Summary
Remote Sensing Seminar

Lectures in Maratea

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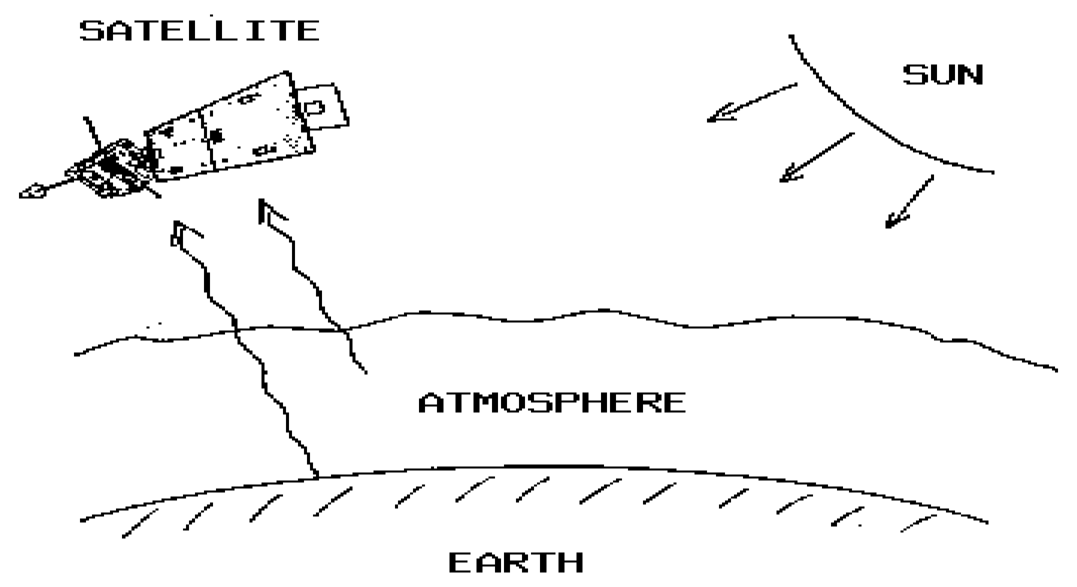
NOAA/NESDIS/ORA

22-31 May 2003

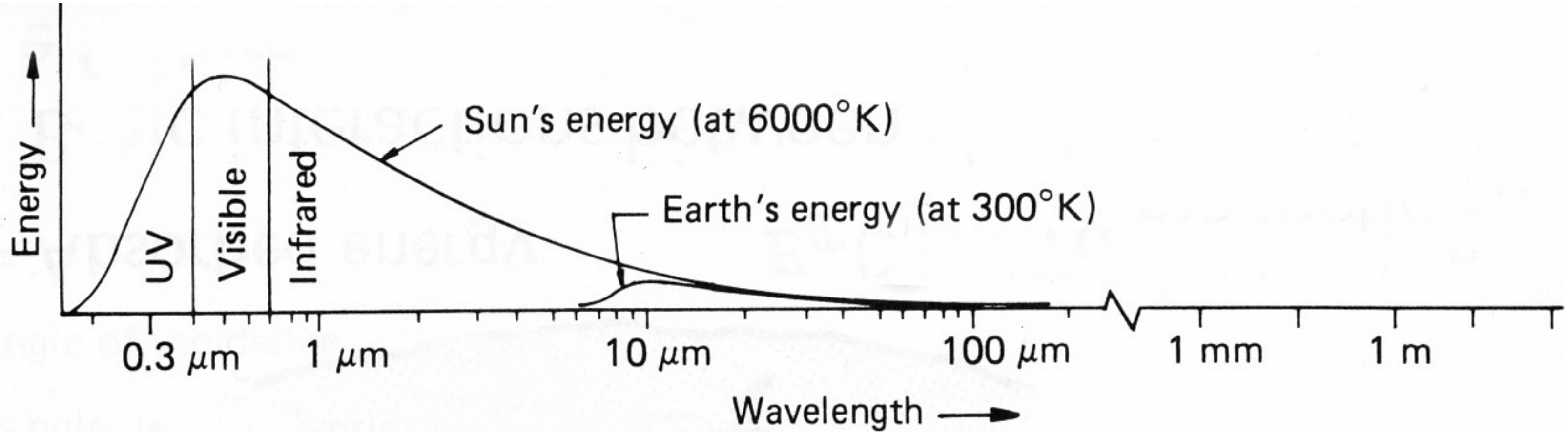
Satellite remote sensing of the Earth-atmosphere

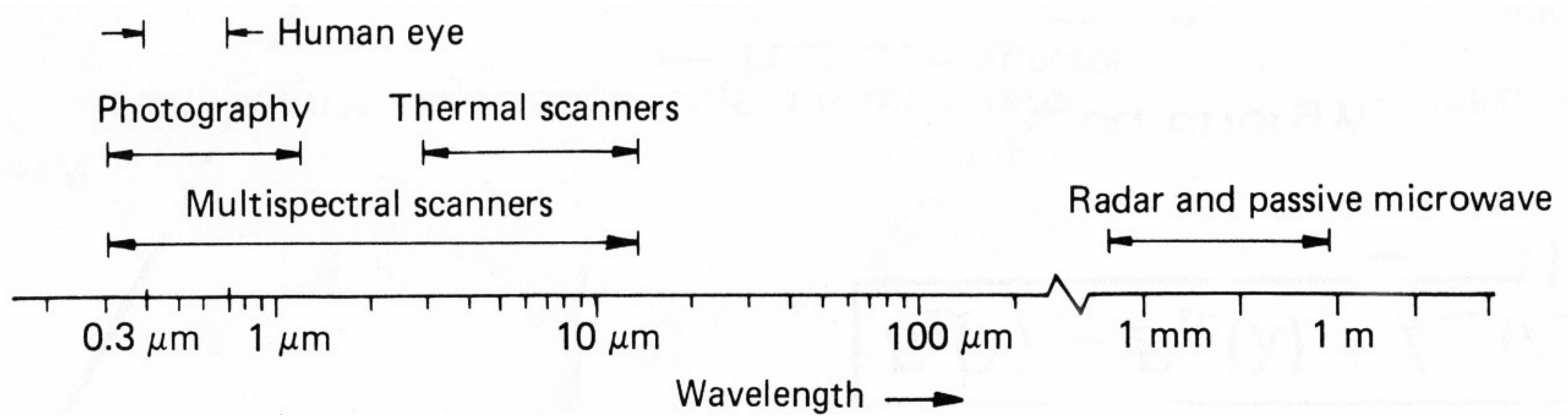


Observations depend on

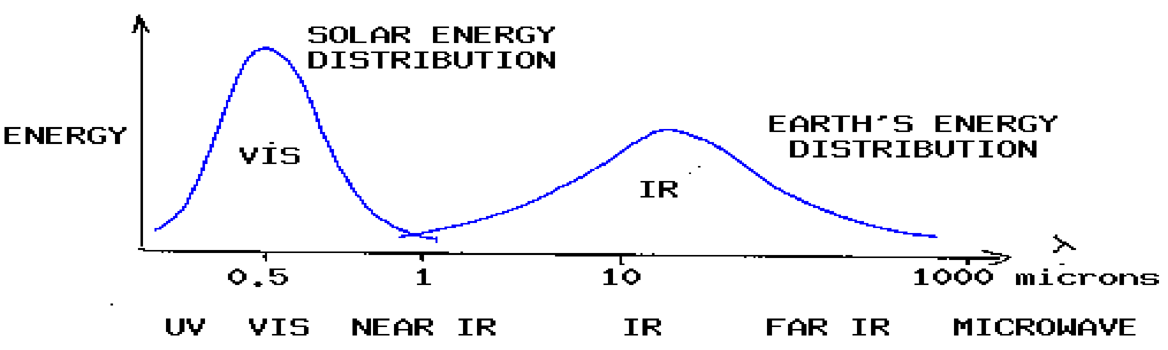
telescope characteristics (resolving power, diffraction)
detector characteristics (signal to noise)
communications bandwidth (bit depth)
spectral intervals (window, absorption band)
time of day (daylight visible)
atmospheric state (T, Q, clouds)
earth surface (Ts, vegetation cover)

Spectral Characteristics of Energy Sources and Sensing Systems





Solar (visible) and Earth emitted (infrared) energy

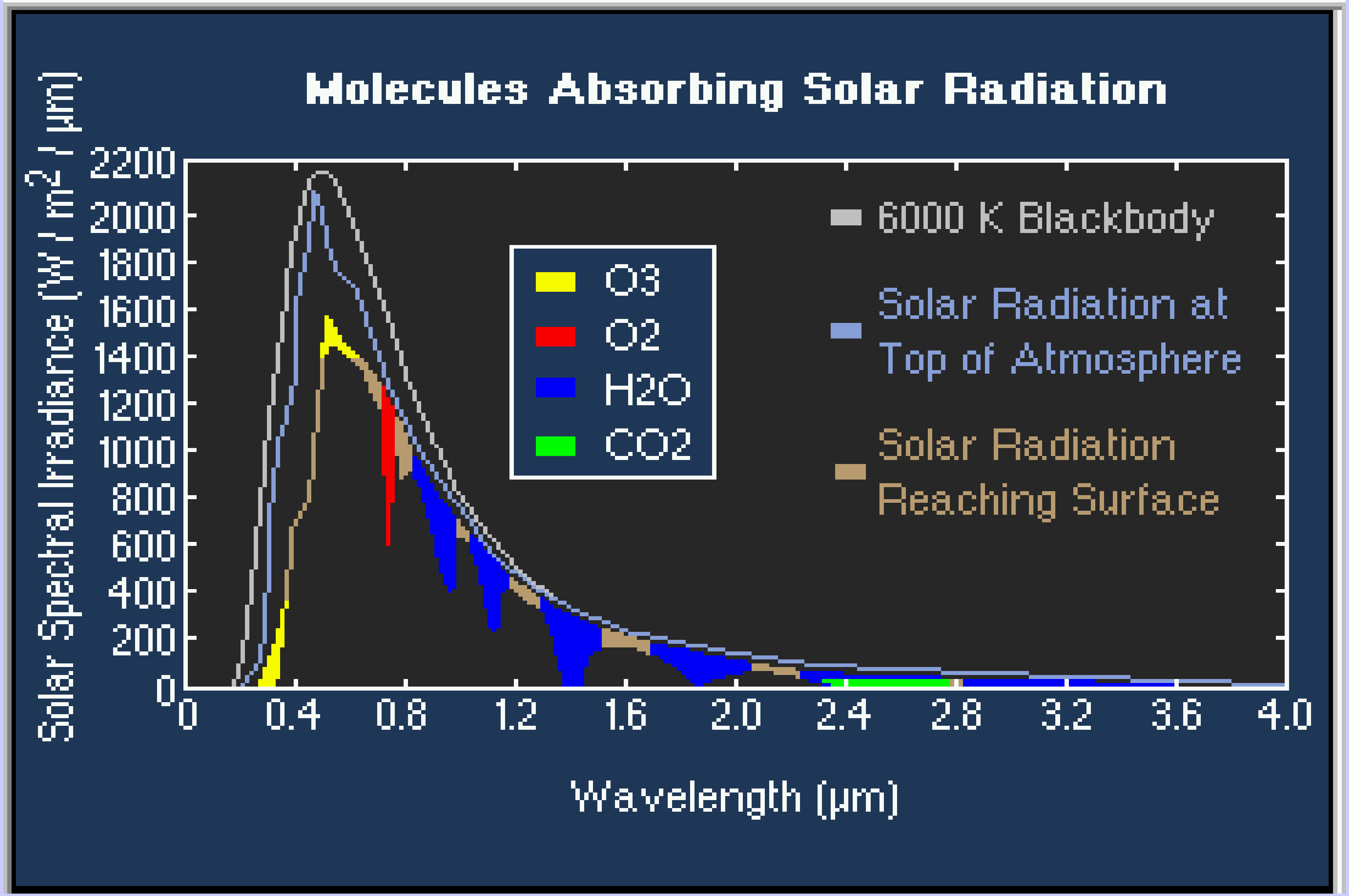


Incoming solar radiation (mostly visible) drives the earth-atmosphere (which emits infrared).

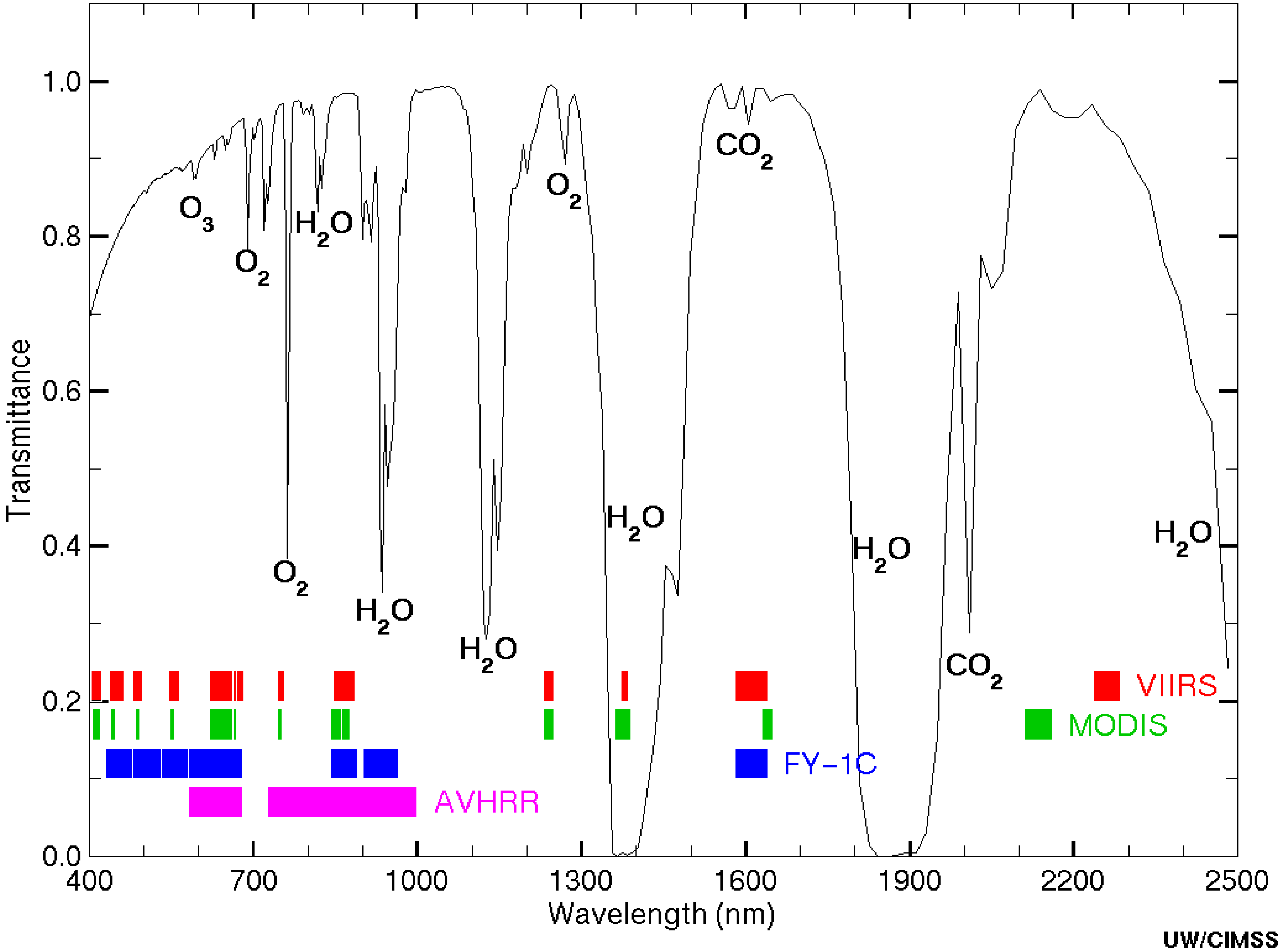
Over the annual cycle, the incoming solar energy that makes it to the earth surface (about 50 %) is balanced by the outgoing thermal infrared energy emitted through the atmosphere.

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

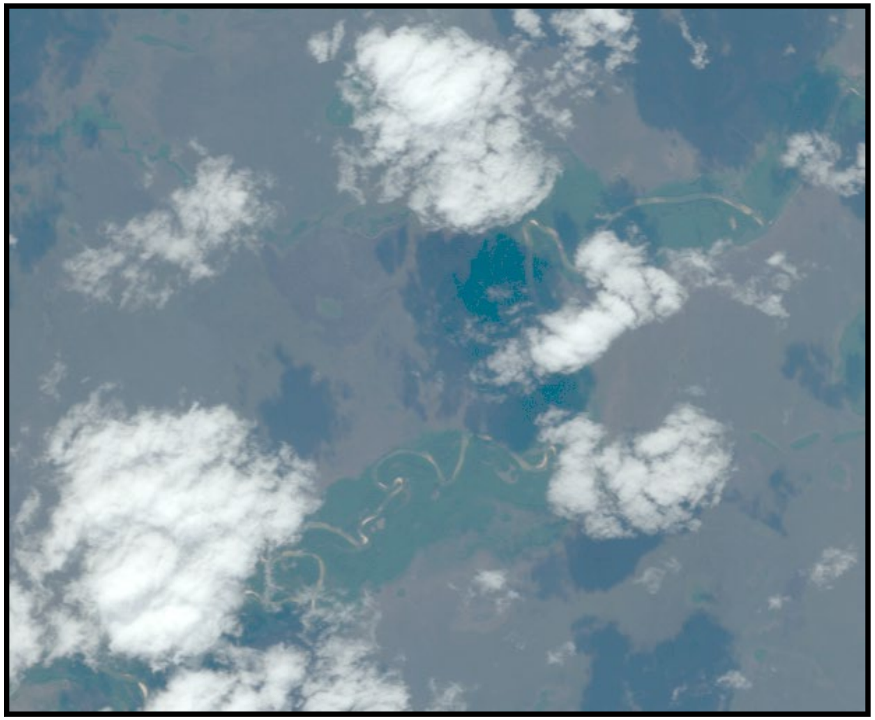


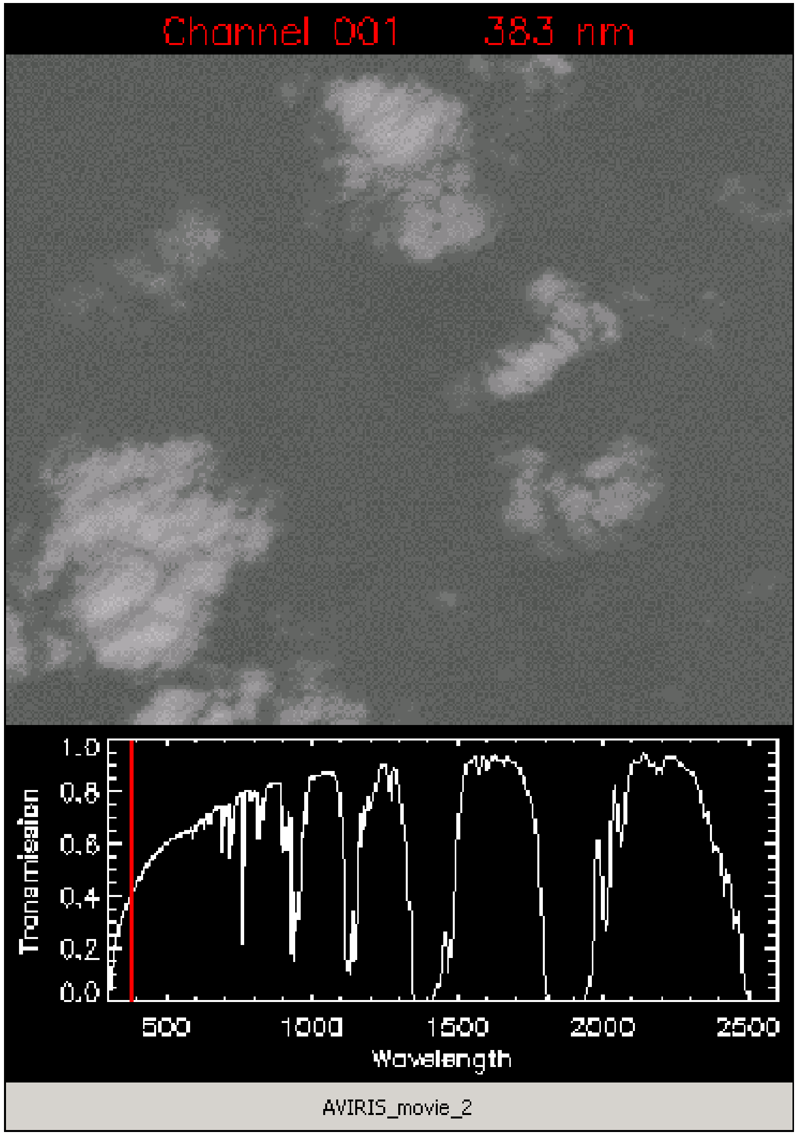
VIIRS, MODIS, FY-1C, AVHRR



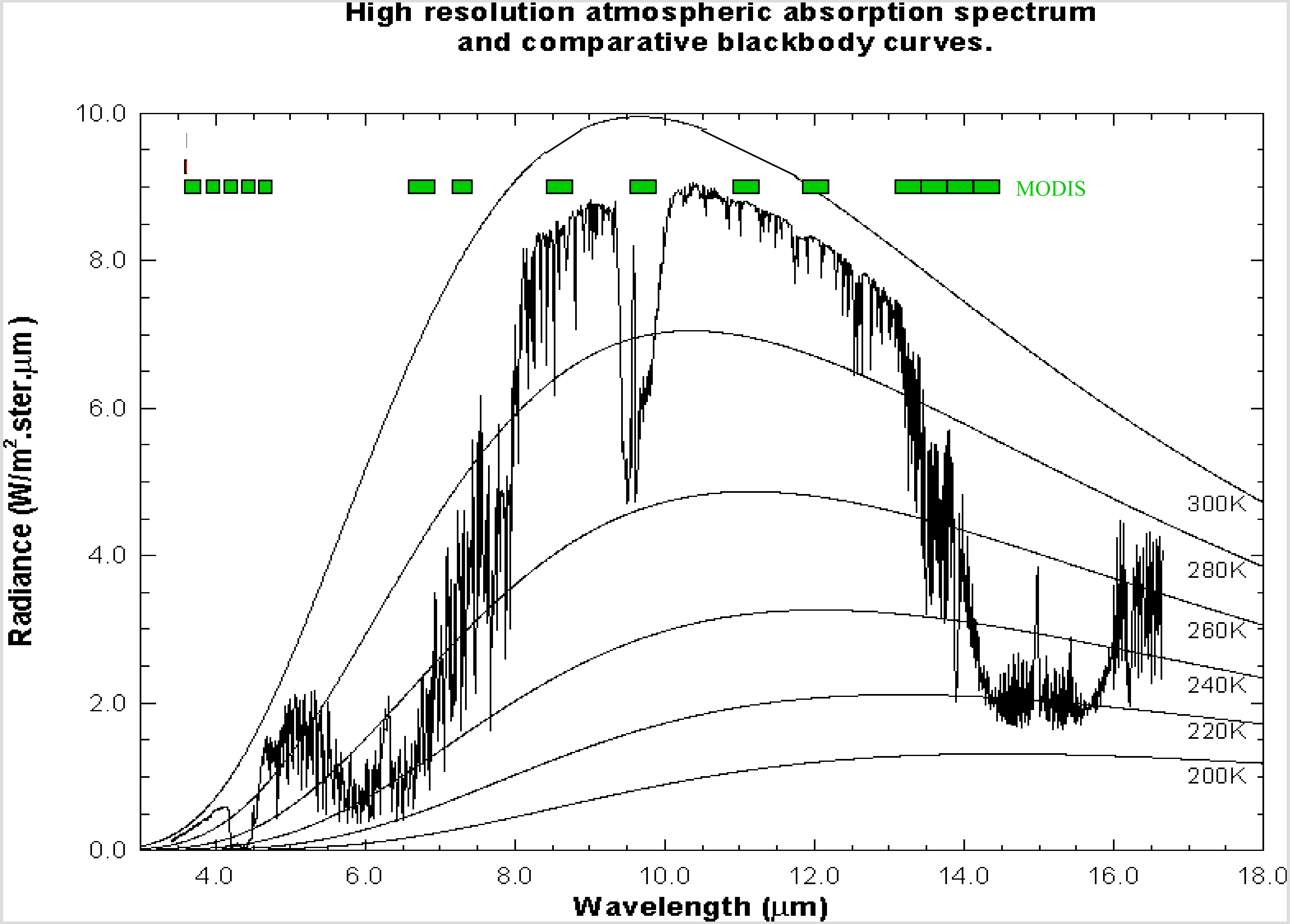
AVIRIS Movie #2

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

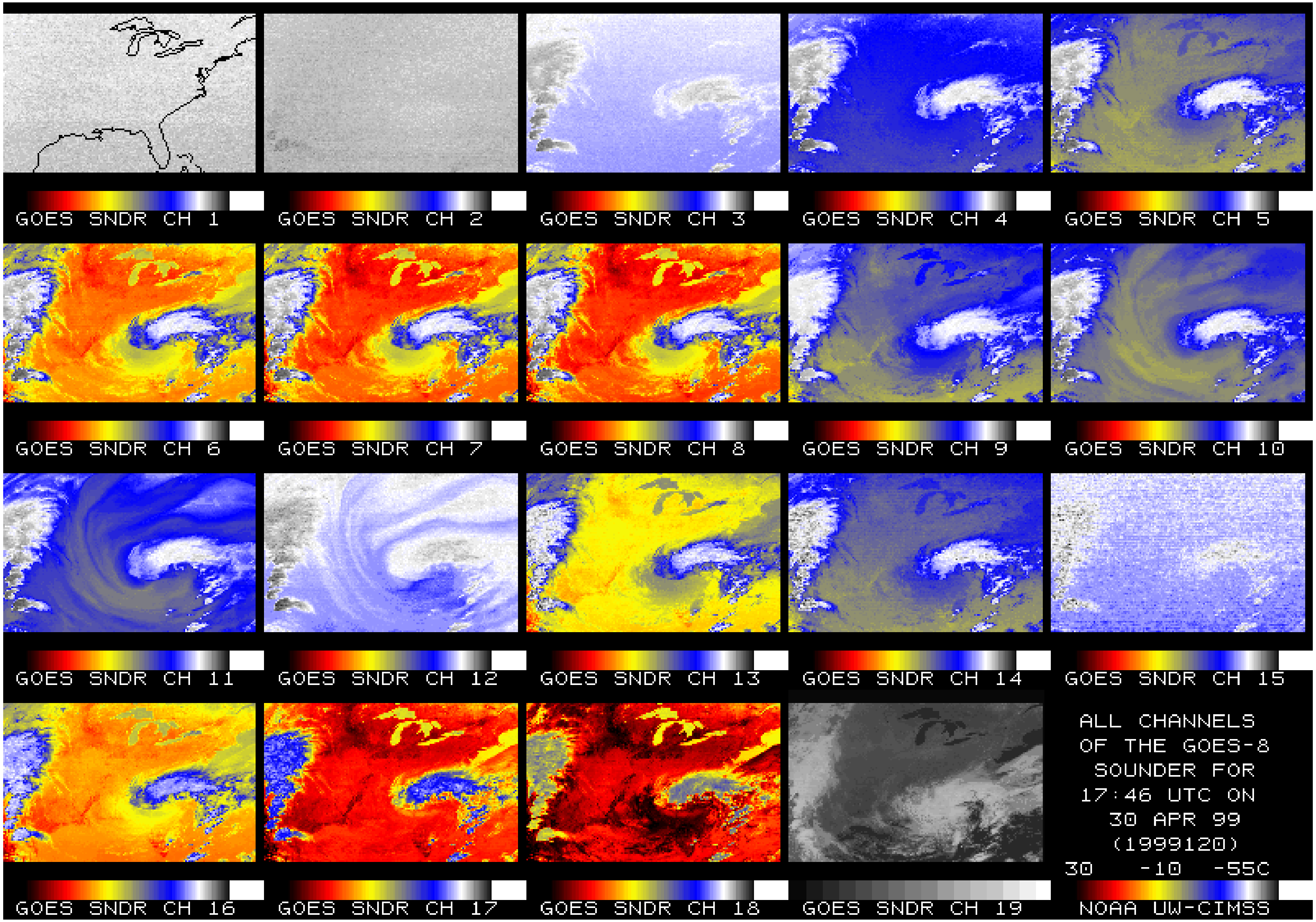




MODIS IR Spectral Bands

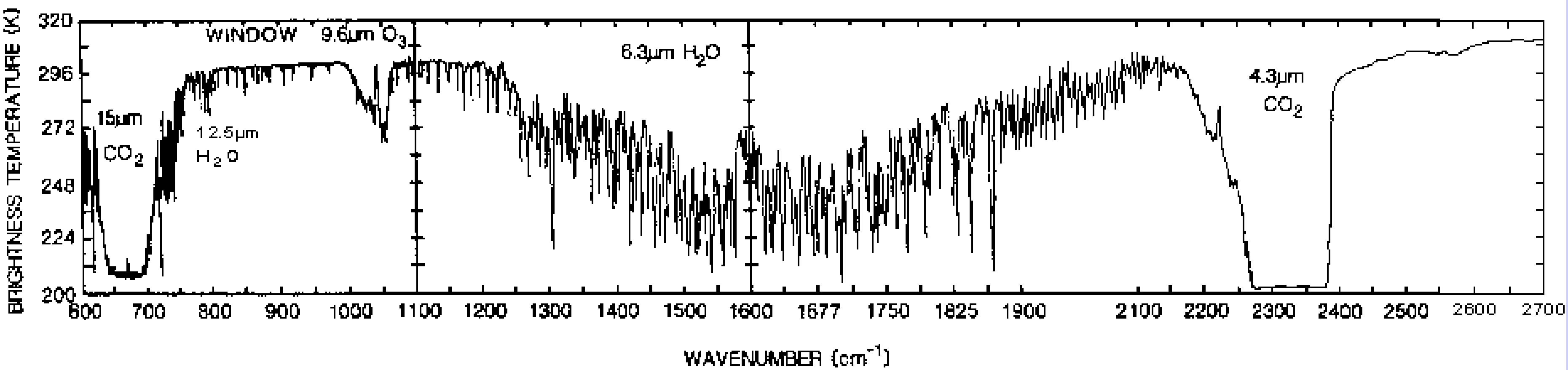


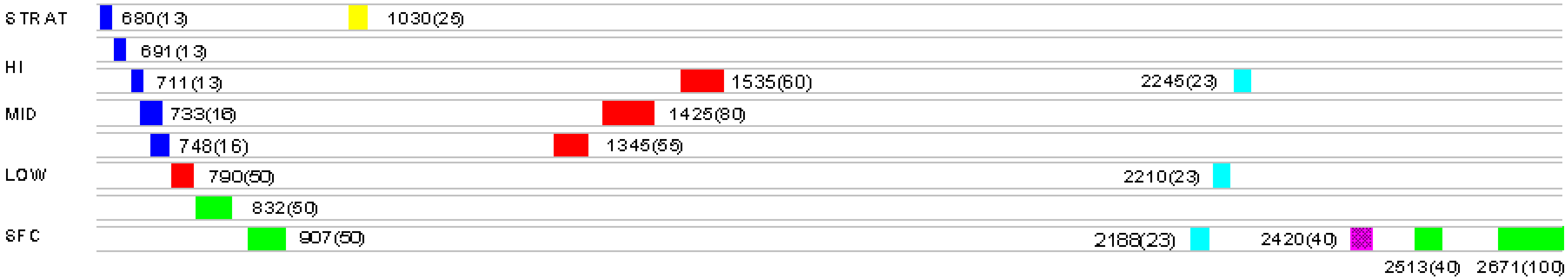
Current GOES Sounder Spectral Bands: 14.7 to 3.7 um and vis



GOES Sounder Spectral Bands: 14.7 to 3.7 um and vis

EARTH EMITTED SPECTRA

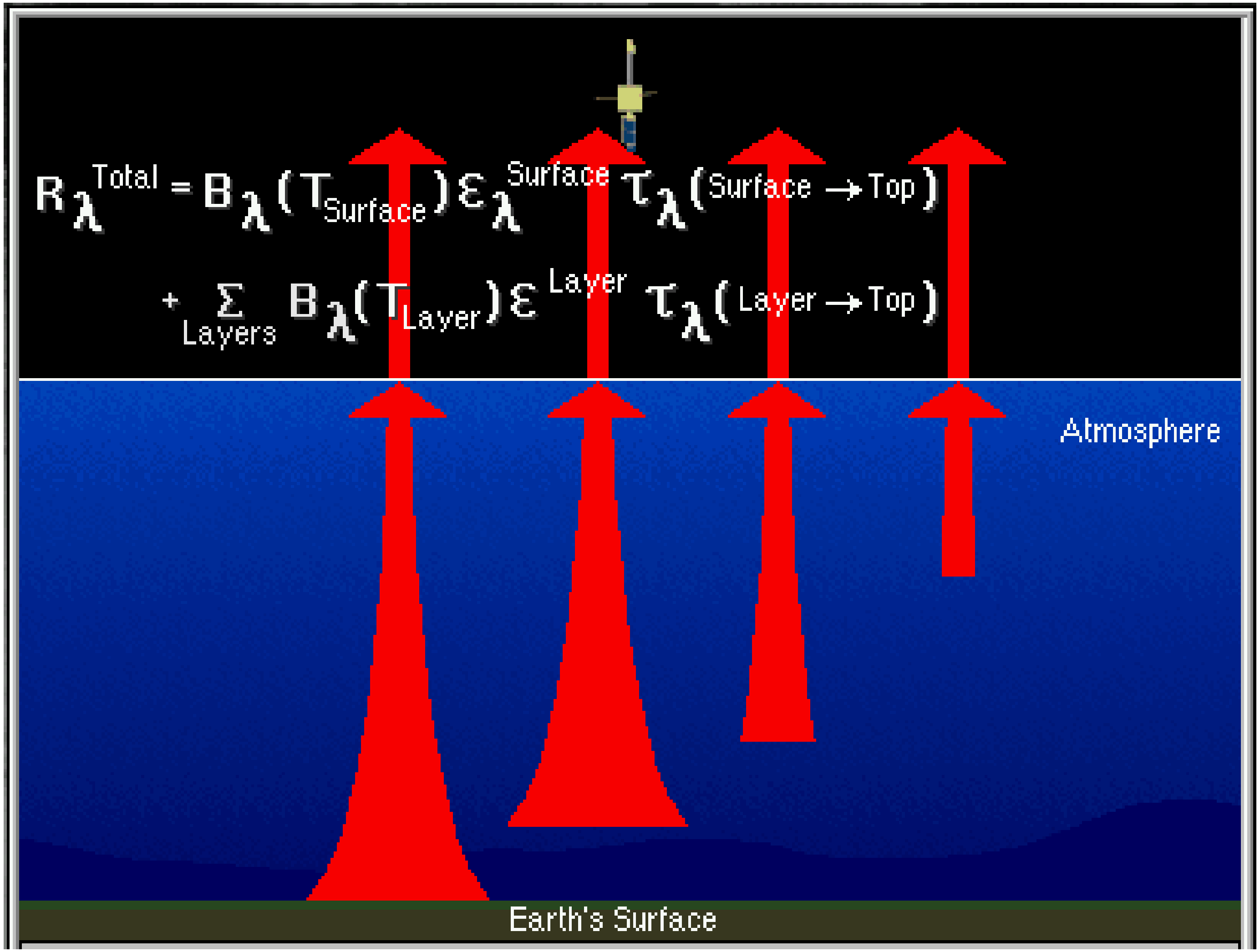




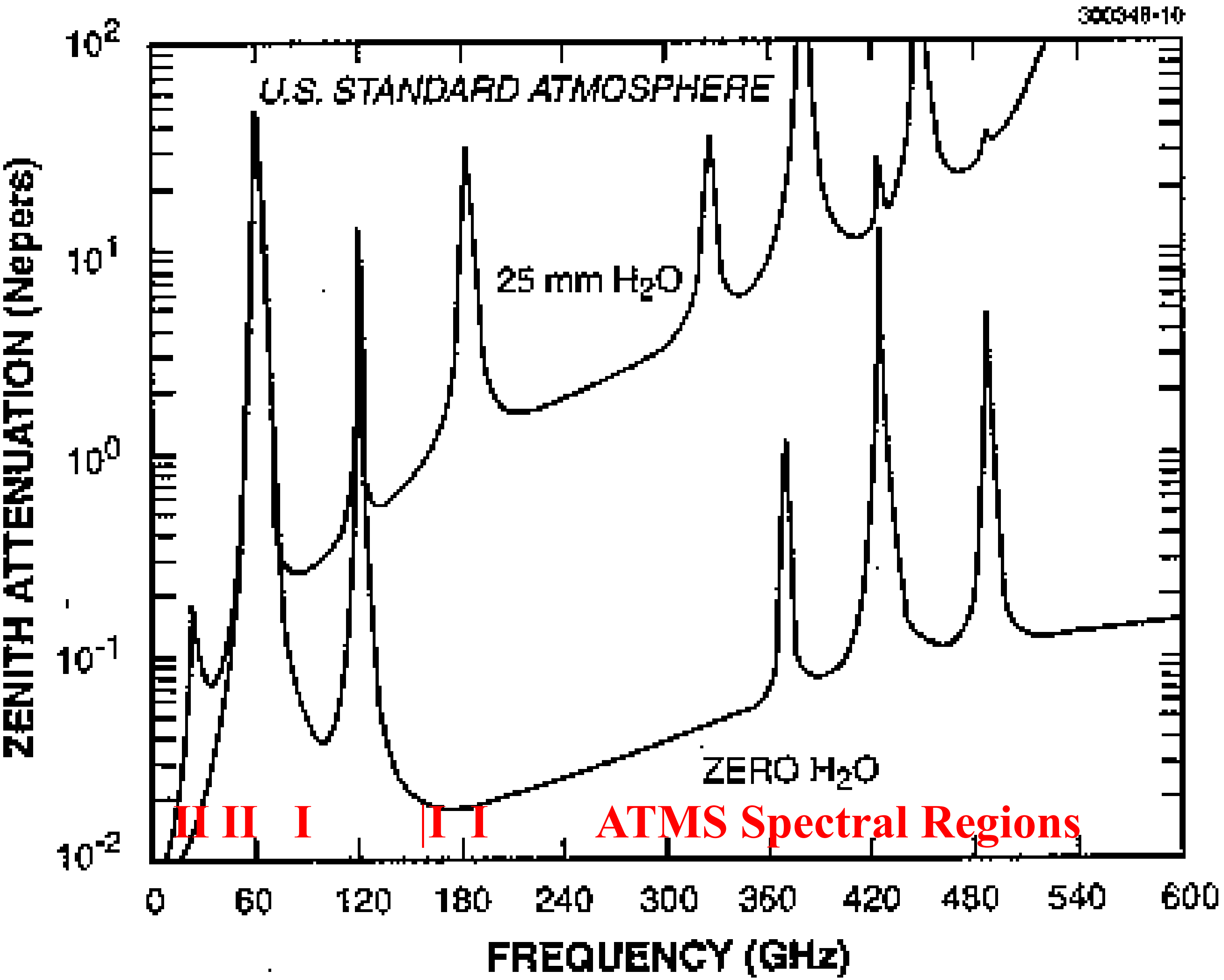
GOES-I SOUNDER SPECTRAL BANDS

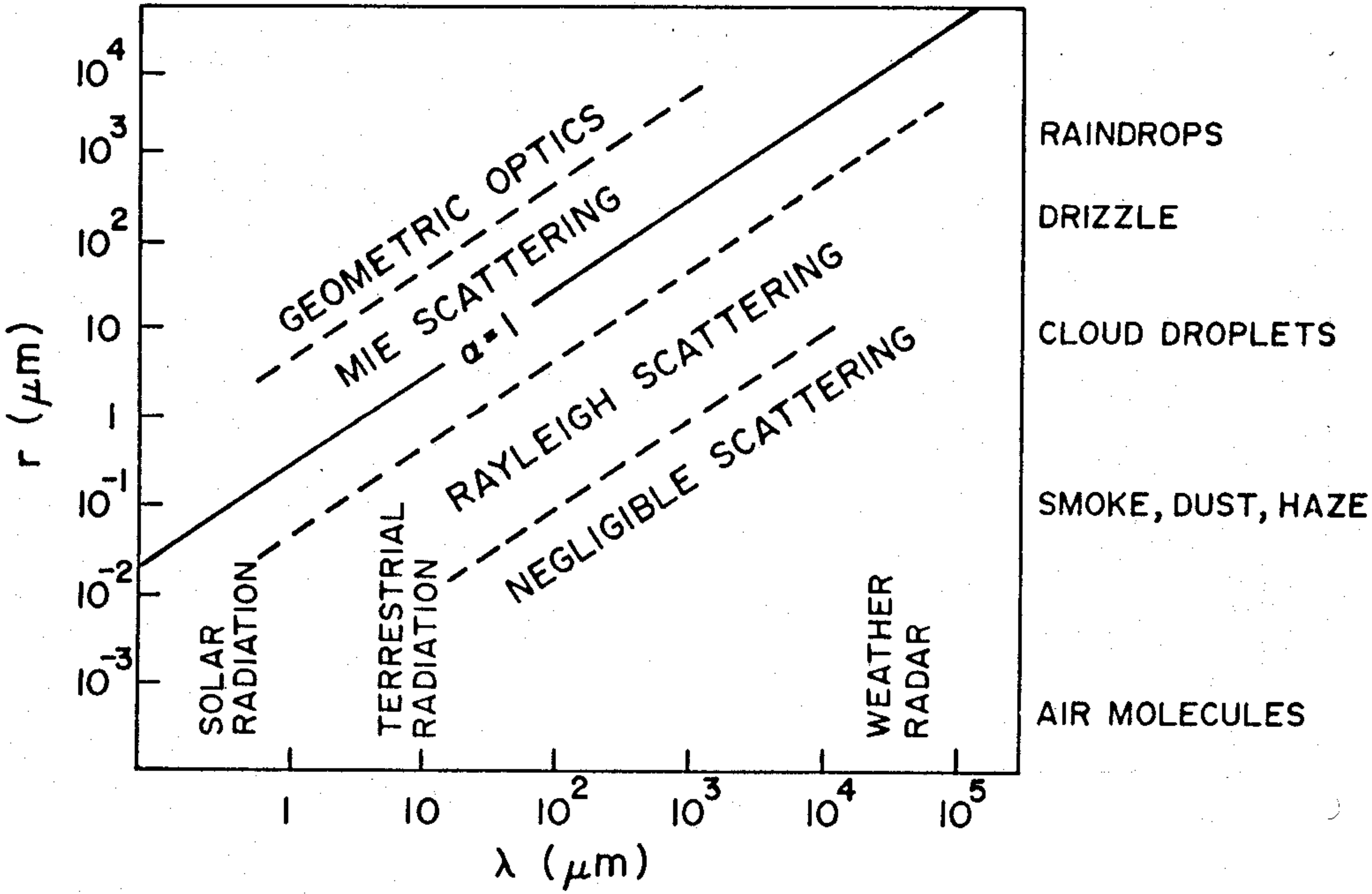
COOPERATIVE INSTITUTE FOR METEOROLOGICAL SATELLITE STUDIES

Radiative Transfer through the Atmosphere



$$R_\lambda^{\mathrm{Total}} = B_\lambda(T_{\mathrm{Surface}})\,\varepsilon_\lambda^{\mathrm{Surface}}\,\tau_\lambda(\mathrm{Surface} \rightarrow \mathrm{Top}) + \sum_{\mathrm{Layers}} B_\lambda(T_{\mathrm{Layer}})\,\varepsilon_\lambda^{\mathrm{Layer}}\,\tau_\lambda(\mathrm{Layer} \rightarrow \mathrm{Top})$$


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


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

Radiation is governed by Planck's Law

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} -1] \}$$

In microwave region $c_2/\lambda T << 1$ so that

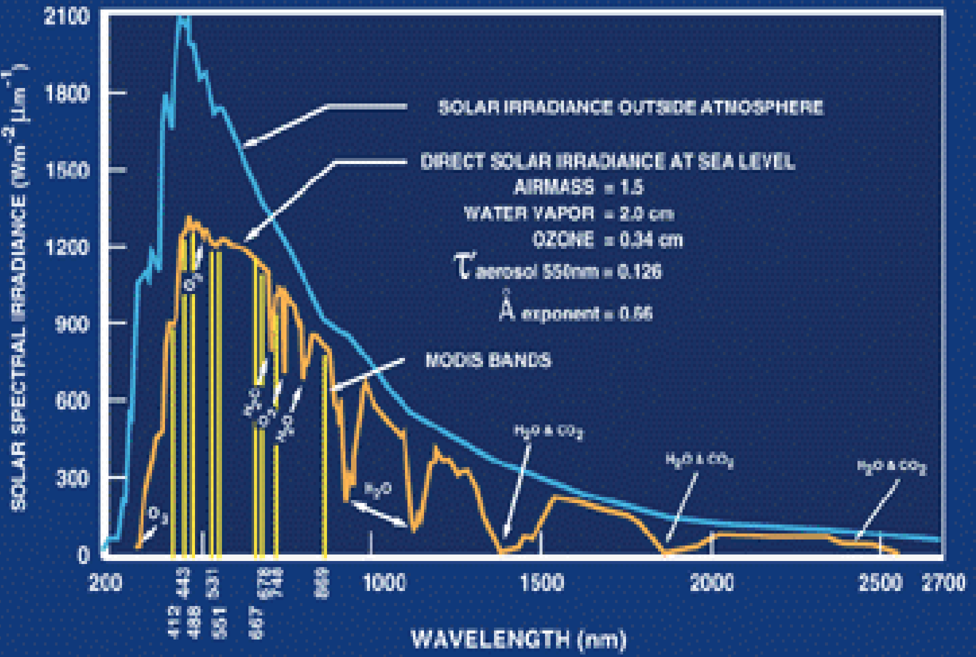
$$e^{c_2/\lambda T} = 1 + c_2/\lambda T + \text{second order}$$

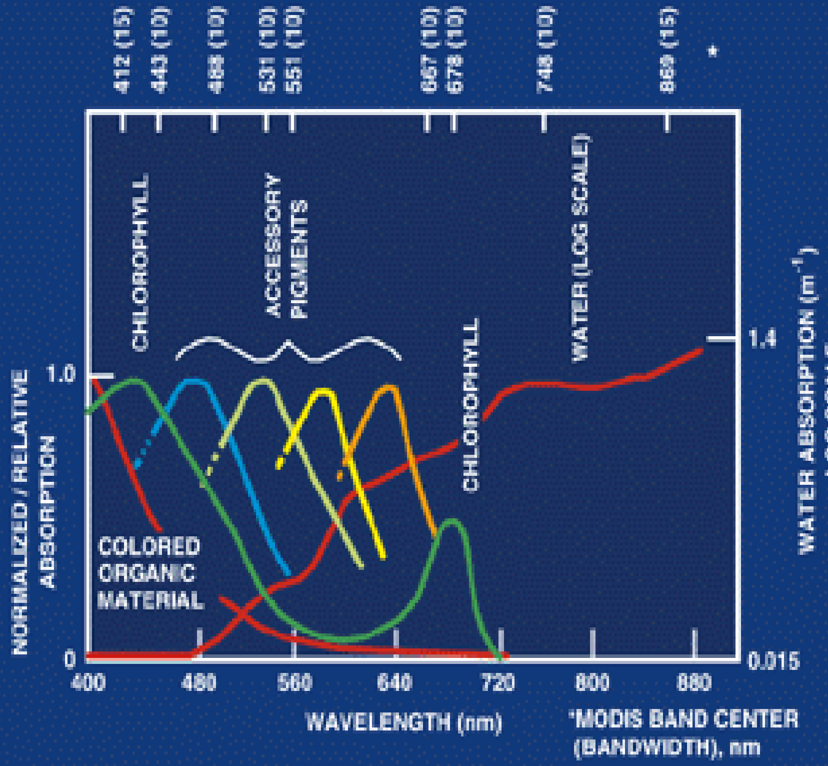
And classical Rayleigh Jeans radiation equation emerges

$$B_\lambda(T) \approx [c_1 / c_2] [T / \lambda^4]$$

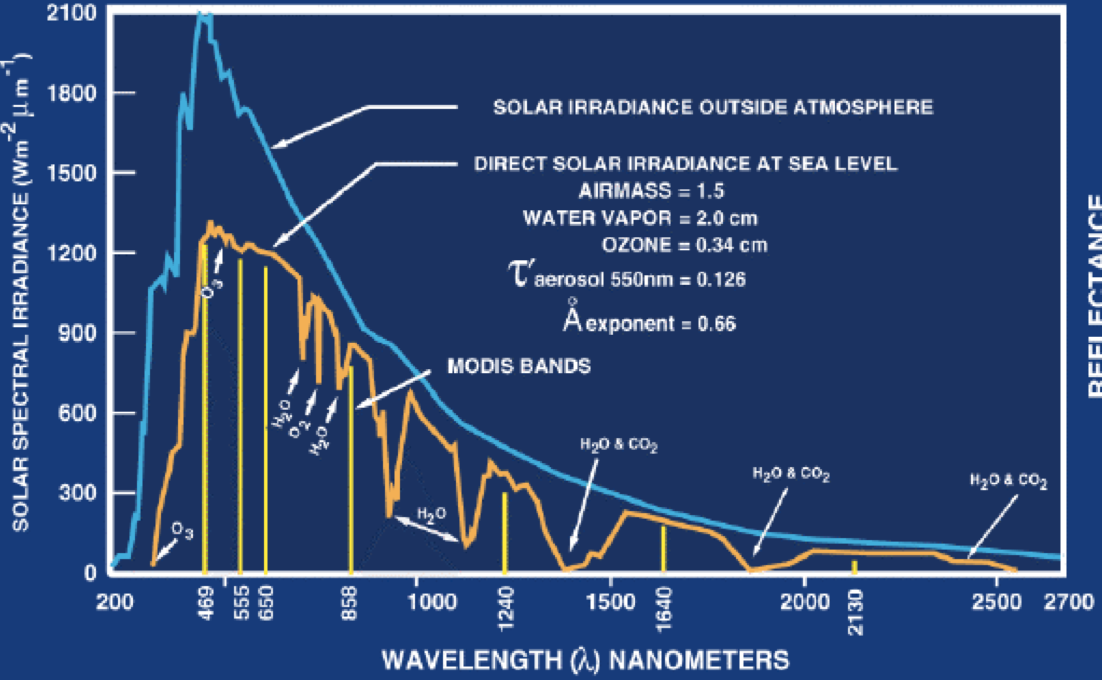
Radiance is linear function of brightness temperature.

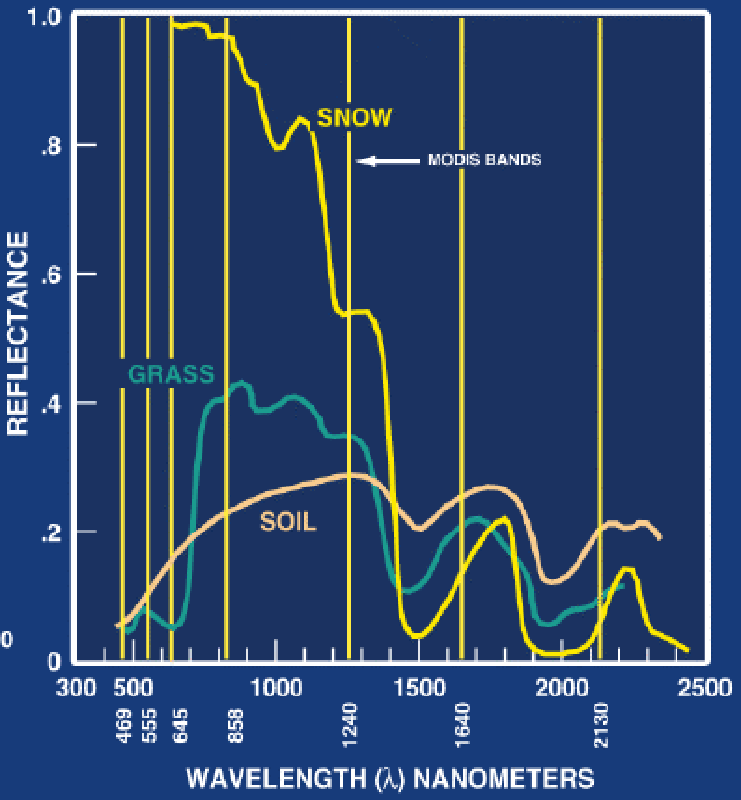
OCEAN-SOLAR RADIATION



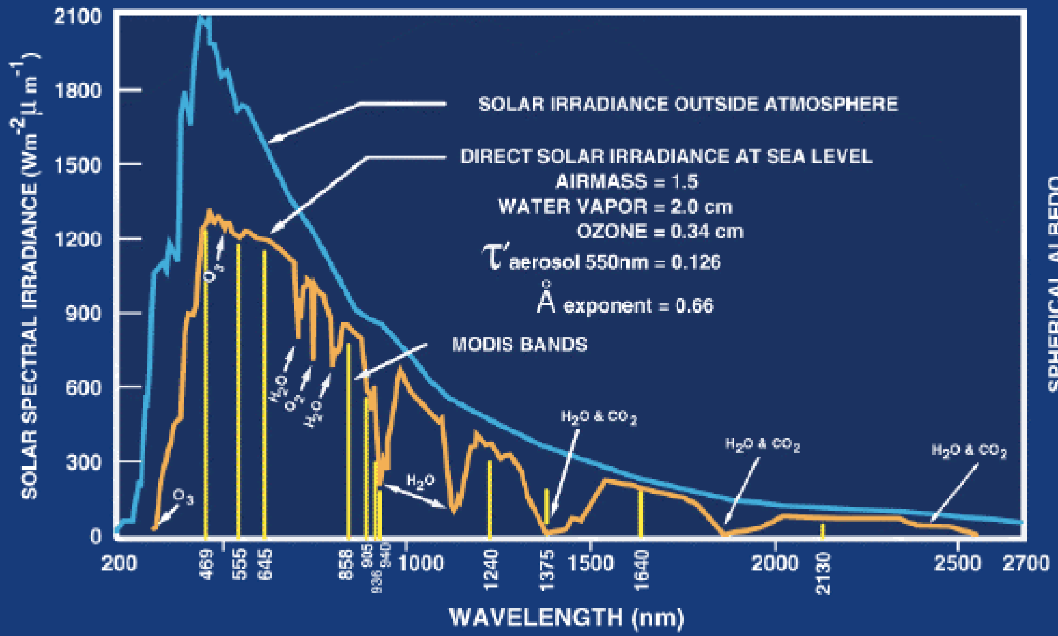


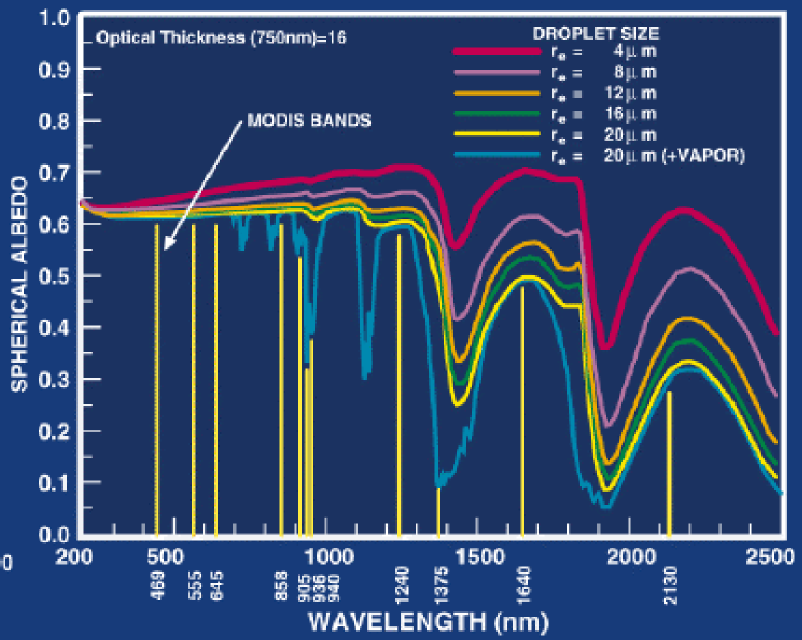
LAND-SOLAR RADIATION



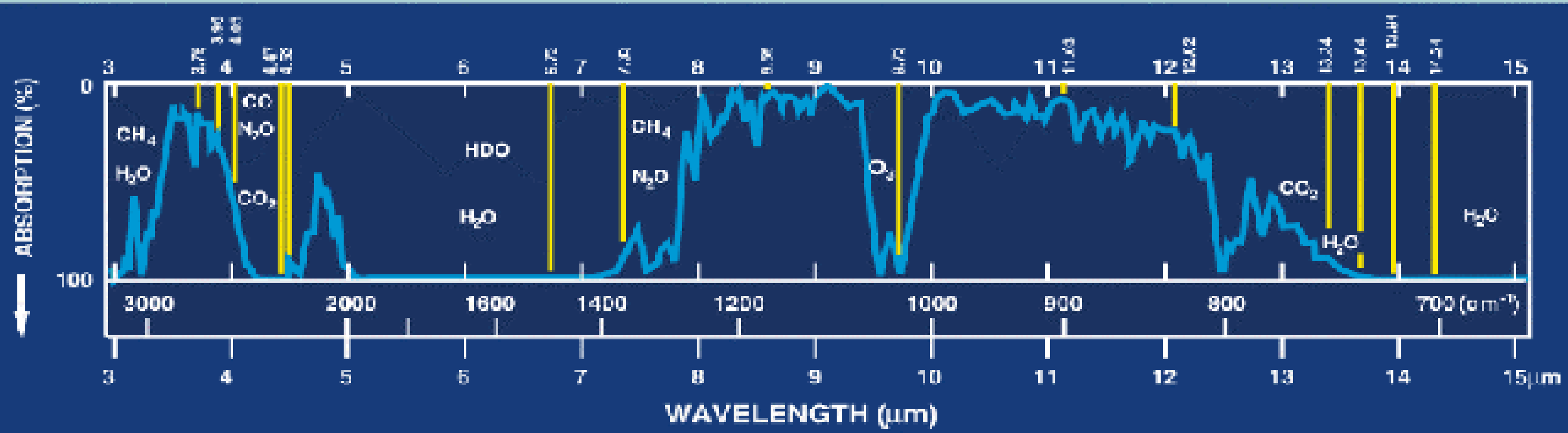


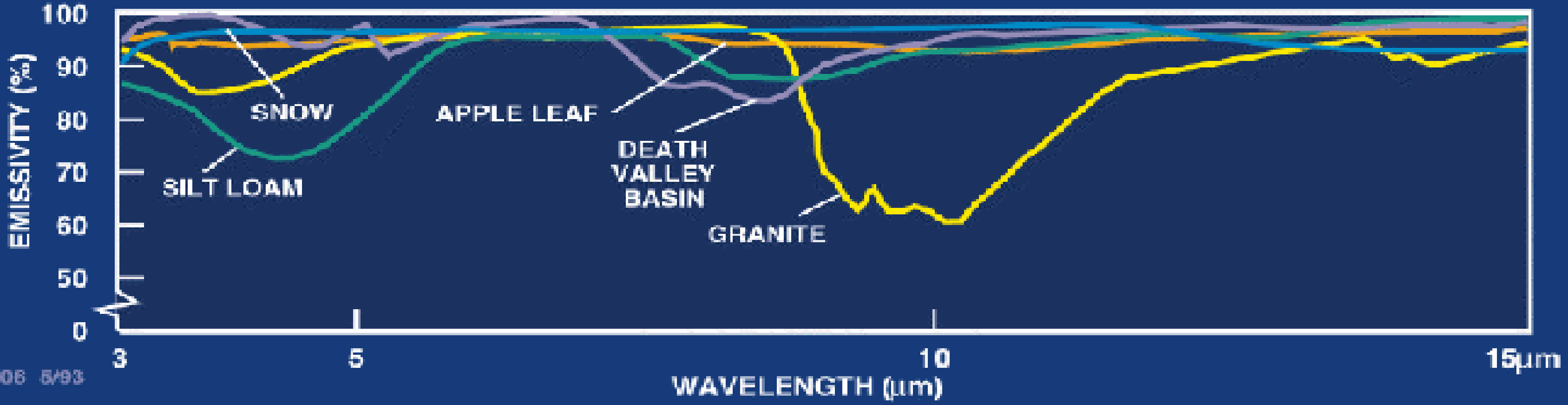
ATMOSPHERE-SOLAR RADIATION





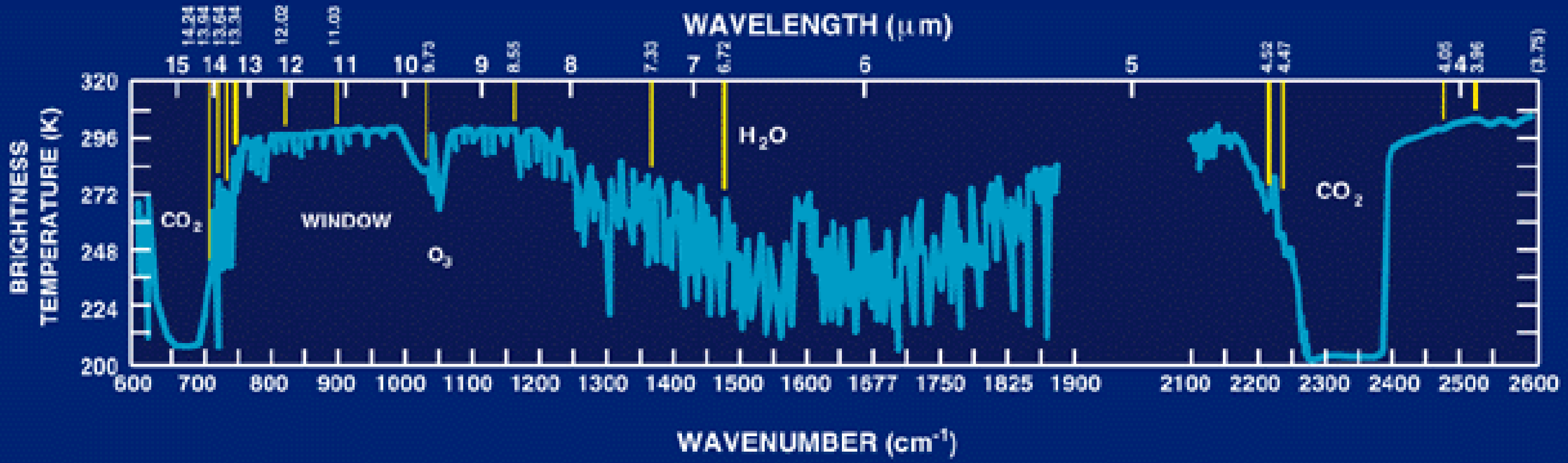
LAND - THERMAL RADIATION

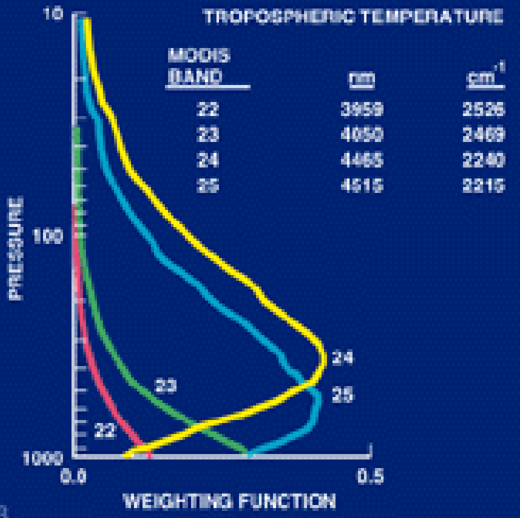




C351.006 5/93

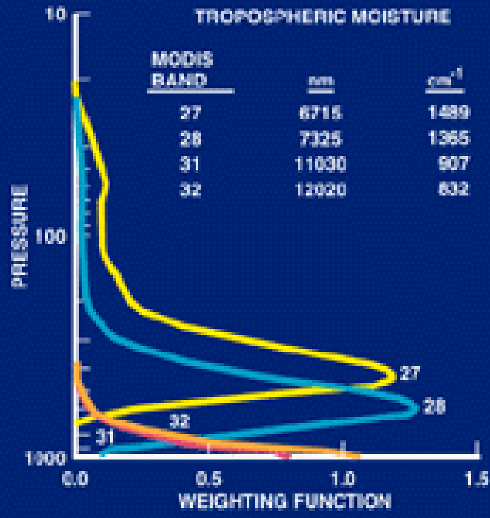
ATMOSPHERE - THERMAL RADIATION





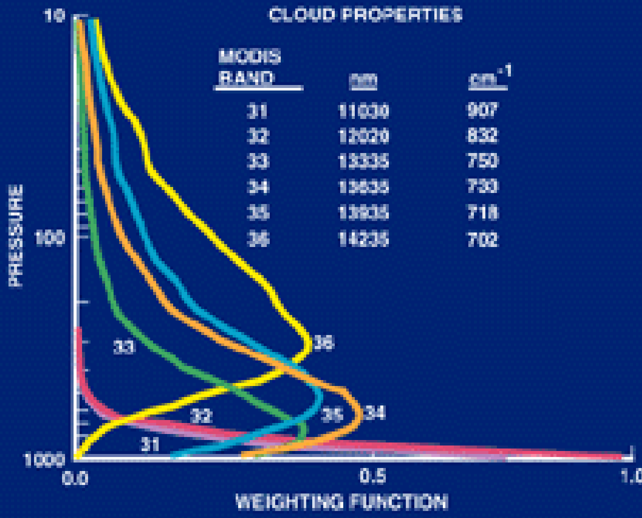
TROPOSPHERIC TEMPERATURE

MODIS BAND	nm	cm^{-1}
22	3959	2526
23	4050	2469
24	4465	2240
25	4515	2215



TROPOSPHERIC MOISTURE

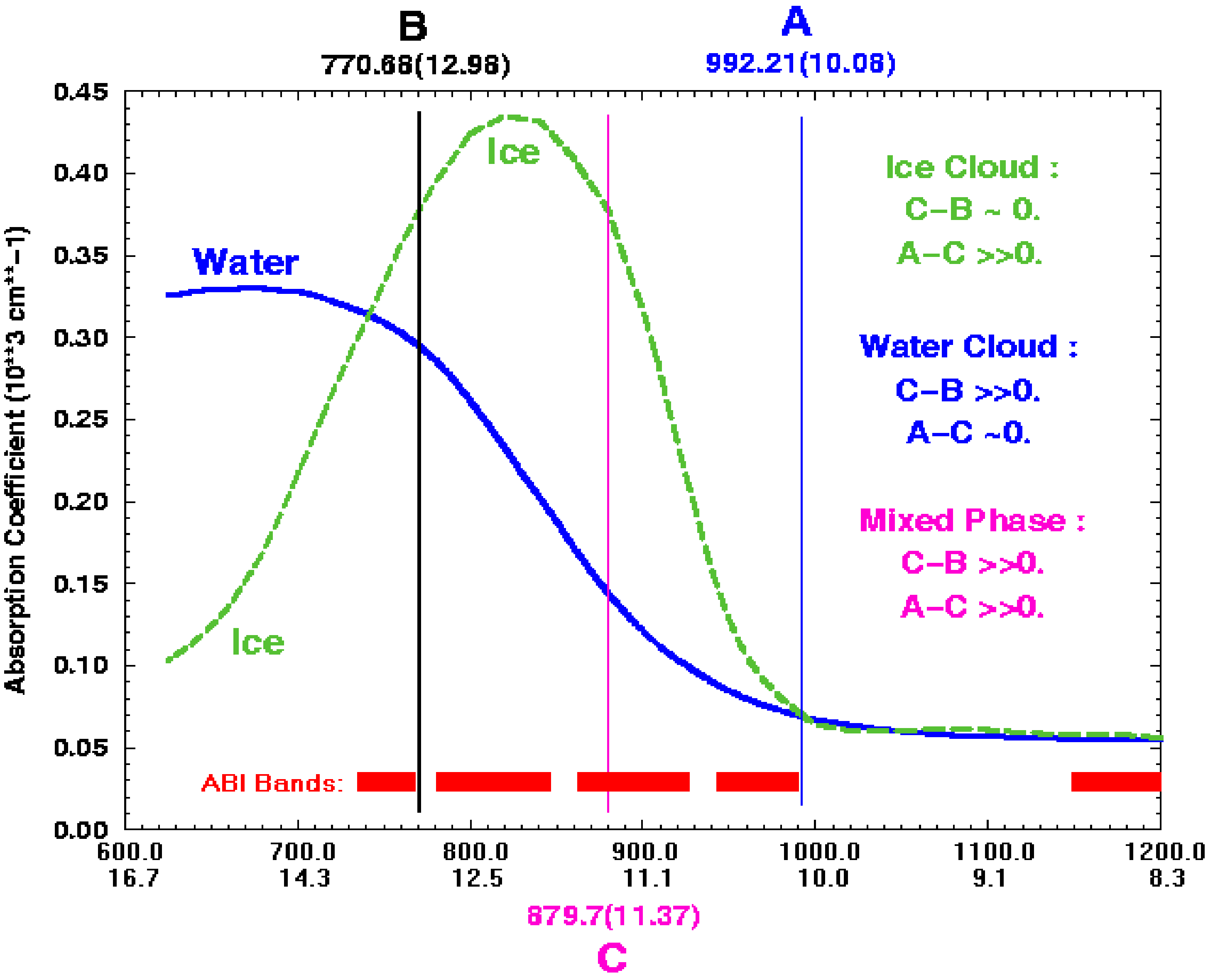
MODIS BAND	nm	cm^{-1}
27	6715	1489
28	7325	1365
31	11030	907
32	12020	832



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

Multispectral data reveals improved information about ice / water clouds

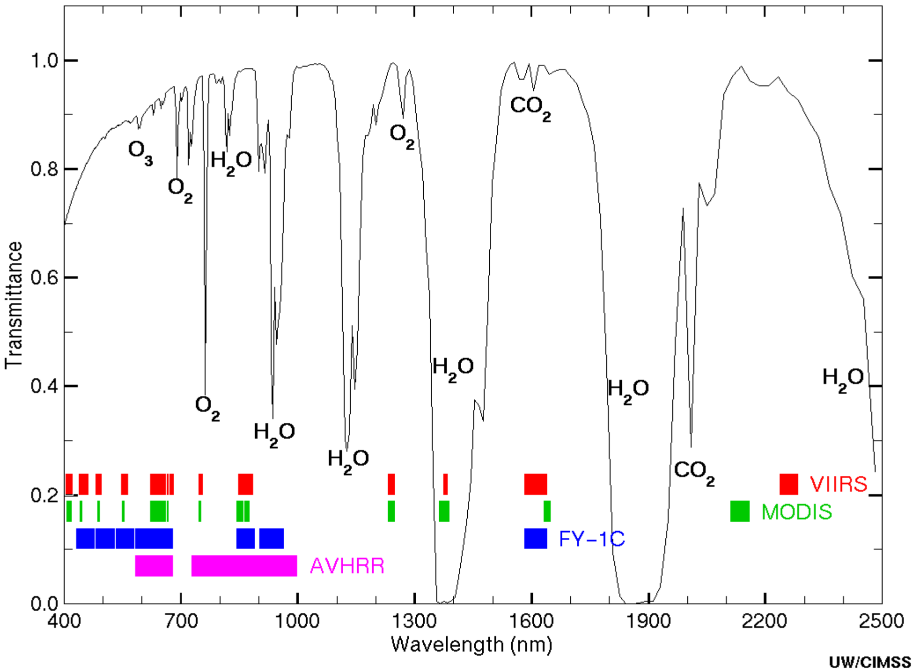


Ice Cloud :
C–B ~ 0.
A–C >>0.

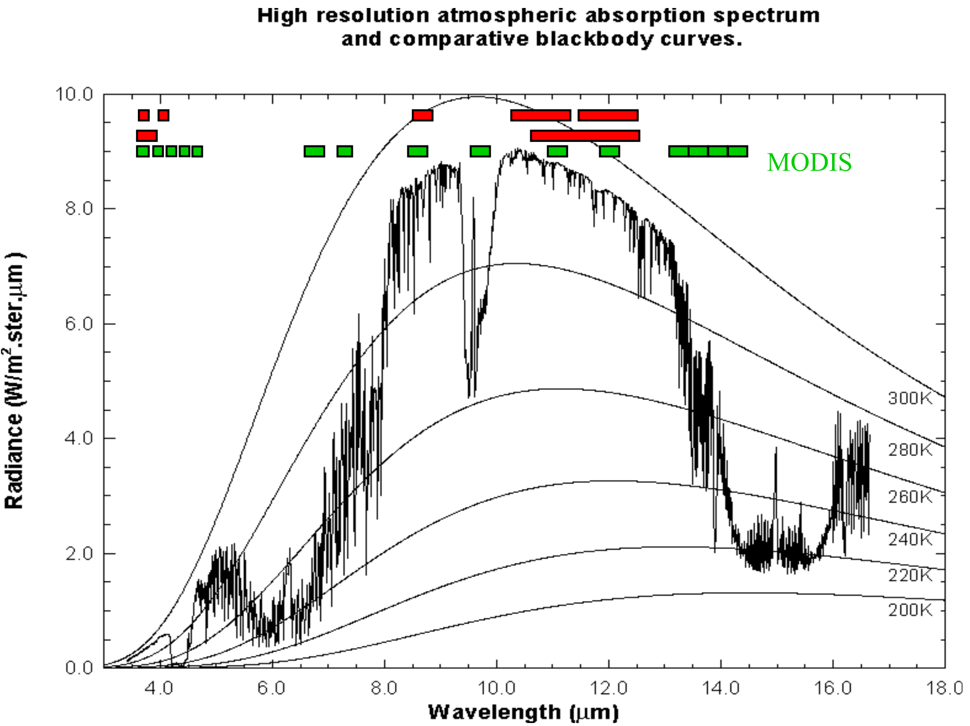
Water Cloud :
C–B >>0.
A–C ~0.

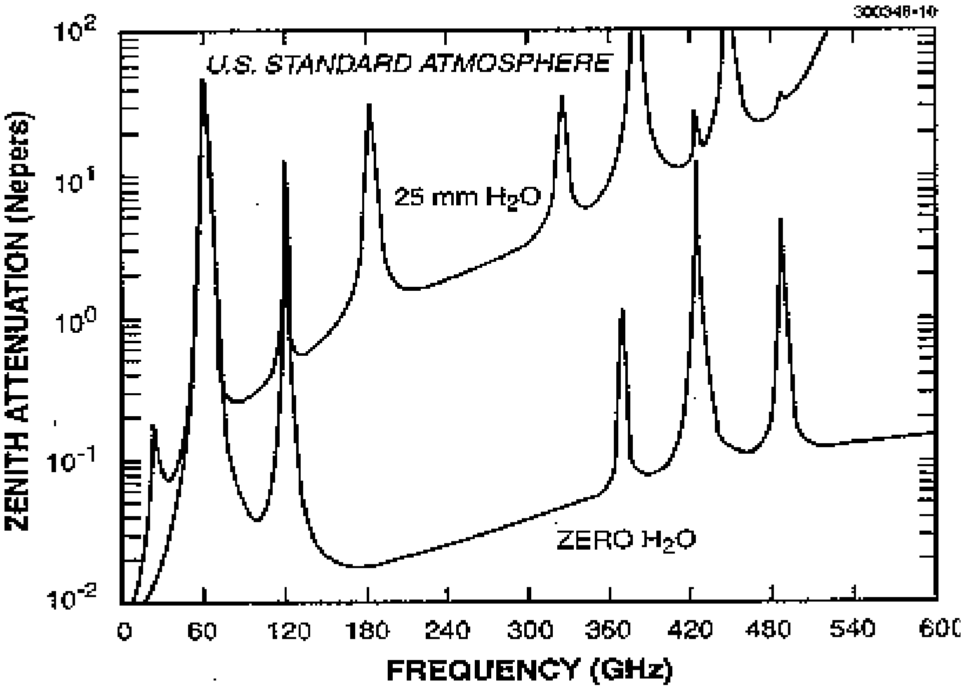
Mixed Phase :
C–B >>0.
A–C >>0.

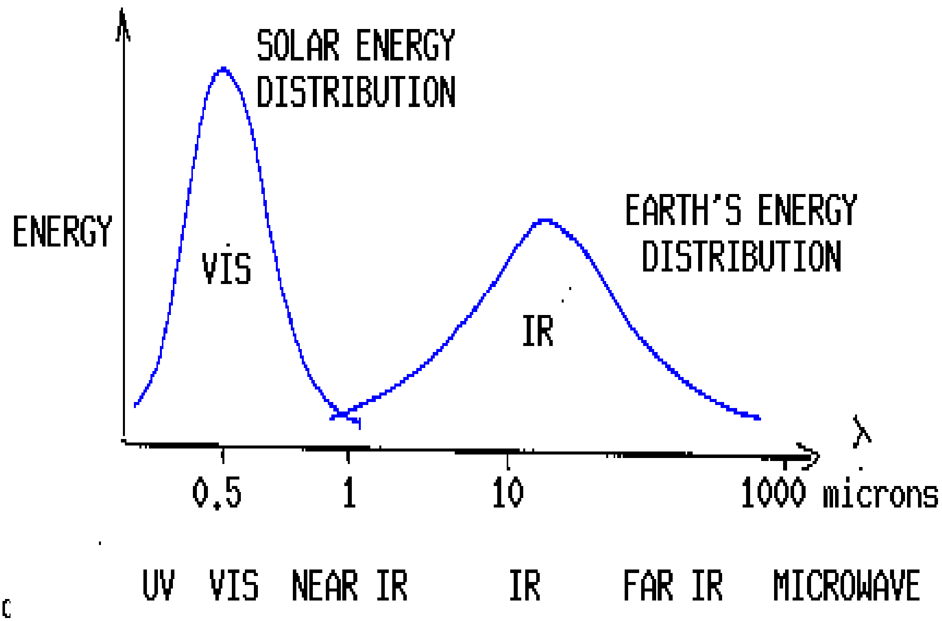
SSEC/CIMSS

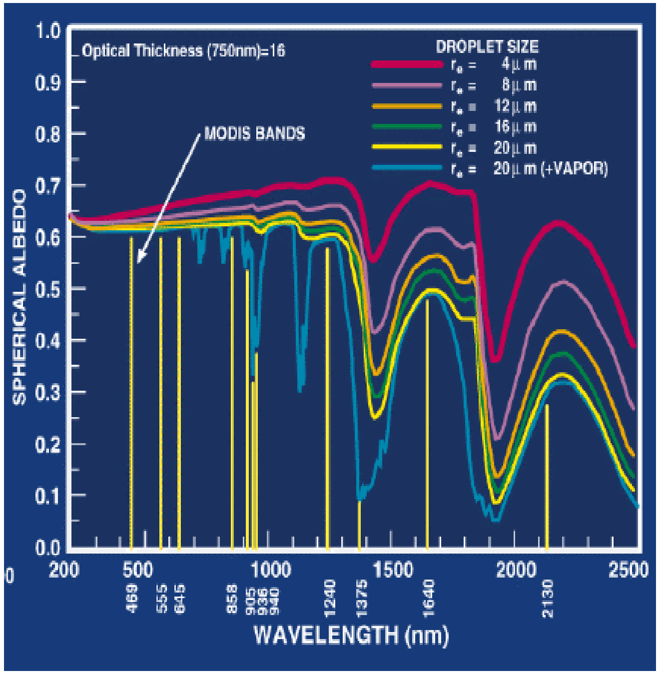

Transmittance
1.0
0.8
0.6
0.4
0.2
0.0
O_3
O_2
H_2O
O_2
H_2O
H_2O
O_2
H_2O
CO_2
H_2O
CO_2
H_2O
VIIRS
MODIS
FY-1C
AVHRR
400
700
1000
1300
1600
1900
2200
2500
Wavelength (nm)

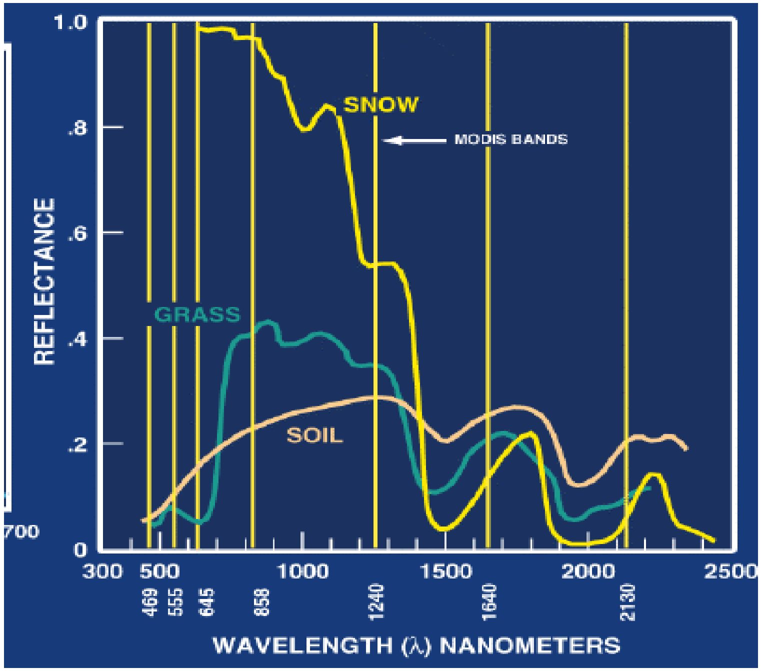
UW/CIMSS

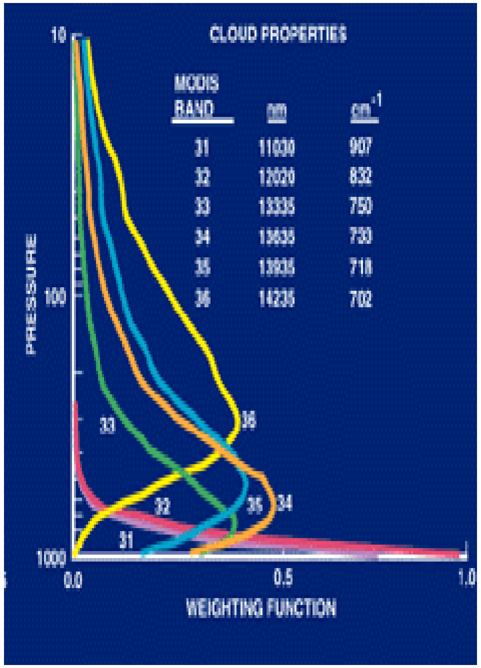

High resolution atmospheric absorption spectrum
and comparative blackbody curves.
Radiance (W/m^2.ster.μm)
10.0
8.0
6.0
4.0
2.0
0.0
MODIS
300K
280K
260K
240K
220K
200K
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Wavelength (μm)


300348-10
U.S. STANDARD ATMOSPHERE
ZENITH ATTENUATION (Nepers)
10^2
10^1
10^0
10^{-1}
10^{-2}
25 mm H_2O
ZERO H_2O
0
60
120
180
240
300
360
420
480
540
600
FREQUENCY (GHz)

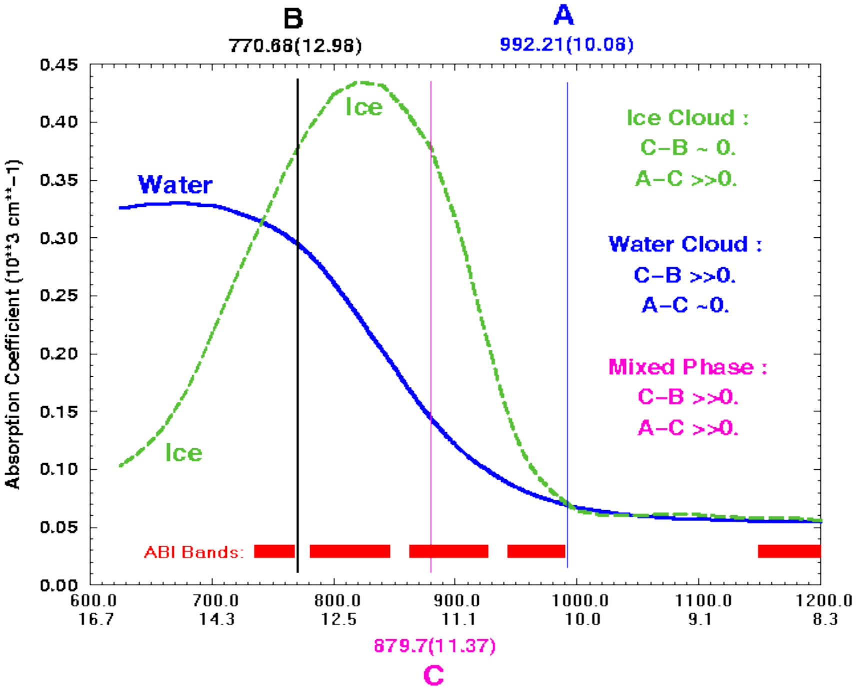

SOLAR ENERGY DISTRIBUTION
EARTH'S ENERGY DISTRIBUTION
ENERGY
VIS
IR
λ
0.5
1
10
1000 microns
UV
VIS
NEAR IR
IR
FAR IR
MICROWAVE

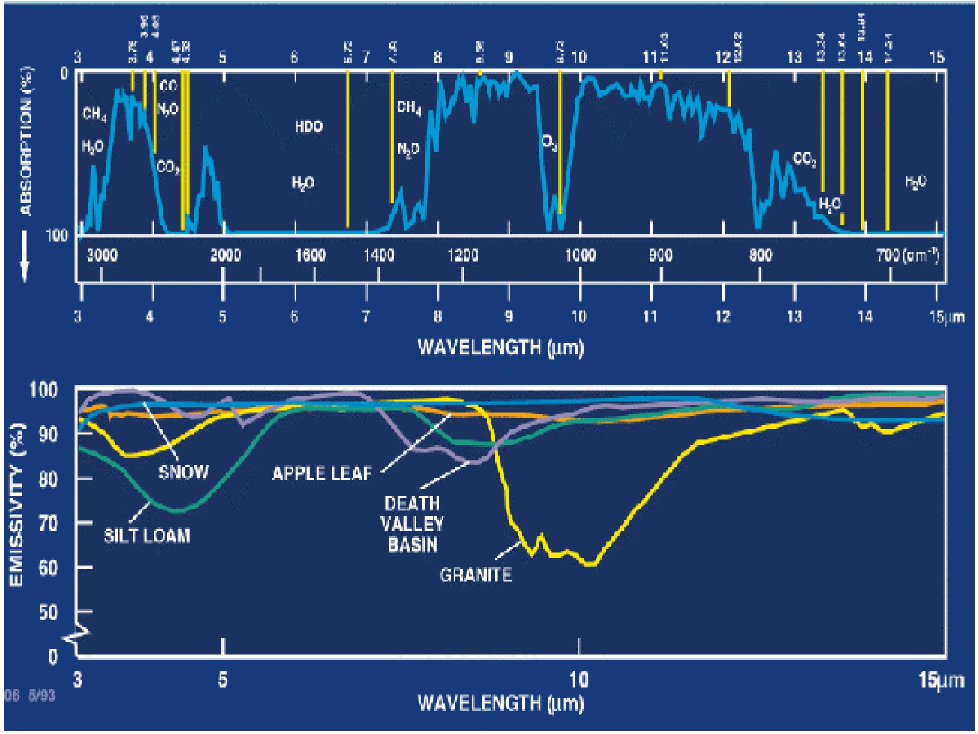


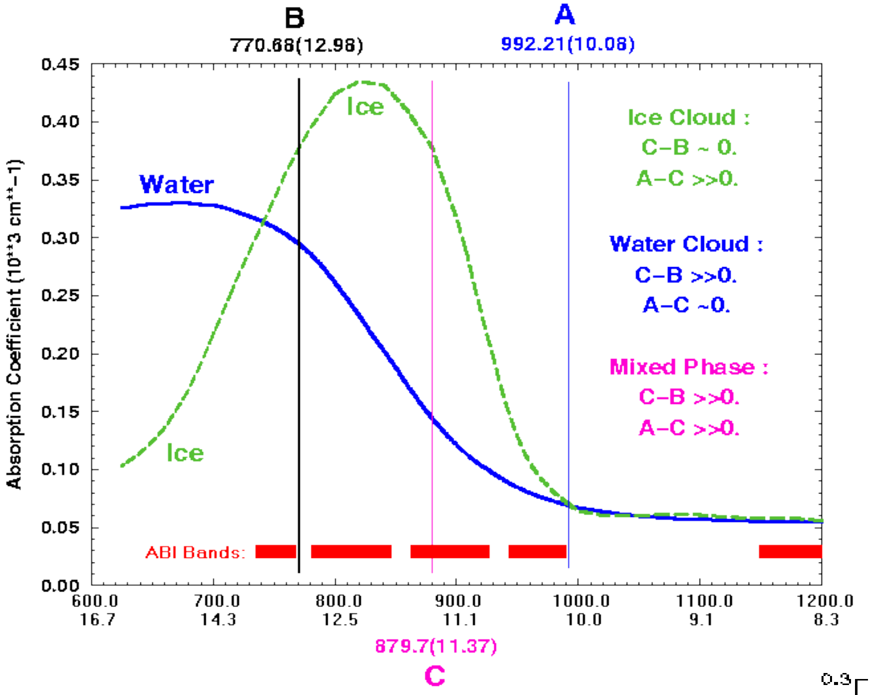


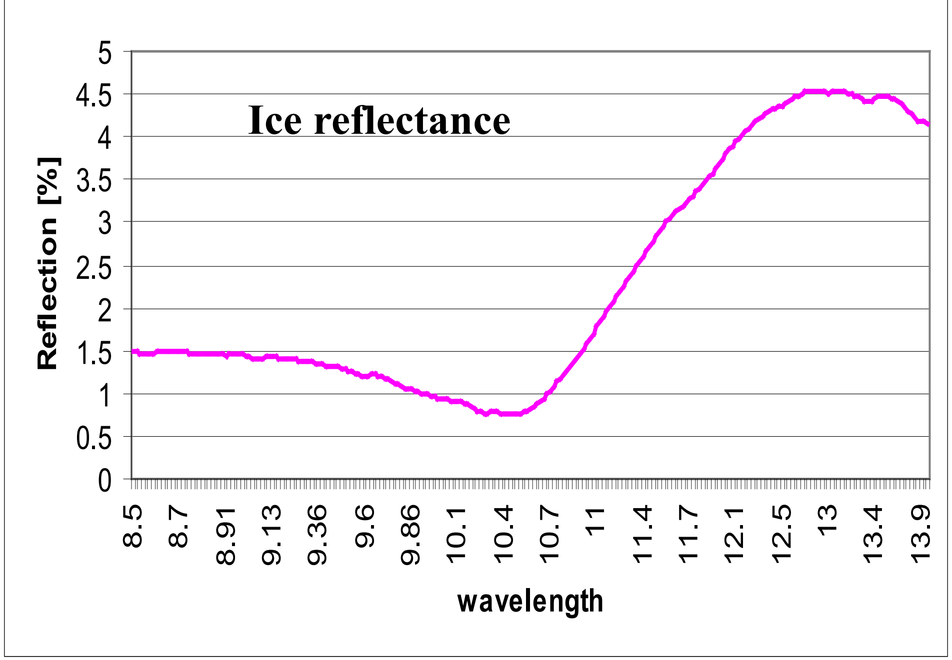


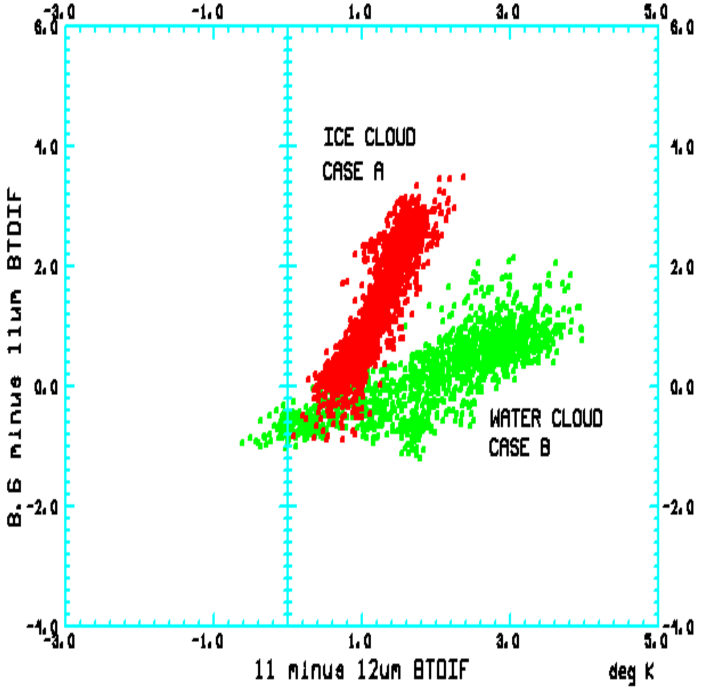
MODIS BAND	nm	cm^{-1}
31	11030	907
32	12020	832
33	13335	750
34	13635	730
35	13935	718
36	14235	702

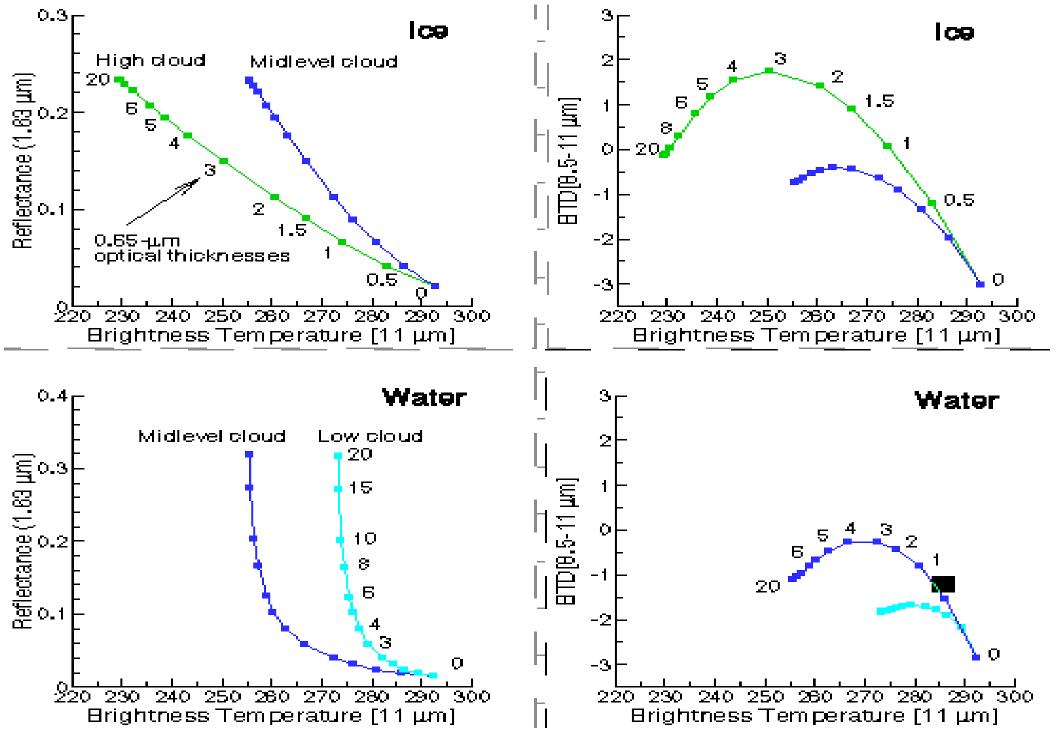





B
770.68(12.98)
A
992.21(10.08)
Ice
Water
Ice
Ice Cloud :
C–B ~ 0.
A–C >>0.
Water Cloud :
C–B >>0.
A–C ~0.
Mixed Phase :
C–B >>0.
A–C >>0.
ABI Bands:
Absorption Coefficient (10**3 cm**-1)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
600.0 16.7
700.0 14.3
800.0 12.5
900.0 11.1
1000.0 10.0
1100.0 9.1
1200.0 8.3
879.7(11.37)
C


Ice reflectance
Reflection [%]
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
8.5
8.7
8.91
9.13
9.36
9.6
9.86
10.1
10.4
10.7
11
11.4
11.7
12.1
12.5
13
13.4
13.9
wavelength

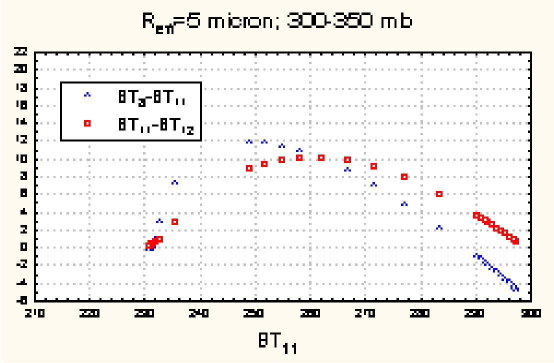

ICE CLOUD
CASE A
WATER CLOUD
CASE B
8.6 minus 11um BTDIF
11 minus 12um BTDIF
deg K
-3.0
-1.0
1.0
3.0
5.0
6.0
4.0
2.0
0.0
-2.0
-4.0

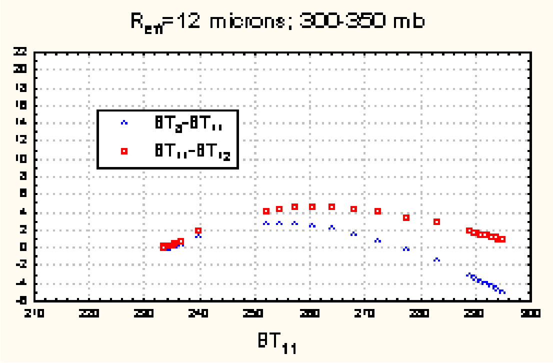

Ice
High cloud
Midlevel cloud
20
6
5
4
3
2
1.5
1
0.5
0
0.65-µm optical thicknesses
Reflectance (1.63 µm)
0.3
0.2
0.1
0
220 230 240 250 260 270 280 290 300
Brightness Temperature [11 µm]
Ice
BTD[8.5-11 µm]
3
2
1
0
-1
-2
-3
20
8
6
5
4
3
2
1.5
1
0.5
0
220 230 240 250 260 270 280 290 300
Brightness Temperature [11 µm]
Water
Midlevel cloud
Low cloud
20
15
10
8
6
4
3
0
Reflectance (1.63 µm)
0.4
0.3
0.2
0.1
0
220 230 240 250 260 270 280 290 300
Brightness Temperature [11 µm]
Water
BTD[8.5-11 µm]
3
2
1
0
-1
-2
-3
20
6
5
4
3
2
1
0
220 230 240 250 260 270 280 290 300
Brightness Temperature [11 µm]

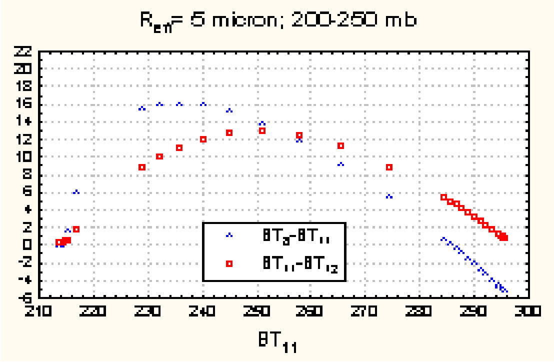
MAS 02/02/1997 16:38:31 UTC
Band 02 (0.66 micron)
Gain Corrected Counts

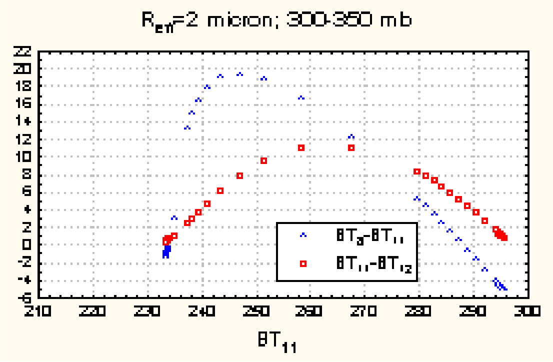
MAS 02/02/1997 16:38:31 UTC
Bands 44-45 (10.46-10.96 micron)
Brightness Temperature (Kelvin)

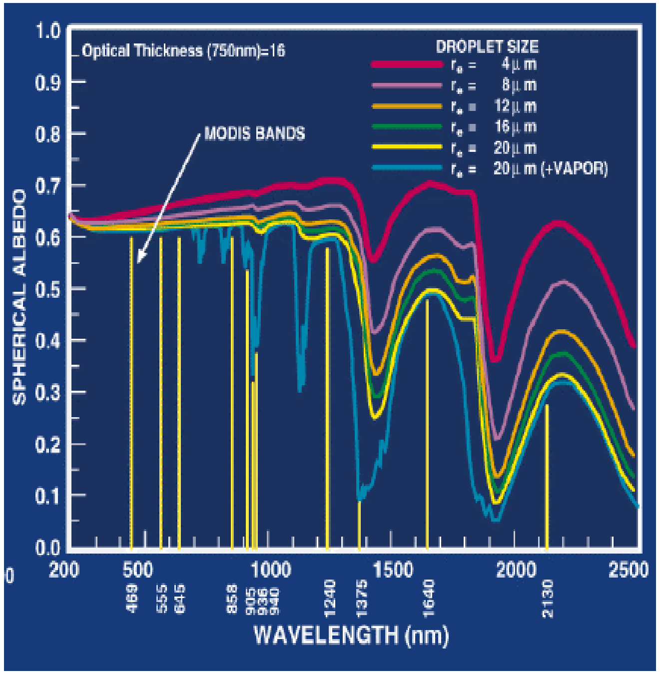
MAS 02/02/1997 16:38:31 UTC
Bands 42-44 (8.54-10.46 micron)
Brightness Temperature (Kelvin)

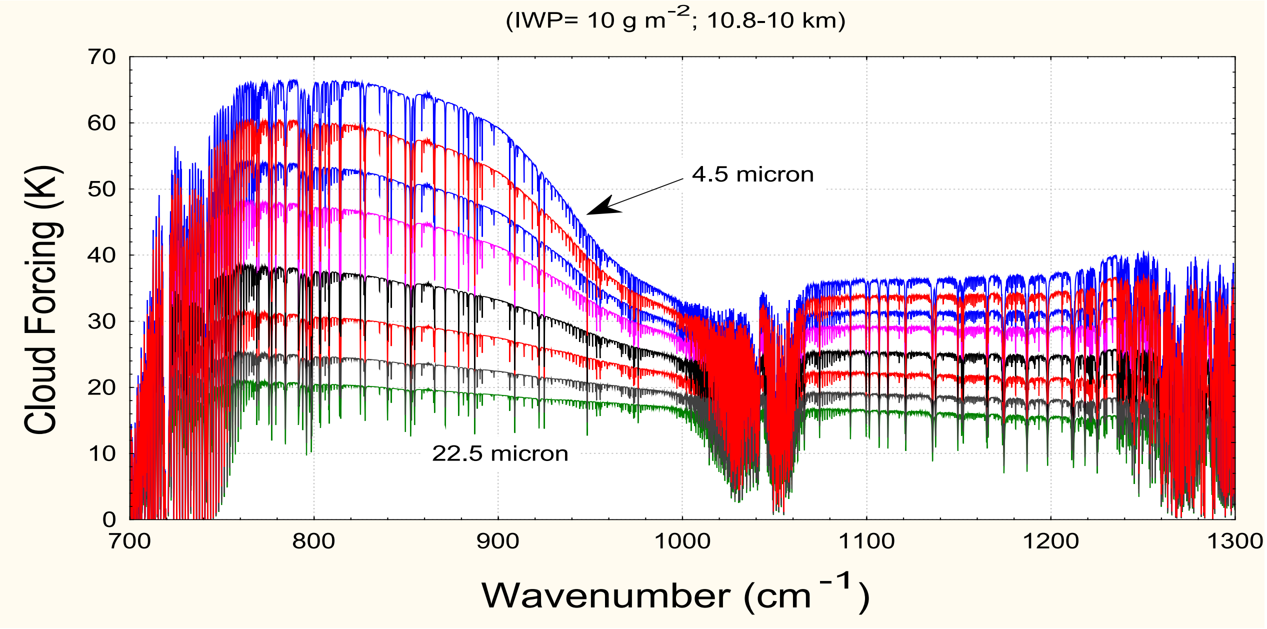

R$_{eff}$=5 micron; 300-350 mb
BT$_8$-BT$_{11}$
BT$_{11}$-BT$_{12}$
BT$_{11}$
210
220
230
240
250
260
270
280
290
300
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6

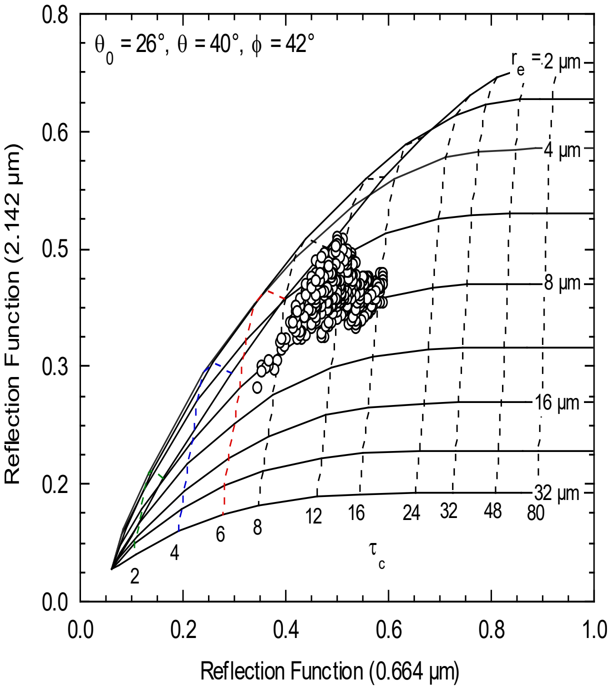

R$_{eff}$=12 microns; 300-350 mb
BT$_8$-BT$_{11}$
BT$_{11}$-BT$_{12}$
BT$_{11}$
210
220
230
240
250
260
270
280
290
300
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6


R$_{eff}$= 5 micron; 200-250 mb
BT$_8$-BT$_{11}$
BT$_{11}$-BT$_{12}$
BT$_{11}$
210
220
230
240
250
260
270
280
290
300
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6


R$_{eff}$=2 micron; 300-350 mb
BT$_8$-BT$_{11}$
BT$_{11}$-BT$_{12}$
BT$_{11}$
210
220
230
240
250
260
270
280
290
300
22
20
18
16
14
12
10
8
6
4
2
0
-2
-4
-6


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
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
200
500
1000
1500
2000
2500
469
555
645
858
905
936
940
1240
1375
1640
2130
WAVELENGTH (nm)


(IWP= 10 g m^{-2}; 10.8-10 km)
4.5 micron
22.5 micron
Cloud Forcing (K)
70
60
50
40
30
20
10
0
700
800
900
1000
1100
1200
1300
Wavenumber (cm^{-1})


θ_0 = 26°, θ = 40°, ϕ = 42°
r$_e$ = 2 μm
4 μm
8 μm
16 μm
32 μm
2
4
6
8
12
16
24
32
48
80
τ_c
Reflection Function (2.142 μm)
Reflection Function (0.664 μm)
0.8
0.6
0.5
0.3
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

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 x 10-5 $(mW/m^2/ster/cm^{-4})$

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 $E = \pi \int_o^\infty B(\nu,T)\, d\nu = \sigma T^4$, where σ = 5.67 x 10-8 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

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)

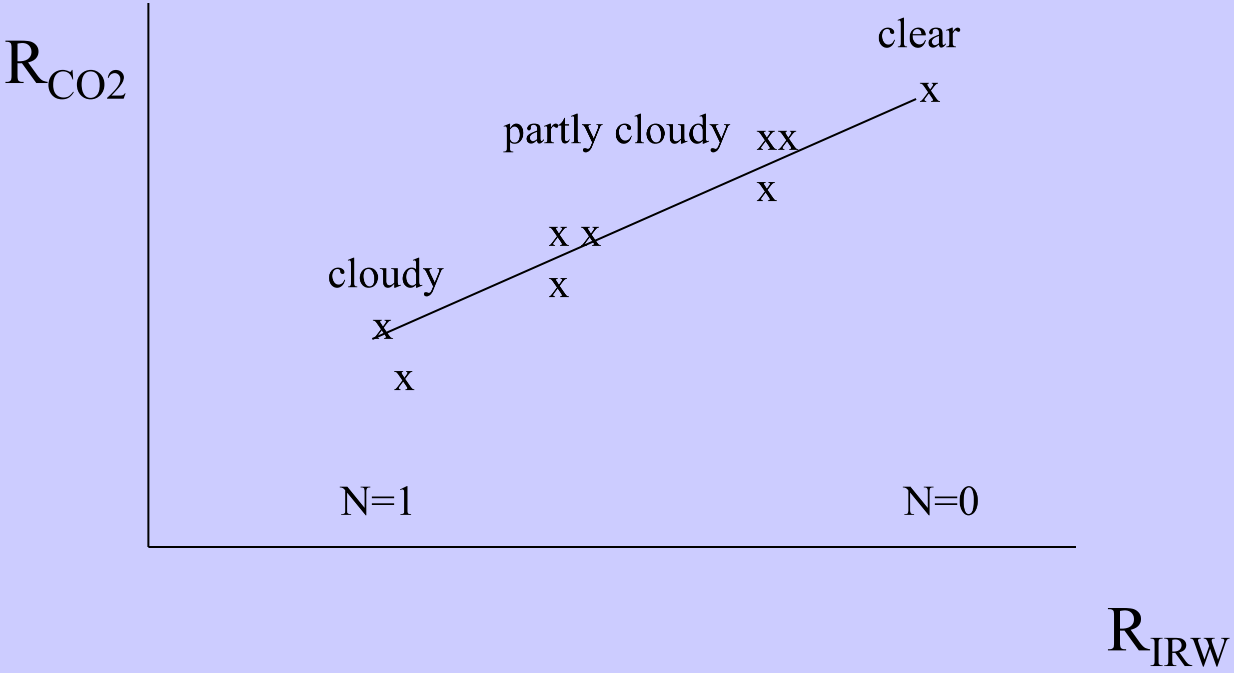
$$(I_\lambda - I_\lambda^{clr}) = \eta\varepsilon_\lambda \int_{p_s}^{p_c} \tau_\lambda \, dB_\lambda \, .$$

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.

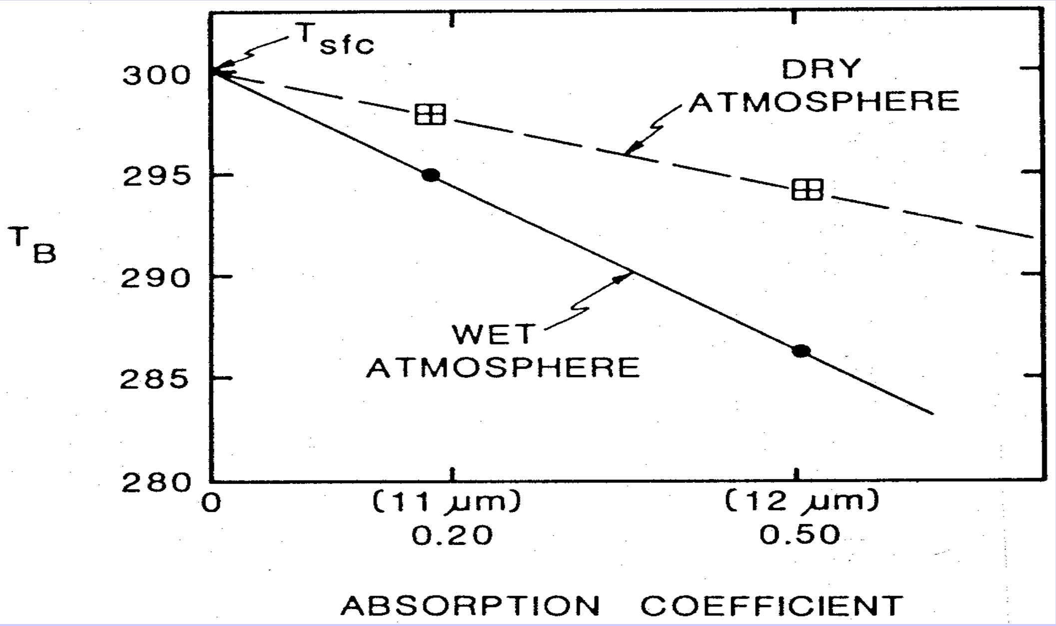
Moisture

Moisture attenuation in atmospheric windows varies linearly with optical depth.

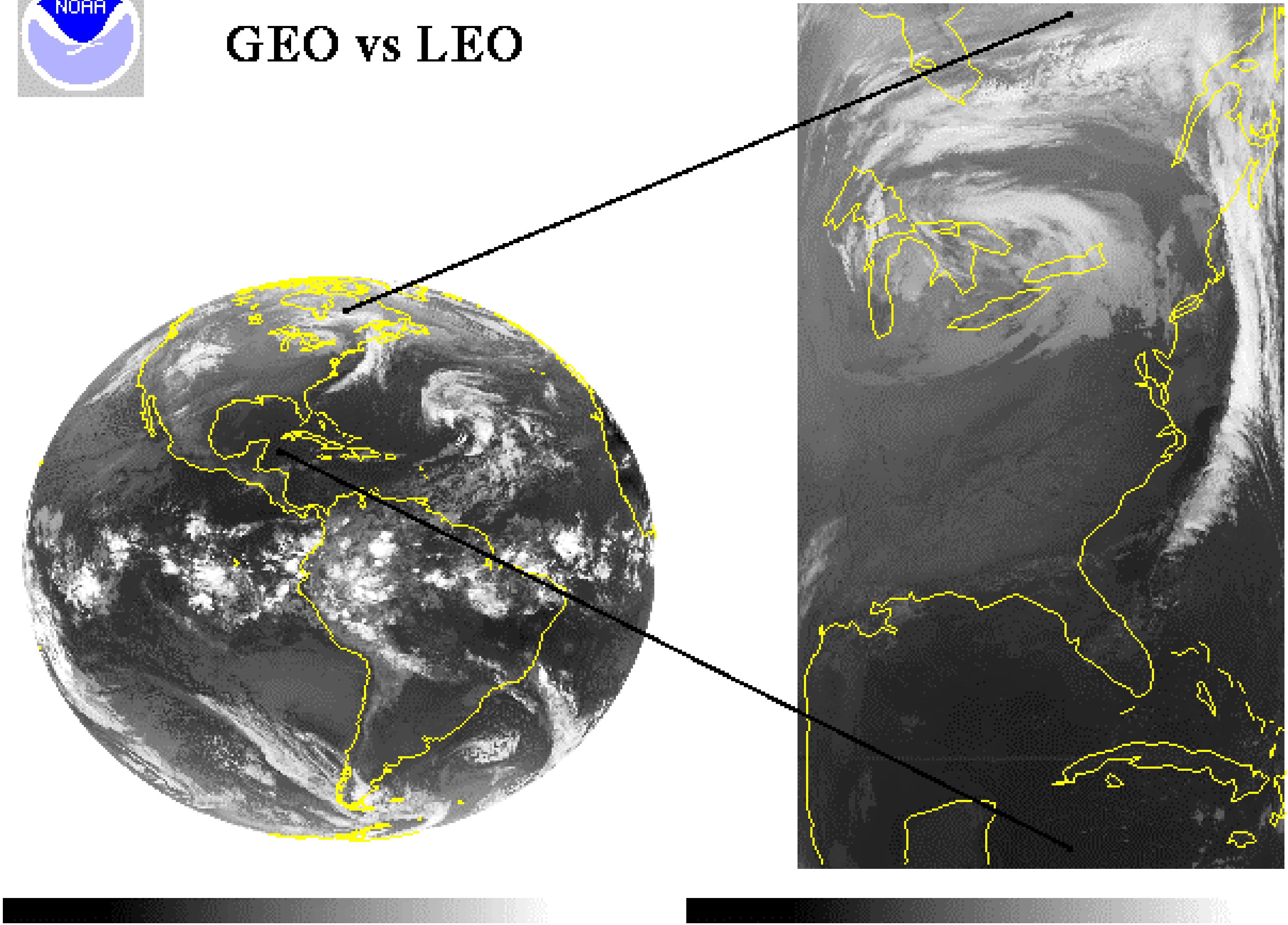
$$\tau_\lambda = e^{-k_\lambda u} = 1 - k_\lambda u$$

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