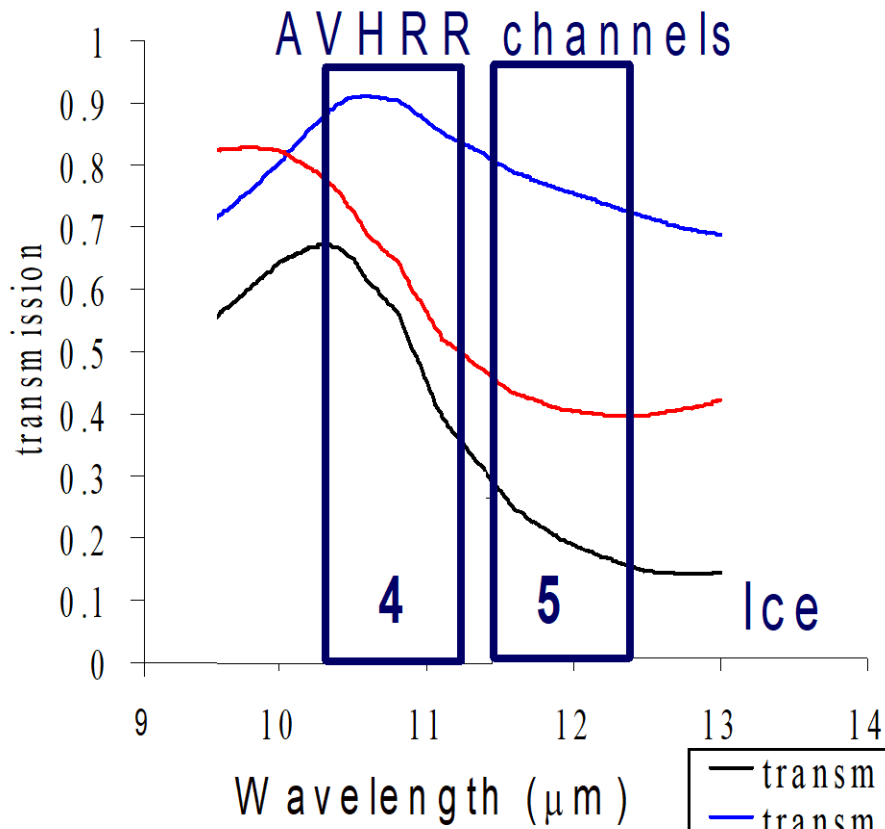
Given the spectral response of a surface or atmospheric feature

Select a part of the spectrum where the reflectance or absorption changes with wavelength

e.g. transmission through ash



If 11 μm sees the same or higher BT than 12 μm the atmosphere viewed does not contain volcanic ash; if 12 μm sees considerably higher BT than 11 μm then the atmosphere probably contains volcanic ash



— transmission (total)
 — transmission (scattering)
 — transmission (absorption)

BT11-BT12 > 0 for ice
BT11-BT12 < 0 for volcanic ash
Frank Honey 1980s

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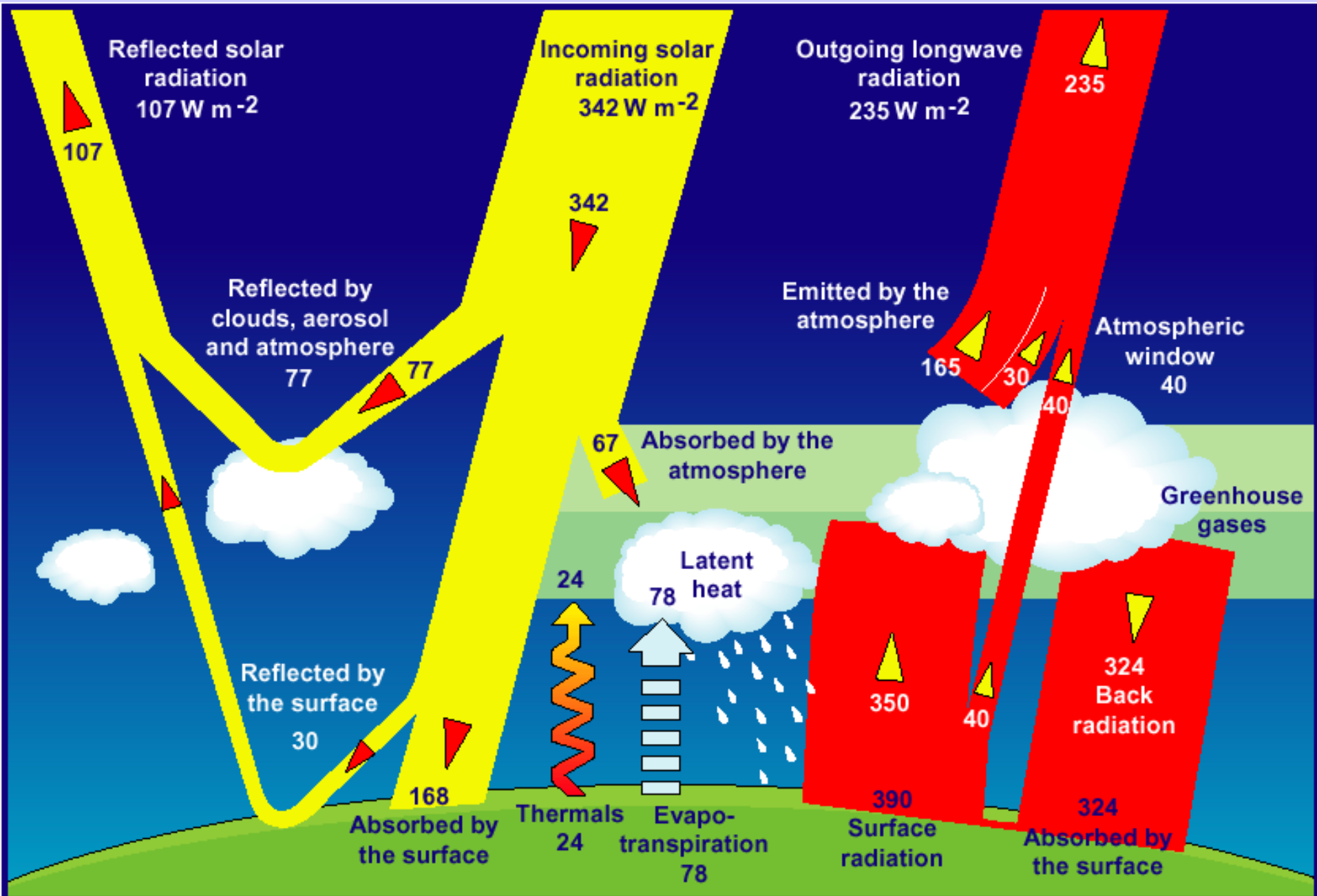
EOS Terra & Aqua MODIS

Multispectral Signatures

(Ocean Color, Snow/Ice, Vegetation, Aerosols, Clouds, Moisture, Fires, Volcanic Ash)

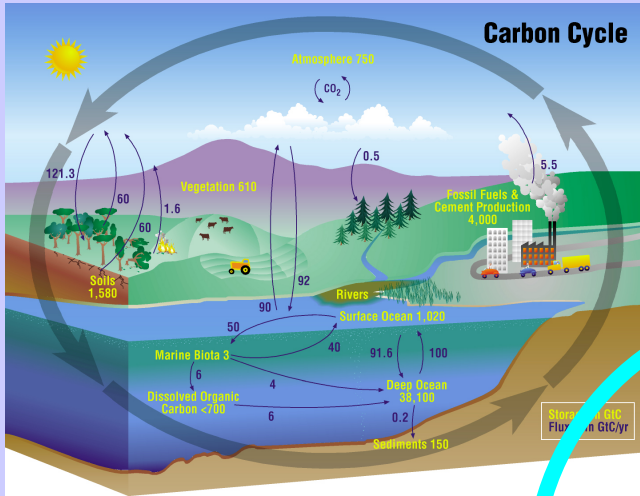
Detecting Climate Trends

Climate System Energy Balance

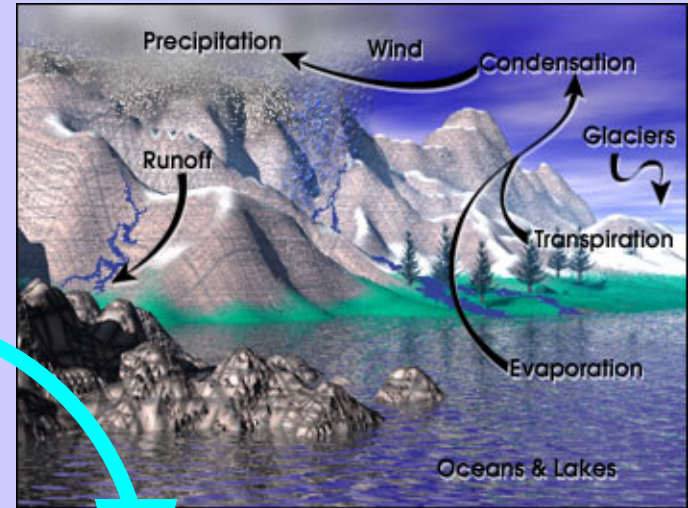


Major Climate System Elements

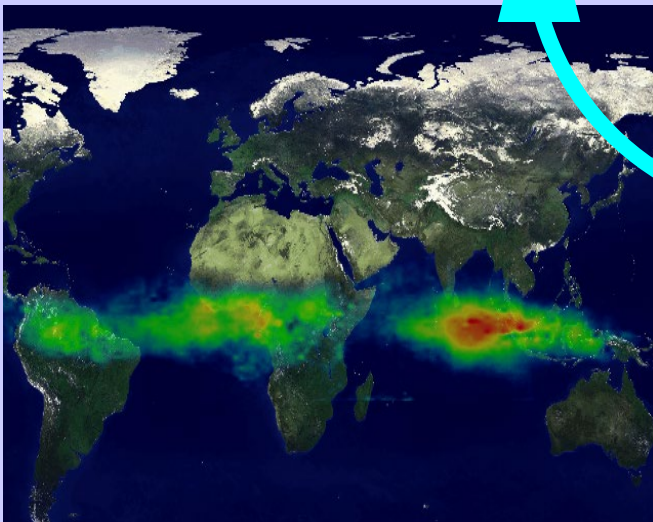
Carbon Cycle



Water & Energy Cycle

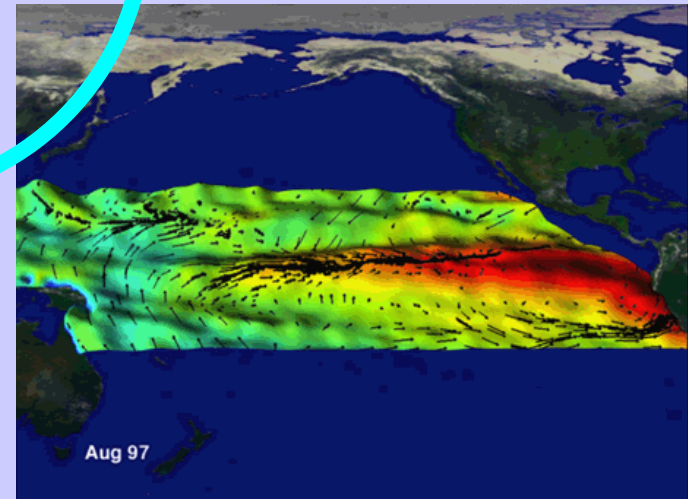


Atmospheric Chemistry

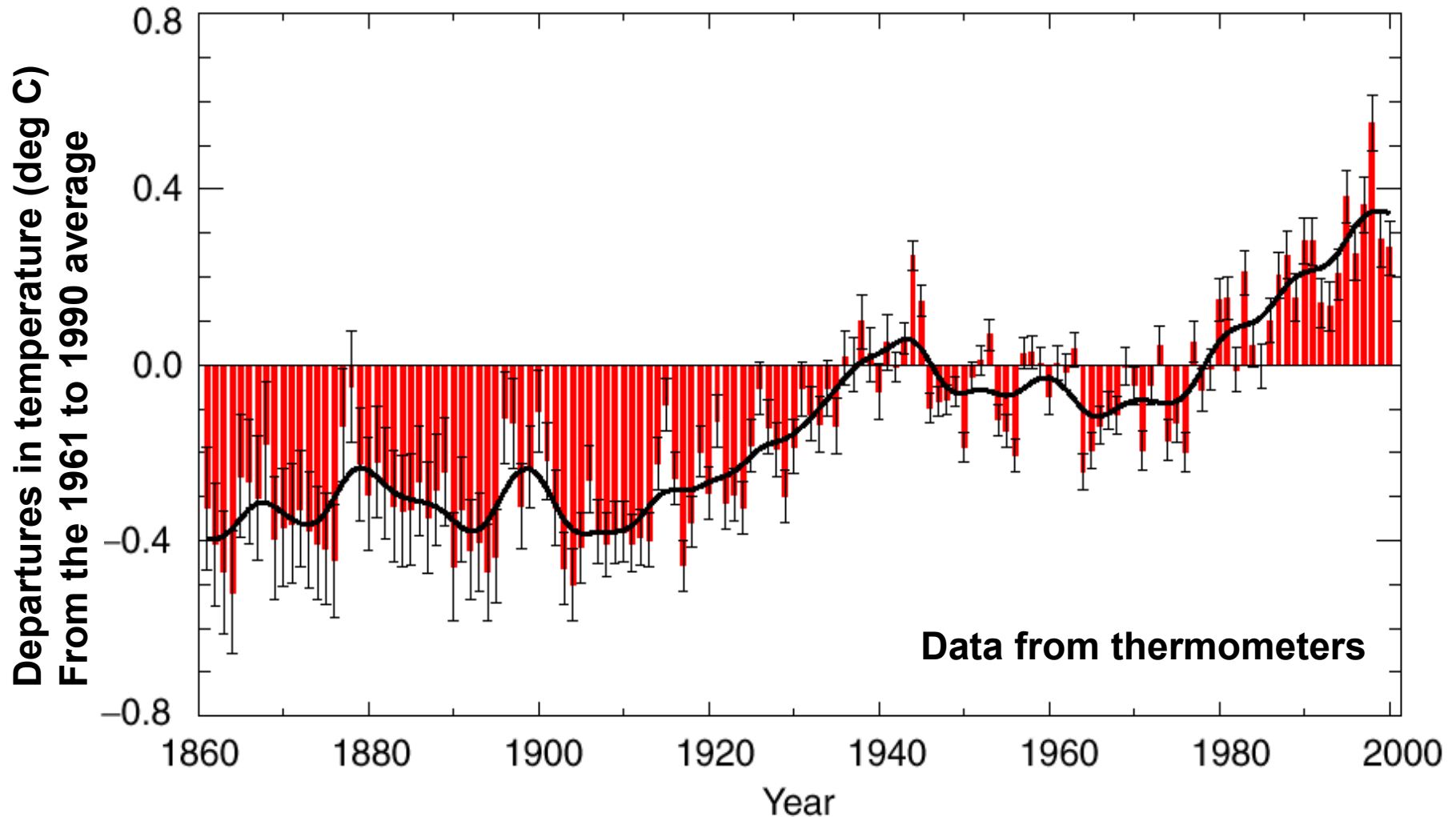


**Coupled
Chaotic
Nonlinear**

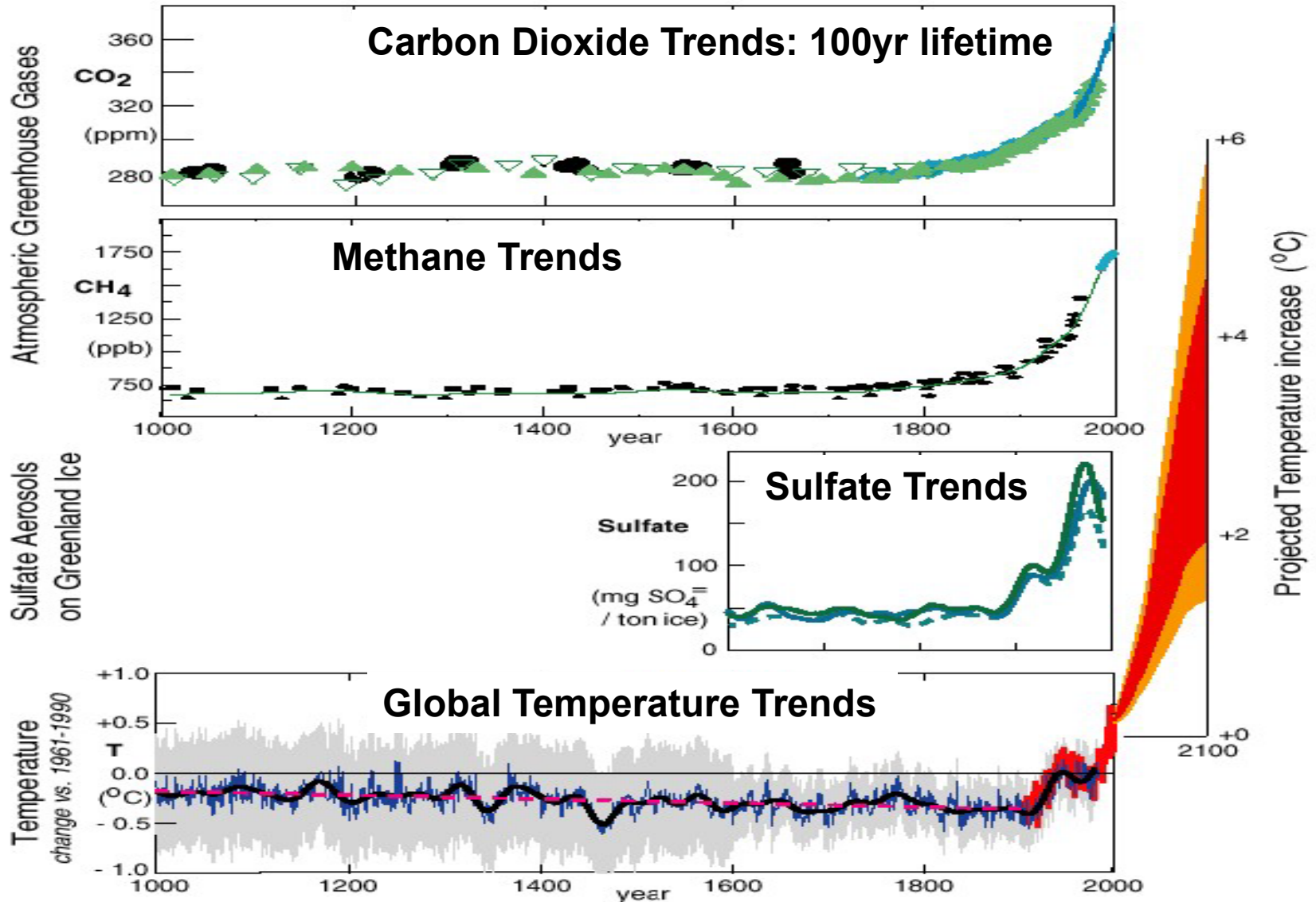
**Atmosphere and Ocean
Dynamics**



What global surface temperature change has occurred so far?



Human Influence on Climate



Cloud Feedback is a key unknown

Stephens et al, 2005

- Climate Variability is key NOAA mission. It supports our mission for real-time cloud remote sensing.
- Clouds are major uncertainty in climate models. Satellite records are now long enough to begin to offer some relevant constraints if they are credible.
- The scientific relevance of the cloud climate records from EOS and NPOESS will be much larger if we can extend selected time series back in time using the AVHRR data.

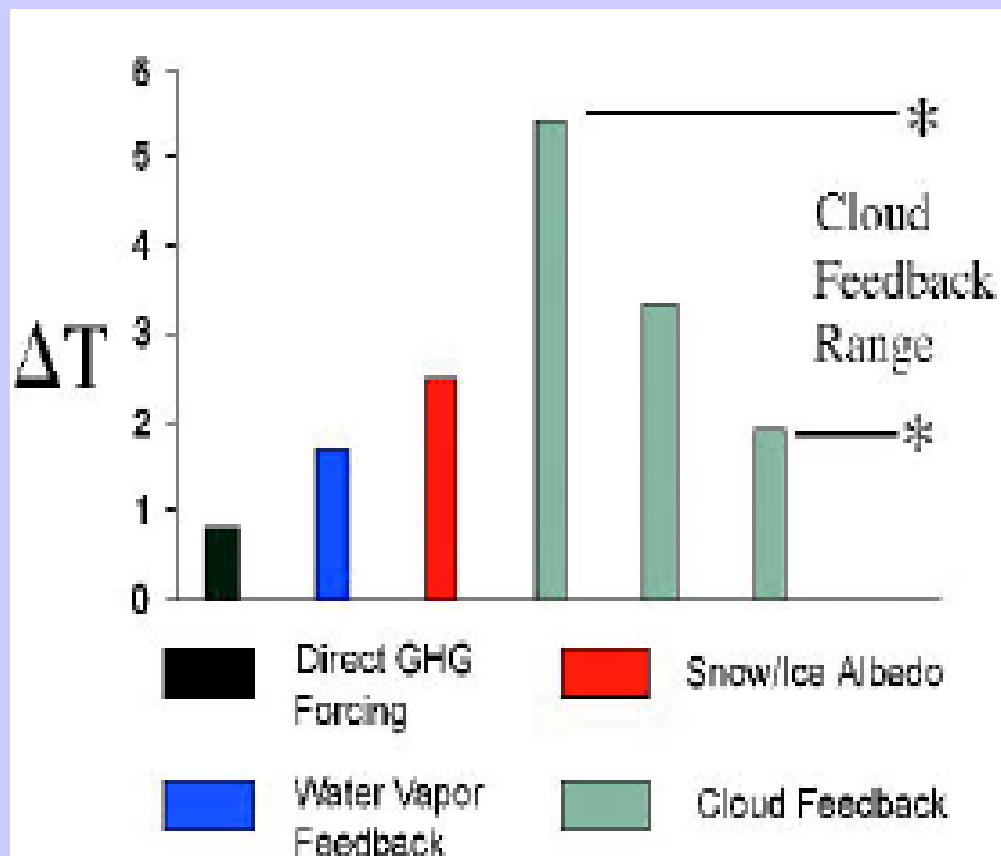
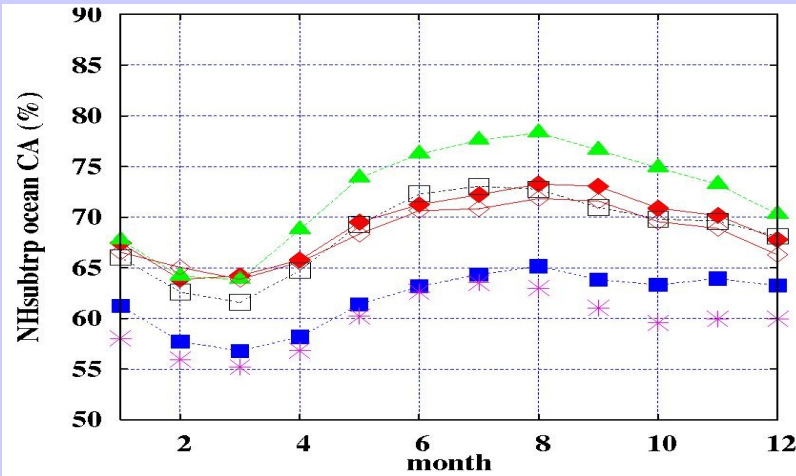


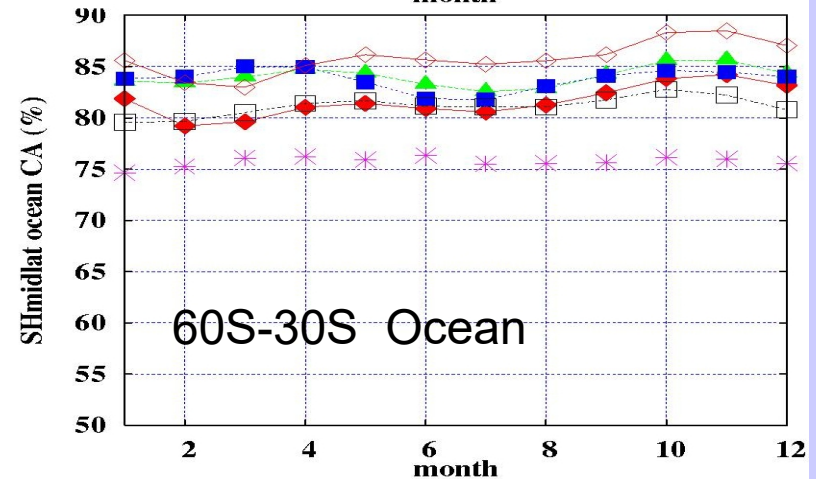
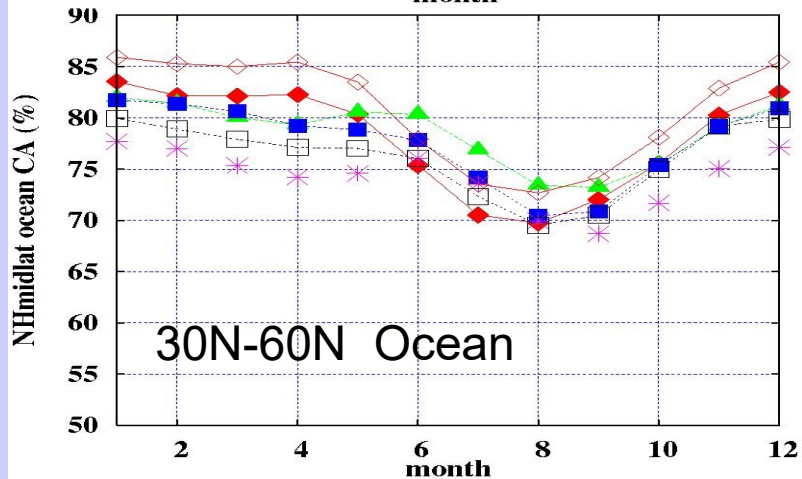
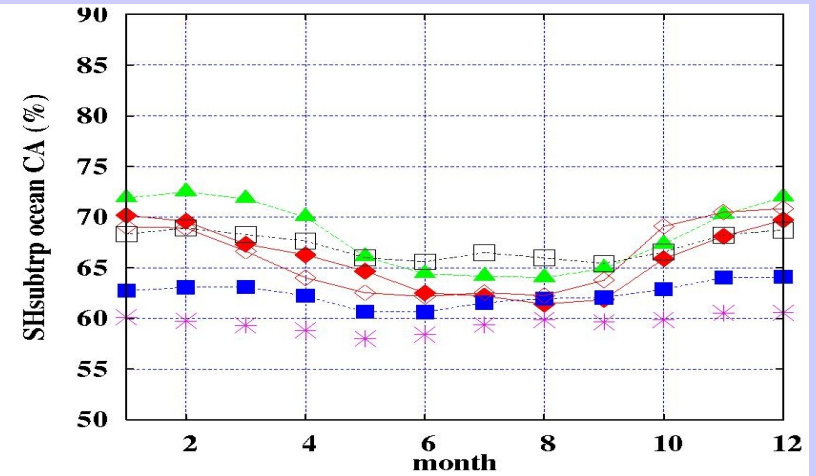
FIG. 13. The response of a single climate model to an imposed doubling of CO₂ as different feedbacks are systematically added in the model (adapted from Senior and Mitchell 1993). Different treatments of cloud processes in the model produce a large spread in predicted surface temperature due to CO₂ doubling.

Annual Cycle of Total Cloud Amount

0-30N Ocean



30S – 0N Ocean

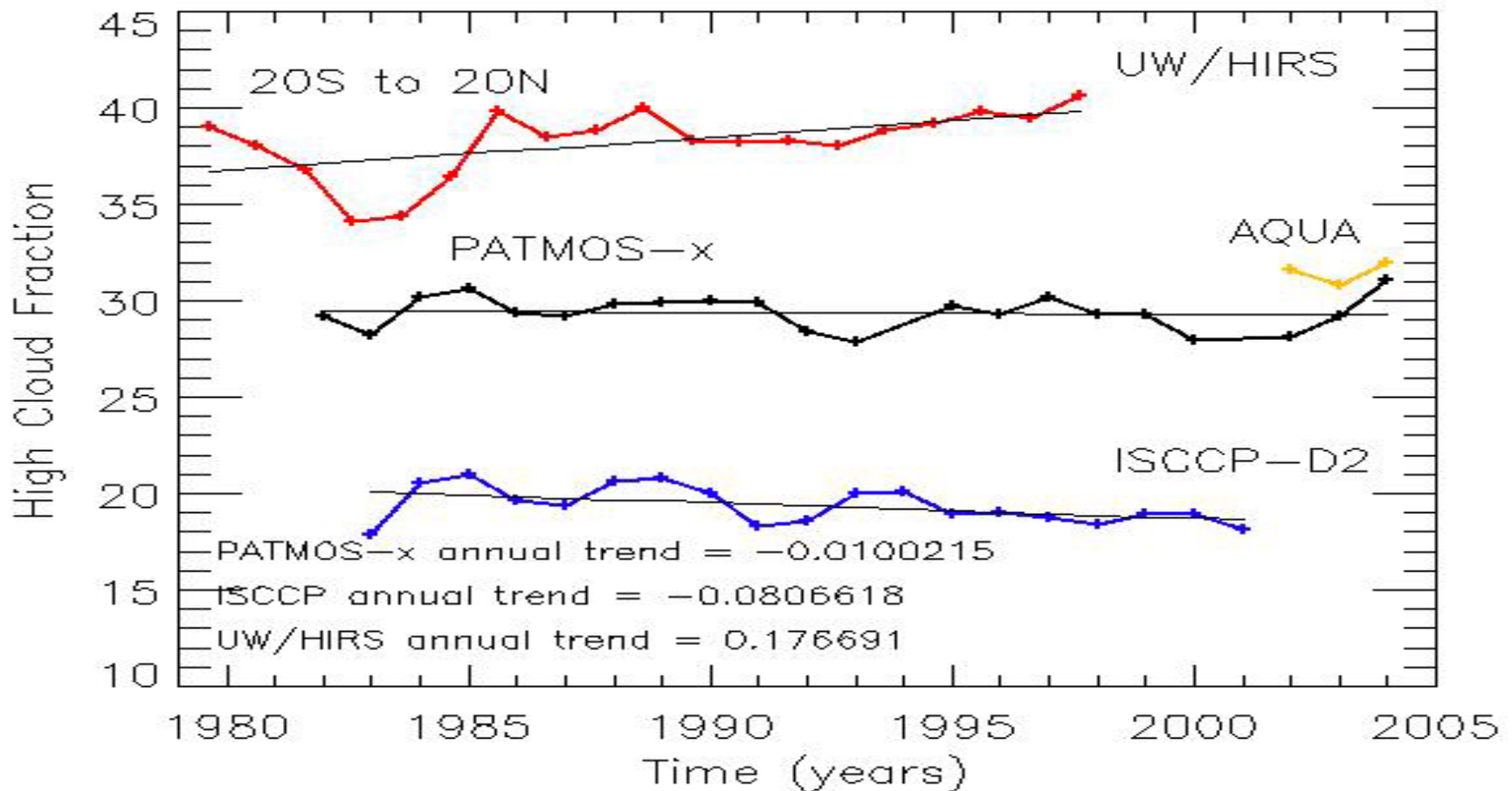


ISCCP, SOBS, UW/HIRS, TOVS/HIRS, PATMOS-x, MODIS

Seasonal cycles all agree through 10% spread on magnitudes.

Detection of High Cloud Differs Appreciably

A series of GEWEX workshops to assess the state of the various satellite cloud climatologies (ISCCP, HIRS, PATMOS-x, MODIS) found large disagreement in the high cloud long-term time-series. Work remains to be done.



Key Areas of Uncertainty **in Understanding Climate & Global Change**

- * Earth's radiation balance and the influence of clouds on radiation and the hydrologic cycle
- * Oceanic productivity, circulation and air-sea exchange
- * Transformation of greenhouse gases in the lower atmosphere, with emphasis on the carbon cycle
- * Changes in land use, land cover and primary productivity, including deforestation
- * Sea level variability and impacts of ice sheet volume
- * Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone
- * Volcanic eruptions and their role in climate change

Striving for the Sustainable Society

“A place where humans and their use of the environment
are in balance with nature”

“living in harmony with the environment and having
resilience to natural hazards”