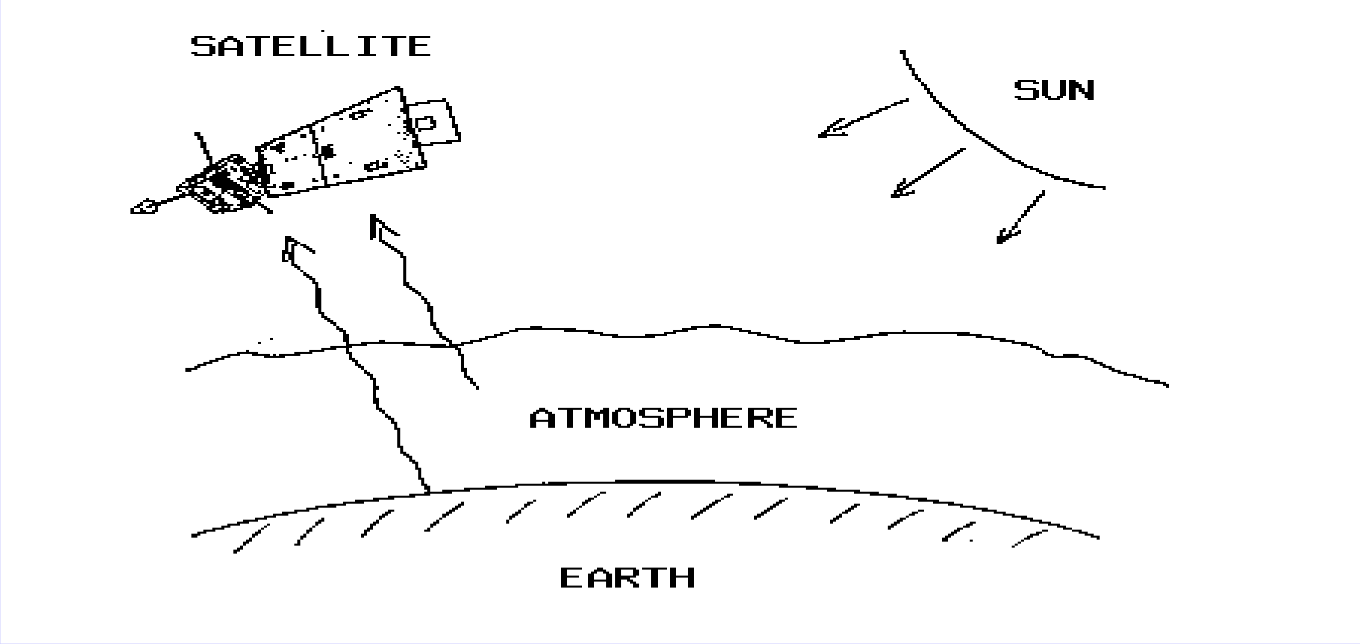
Remote Sensing - Multispectral Applications

Lectures in Maratea
22 – 31 May 2003

Paul Menzel
NOAA/NESDIS/ORA

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

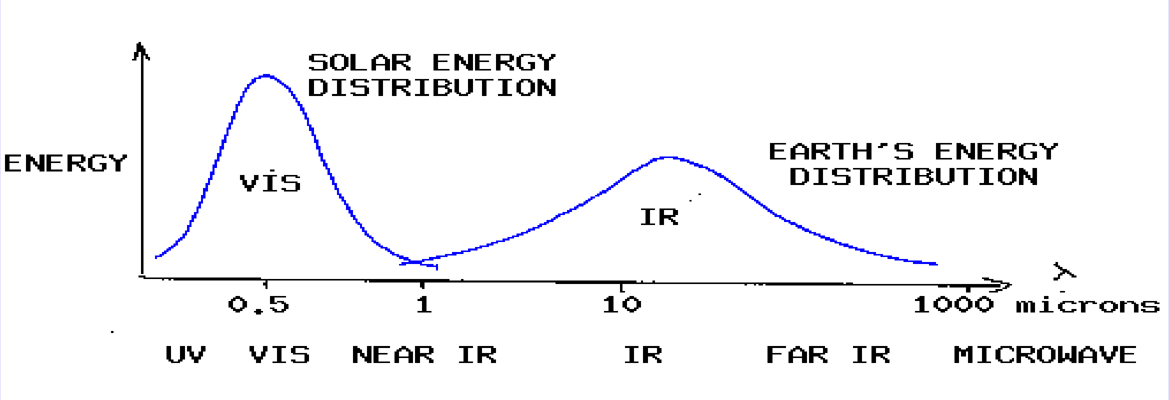
* covers a broader portion of the spectrum than the human eye

* 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

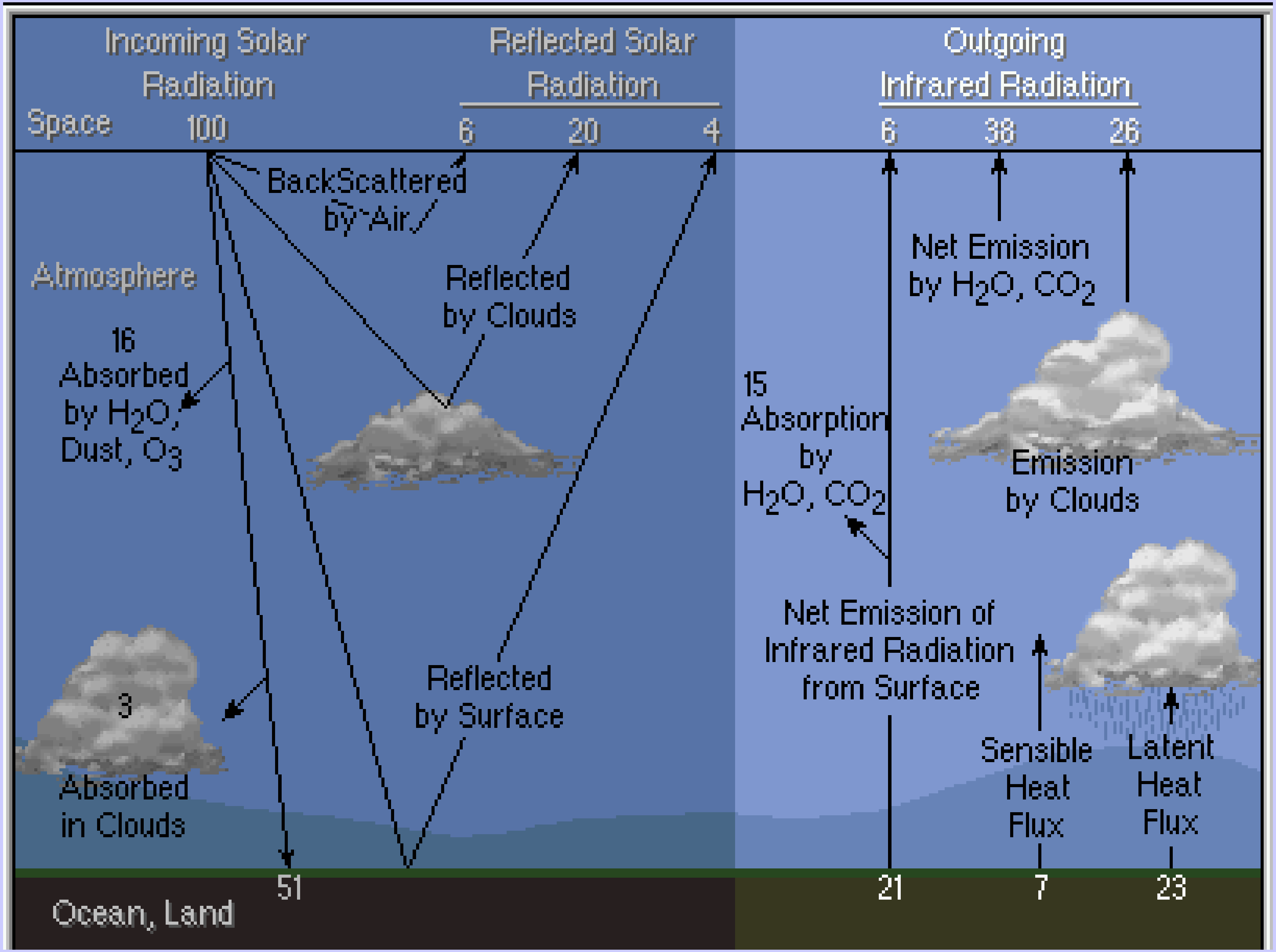
* Changes in land use, land cover and primary productivity, including deforestation

* Sea level variability and impacts of ice sheet volume

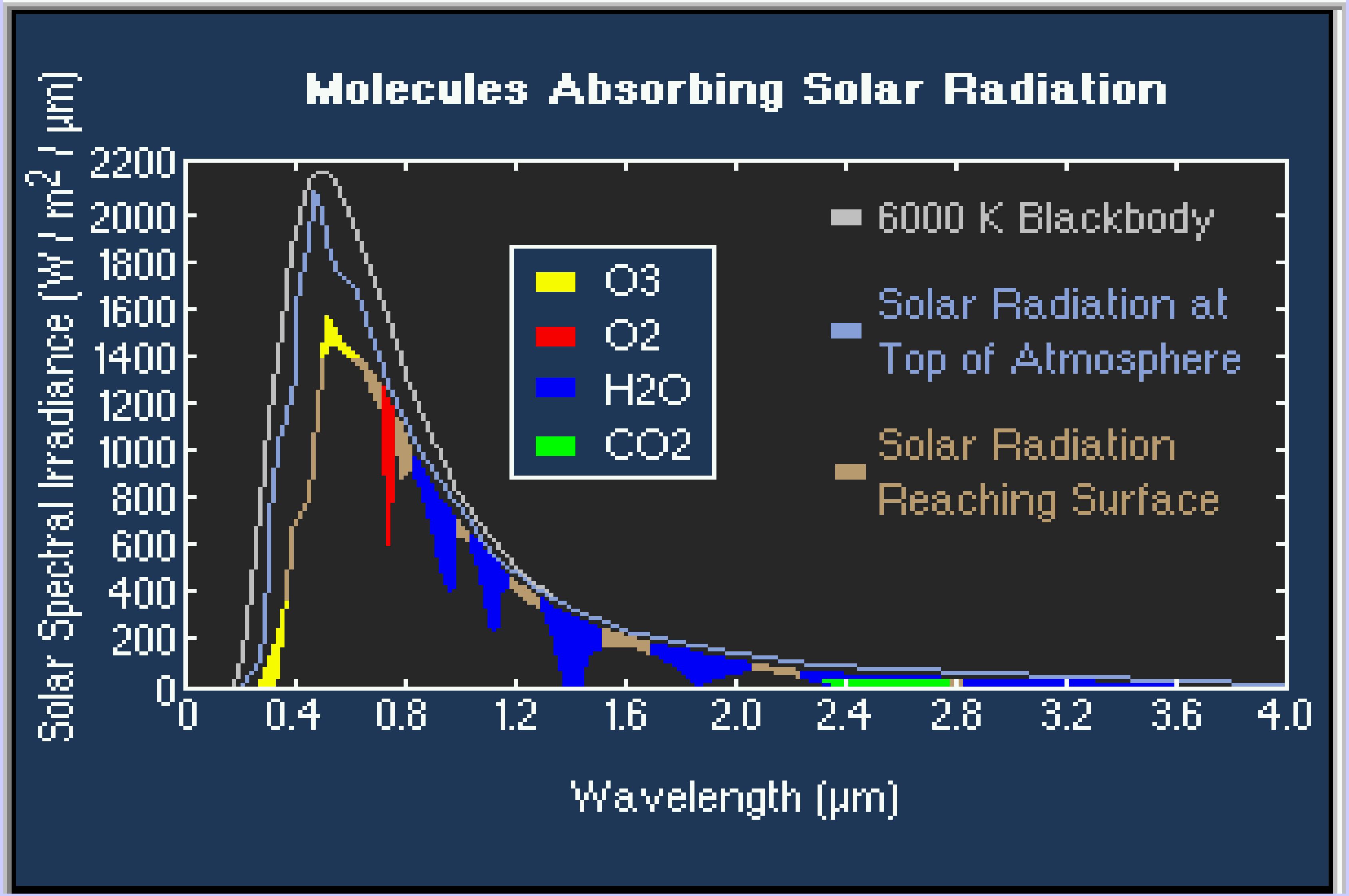
* Chemistry of the middle and upper stratosphere, including sources and sinks of stratospheric ozone

* Volcanic eruptions and their role in climate change

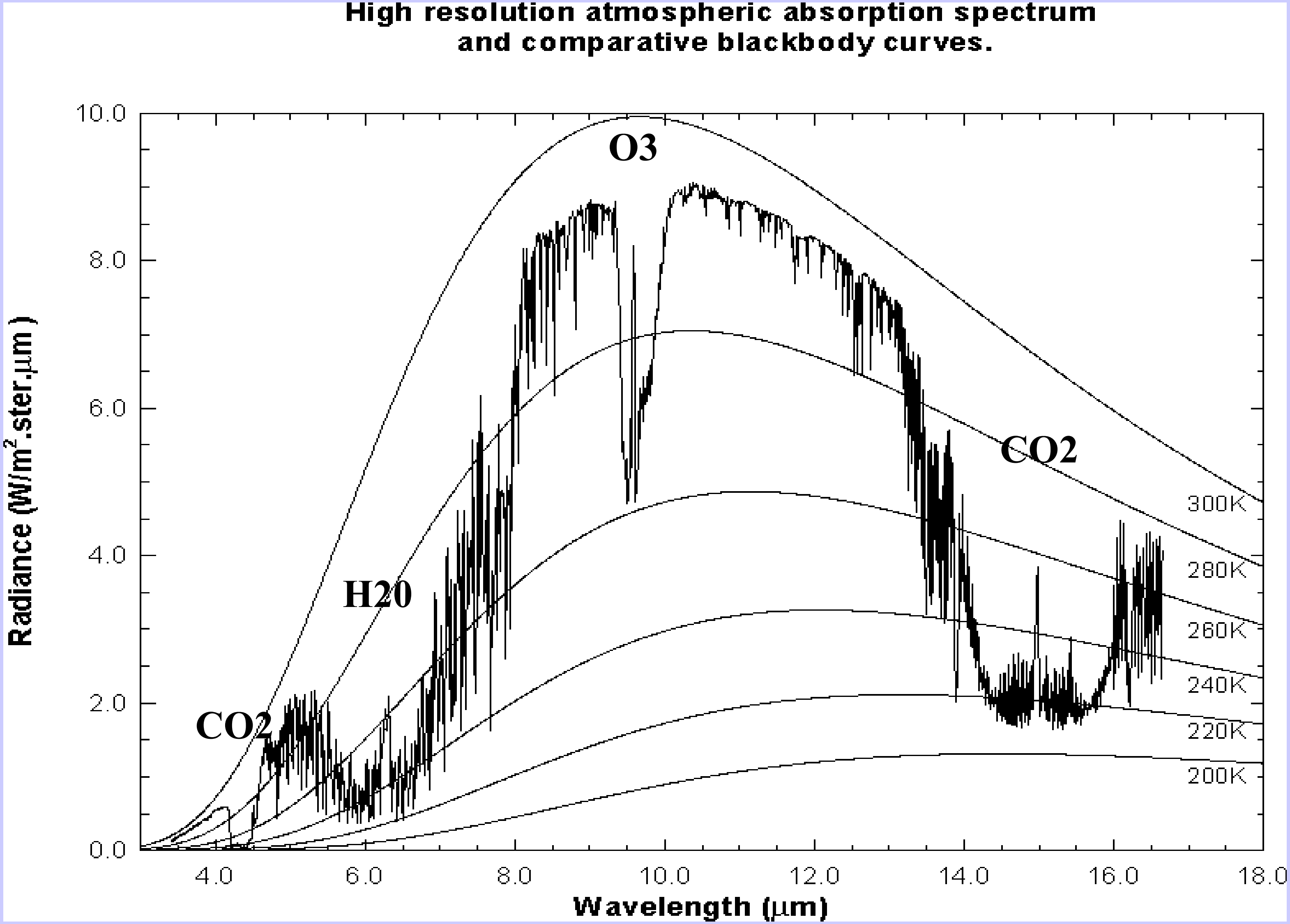
Radiative Energy Balance



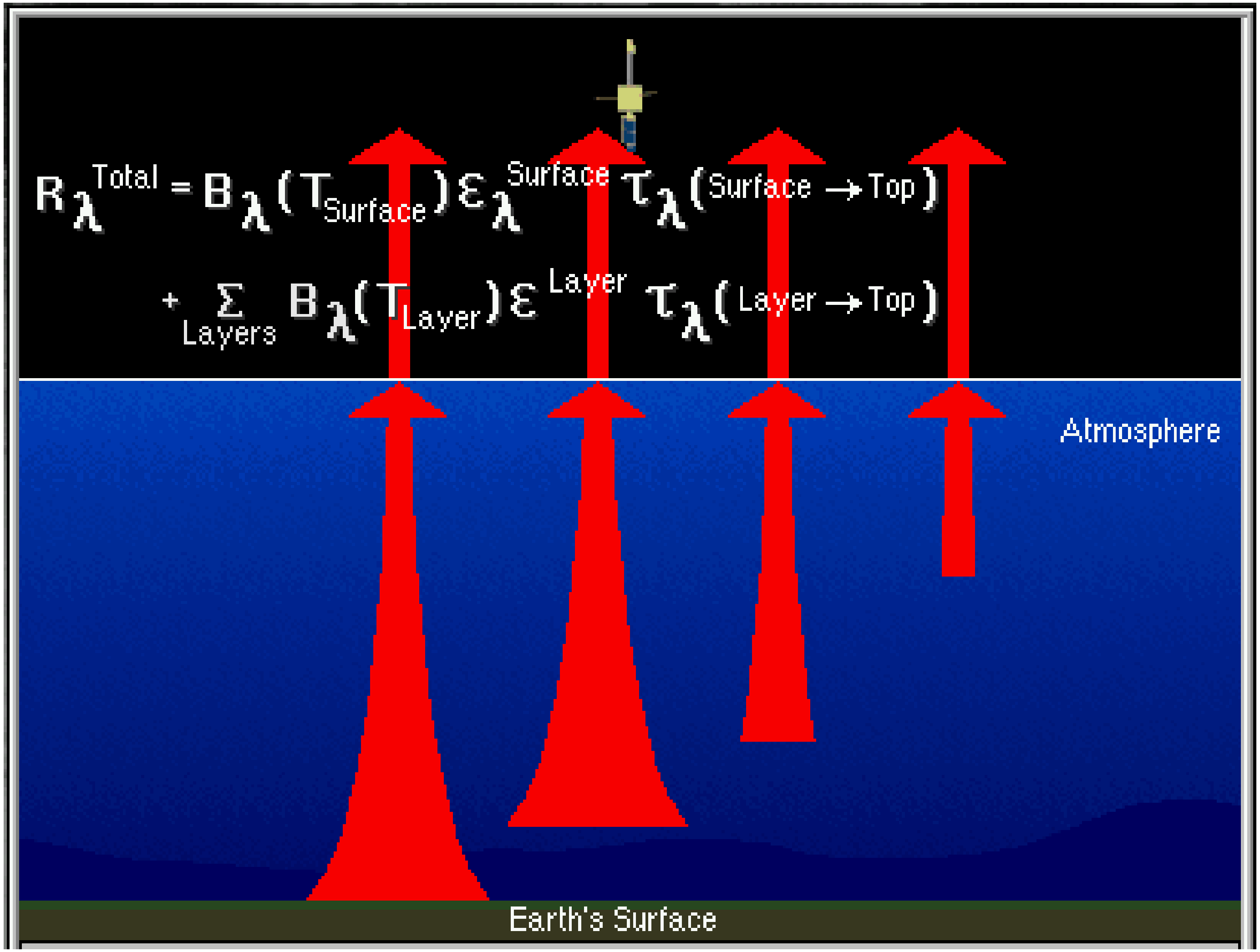
Solar Spectrum

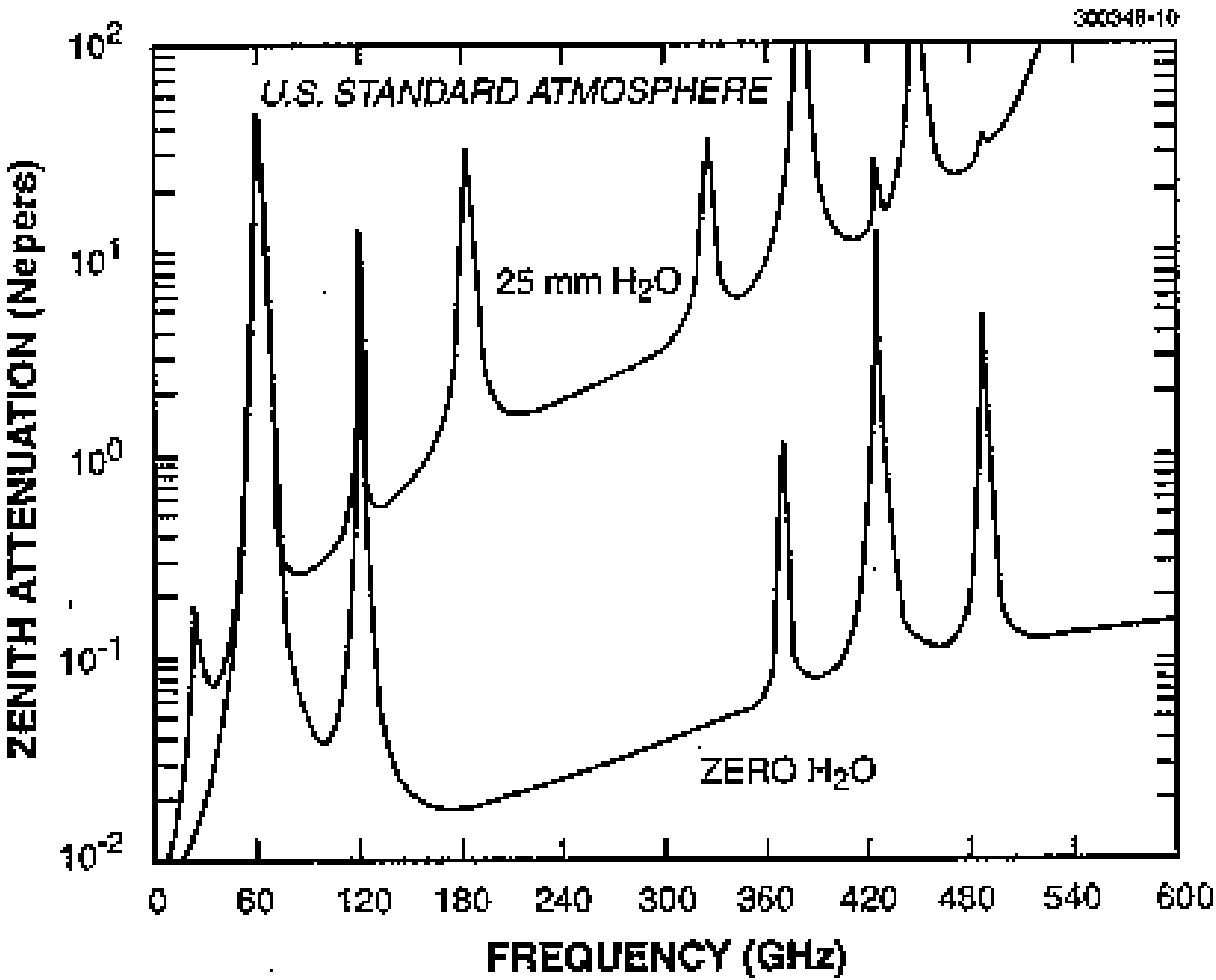


Earth emitted spectra overlaid on Planck function envelopes

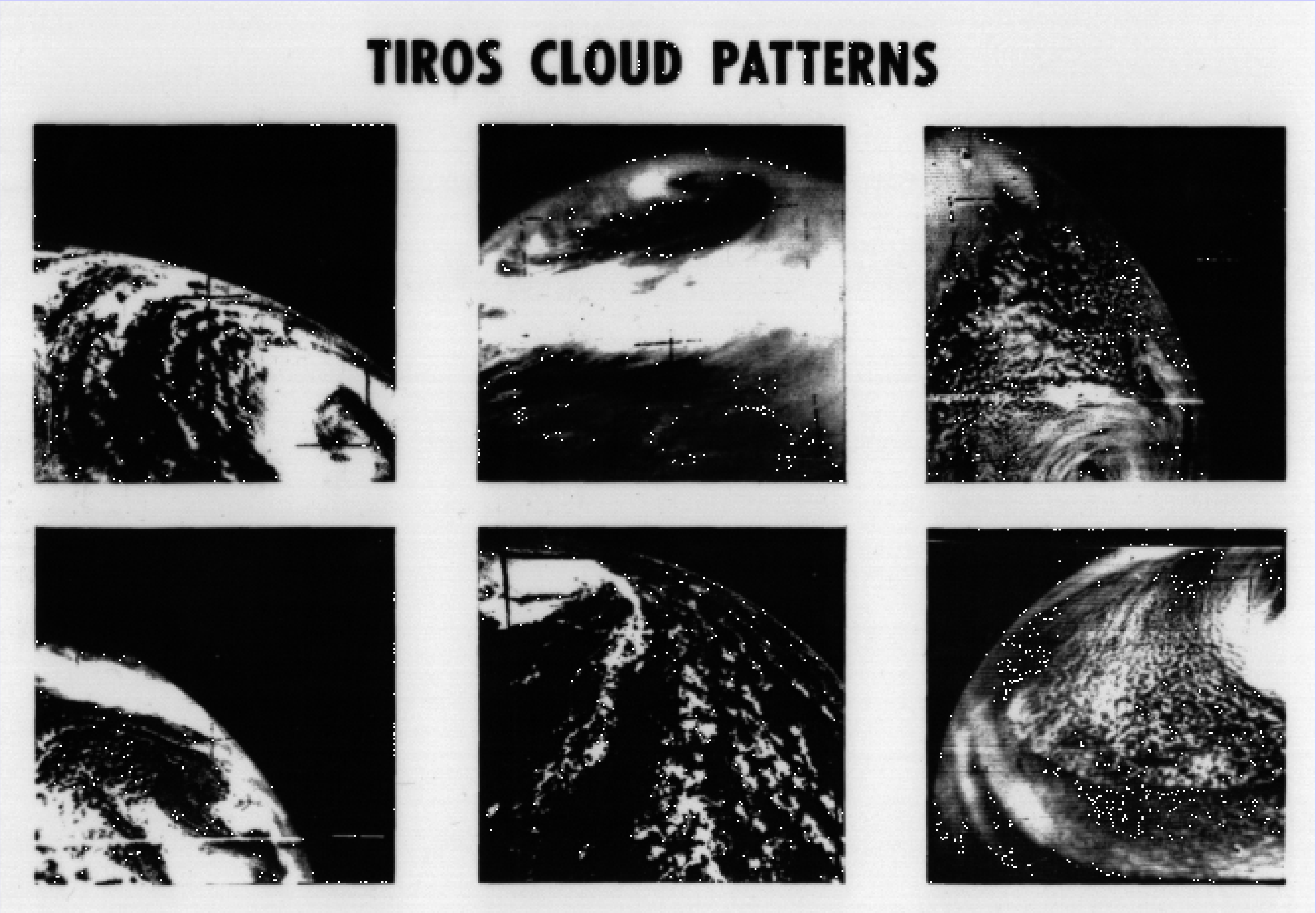


Radiative Transfer through the Atmosphere




U.S. STANDARD ATMOSPHERE
25 mm H_2O
ZERO H_2O
ZENITH ATTENUATION (Nepers)
10^2
10^1
10^0
10^{-1}
10^{-2}
0
60
120
180
240
300
360
420
480
540
600
FREQUENCY (GHz)

Clouds viewed from polar orbiting TIROS launched 1 Apr 1960



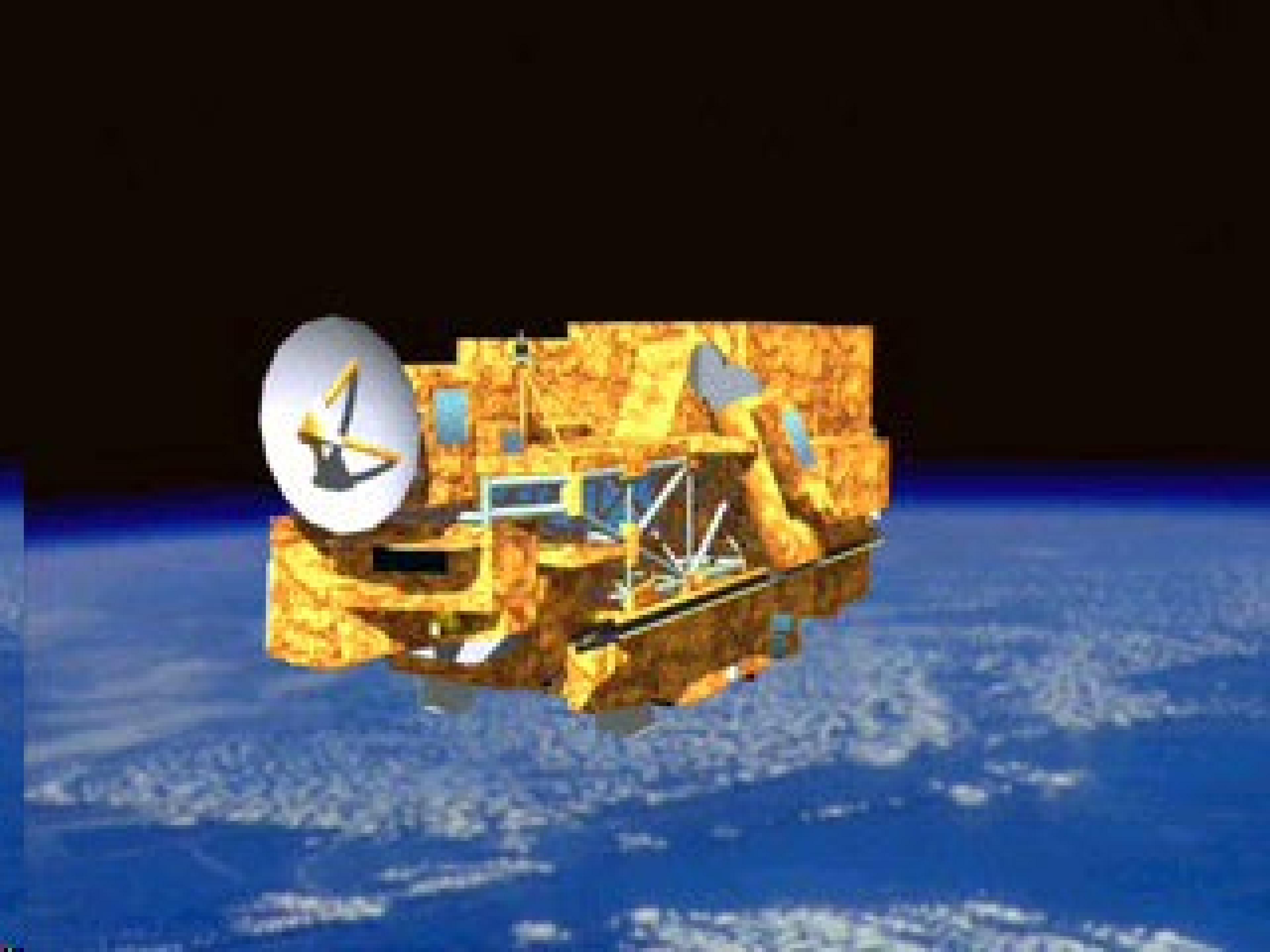
Evolution of Leo Obs

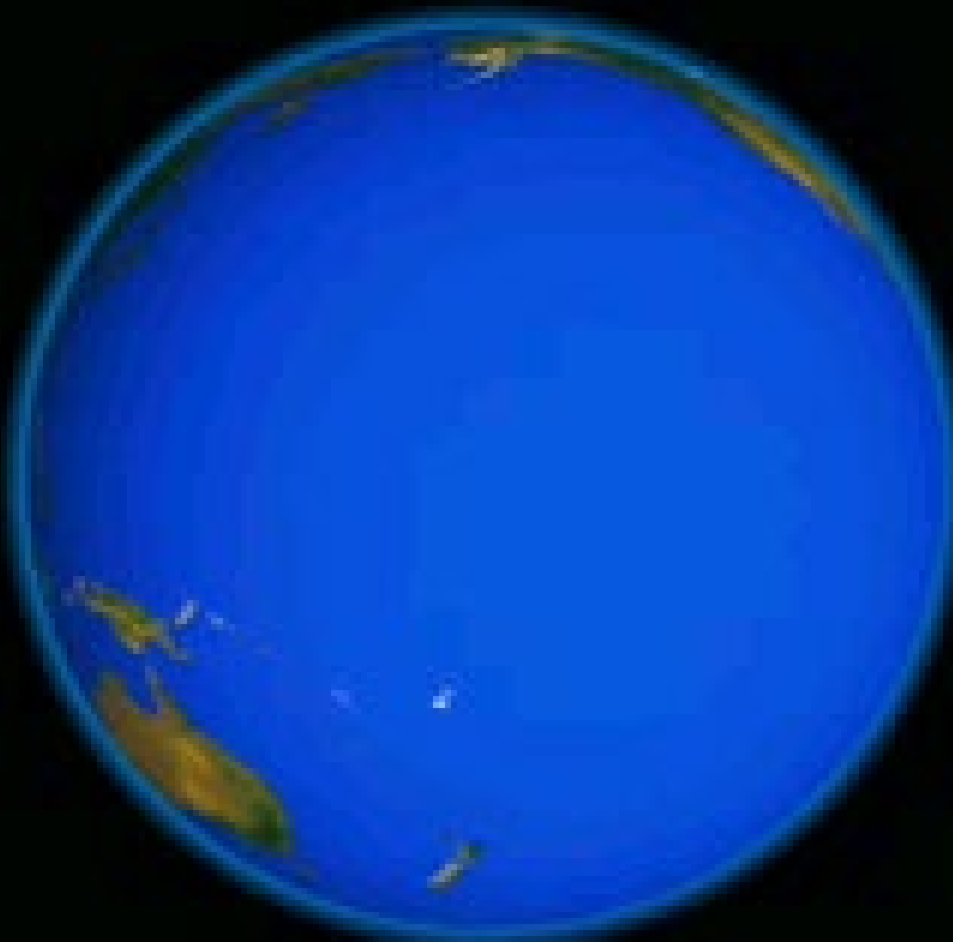
Terra was launched in 1999 and the EOS Era began

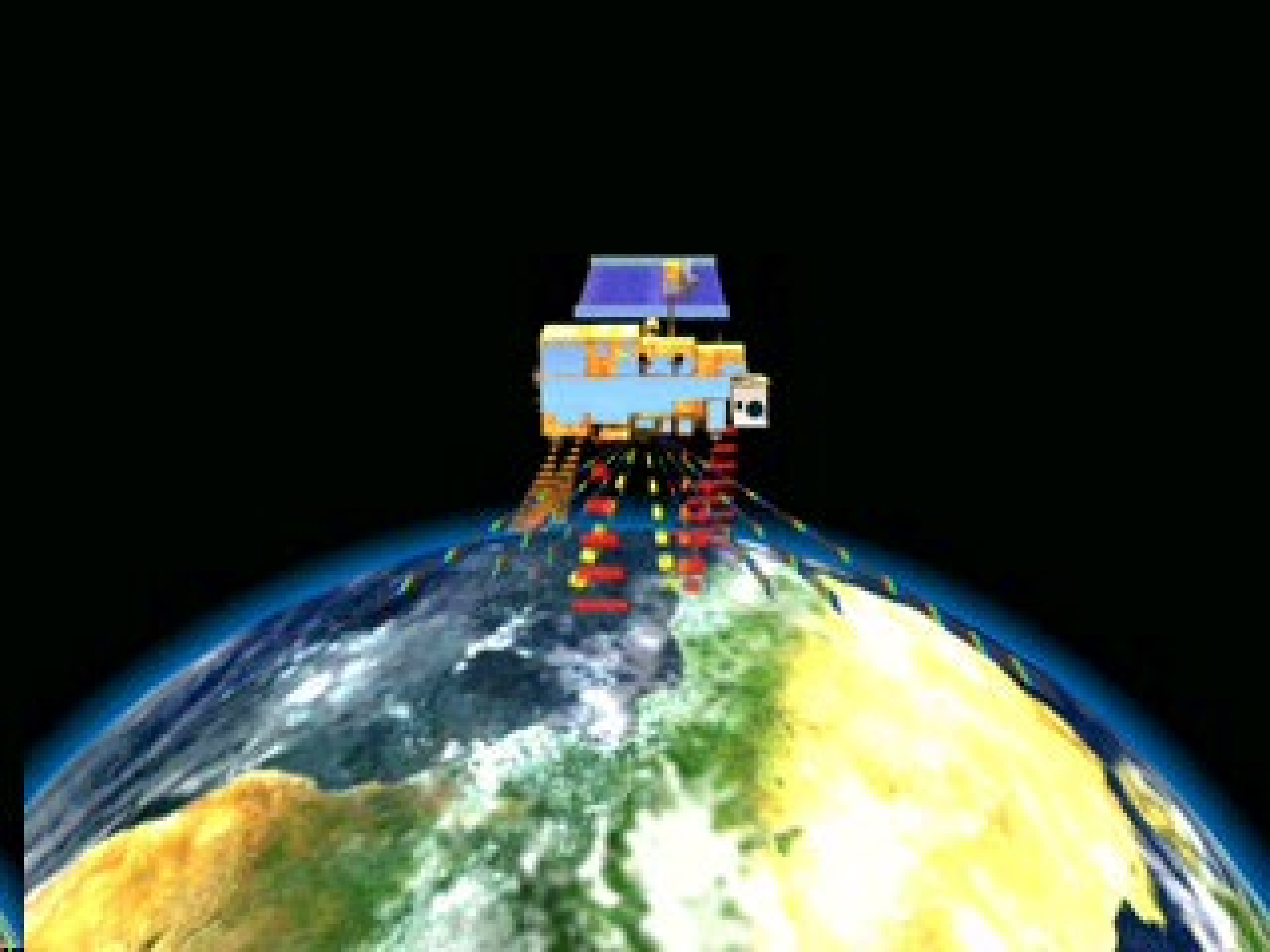
MODIS, CERES, MOPITT, ASTER, and MISR reach polar orbit

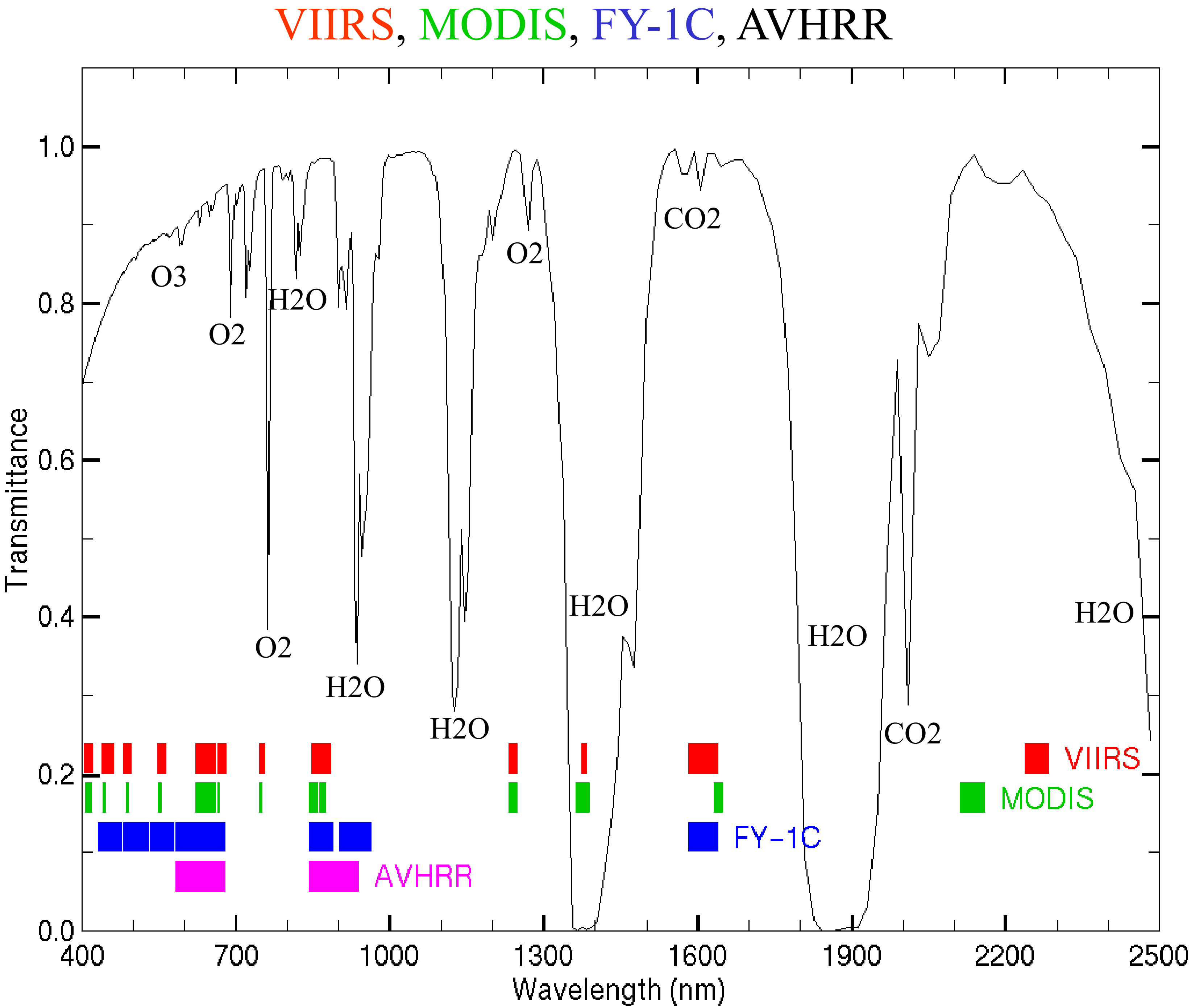
Aqua and ENVISAT followed in 2002

MODIS and MERIS leading to VIIRS
AIRS leading to IASI and CrIS
AMSU leading to ATMS



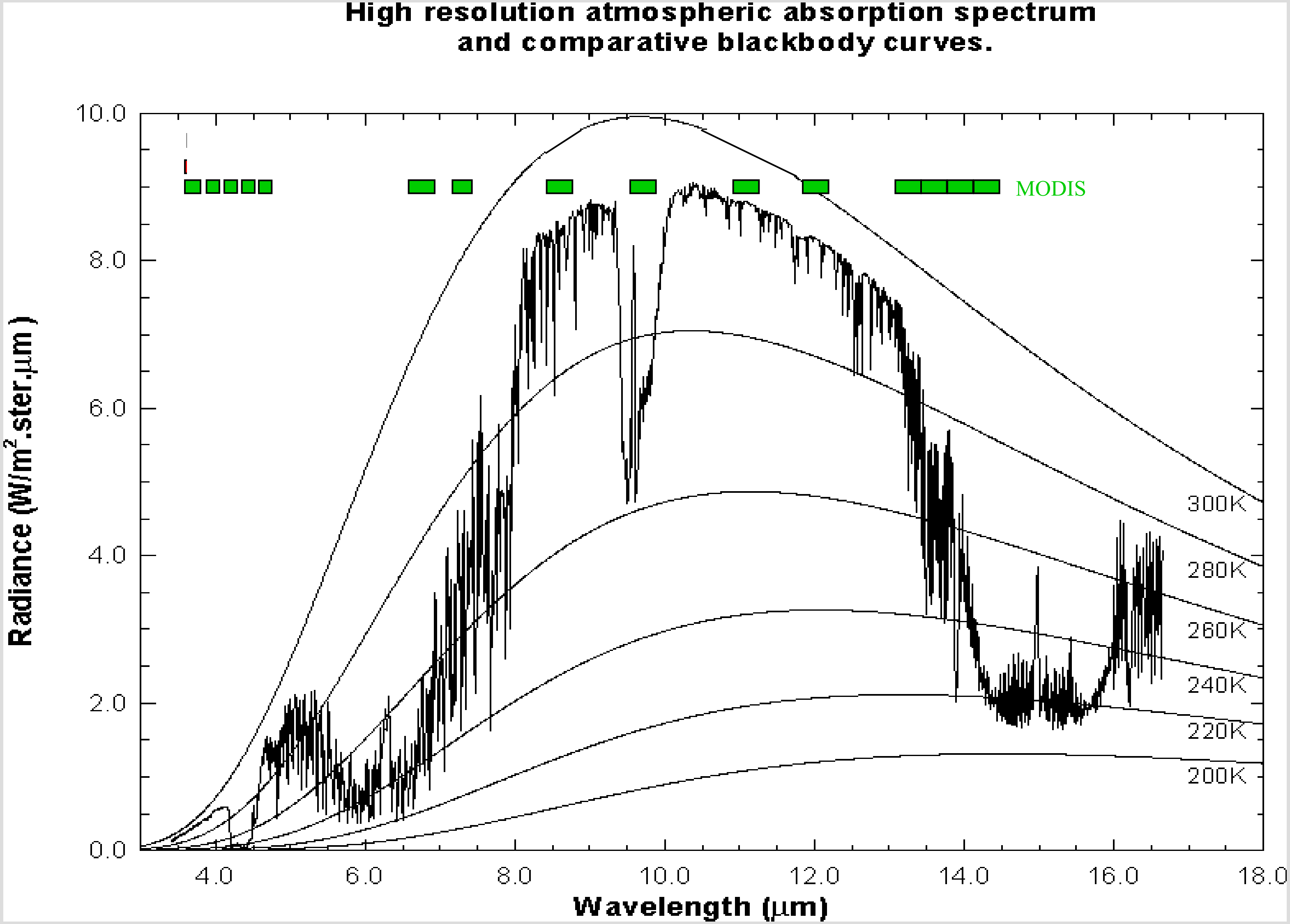




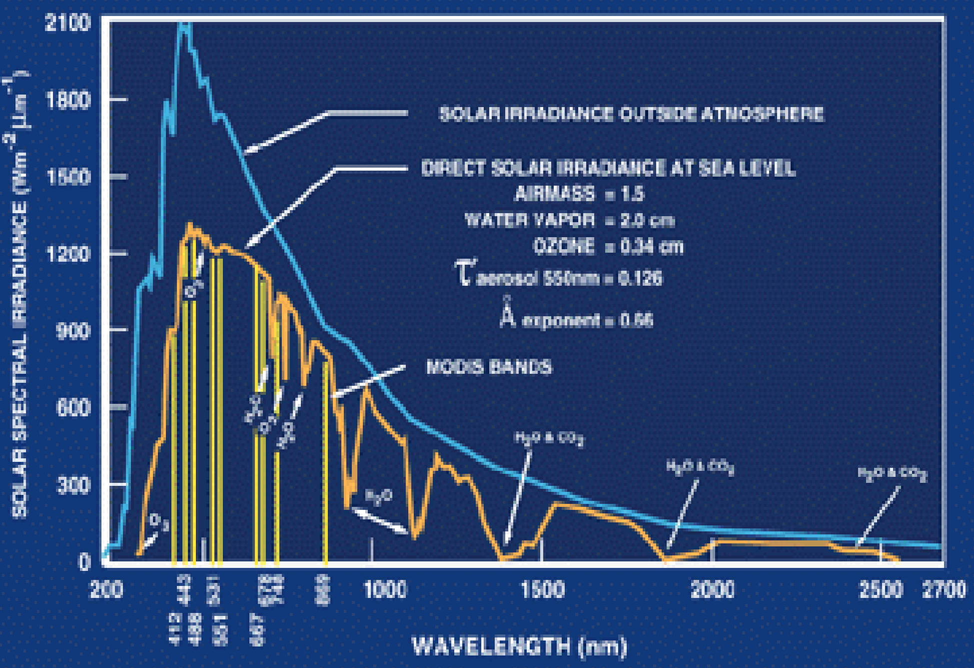


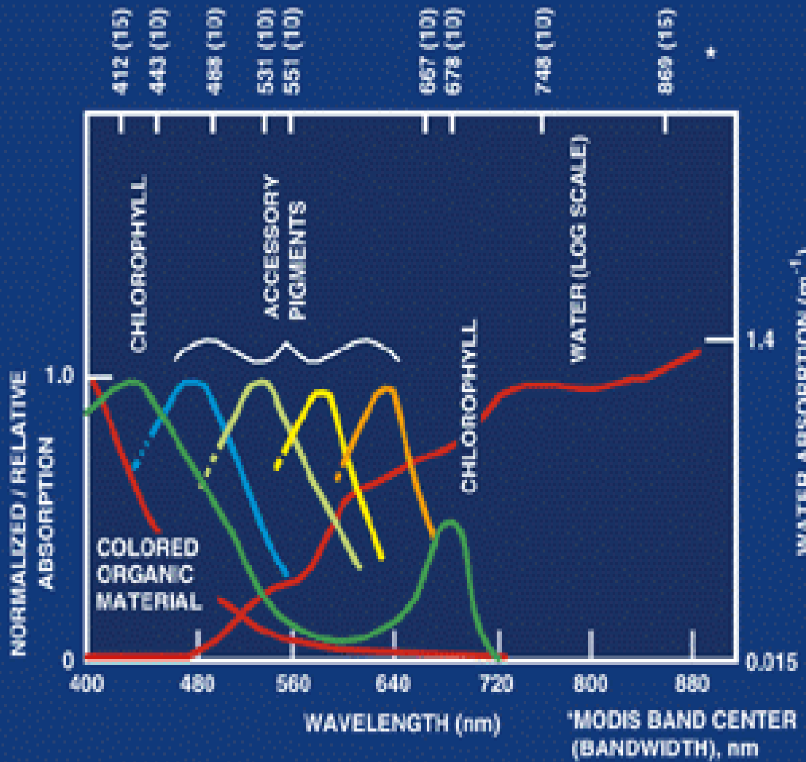
VIIRS, MODIS, FY-1C, AVHRR
Transmittance
Wavelength (nm)
1.0
0.8
0.6
0.4
0.2
0.0
400
700
1000
1300
1600
1900
2200
2500
O3
O2
H2O
O2
H2O
H2O
O2
H2O
CO2
H2O
CO2
H2O
VIIRS
MODIS
FY-1C
AVHRR

MODIS IR Spectral Bands

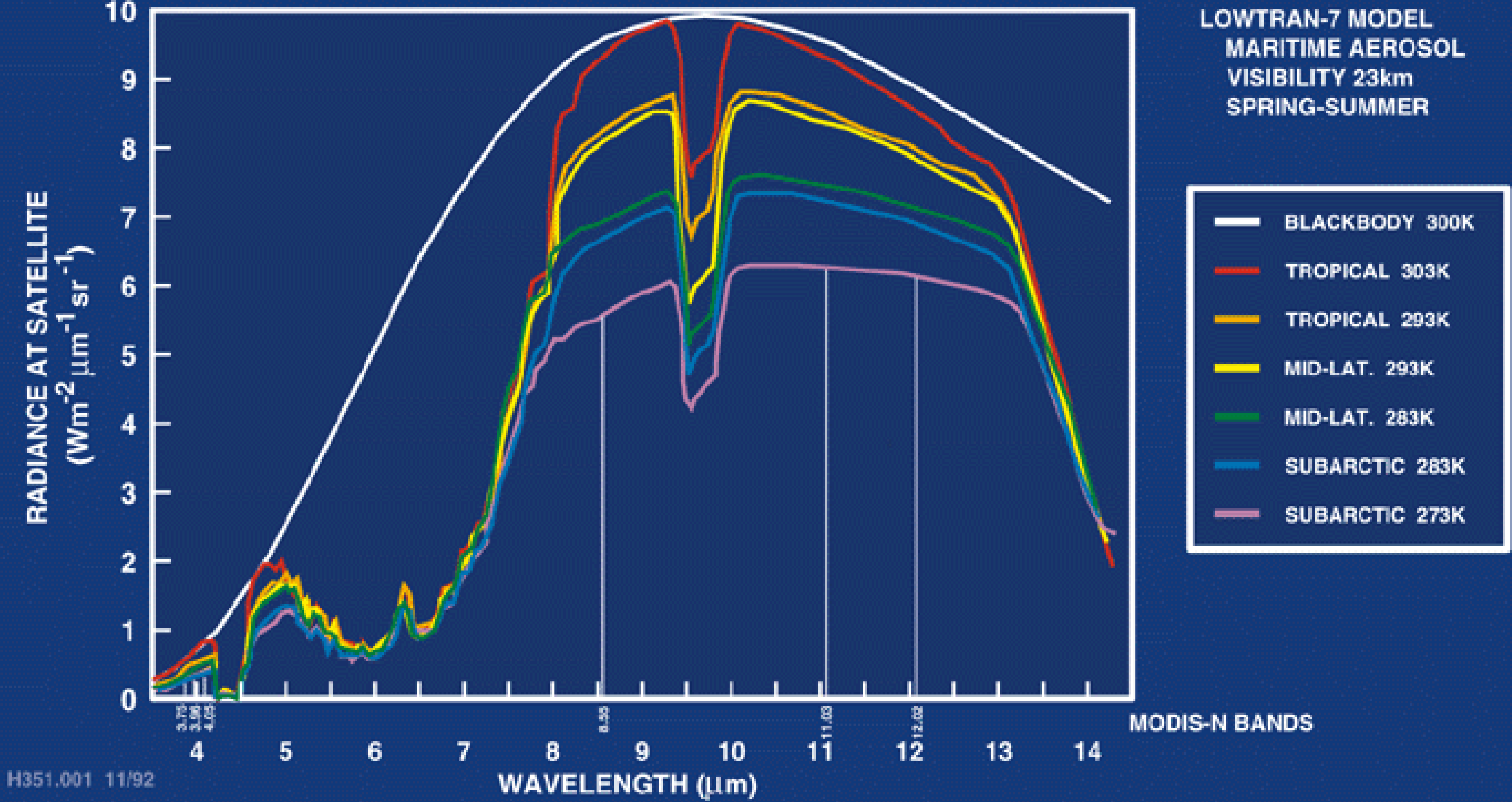


OCEAN-SOLAR RADIATION

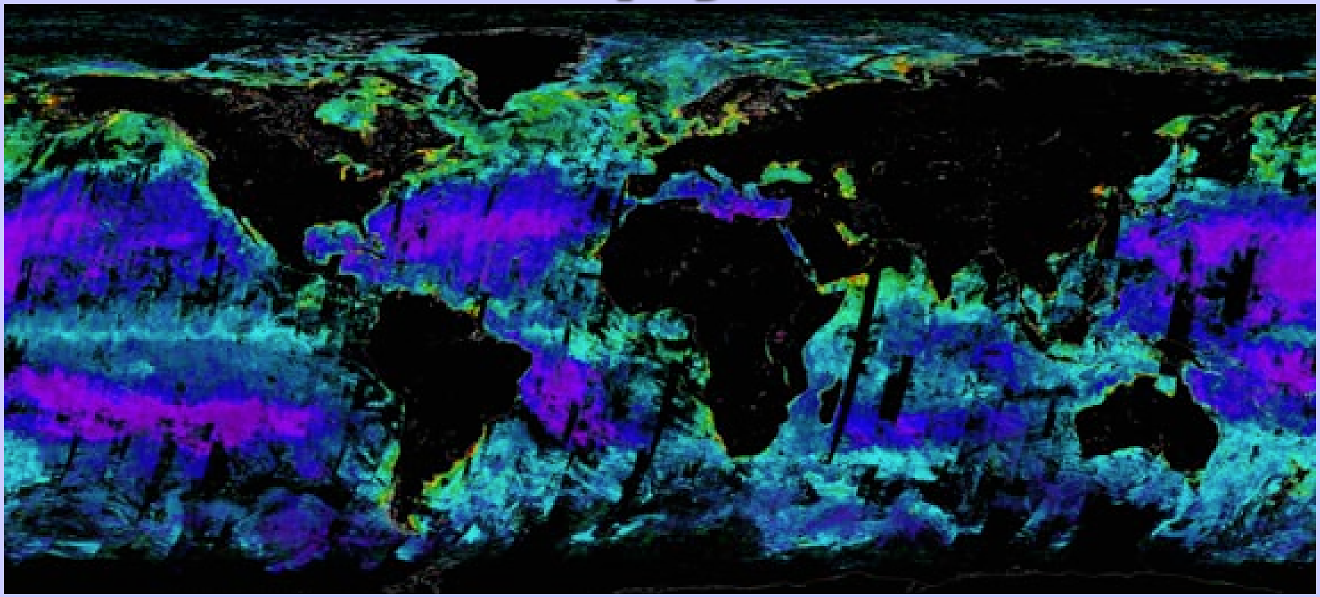




MODIS SEA SURFACE TEMPERATURE



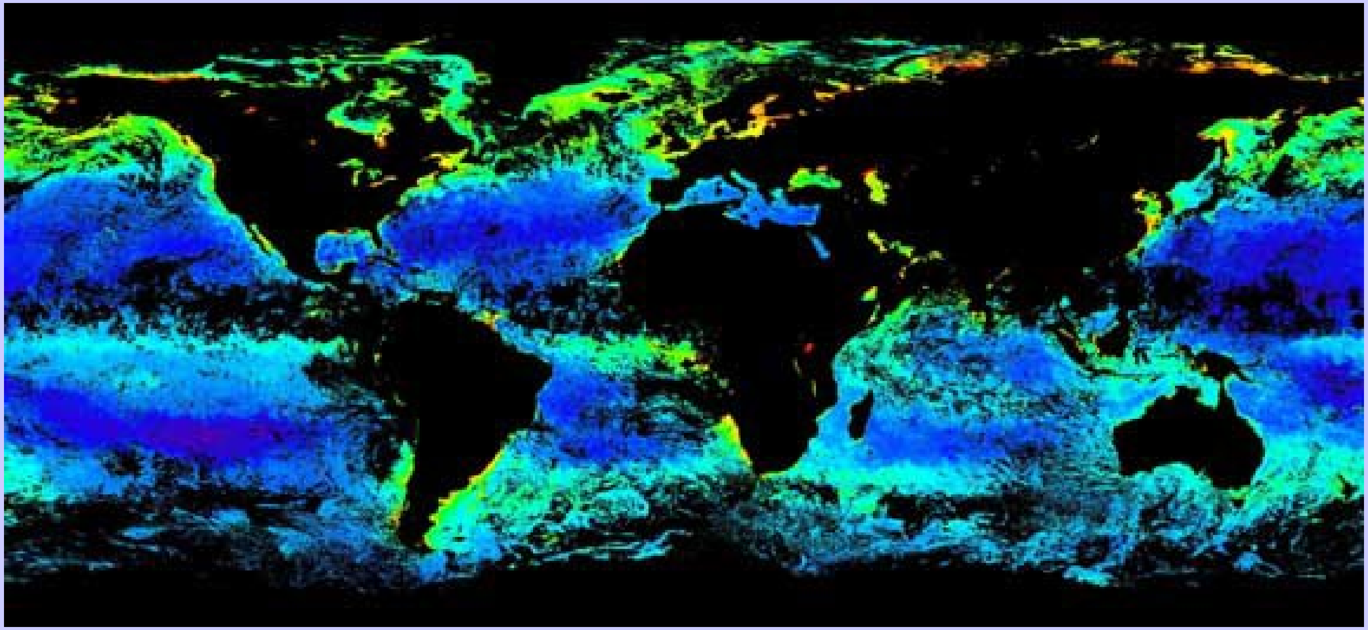
Chlorophyll - MODIS and SeaWiFS



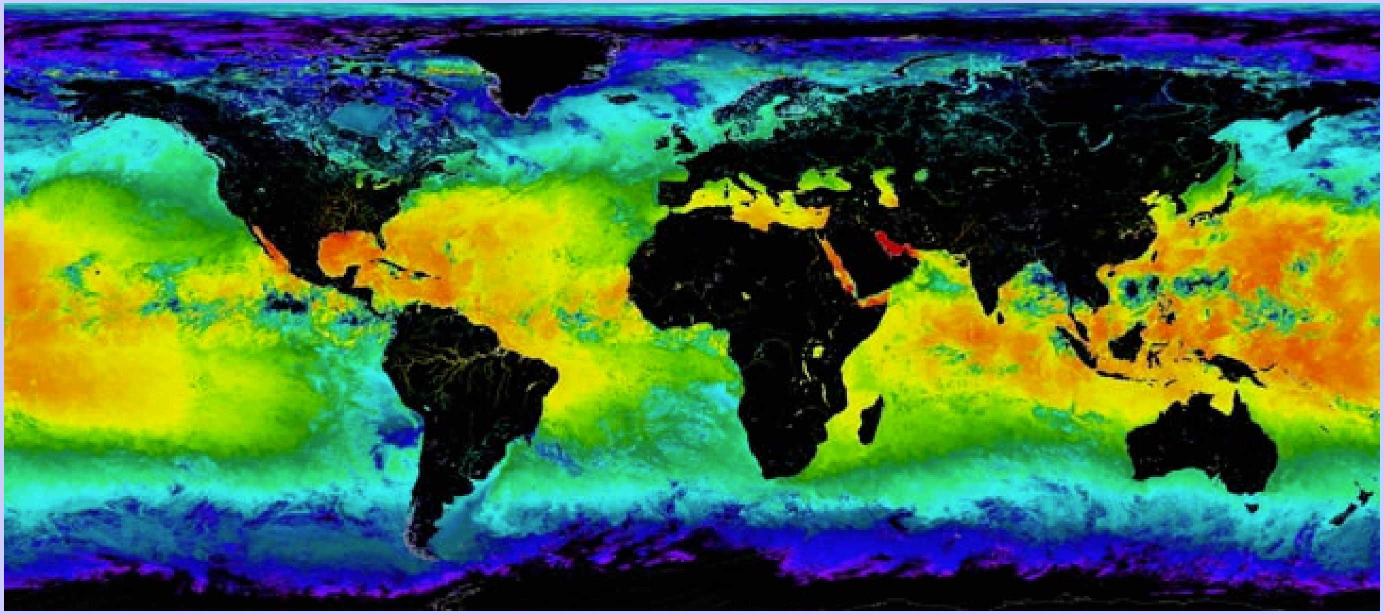
MODIS Chlor
243-250, 2000
U. Miami

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



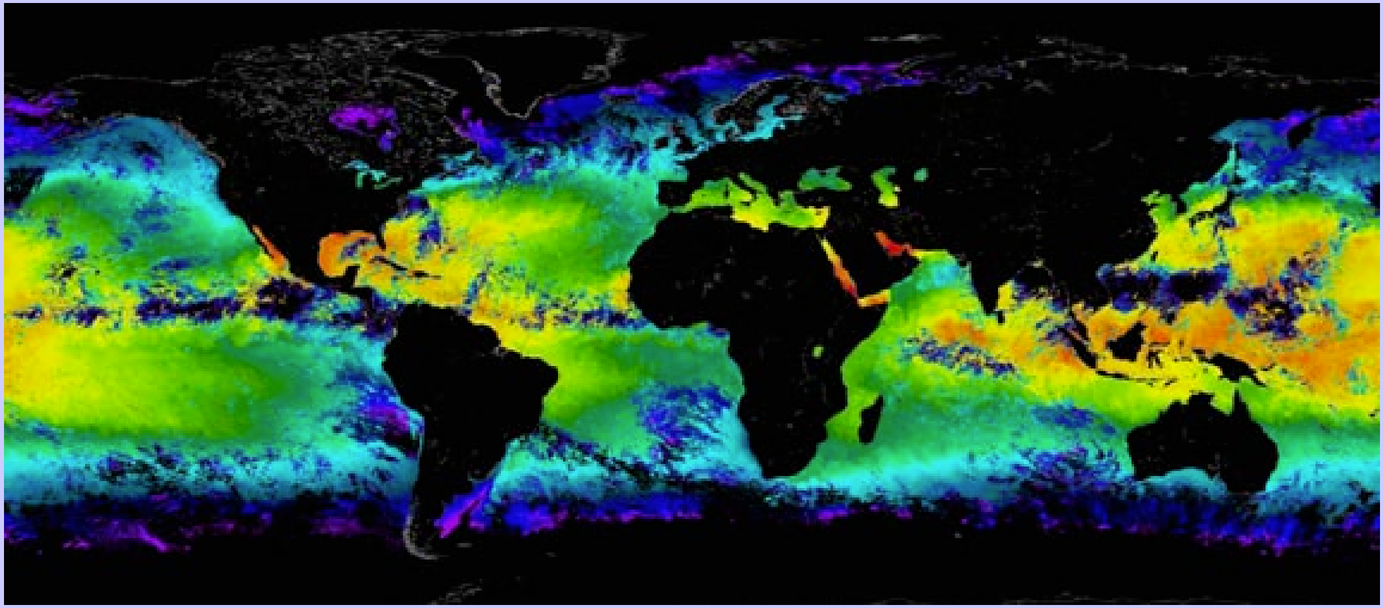
SST - MODIS and AVHRR



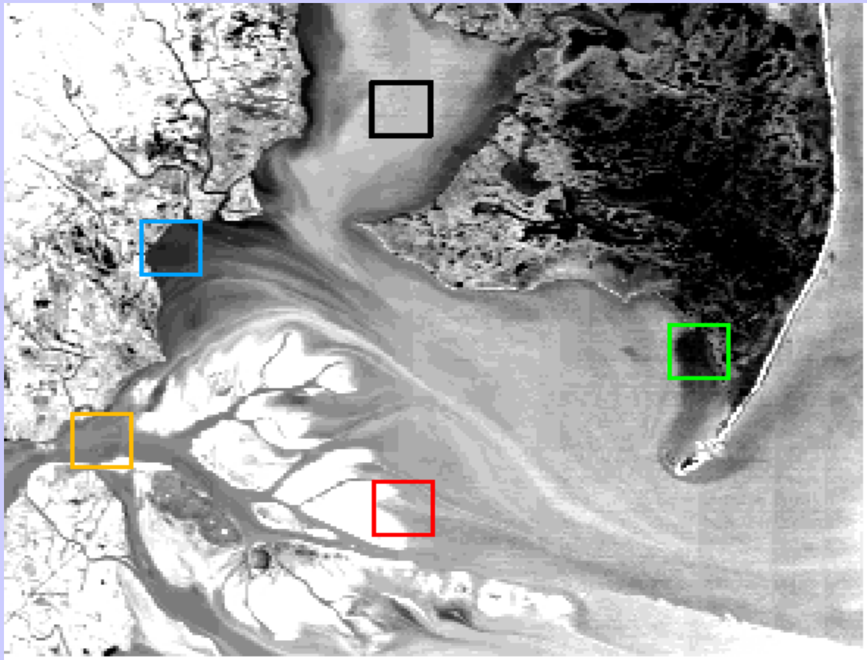
MODIS 4 micron
Night SST

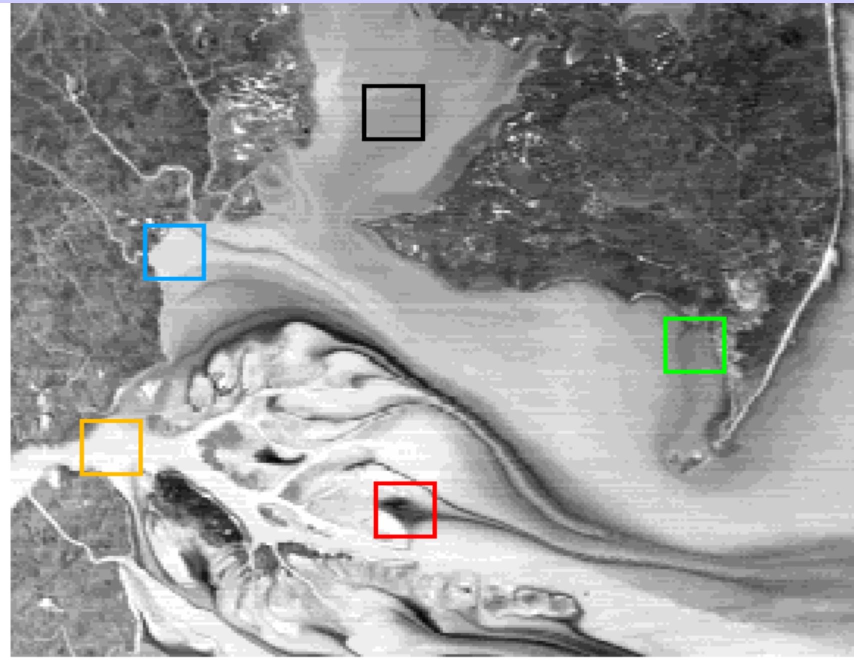
Improved coverage in tropical regions. Color scales are not identical, cloud mask is not applied.

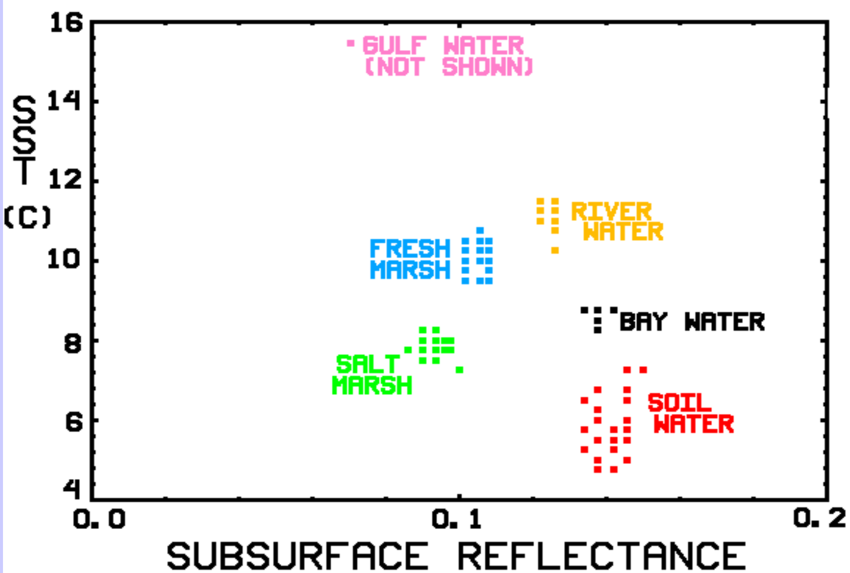
AVHRR
Night SST




MODIS views the Mississippi







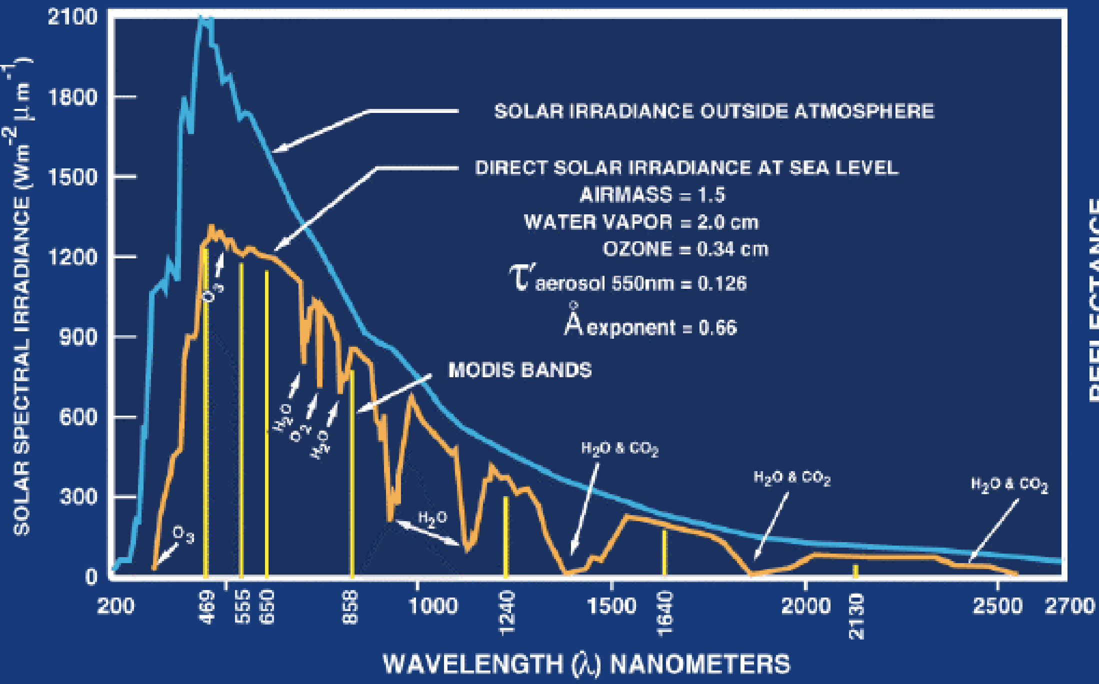
MAMS WATER TYPE ANALYSIS
DEC 4 1990

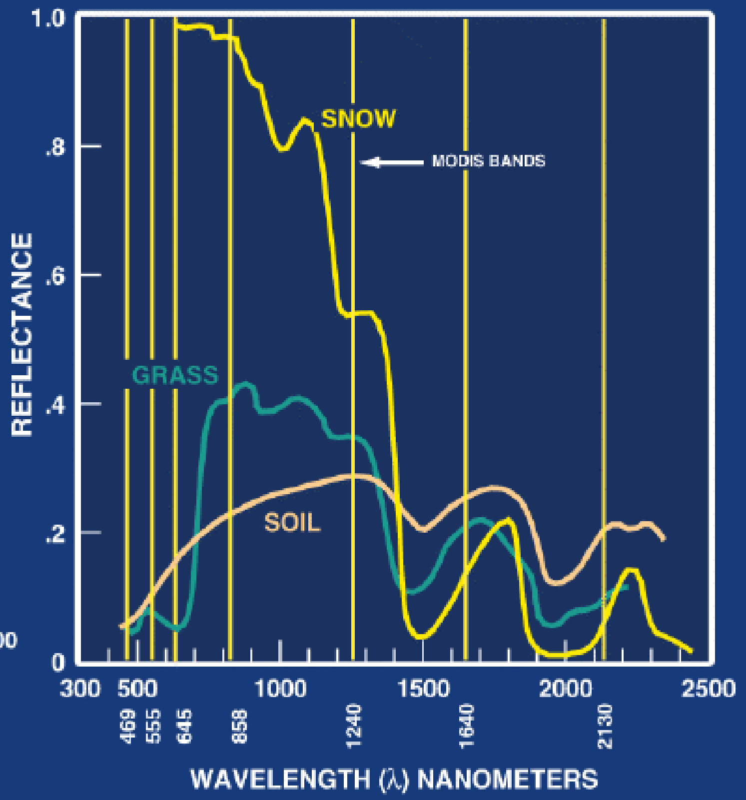
SHOWN:

* .66um REFLECTANCE (LEFT)
* SPLIT WINDOW SST (RIGHT)

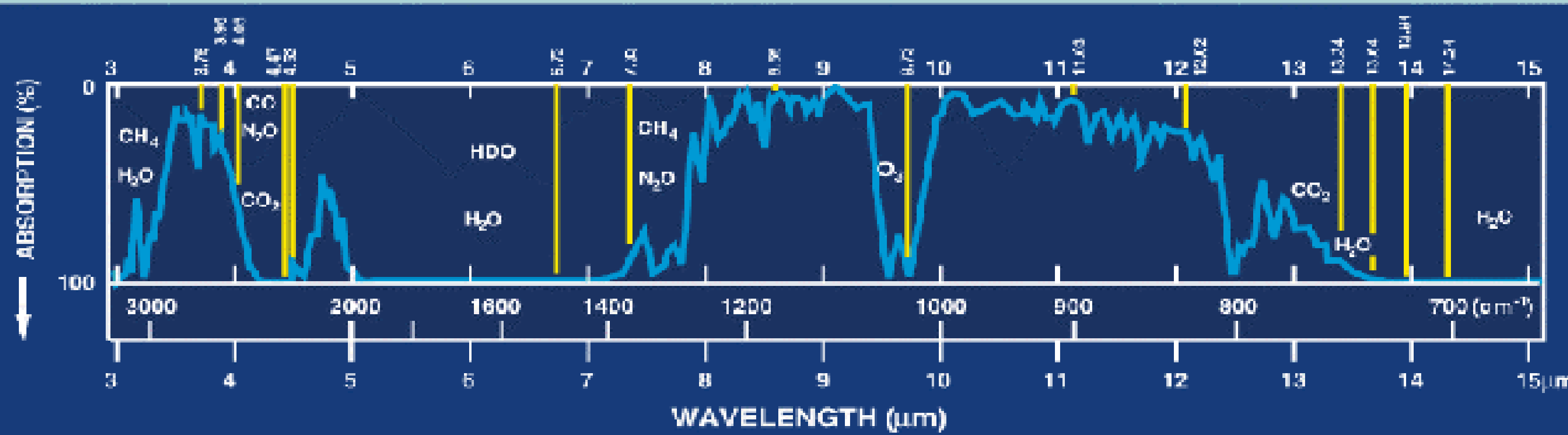
0005 ACFT 09 4 DEC 91338 164701 53491 00035 01.50

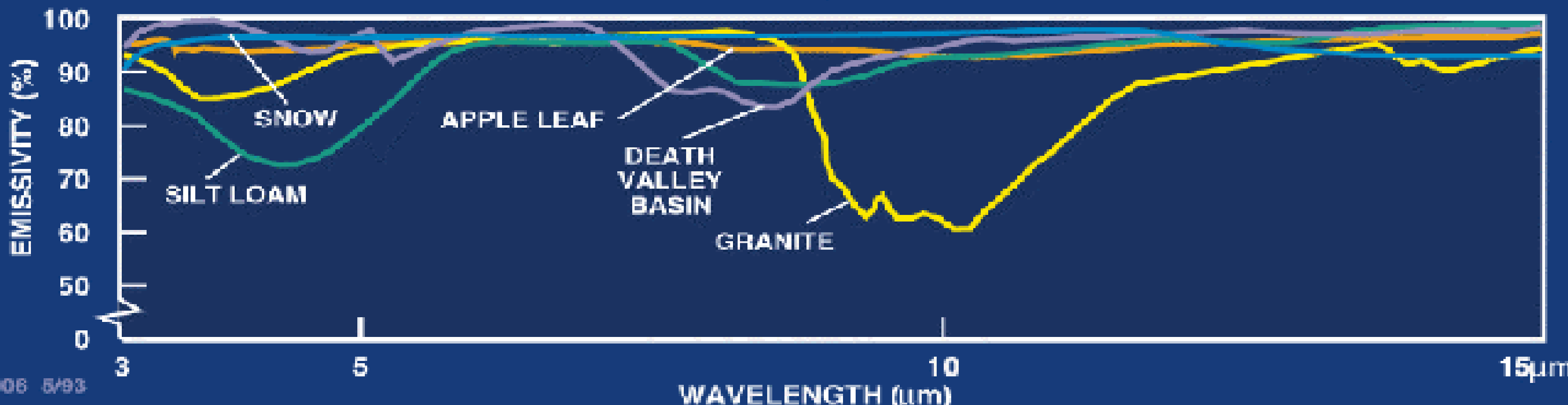
LAND-SOLAR RADIATION



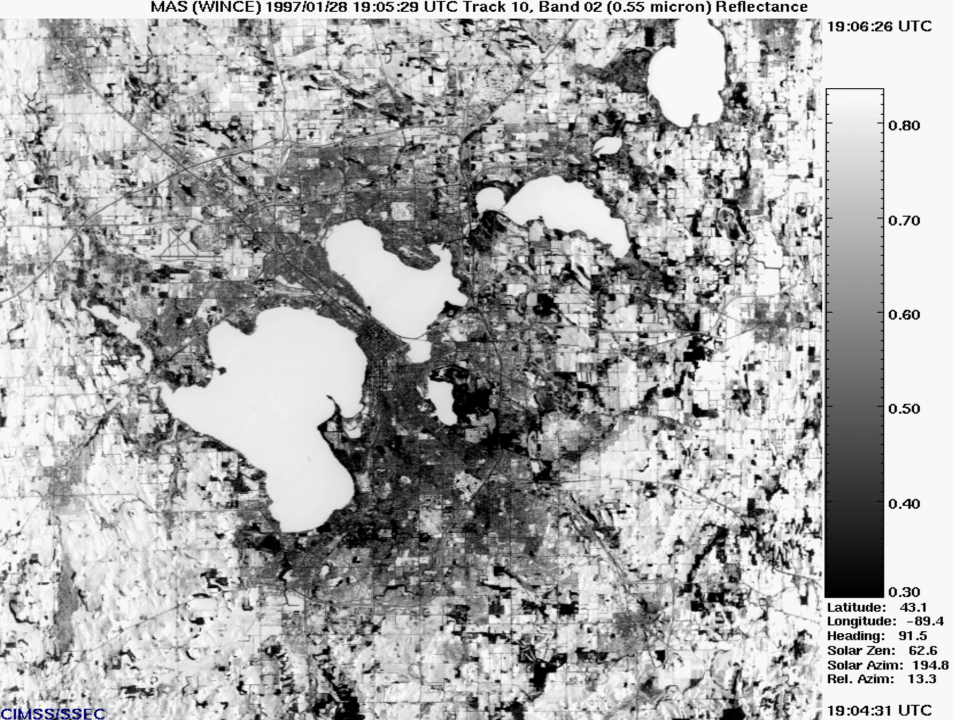


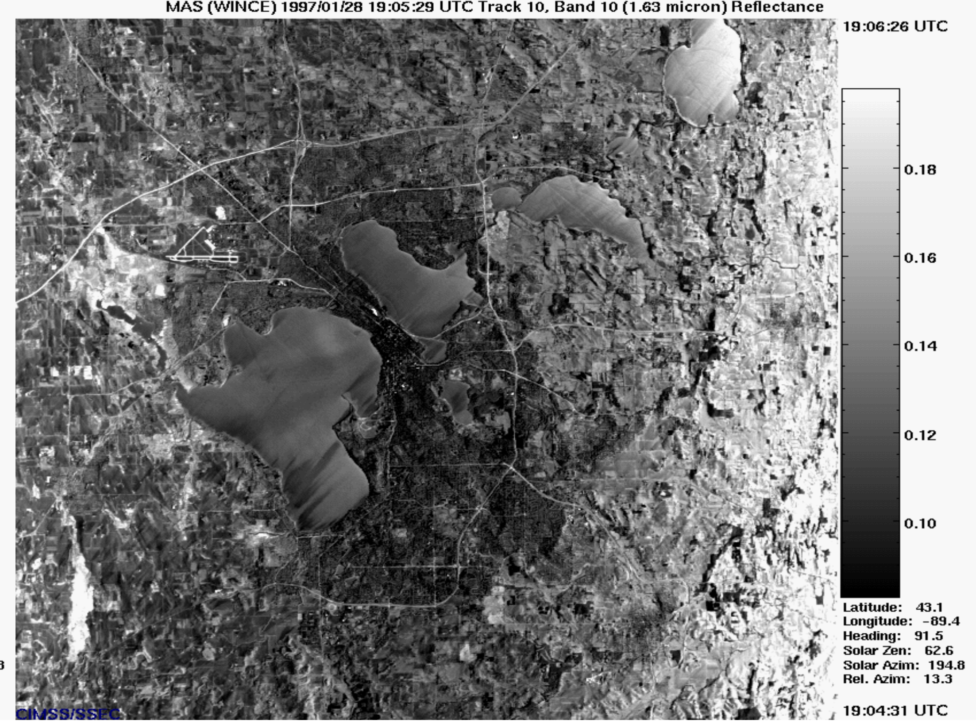
LAND - THERMAL RADIATION



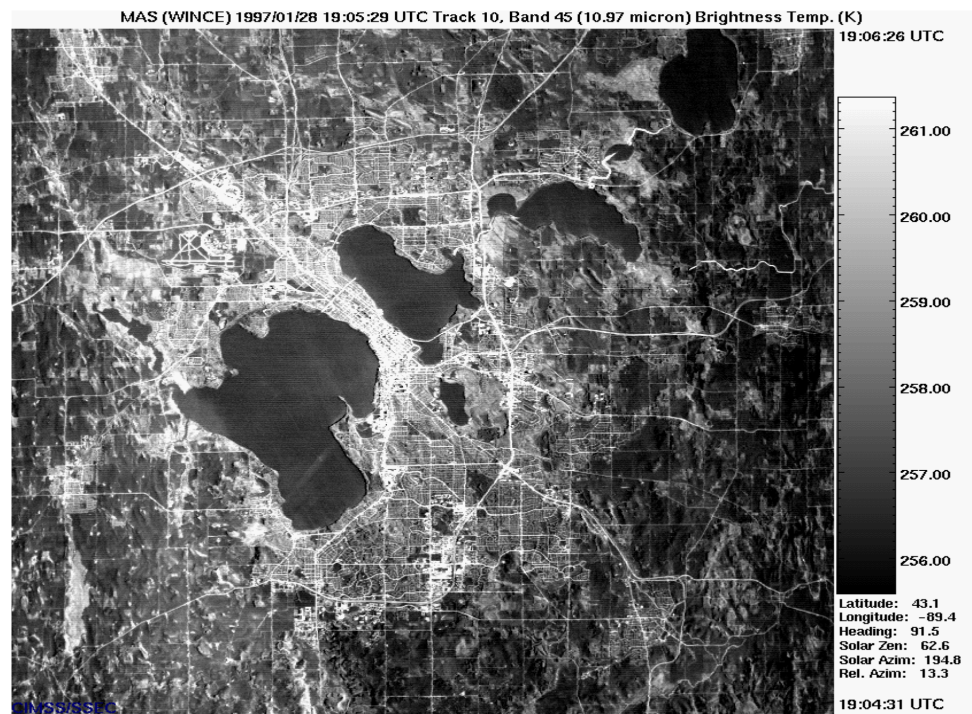


C351.006 5/93



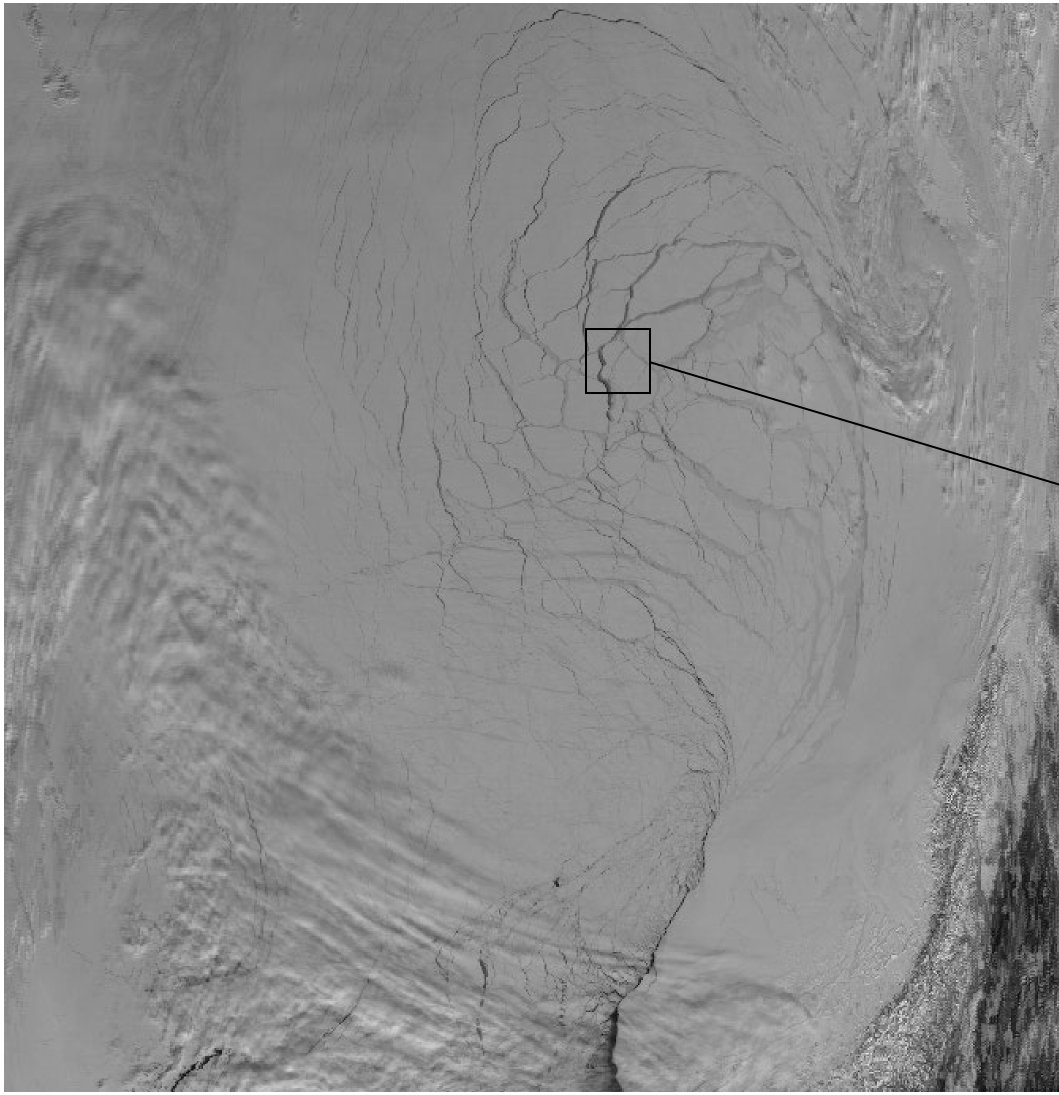


MODIS Airborne Simulator (MAS) 0.6, 1.6, & 11.0 um data over Madison in Jan 97

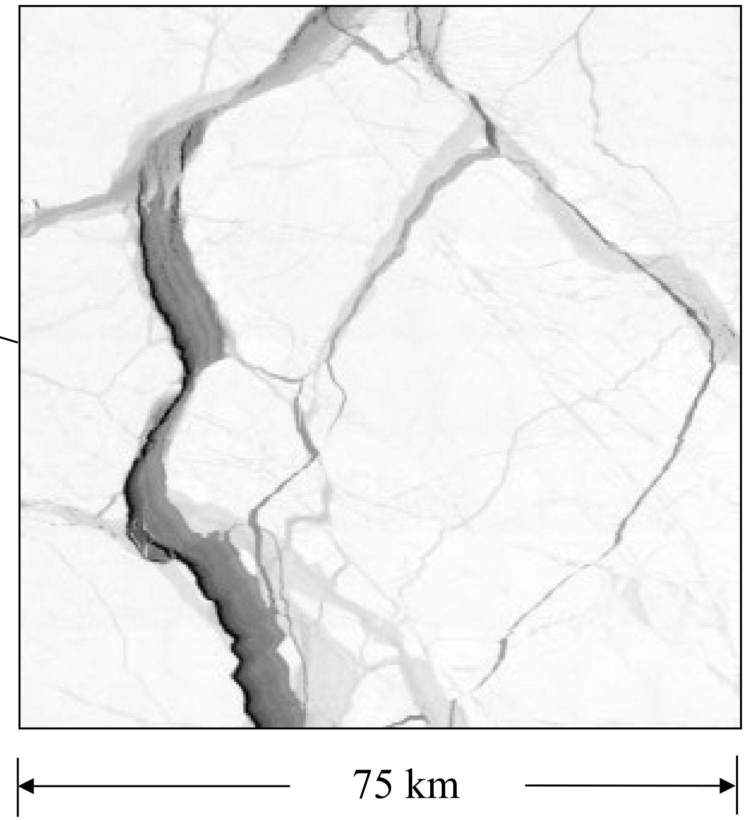


Observing Sea Ice Leads With MODIS

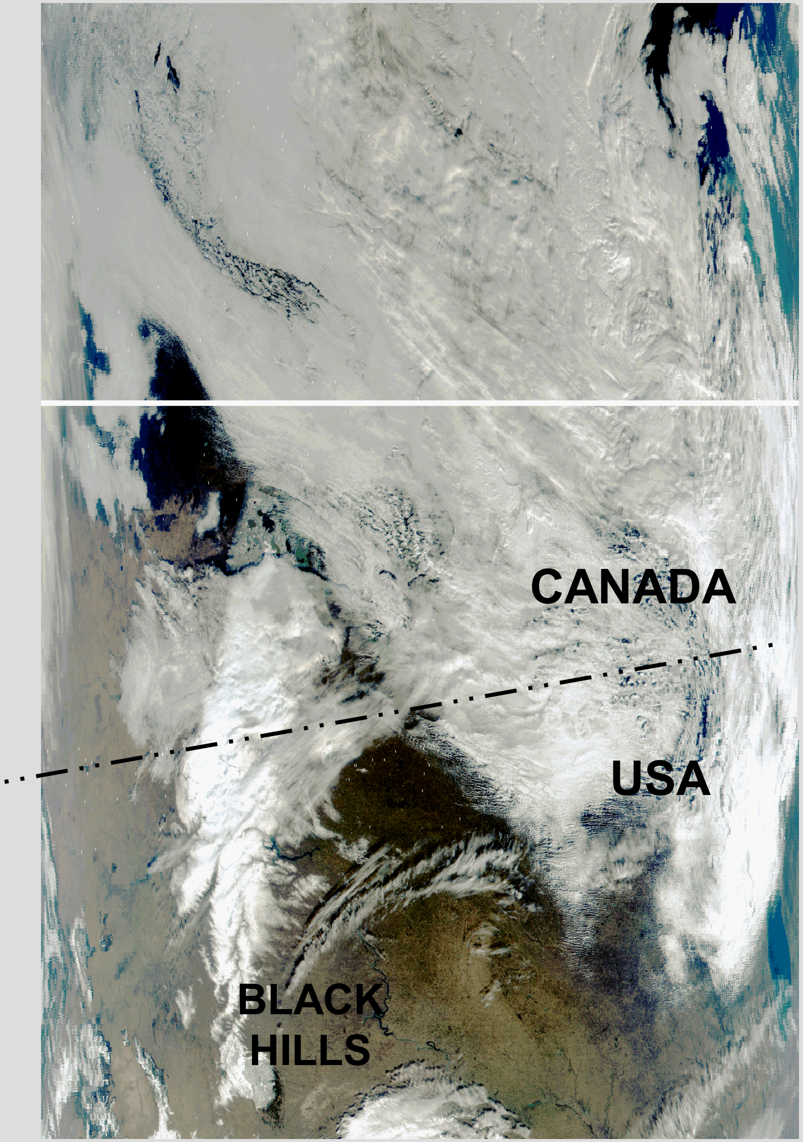
MODIS Band 1 Image of Western Arctic, 1 km (subsampled)



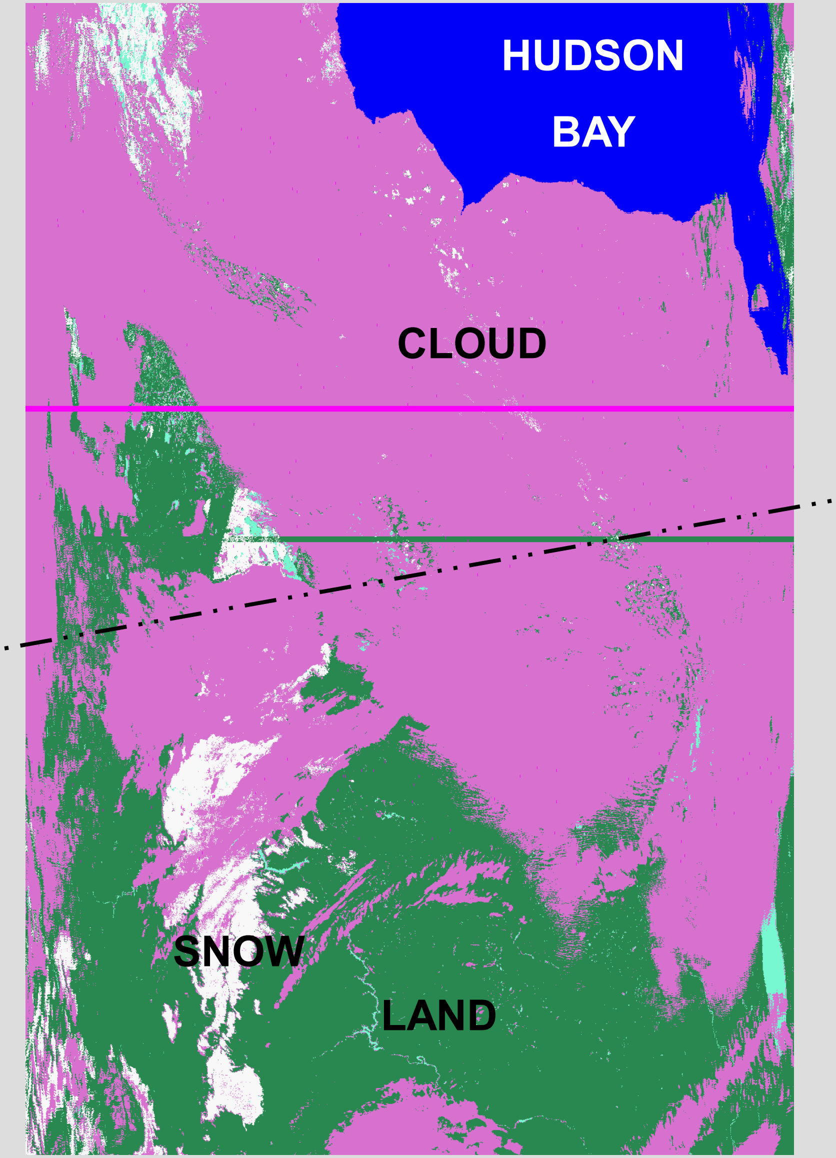
MODIS Full Resolution, 250 m Pixels



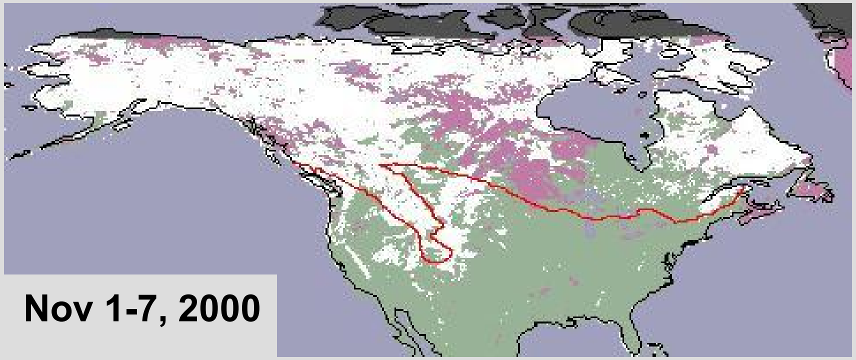
MODIS Image and snow map - November 3, 2000



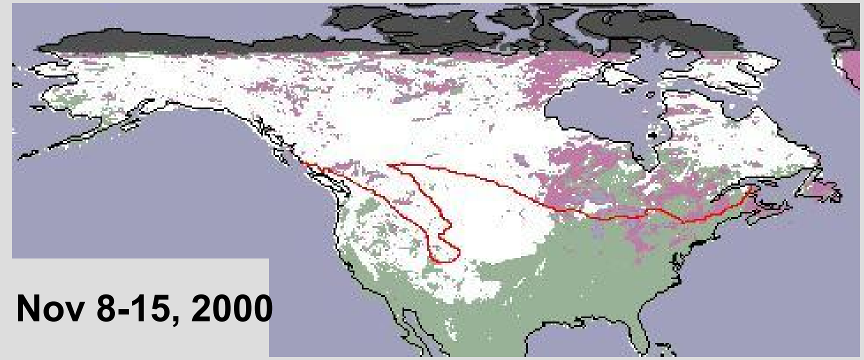
MODIS bands 1, 4, 3



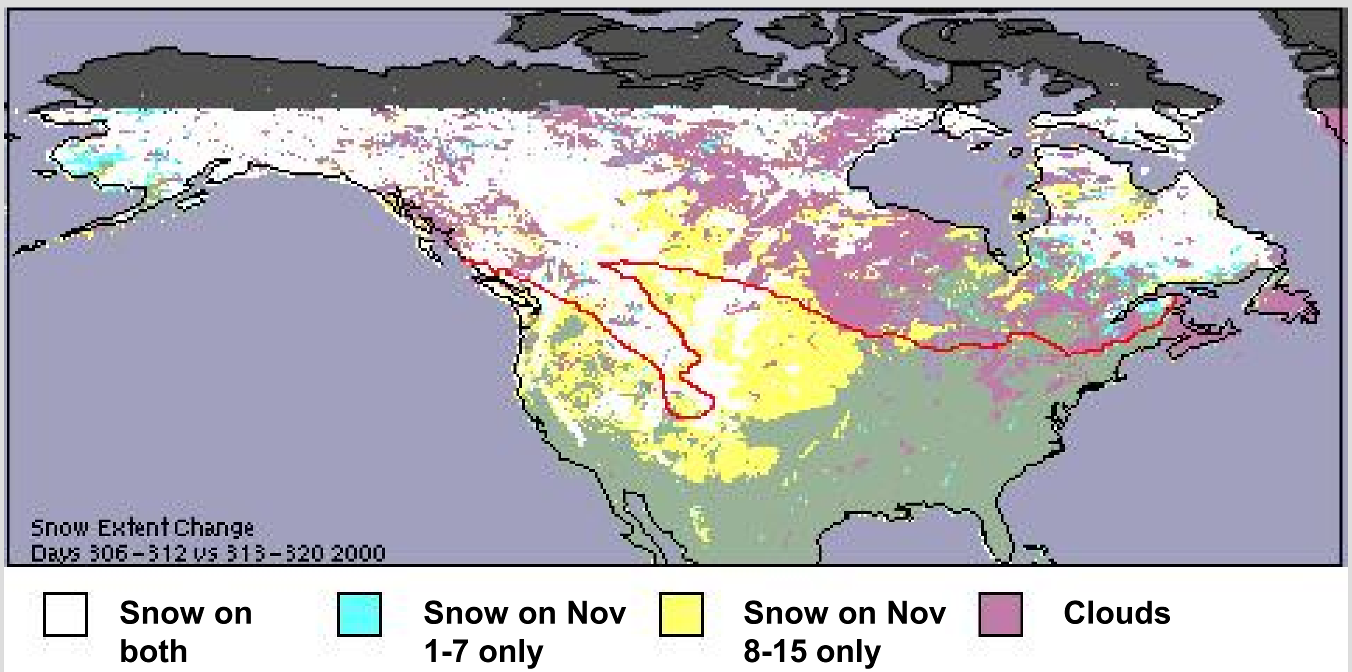
9.0 million sq. km of snow cover



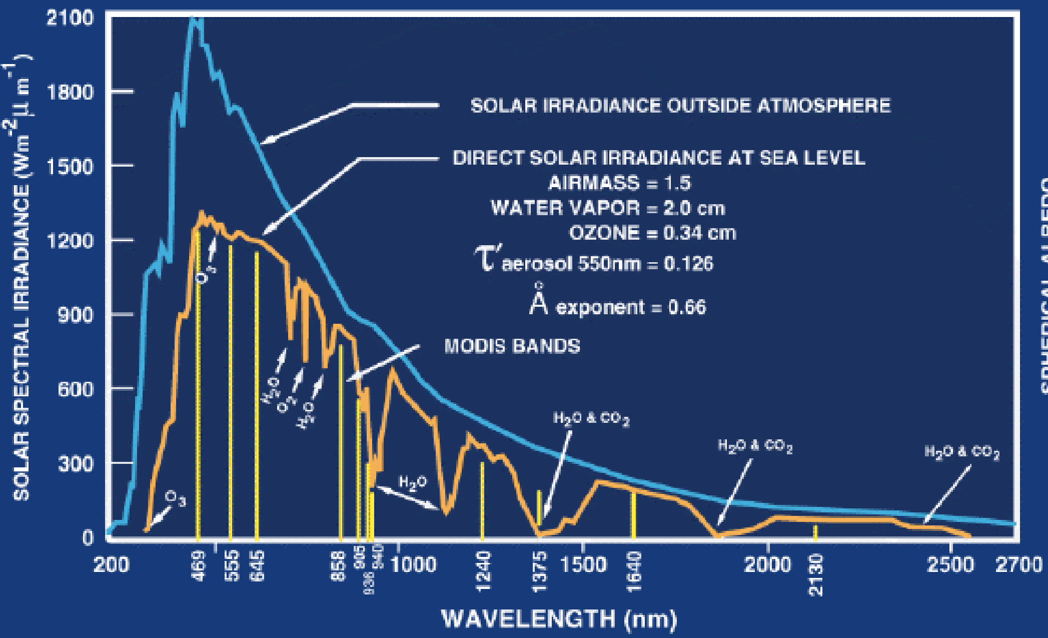
10.8 million sq. km of snow cover

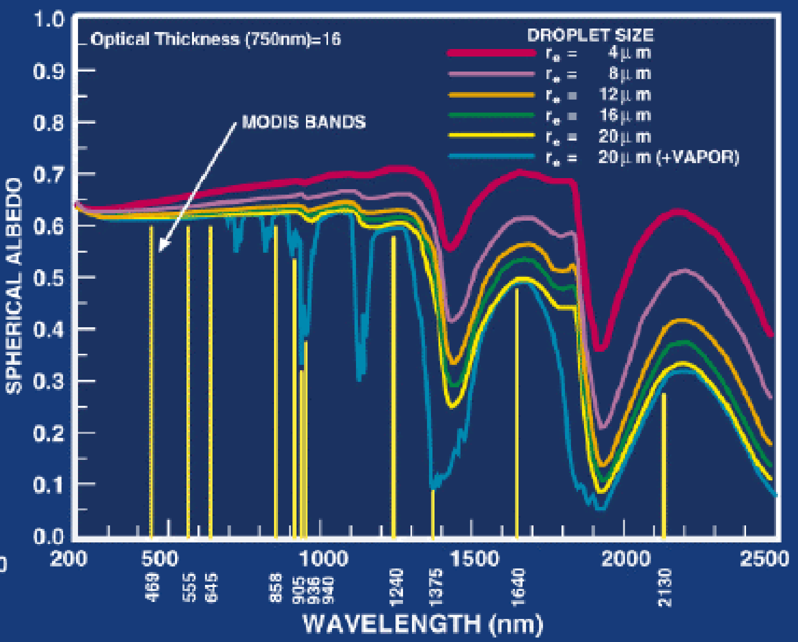


Change in maximum snow extent between two composite periods seen above (1.8 million sq. km)

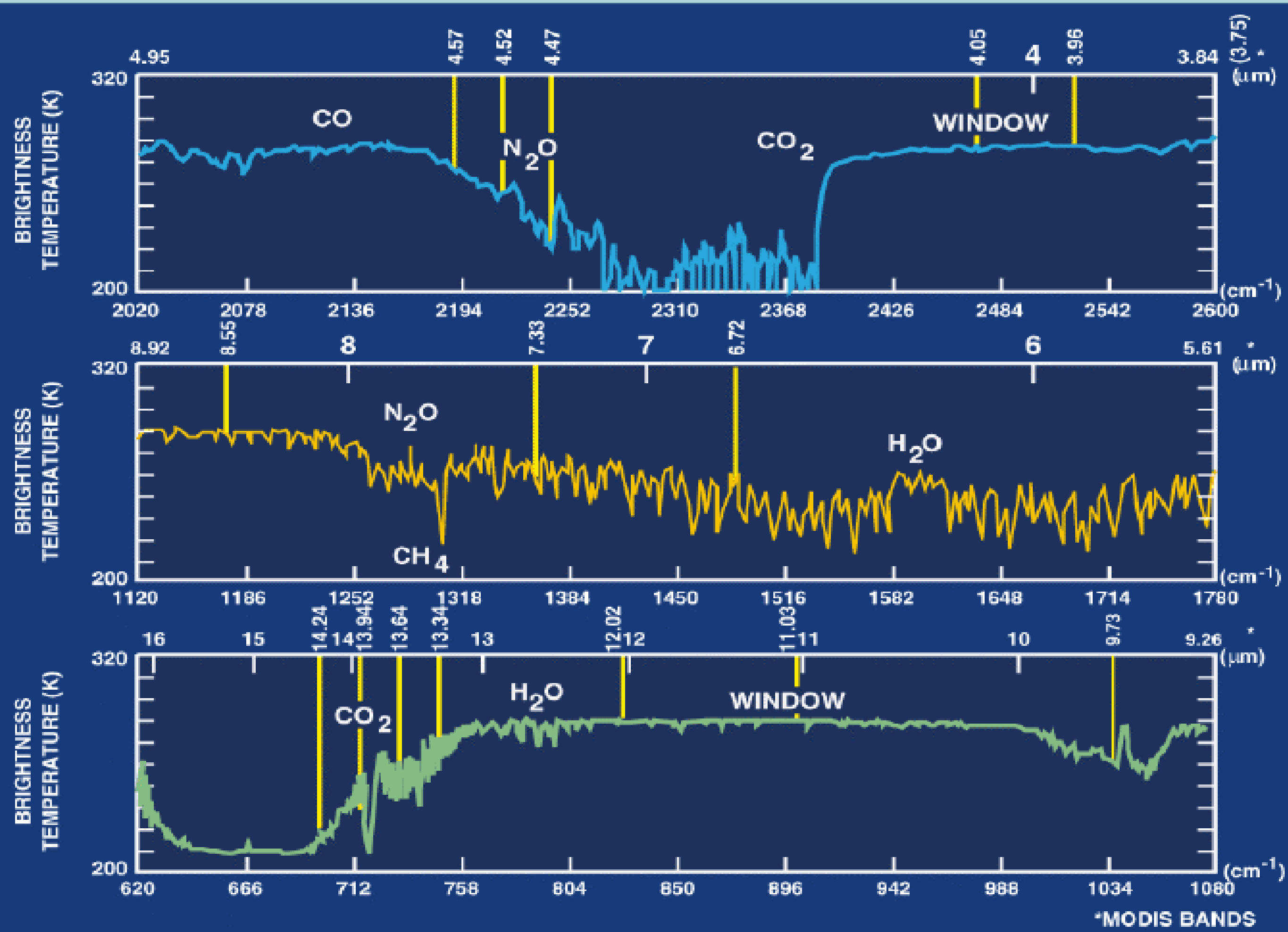


ATMOSPHERE-SOLAR RADIATION

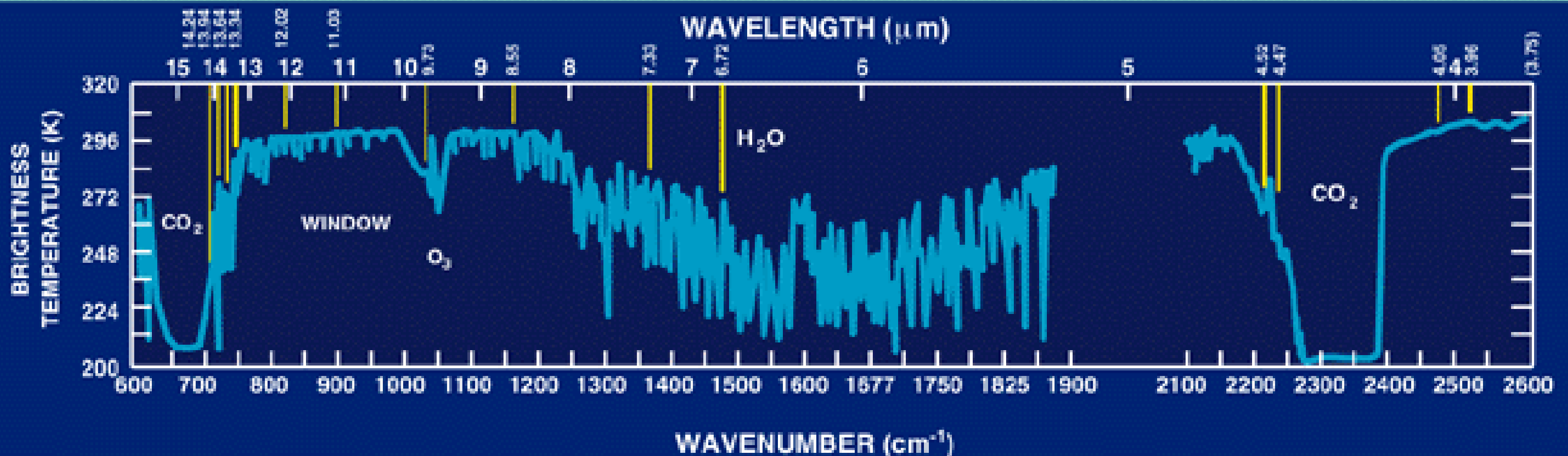


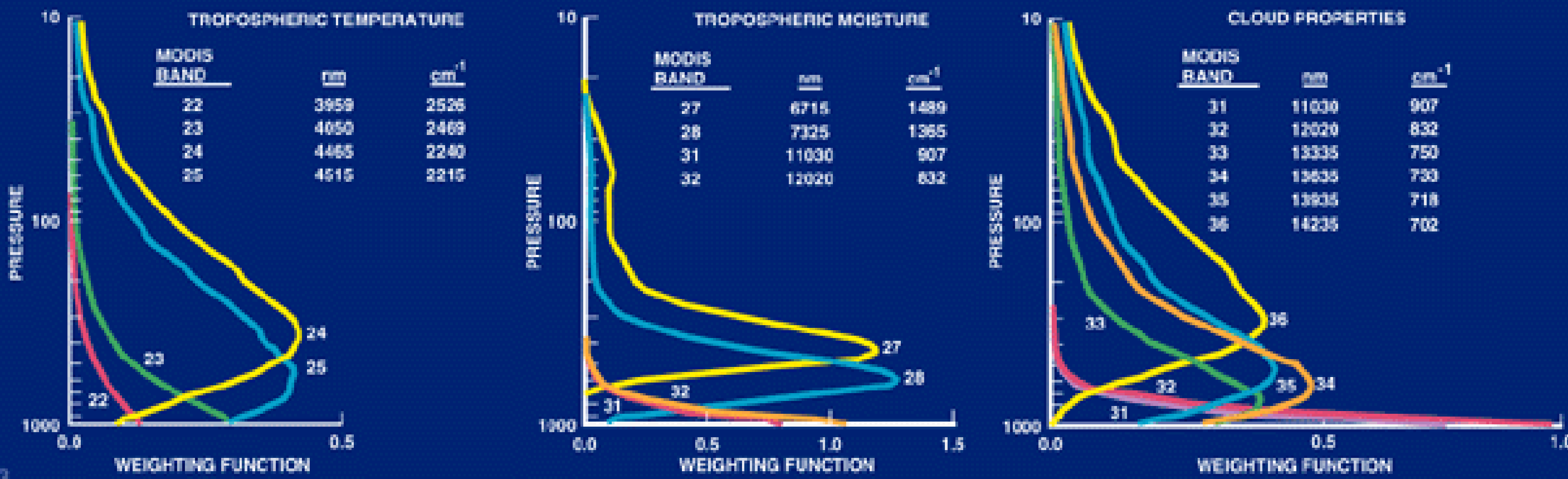


ATMOSPHERE - CLEAR SKY
THERMAL EMISSION

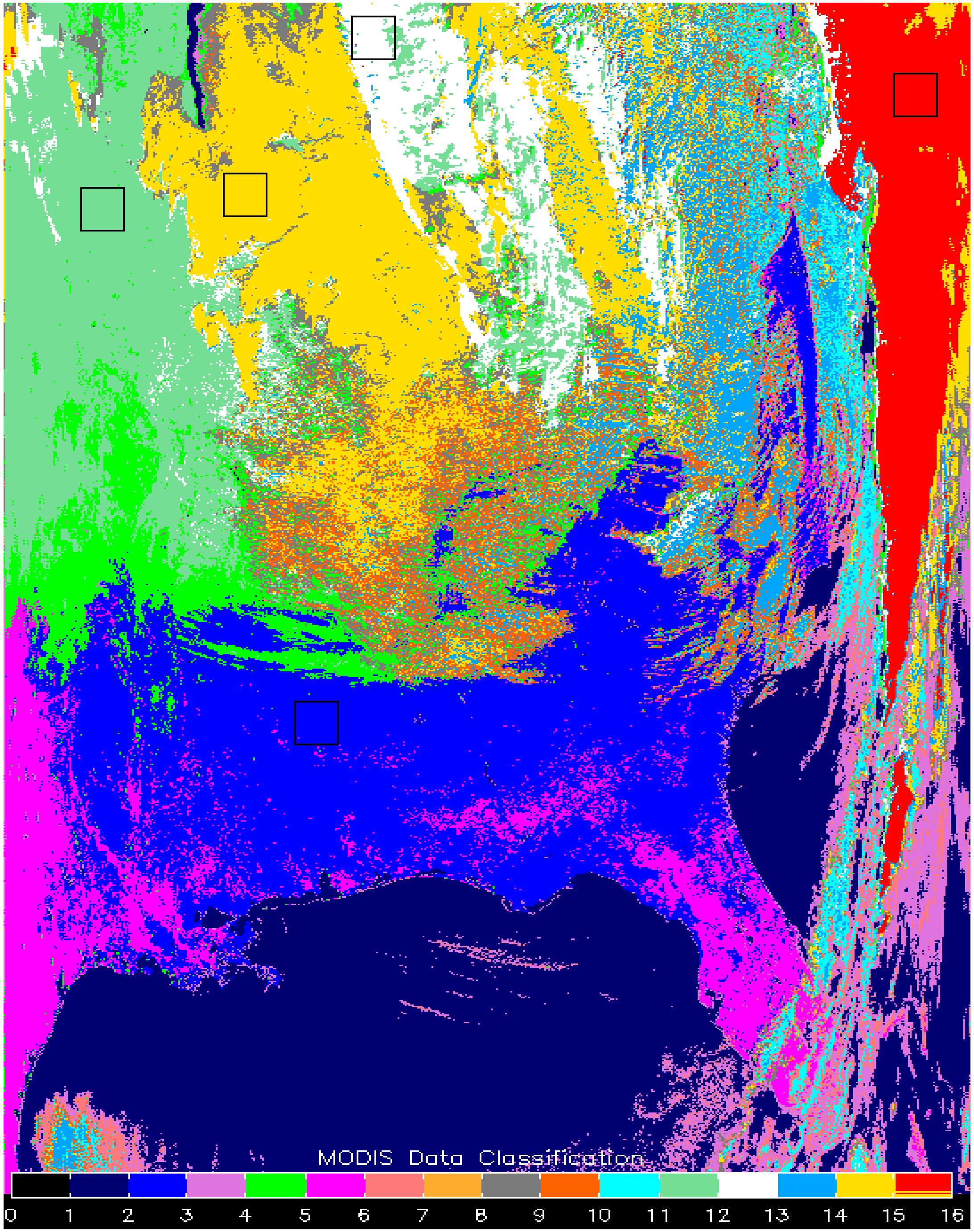


ATMOSPHERE - THERMAL RADIATION





MODIS identifies cloud classes



Hi cld

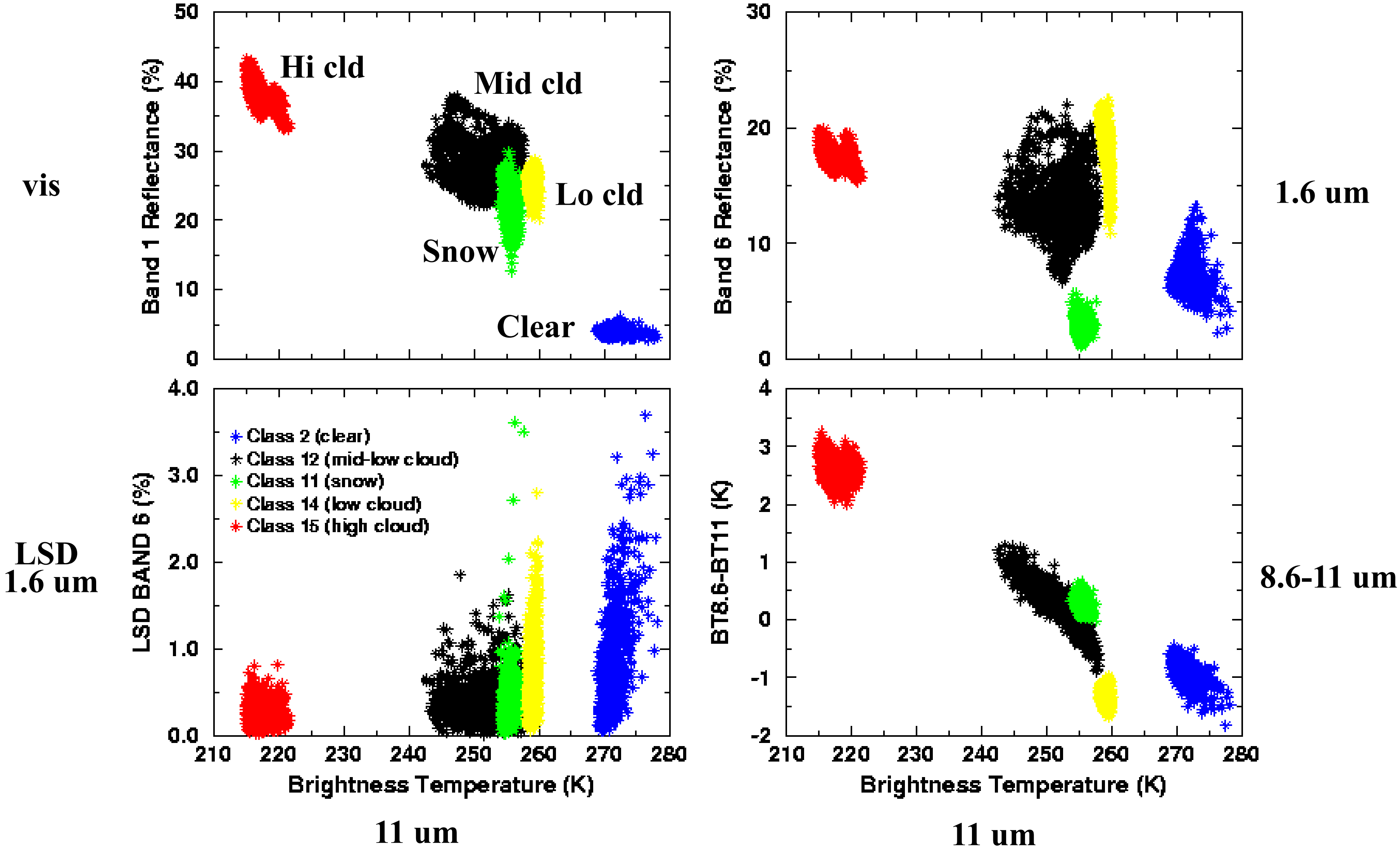
Mid cld

Lo cld

Snow

clr

Clouds separate into classes when multispectral radiance information is viewed



Cloud Properties

True Color Image

Cloud Mask

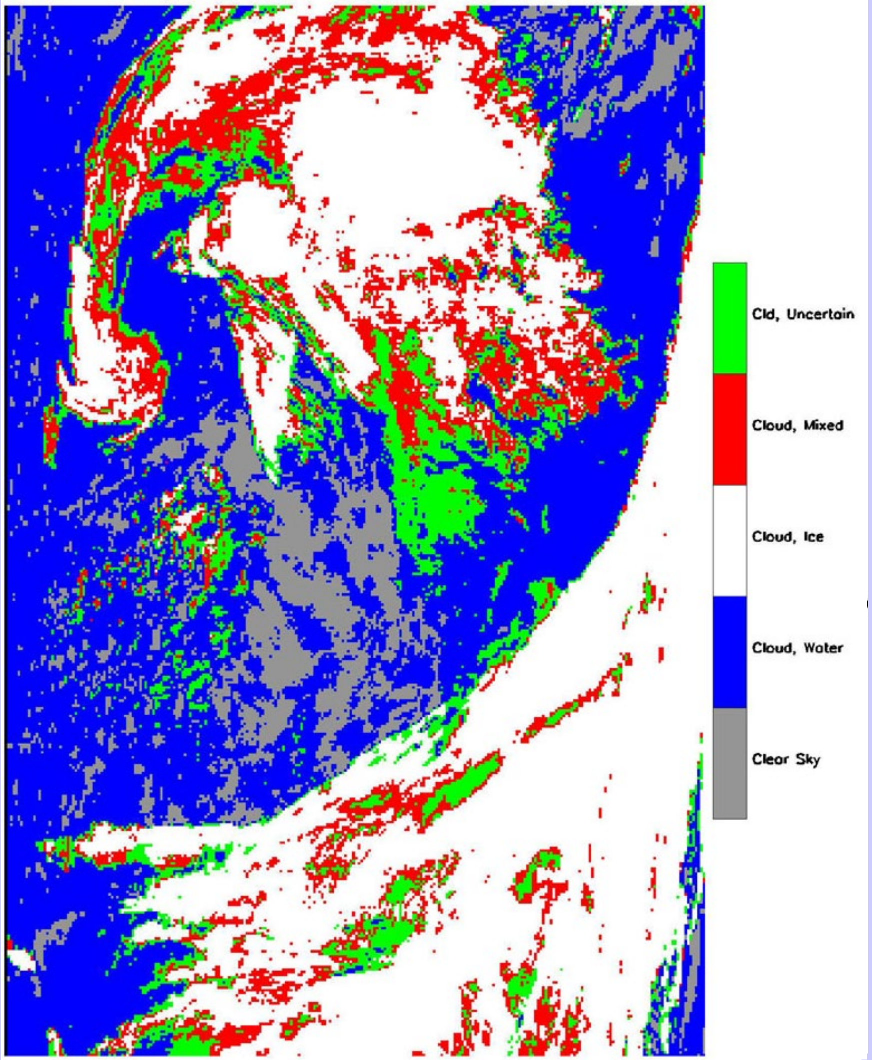
Land Classification

Cloud Opt Thickness

Cloud Eff Radius

Cloud Top Temp

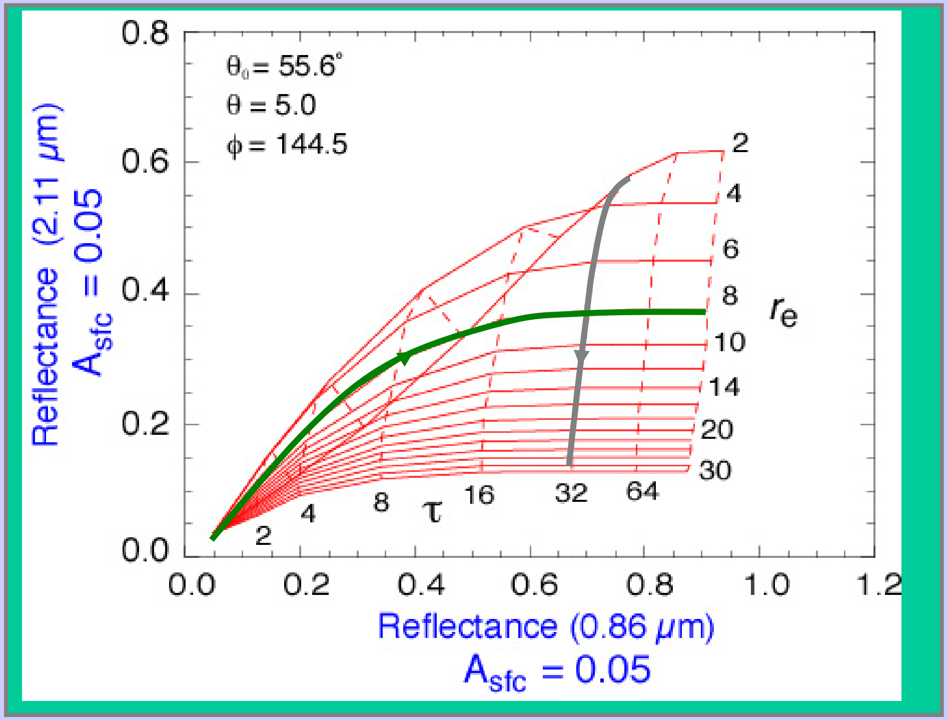
Bispectral Phase



October 1, 2001

Cloud optical, microphysical properties

retrieval space example



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

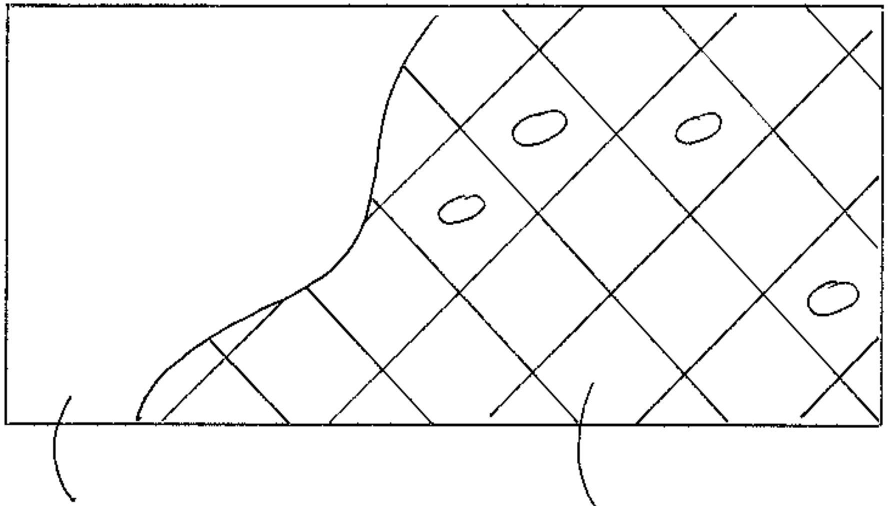
2.1 μm reflectance reaches limiting values with optical thickness

Liquid water cloud
ocean surface

S. Platnick, ISSAOS '02

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

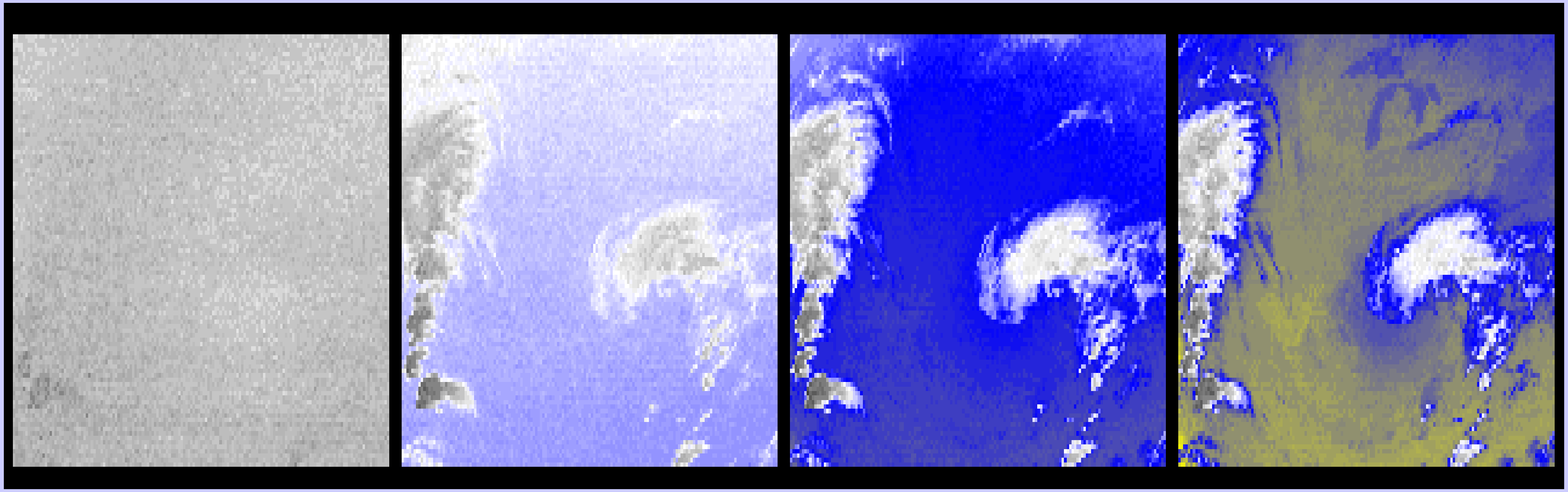
$$R_c = [1 - \varepsilon] R_a + \varepsilon R_b(p_c)$$

so together

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

Two unknowns, ε and Pc, require two measurements

CO2 channels see to different levels in the atmosphere

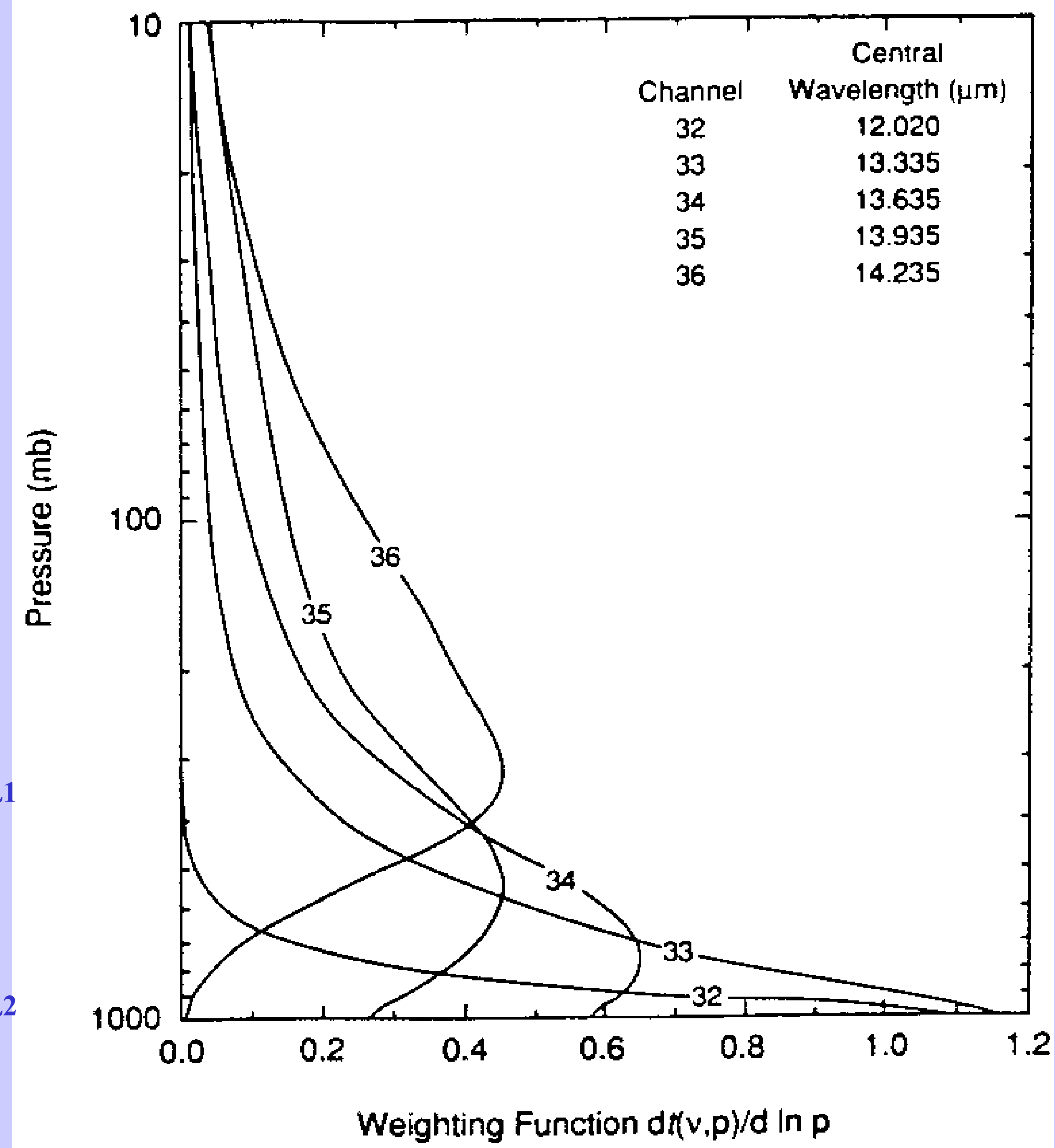


Different ratios reveal cloud properties at different levels

hi - 14.2/13.9
mid - 13.9/13.6
low - 13.6/13.3

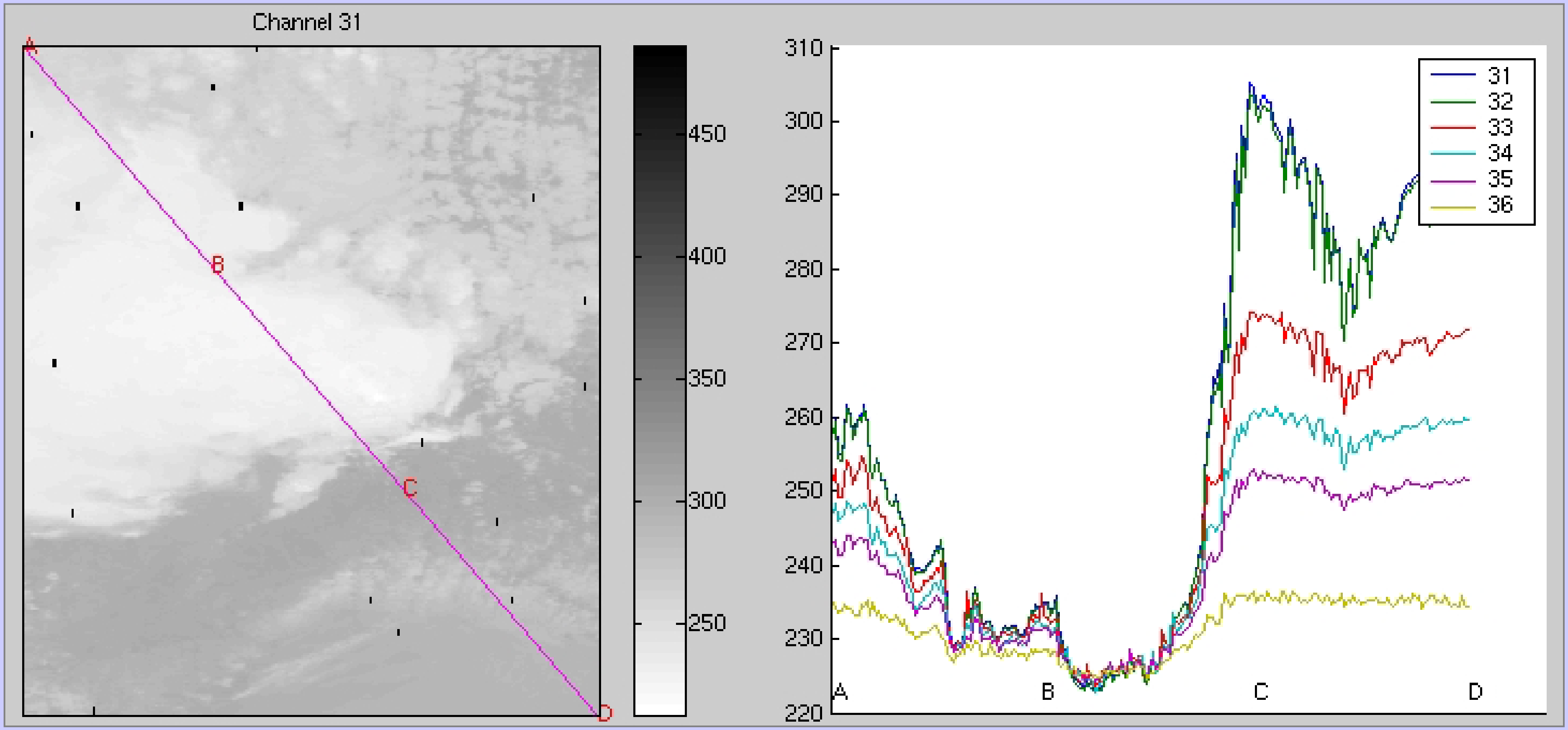
Meas **Calc**

$$\frac{(I_{\lambda 1}-I_{\lambda 1}^{clr})}{(I_{\lambda 2}-I_{\lambda 2}^{clr})} = \frac{\eta\varepsilon_{\lambda 1}\int_{p_s}^{p_c} \tau_{\lambda 1}\, dB_{\lambda 1}}{\eta\varepsilon_{\lambda 2}\int_{p_s}^{p_c} \tau_{\lambda 2}\, dB_{\lambda 2}}$$

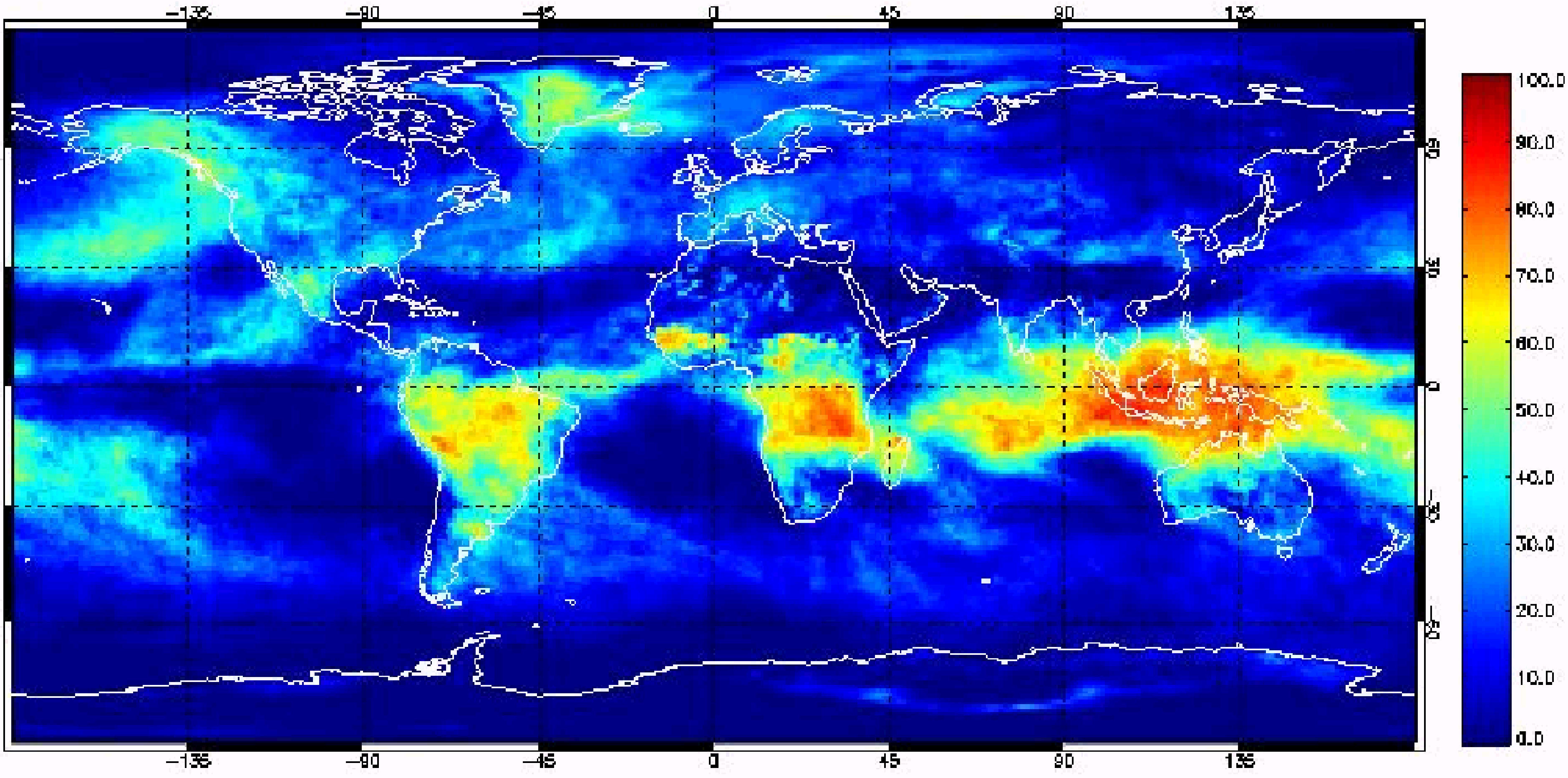


BT in and out of clouds for MODIS CO_2 bands

- demonstrate weighting functions and cloud top algorithm

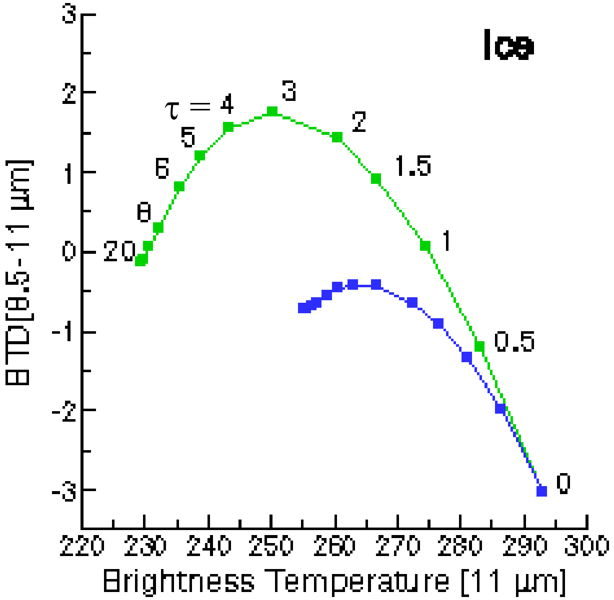


January 2001: MODIS High Clouds (0–400 mb)



MODISHighClouds

Simulations of Ice and Water Phase Clouds
8.5 - 11 μm BT Differences

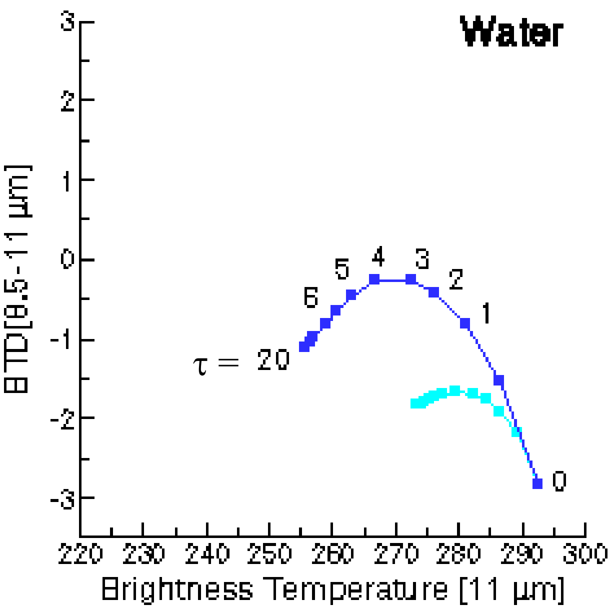


High Ice clouds

• BTD[8.5-11] > 0 over a large range of optical thicknesses τ
• T_{cld} = 228 K

Midlevel clouds

• BTD[8.5-11] values are similar (*i.e.*, negative) for both water and ice clouds
• T_{cld} = 253 K



Low-level, warm clouds

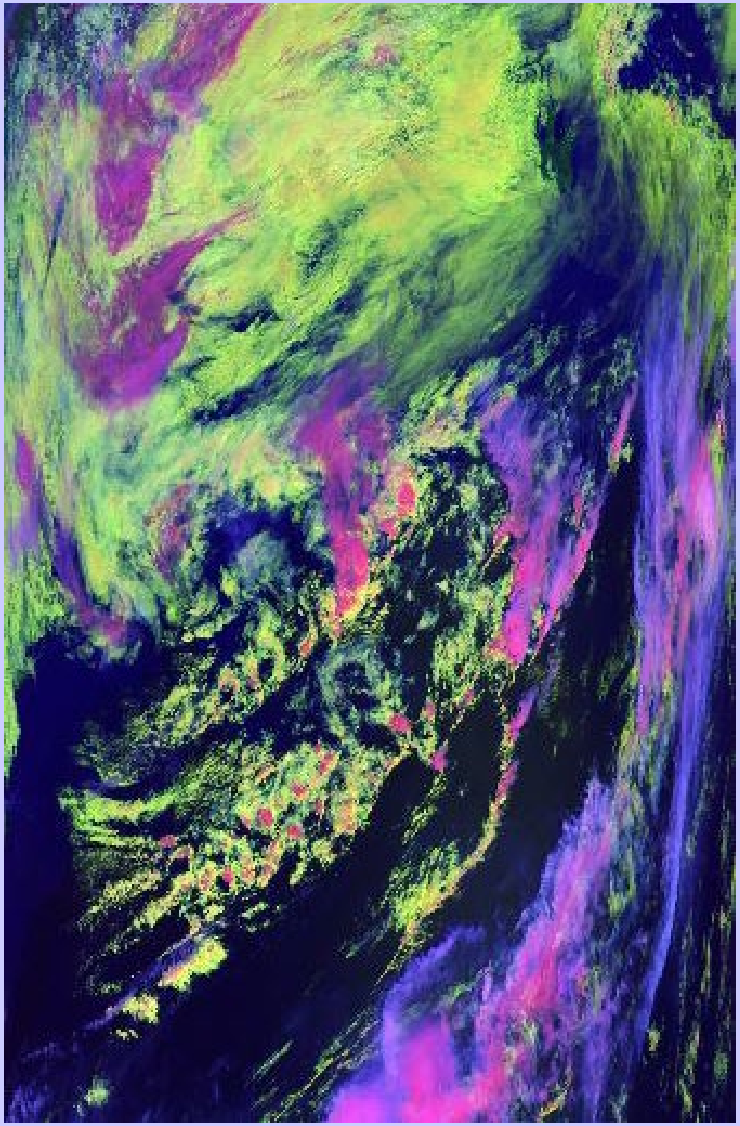
• BTD[8.5-11] values always negative
• T_{cld} = 273 K

*Ice: Cirrus model derived from FIRE-I in-situ data (*Nasiri et al, 2002)
Water: r_e=10 μm
Angles: θ_o = 45°, θ = 20°, and ϕ = 40°
Profile: midlatitude summer

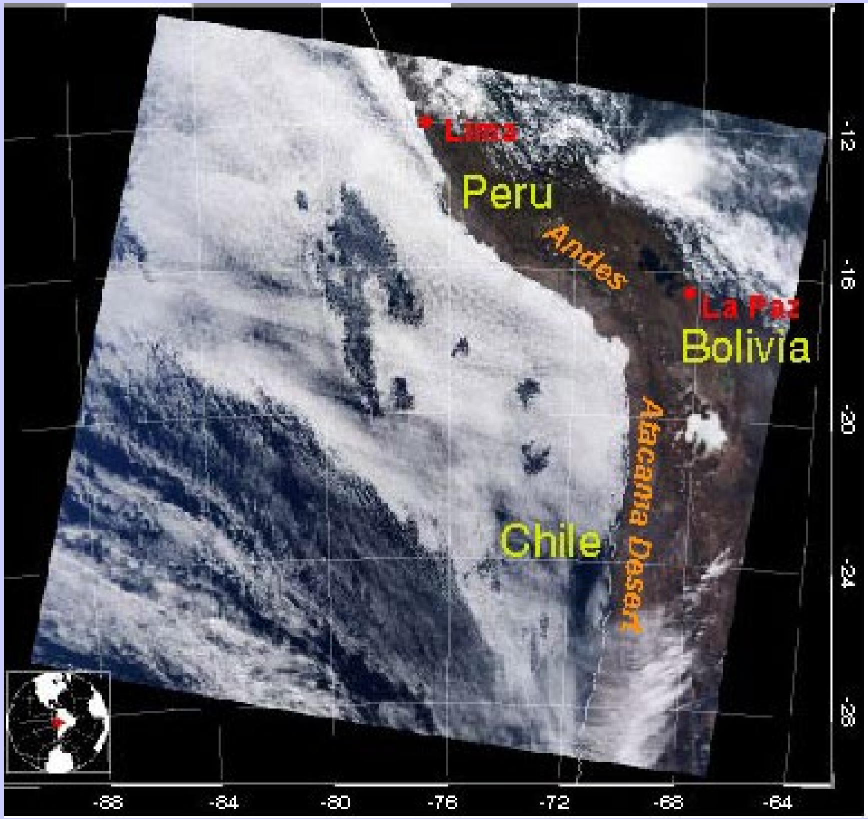
MODIS Direct Broadcast

May 14, 2003 at 1458 UTC (Terra)

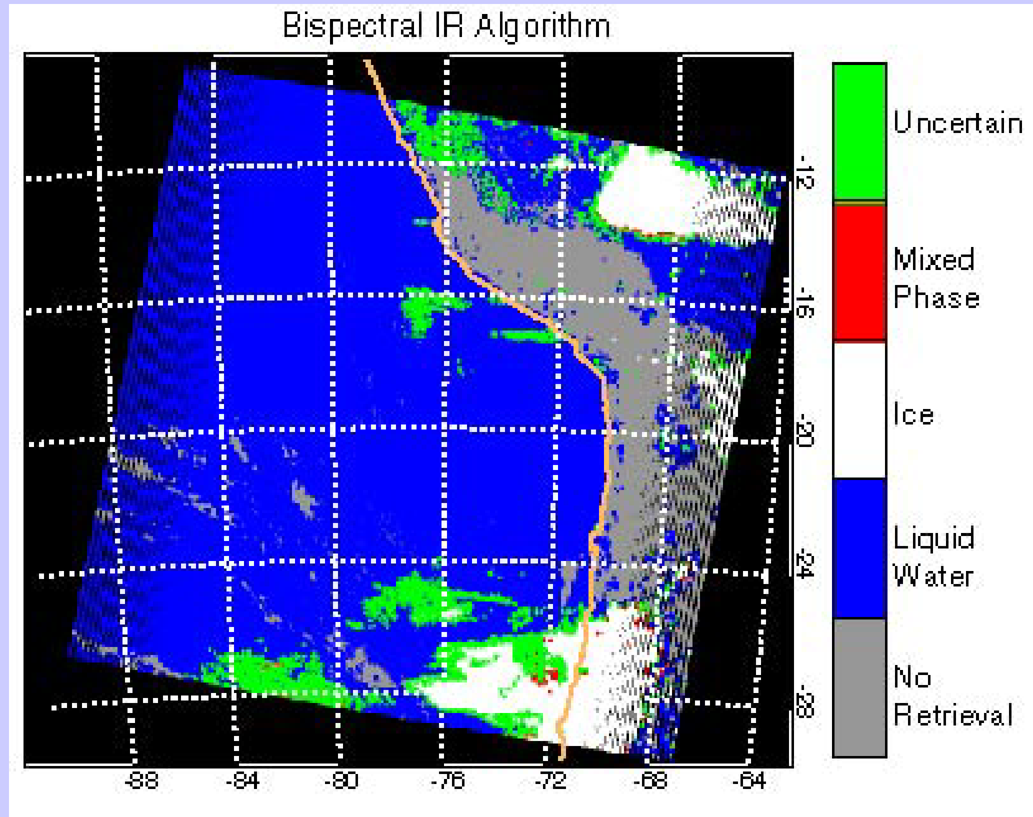
1-km resolution



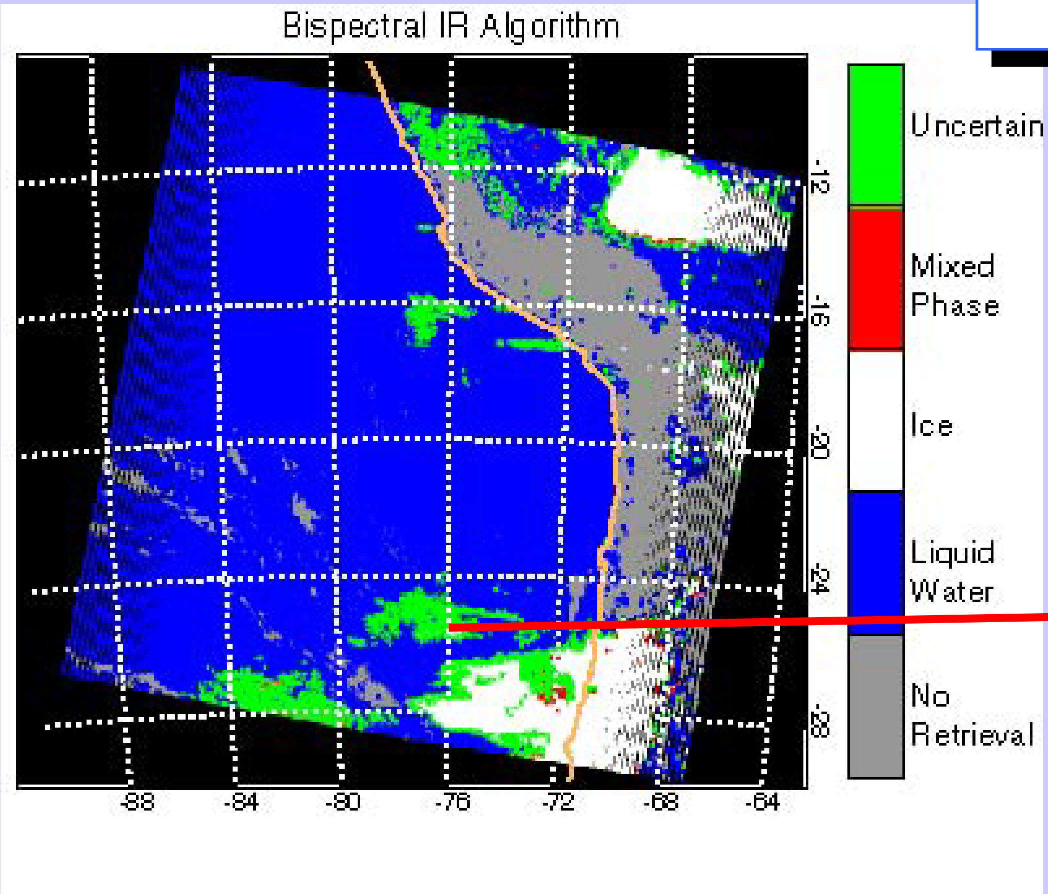
Cloud Phase

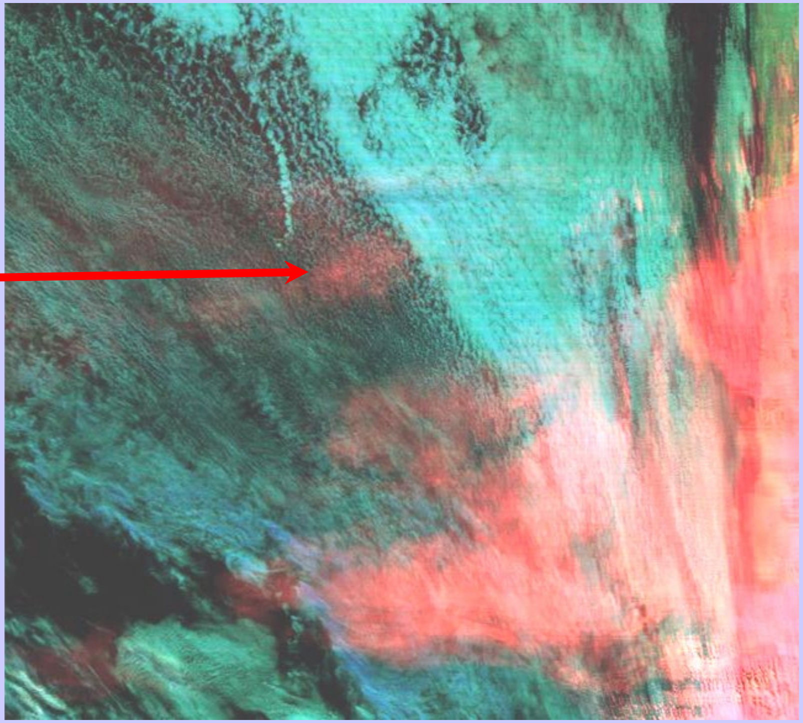


18 July 2001

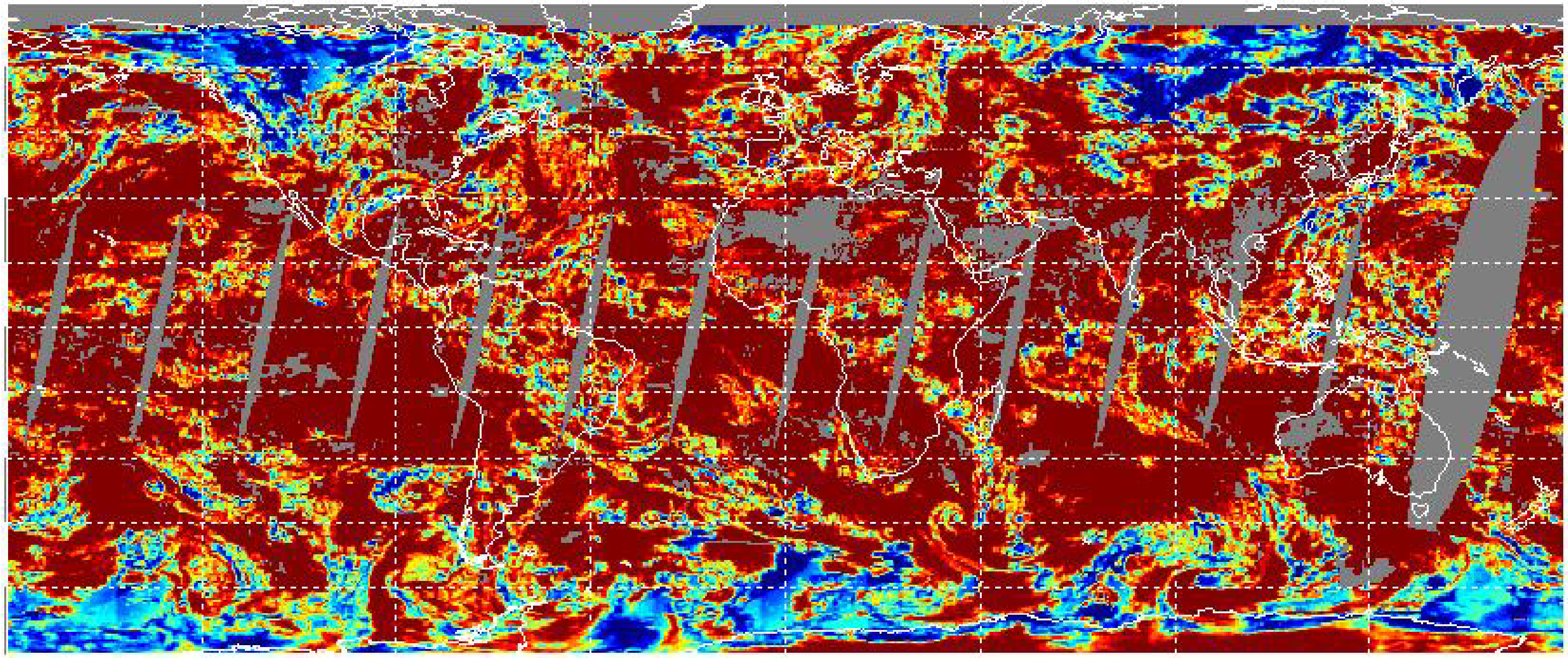


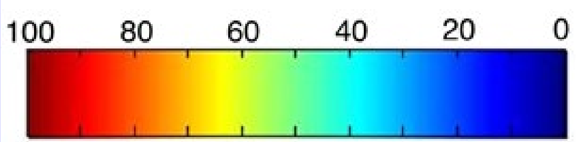
Multilayered Clouds





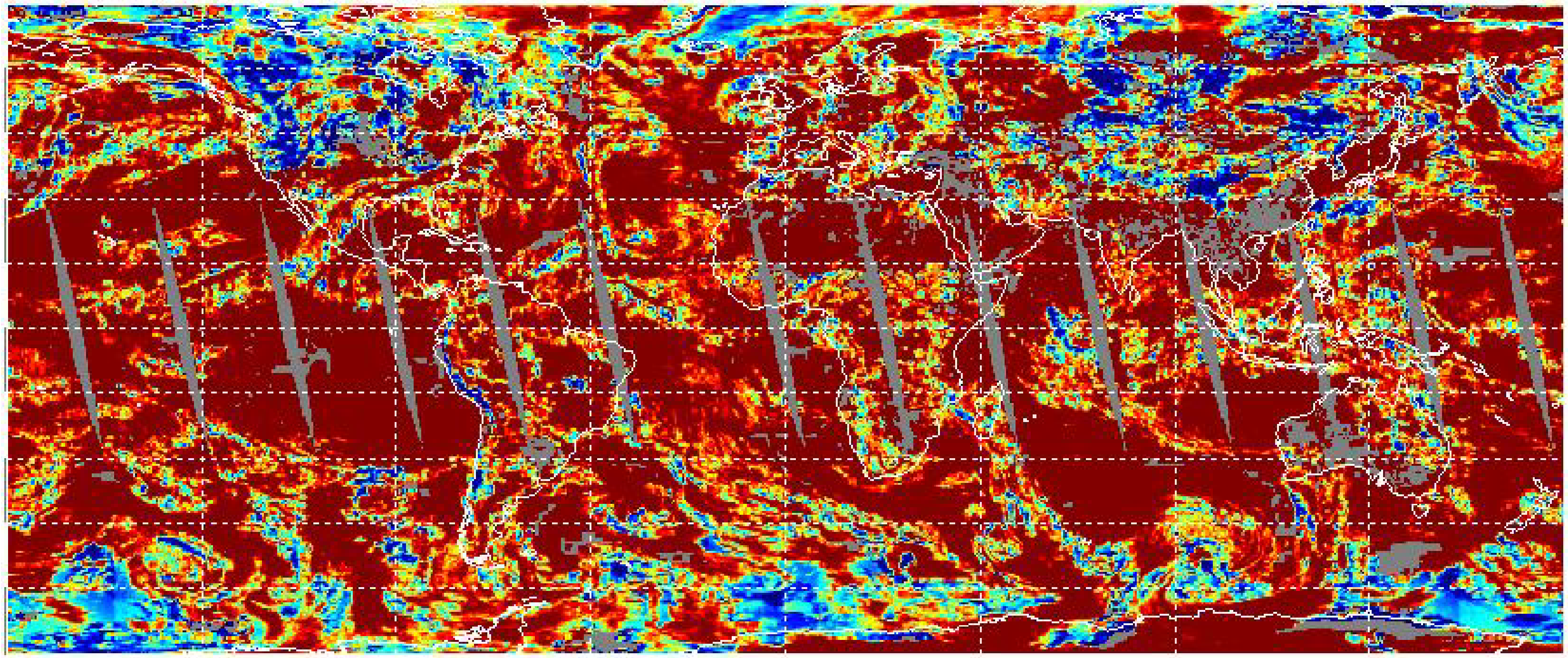
MODIS Cloud Thermodynamic Phase
Percentage Ice and Water Cloud
05 Nov. 2000 -Daytime Only

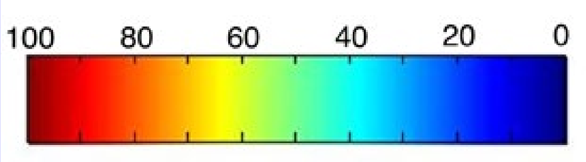




frequency of occurrence in percent (%)

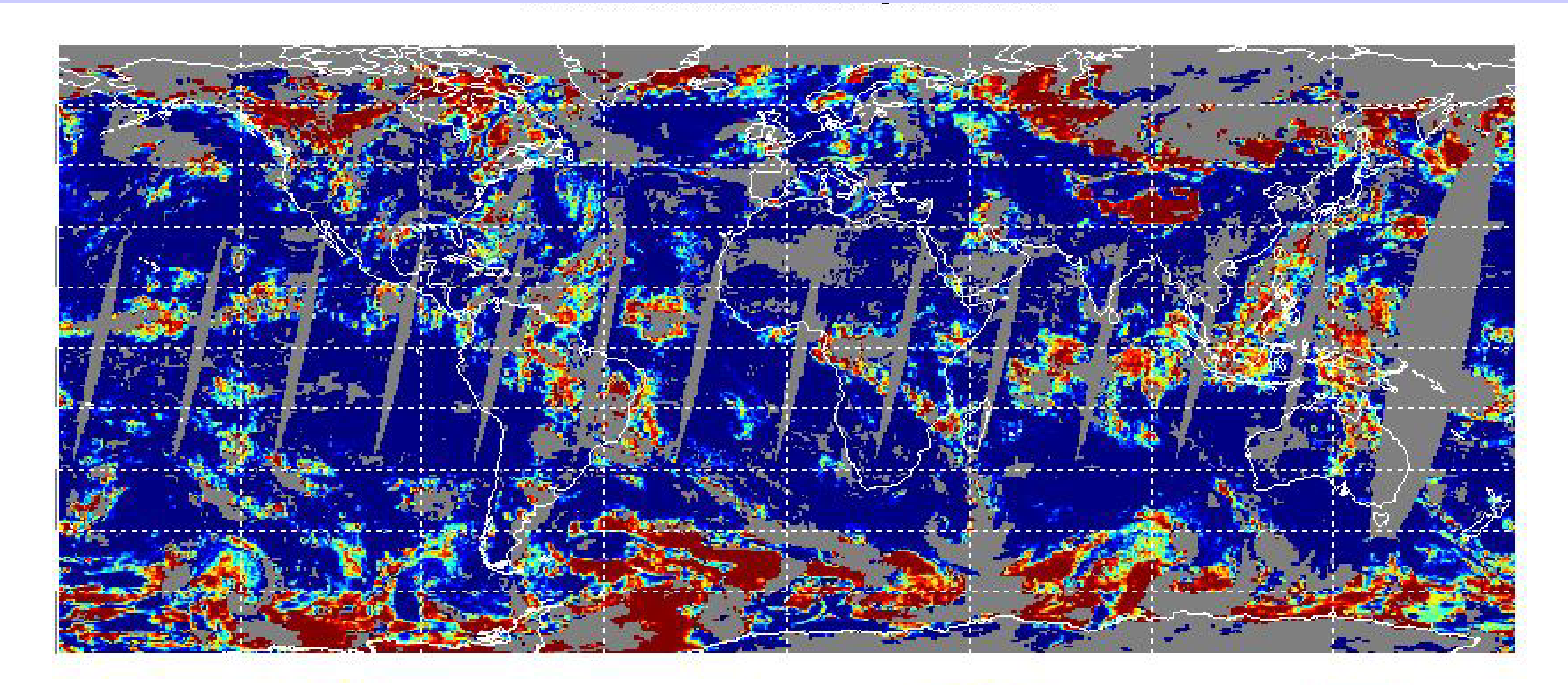
MODIS Cloud Thermodynamic Phase
Percentage Ice and Water Cloud
05 Nov. 2000 - Nighttime Only

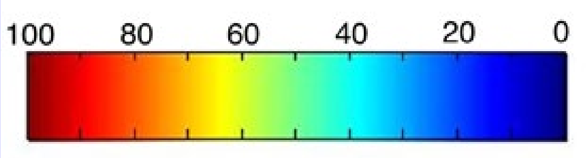




frequency of occurrence in percent (%)

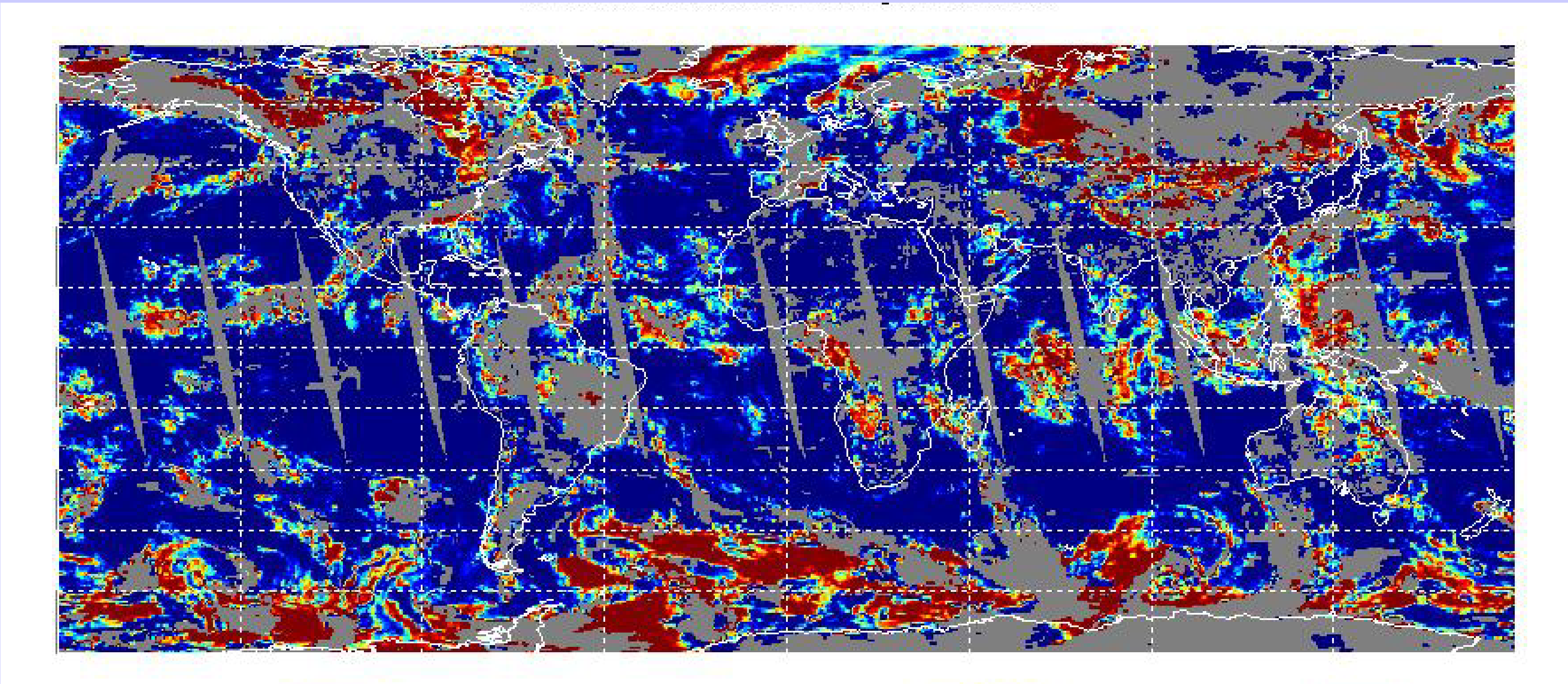
MODIS Frequency of Co-occurrence Water Phase with 253 K < T_{cld} < 268 K 05 Nov. 2000 - Daytime Only

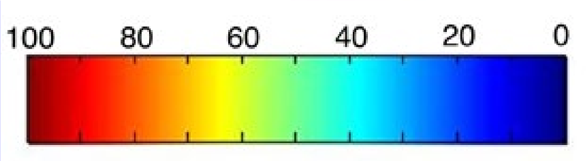




frequency of occurrence in percent (%)

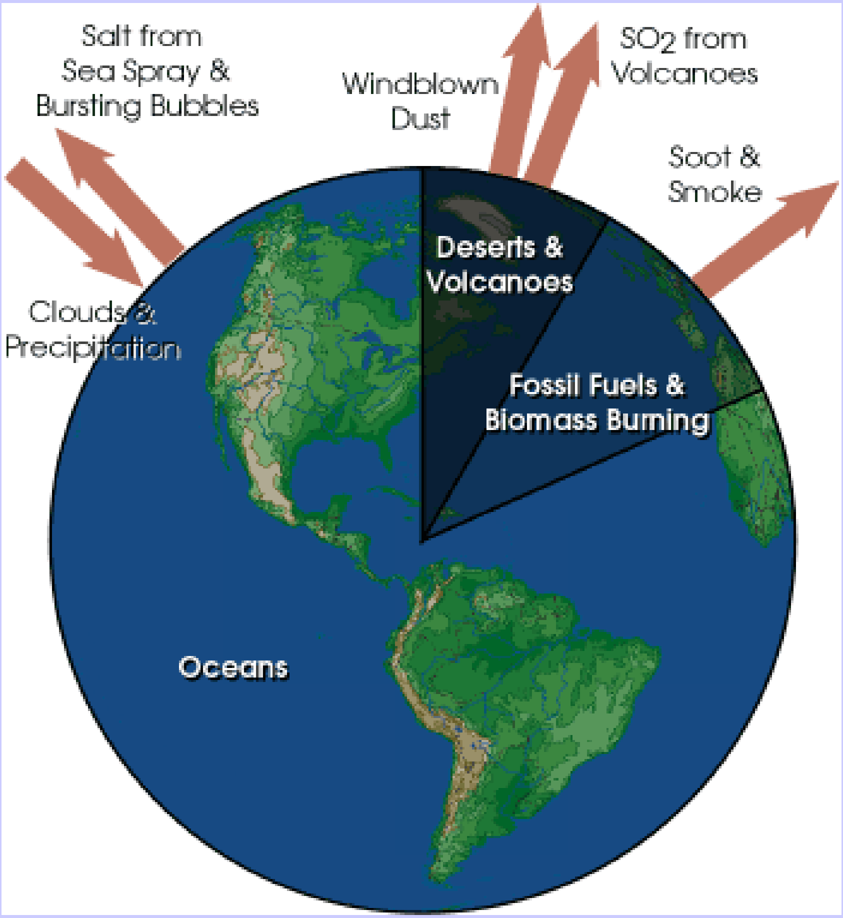
MODIS Frequency of Co-occurrence Water Phase with 253 K < T_{cld} < 268 K 05 Nov. 2000 - Nighttime Only





frequency of occurrence in percent (%)

Aerosol Types and Origin



- Aerosol particles larger than about 1 μm in size are produced by windblown dust and sea salt from sea spray and bursting bubbles
- Aerosols smaller than 1 μm 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

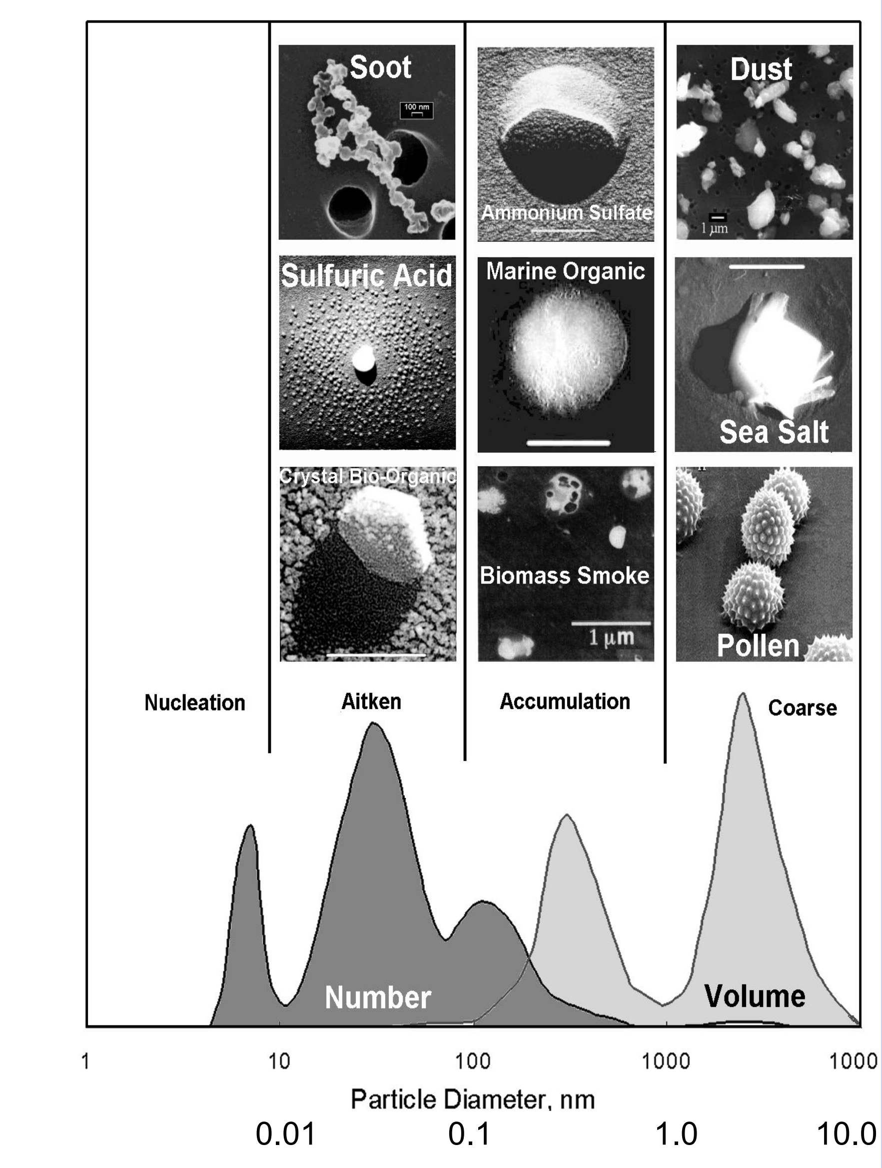
There are 3 modes :

- « **nucleation** »: radius is between 0.002 and 0.05 μm. They result from combustion processes, photo-chemical reactions, etc.

- « **accumulation »:** radius is between 0.05 μm and 0.5 μm. Coagulation processes.

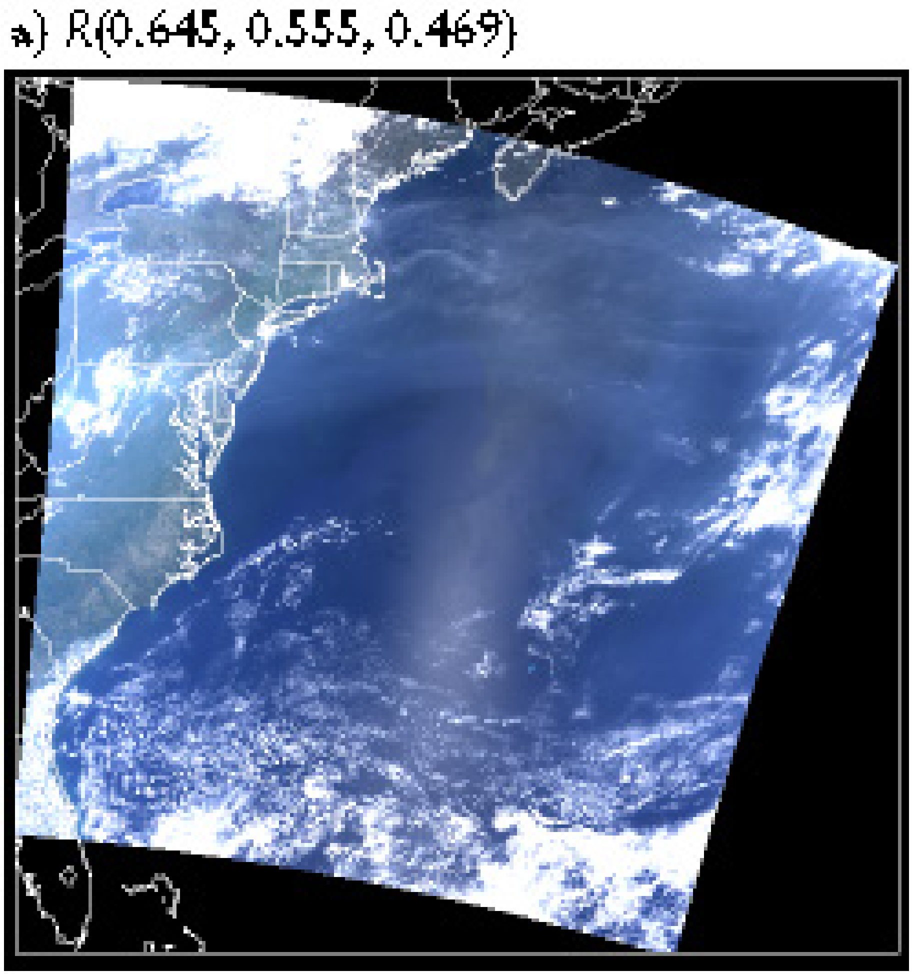
- « **coarse** »: larger than 1 μm. From mechanical processes like aeolian erosion.

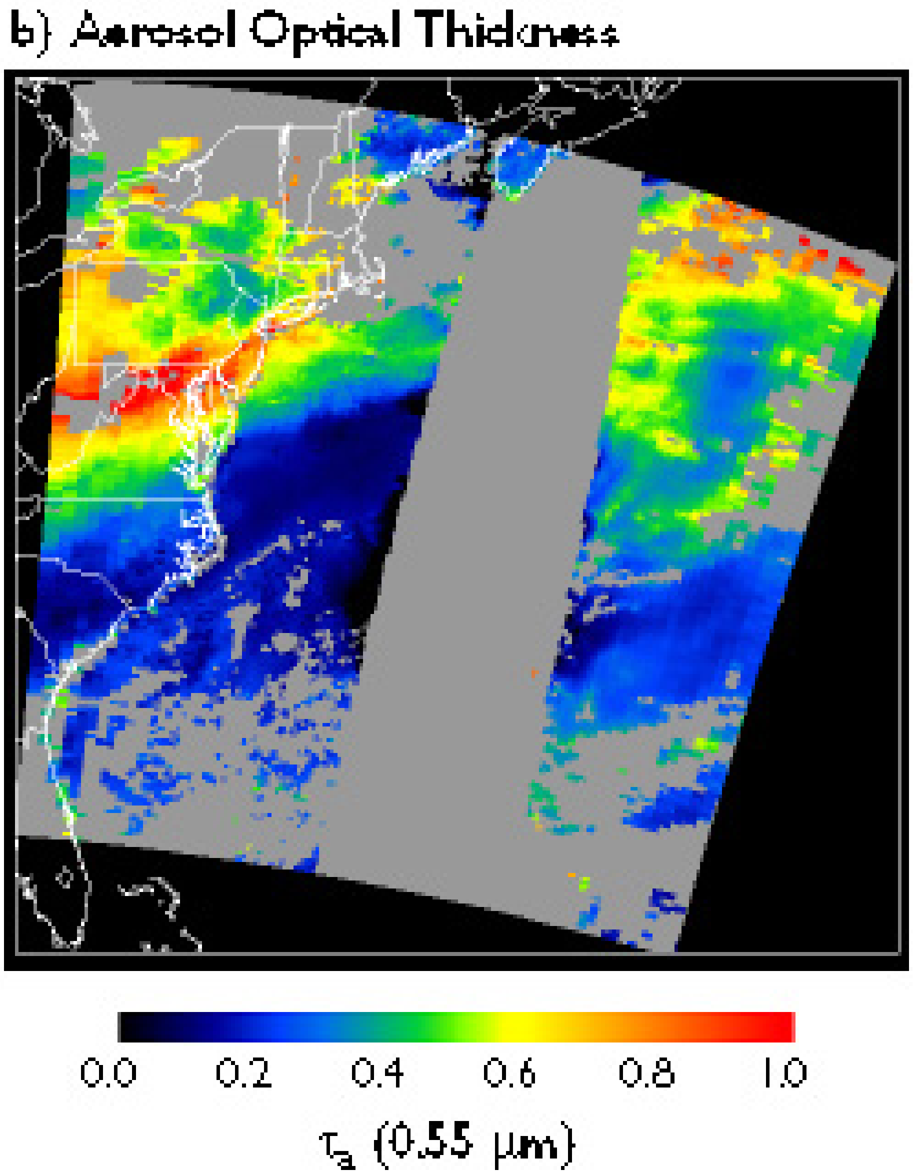
« fine » particles (nucleation and accumulation) result from anthropogenic activities, coarse particles come from natural processes.



True color composite

AOT (0.55 um)





Ohio Valley pollution heading over N. Atlantic

- Effect of aerosol on climate:

Cooling past climates, possibly warming future climates

- Effect of aerosol on hydrologic cycle:

Less evaporation from cooler land and ocean, more stable atmosphere, less clouds and precipitation.

- Effect of aerosol on health: May be more important then ozone in causing cancer and heart problems.

- **Effect on agriculture, vegetation**: Shift of precipitation away from polluted land, less sunlight to vegetation

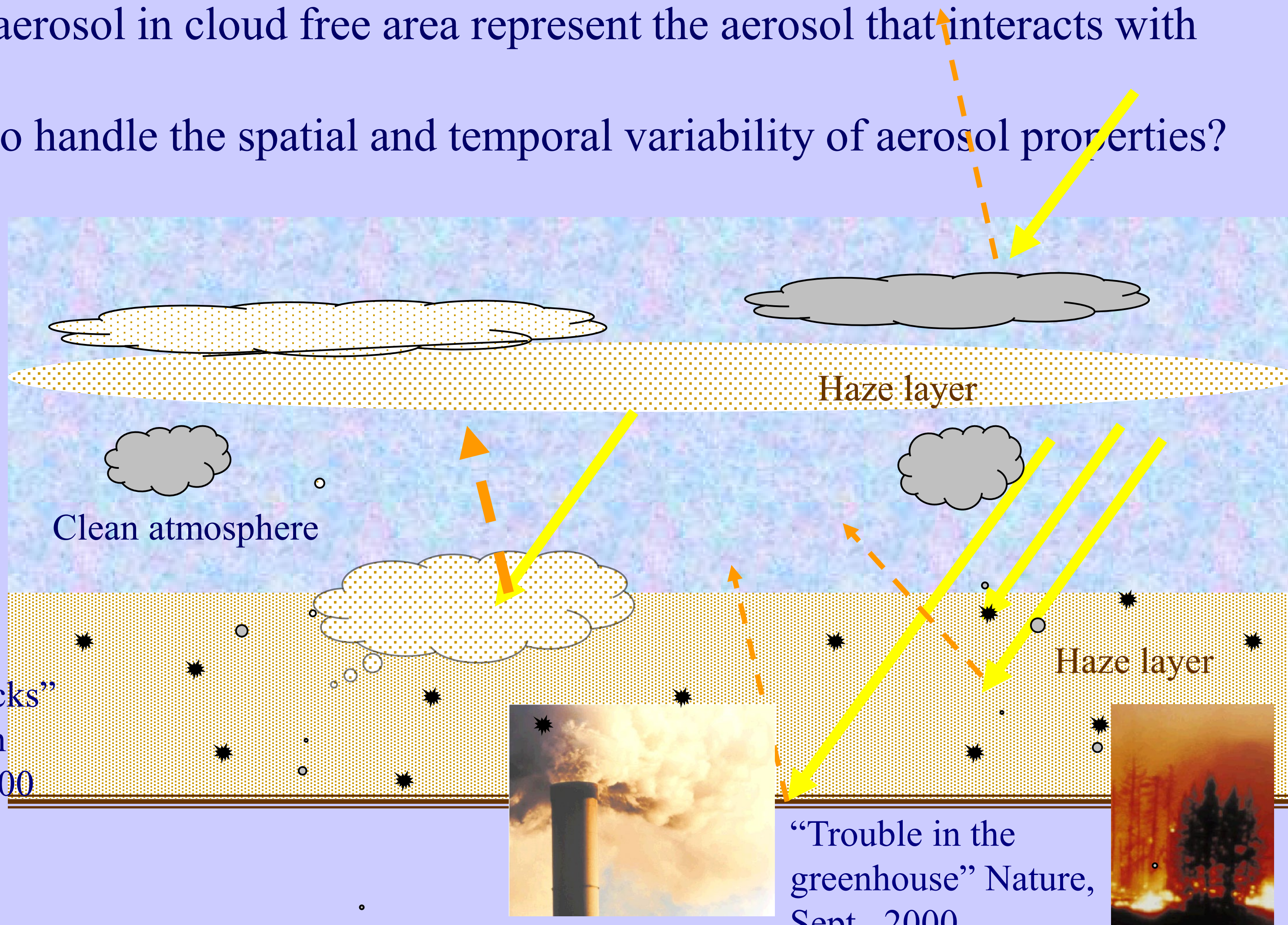
Aerosol, their sources and effects on climate

Properties	Net effect	Aerosol type	Main Source
Reflect sunlight	Cool the earth	Desert dust, sulfate smog	dry lake beds industry
Absorb sunlight	**Heat the earth & atmosphere reduce cloudiness**	**Black carbon**	**biomass burning dirty engines**
Cloud Condensation Nuclei	brighter clouds less precipitation	sulfate smog smoke	industry fires

Remote sensing of Aerosol

<u>Open questions</u>: - Where does aerosol begin and cloud ends?

- Does aerosol in cloud free area represent the aerosol that interacts with clouds?
- How to handle the spatial and temporal variability of aerosol properties?



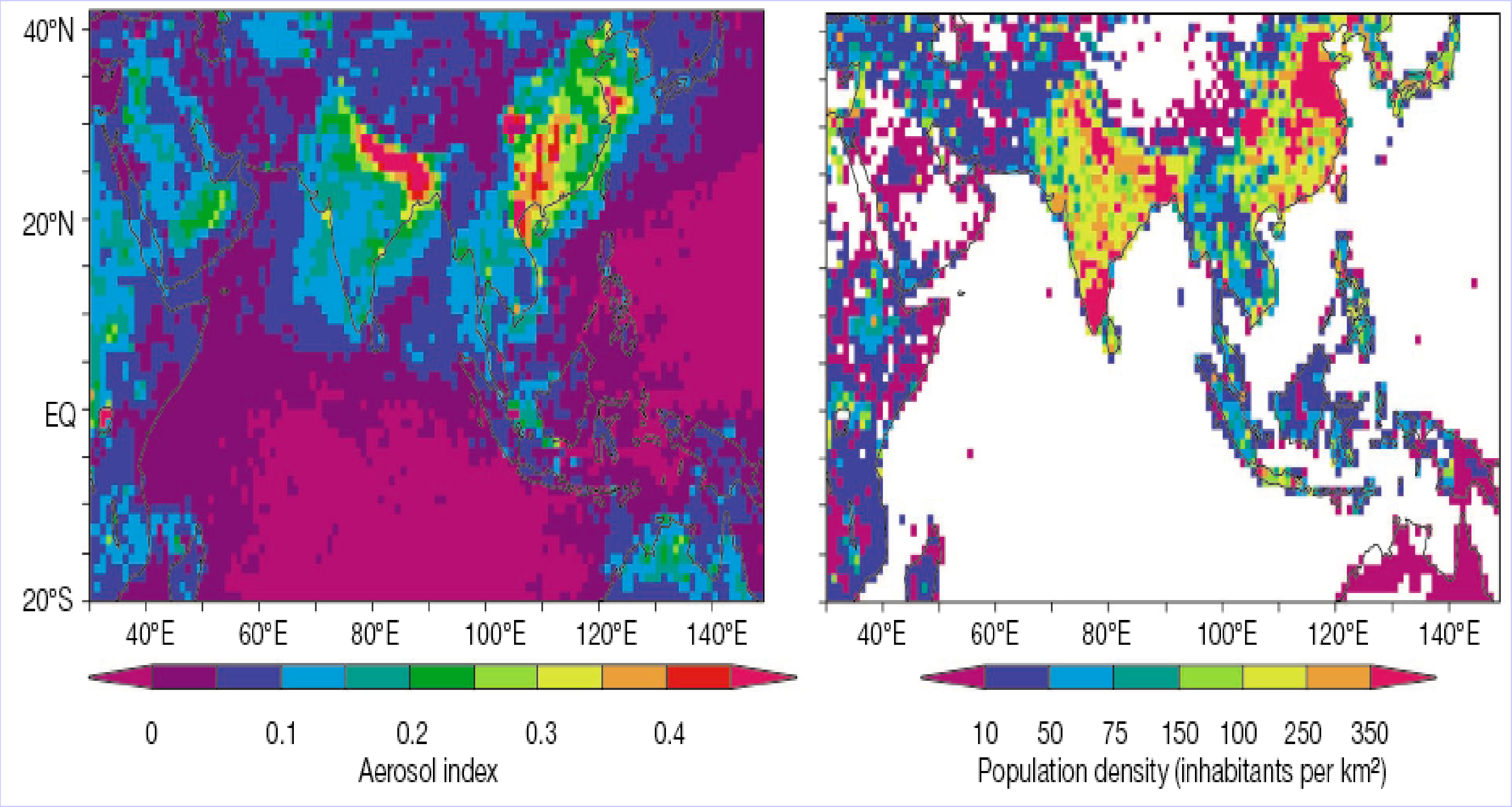
”Toxic trucks” Washington Post 11/19/00

“Trouble in the greenhouse” Nature, Sept., 2000

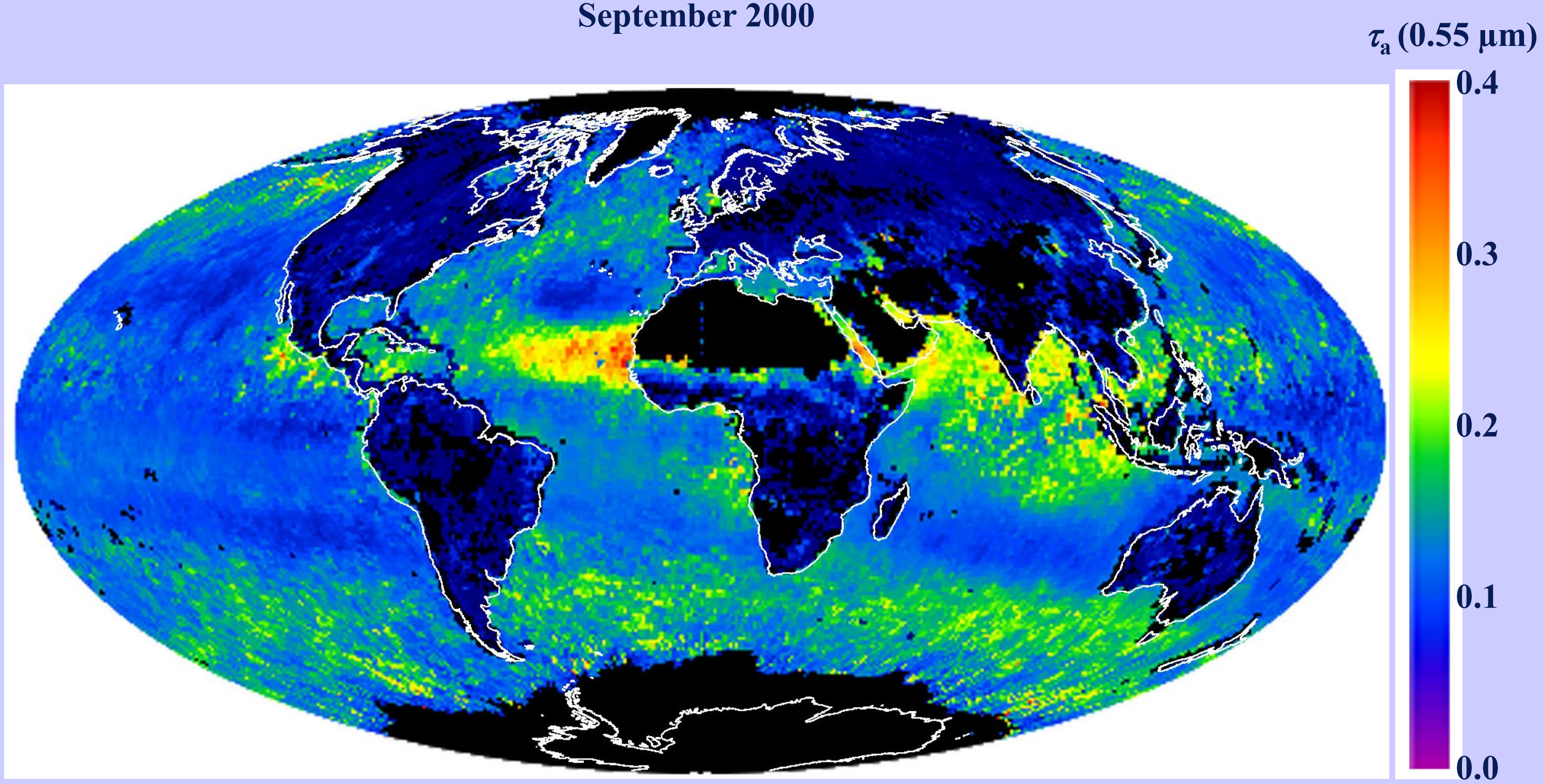
Does Population cause Pollution ?

POLDER aerosol index Feb. 1997 & population density

(Kaufman, Tanré & Boucher, Nature 2002)

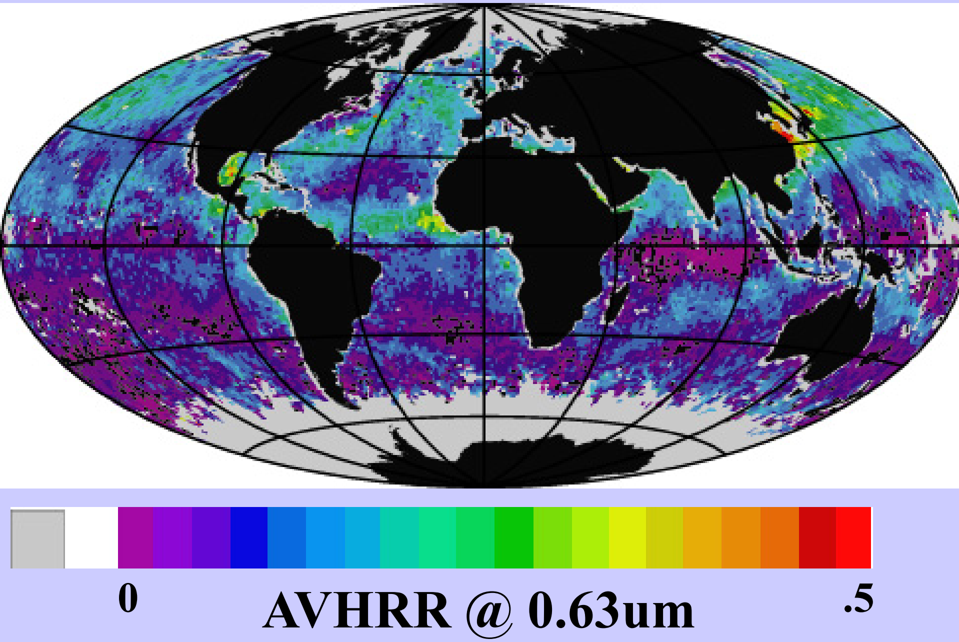


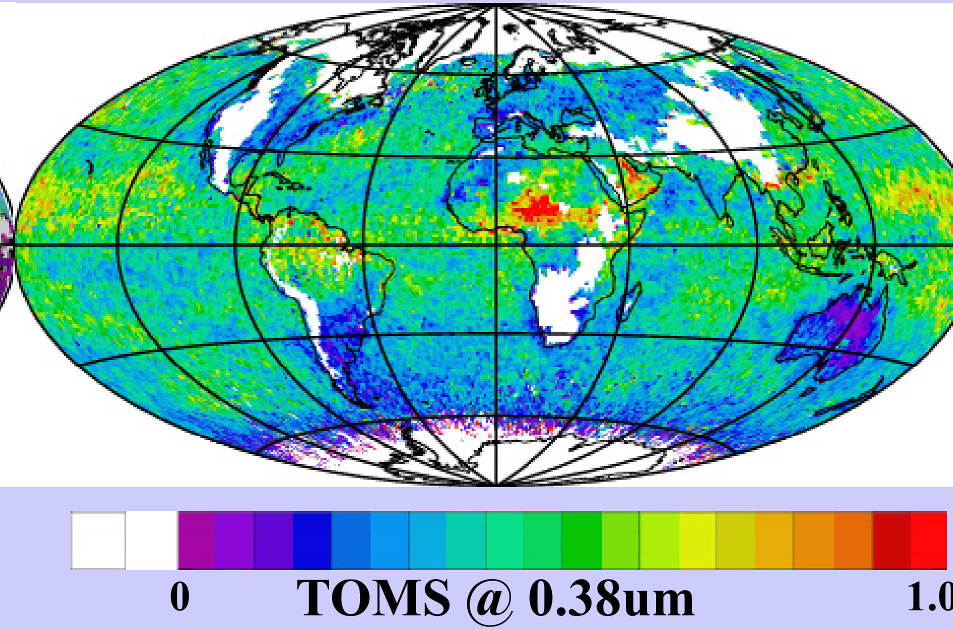
Aerosol Optical Thickness
(Coarse Particle Mode)

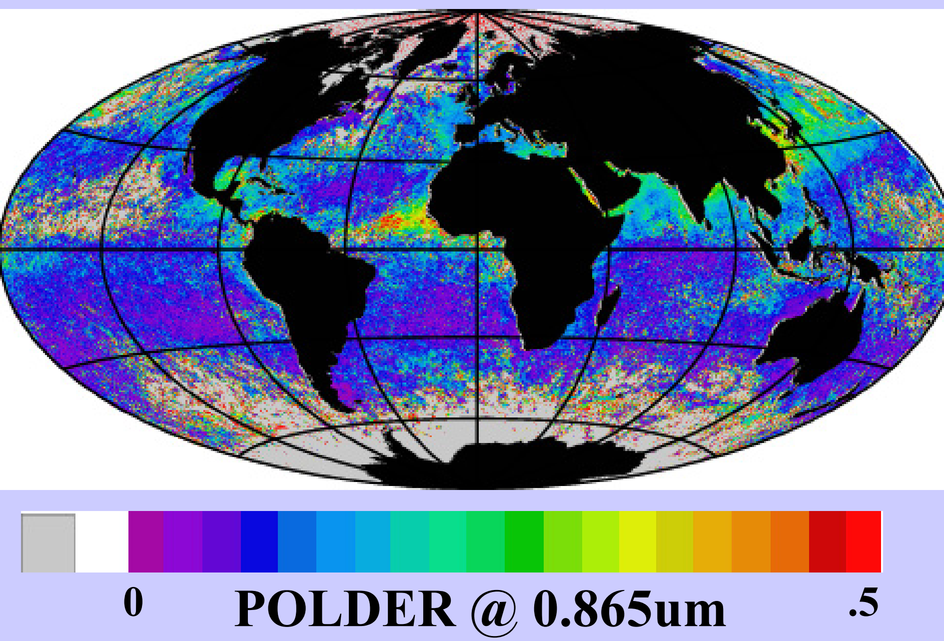


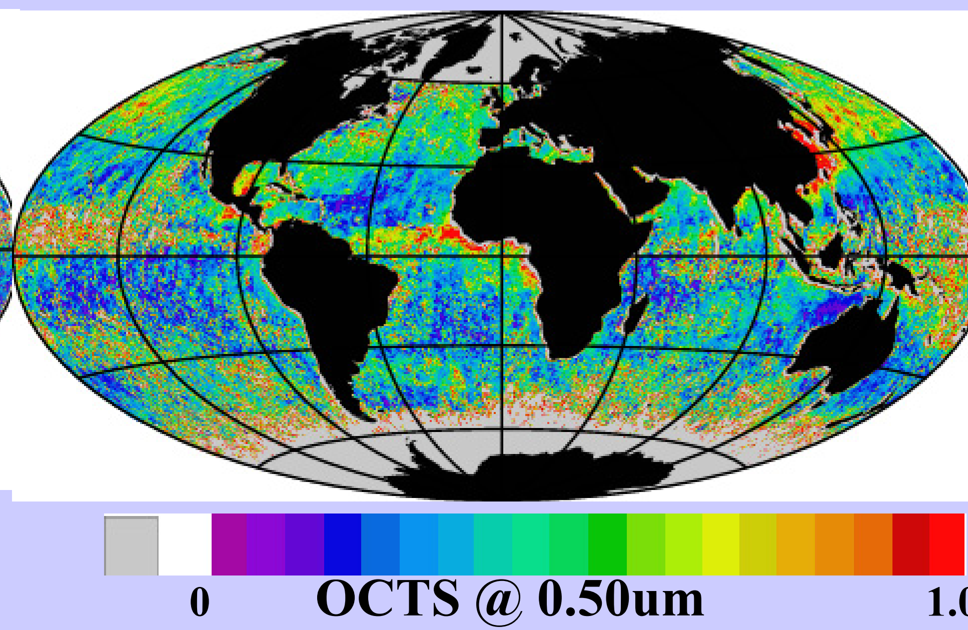
bands for aerosol retrieval over ocean (550, 660, 865, 1230, 1640, 2130 nm)

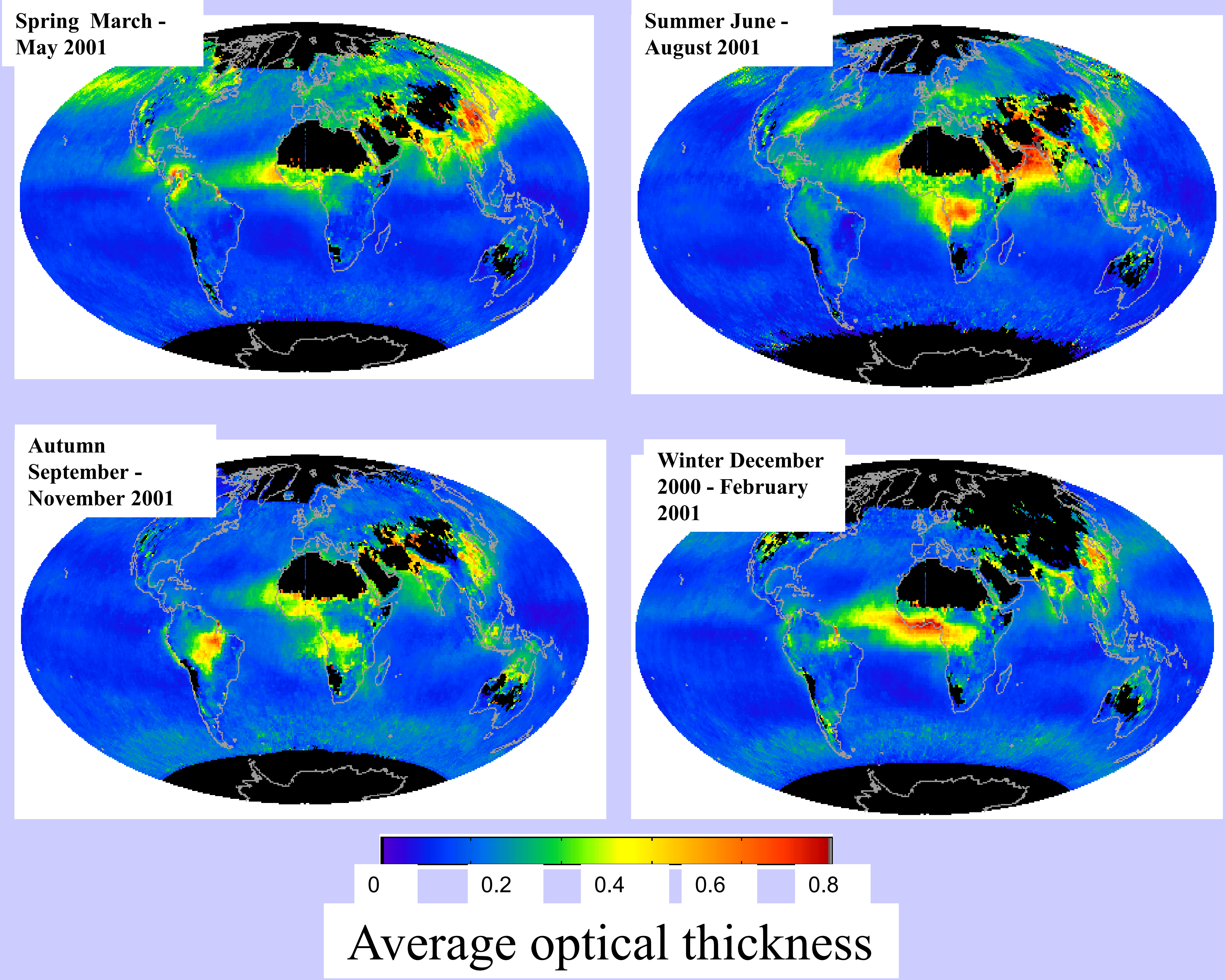
Global AOT for April 1997







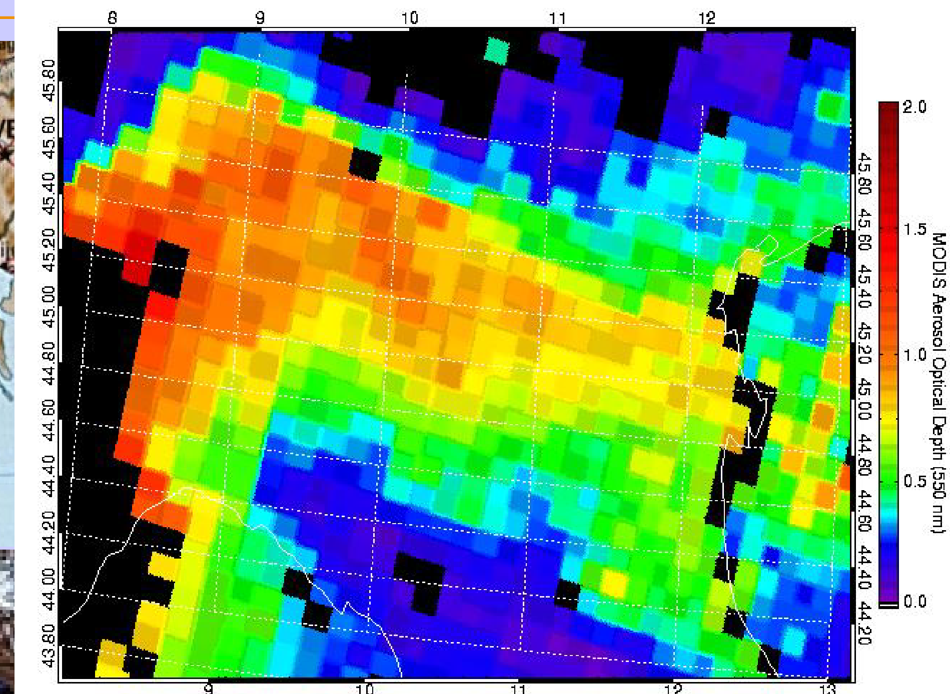


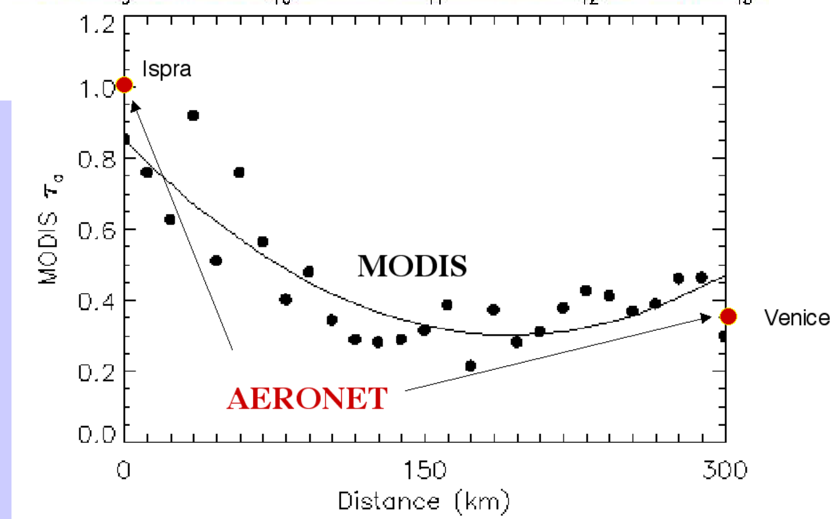

Spring March - May 2001
Summer June - August 2001
Autumn September - November 2001
Winter December 2000 - February 2001
0
0.2
0.4
0.6
0.8
Average optical thickness

Example: pollution accumulating under the Alps

600 km

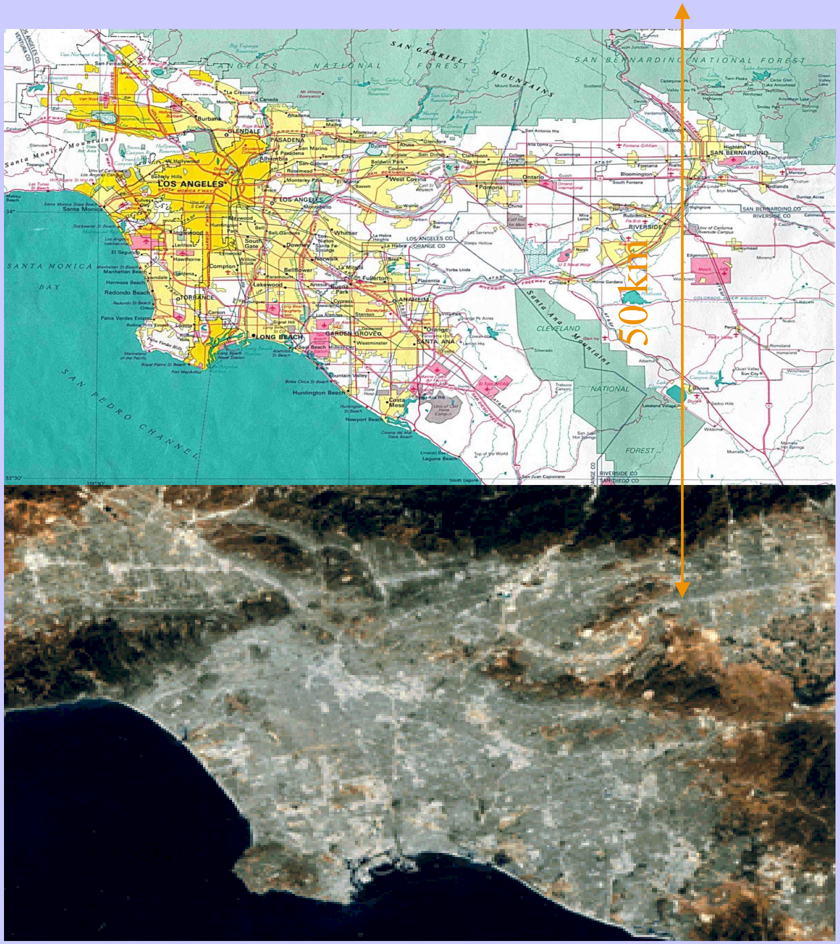
MODIS aerosol optical thickness

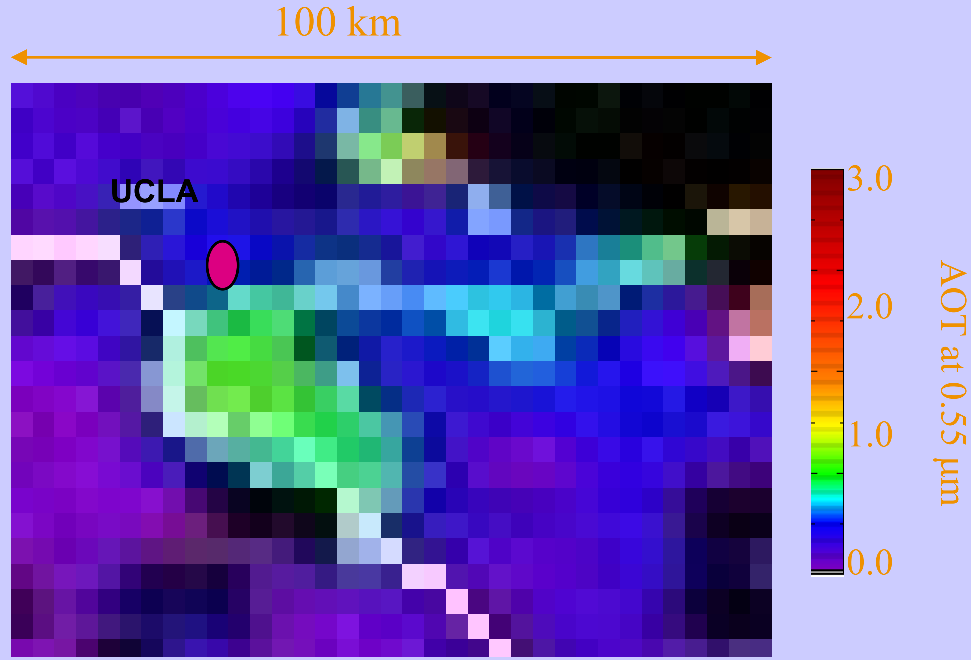




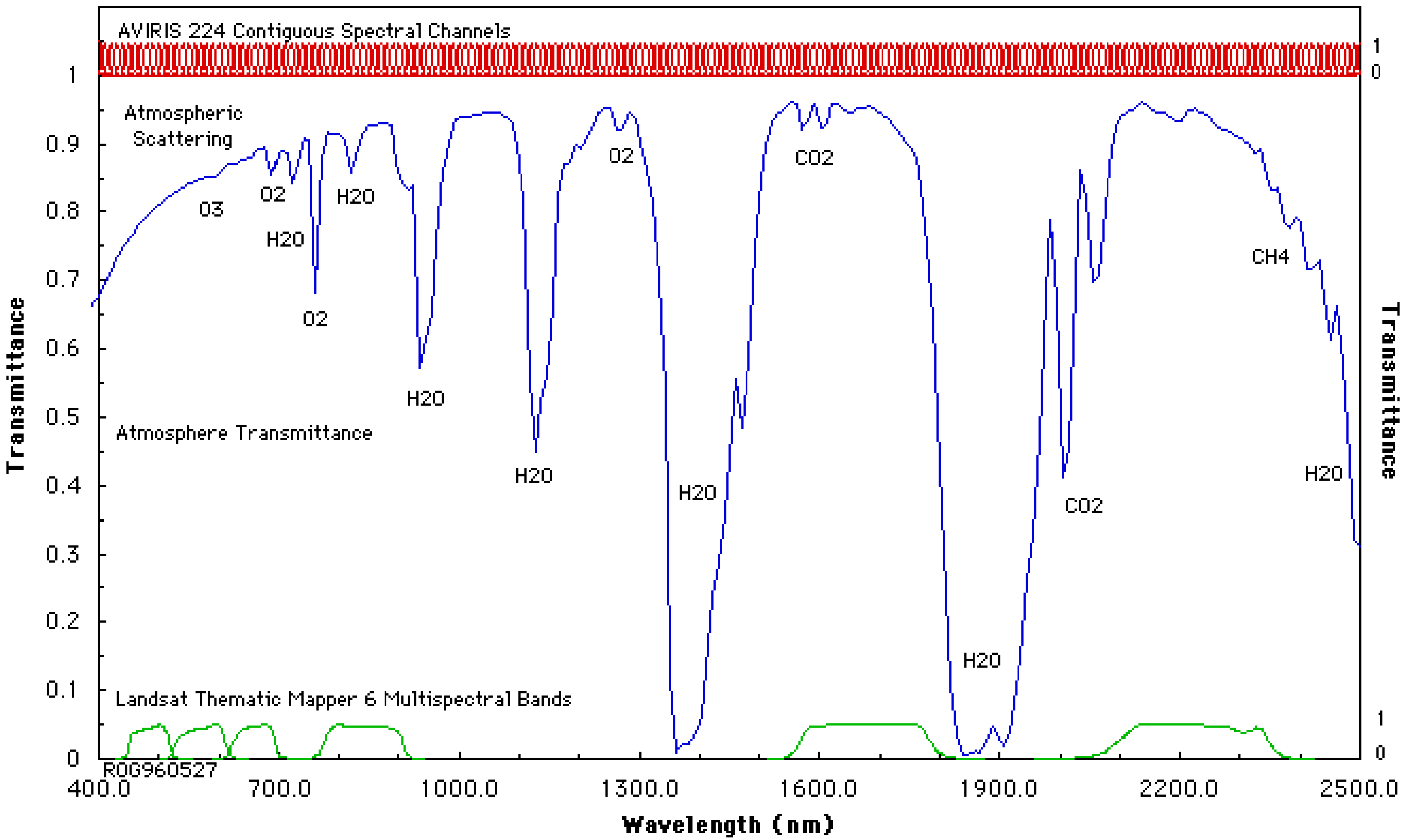
Allen Chu, SSAI/GSFC

Example: Los Angeles



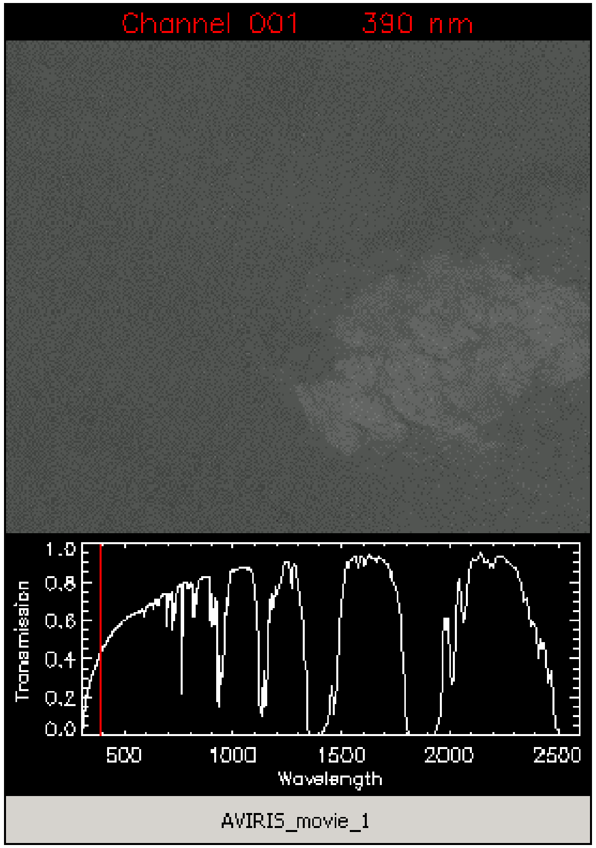


Measurements in the Solar Reflected Spectrum across the region covered by AVIRIS

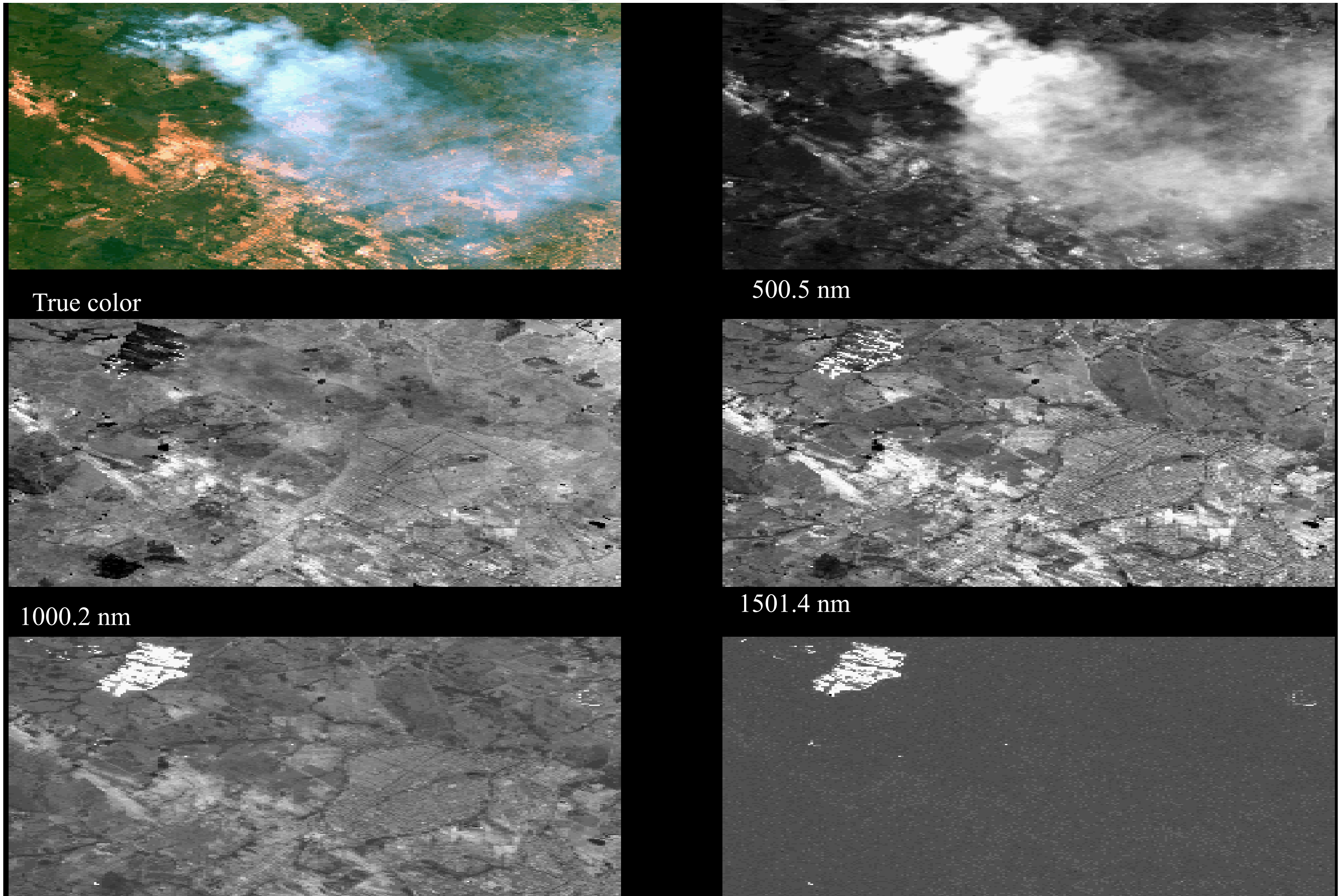


AVIRIS Movie #1

AVIRIS Image - Linden CA 20-Aug-1992
224 Spectral Bands: 0.4 - 2.5 μm
Pixel: 20m x 20m   Scene: 10km x 10km



Cuiaba Brazil mosaic on 25 August 1995 shows a forest clearing fire. True color image, and single band images in black and white.

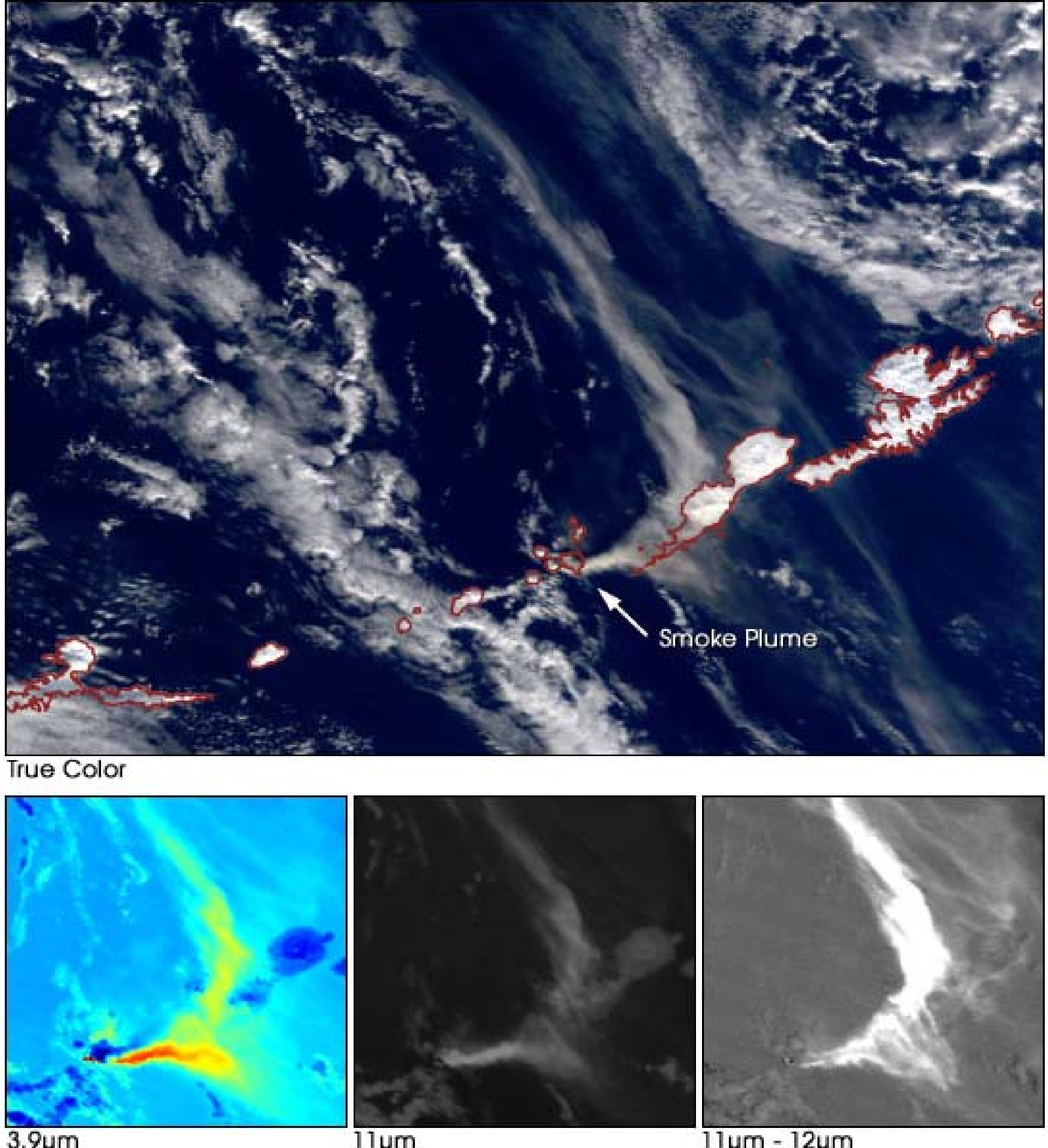


2000.5 nm

2508.5 nm

Ash Plume Detection

Mt. Cleveland Eruption 19 Feb 2001



MODIS detects ship tracks

Ship Tracks occur in marine stratocumulus regions of the globe

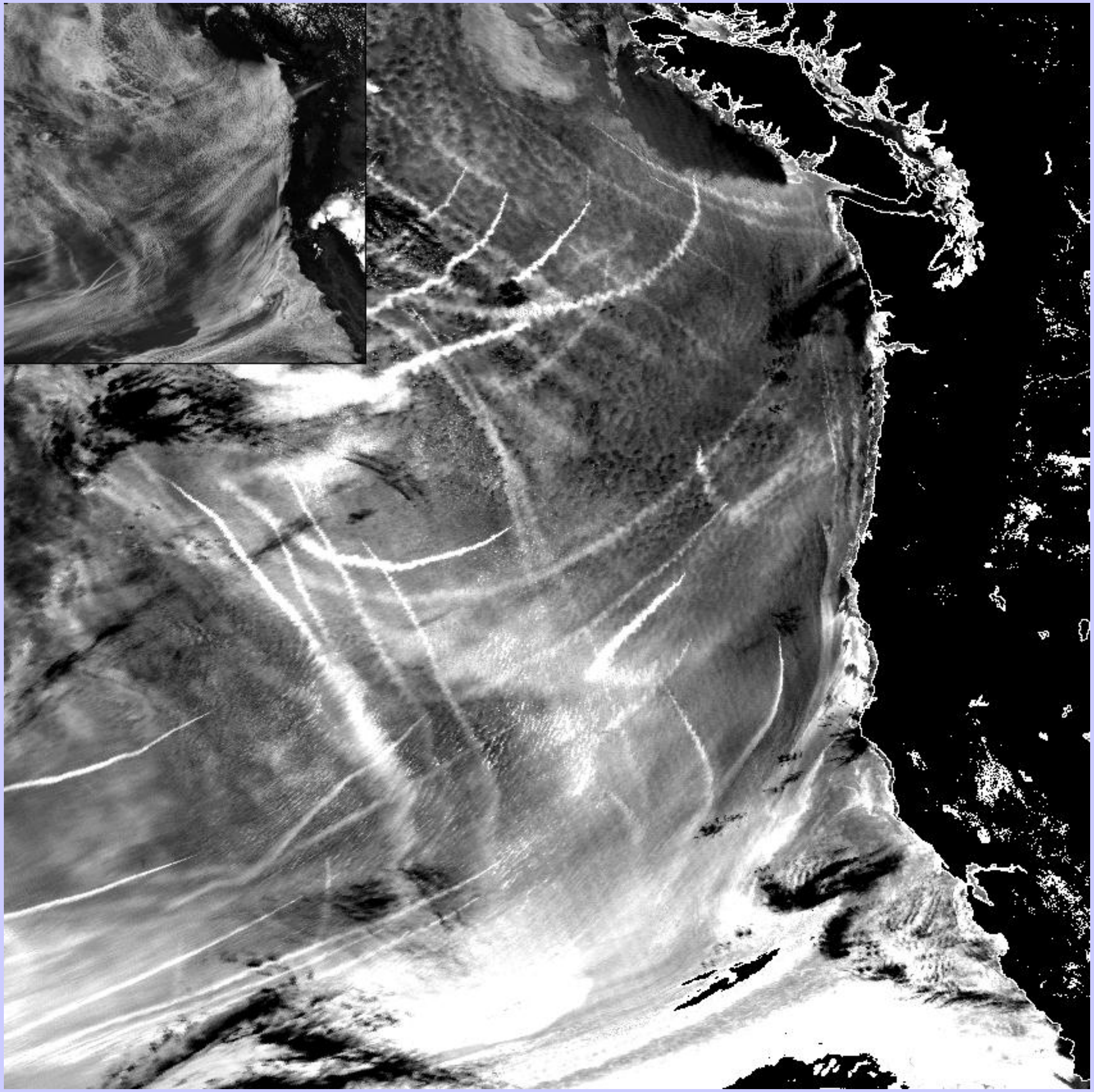
- California, Azores, Namibia, and Peru

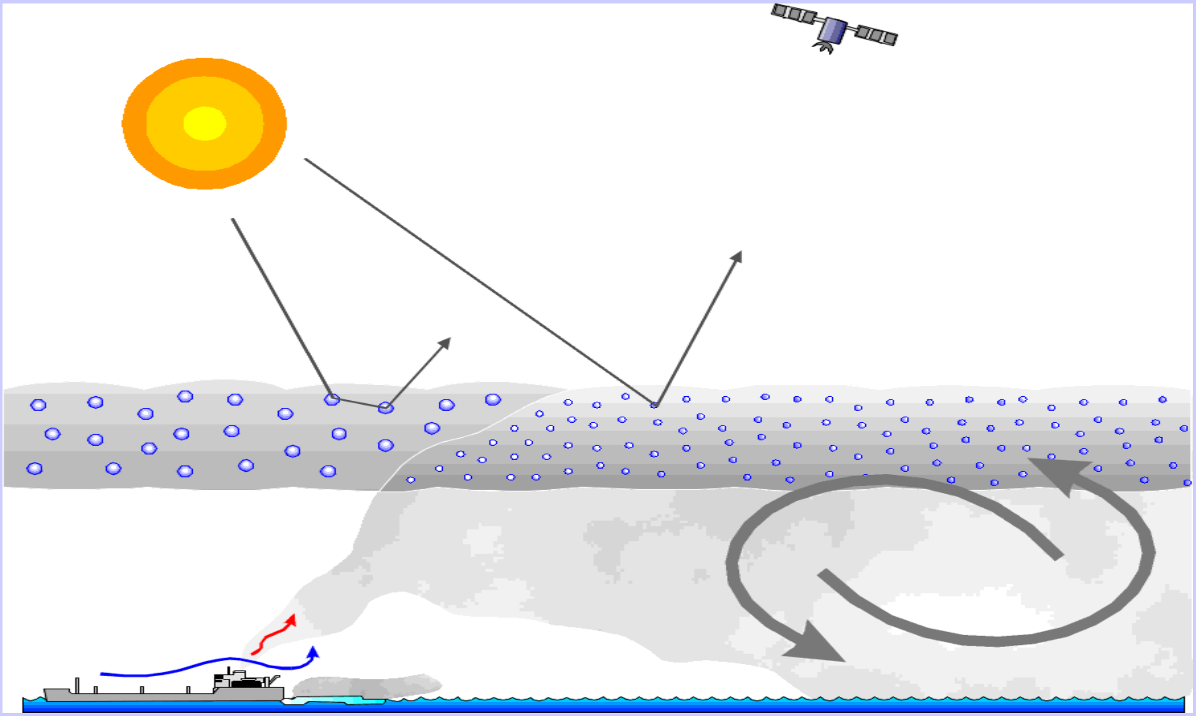
Conditions for formation

- 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 μm

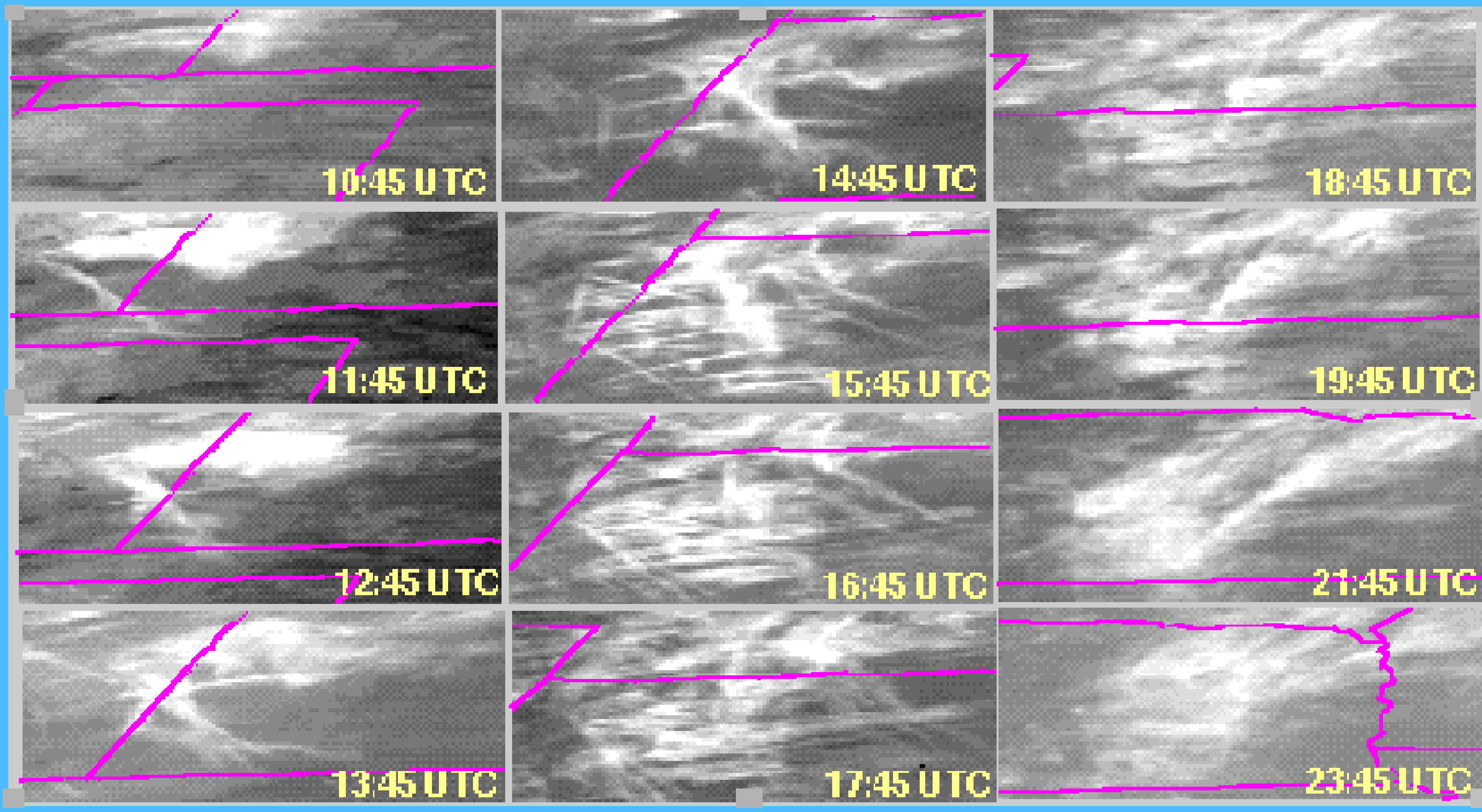
- Larger number of small droplets arising from particulate emission from ships



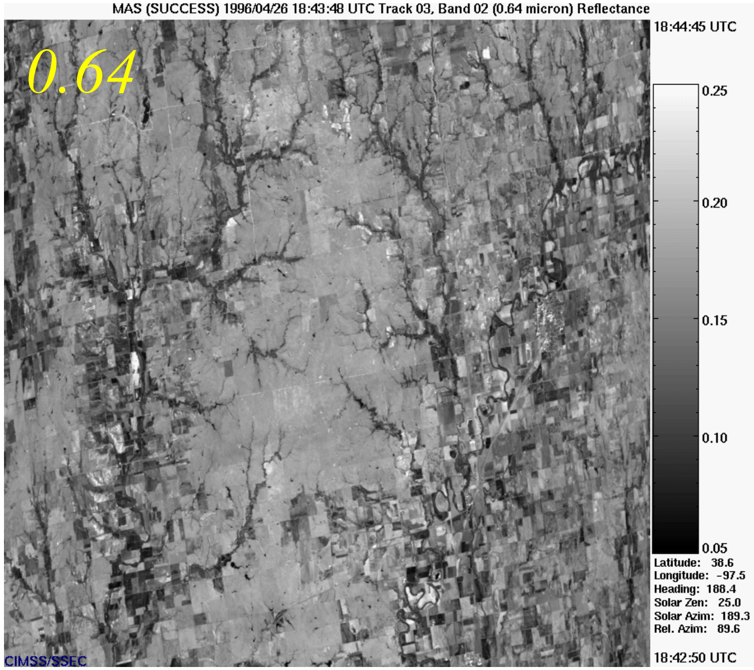


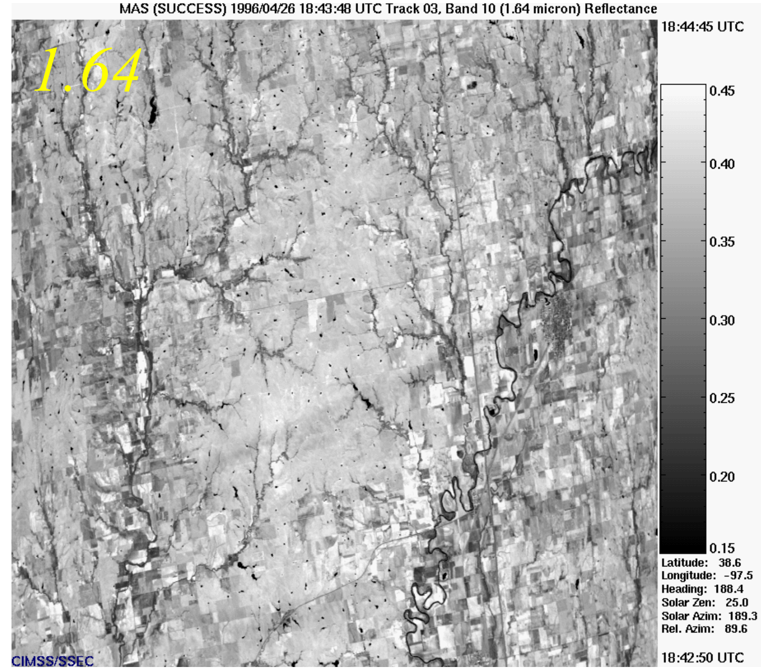
* Particles emitted by ships increase concentration of cloud condensation nuclei (CCN) in the air
* Increased CCN increase concentration of cloud droplets and reduce average size of the droplets
* Increased concentration and smaller particles reduce production of drizzle (100 μm radius) droplets in clouds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

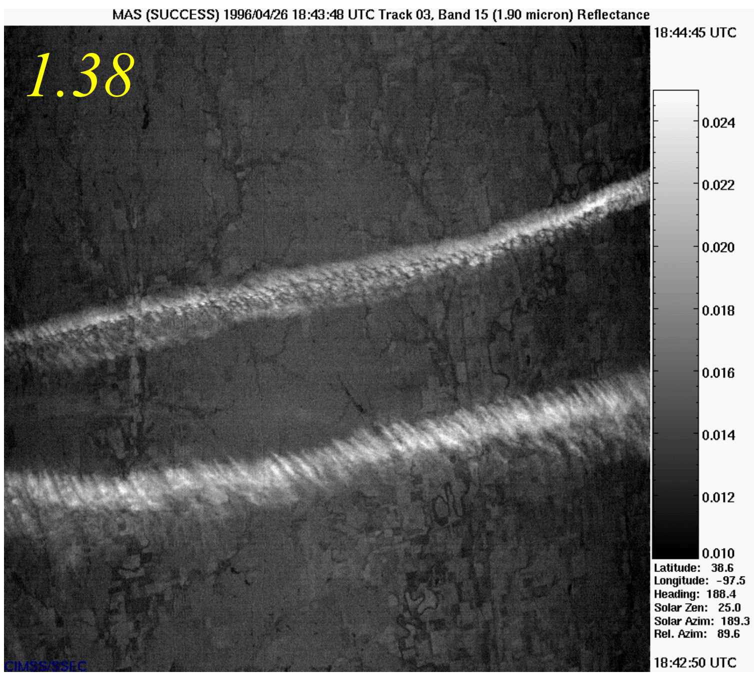
CIRRUS FORMATION BY CONTRAILS OVER CENTRAL U.S. IN GOES-8 IR IMAGERY
October 26, 1996

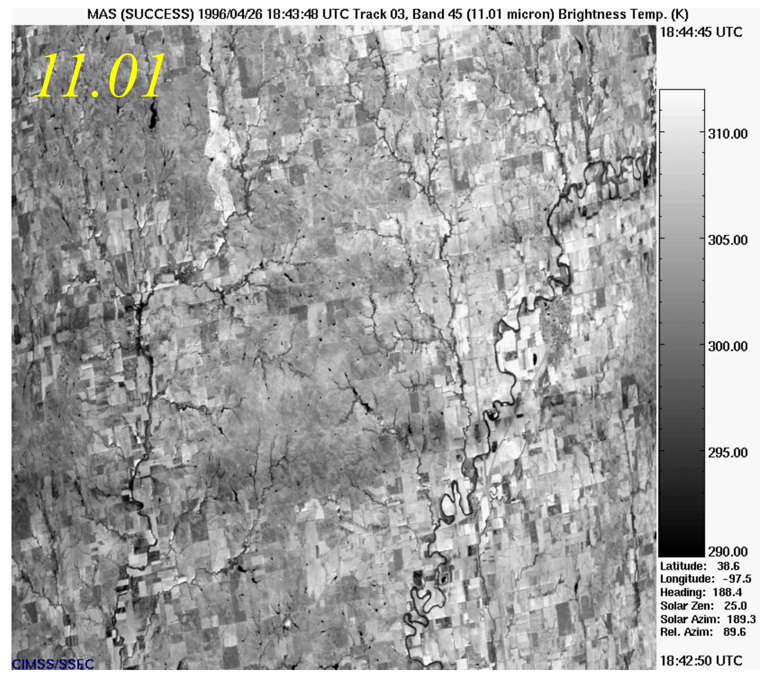


Minnis et al., *Science*, 1999

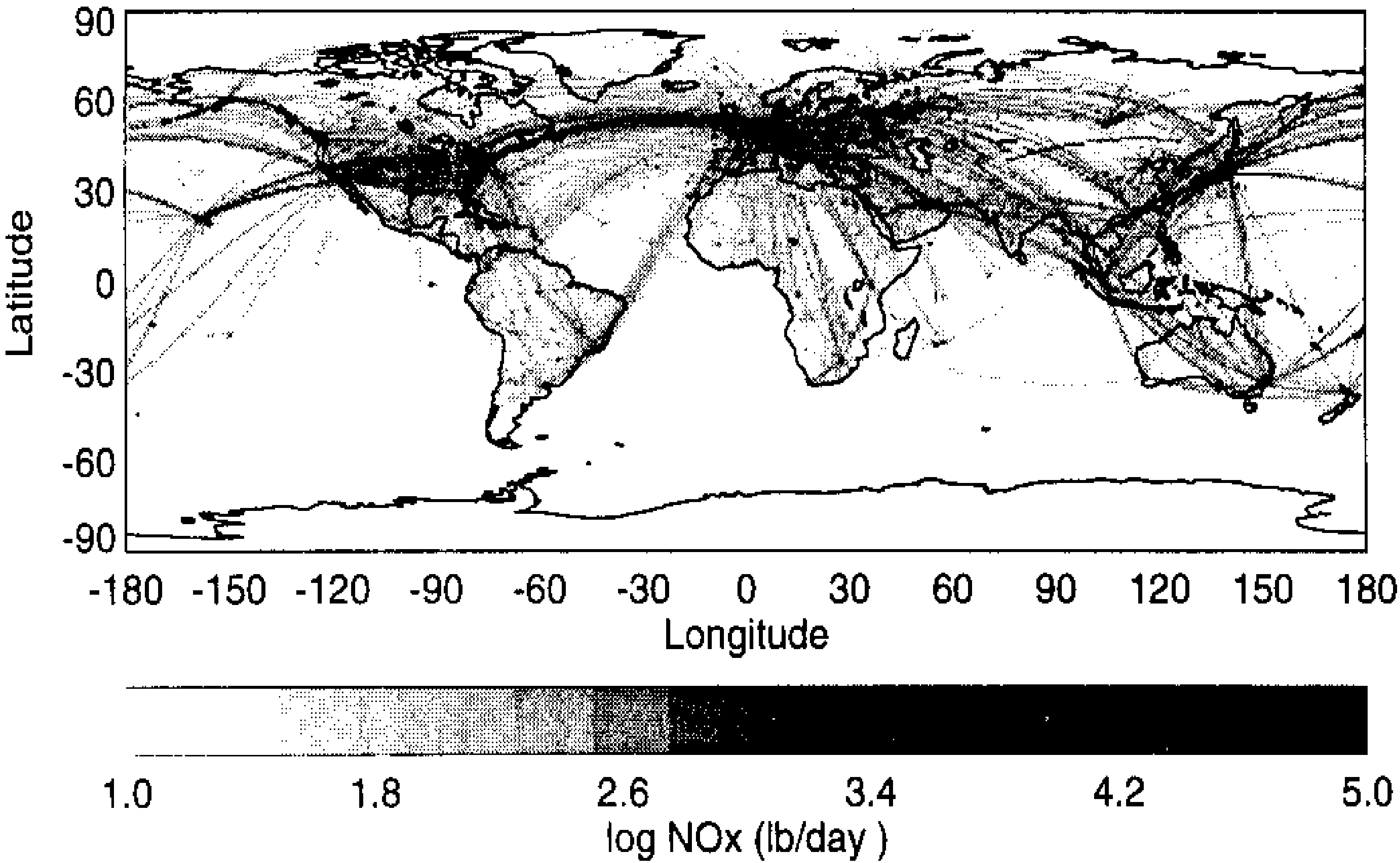

MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 02 (0.64 micron) Reflectance
0.64
18:44:45 UTC
0.25
0.20
0.15
0.10
0.05
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
18:42:50 UTC
CIMSS/SSEC


MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 10 (1.64 micron) Reflectance
1.64
18:44:45 UTC
0.45
0.40
0.35
0.30
0.25
0.20
0.15
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
18:42:50 UTC
CIMSS/SSEC

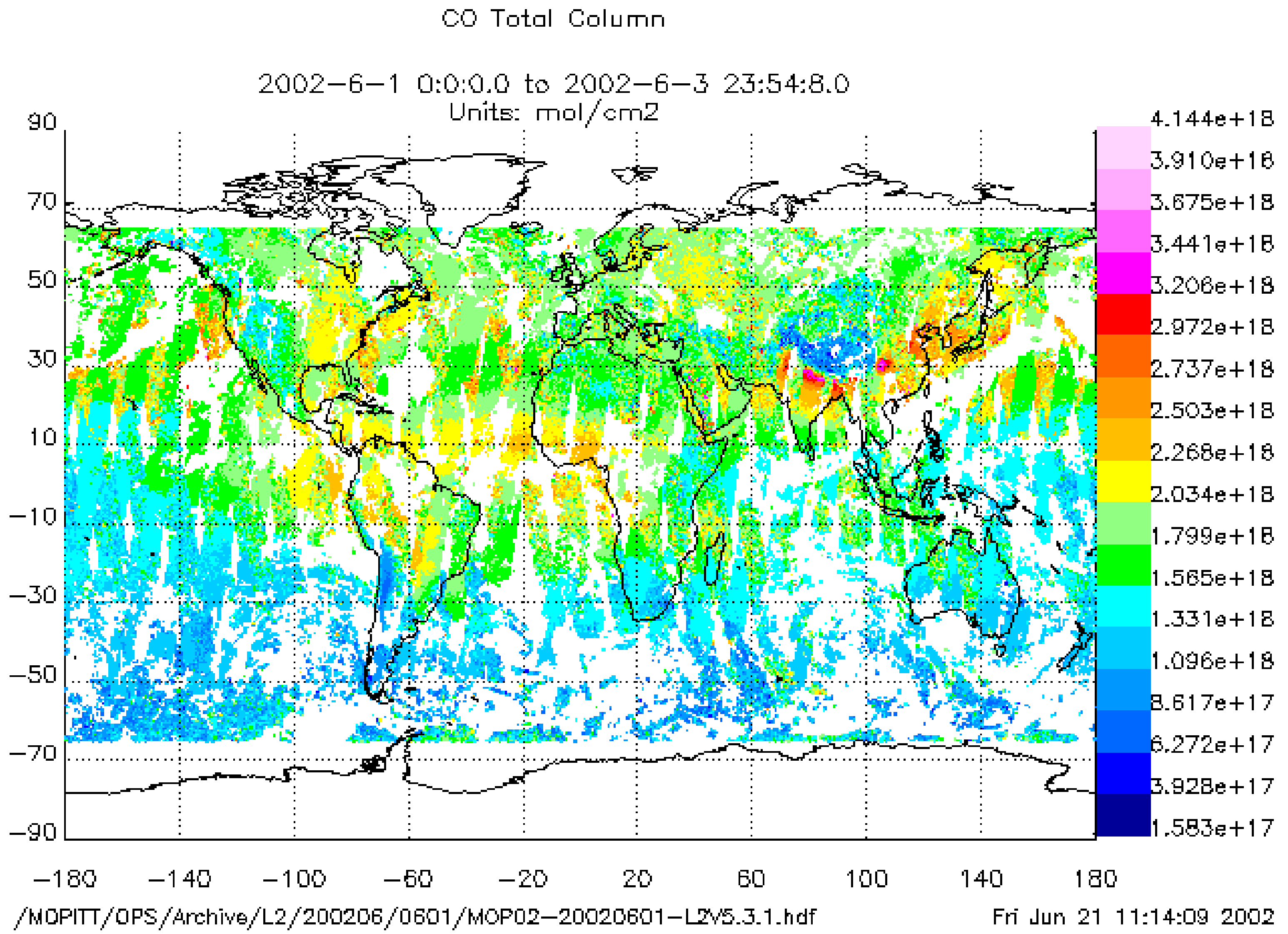

MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 15 (1.90 micron) Reflectance
1.38
18:44:45 UTC
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
18:42:50 UTC
CIMSS/SSEC


MAS (SUCCESS) 1996/04/26 18:43:48 UTC Track 03, Band 45 (11.01 micron) Brightness Temp. (K)
11.01
18:44:45 UTC
310.00
305.00
300.00
295.00
290.00
Latitude: 38.6
Longitude: -97.5
Heading: 188.4
Solar Zen: 25.0
Solar Azim: 189.3
Rel. Azim: 89.6
18:42:50 UTC
CIMSS/SSEC

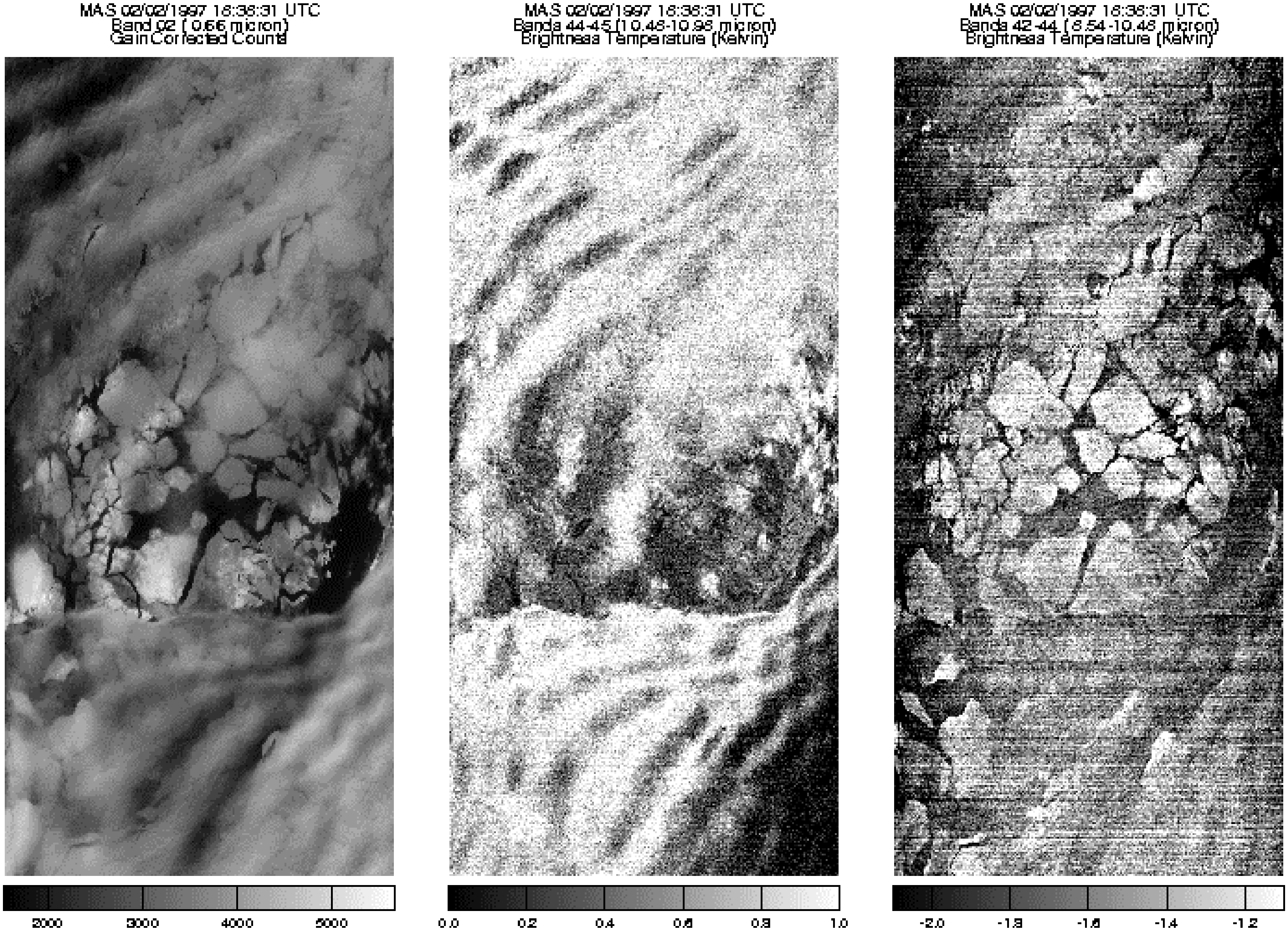
Is cirrus related to air traffic?



MOPITT CO Column 1-3 June 2002
(Phase 2 Data)

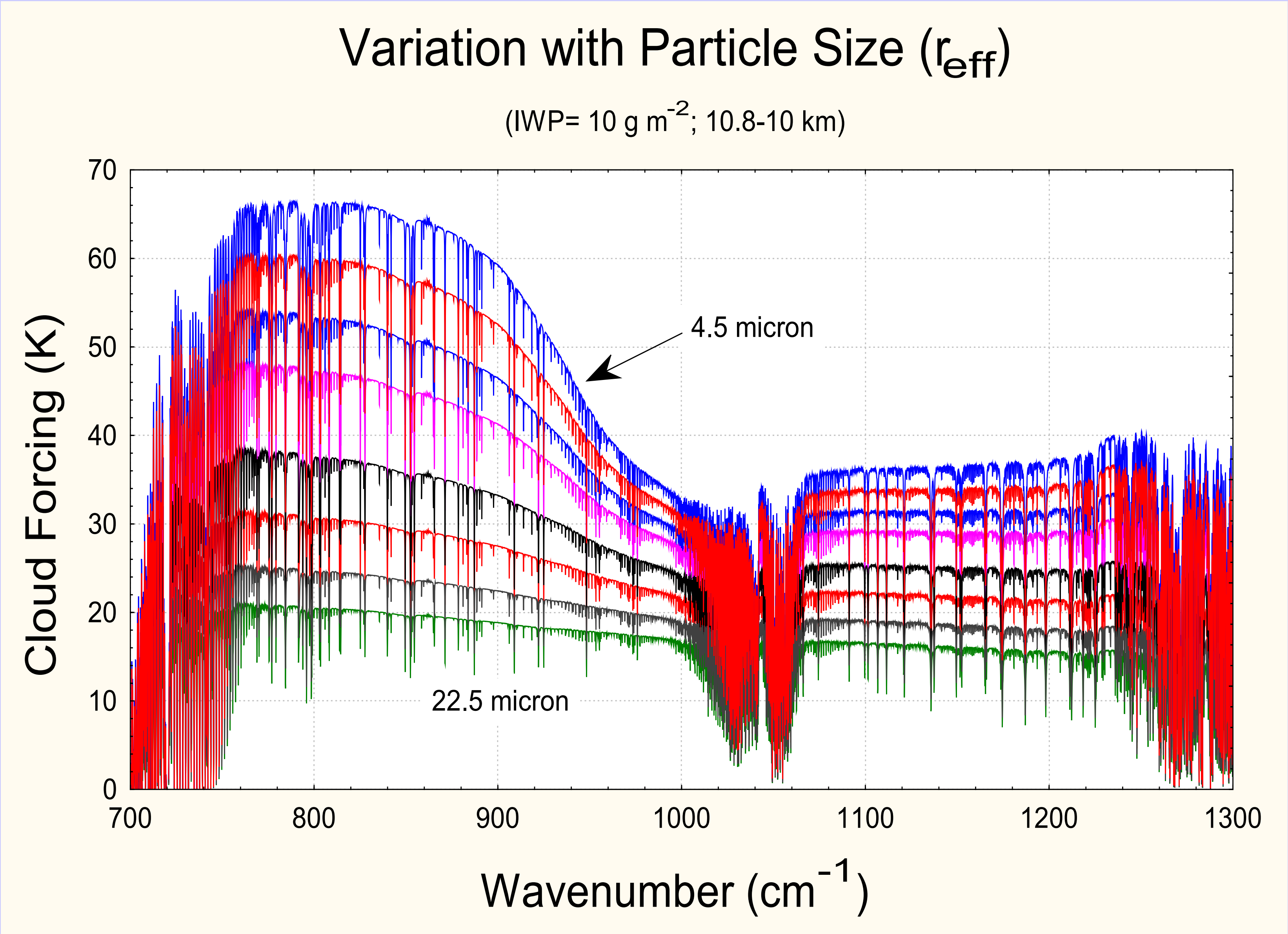


8.6 - 10.5 um observations of sea ice through low cloud cover

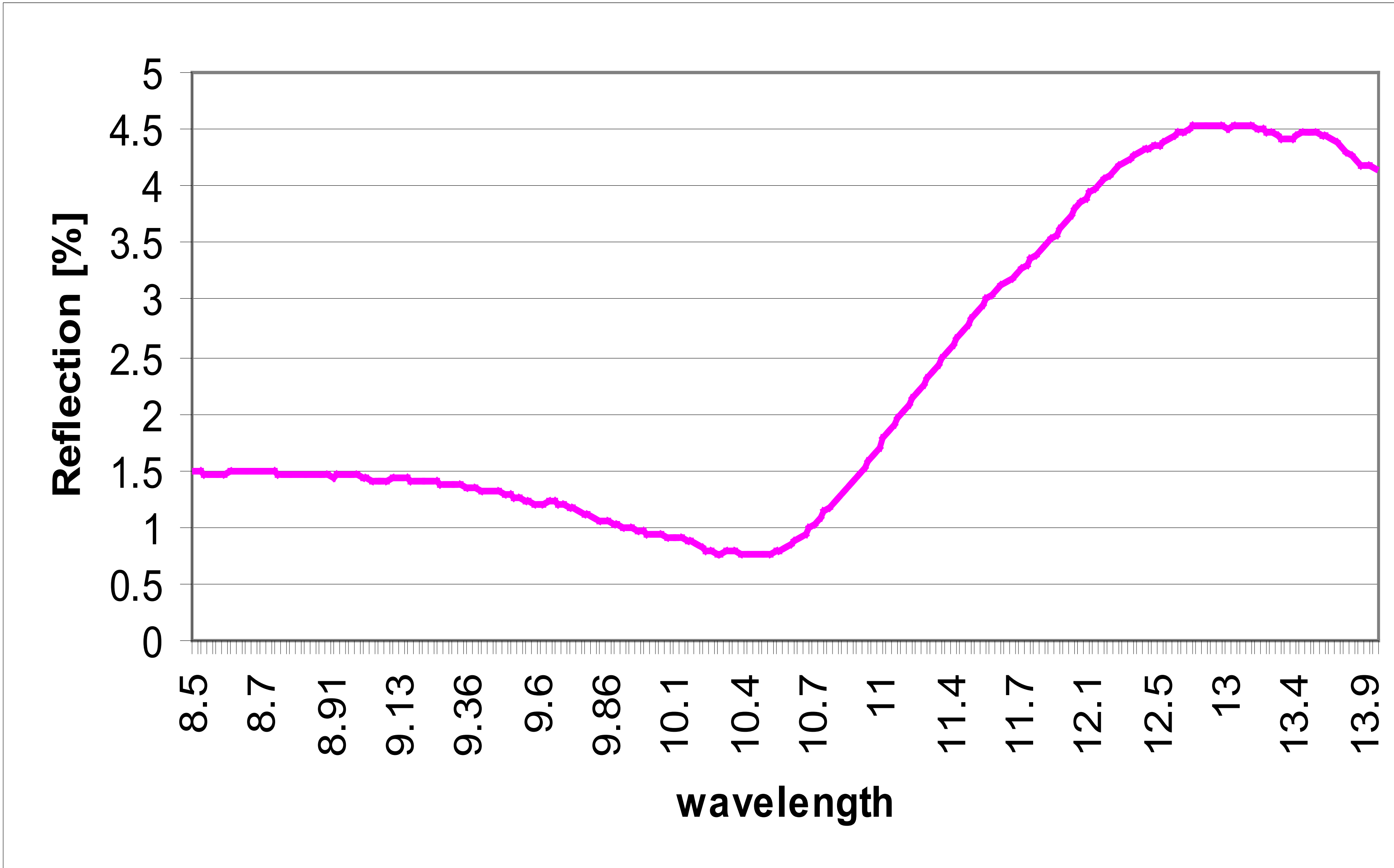


.66 um 10.5 – 11 um 8.6 - 10.5 um

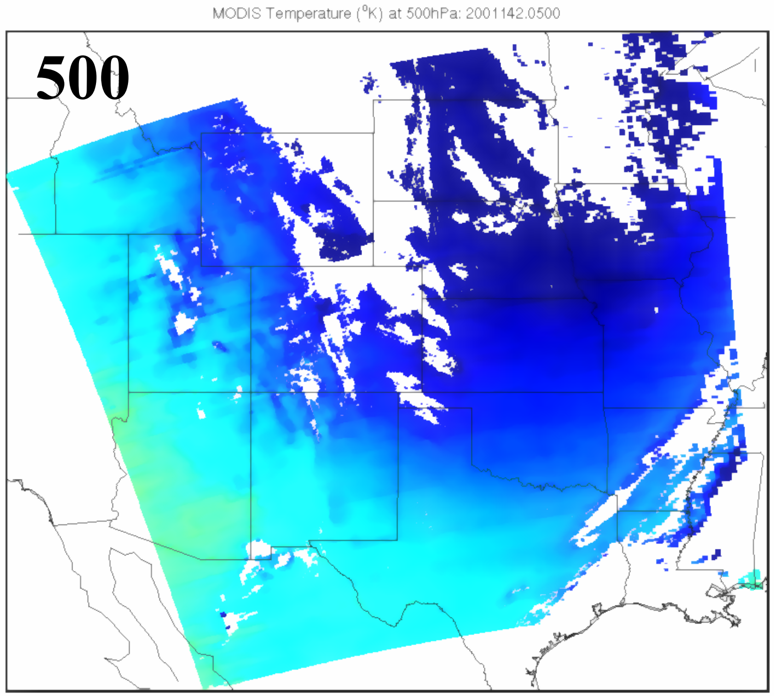
Cloud particle size is revealed in high resolution infrared spectra

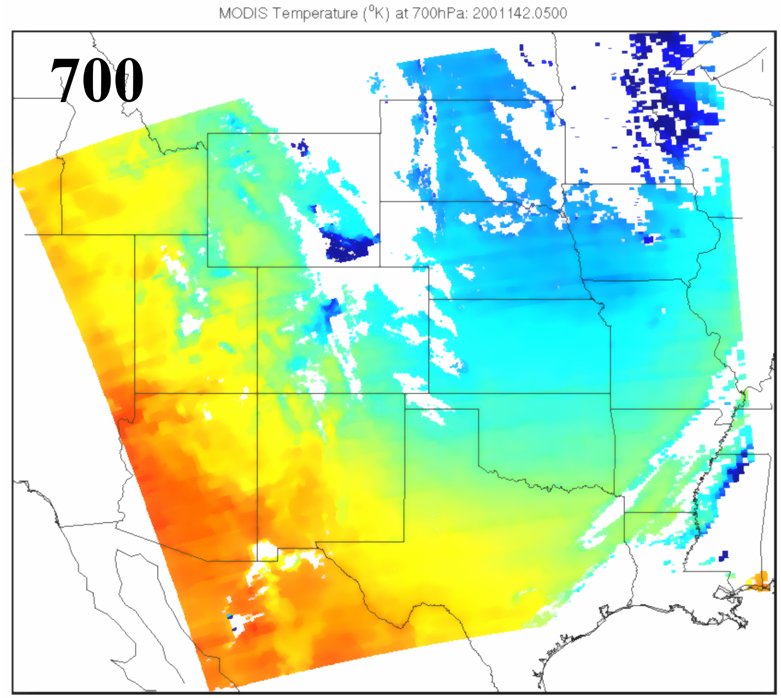


8.6 um sees more reflection than 10.5 um image over snow

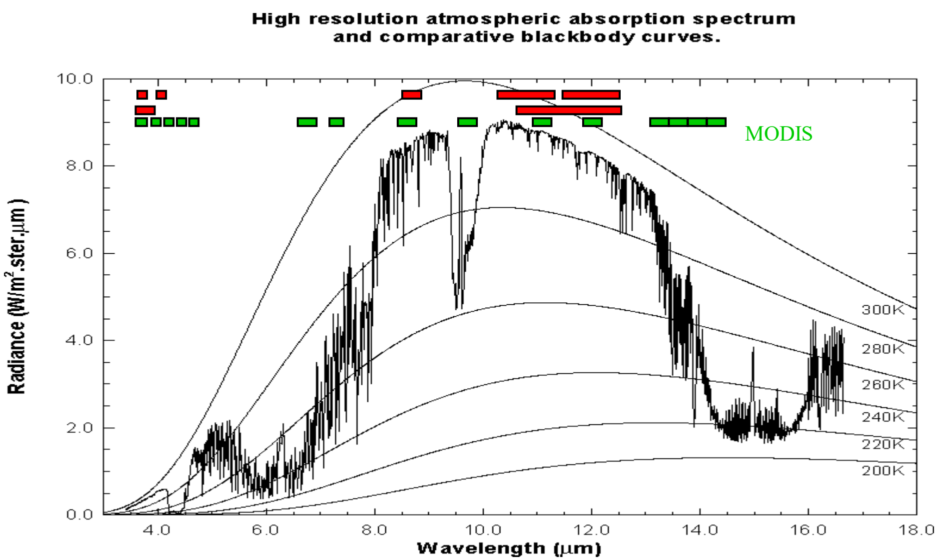


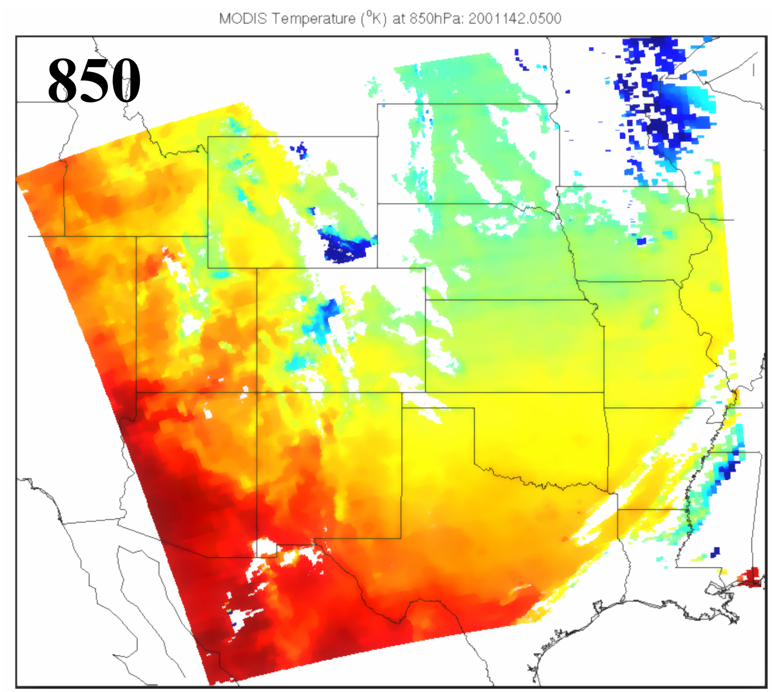
T(p)

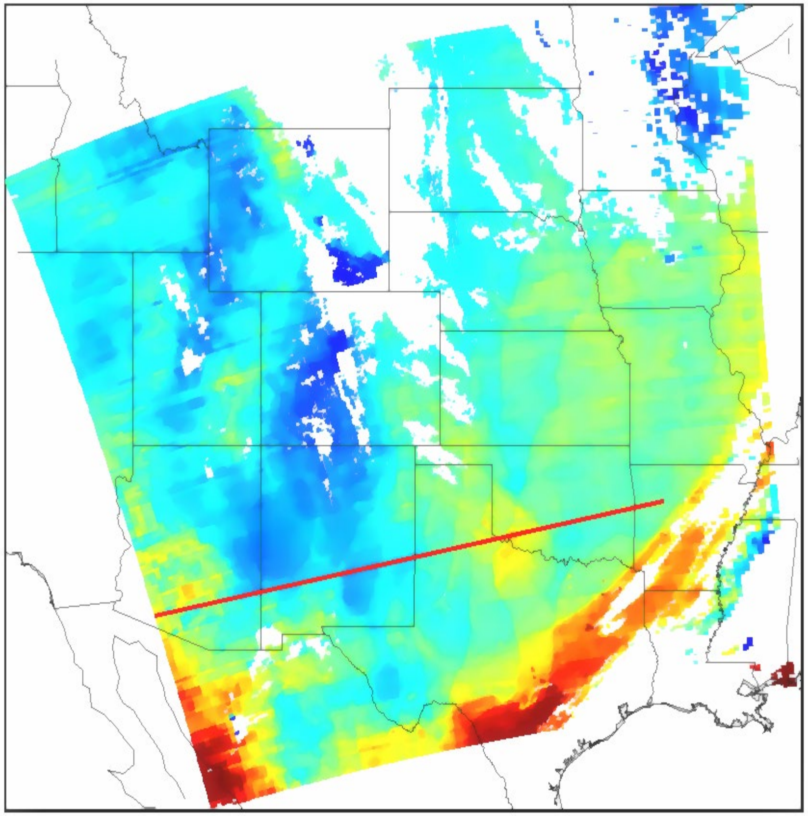

MODIS Temperature (°K) at 500hPa: 2001142.0500
500

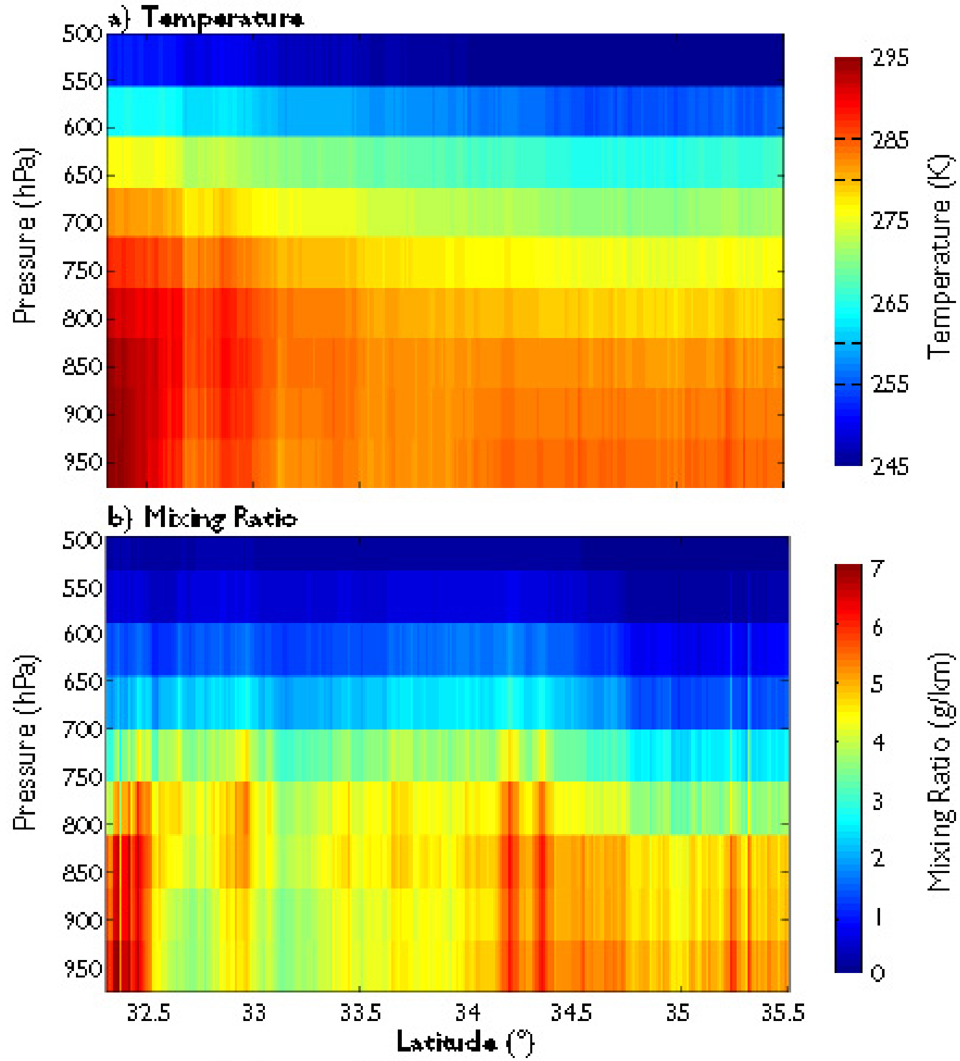

MODIS Temperature (°K) at 700hPa: 2001142.0500
700


260
265
270
275
280
285
290
295

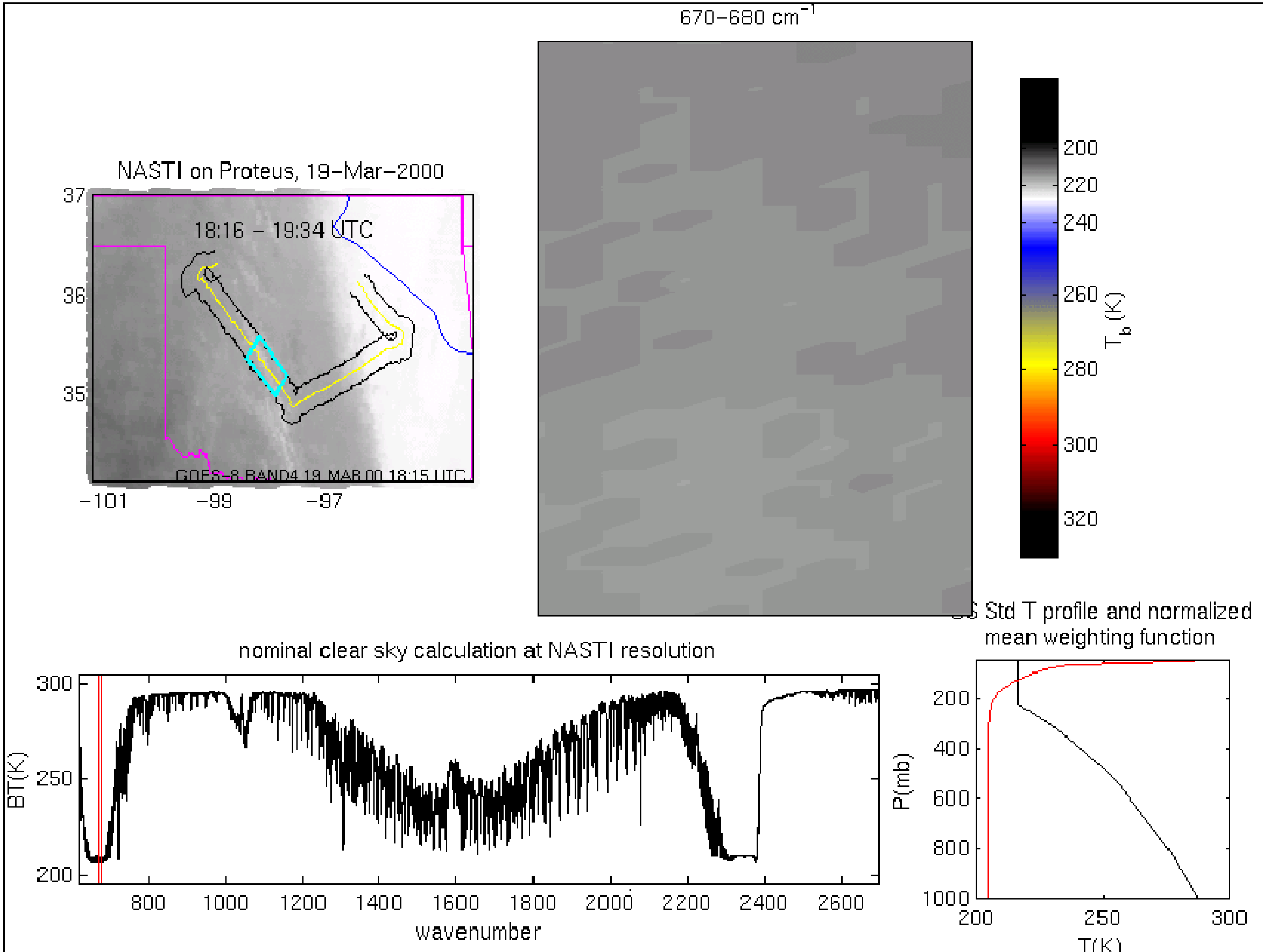

High resolution atmospheric absorption spectrum
and comparative blackbody curves.
MODIS
Radiance (W/m².ster.µm)
Wavelength (µm)
300K
280K
260K
240K
220K
200K
0.0
2.0
4.0
6.0
8.0
10.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0


MODIS Temperature (°K) at 850hPa: 2001142.0500
850





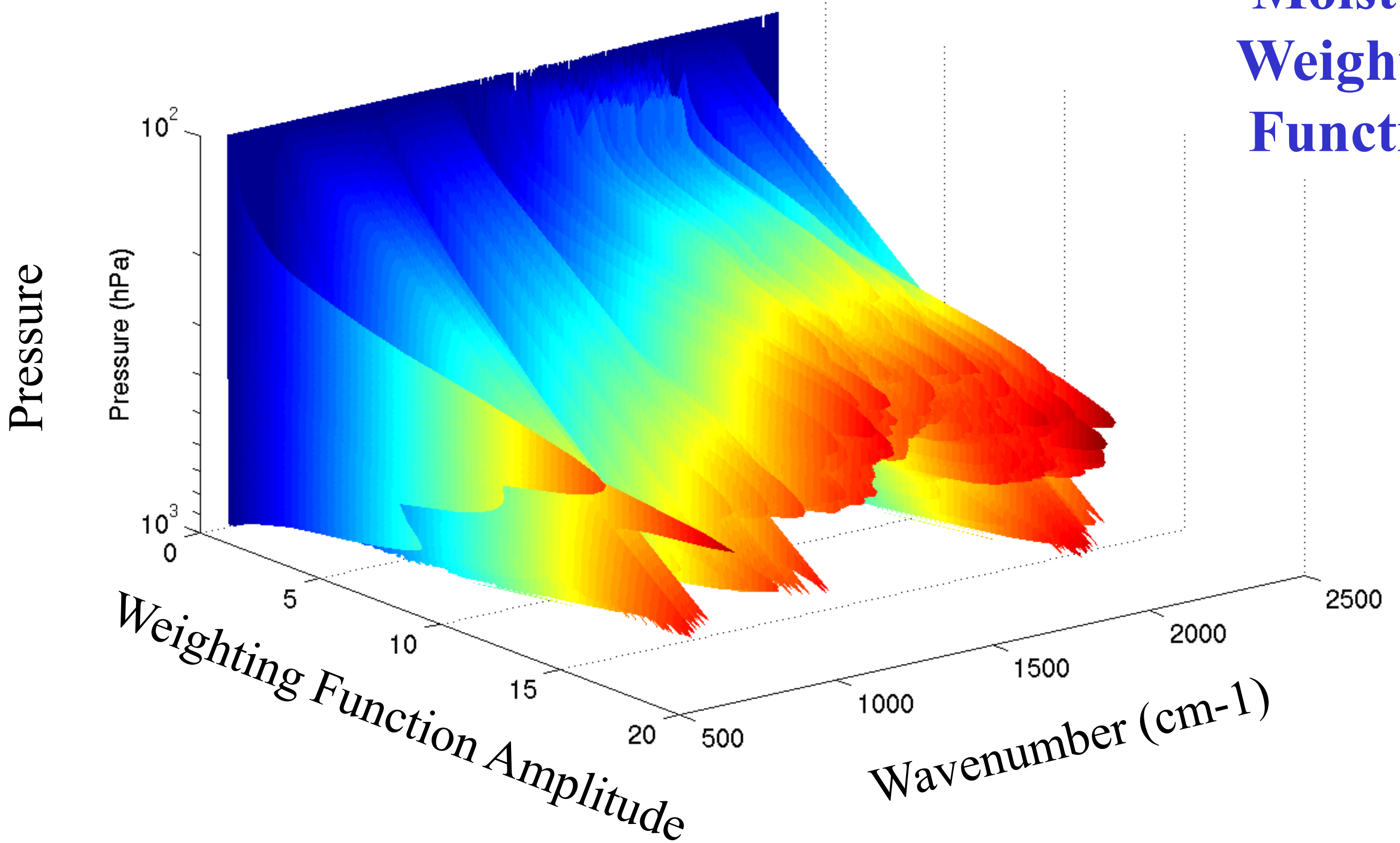
Clear sky layers of temperature and moisture



nasti_movie4_color_75

These water vapor weighting functions reflect the radiance sensitivity of the specific channels to a water vapor % change at a specific level (equivalent to dR/dlnq scaled by dlnp).

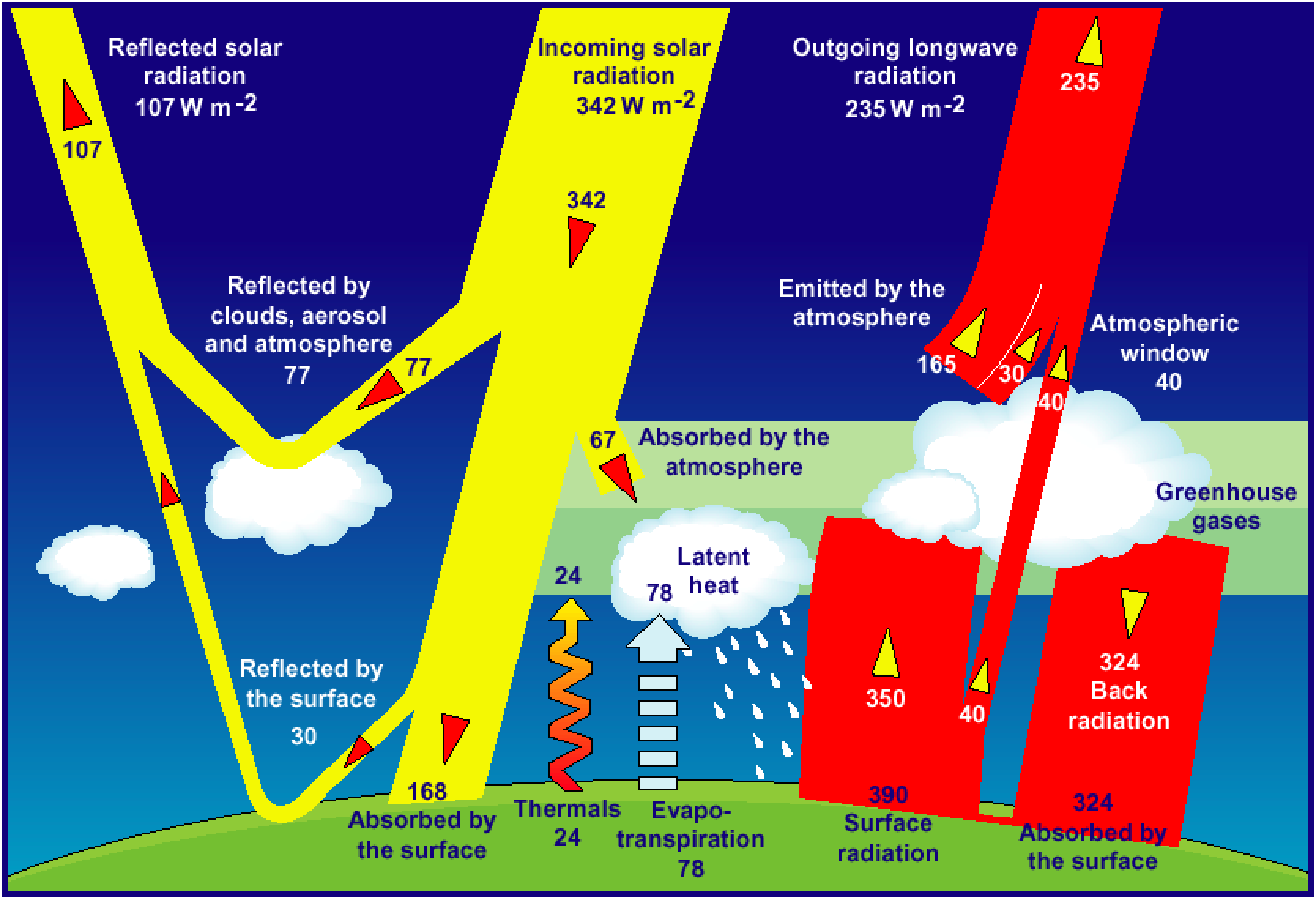
Moisture Weighting Functions



UW/CIMSS

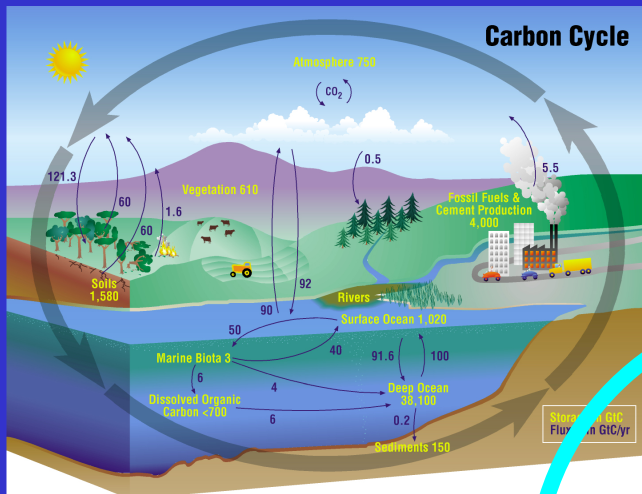
The advanced sounder has more and sharper weighting functions

Climate System Energy Balance

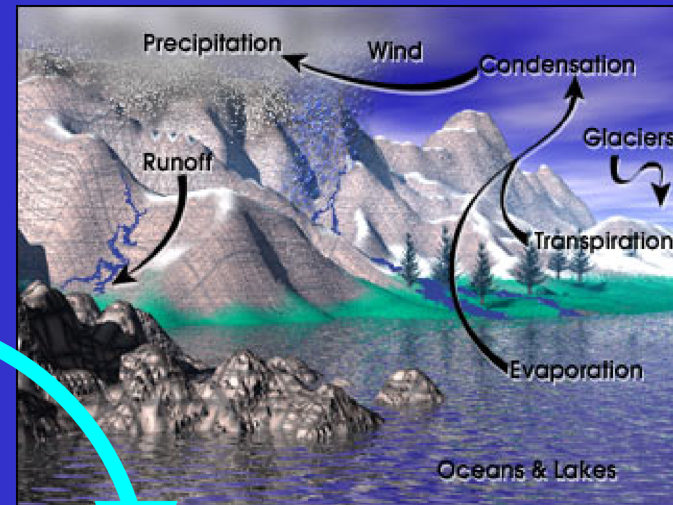


Major Climate System Elements

Carbon Cycle

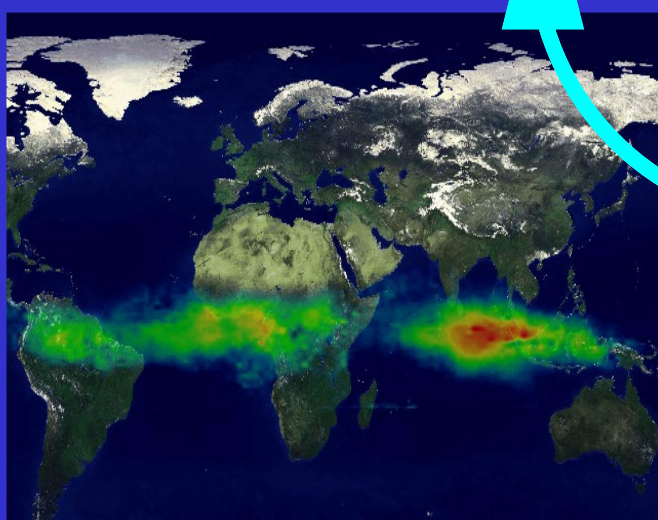


Water & Energy Cycle

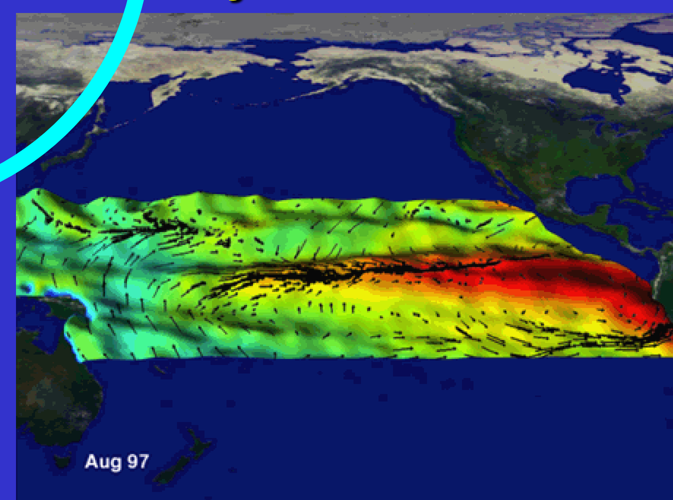


Coupled Chaotic Nonlinear

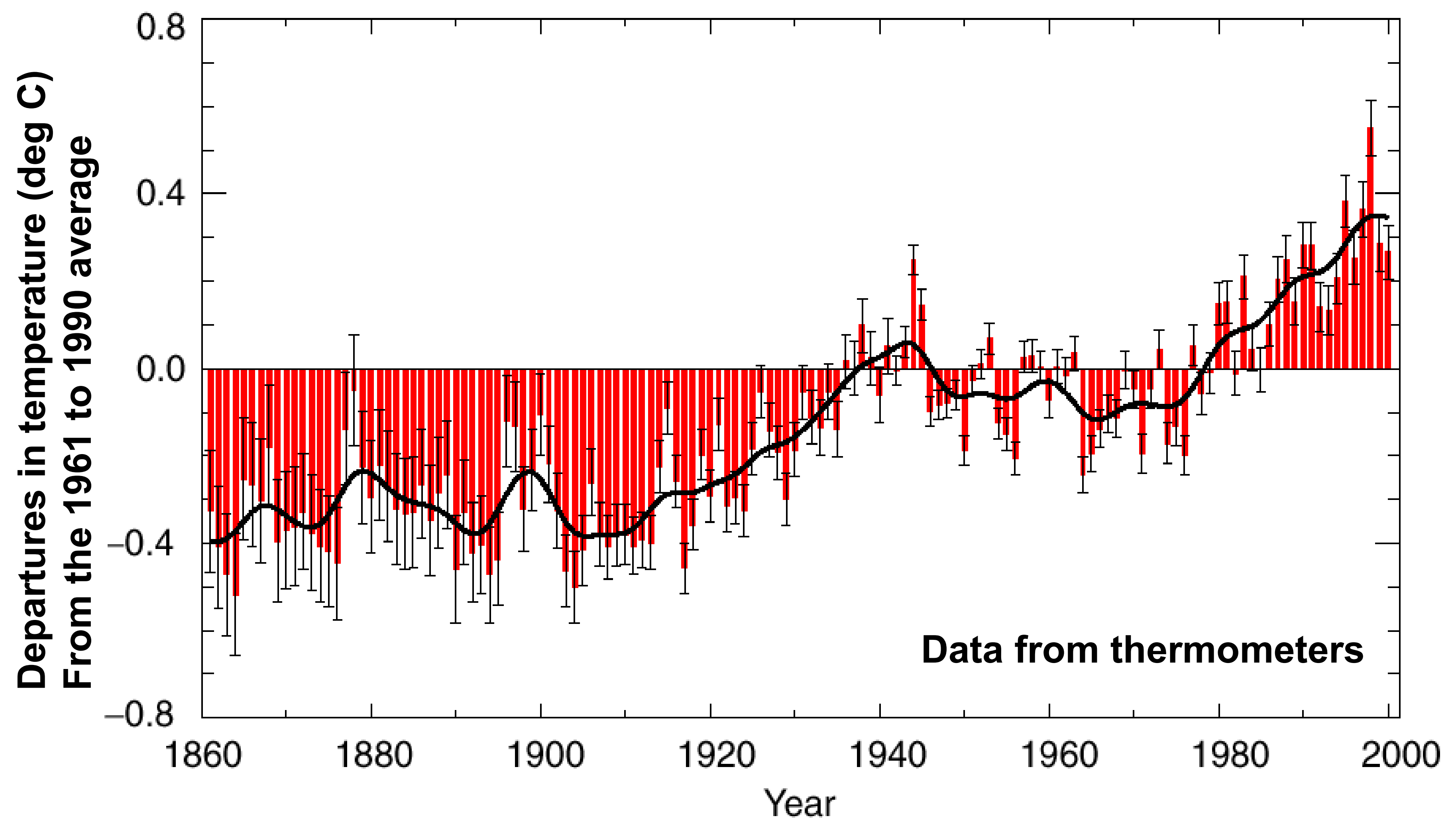
Atmospheric Chemistry



Atmosphere and Ocean Dynamics

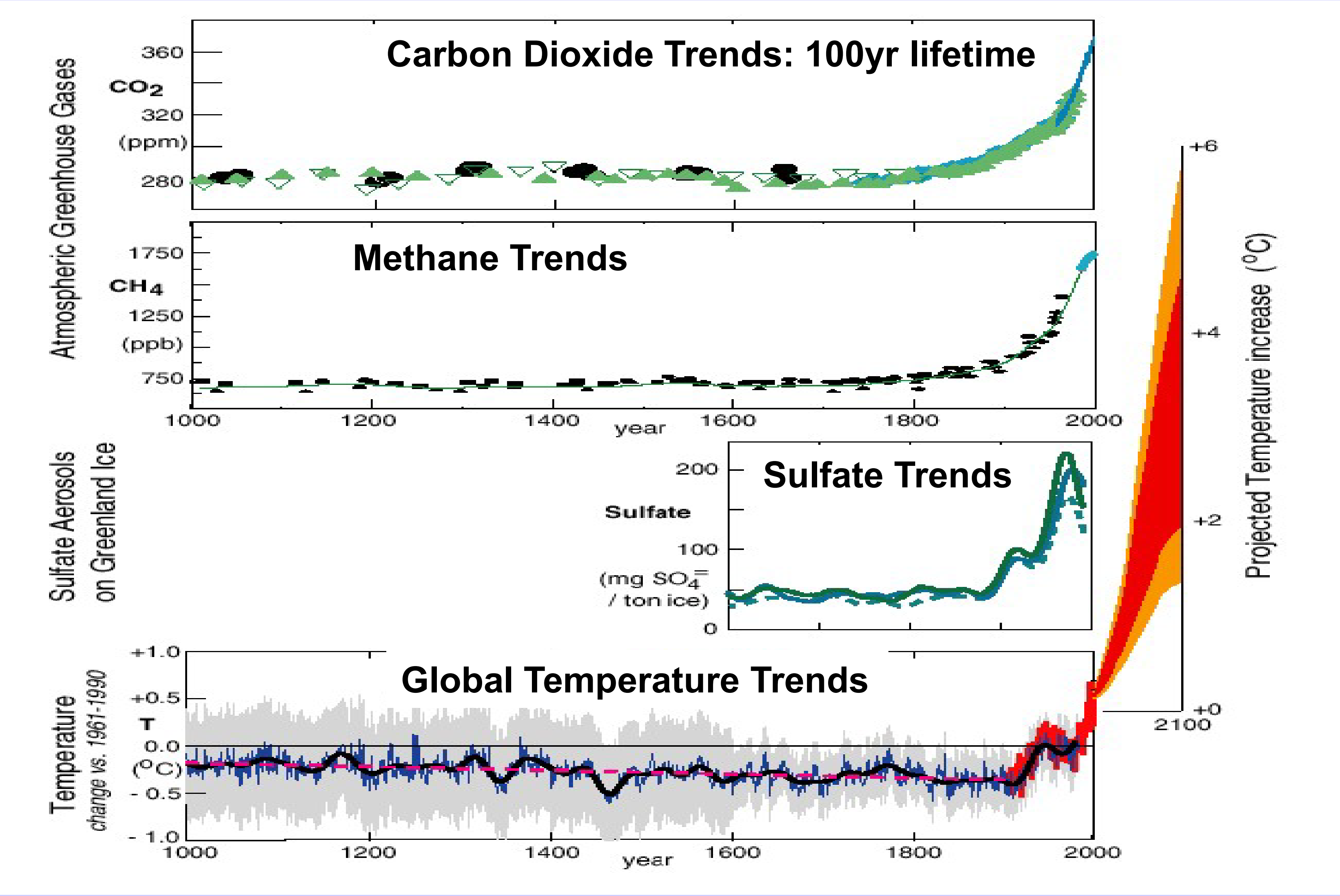


What global surface temperature change has occurred so far?



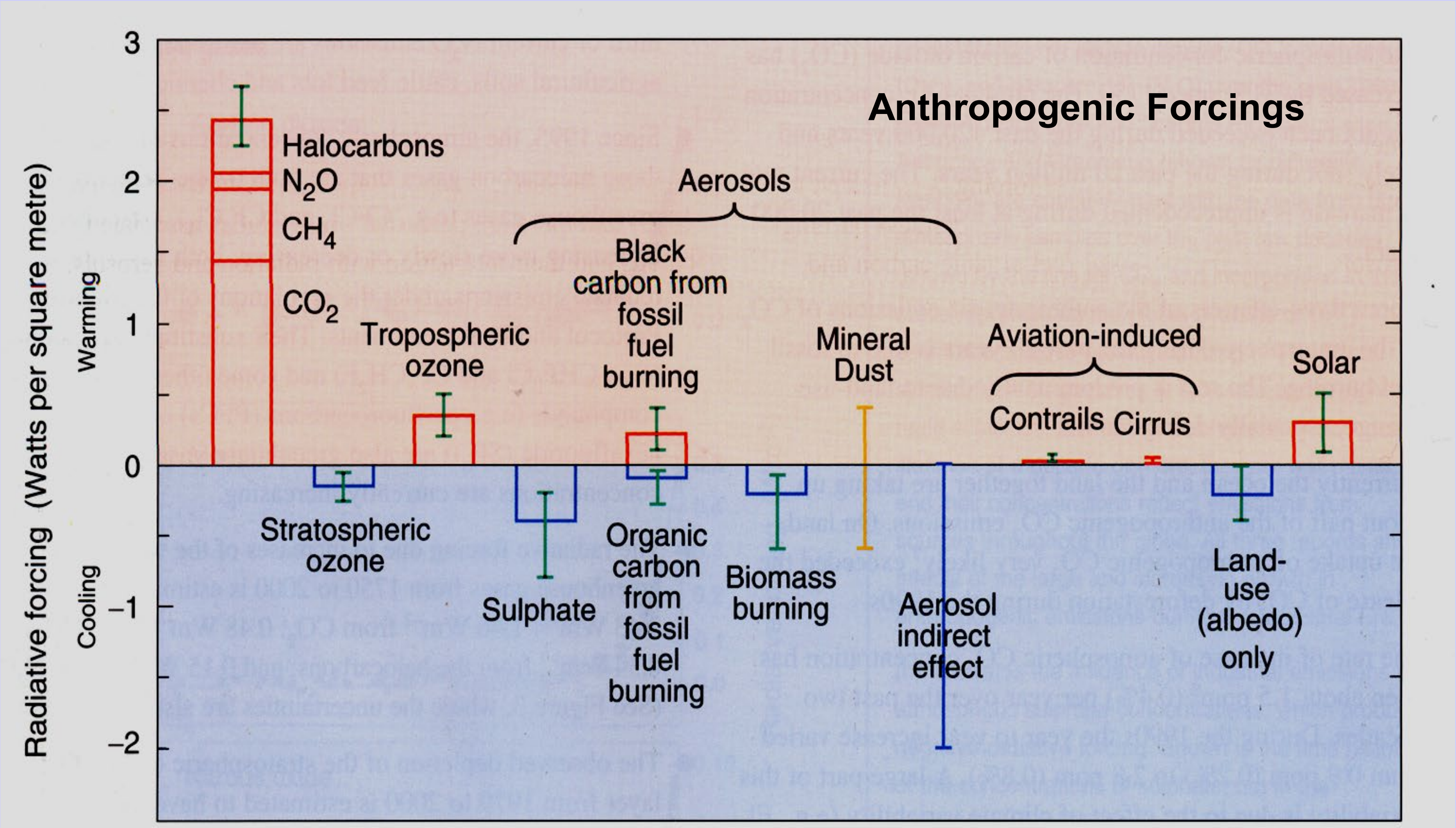
IPCC 2001

Human Influence on Climate



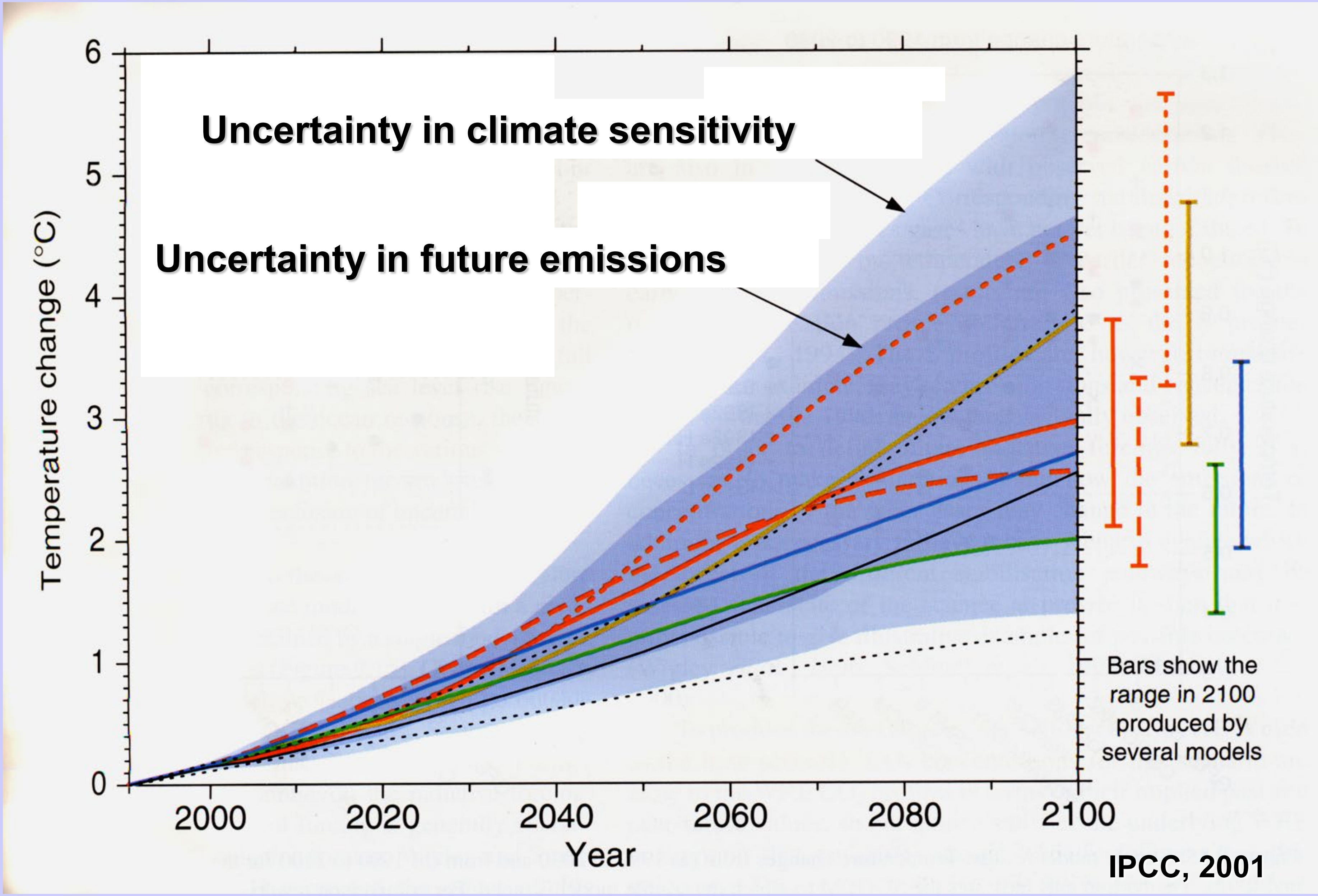
From M. Prather University of California at Irvine

Radiative Forcing from 1750 to 2000



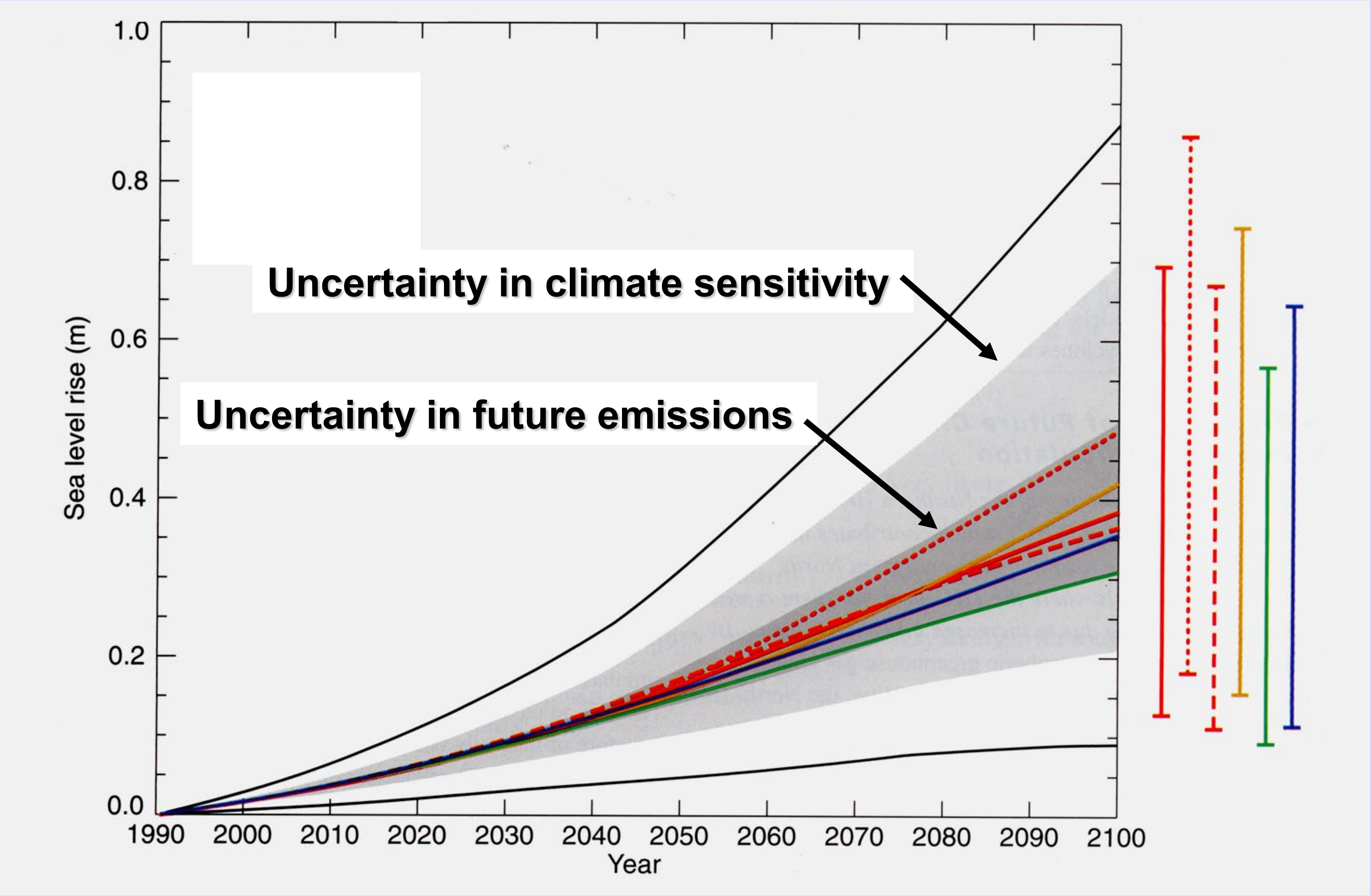
IPCC, 2001

Global Temperature Predictions



IPCC, 2001

Predicted Sea Level rise from 1990 to 2100



IPCC, 2001

Remote Sensing Products

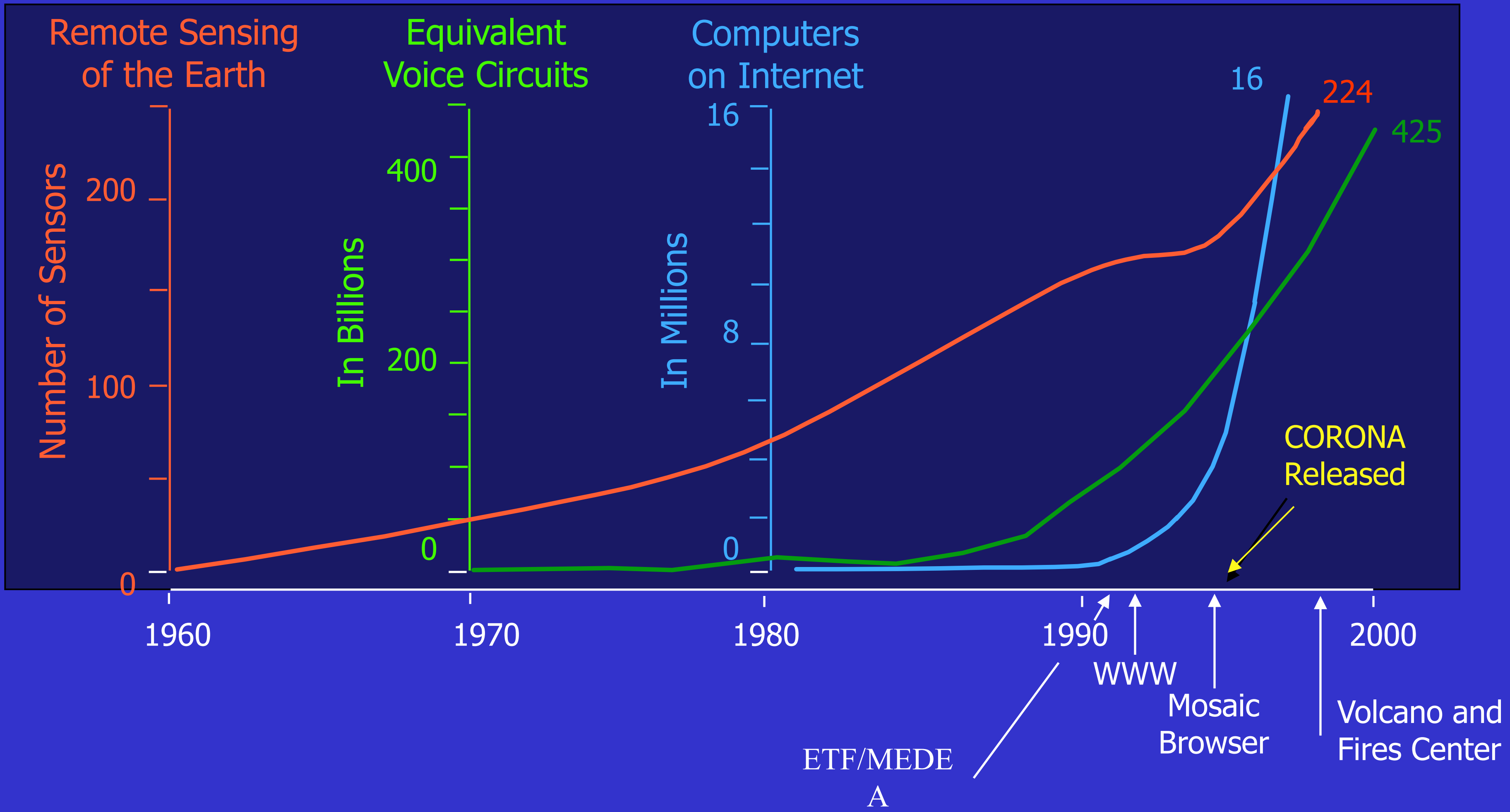
- ★ Atmospheric Vertical Moisture Profile
- ★ Atmospheric Vertical Temp Profile
- ★ Imagery
- ★ Sea Surface Temperature
- ★ Sea Surface Winds
- ★ Soil Moisture
- Aerosol Optical Thickness
- Aerosol Particle Size
- Albedo (Surface)
- Auroral Boundary
- Auroral Imagery
- Cloud Base Height
- Cloud Cover/Layers
- Cloud Effective Particle Size
- Cloud Ice Water Path
- Cloud Liquid Water
- Cloud Optical Depth/Transmittance
- Cloud Top Height
- Cloud Top Pressure
- Cloud Top Temperature
- Currents (Ocean)

- Downward Longwave Radiance (Sfc)
- Electric Fields
- Electron Density Profile
- Fresh Water Ice
- Geomagnetic Field
- Ice Surface Temperature
- Energetic Ions
- In-situ Plasma Fluctuations
- In-situ Plasma Temperature
- Insolation
- Medium Energy Charged Particles
- Ionospheric Scintillation
- Land Surface Temperature
- Littoral Sediment Transport
- Net Heat Flux
- Net Short Wave Radiance (TOA)
- Neutral Density Profile
- Neutral Winds
- Normalized Difference Vegetation Index
- Ocean Color/Chlorophyll
- Ocean Wave Characteristics

- Ozone - Total Column/Profile
- Precipitable Water
- Precipitation Type/Rate
- Pressure (Surface/Profile)
- Sea Ice Age and Edge Motion
- Sea Surface Height/Topography
- Snow Cover/Depth
- Solar Irradiance
- Supra-Thermal - Auroral Particles
- Surface Wind Stress
- Suspended Matter
- Total Auroral Energy Deposition
- Total Longwave Radiance (TOA)
- Total Water Content
- Turbidity
- Vegetation Index/Surface Type

Atmospheric | Oceanic | Terrestrial | Space | Climate

Sensors, Communications, and Computers



Remote Sensing of the Earth's Environment from Terra
August 25-30, 2002
L'Aquila, ItalyScuola Superiore Guglielmo Reiss Romoli

are now available in a 2 CD set, one containing the PowerPoint lectures and the other the many QuickTime and mpeg movies that were shown during the course (plus one IDL script for bidirectional reflection distribution function). You can find a description of the course and an order form for requesting the CDs at:
http://eospso.gsfc.nasa.gov/eos_homepage/course/
The course material provides a wealth of teaching material that may be of interest to a much broader research community, and those interested in learning more about this extraordinary space-based observing mission.

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