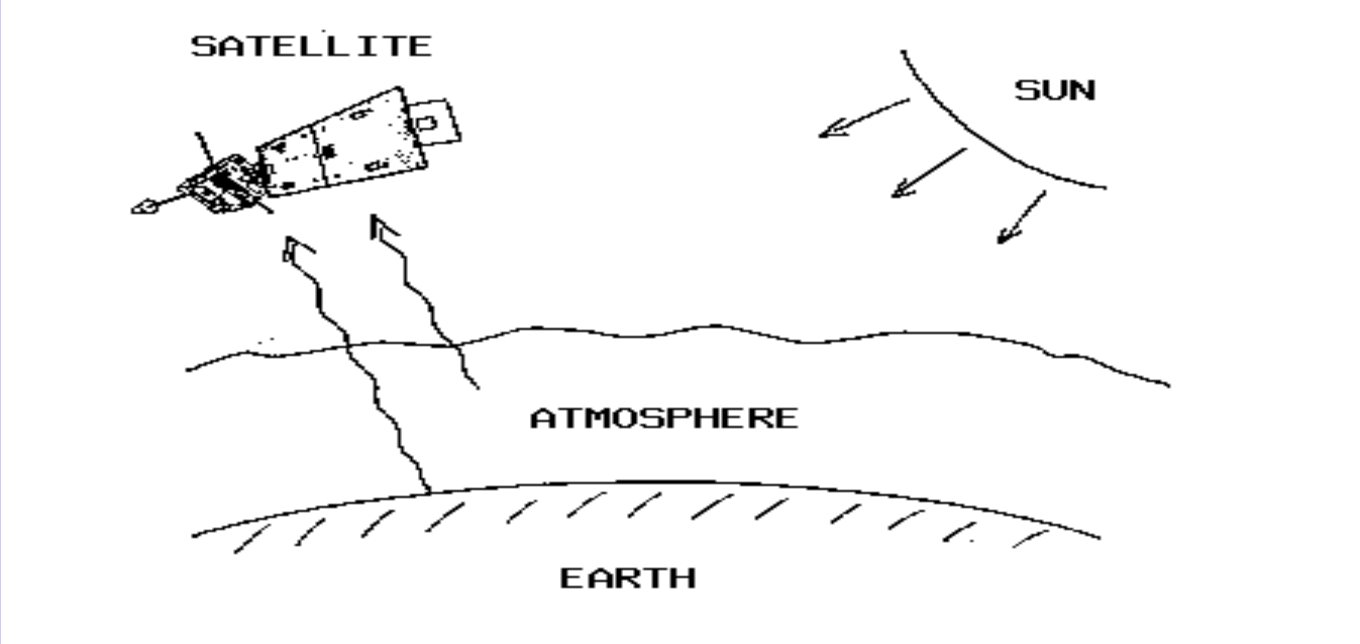
Summary
Remote Sensing Seminar

Lectures in Bertinoro

Paul Menzel
NOAA/NESDIS/ORA

23 Aug – 2 Sep 2004

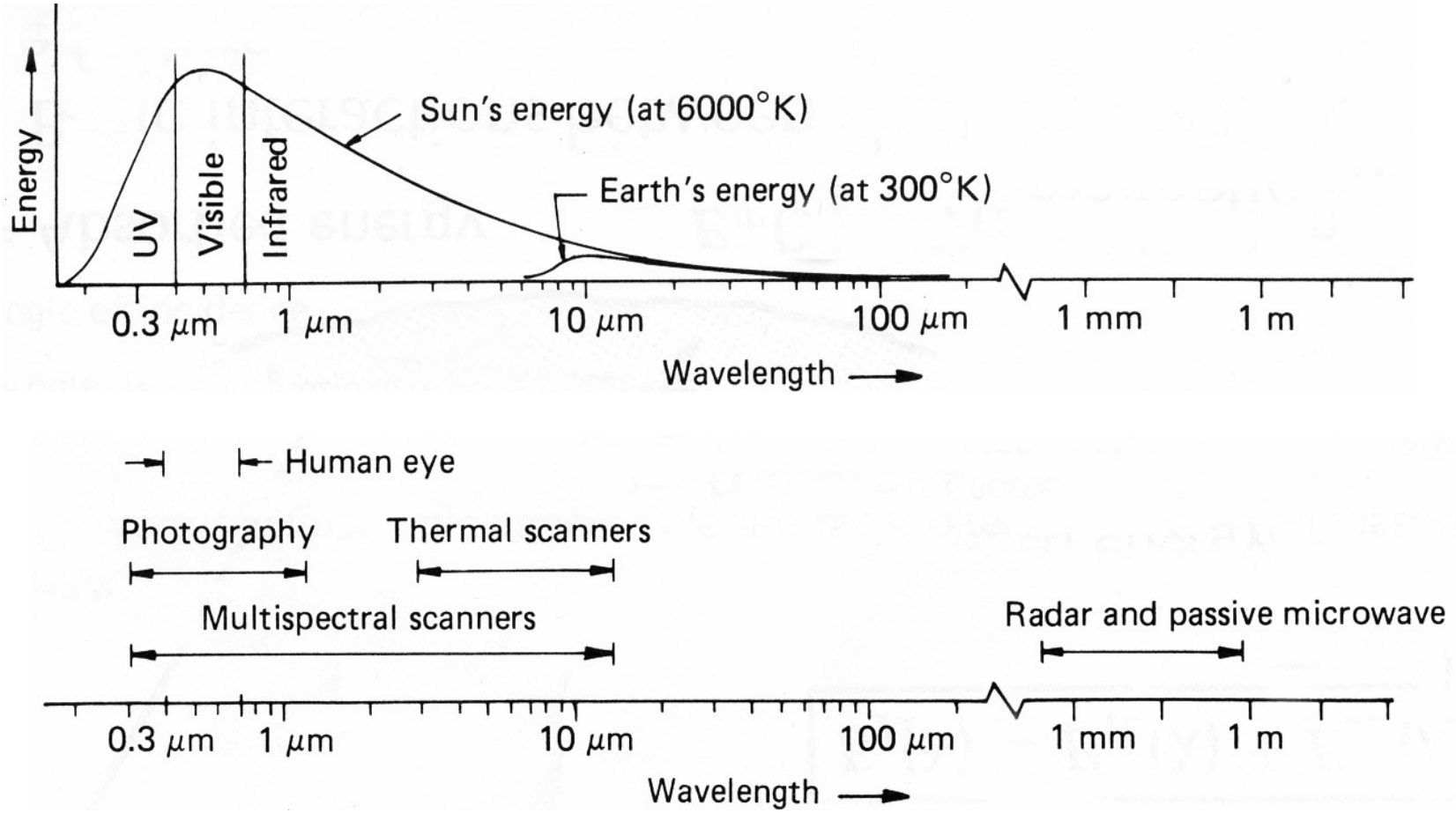
Satellite remote sensing of the Earth-atmosphere



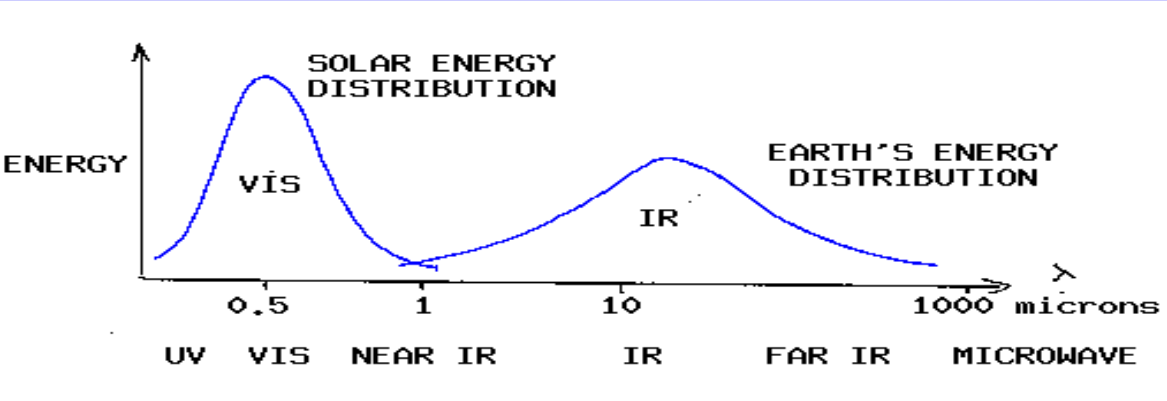
Observations depend on

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)

Spectral Characteristics of Energy Sources and Sensing Systems



Solar (visible) and Earth emitted (infrared) energy

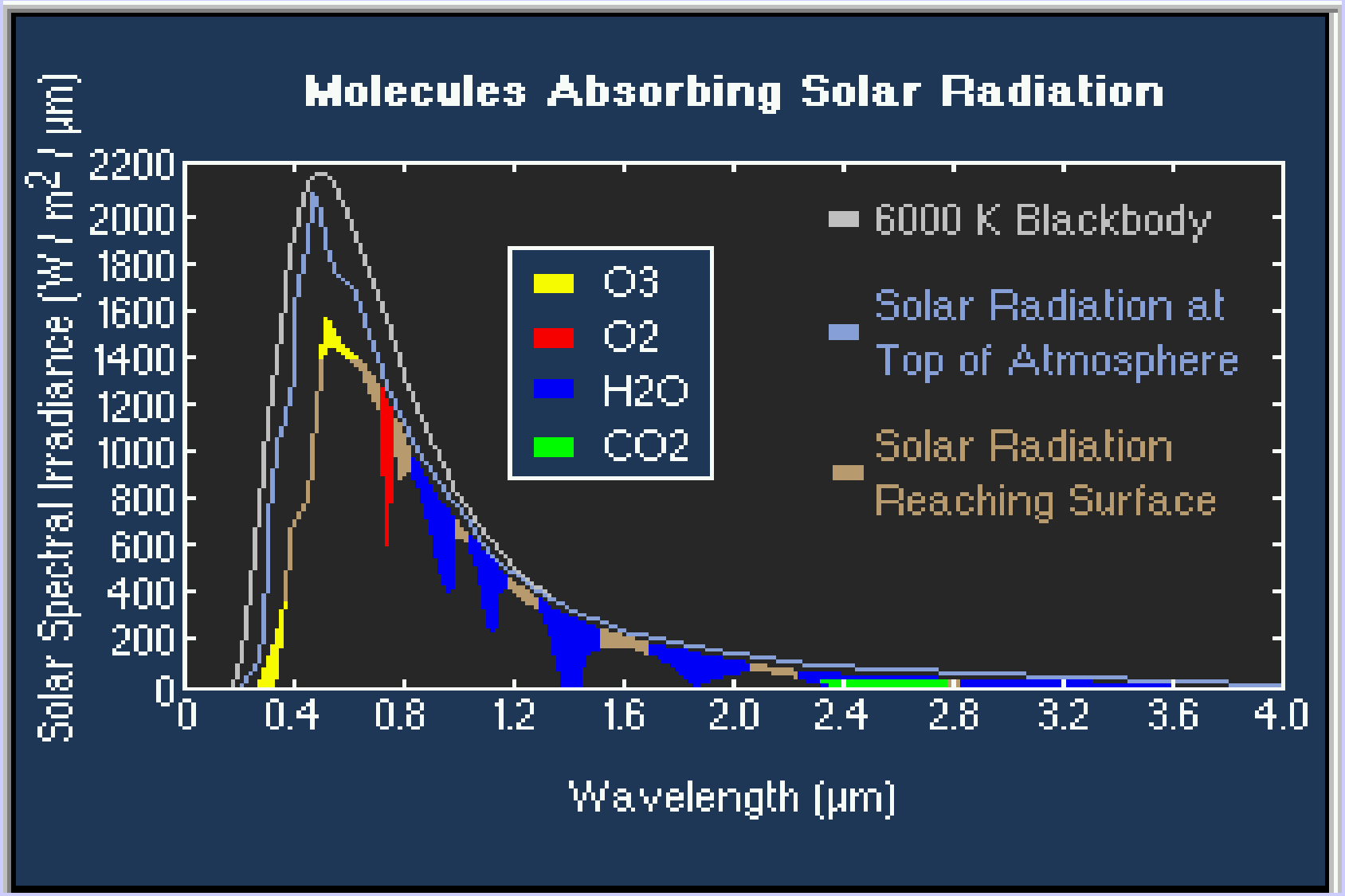


Incoming solar radiation (mostly visible) drives the earth-atmosphere (which emits infrared).

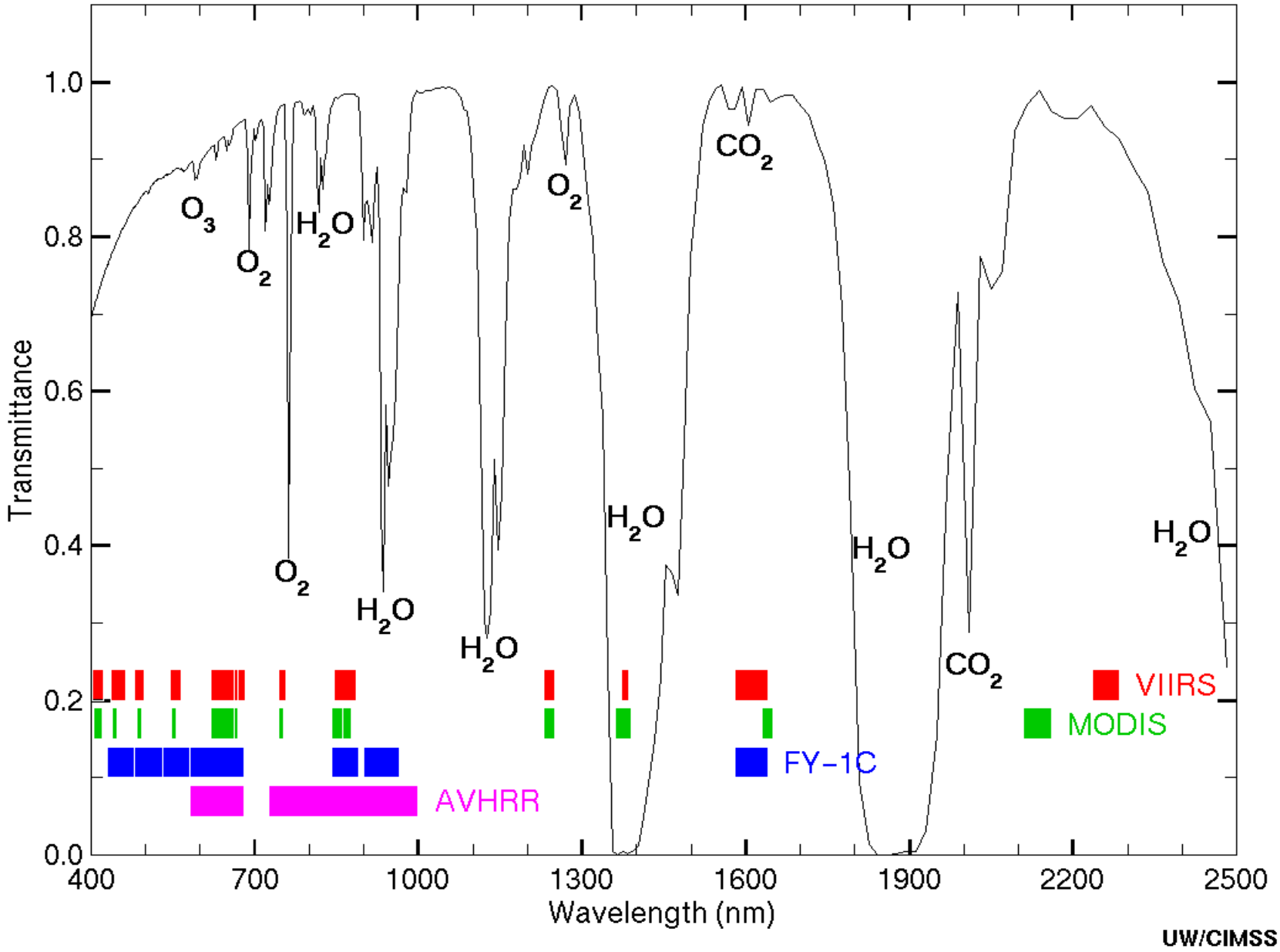
Over the annual cycle, the incoming solar energy that makes it to the earth surface (about 50 %) is balanced by the outgoing thermal infrared energy emitted through the atmosphere.

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.

Solar Spectrum

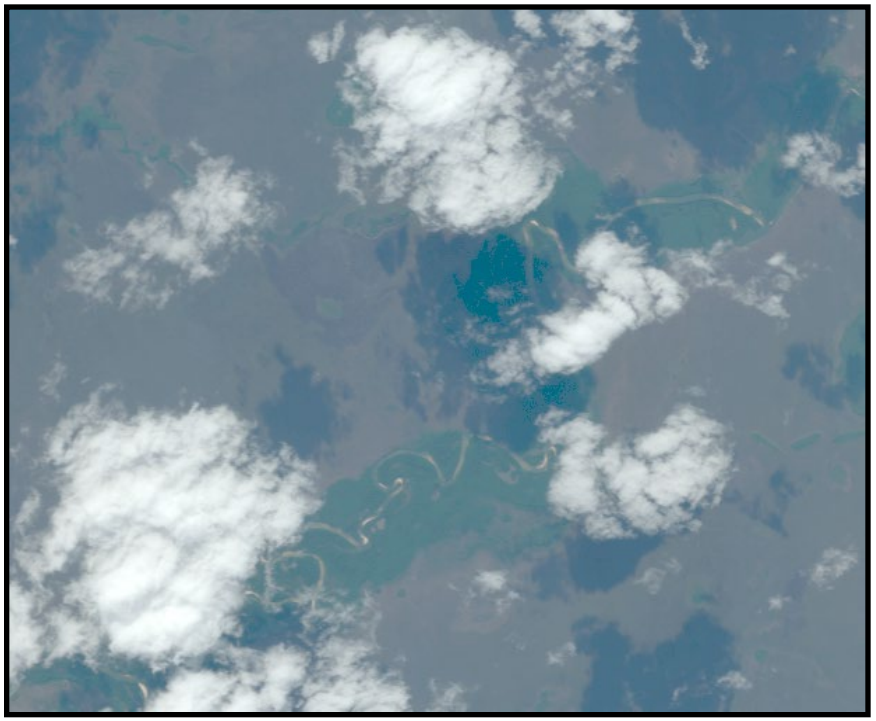


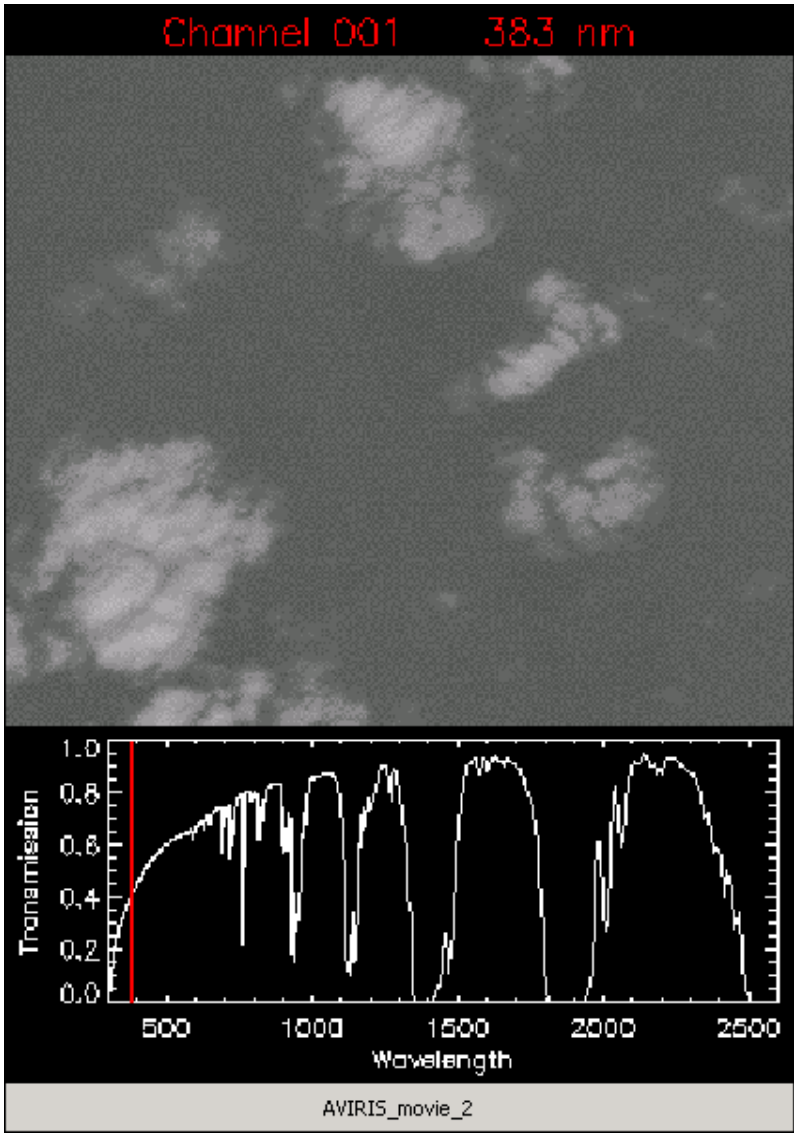
VIIRS, MODIS, FY-1C, AVHRR



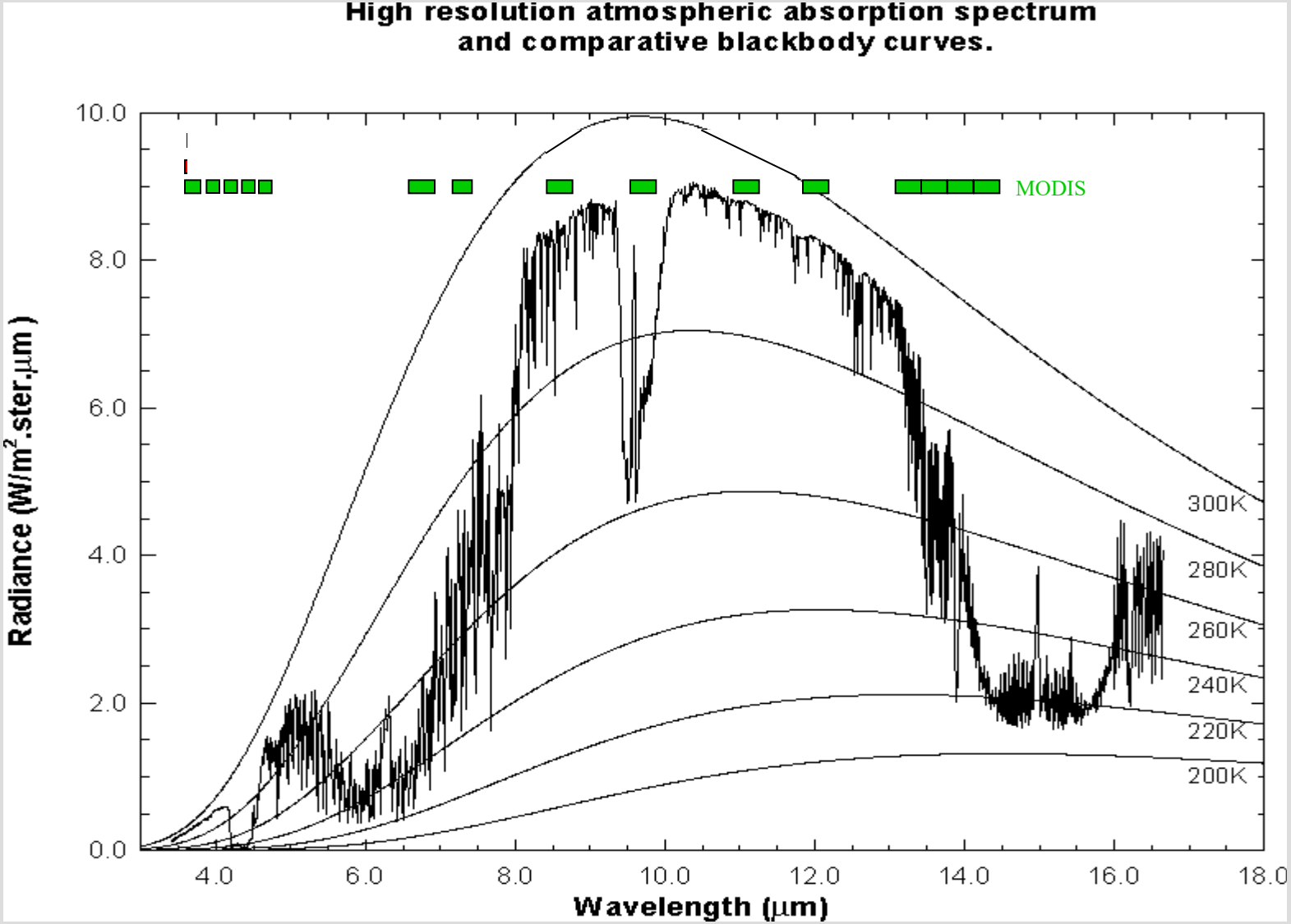
AVIRIS Movie #2

AVIRIS Image - Porto Nacional, Brazil
20-Aug-1995
224 Spectral Bands: 0.4 - 2.5 μm
Pixel: 20m x 20m Scene: 10km x 10km

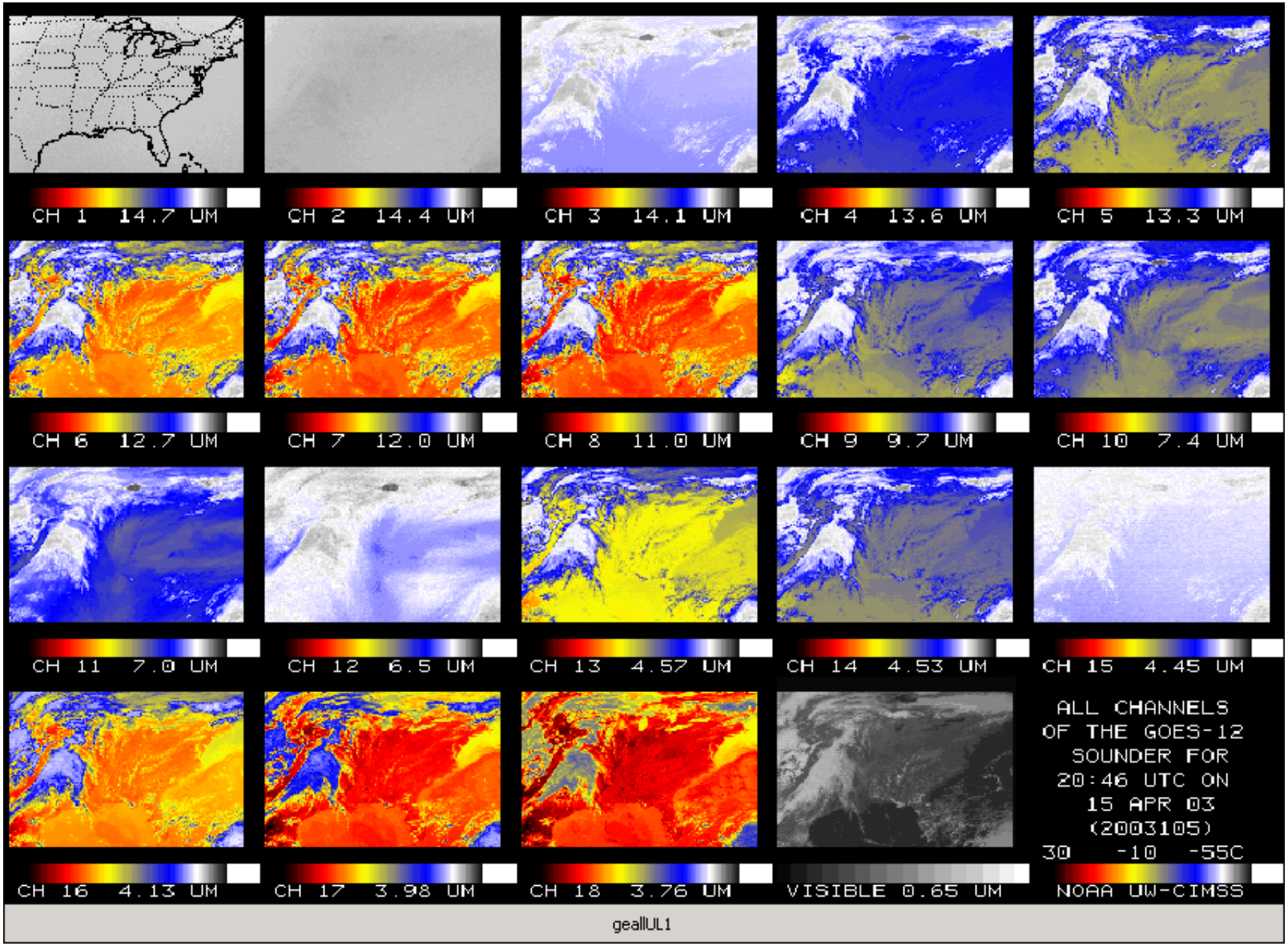




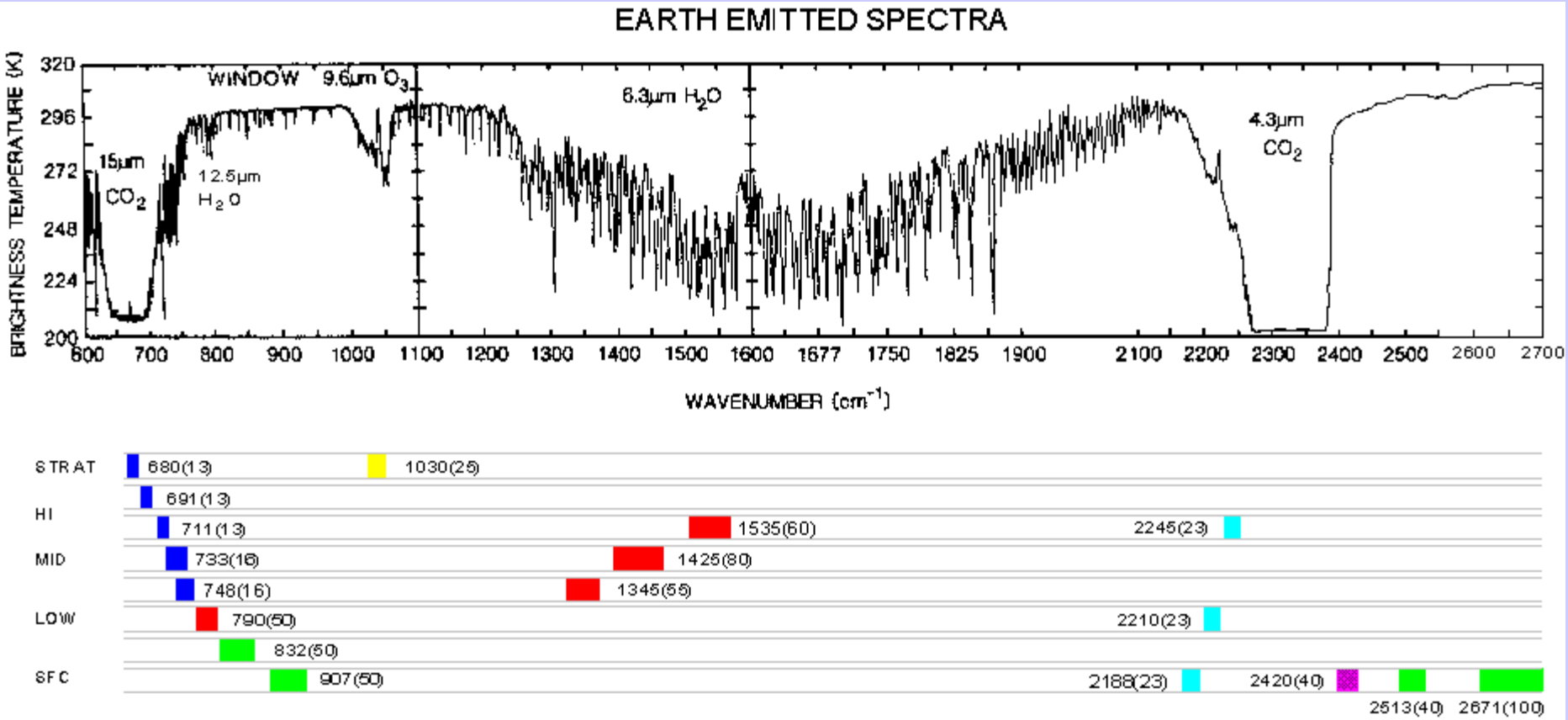
MODIS IR Spectral Bands



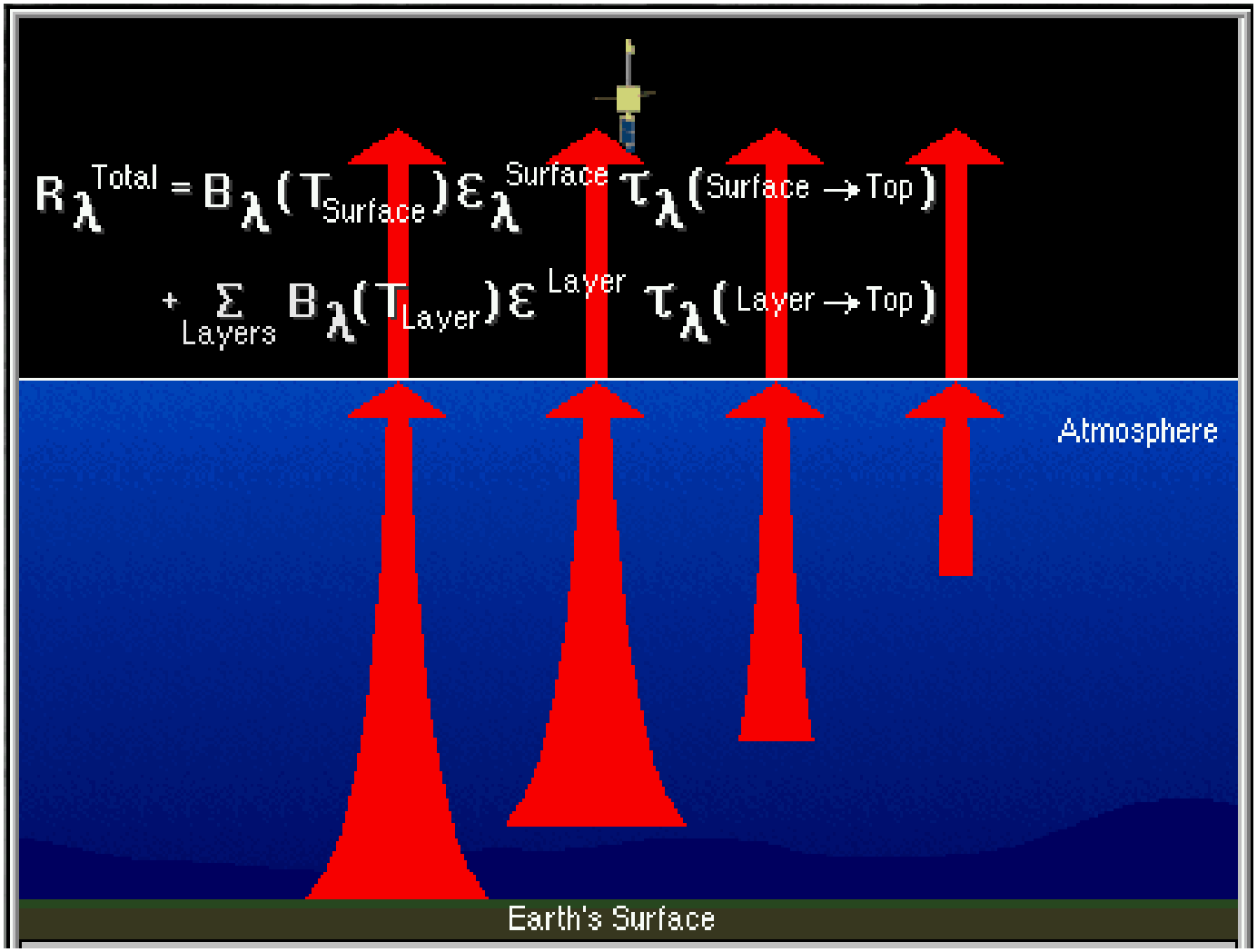
GOES-12 Sounder – Radiances – all bands from 14.7 to 3.7 um and vis



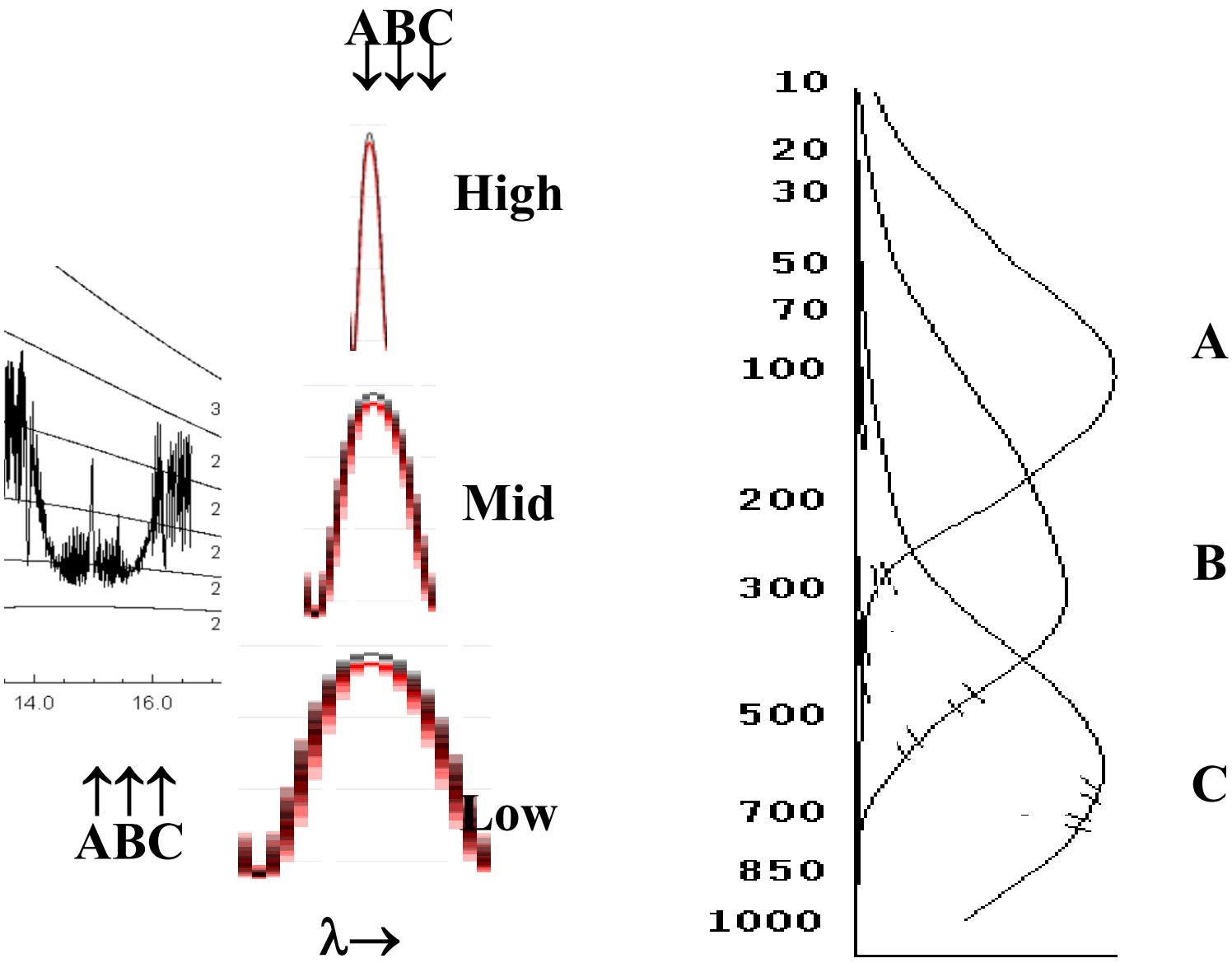
GOES Sounder Spectral Bands: 14.7 to 3.7 um and vis



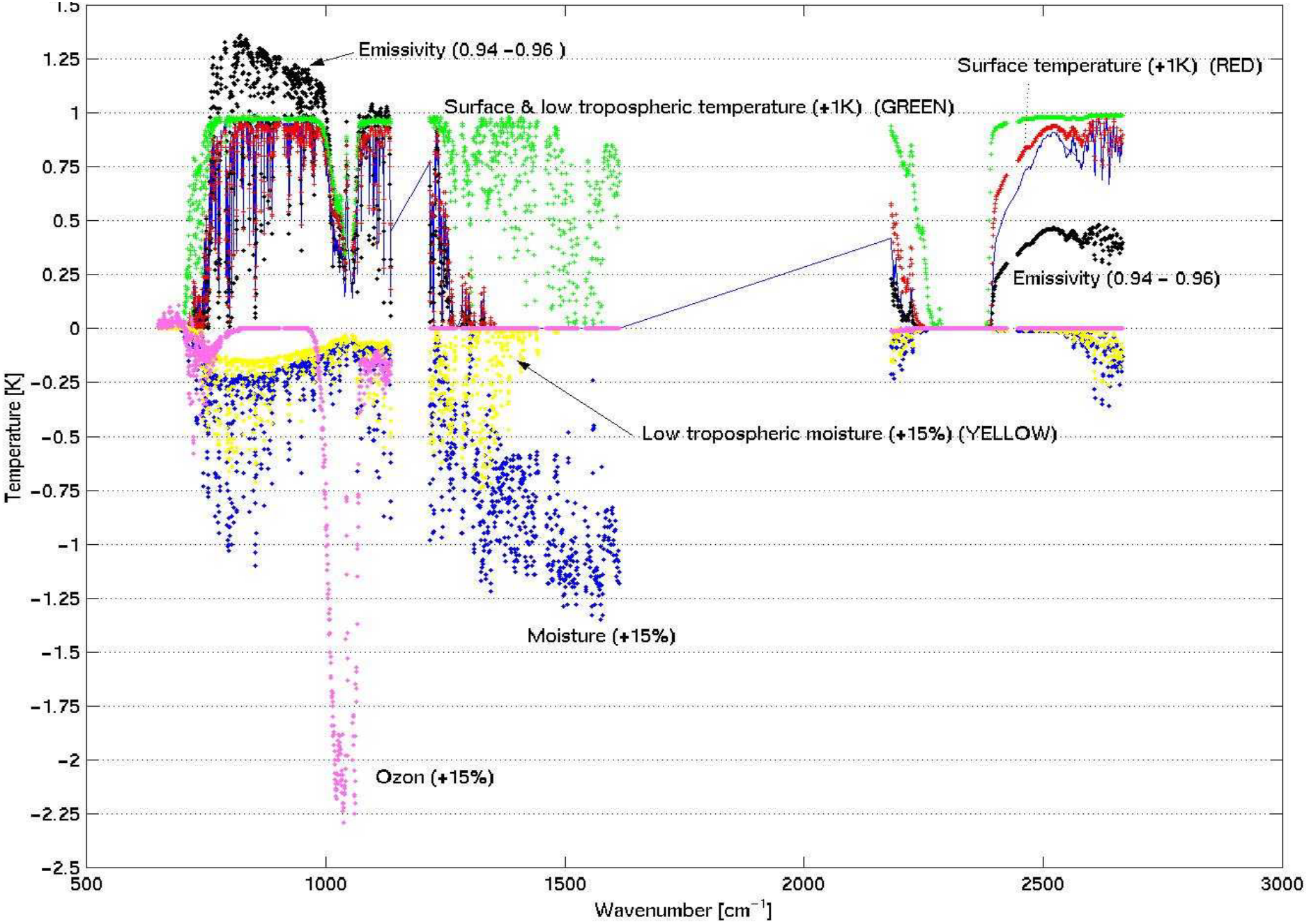
Radiative Transfer through the Atmosphere

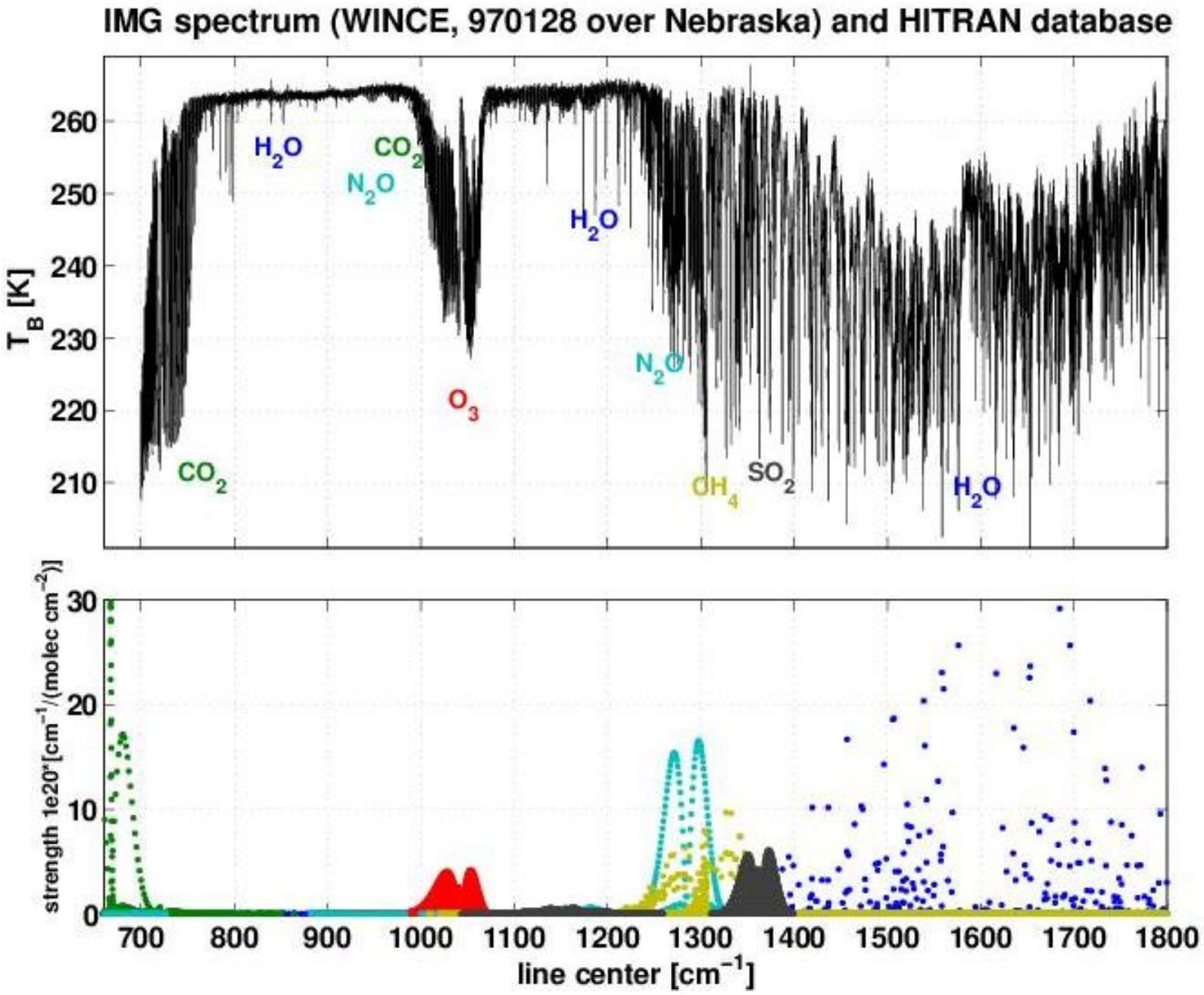


line broadening with pressure helps to explain weighting functions

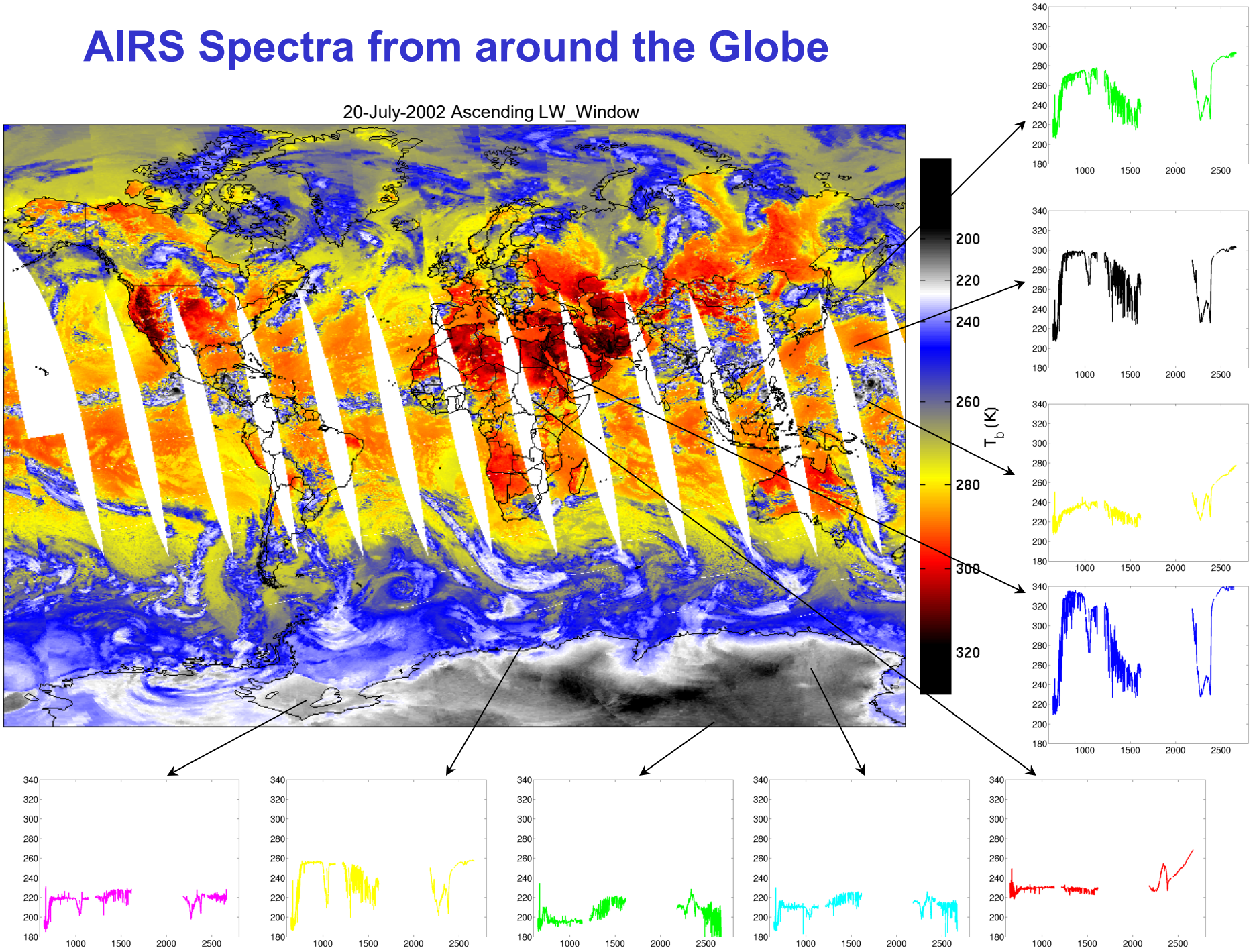


AIRS radiance changes (in deg K) to atm & sfc changes



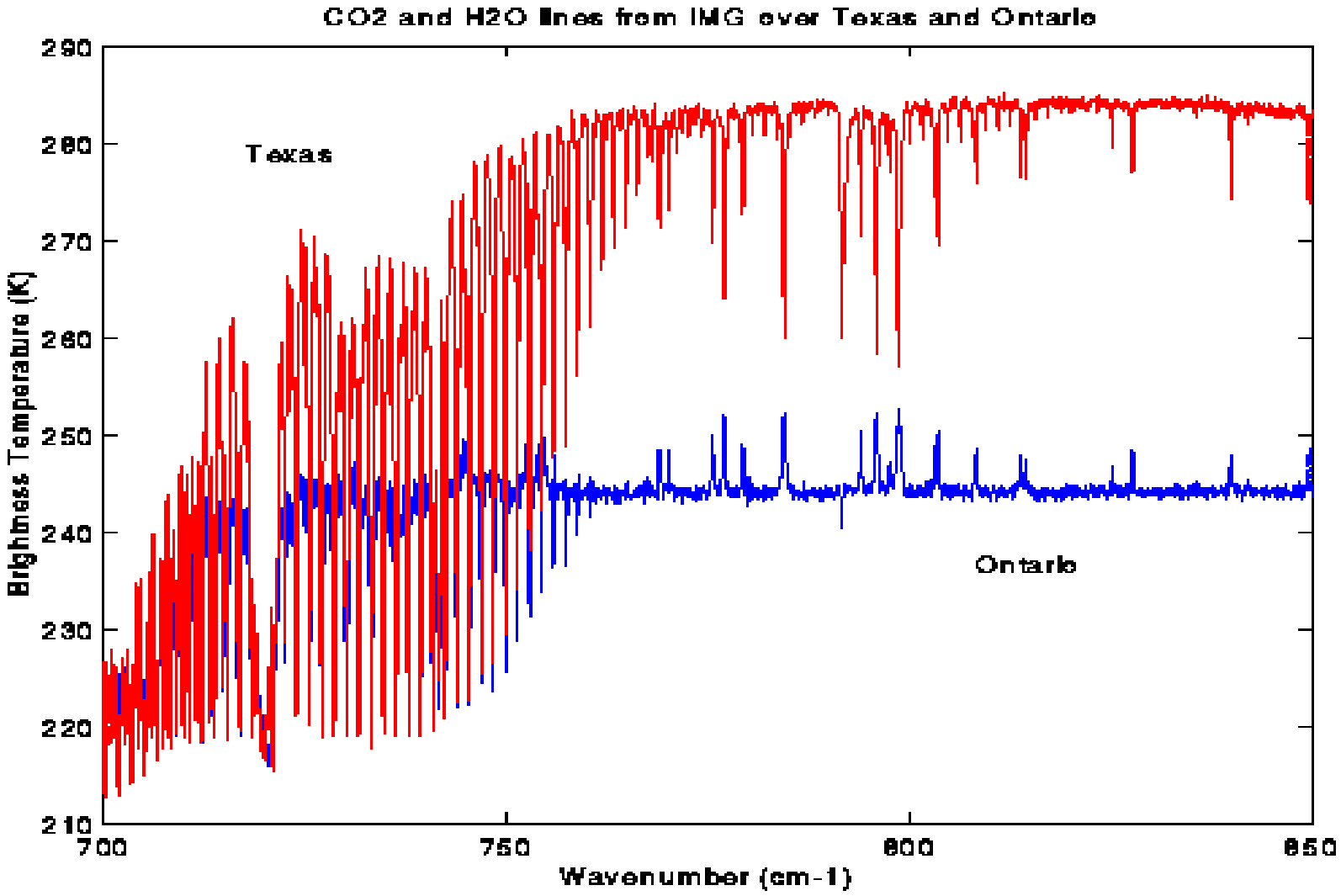

IMG spectrum (WINCE, 970128 over Nebraska) and HITRAN database
T_B [K]
260
250
240
230
220
210
H2O
CO2
N2O
H2O
N2O
O3
CO2
CH4
SO2
H2O
strength 1e20*[cm^-1/(molec cm^-2)]
30
20
10
0
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
line center [cm^-1]

AIRS Spectra from around the Globe



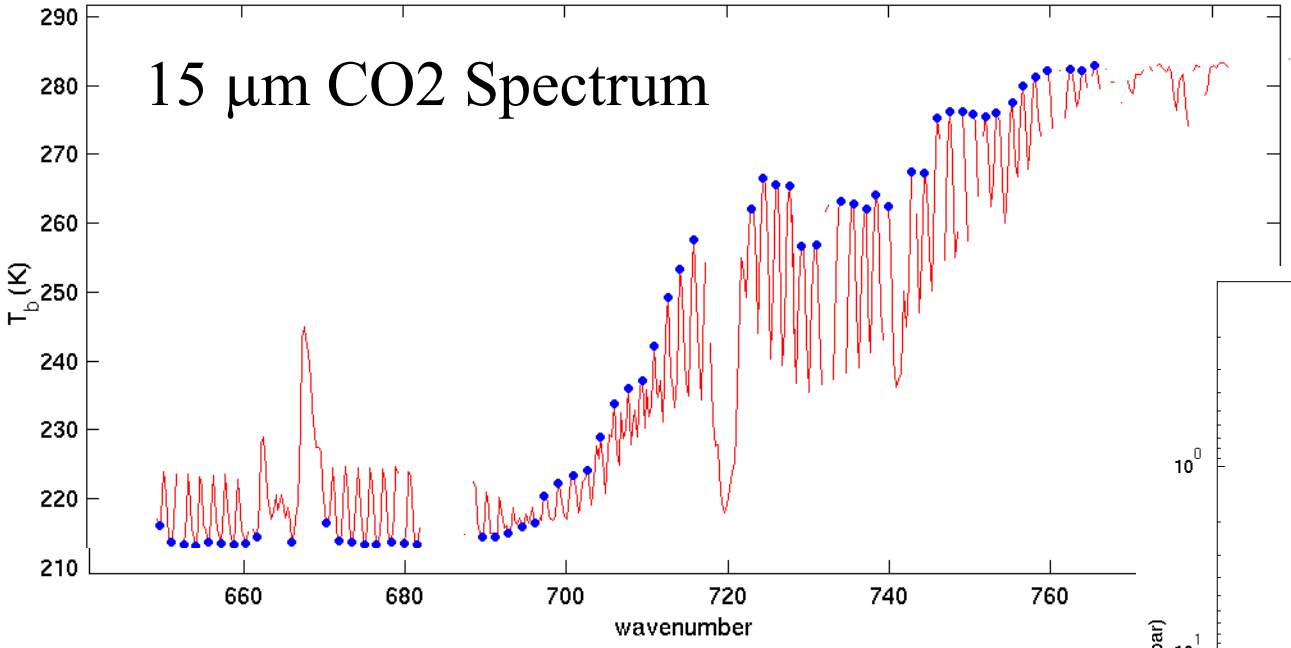
Sensitivity of High Spectral Resolution to Boundary Layer Inversions and Surface/atmospheric Temperature differences

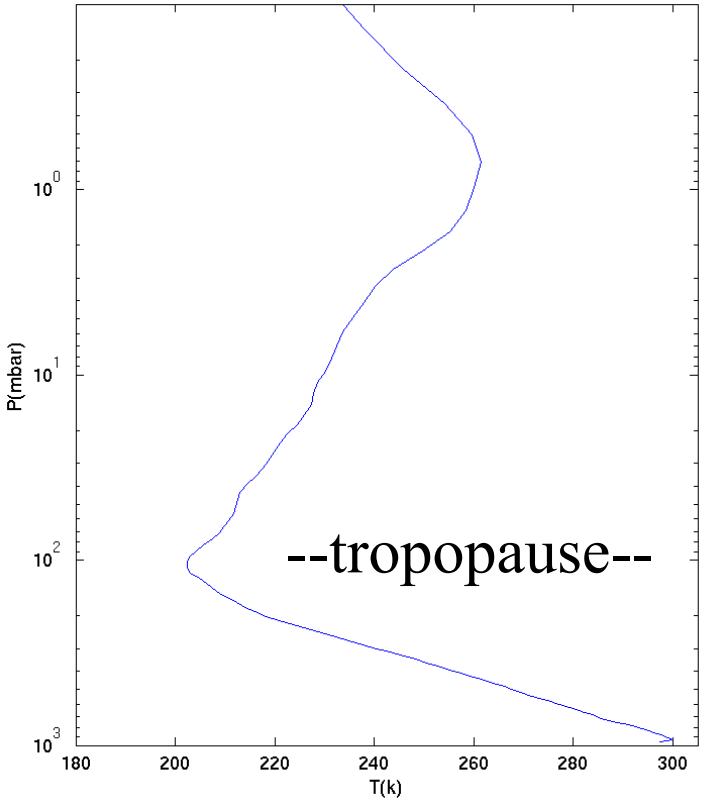
(from IMG Data, October, December 1996)



Twisted Ribbon formed by CO_2 spectrum:

Tropopause inversion causes On-line & off-line patterns to cross



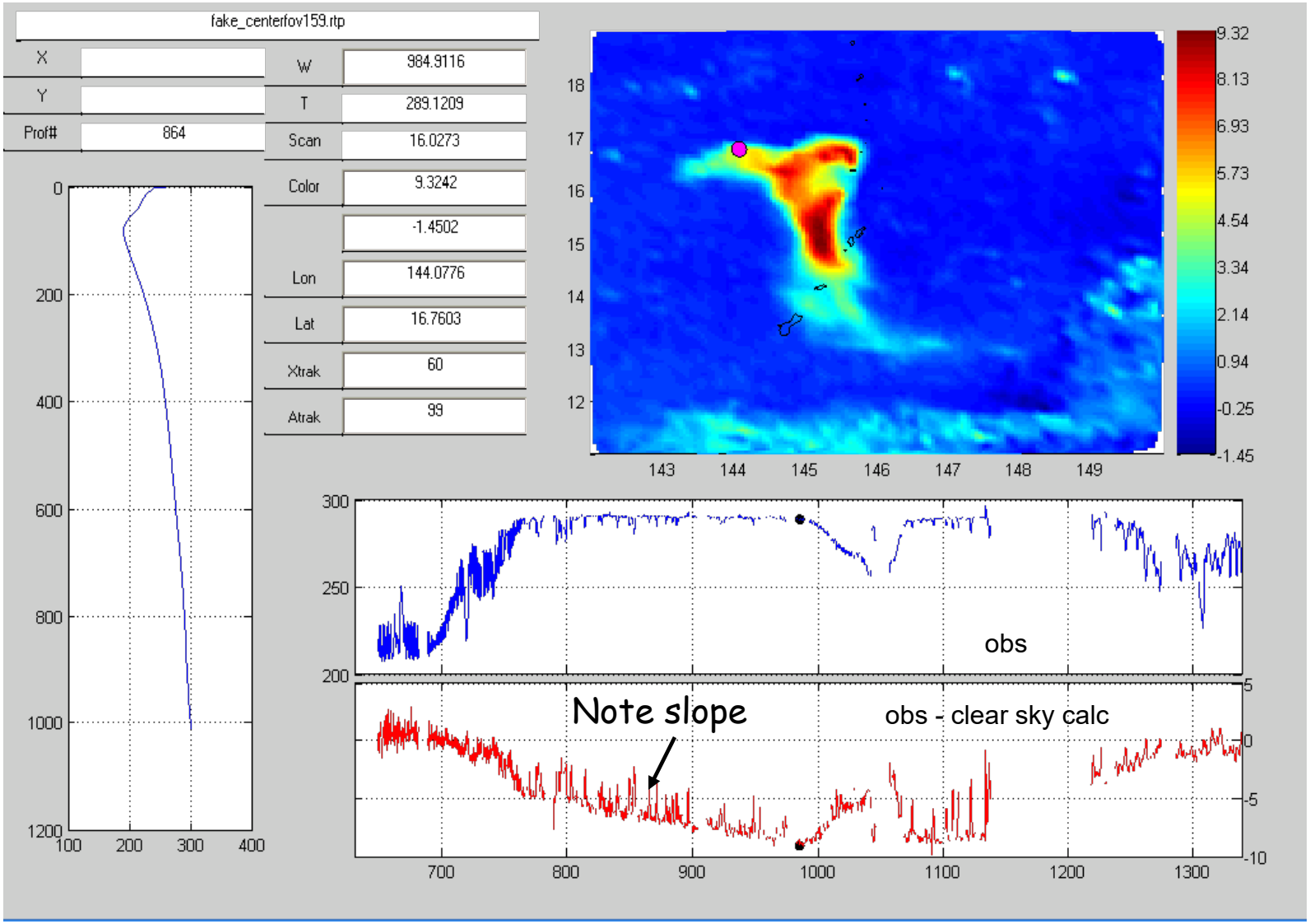


Blue between-line T_b
warmer for tropospheric channels,
colder for stratospheric channels

Signature not available at low resolution

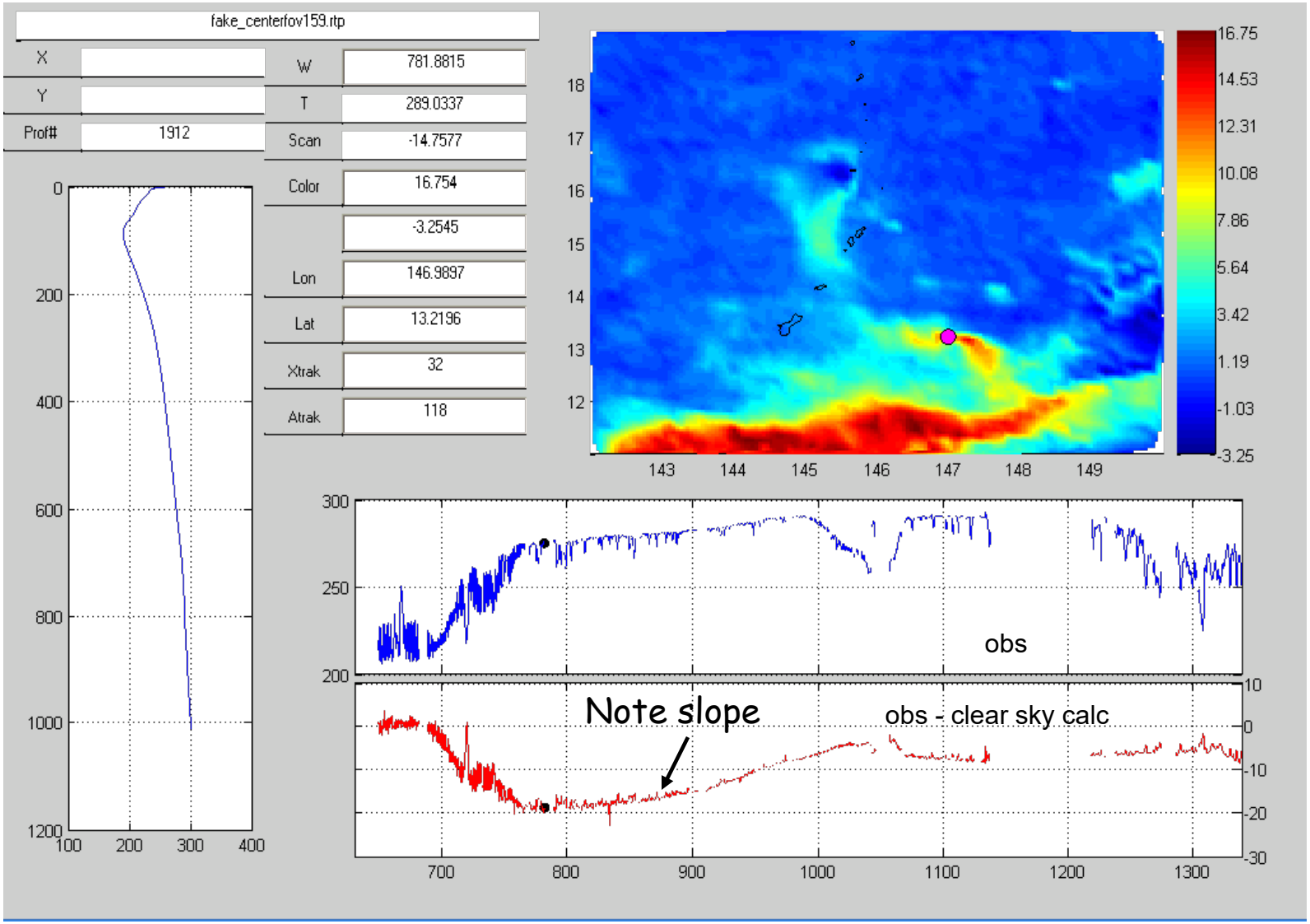
Silicate (ash cloud) signal at Anatahan, Mariana Is

Image is ECMWF bias difference of 1227 cm^{-1} – 984 cm^{-1} (double difference)



Cirrus signal at Anatahan

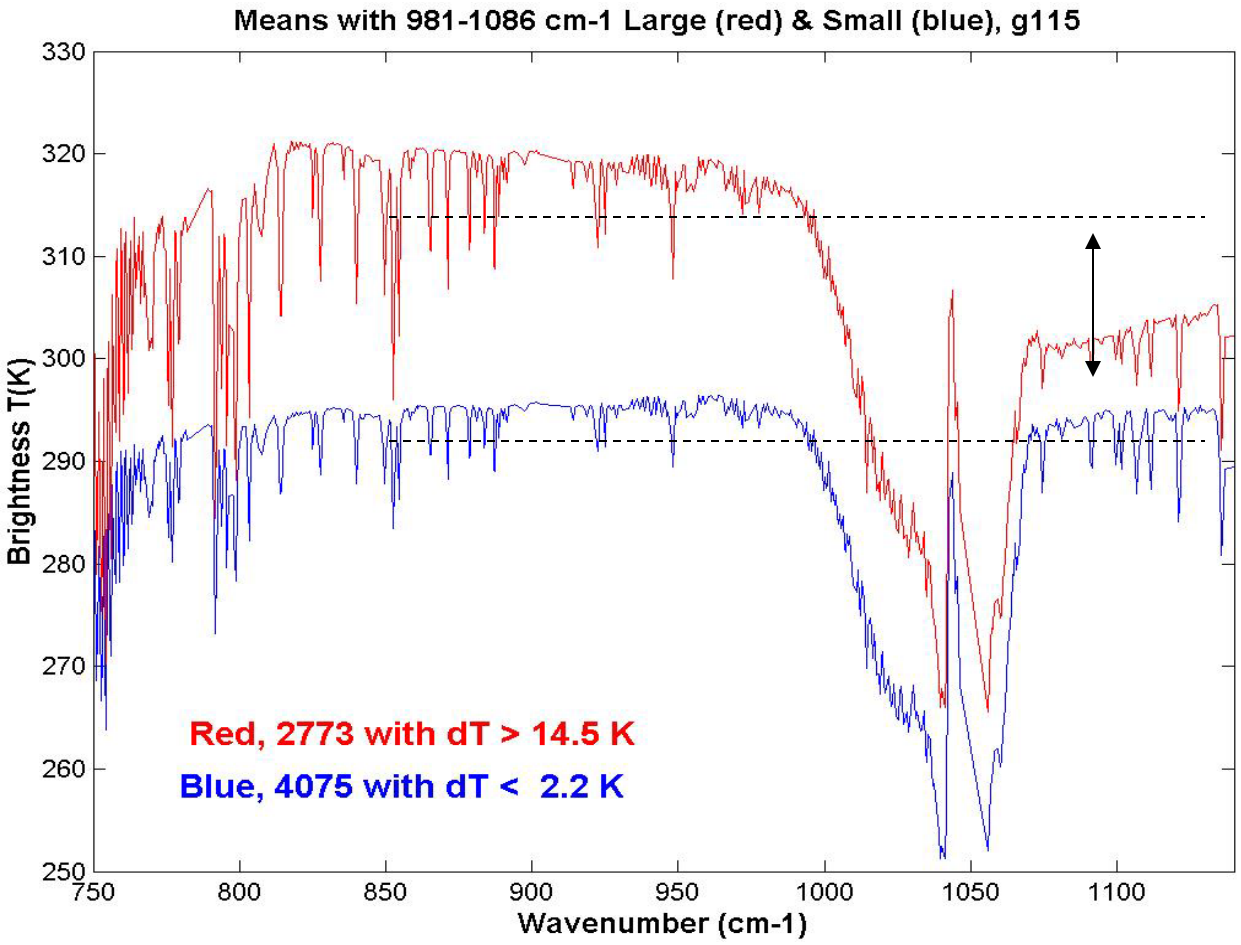
Image is ECMWF T_b bias difference of 1227 cm^{-1} – 781 cm^{-1} (double difference)



Inferring surface properties with AIRS high spectral resolution data

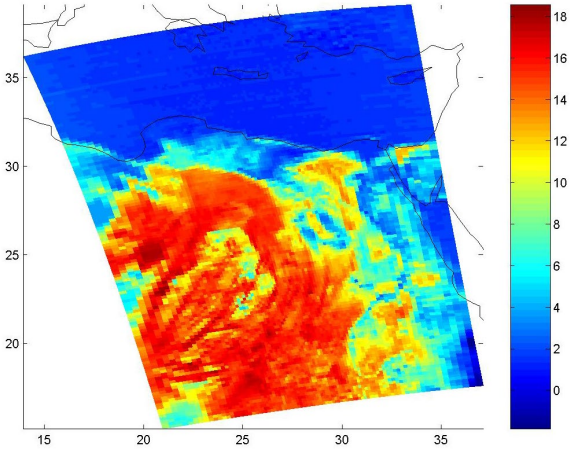
Barren region detection if T1086 < T981

Barren vs Water/Vegetated

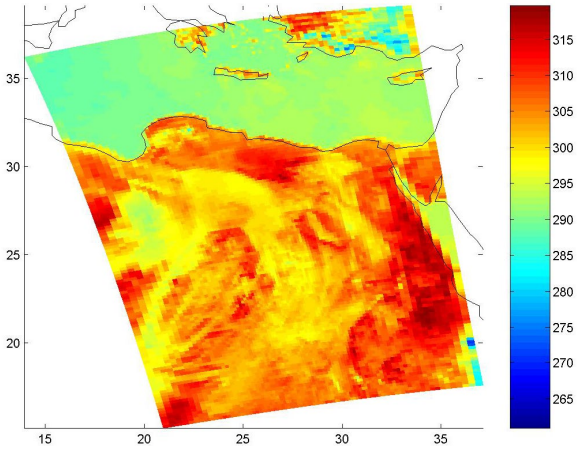


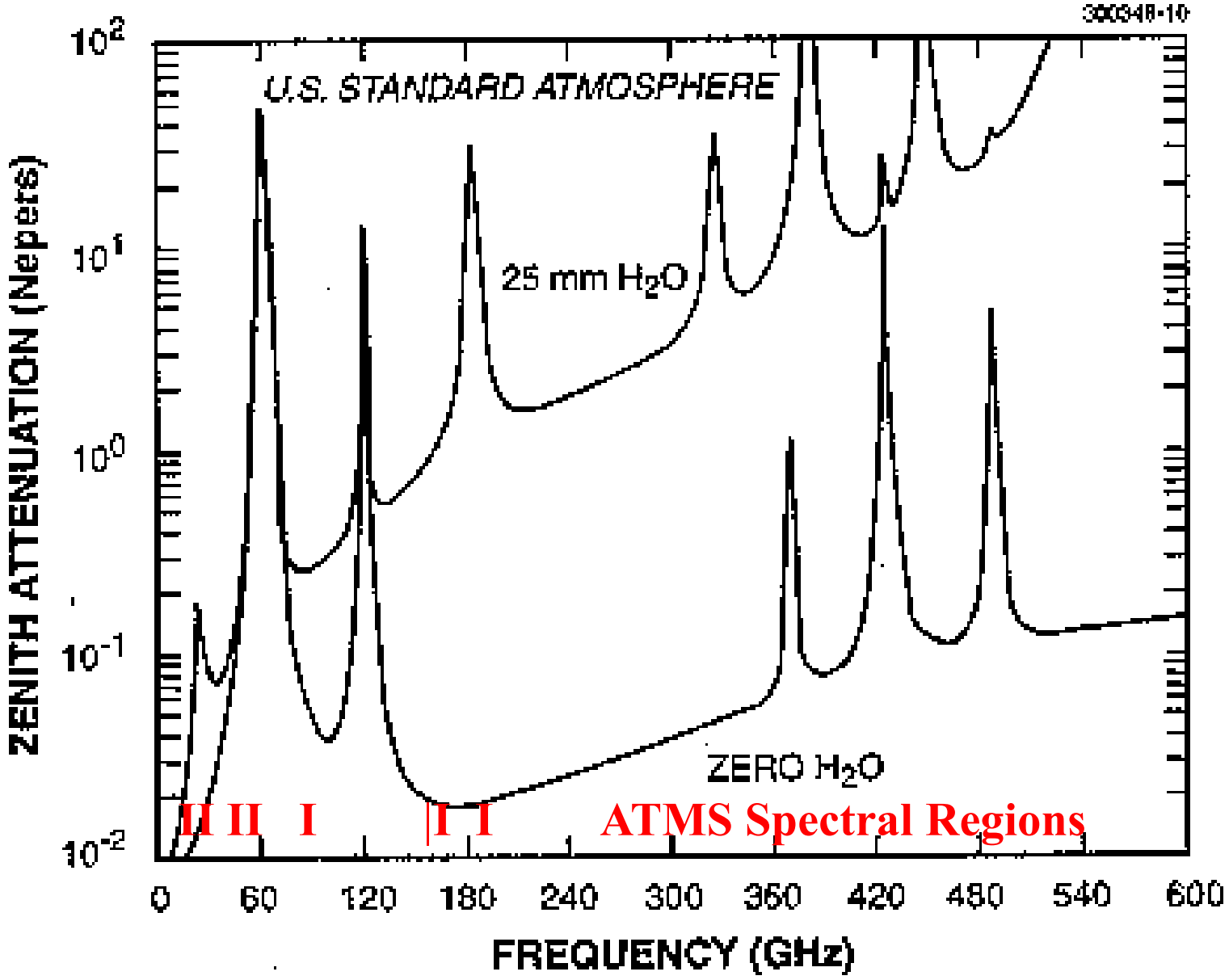
AIRS data from 14 June 2002

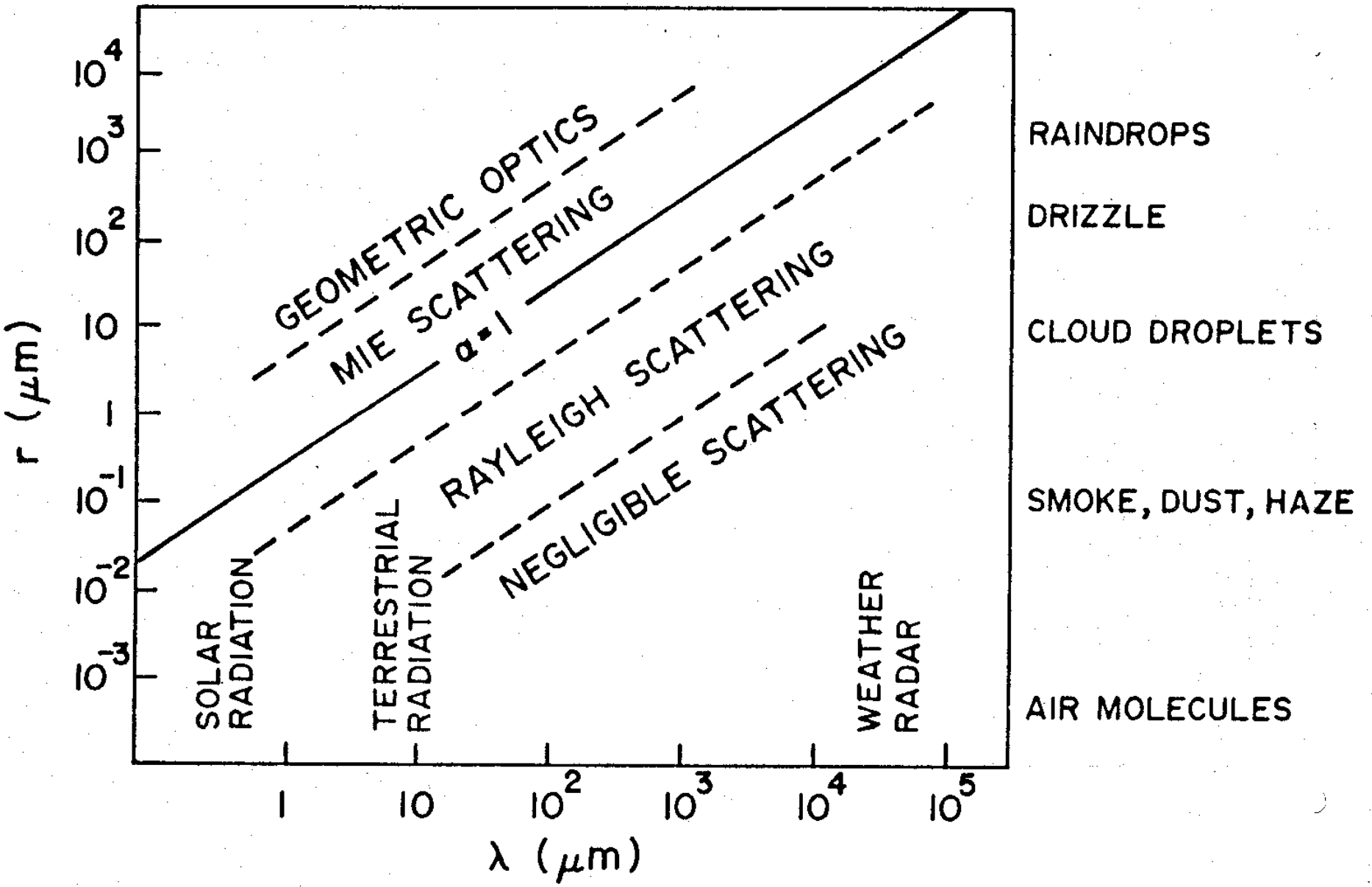
T(981 cm^{-1})-T(1086 cm^{-1})



T(1086 cm^{-1})




300348-10
U.S. STANDARD ATMOSPHERE
25 mm H2O
ZERO H2O
ZENITH ATTENUATION (Nepers)
FREQUENCY (GHz)
10^2
10^1
10^0
10^-1
10^-2
0
60
120
180
240
300
360
420
480
540
600
II II I
I I
ATMS Spectral Regions


GEOMETRIC OPTICS
MIE SCATTERING
α=1
RAYLEIGH SCATTERING
NEGLIGIBLE SCATTERING
SOLAR RADIATION
TERRESTRIAL RADIATION
WEATHER RADAR
r (μm)
λ (μm)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
1
10
10^2
10^3
10^4
10^5
RAINDROPS
DRIZZLE
CLOUD DROPLETS
SMOKE, DUST, HAZE
AIR MOLECULES

Aerosol Size Distribution

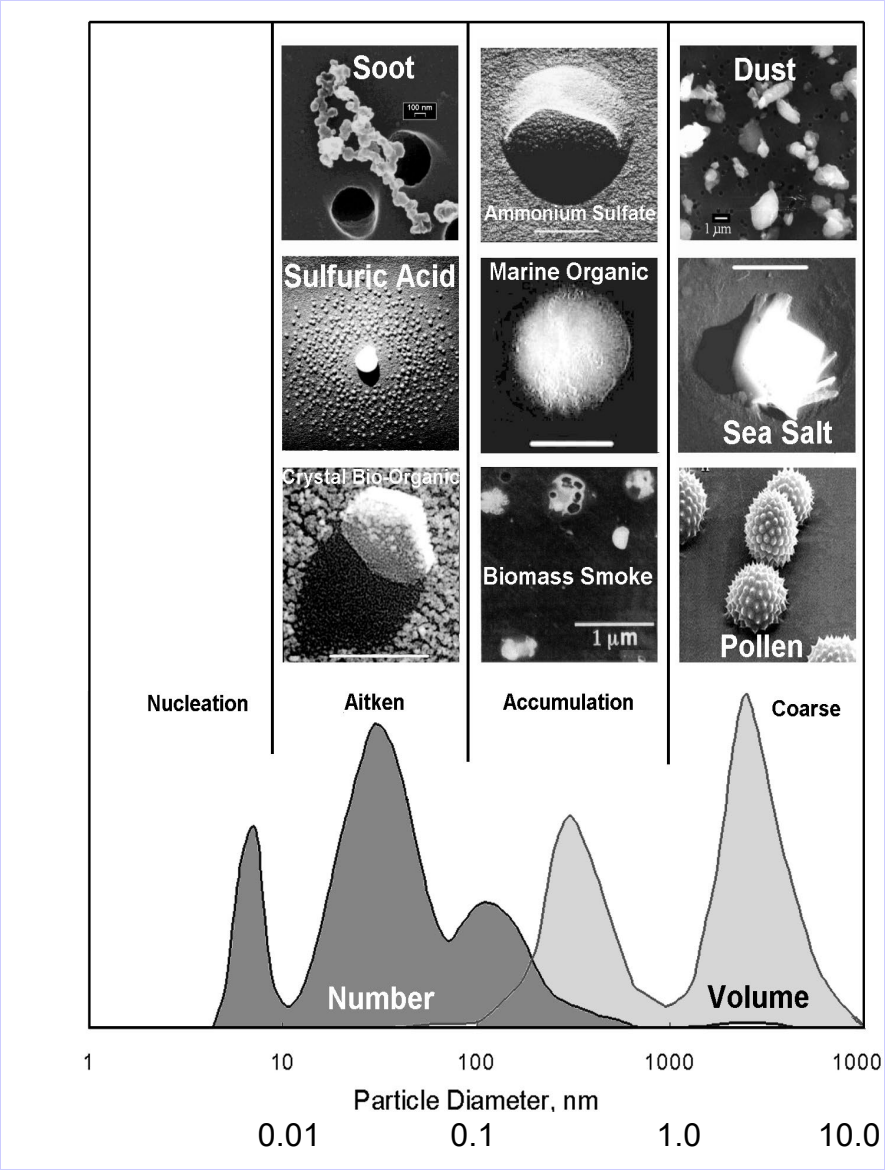
There are 3 modes :

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

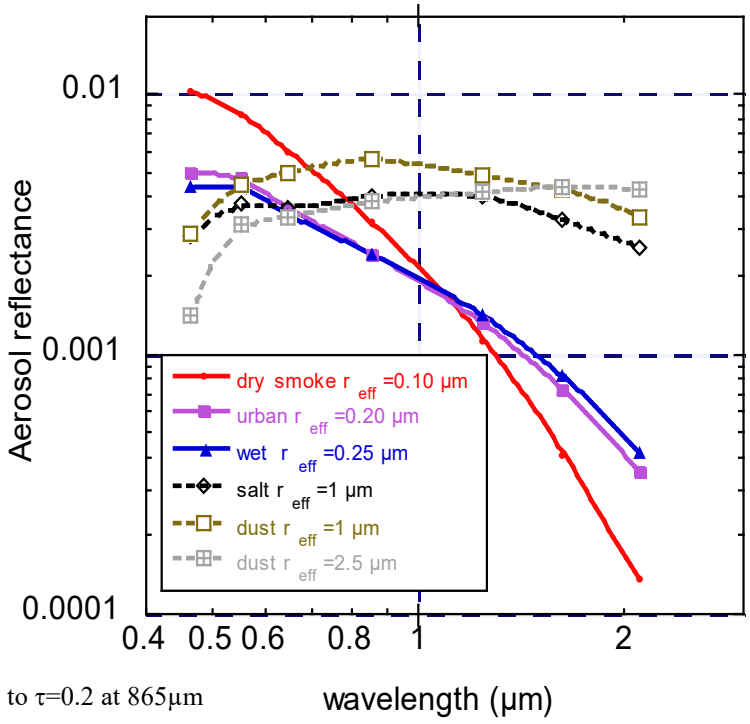
- « **accumulation** »: radius is between 0.05 µm and 0.5 µm. Coagulation processes.

- « **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.



Aerosols over Ocean



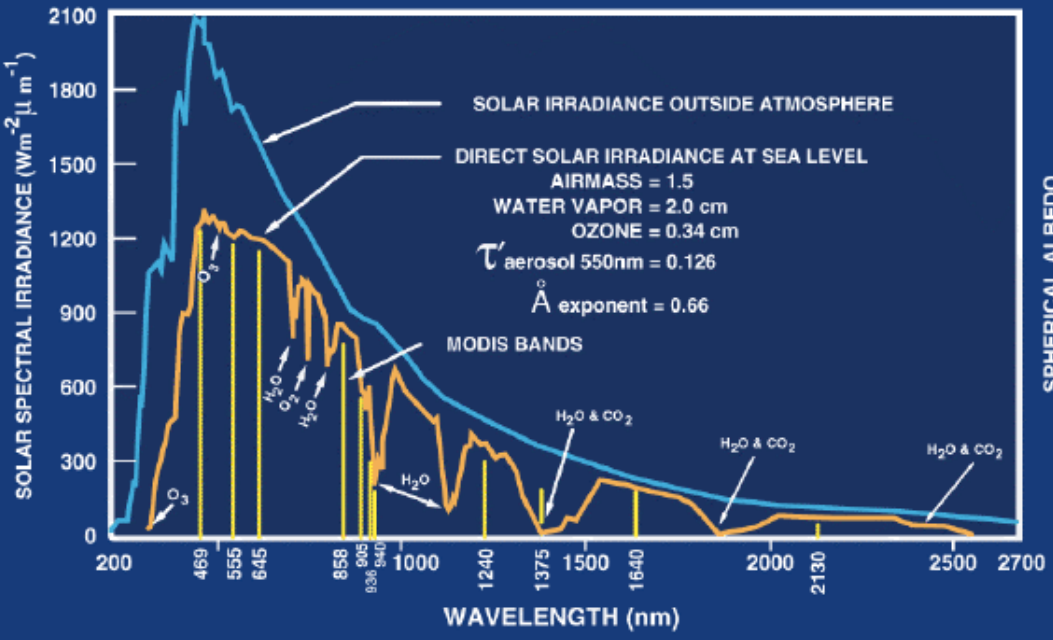
Normalized to τ=0.2 at 865μm

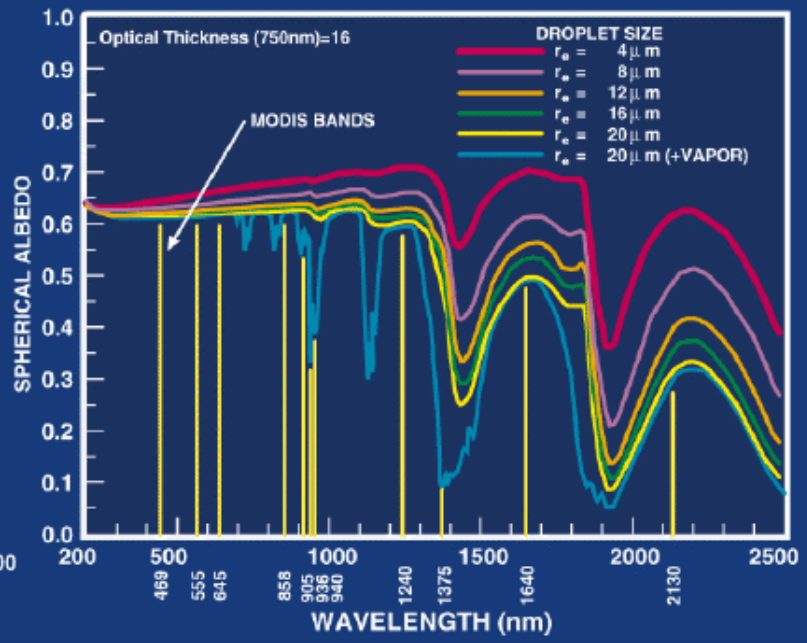
- Radiance data in 6 bands (550-2130nm).
- Spectral radiances (LUT) to derive the aerosol size distribution
- Two modes (accumulation 0.10-0.25μm; coarse1.0-2.5μm); ratio is a free parameter
- Radiance at 865μm to derive τ

Ocean products :

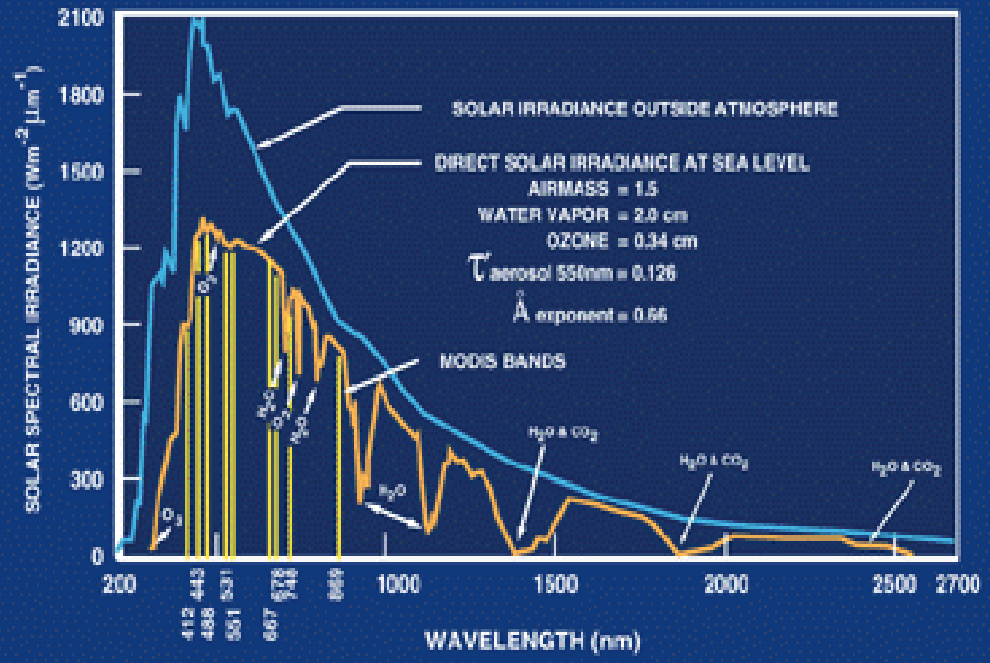
- The total Spectral Optical thickness
- The effective radius
- The optical thickness of small & large modes/ratio between the 2 modes

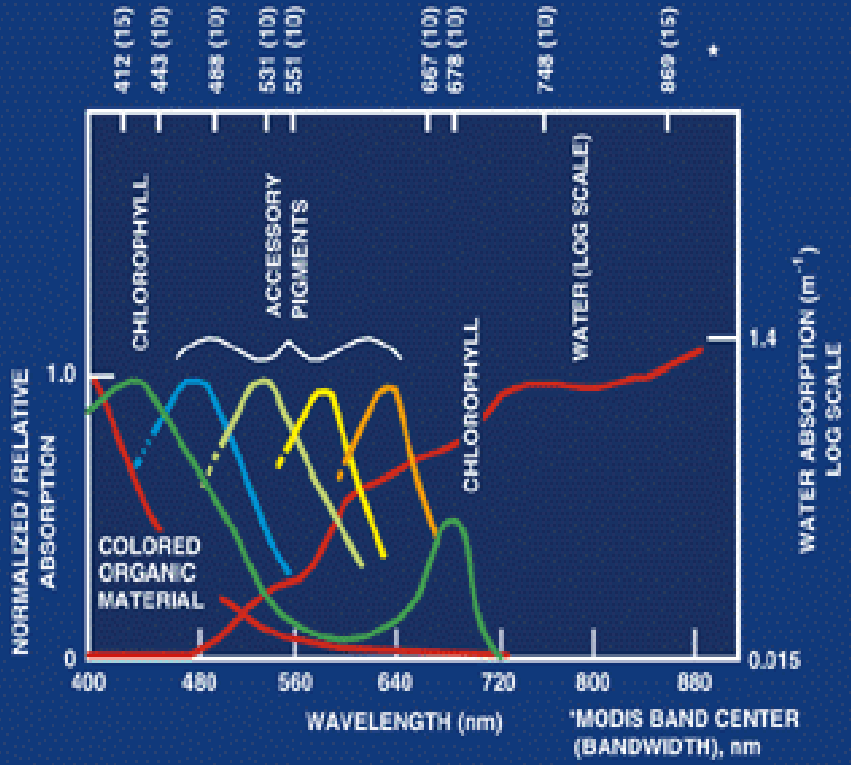
ATMOSPHERE-SOLAR RADIATION



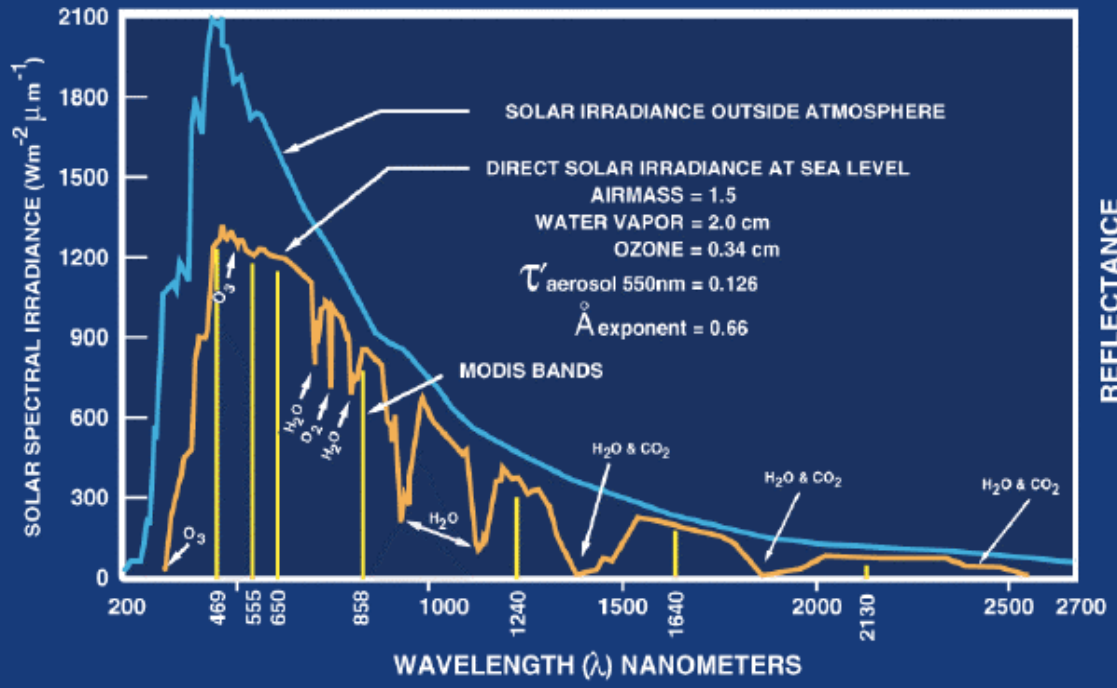


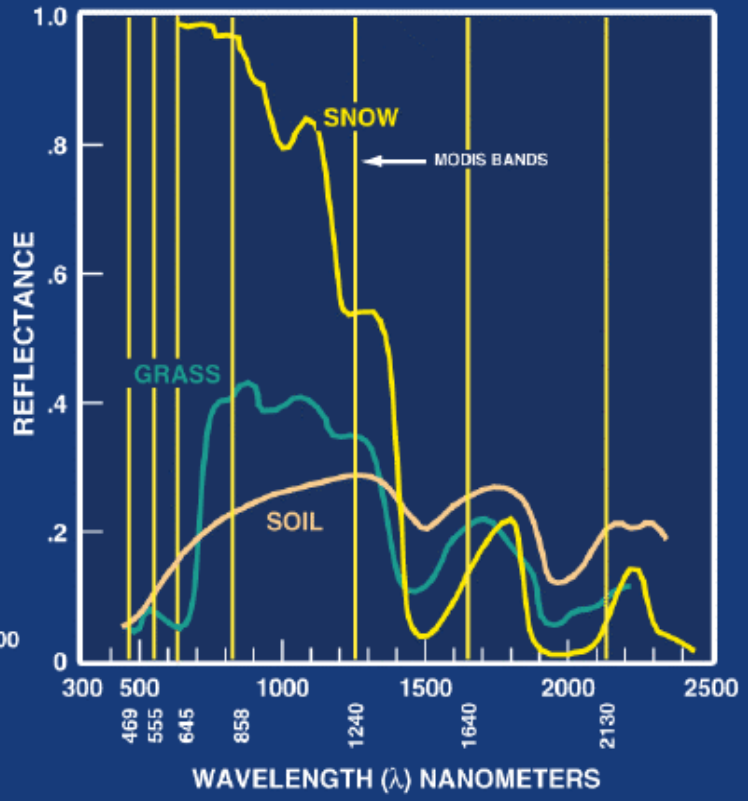
OCEAN-SOLAR RADIATION



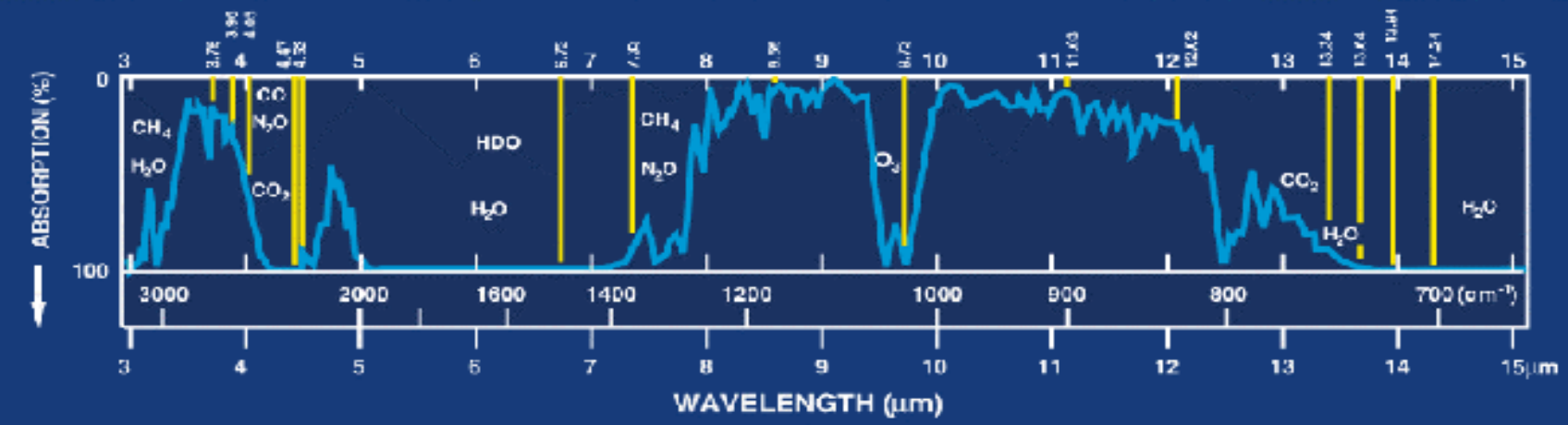


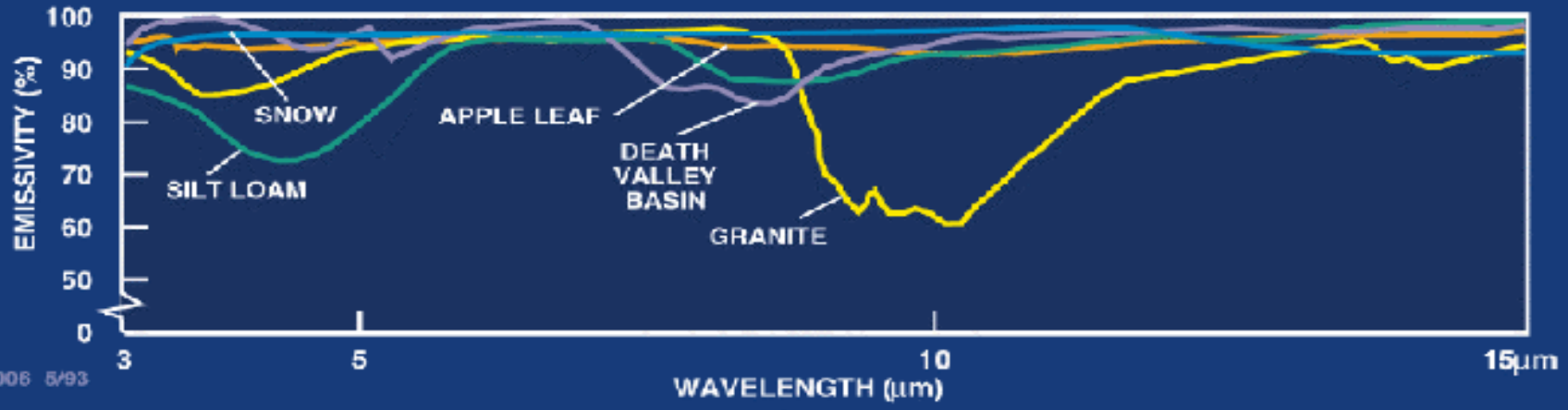
LAND-SOLAR RADIATION





LAND - THERMAL RADIATION





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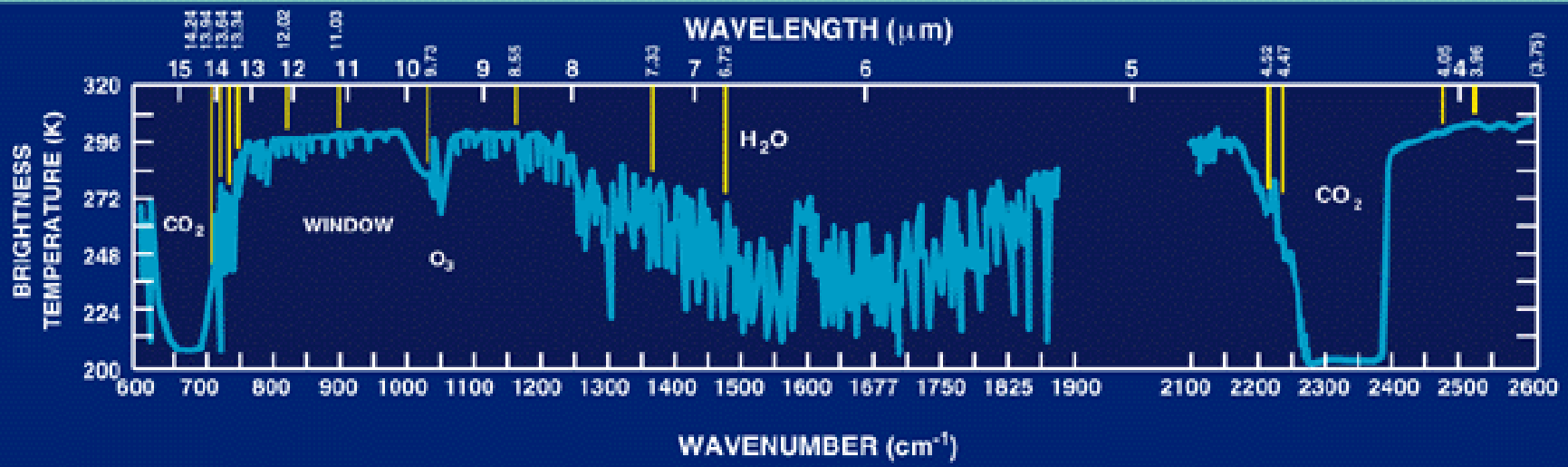
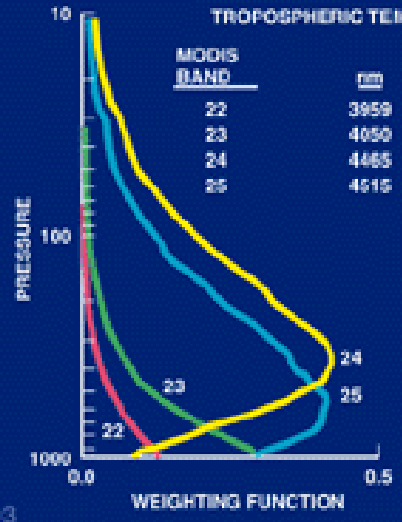
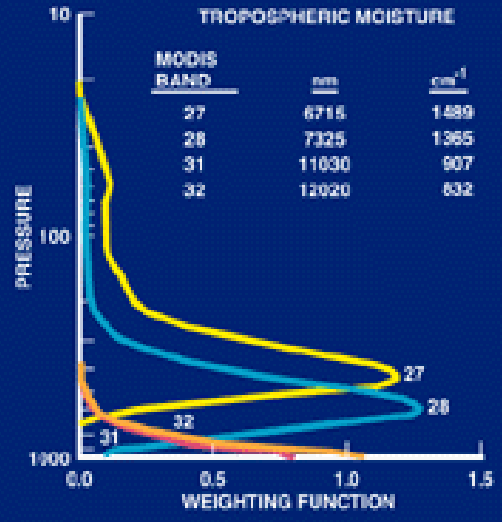
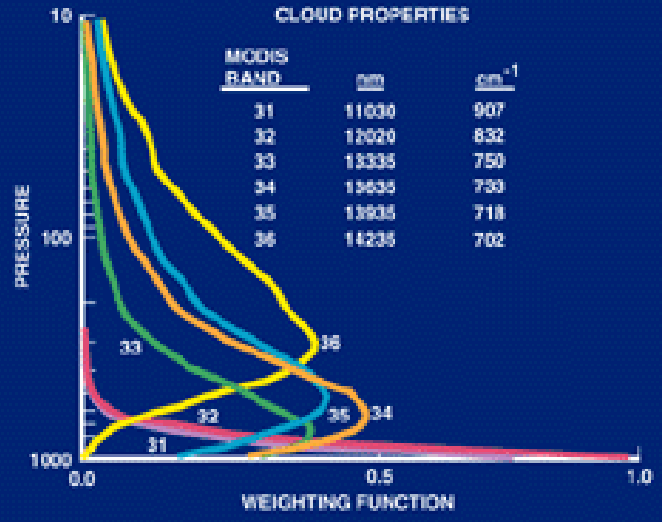
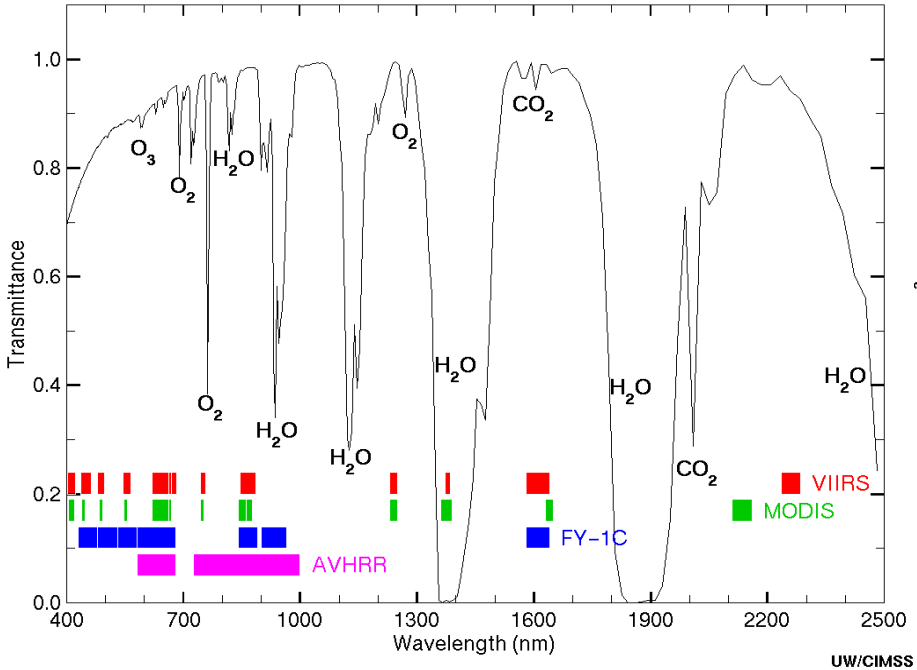
ATMOSPHERE - THERMAL RADIATION

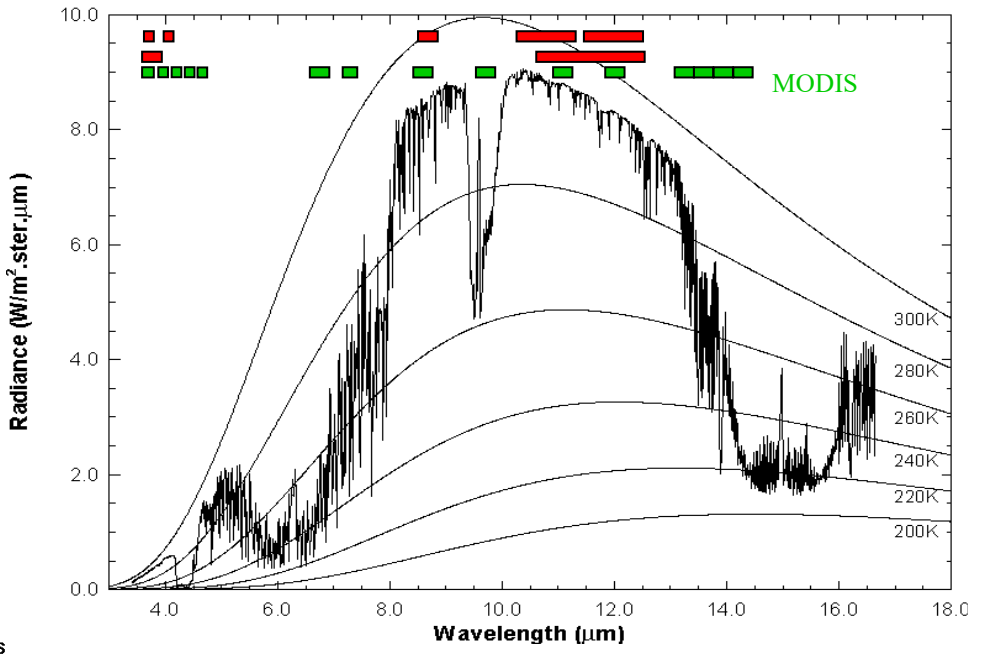


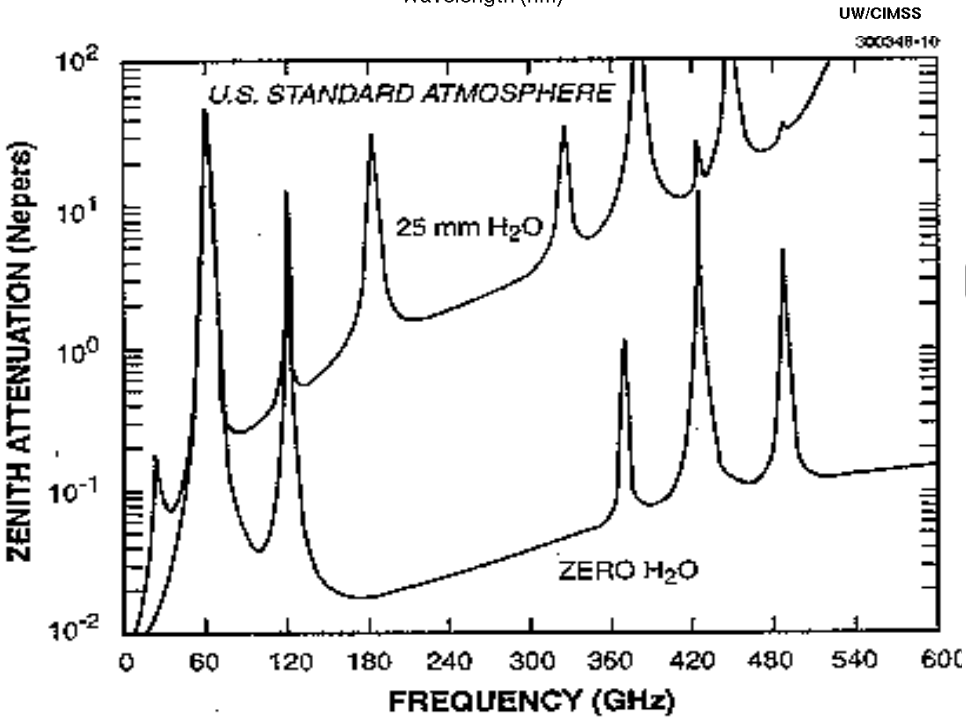


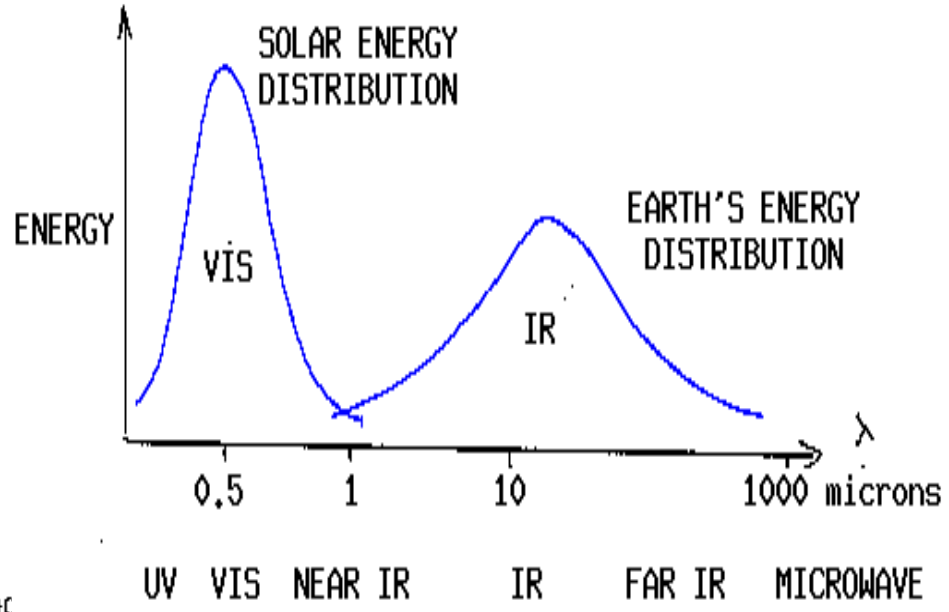


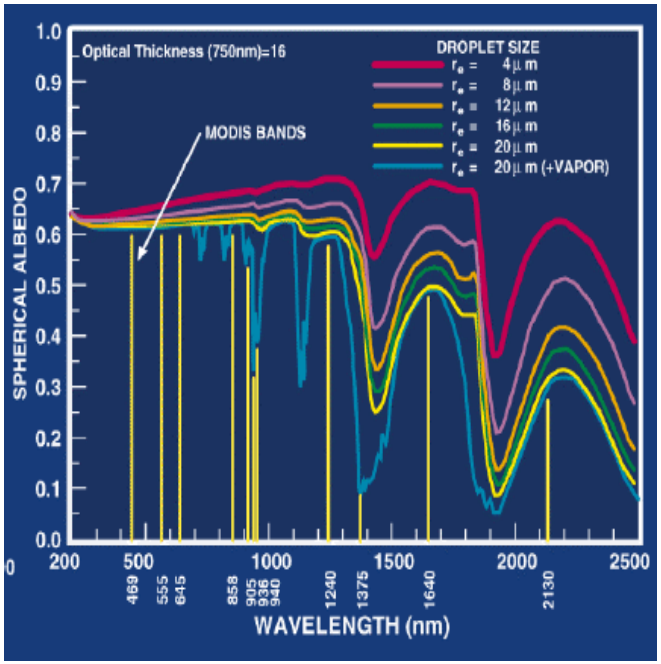


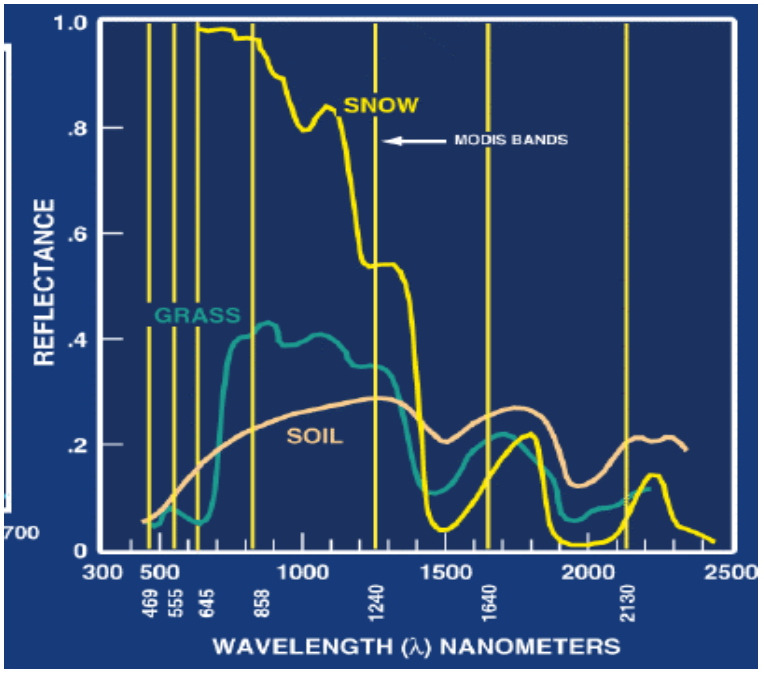

Transmittance
Wavelength (nm)
O3
O2
H2O
O2
H2O
O2
CO2
H2O
H2O
H2O
CO2
H2O
VIIRS
MODIS
FY-1C
AVHRR

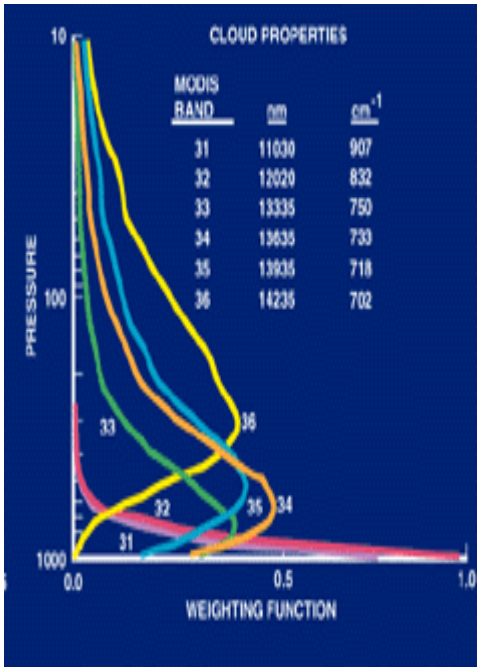

High resolution atmospheric absorption spectrum
and comparative blackbody curves.
Radiance (W/m2.ster.μm)
Wavelength (μm)
MODIS
300K
280K
260K
240K
220K
200K

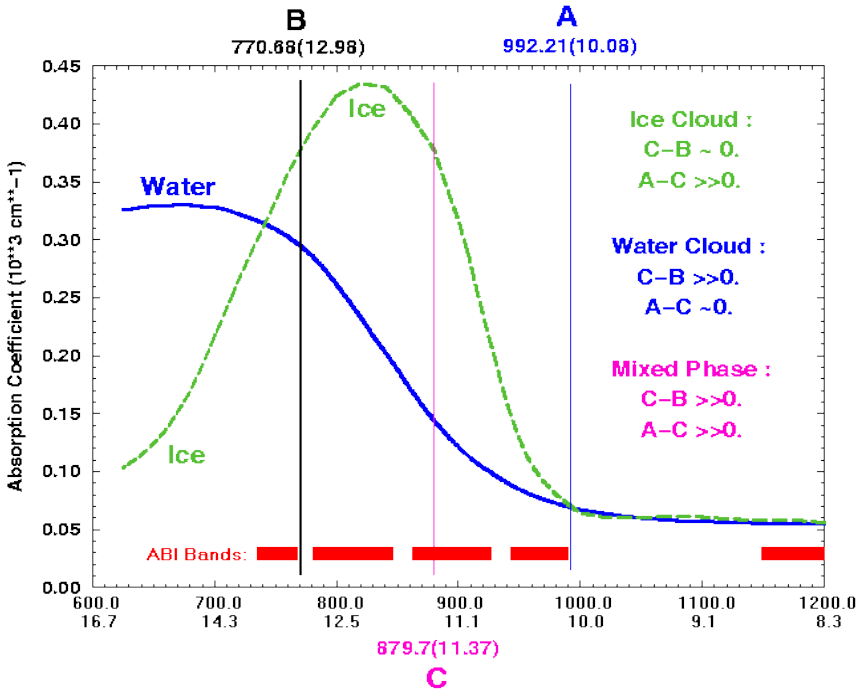

UW/CIMSS
U.S. STANDARD ATMOSPHERE
25 mm H2O
ZERO H2O
ZENITH ATTENUATION (Nepers)
FREQUENCY (GHz)

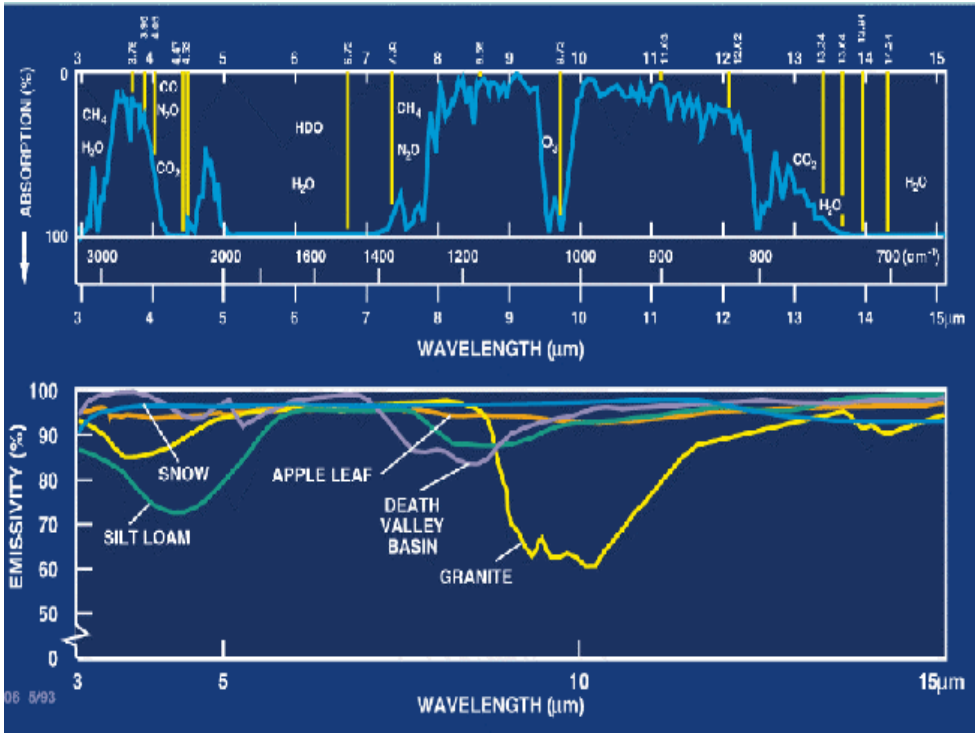

SOLAR ENERGY
DISTRIBUTION
EARTH'S ENERGY
DISTRIBUTION
ENERGY
VIS
IR
λ
0.5
1
10
1000 microns
UV VIS NEAR IR IR FAR IR MICROWAVE

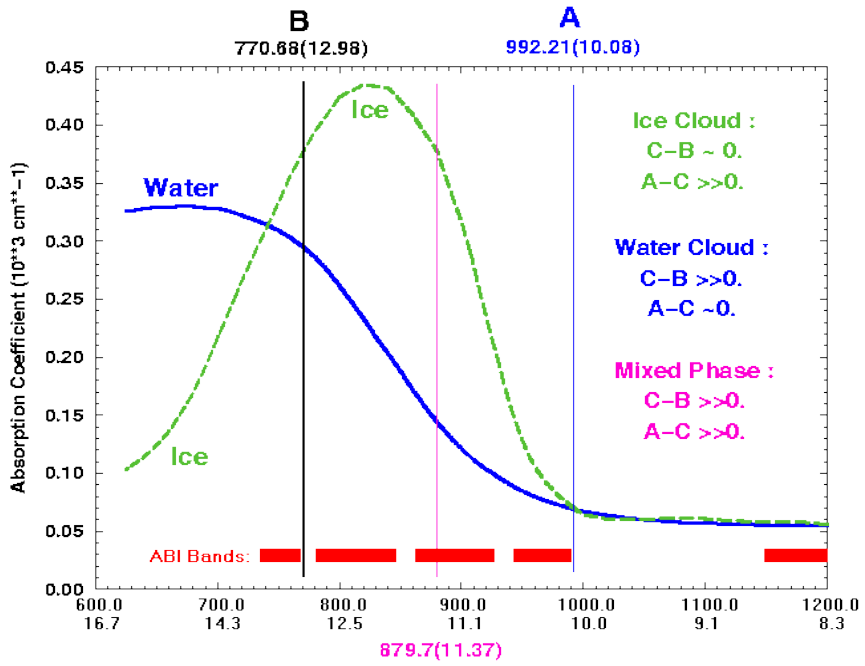

Optical Thickness (750nm)=16
DROPLET SIZE
r_e = 4μm
r_e = 8μm
r_e = 12μm
r_e = 16μm
r_e = 20μm
r_e = 20μm (+VAPOR)
MODIS BANDS
SPHERICAL ALBEDO
WAVELENGTH (nm)

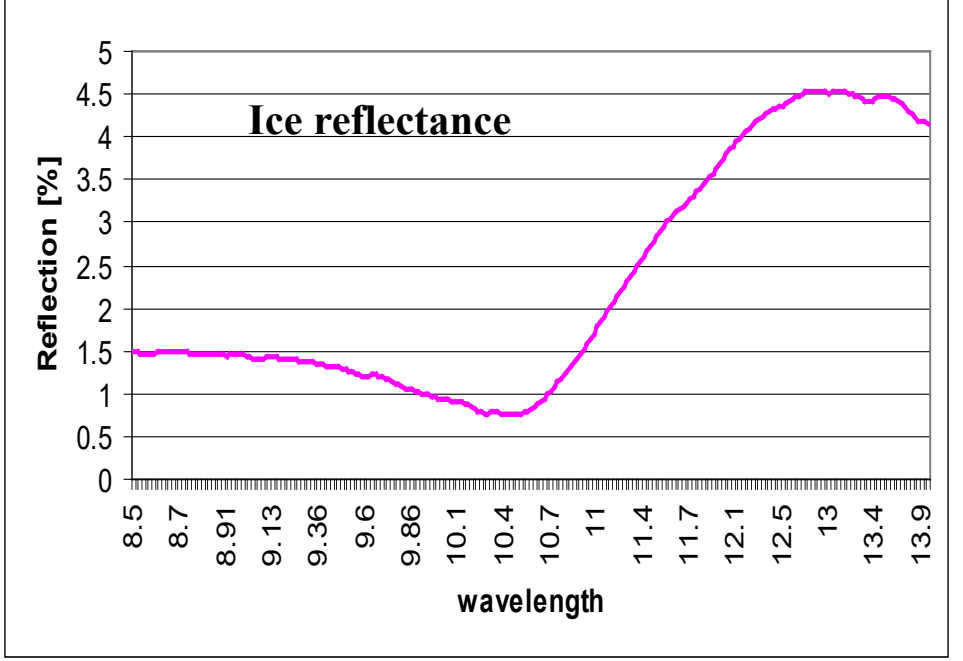

SNOW
MODIS BANDS
GRASS
SOIL
REFLECTANCE
WAVELENGTH (λ) NANOMETERS

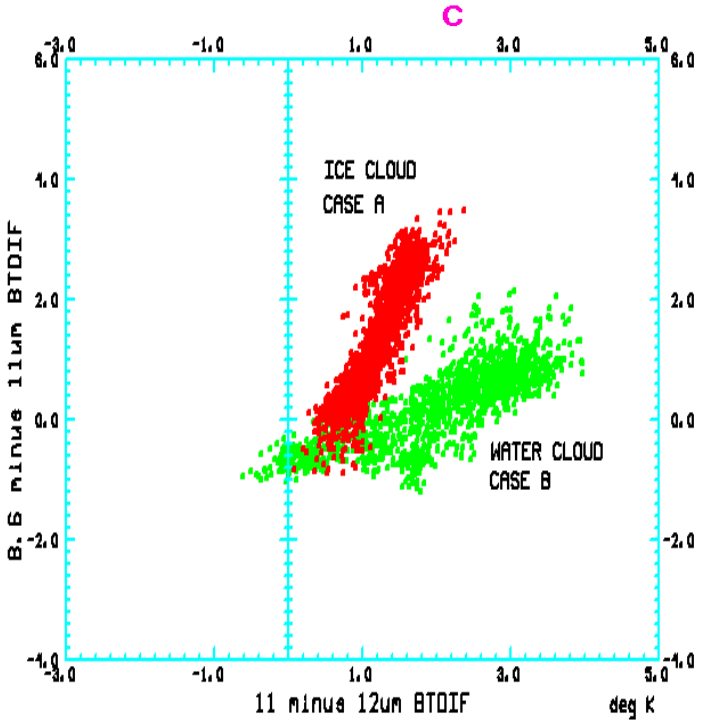

CLOUD PROPERTIES
MODIS BAND
nm
cm⁻¹
31 11030 907
32 12020 832
33 13335 750
34 13635 733
35 13935 718
36 14235 702
PRESSURE
WEIGHTING FUNCTION

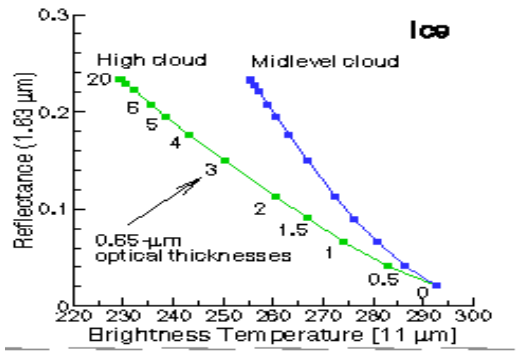

B
770.68(12.98)
A
992.21(10.08)
Ice
Water
Ice
Ice Cloud :
C–B ~ 0.
A–C >>0.
Water Cloud :
C–B >>0.
A–C ~0.
Mixed Phase :
C–B >>0.
A–C >>0.
ABI Bands:
Absorption Coefficient (10**3 cm**-1)
879.7(11.37)
C

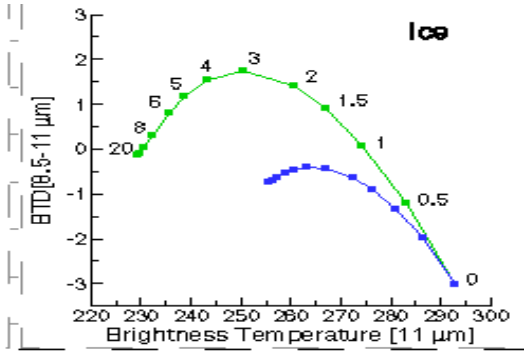

ABSORPTION (%)
WAVELENGTH (μm)
EMISSIVITY (%)
SNOW
APPLE LEAF
SILT LOAM
DEATH VALLEY BASIN
GRANITE
WAVELENGTH (μm)

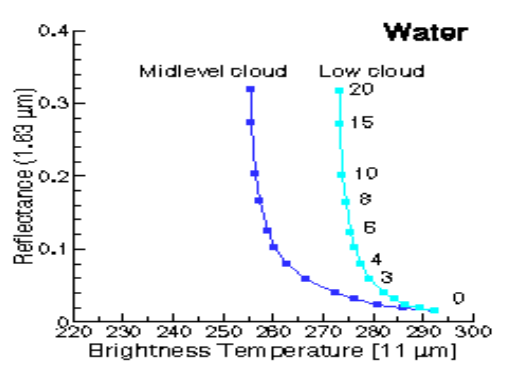

B
770.68(12.98)
A
992.21(10.08)
Ice
Water
Ice
Ice Cloud :
C-B ~ 0.
A-C >>0.
Water Cloud :
C-B >>0.
A-C ~0.
Mixed Phase :
C-B >>0.
A-C >>0.
ABI Bands:
Absorption Coefficient (10**3 cm**-1)
879.7(11.37)

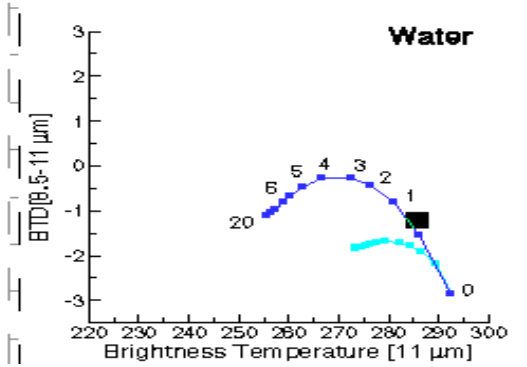

Ice reflectance
Reflection [%]
wavelength


C
ICE CLOUD
CASE A
WATER CLOUD
CASE B
8.6 minus 11um BTDIF
11 minus 12um BTDIF
deg K

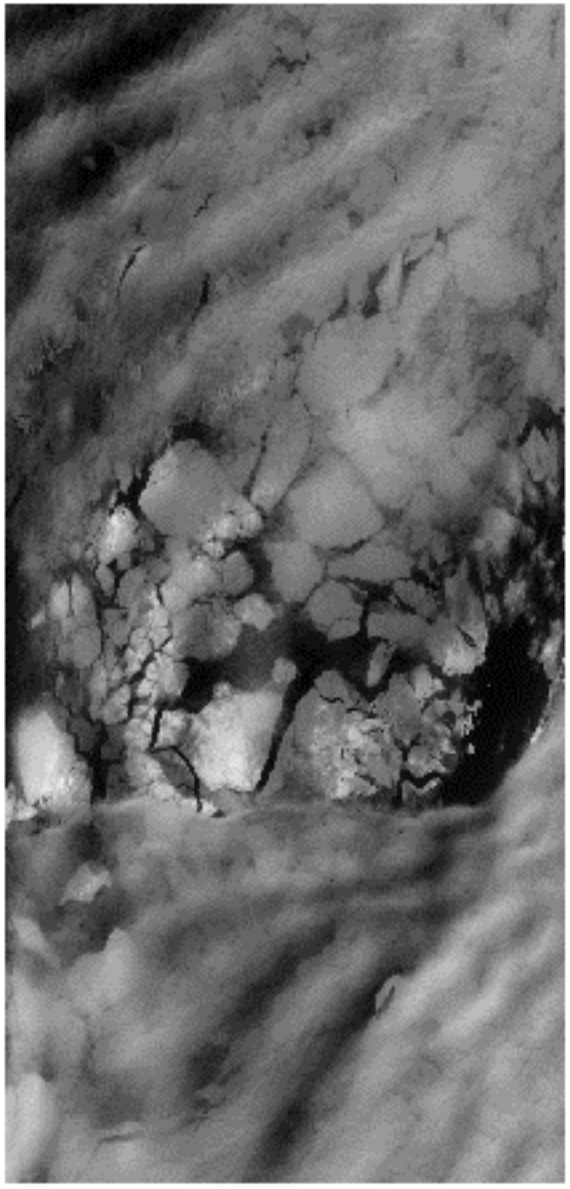

Ice
High cloud
Midlevel cloud
0.65-µm
optical thicknesses
Reflectance (1.63 µm)
Brightness Temperature [11 µm]


Ice
BTD[8.5-11 µm]
Brightness Temperature [11 µm]


Water
Midlevel cloud
Low cloud
Reflectance (1.63 µm)
Brightness Temperature [11 µm]


Water
BTD[8.5-11 µm]
Brightness Temperature [11 µm]

MAS 02/02/1997 16:36:31 UTC
Band 02 (0.66 micron)
Gain Corrected Counts



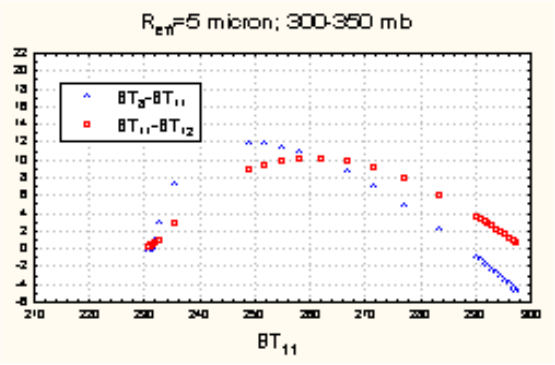
2000 3000 4000 5000

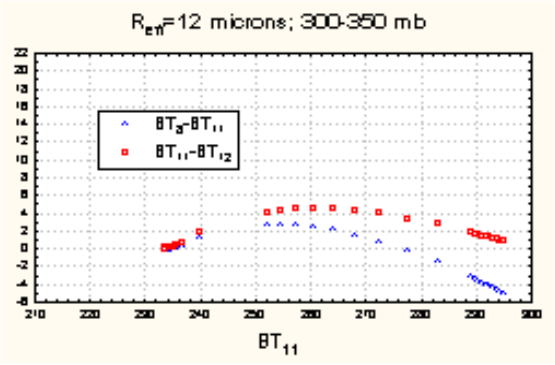
MAS 02/02/1997 16:36:31 UTC
Banda 44-45 (10.46-10.96 micron)
Brightness Temperature (Kelvin)

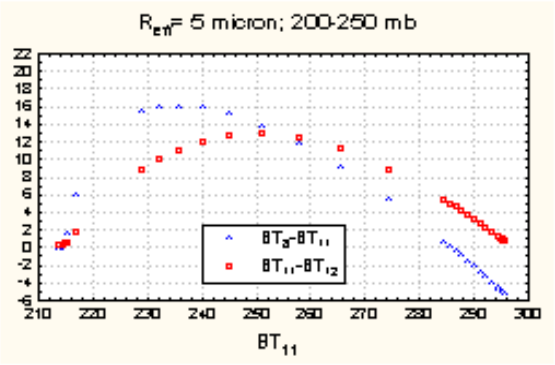
0.0 0.2 0.4 0.6 0.8 1.0

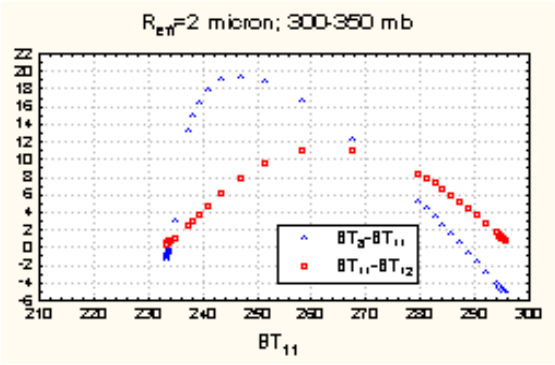
MAS 02/02/1997 16:36:31 UTC
Banda 42-44 (8.54-10.46 micron)
Brightness Temperature (Kelvin)

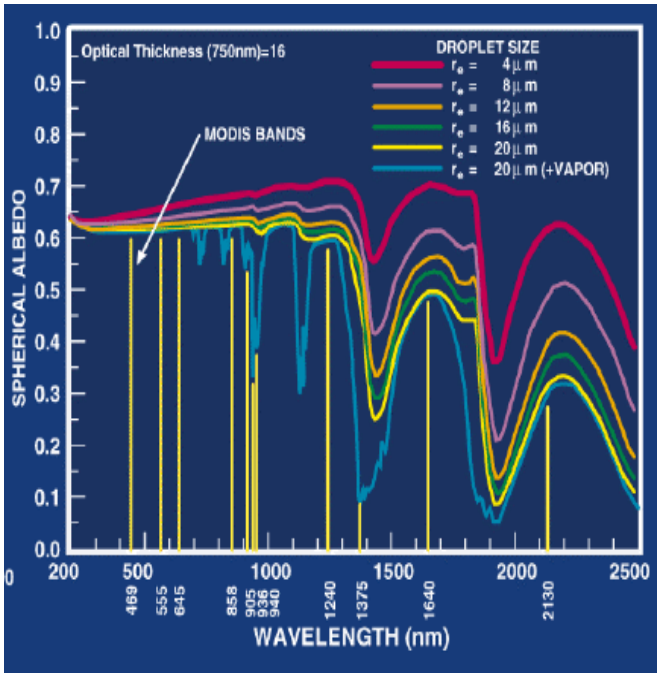
-2.0 -1.8 -1.6 -1.4 -1.2

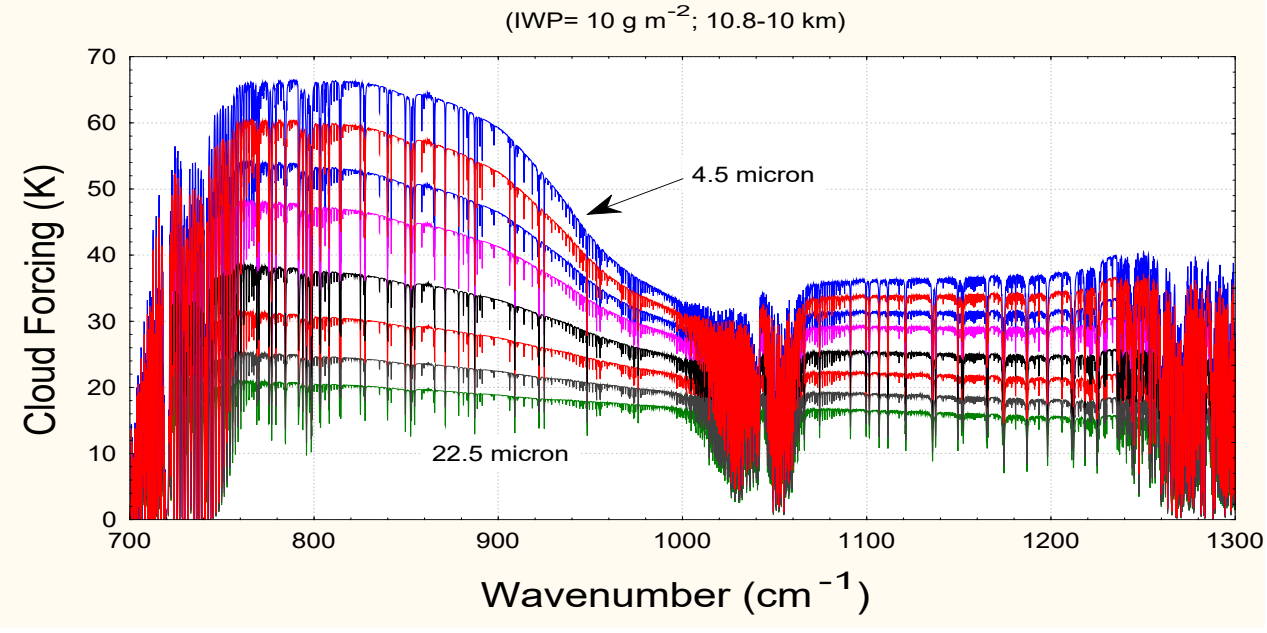

R_{eff}=5 micron; 300-350 mb
BT_8-BT_{11}
BT_{11}-BT_{12}
BT_{11}

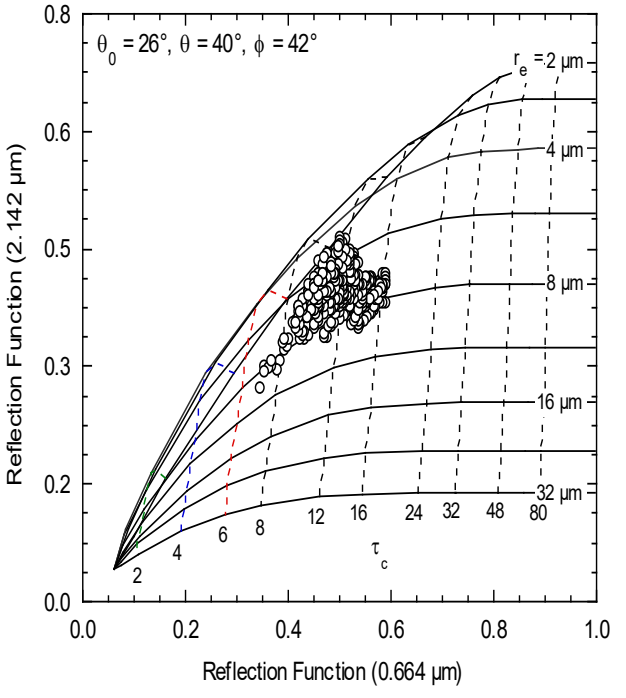

R_{eff}=12 microns; 300-350 mb
BT_8-BT_{11}
BT_{11}-BT_{12}
BT_{11}


R_{eff}= 5 micron; 200-250 mb
BT_8-BT_{11}
BT_{11}-BT_{12}
BT_{11}

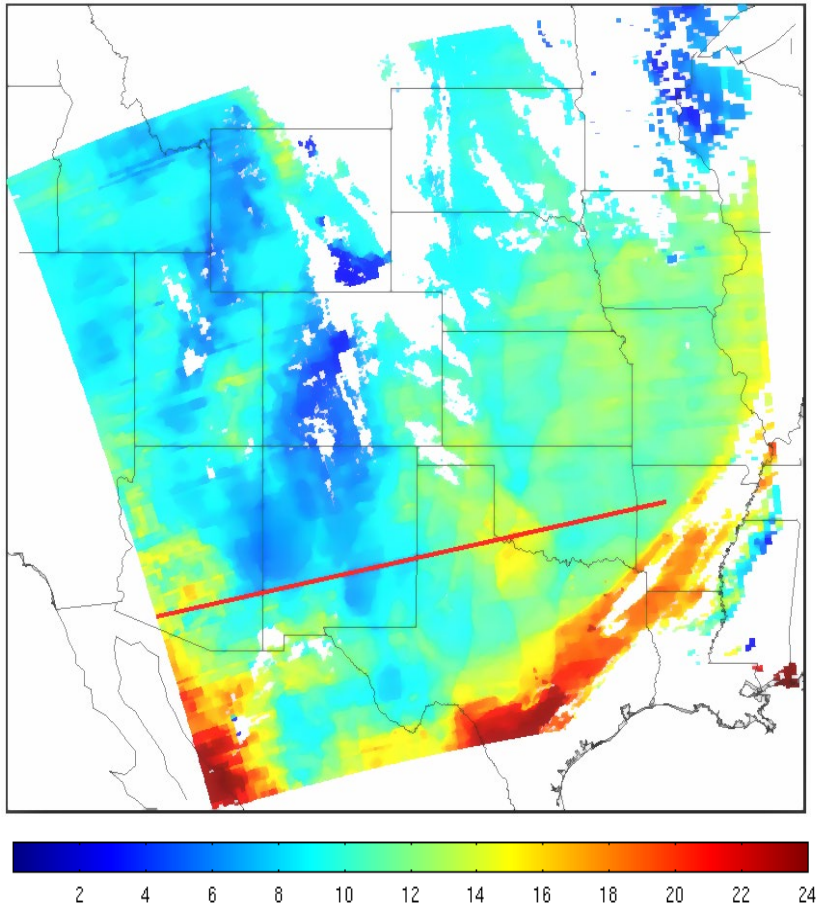

R_{eff}=2 micron; 300-350 mb
BT_8-BT_{11}
BT_{11}-BT_{12}
BT_{11}

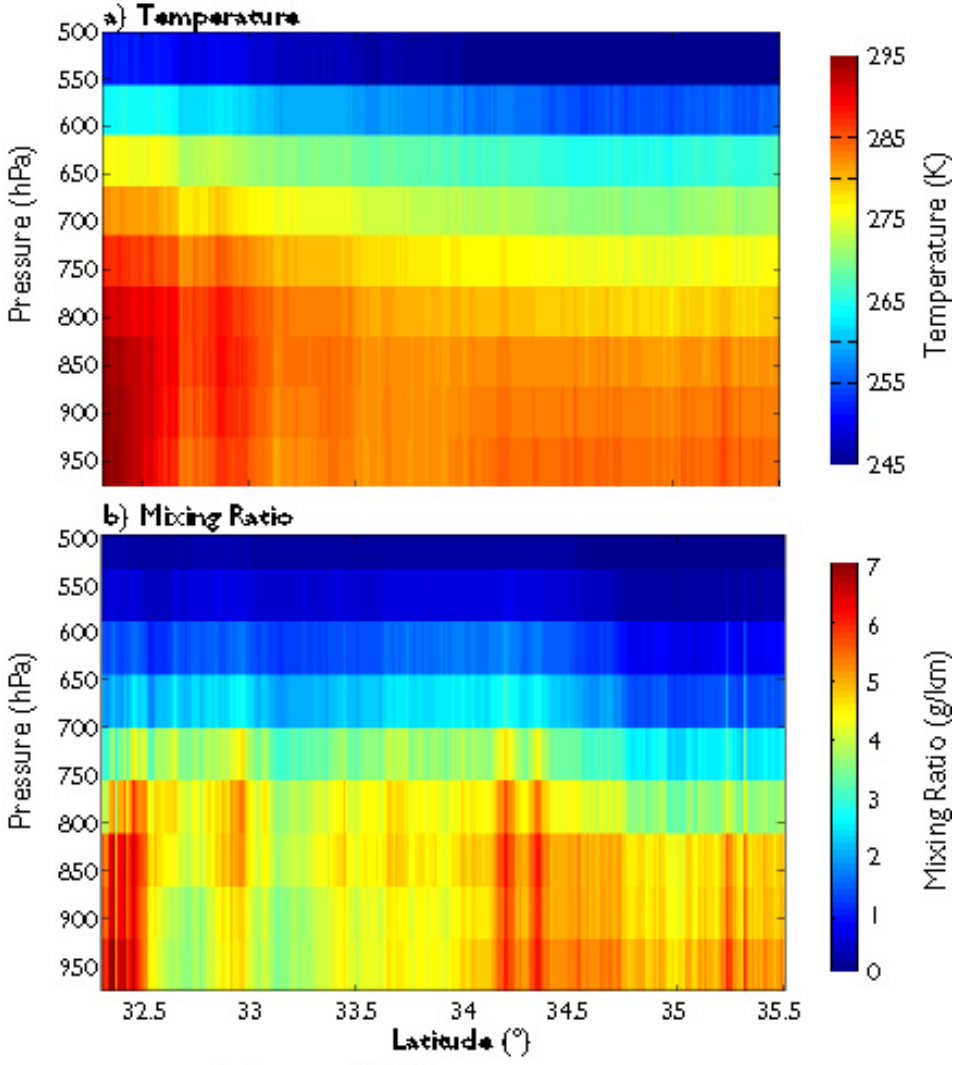

Optical Thickness (750nm)=16
DROPLET SIZE
r_e = 4 μm
r_e = 8 μm
r_e = 12 μm
r_e = 16 μm
r_e = 20 μm
r_e = 20 μm (+VAPOR)
MODIS BANDS
SPHERICAL ALBEDO
WAVELENGTH (nm)


(IWP= 10 g m^{-2}; 10.8-10 km)
4.5 micron
22.5 micron
Cloud Forcing (K)
Wavenumber (cm^{-1})

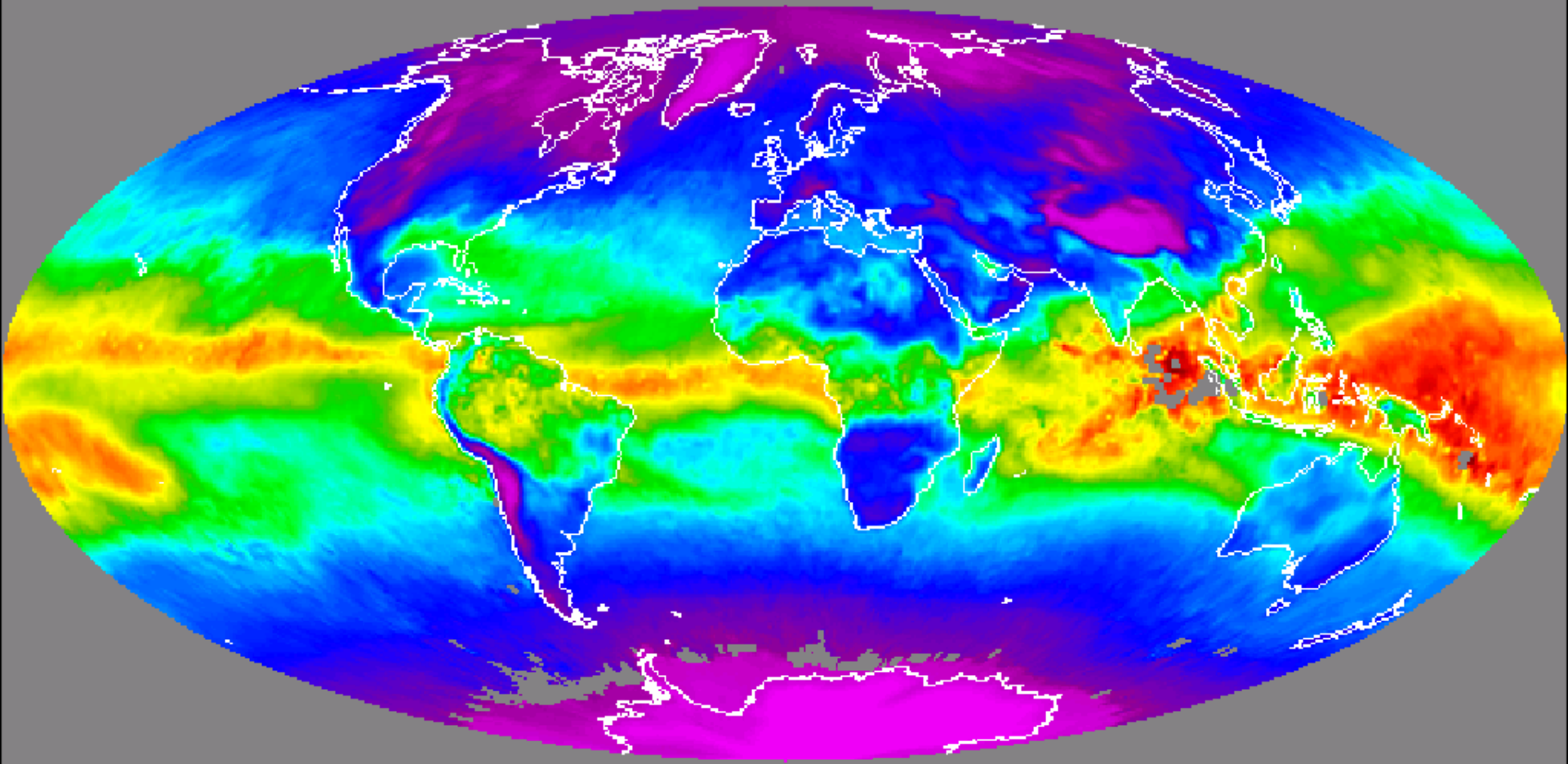

θ_0 = 26°, θ = 40°, ϕ = 42°
r_e = 2 μm
4 μm
8 μm
16 μm
32 μm
τ_c
Reflection Function (2.142 μm)
Reflection Function (0.664 μm)

MODIS TPW





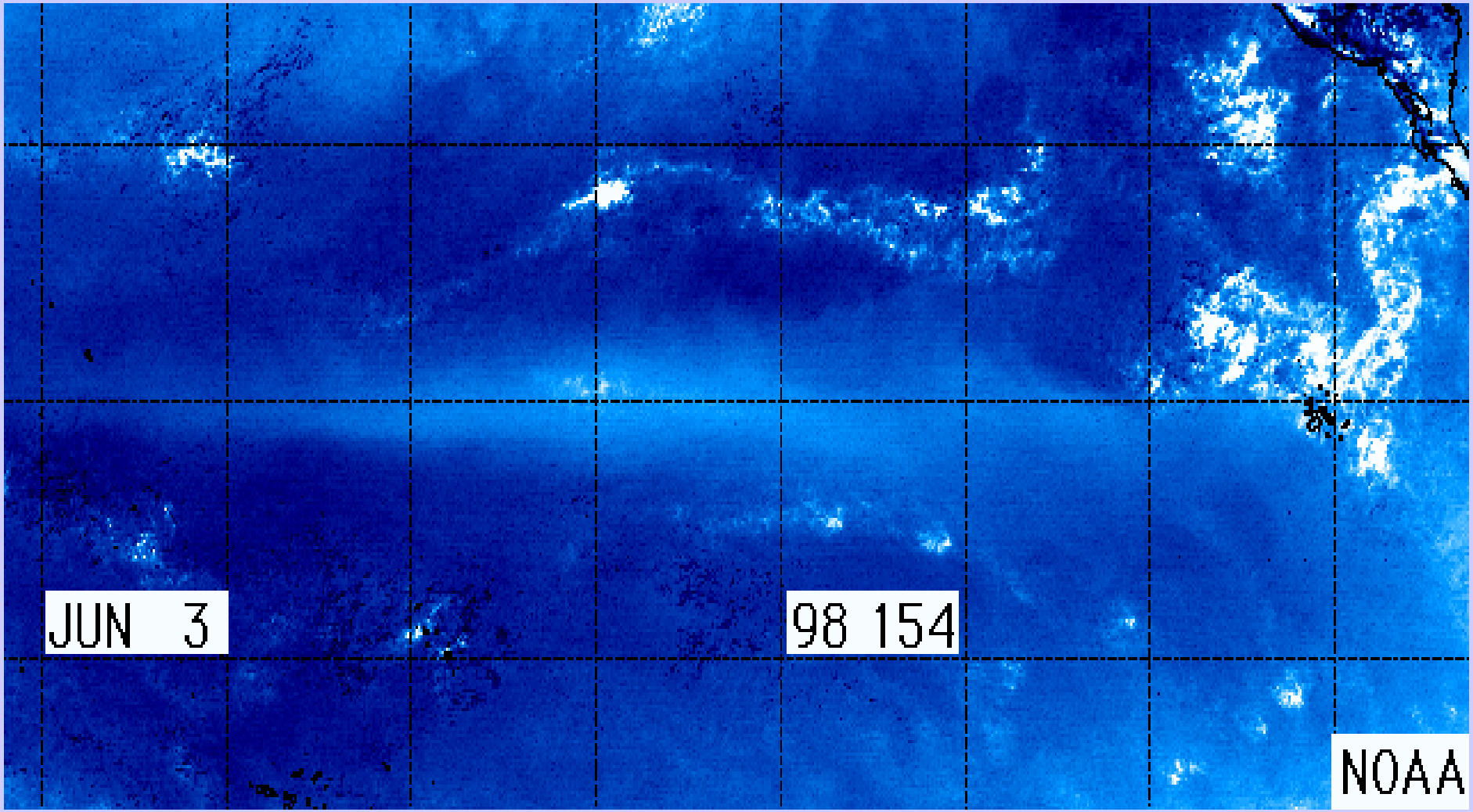
Clear sky layers of temperature and moisture on 2 June 2001



1 MAY 2002 **Global TPW from Seemann**

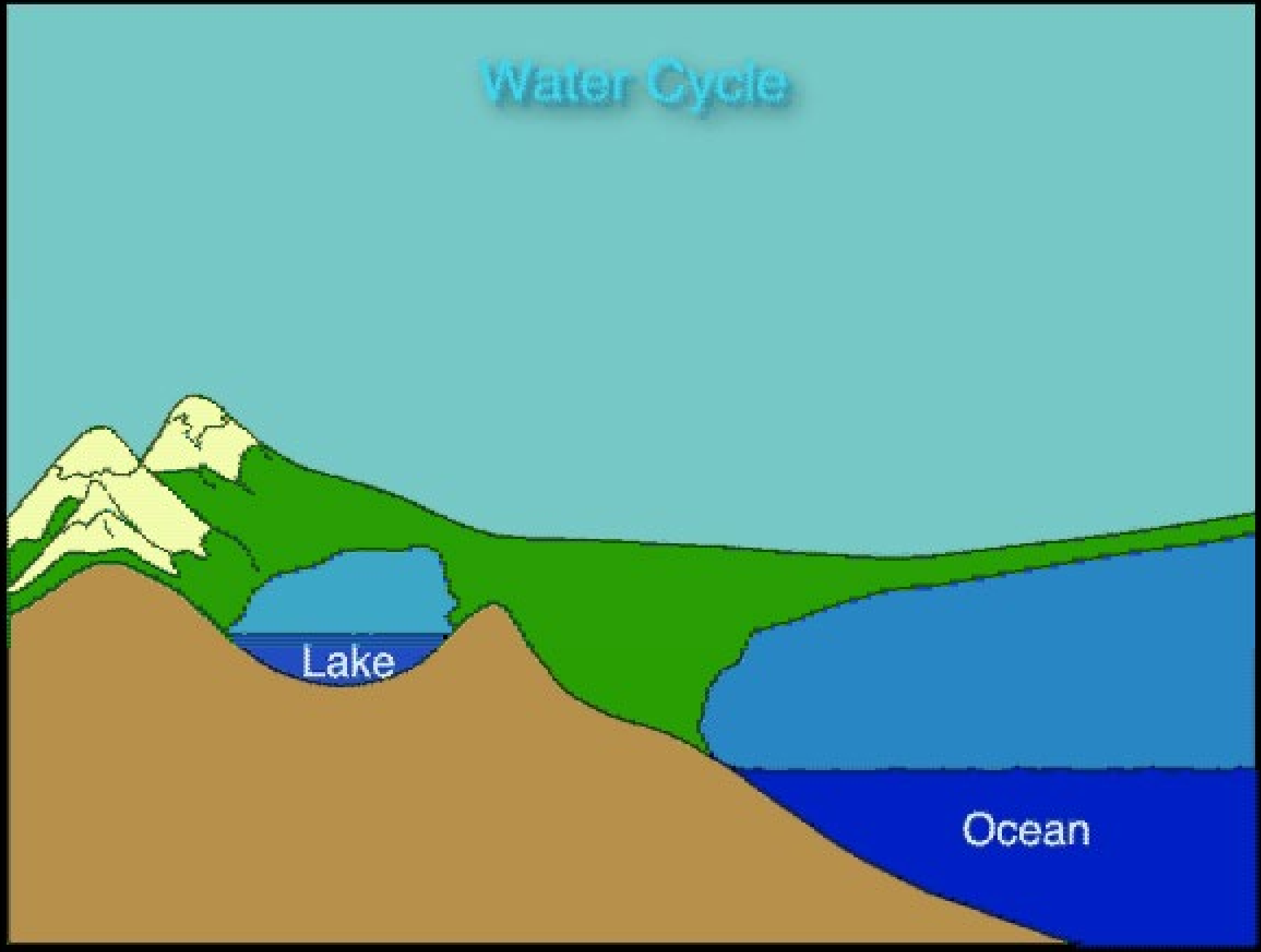
TPW_Terra_2002

Snow Cover from Hall



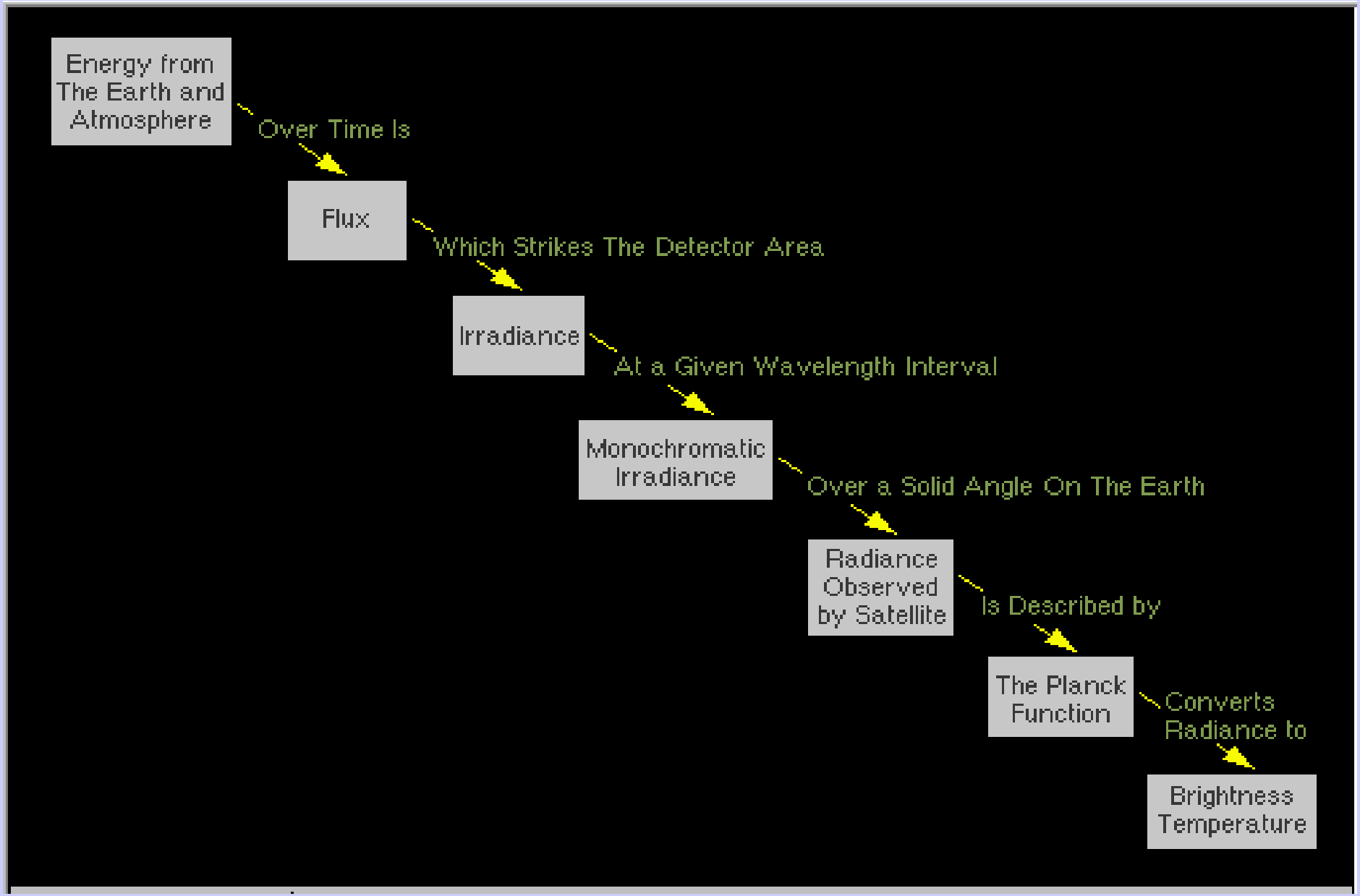
SST Waves from Legeckis

Energy Cycle From Levizzani



Water Cycle From Levizzani

Terminology of radiant energy



Definitions of Radiation

QUANTITY	SYMBOL	UNITS
Energy	dQ	Joules
Flux	dQ/dt	Joules/sec = Watts
Irradiance	$dQ/dt/dA$	Watts/meter^2
Monochromatic Irradiance	$dQ/dt/dA/d\lambda$	W/m^2/micron
	or	
	$dQ/dt/dA/d\nu$	W/m^2/cm^{-1}
Radiance	$dQ/dt/dA/d\lambda/d\Omega$	W/m^2/micron/ster
	or	
	$dQ/dt/dA/d\nu/d\Omega$	W/m^2/cm^{-1}/ster

Using wavenumbers

Planck's Law $B(\nu,T) = c_1\nu^3 / [e^{c_2\nu/T} - 1]$ $(mW/m^2/ster/cm^{-1})$

where ν = # wavelengths in one centimeter (cm-1)

T = temperature of emitting surface (deg K)

$c_1 = 1.191044 \times 10\text{-}5$ $(mW/m^2/ster/cm^{-4})$

$c_2 = 1.438769$ (cm deg K)

Wien's Law $dB(\nu_{max},T) / dT = 0$ where $\nu(max) = 1.95T$

indicates peak of Planck function curve shifts to shorter wavelengths (greater wavenumbers) with temperature increase.

Stefan-Boltzmann Law $E = \pi \int_0^\infty B(\nu,T)\, d\nu = \sigma T^4$, where $\sigma = 5.67 \times 10\text{-}8$ W/m2/deg4.

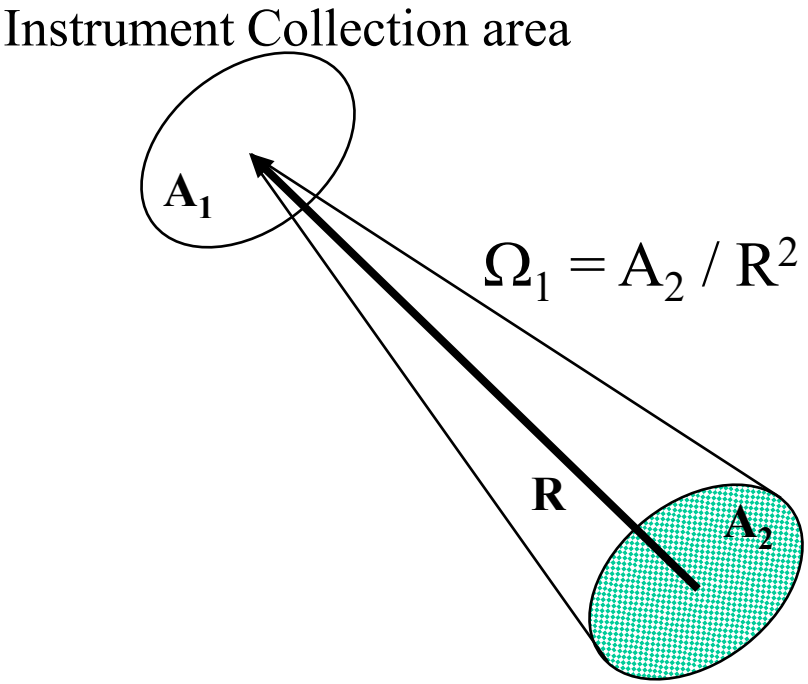
states that irradiance of a black body (area under Planck curve) is proportional to T^4 .

Brightness Temperature

$T = c_2\nu/[\ln(\frac{c_1\nu^3}{B_\nu} + 1)]$ is determined by inverting Planck function

Telescope Radiative Power Capture proportional to throughput AΩ

Spectral Power radiated from A_2 to A_1 = $L(\nu)\, A_1\Omega_1$ mW/cm^{-1}



Radiance from surface
= $L(\nu)$ mW/m^2 sr cm^{-1}

{Note: $A_1 A_2 / R^2 = A_1\Omega_1 = A_2\Omega_2$ }

Radiative Transfer Equation

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

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

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.

RTE in Cloudy Conditions

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

$$I^{c}_\lambda = B_\lambda(T_s)\, \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p))\, d\tau_\lambda \, .$$

$$I^{cd}_\lambda = (1-\varepsilon_\lambda)\, B_\lambda(T_s)\, \tau_\lambda(p_s) + (1-\varepsilon_\lambda) \int_{p_s}^{p_c} B_\lambda(T(p))\, d\tau_\lambda$$

$$+ \varepsilon_\lambda\, B_\lambda(T(p_c))\, \tau_\lambda(p_c) + \int_{p_c}^{o} B_\lambda(T(p))\, d\tau_\lambda$$

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

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

Techniques for dealing with clouds fall into three categories: (a) searching for cloudless fields of view, (b) specifying cloud top pressure and sounding down to cloud level as in the cloudless case, and (c) employing adjacent fields of view to determine clear sky signal from partly cloudy observations.

Cloud Properties

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

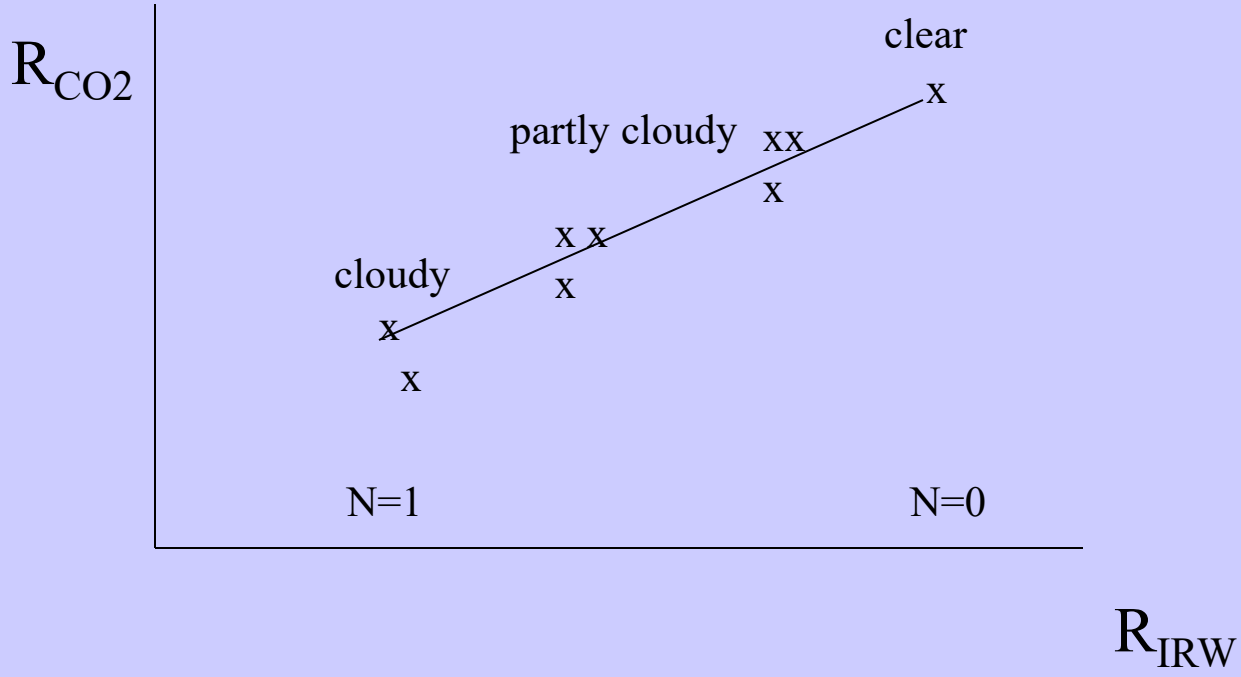
$$(I_\lambda - I_\lambda^{clr}) = \eta\varepsilon_\lambda \int_{p_s}^{p_c} \tau_\lambda \, dB_\lambda \, .$$

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. $\eta\varepsilon_\lambda$ is derived from the infrared window, once p_c is known. This is the essence of the CO2 slicing technique.

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.

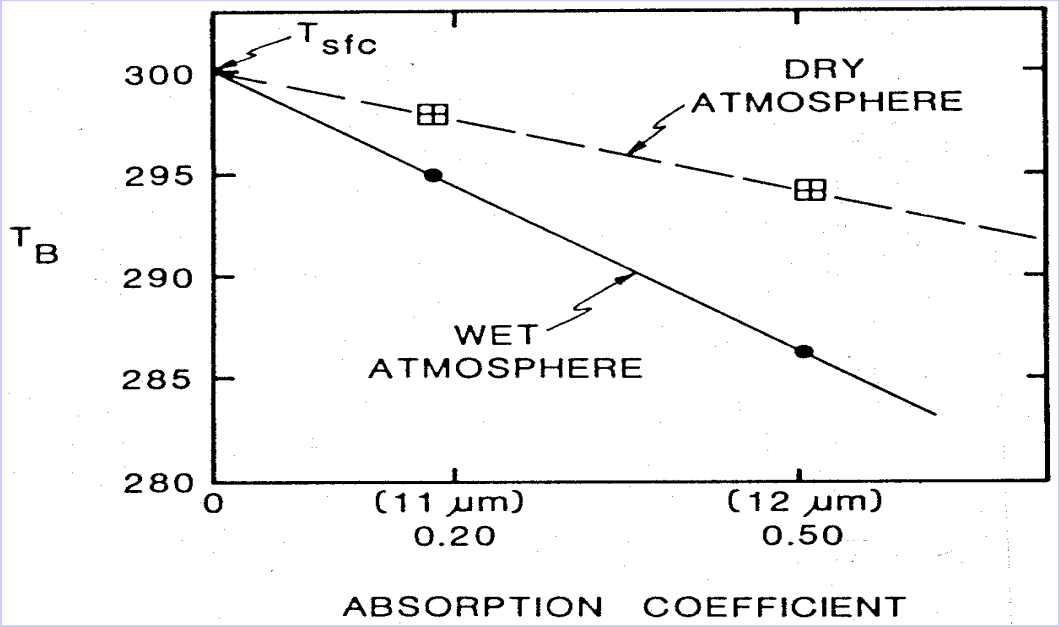
Moisture

Moisture attenuation in atmospheric windows varies linearly with optical depth.

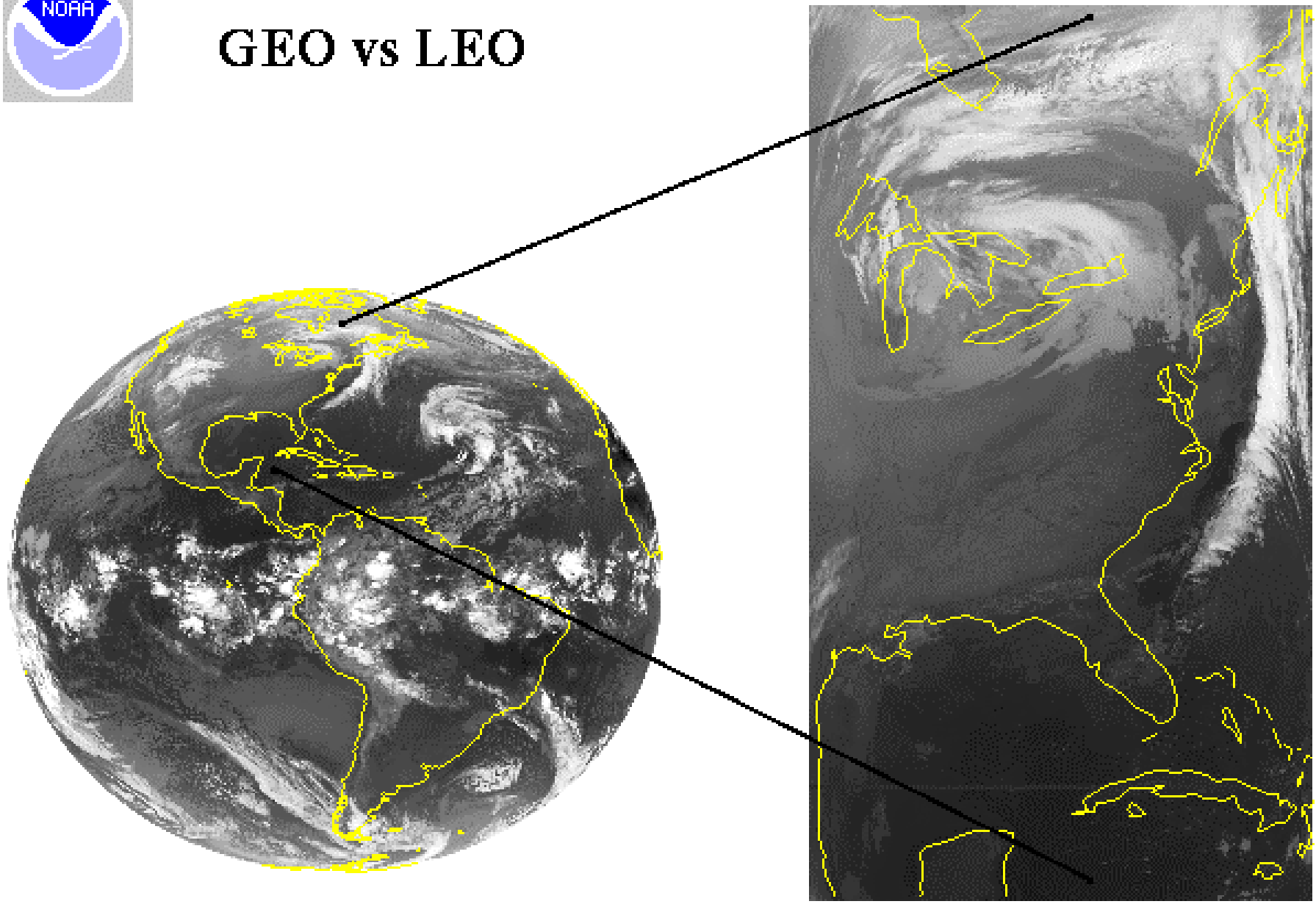
$$\tau_\lambda = e^{-k_\lambda u} = 1 - k_\lambda u$$

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

Moisture content of atmosphere inferred from slope of linear relation.



GEO vs LEO



GOES-8 IMAGER 12UTC 02APR98

NOAA-12 AVHRR 12UTC 02APR98

Comparison of geostationary (geo) and low earth orbiting (leo) satellite capabilities

Geo	Leo
observes process itself (motion and targets of opportunity)	observes effects of process
repeat coverage in minutes ($\Delta t \leq 30$ minutes)	repeat coverage twice daily ($\Delta t = 12$ hours)
full earth disk only	global coverage
best viewing of tropics	best viewing of poles
same viewing angle	varying viewing angle
differing solar illumination	same solar illumination
visible, IR imager (1, 4 km resolution)	visible, IR imager (1, 1 km resolution)
one visible band	multispectral in visible (veggie index)
IR only sounder (8 km resolution)	IR and microwave sounder (17, 50 km resolution)
filter radiometer	filter radiometer, interferometer, and grating spectrometer
diffraction more than leo	diffraction less than geo

Email comments on course to

paoloa@ssec.wisc.edu

Best feature
Worst feature
Suggestions to improve