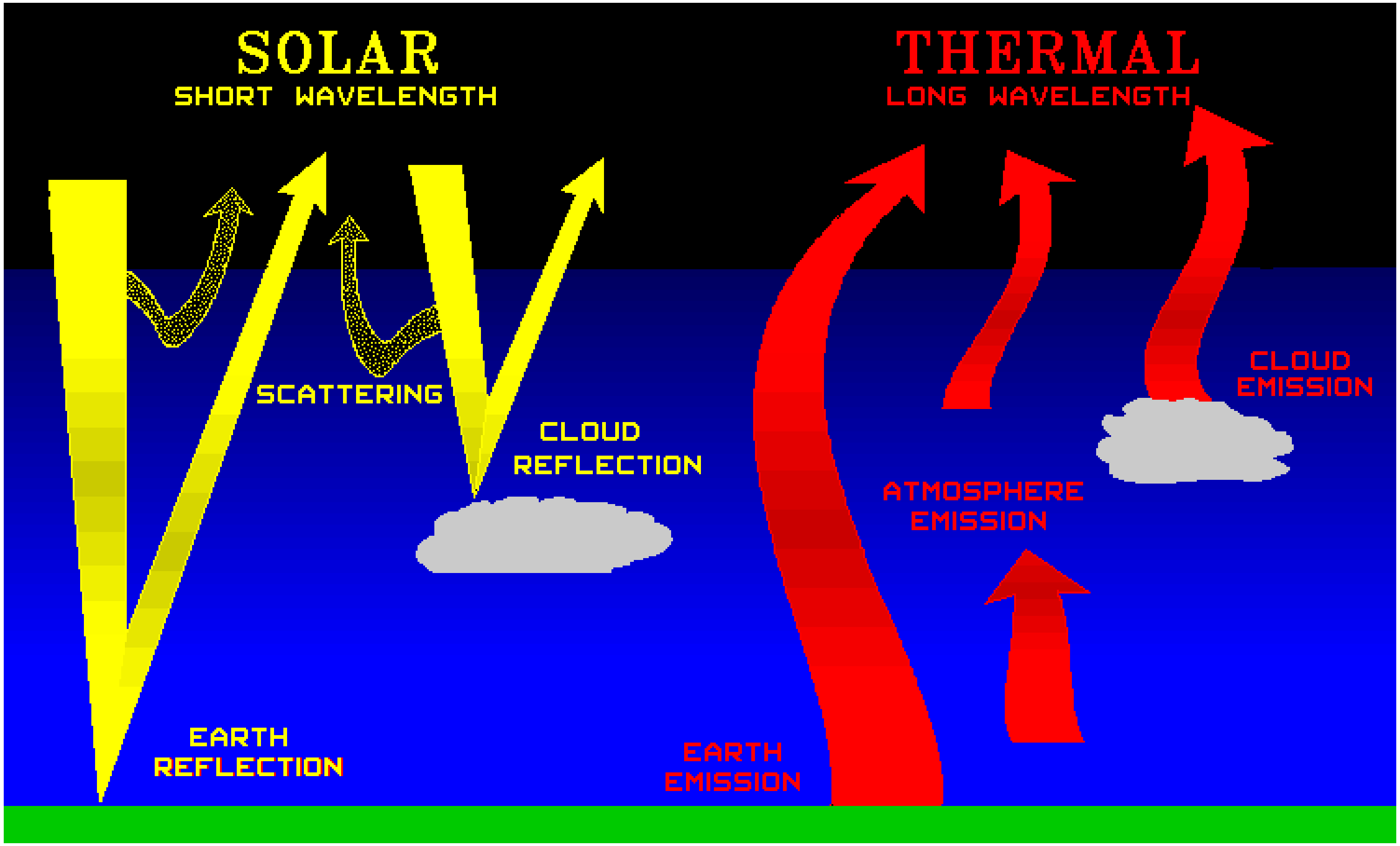
Review of Remote Sensing Fundaments III
Radiative Transfer Equation in the Infrared

Allen Huang
Cooperative Institute for Meteorological Satellite Studies
Space Science & Engineering Center
University of Wisconsin-Madison, USA

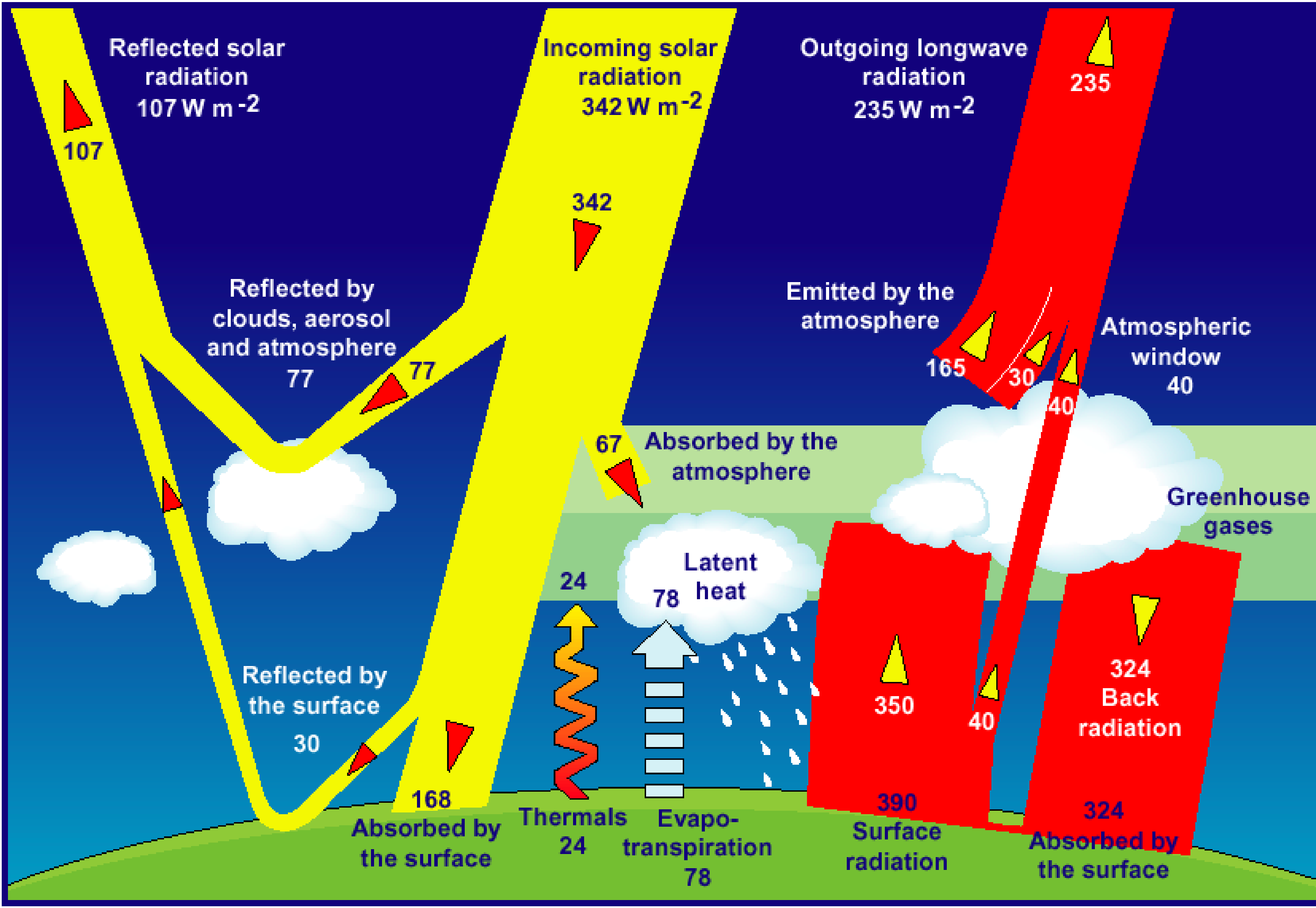
Selected Material Provided by Bill Smith, Paul Menzel, & Paolo Antonelli

GEOSS Americas/Caribbean Remote Sensing Workshop – Transforming Data into Products
26-30 November 2007
CPTEC/INPE Cachoeira Paulista - São Paulo

Using Natural Radiation for Remote Sensing



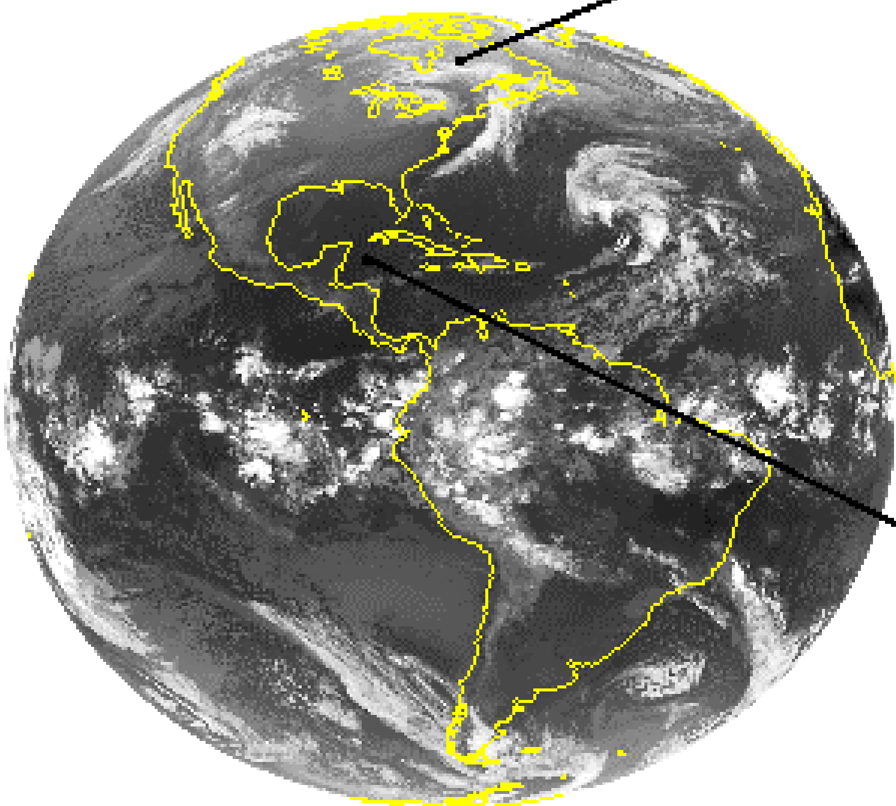
Earth System Energy Balance



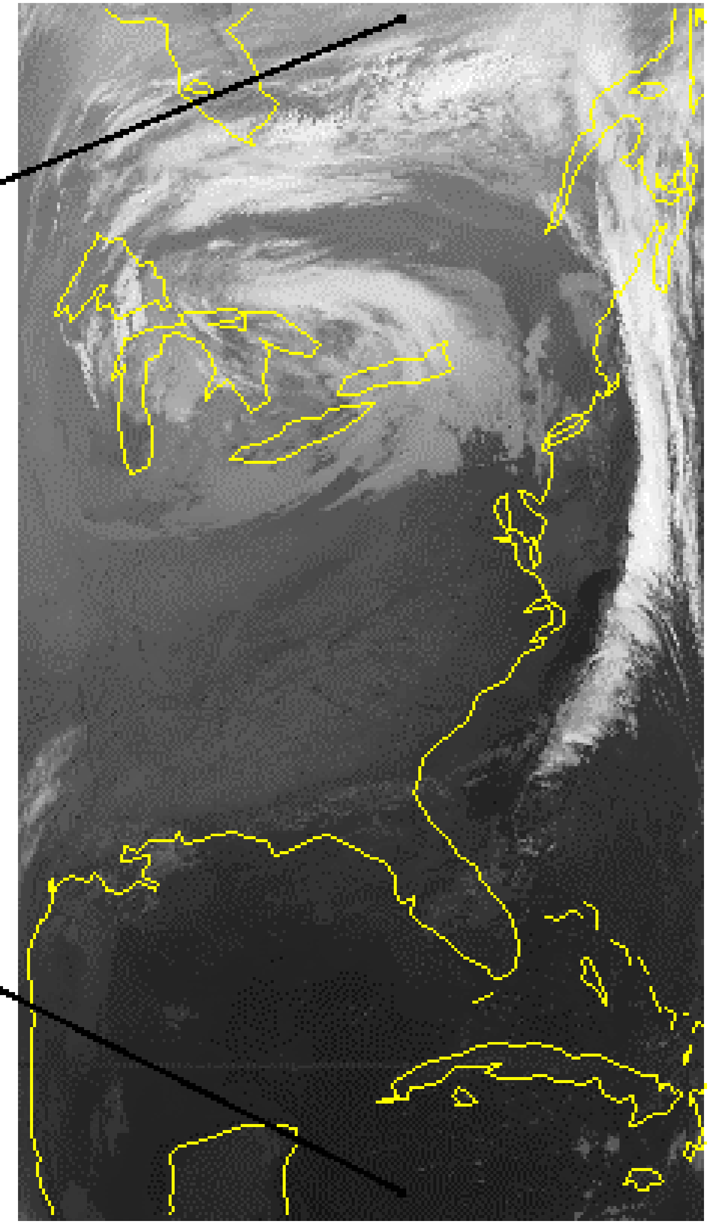
Comparison of geostationary (geo) and low earth orbiting (leo) satellite capabilities

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 interferometer	filter radiometer, interferometer, and grating spectrometer
diffraction more than leo	diffraction less than geo

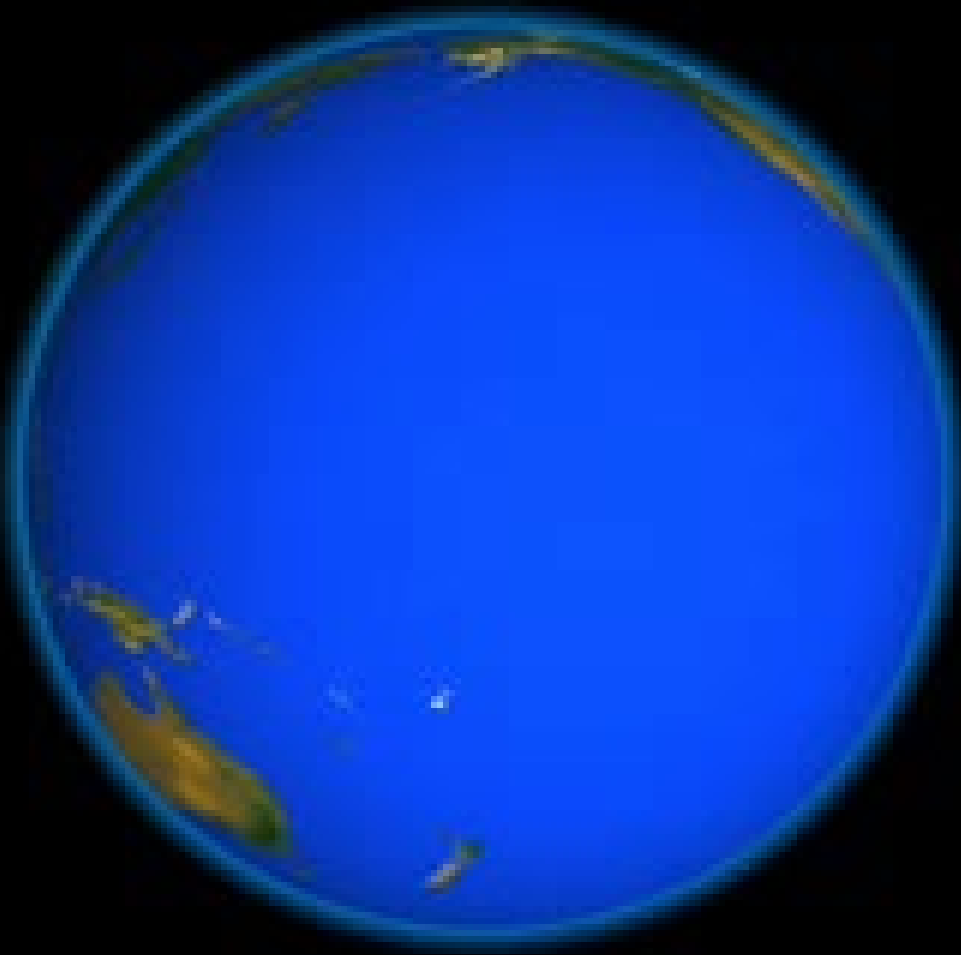
GEO vs LEO



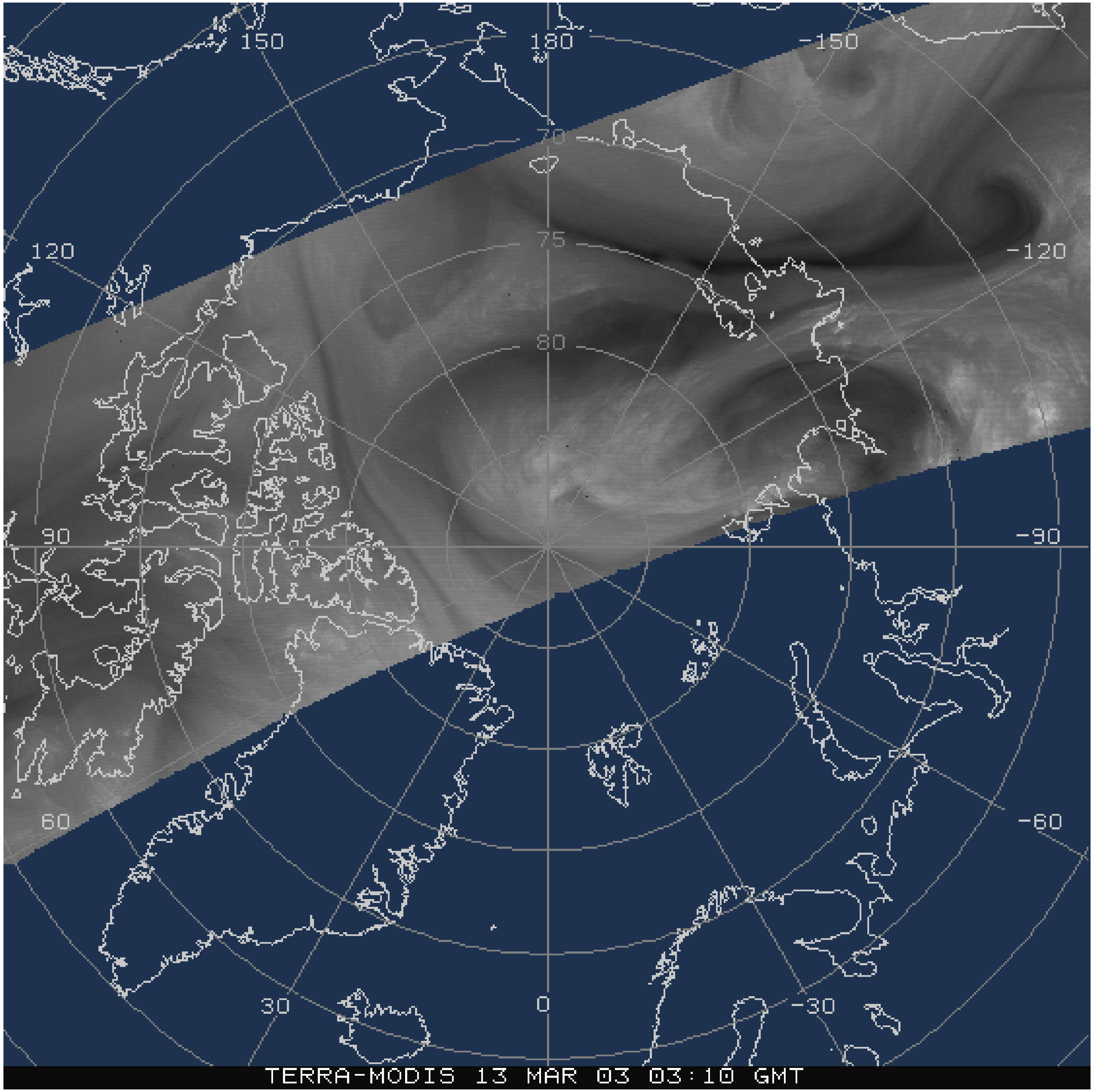
GOES-8 IMAGER 12UTC 02APR98



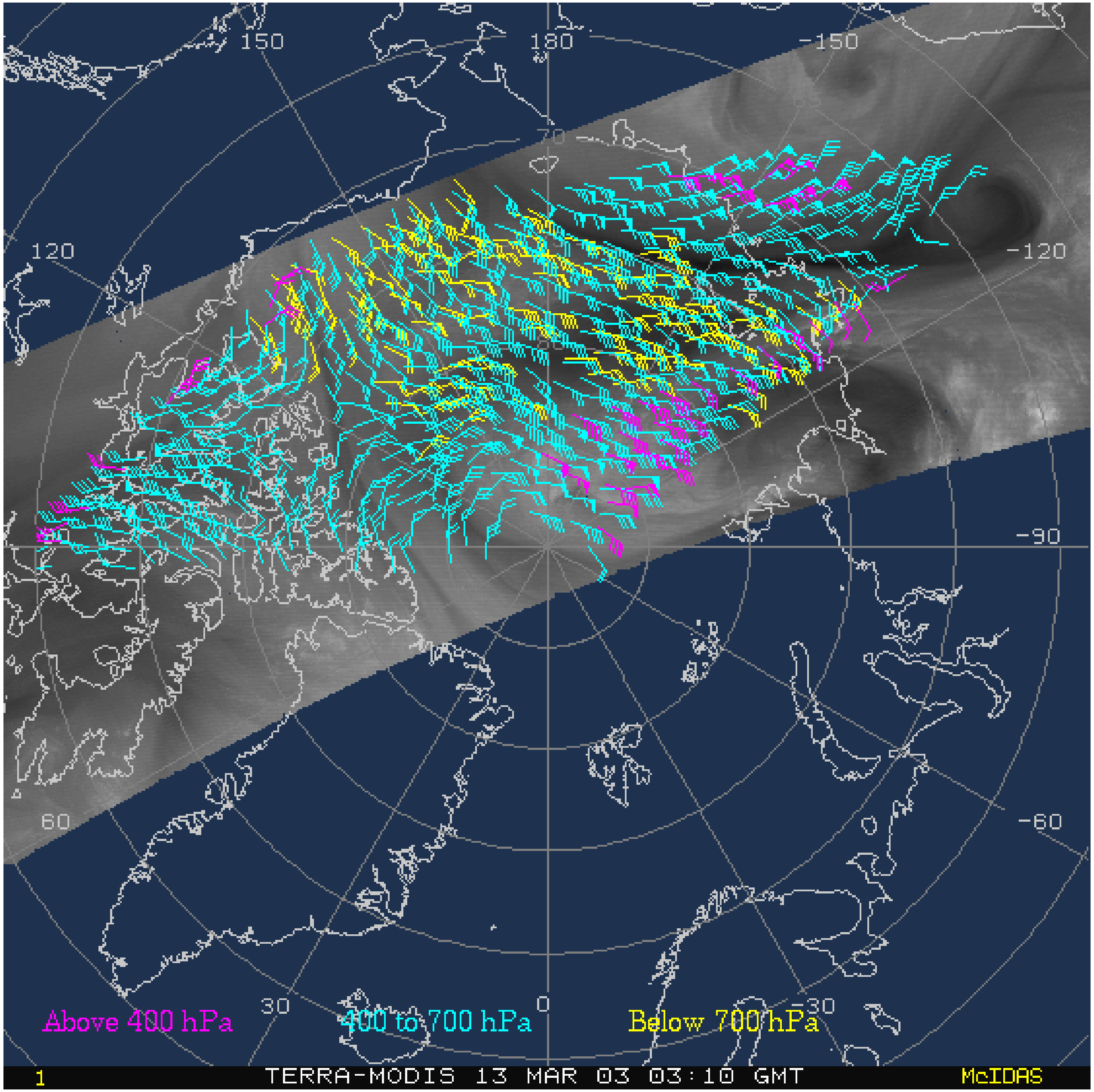
NOAA-12 AVHRR 12UTC 02APR98

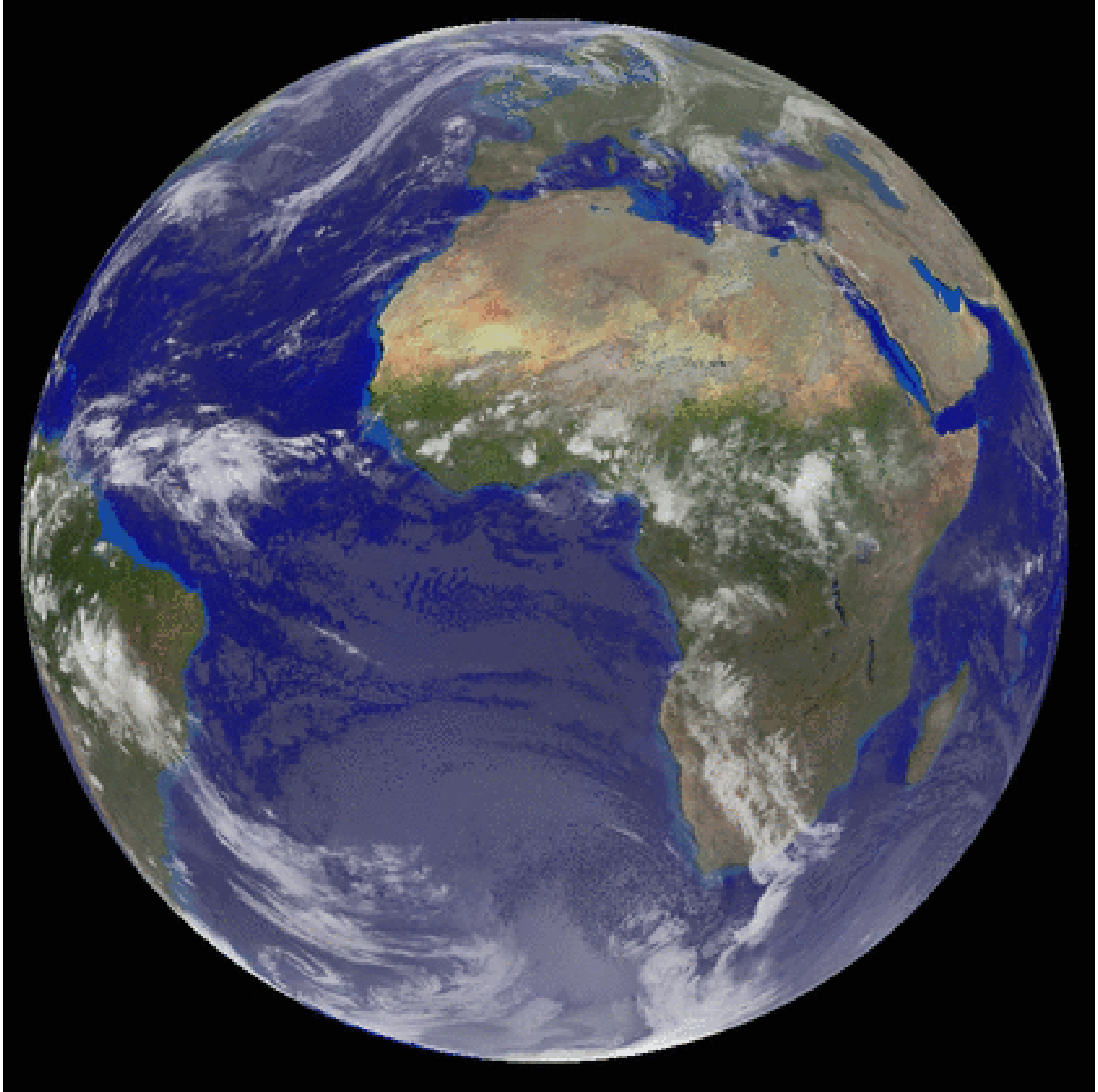


Leo coverage of poles every 100 minutes

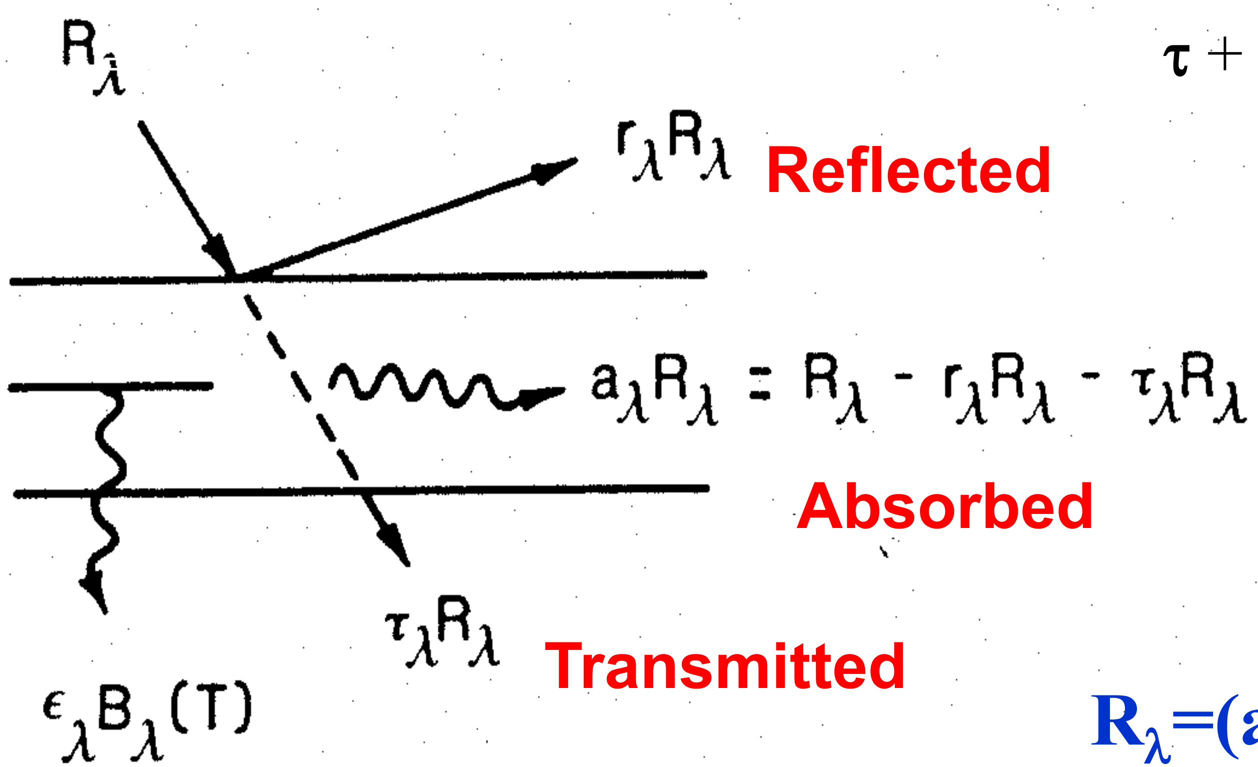


Tracking Polar Atmospheric Motion from Leo Obs





Energy conservation: $\tau + a + r = 1$



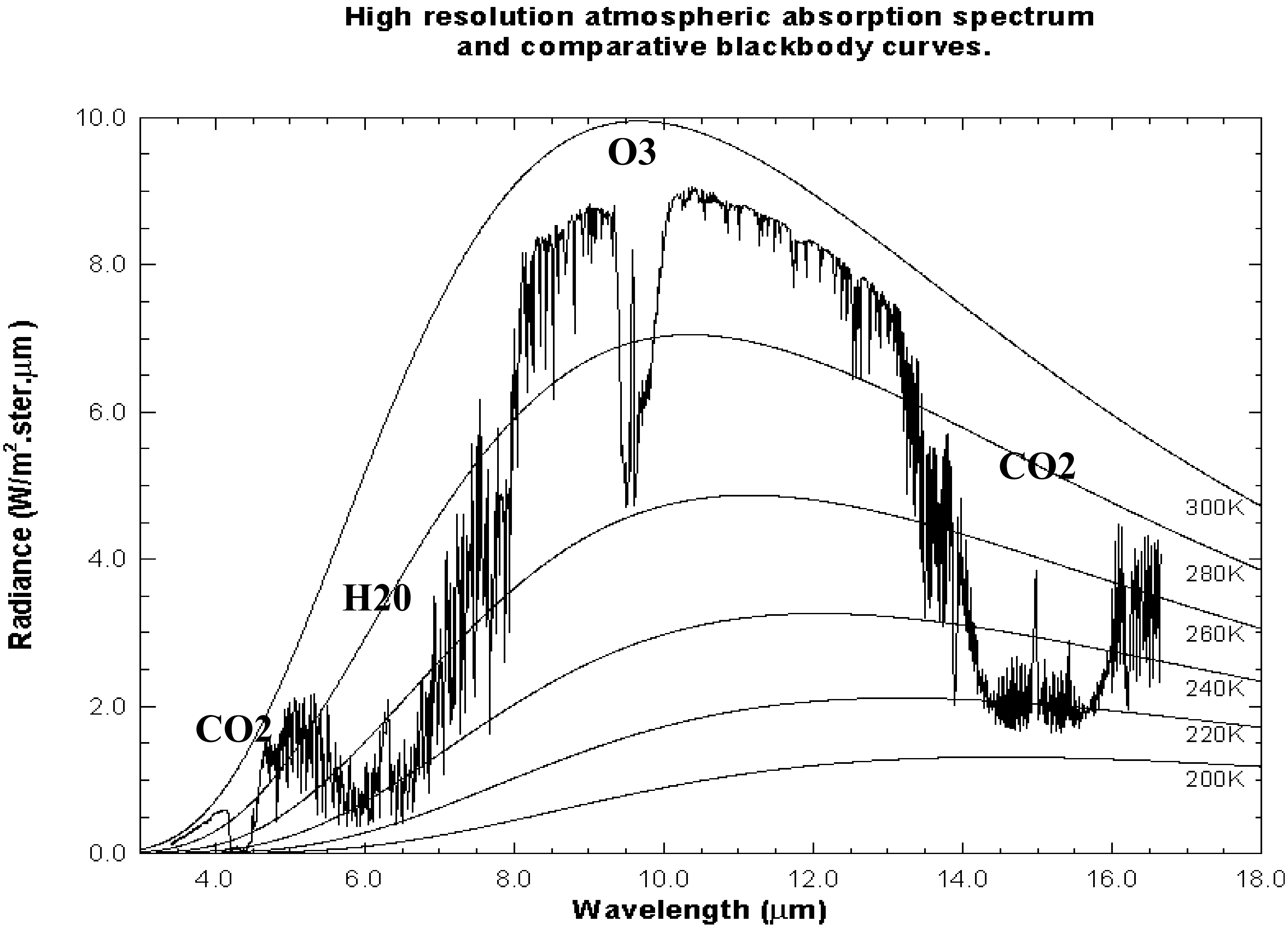
$\tau + a + \cancel{r} = 1$

"ENERGY CONSERVATION"

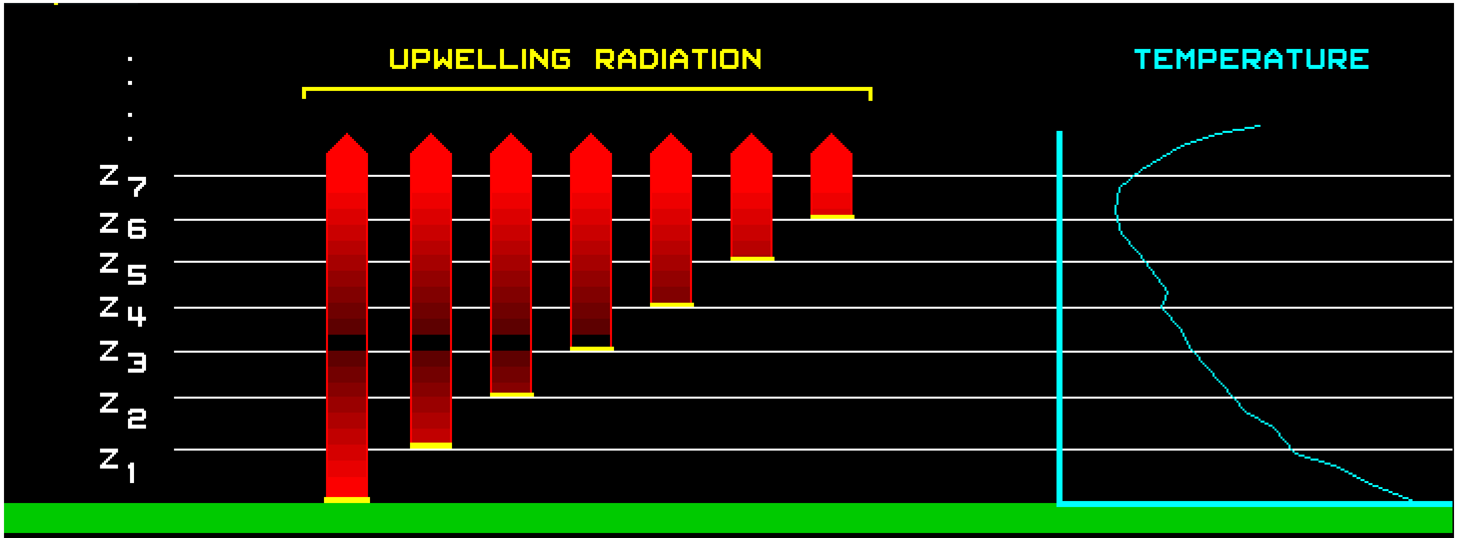
$R_\lambda = (a_\lambda + r_\lambda + \tau_\lambda)\, R_\lambda$

$\tau + a + r = 1$

Earth Emitted Radiance Spectra Overlaid on Planck Radiance Function Envelopes

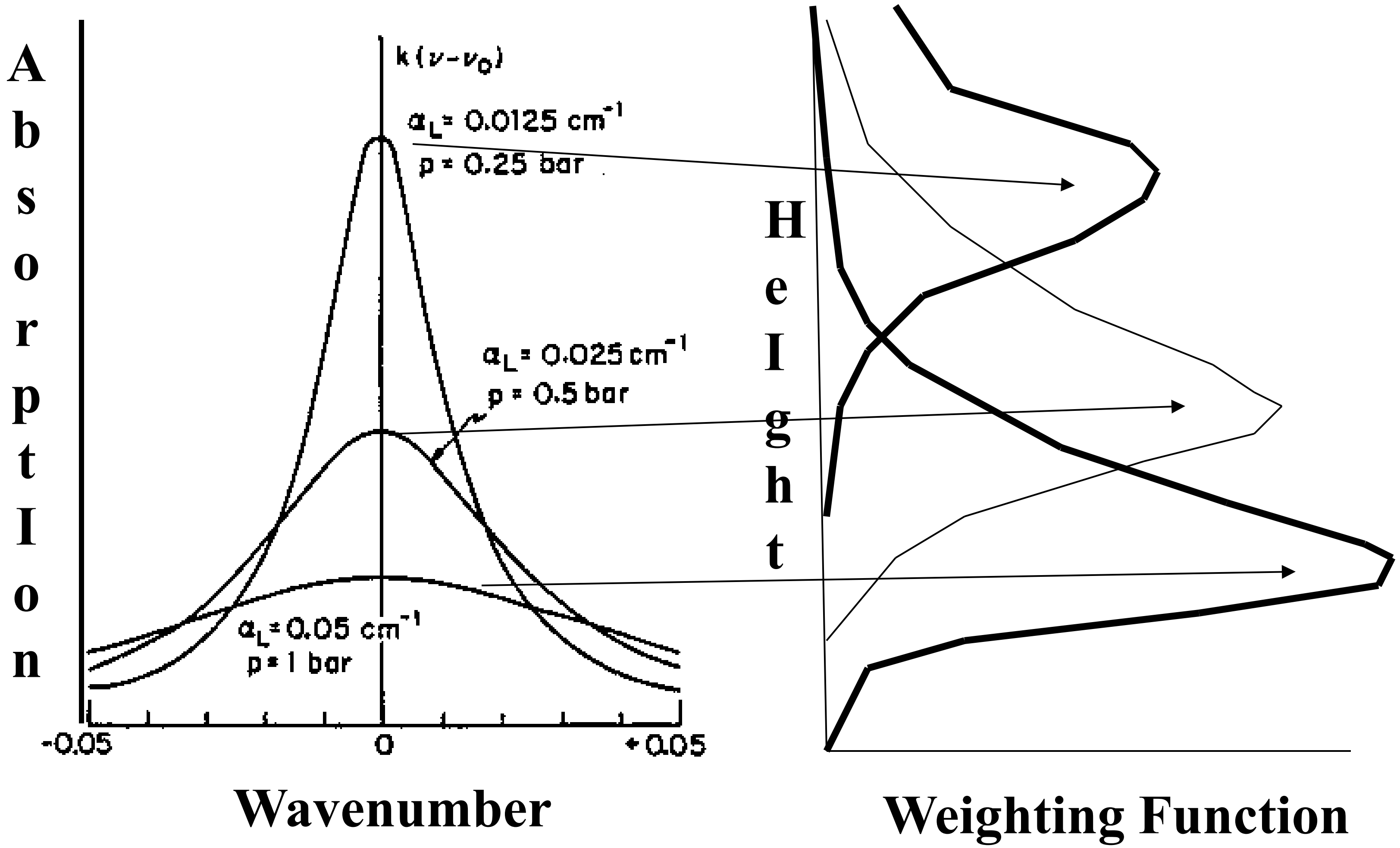


Infrared Atmospheric Sounding



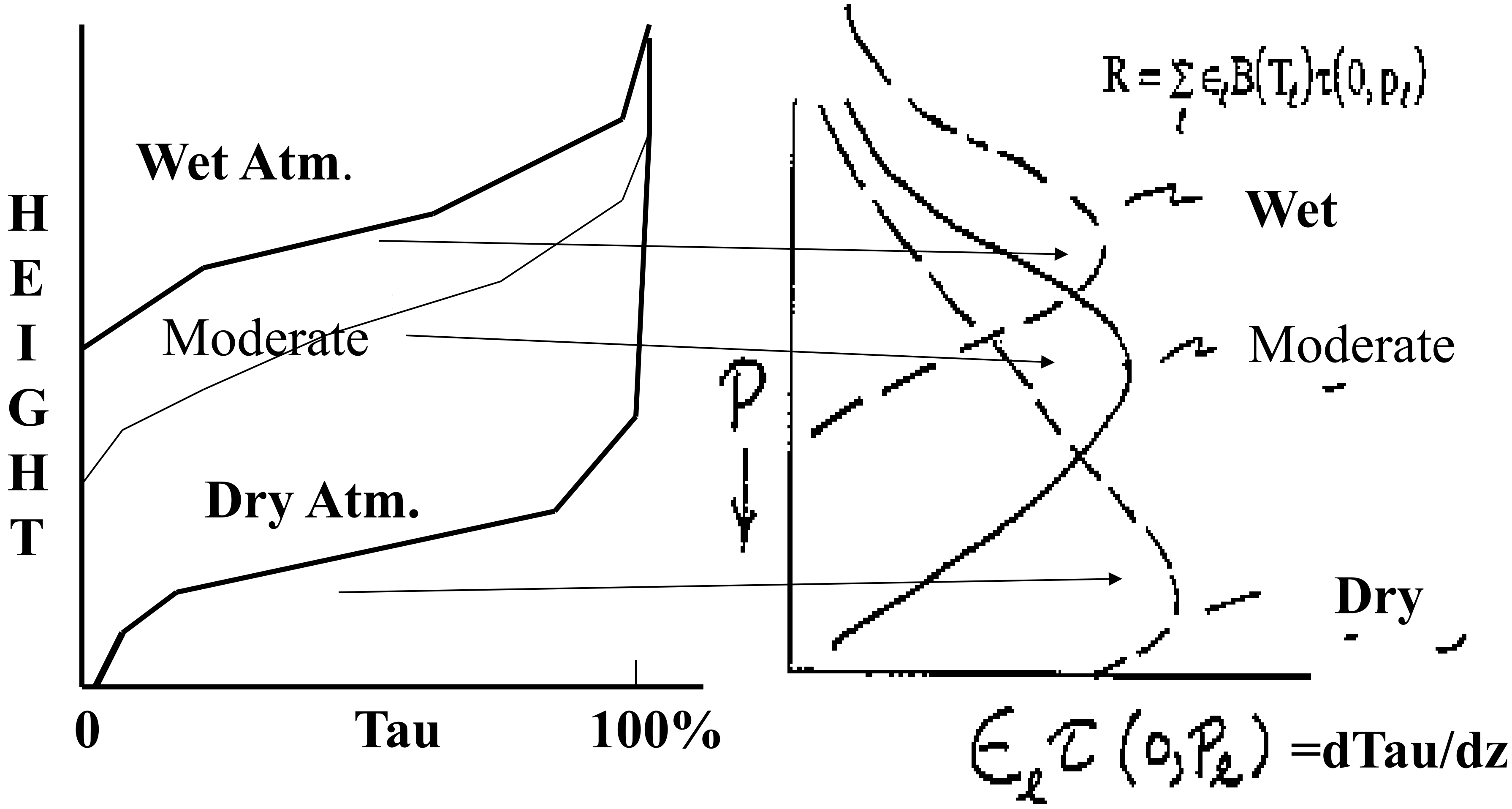
$$
\begin{aligned}
R(n_i) = {} & B(n_i, T(z_0))\, \epsilon(n_i, z_0)\, \tau(n_i, z_0) \\
& + B(n_i, T(z_1))\, \epsilon(n_i, z_1)\, \tau(n_i, z_1) \\
& + B(n_i, T(z_2))\, \epsilon(n_i, z_2)\, \tau(n_i, z_2) \\
& + B(n_i, T(z_3))\, \epsilon(n_i, z_3)\, \tau(n_i, z_3) \\
& + \vdots
\end{aligned}
$$

Pressure Broadening Vs Altitude

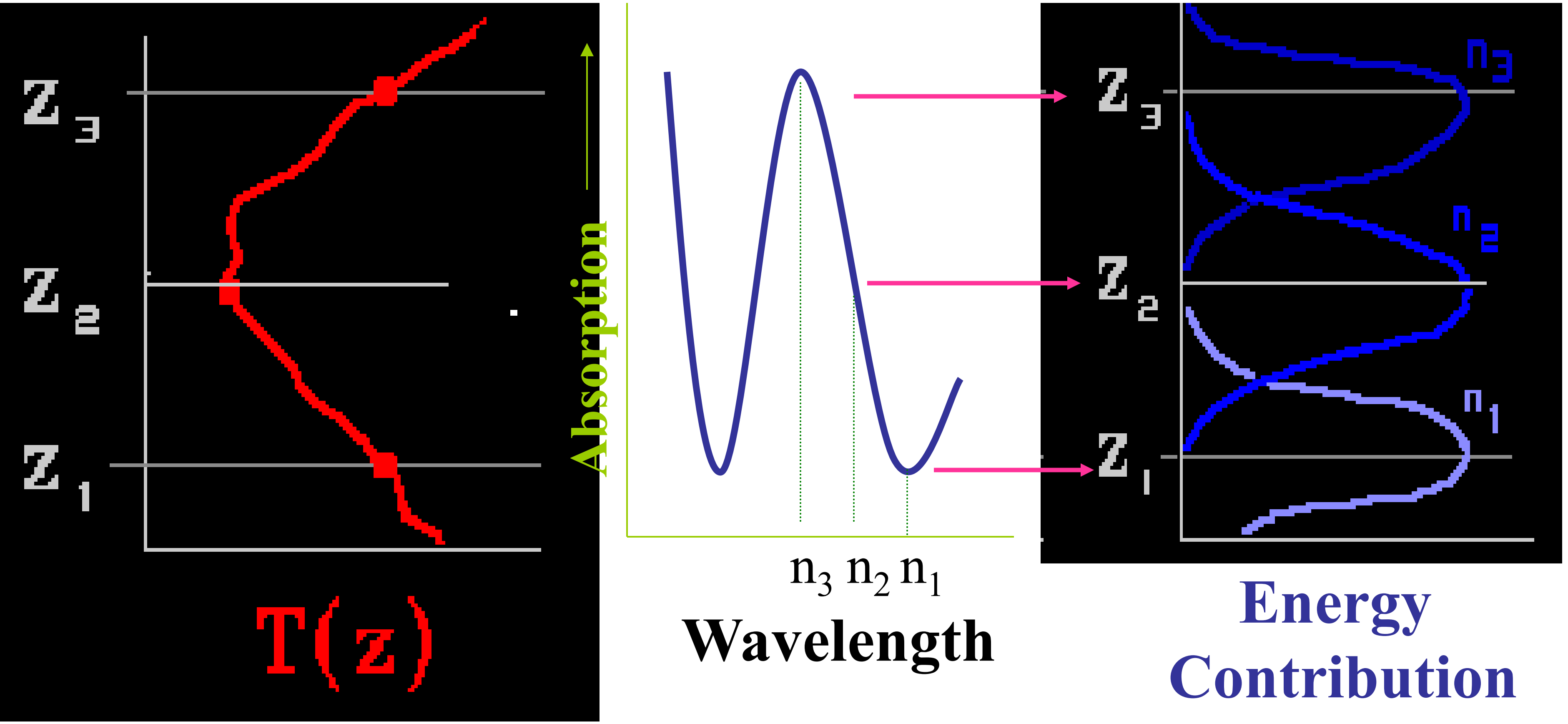


The Weighting Function

For a given water vapor spectral channel



Wavelength Converts to Altitude



Transmittance

Transmission through an absorbing medium for a given wavelength is governed by the number of intervening absorbing molecules (path length u) and their **absorbing power (k_λ)** at that wavelength. Beer's law indicates that **transmittance decays exponentially with increasing path length**

$$\tau_\lambda (z \rightarrow \infty) = e^{-k_\lambda u(z)}$$

where the **path length** is given by $u(z) = \int_z^\infty \rho \, dz$.

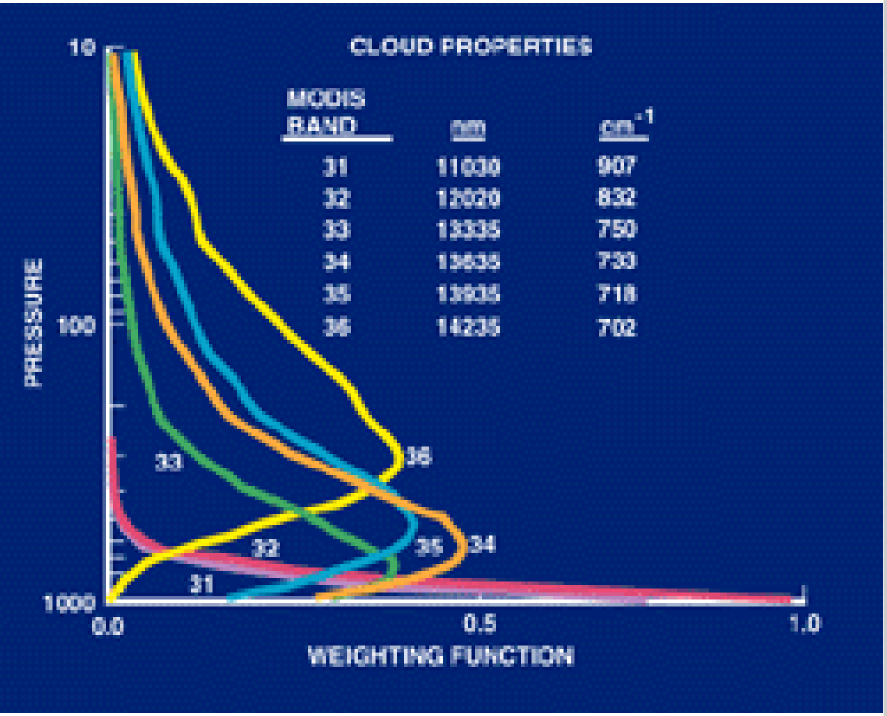
$k_\lambda u$ is a measure of the cumulative depletion that the beam of radiation has experienced as a result of its passage through the layer and is often called the optical depth σ_λ.

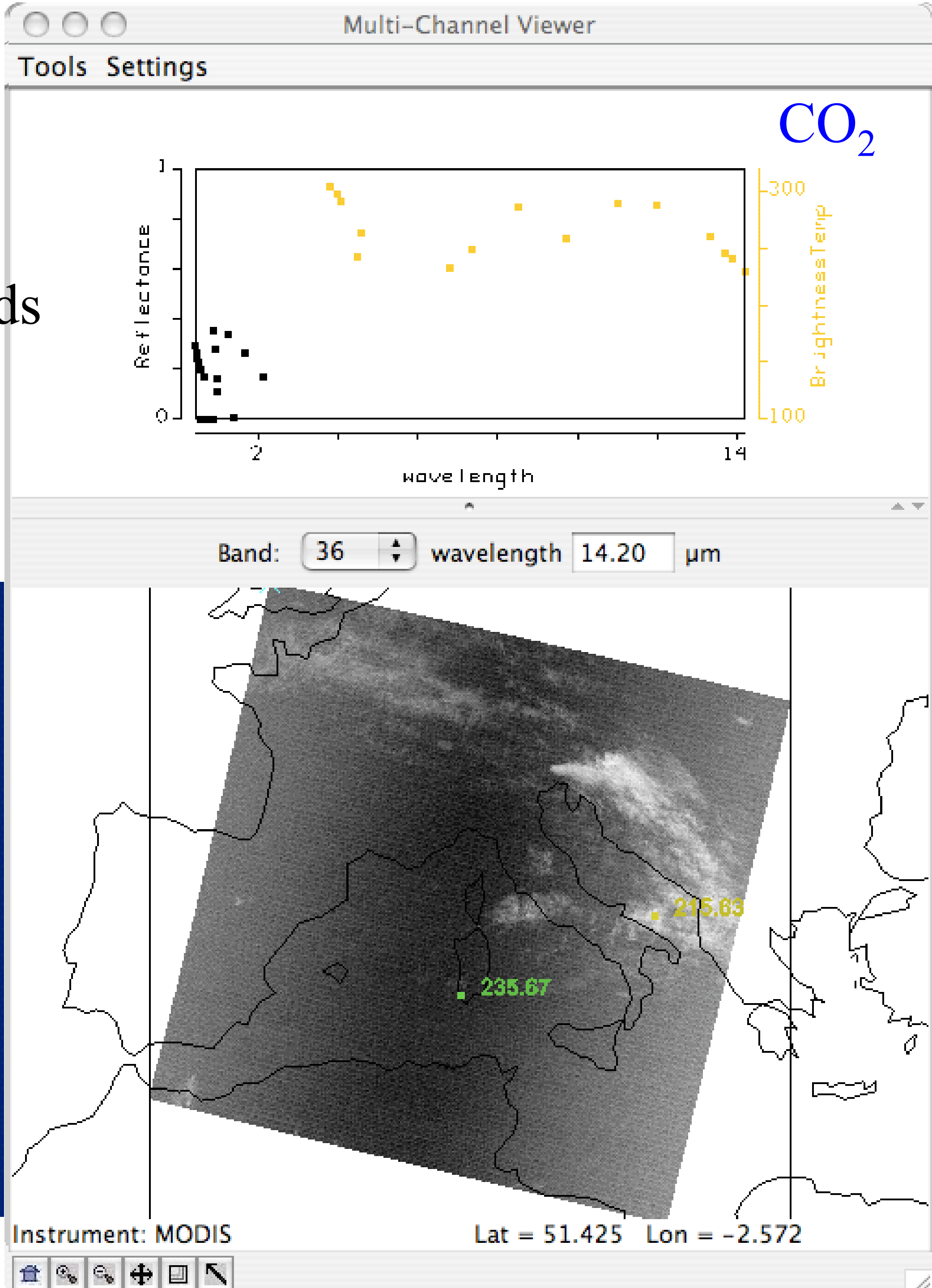
Realizing that the **hydrostatic equation** implies $g \rho \, dz = - q \, dp$

where **q is the mixing ratio** and ρ is the density of the atmosphere, then

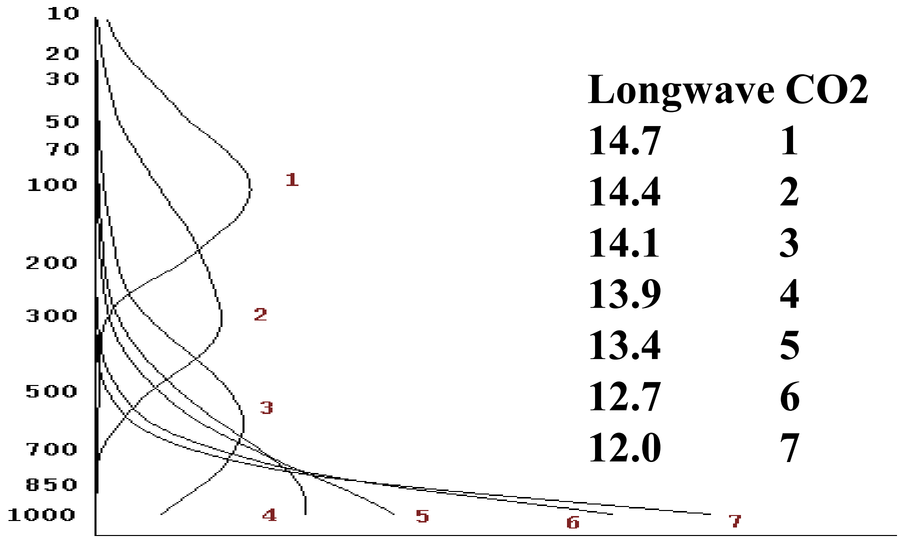
$$u(p) = \int_o^p q \, g^{-1} \, dp \qquad \text{and} \qquad \tau_\lambda (p \rightarrow o) = e^{-k_\lambda u(p)} \quad .$$

MODIS Infrared absorption bands



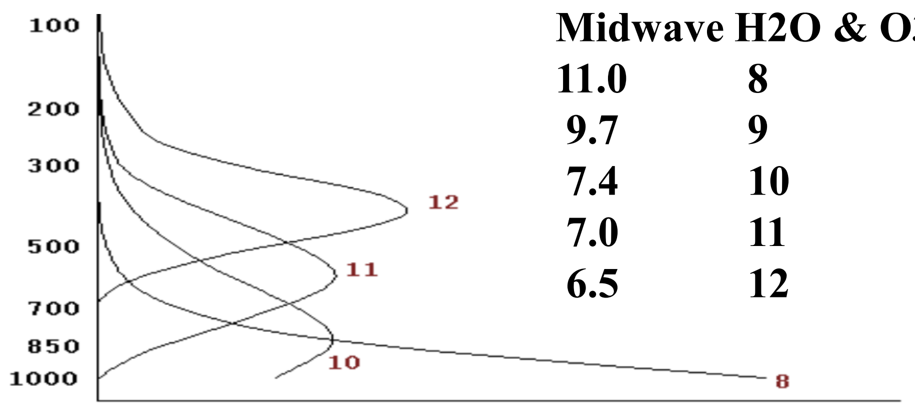


Weighting Functions



Longwave CO_2

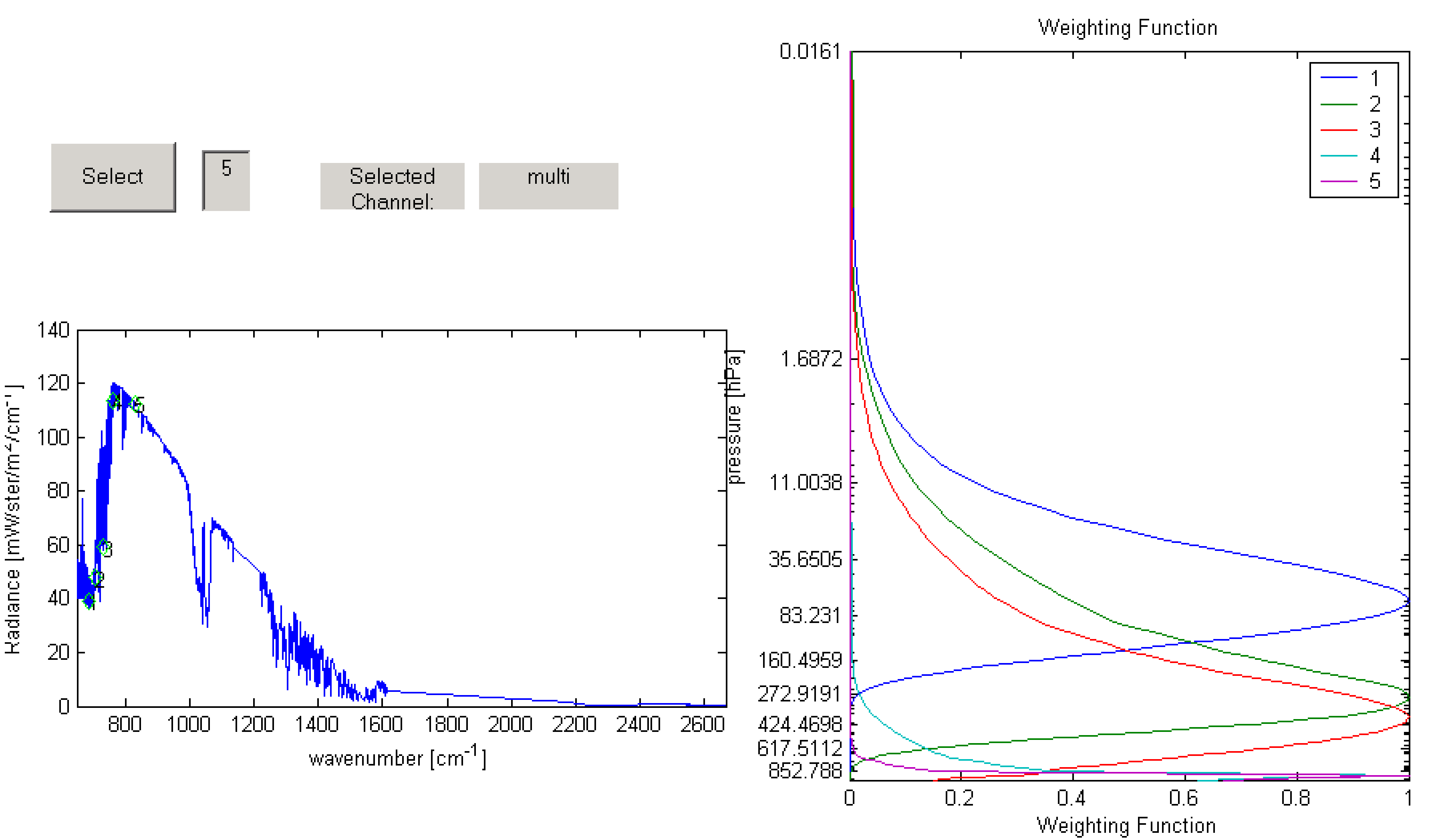
14.7	1	680	CO_2, strat temp
14.4	2	696	CO_2, strat temp
14.1	3	711	CO_2, upper trop temp
13.9	4	733	CO_2, mid trop temp
13.4	5	748	CO_2, lower trop temp
12.7	6	790	H_2O, lower trop moisture
12.0	7	832	H_2O, dirty window



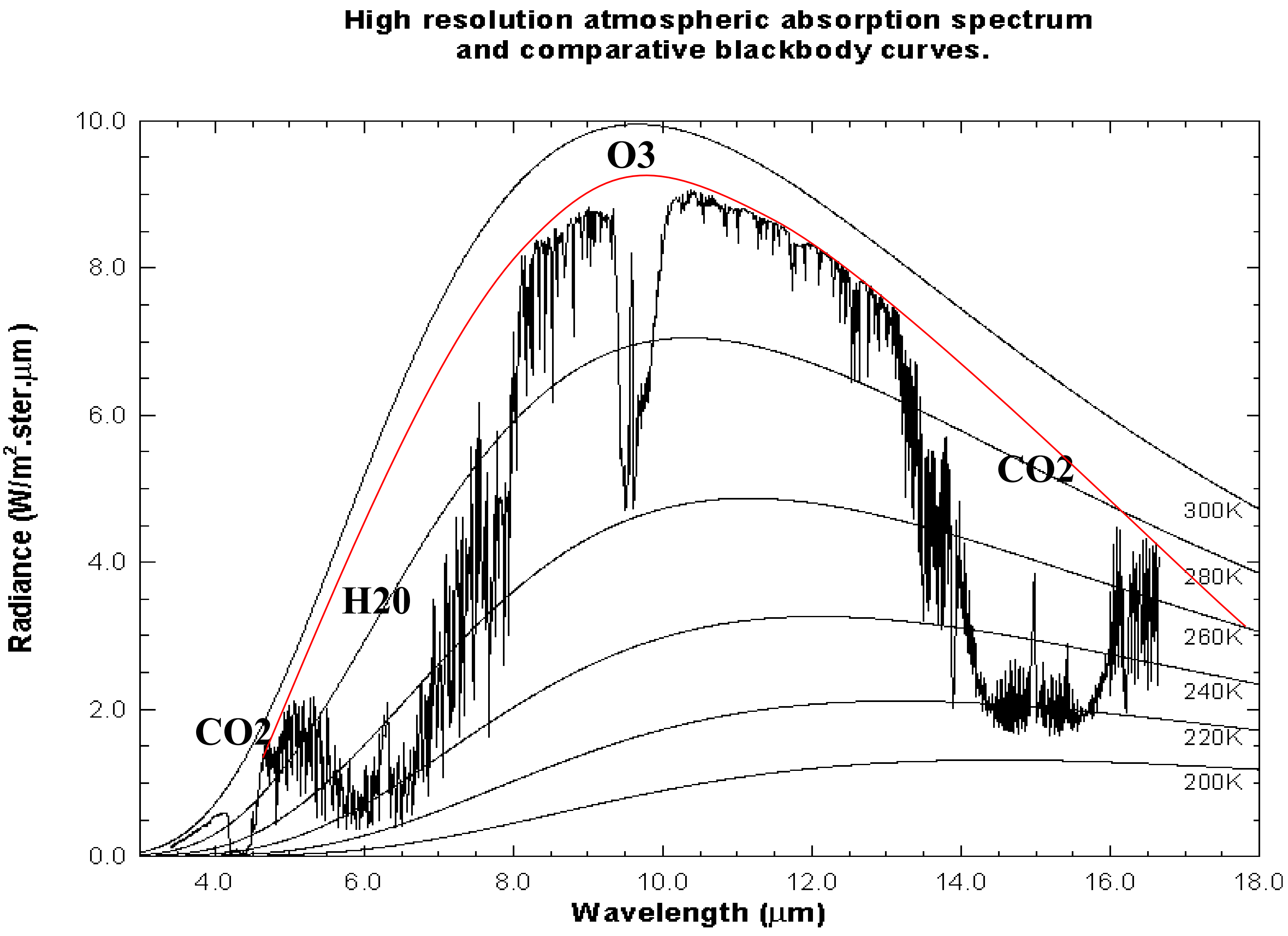
Midwave H_2O & O_3

11.0	8	907	window
9.7	9	1030	O_3, strat ozone
7.4	10	1345	H_2O, lower mid trop moisture
7.0	11	1425	H_2O, mid trop moisture
6.5	12	1535	H_2O, upper trop moisture

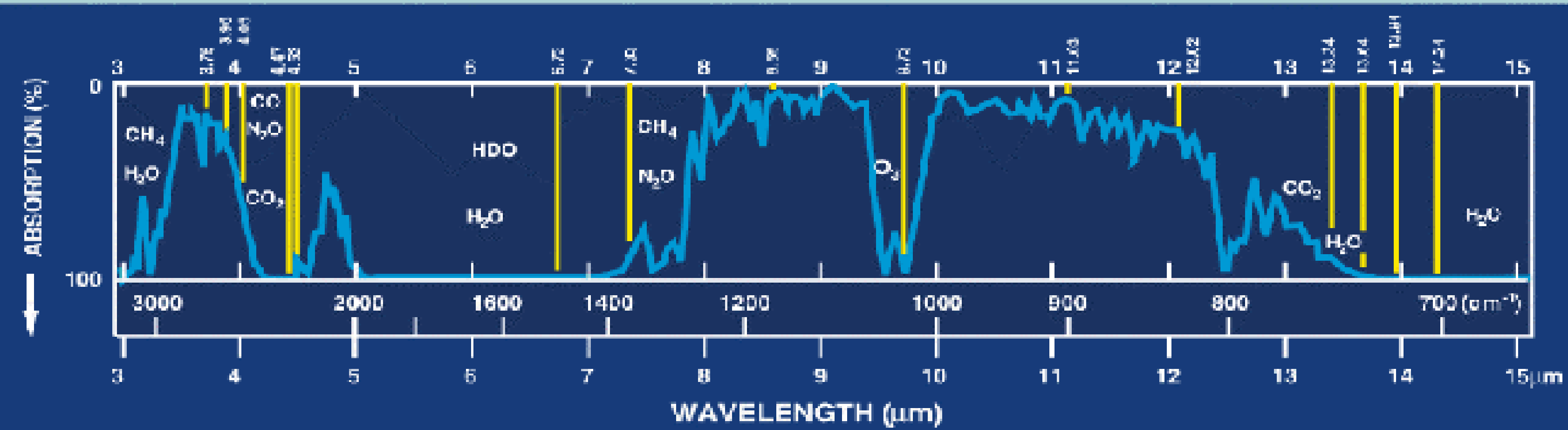
Example of Temperature Weighting functions

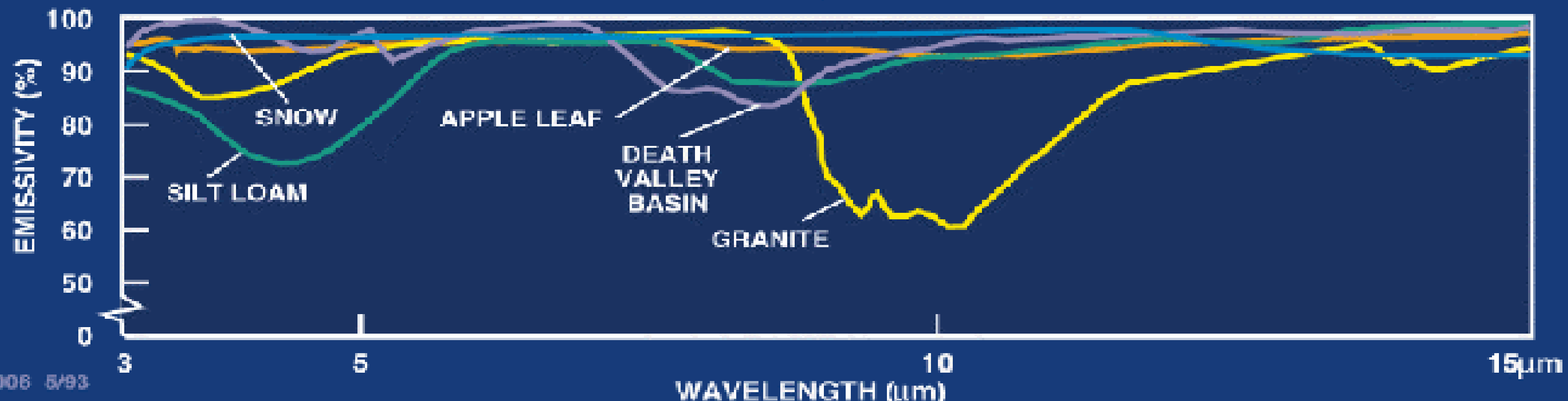


Earth emitted spectra overlaid on Planck function envelopes



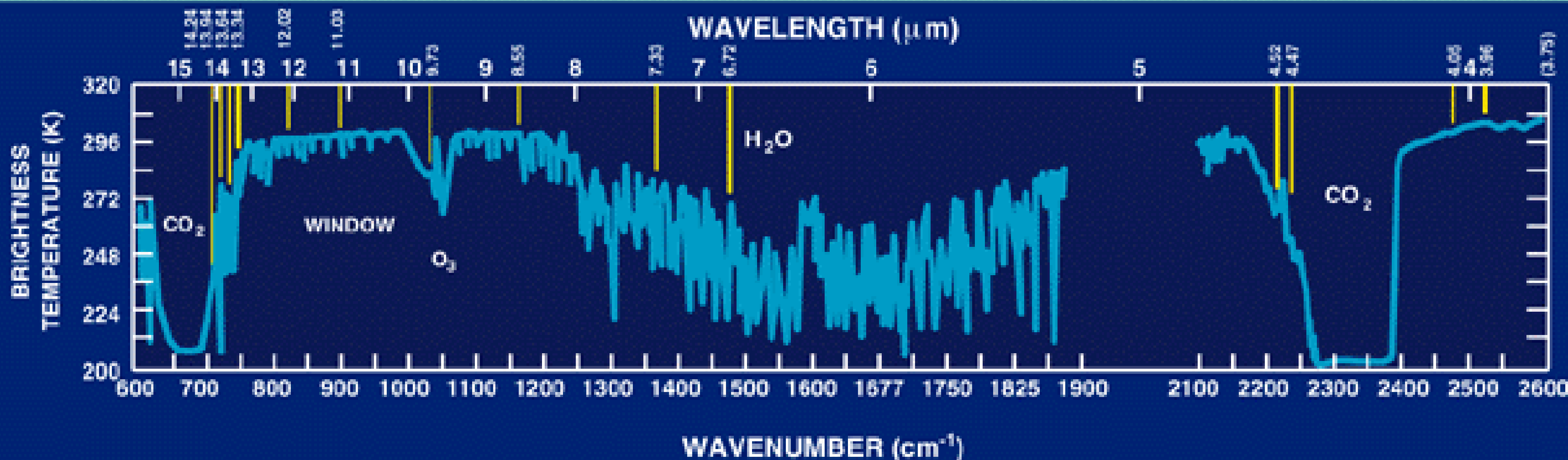
LAND - THERMAL RADIATION

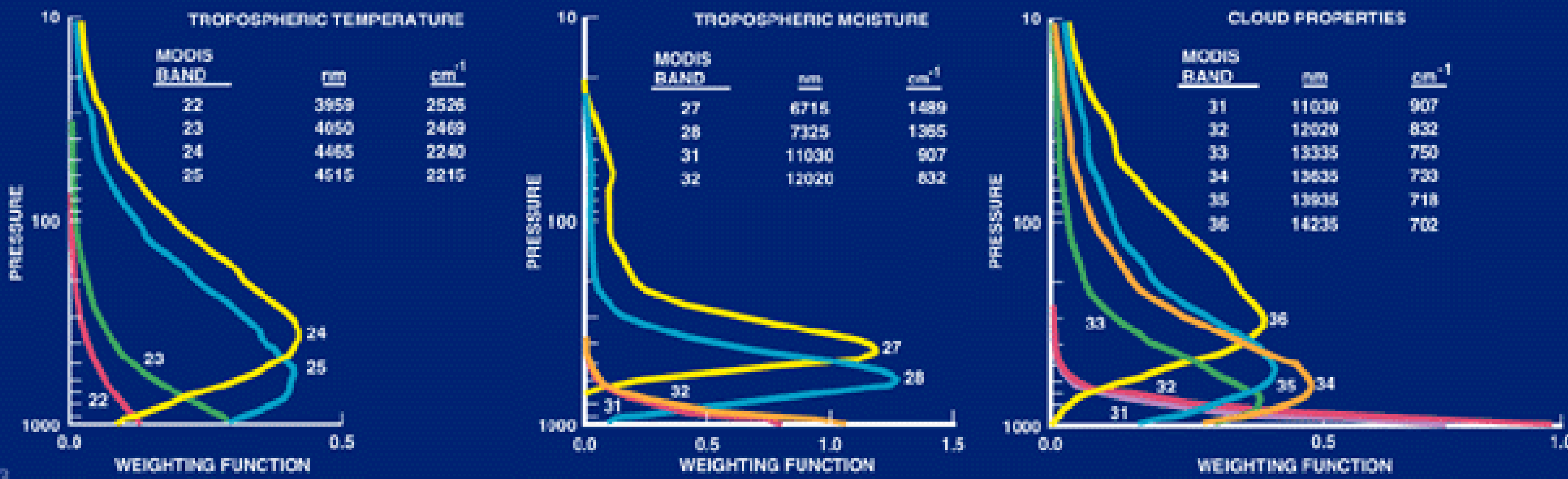




C351.006 5/93

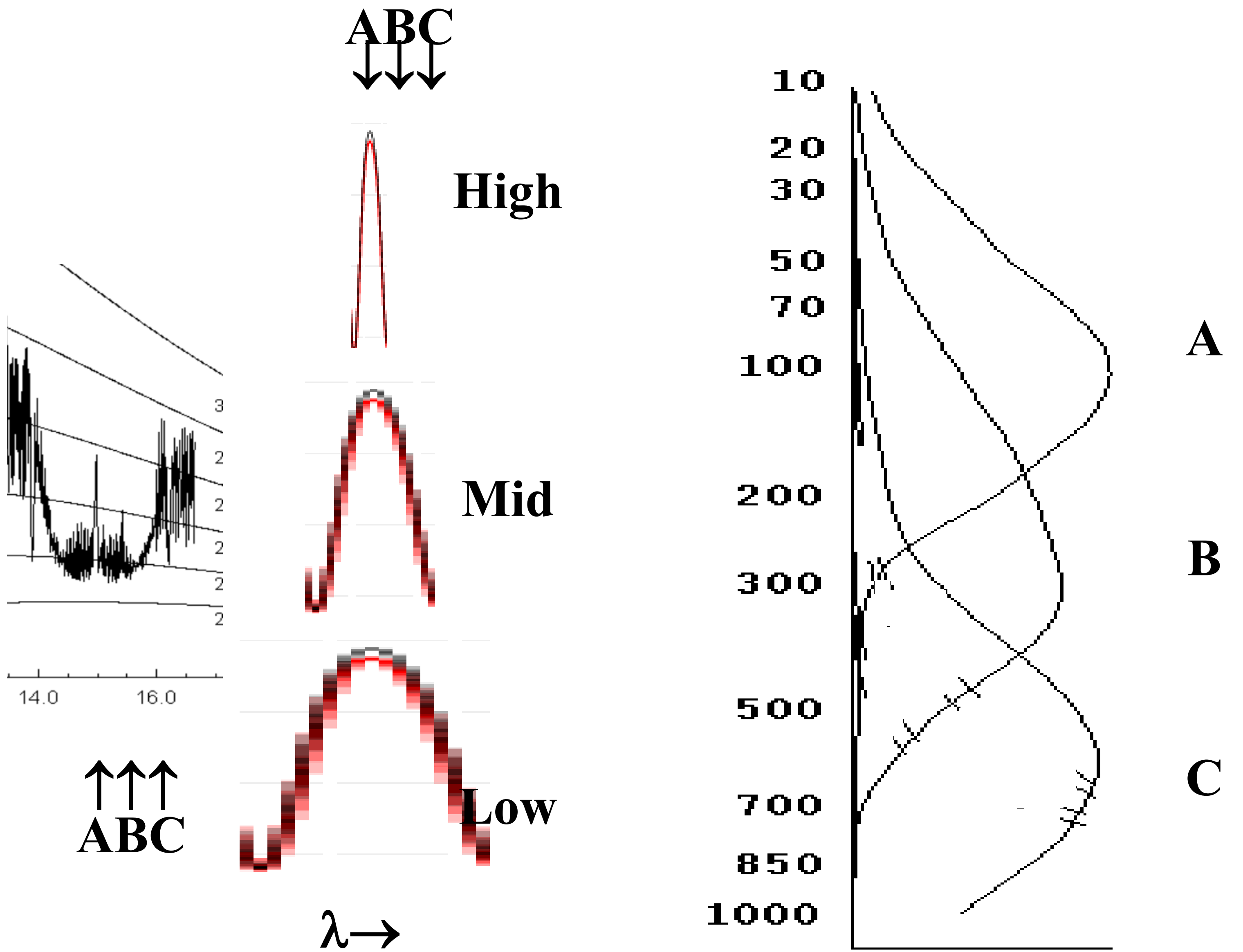
ATMOSPHERE - THERMAL RADIATION



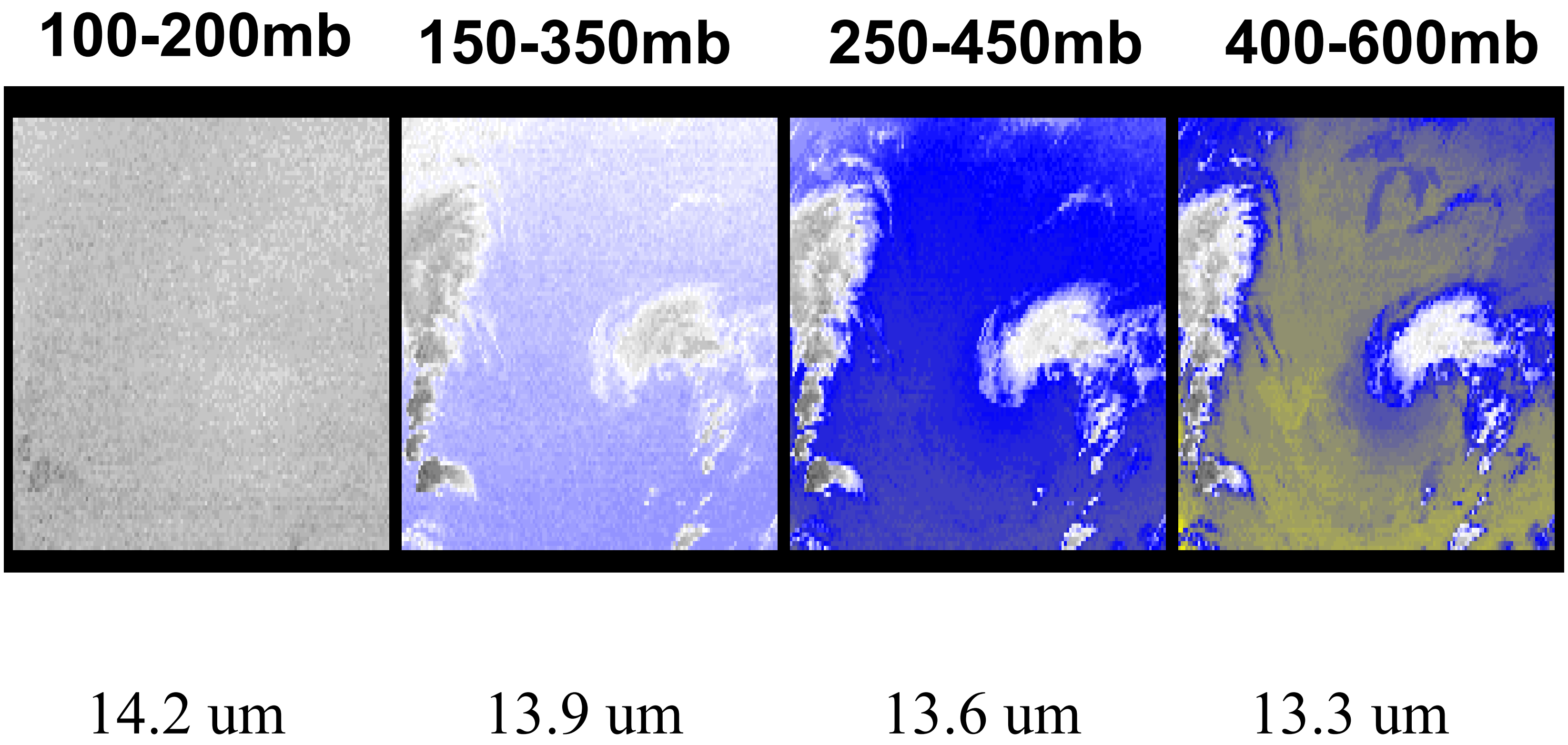


E351.002 5/93

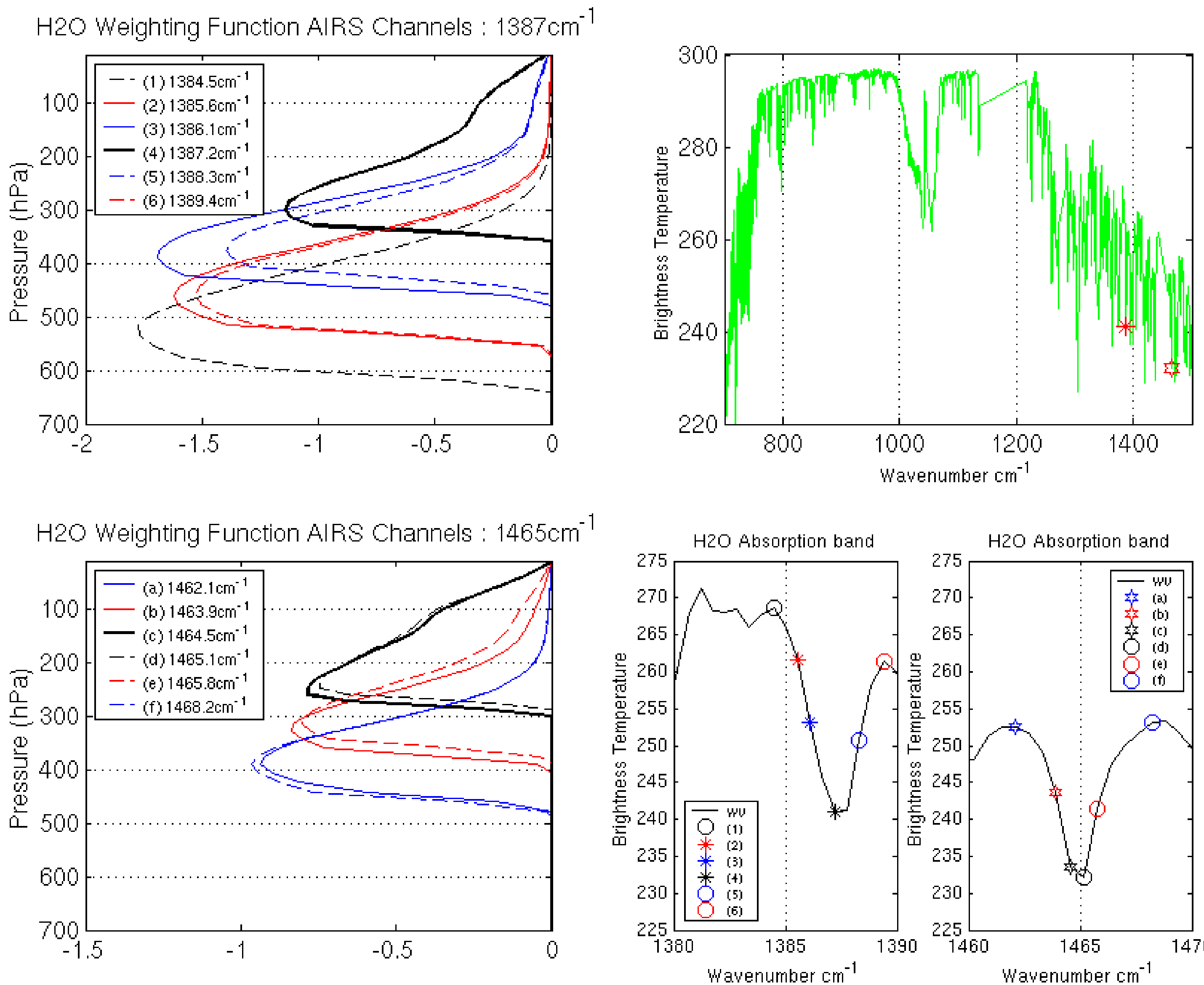
line broadening with pressure helps to explain weighting functions



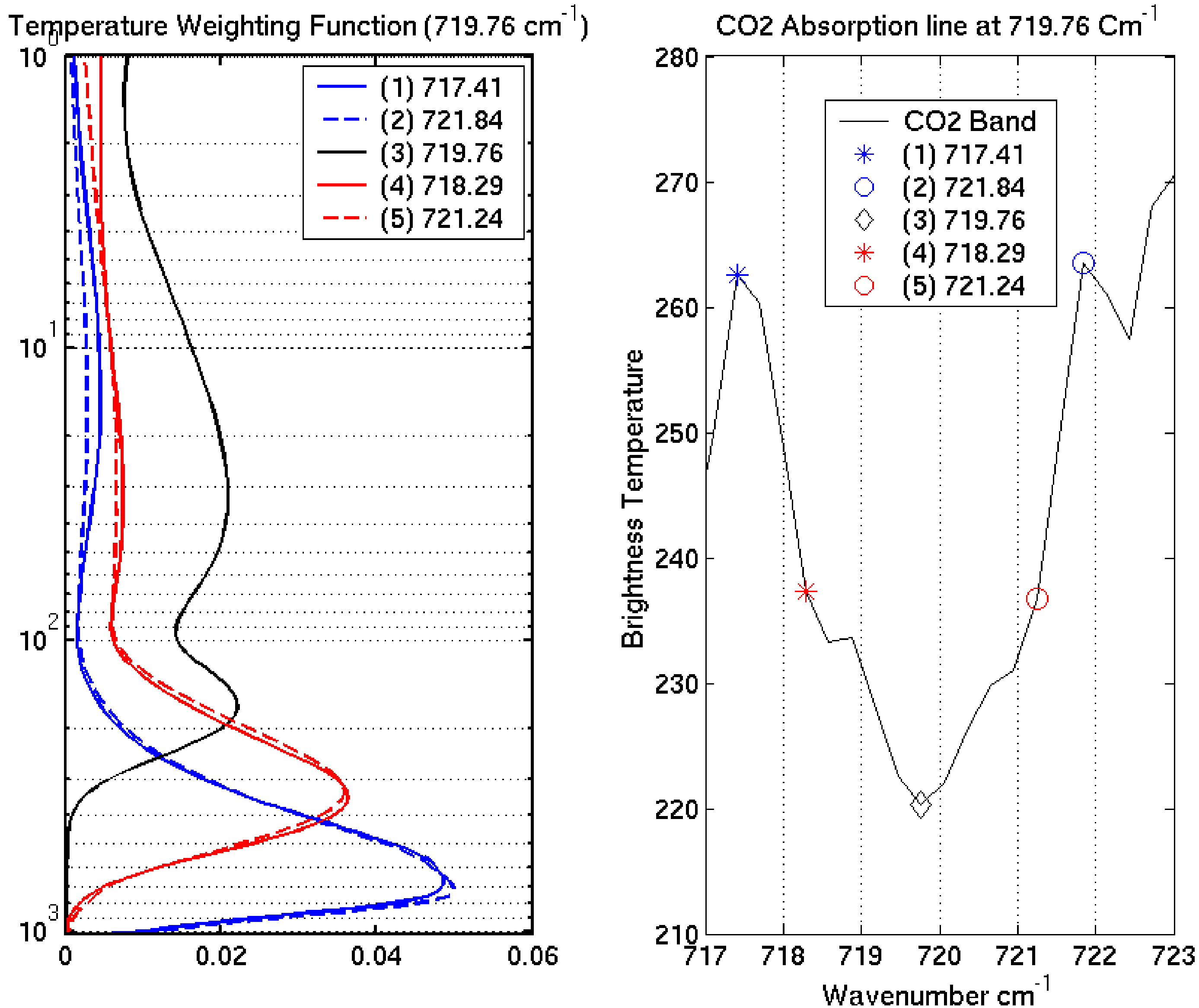
CO2 channels see to different levels in the atmosphere



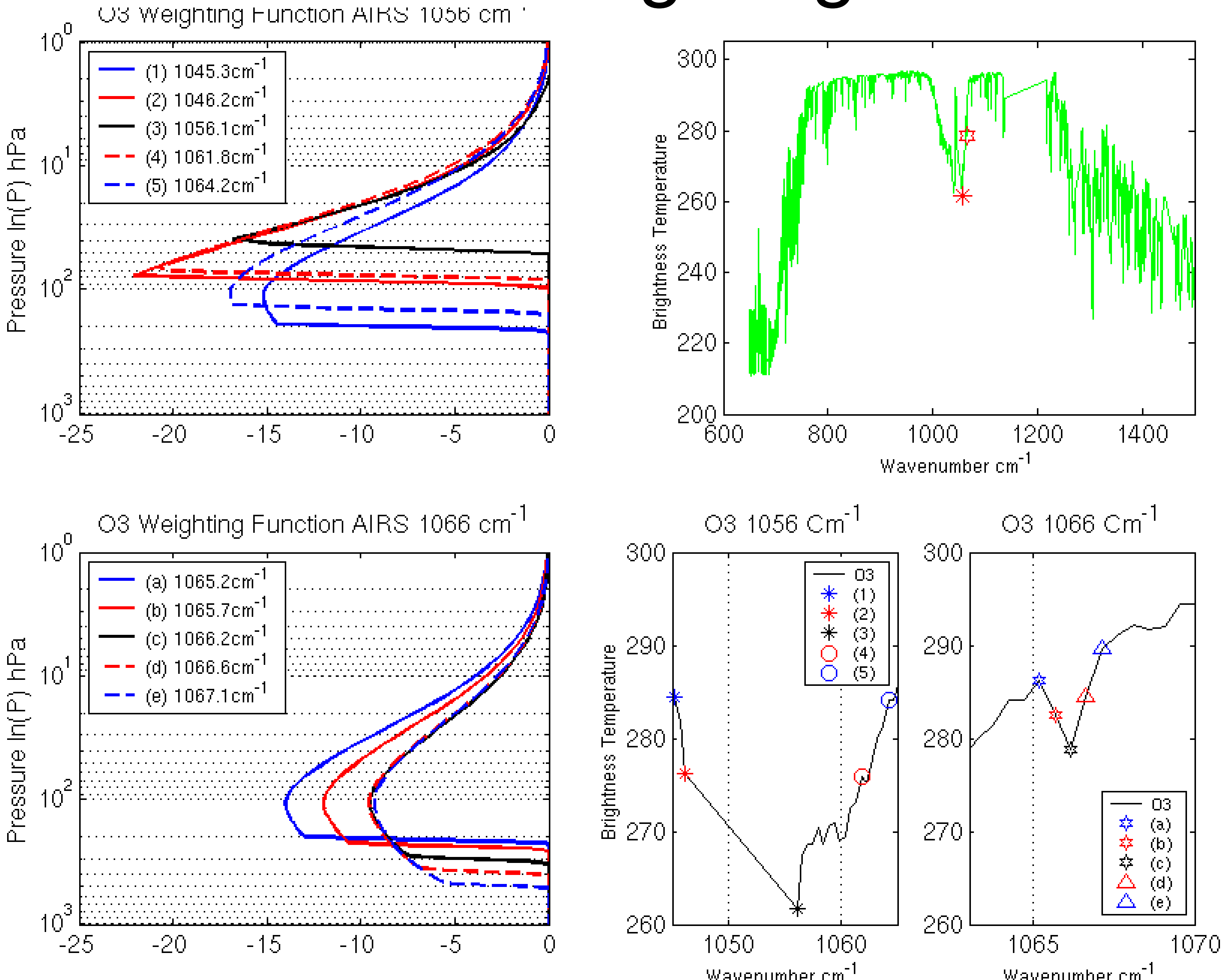
Water Vapor Band Weighting Function



CO_2 Band Weighting Function



Ozone Band Weighting Function



Characteristics of RTE

* Radiance arises from deep and overlapping layers

* The radiance observations are not independent

* There is no unique relation between the spectrum of the outgoing radiance and T(p) or Q(p)

* T(p) is buried in an exponent in the denominator in the integral

* Q(p) is implicit in the transmittance

* Boundary conditions are necessary for a solution; the better the first guess the better the final solution

Radiance received by Satellite

RTE (no scattering) in LTE

$$R_\nu = \tau_{s\nu} \cdot \varepsilon_{s\nu} \cdot B_\nu(T_S)$$ ← Upwelling IR radiation from surface

$$+ \int_{p_s}^{0} B_\nu(T(p))d\tau_\nu(p)$$ ← Upwelling IR radiation from atm. layers

$$- \tau_{s\nu} \cdot r_{s\nu} \cdot \int_{p_s}^{0} B_\nu(T(p))d\tau_\nu^*(p)$$ ← Reflected downwelling IR radiation

$$+ R_\nu^{sun} \cdot \cos(\theta) \cdot \tau_{s\nu}^{sun}(p_s) \cdot r_\nu^{sun}$$ ← Reflected solar radiation

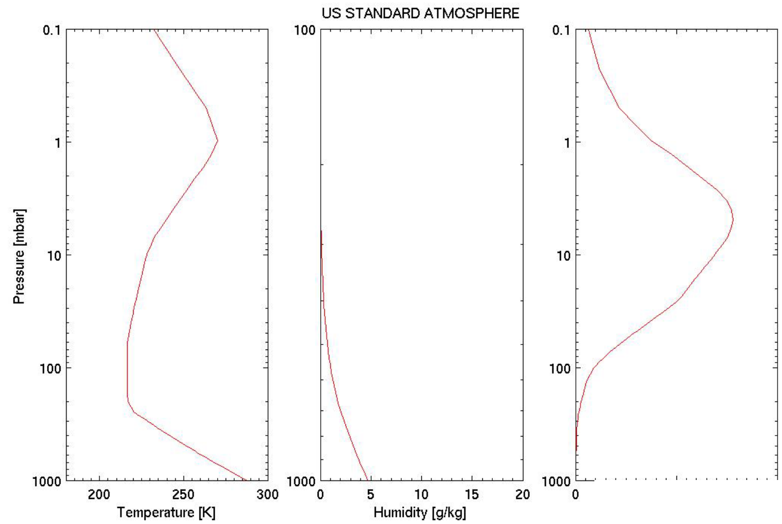
R…radiance, υ…wavenumber, *s*…surface, *p*…pressure, *sun*…solar,

T…temperature, *B*…Planck function, ε …emissivity,

τ…level to space transmittance, θ...local solar zenith angle

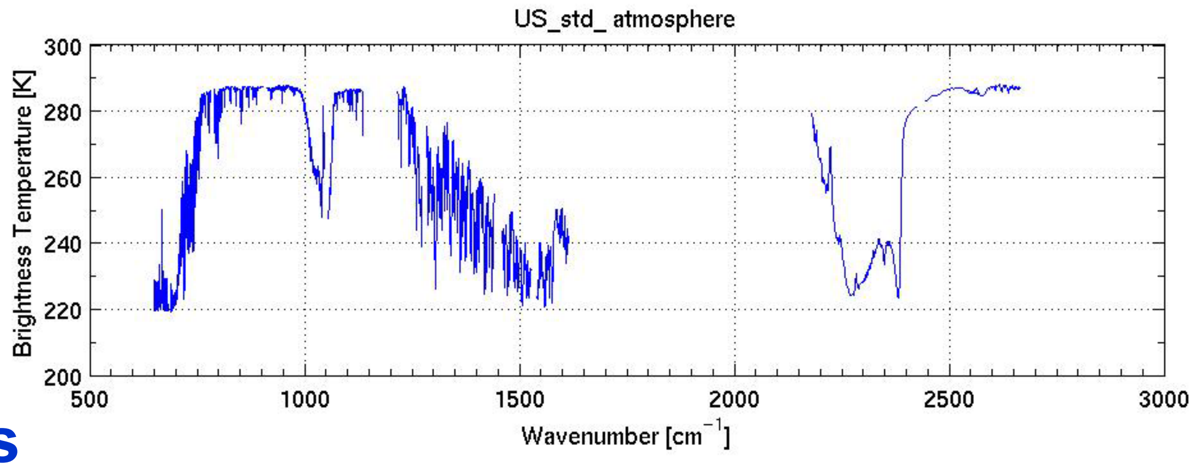
r…reflectivity, with $r = (1- \varepsilon)/\pi$,

τ^*…level to surface (downwelling) transmittance [$\tau^* = \tau_\upsilon^2(p_s)/ \tau_\upsilon(p)$]

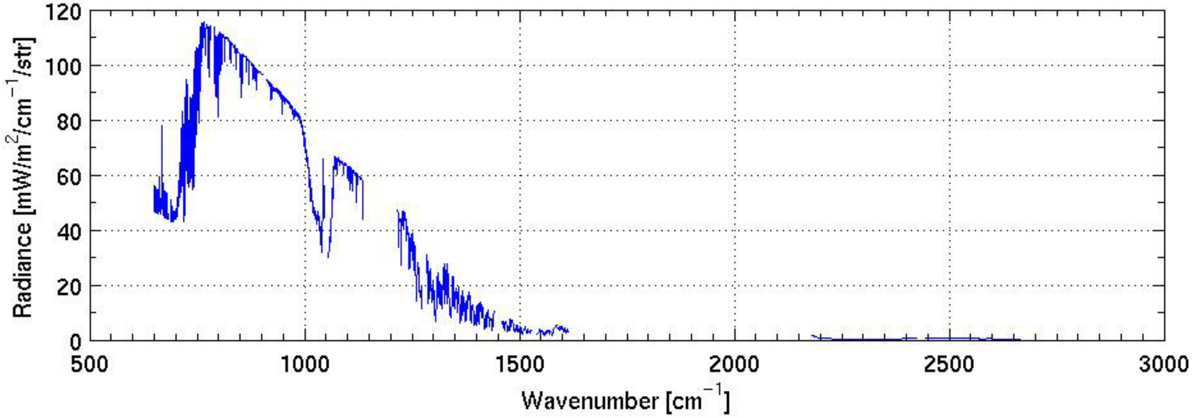


RTE

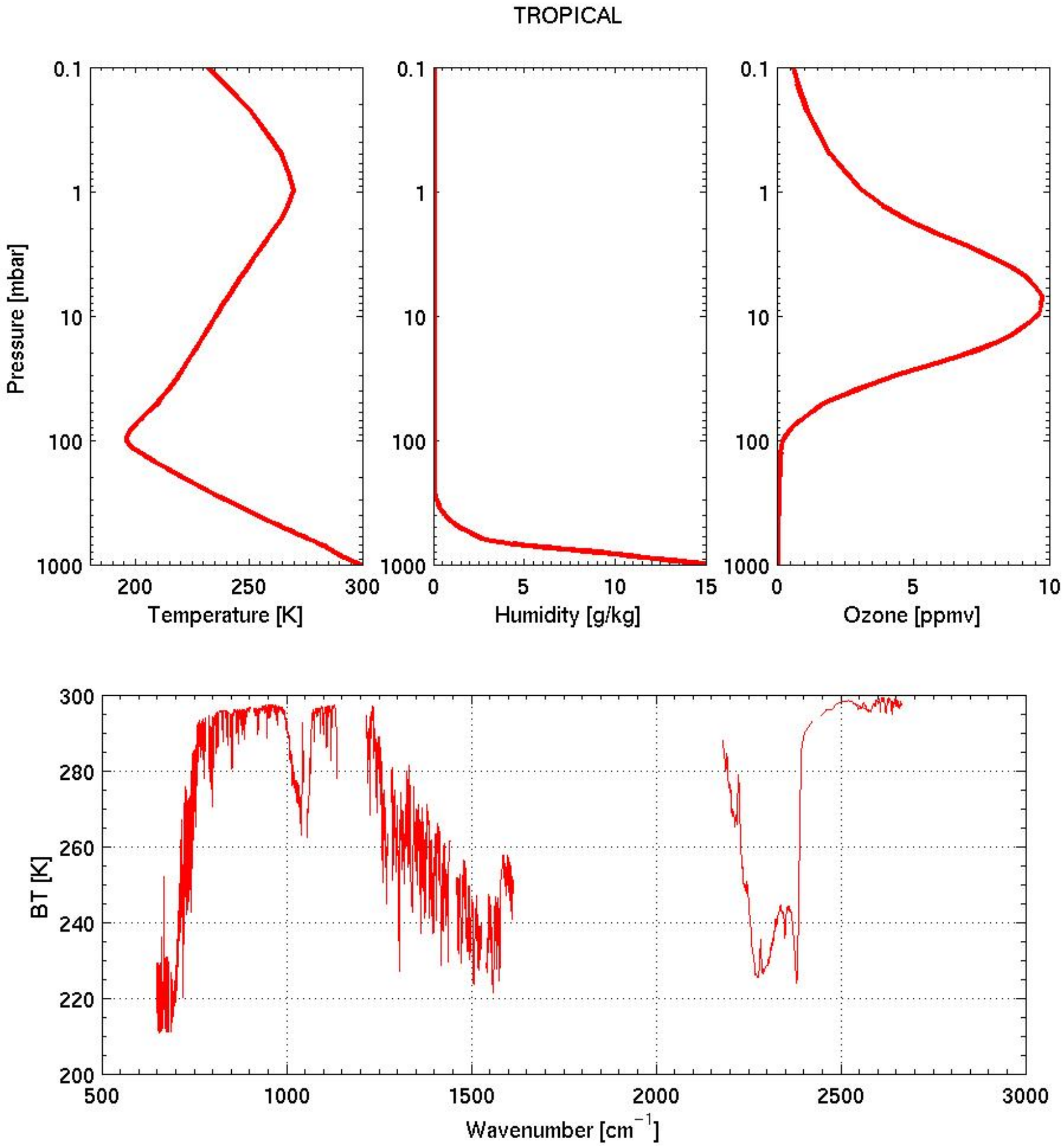
Atmospheric Profile



Satellite IR Radiances



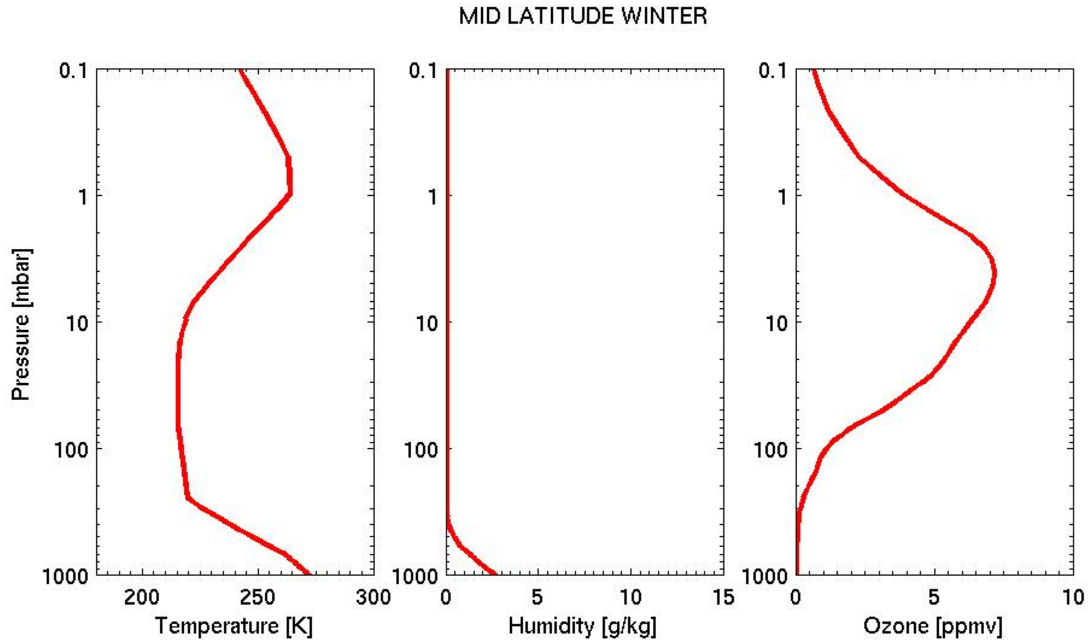
AIRS T,q, O3 profile and simulated spectrum - tropical

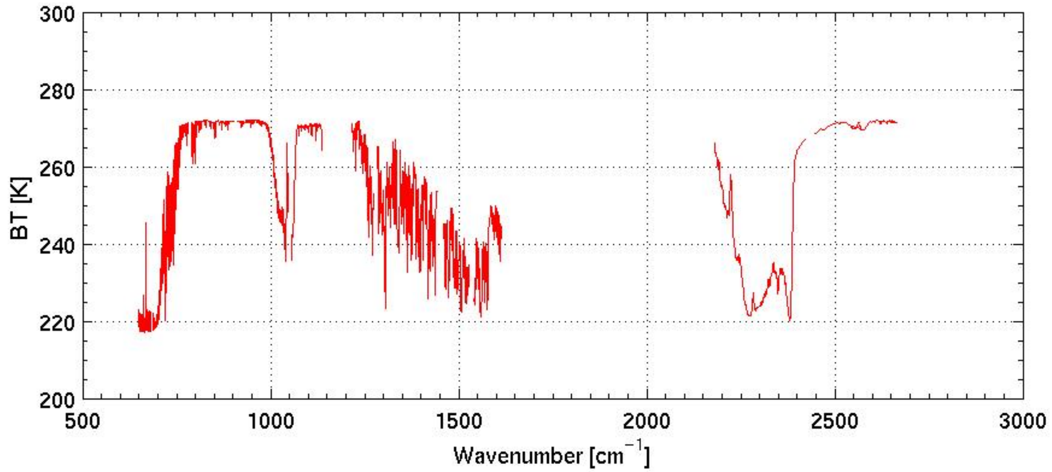


Tropical Profile:

- sharp tropopause at ~100 mbar
- high water vapor amount
- high T gradient in troposphere (~100 K) and stratosphere (~80 K)
- high skin temperatures

AIRS T,q, O3 profile and simulated spectrum – midlatitude winter

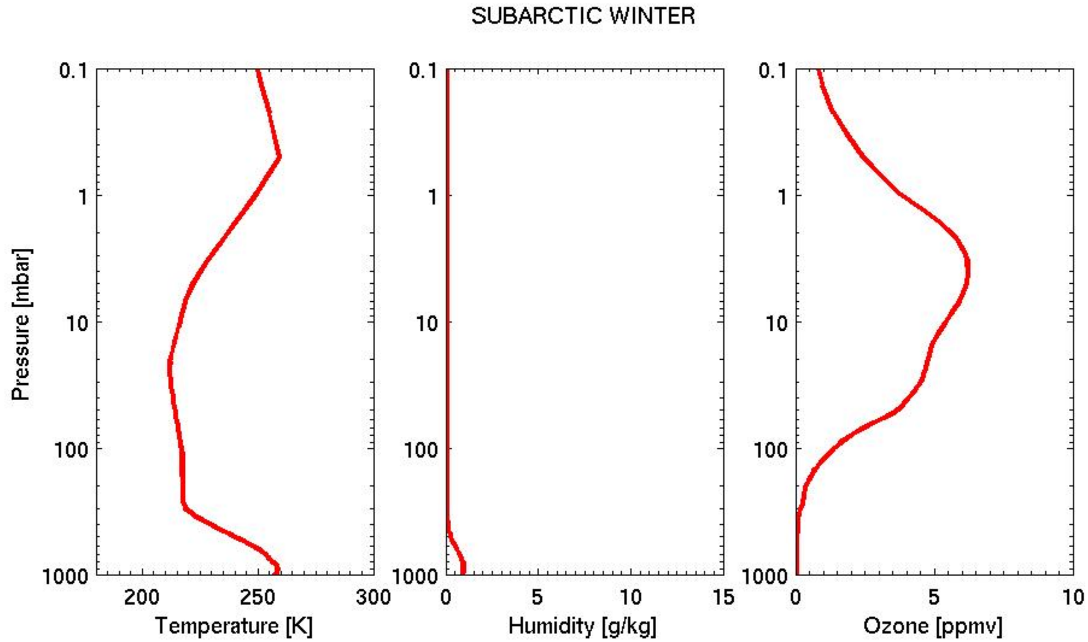


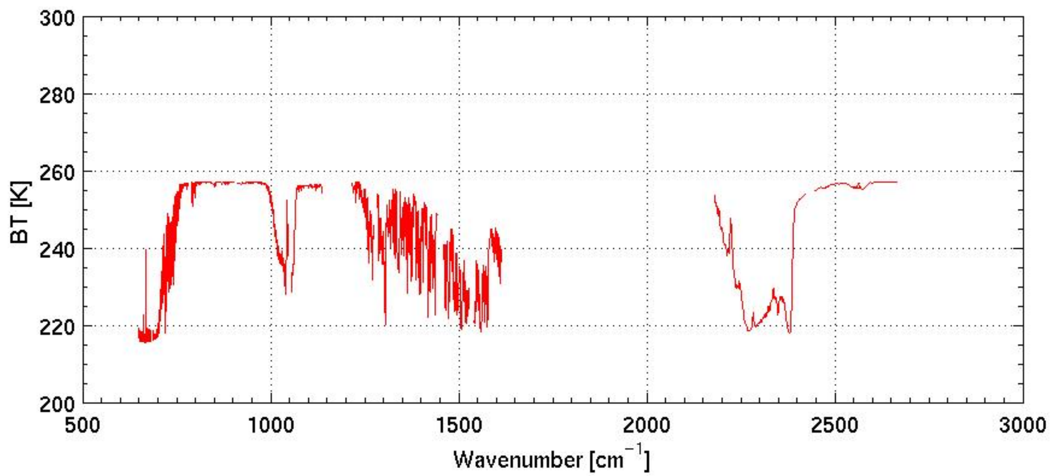


<u>Midlatitude Summer Profile:</u>

- T near surface ~ 260 K
- tropopause at < 100 mbar
- ~constant temperature above tropopause
- smaller T gradient in troposphere and stratosphere
- less moisture
- lower skin temperatures

AIRS T,q, O3 profile and simulated spectrum – subarctic winter





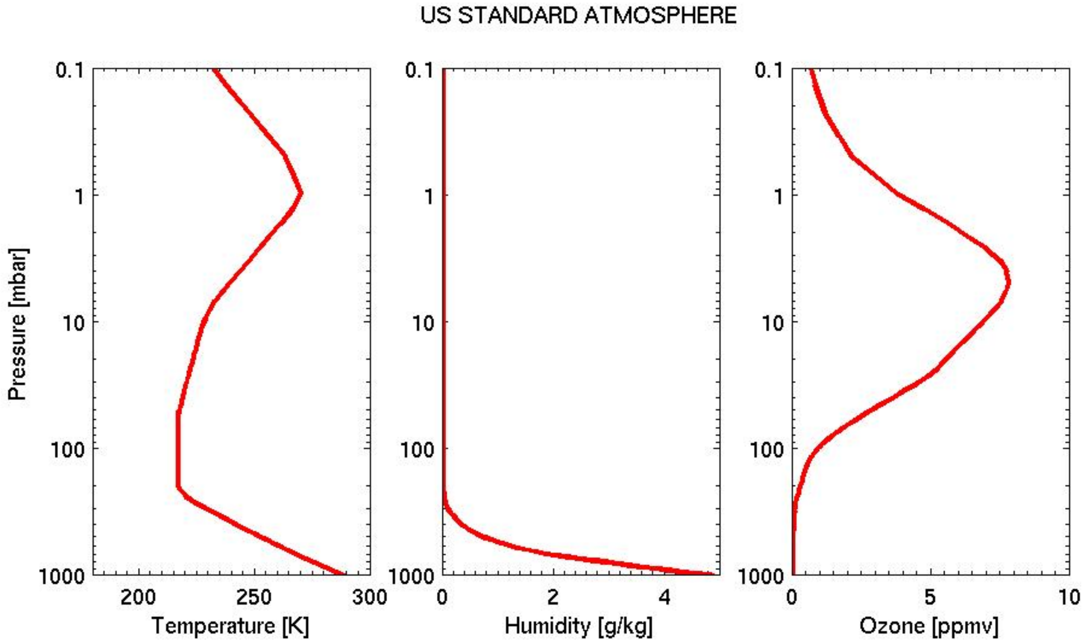
Subarctic Winter Profile:

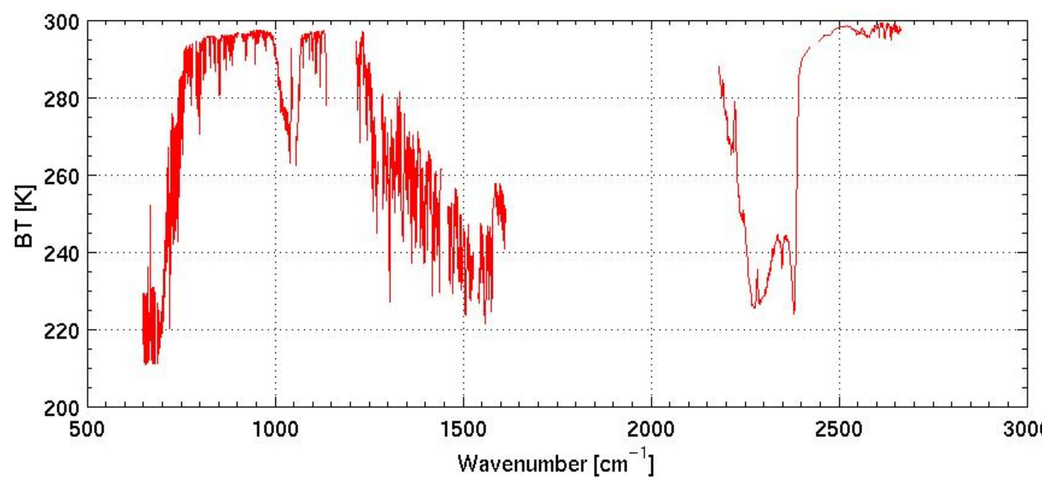
- T near surface < 260 K
- tropopause at < 100 mbar
- ~constant temperature above tropopause (20-200mbar)
- small T gradient in troposphere
- very dry
- low skin temperatures

Opaque Cloud Simulation – Clear Conditions

<u>Clear Profile:</u>

- Skin Temperature ~290 K
- Moisture near surface ~5 g/kg
- Tropopause at ~ 200 mbar
- constant T from 100 to 200 mbar
- maximum ozone at ~5 mbar
- T gradient in troposphere ~80 K

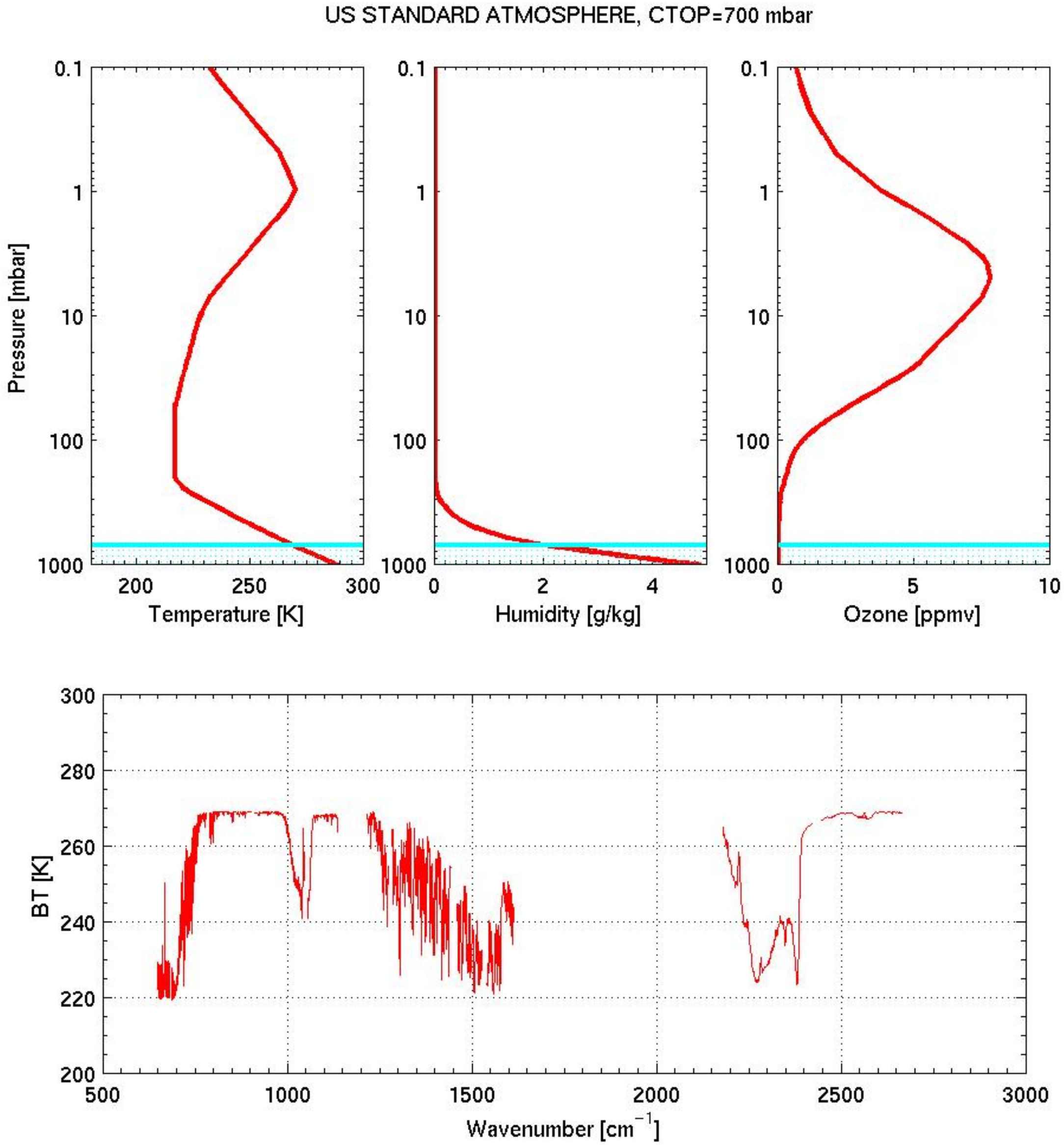




Opaque Cloud Simulation – Cloudtop at 700 mbar

Opaque Cloud at 700 mbar:

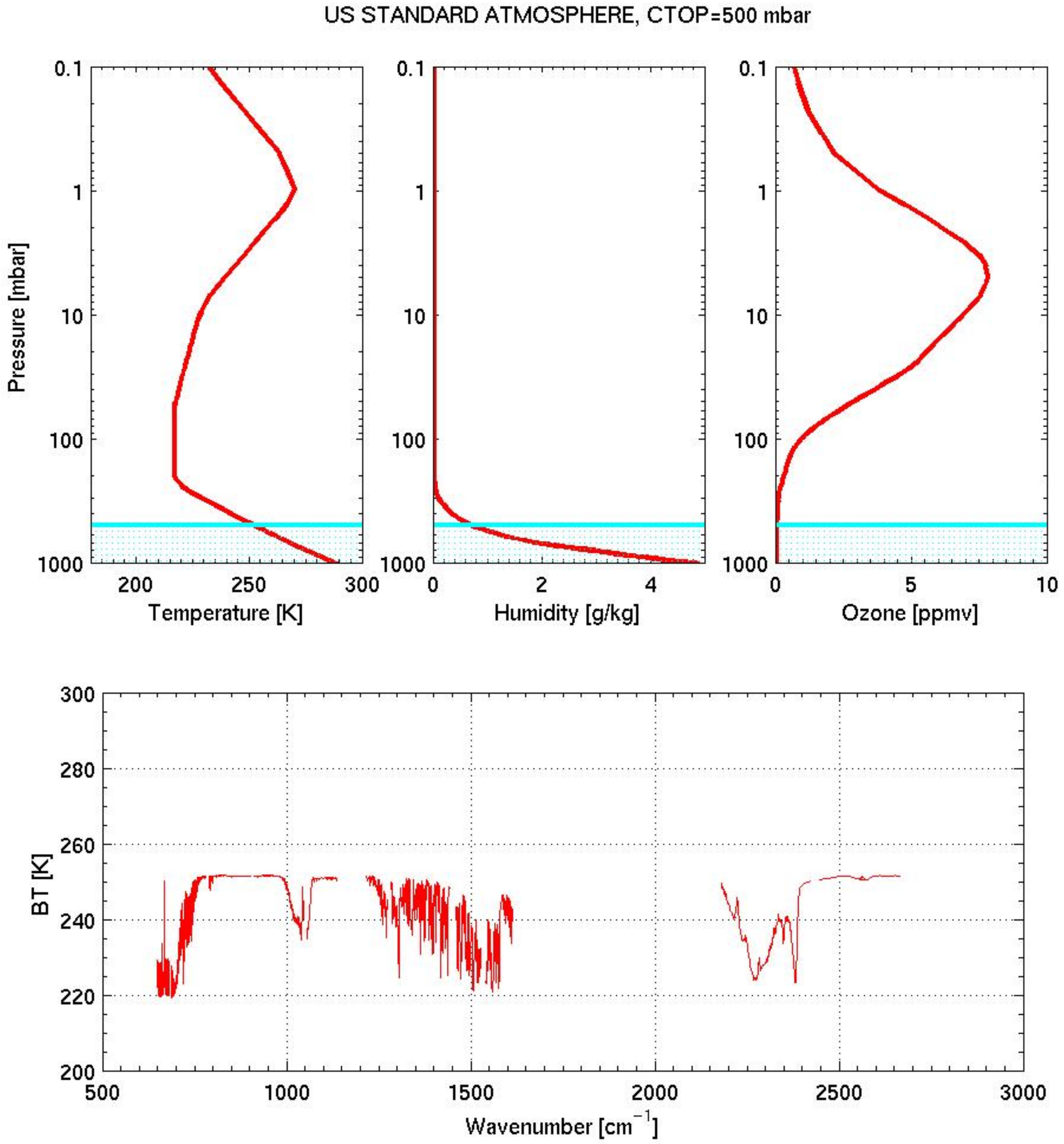
- T at cloudtop at ~270 K
- Moisture at cloudtop ~2 g/kg
- T gradient in troposphere above cloud ~60 K



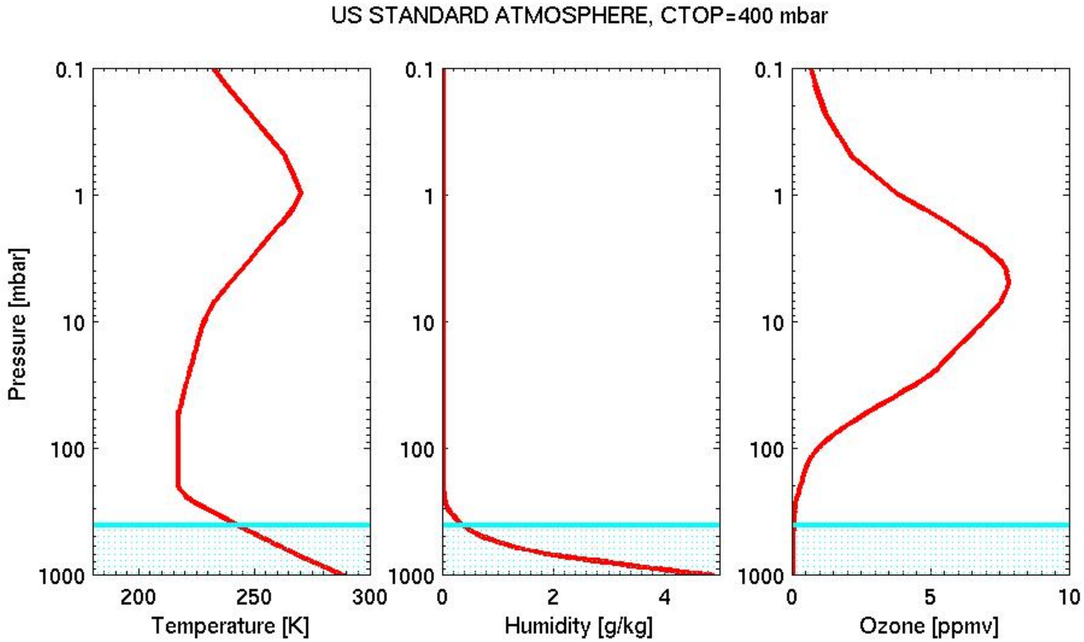
Opaque Cloud Simulation – Cloudtop at 500 mbar

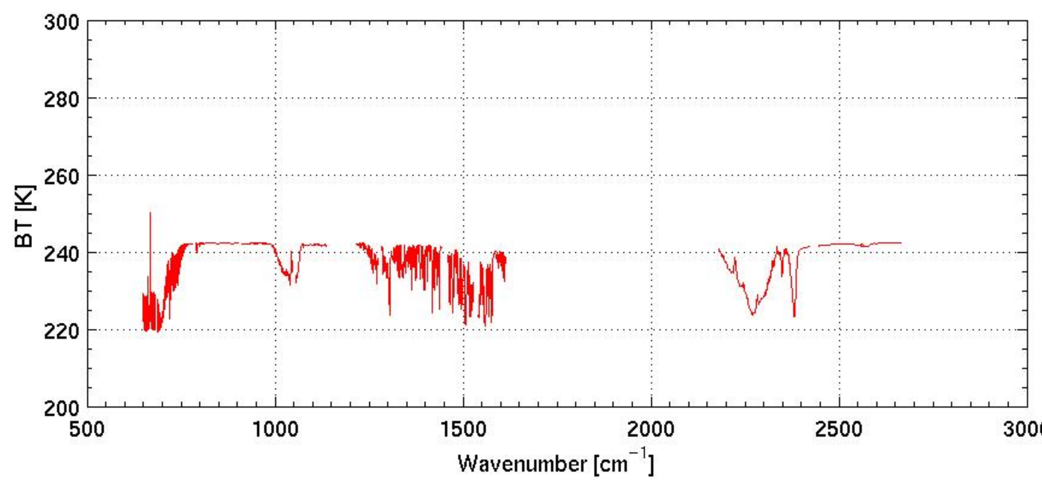
<u>Opaque Cloud at 500 mbar:</u>

- T at cloudtop at ~250 K
- Moisture at cloudtop ~2 g/kg
- T gradient in troposphere above cloud ~30 K



Opaque Cloud Simulation – Cloudtop at 400 mbar

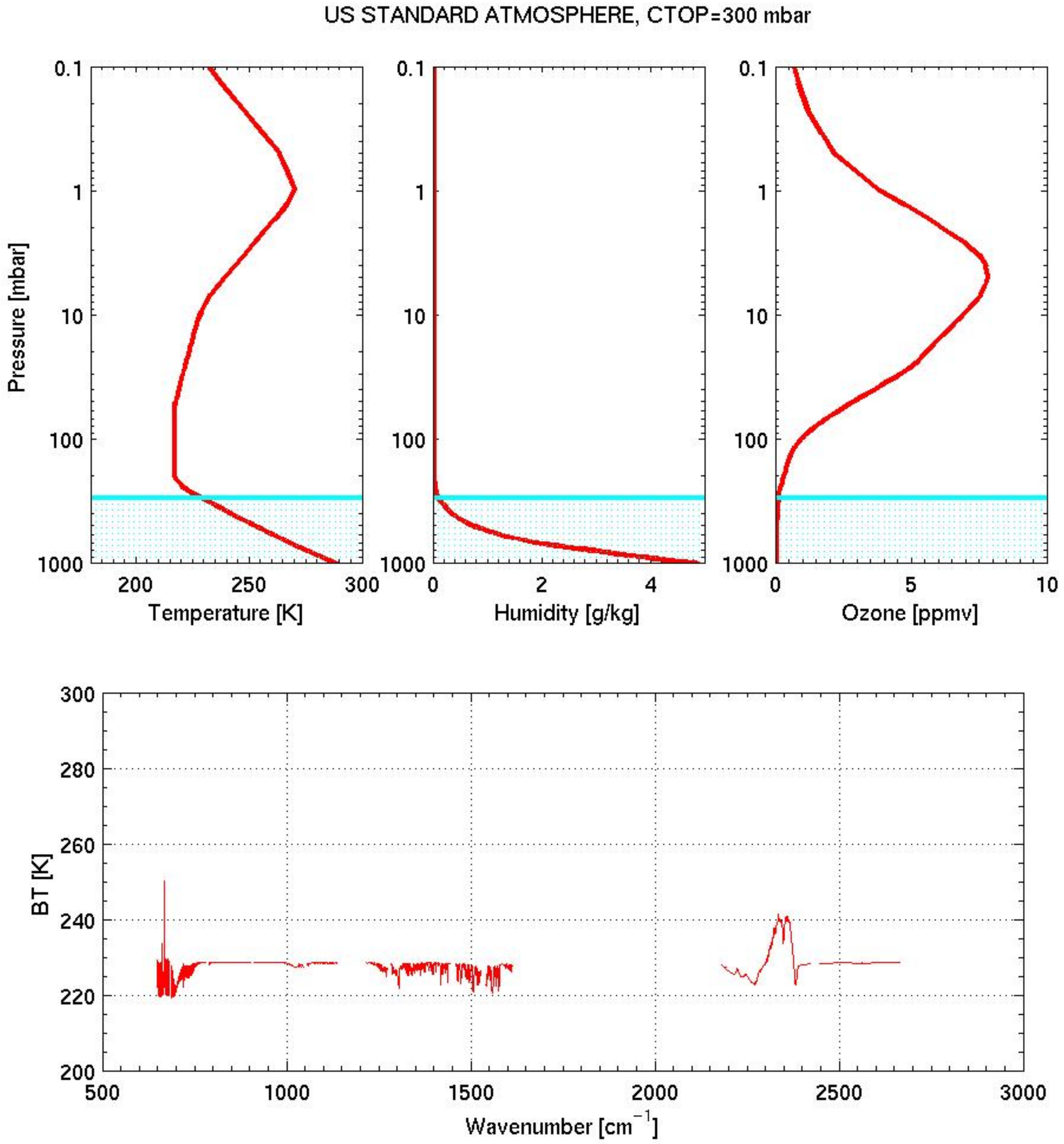




Opaque Cloud at 400 mbar:

- T at cloudtop at ~240 K
- Moisture at cloudtop < 1 g/kg
- T gradient in troposphere above cloud ~20 K
- Few upper layers (~stratopause) warmer than cloudtop

Opaque Cloud Simulation – Cloudtop at 300 mbar



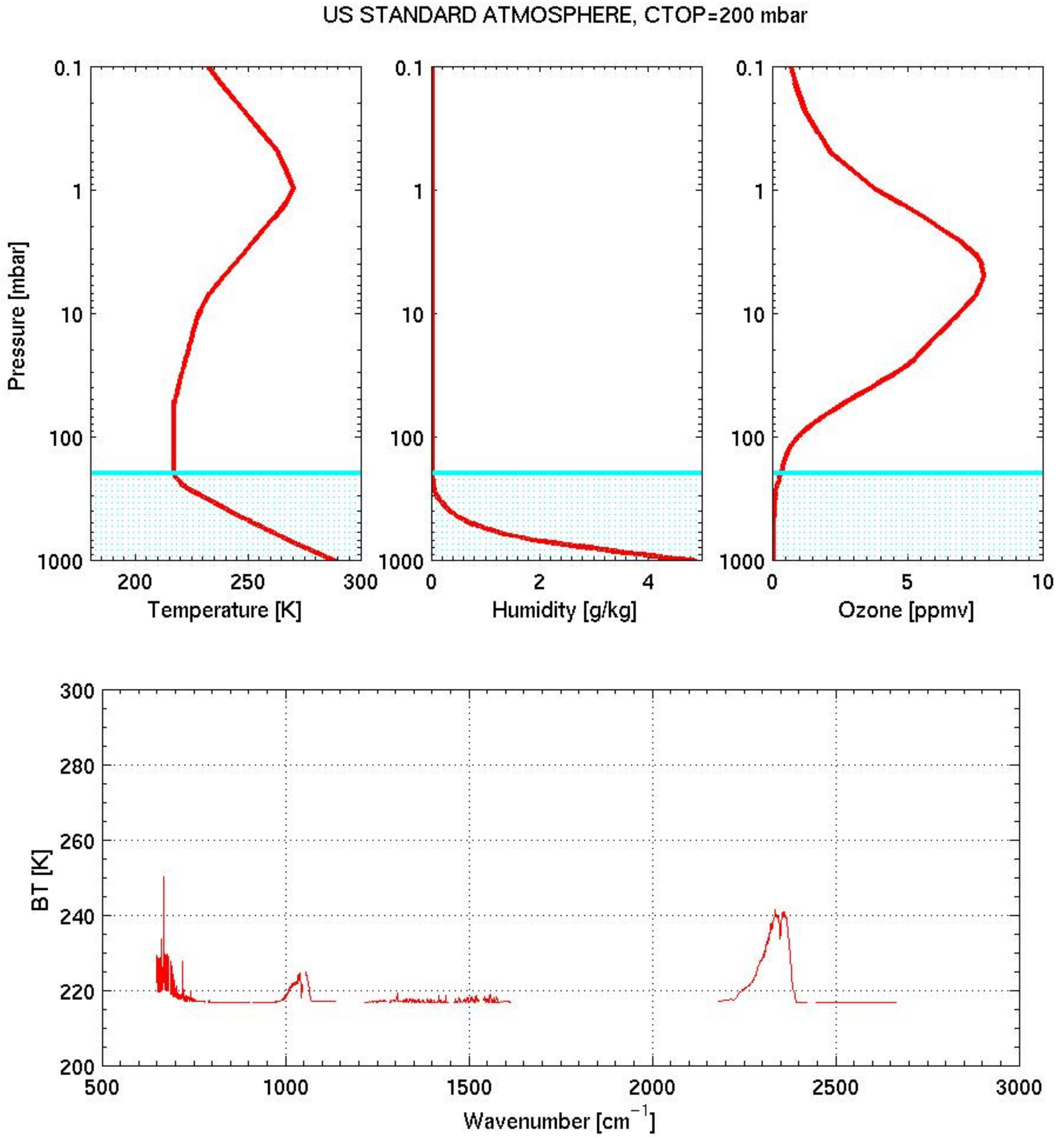
Opaque Cloud at 400 mbar:

- T at cloudtop at ~230 K
- very little moisture above cloud
- T gradient in troposphere above cloud ~10 K
- Upper layers (stratosphere) warmer than cloudtop
- T at Ozone layer ~ T at cloudtop

Opaque Cloud Simulation – Cloudtop at 200 mbar

<u>Opaque Cloud at 200 mbar:</u>

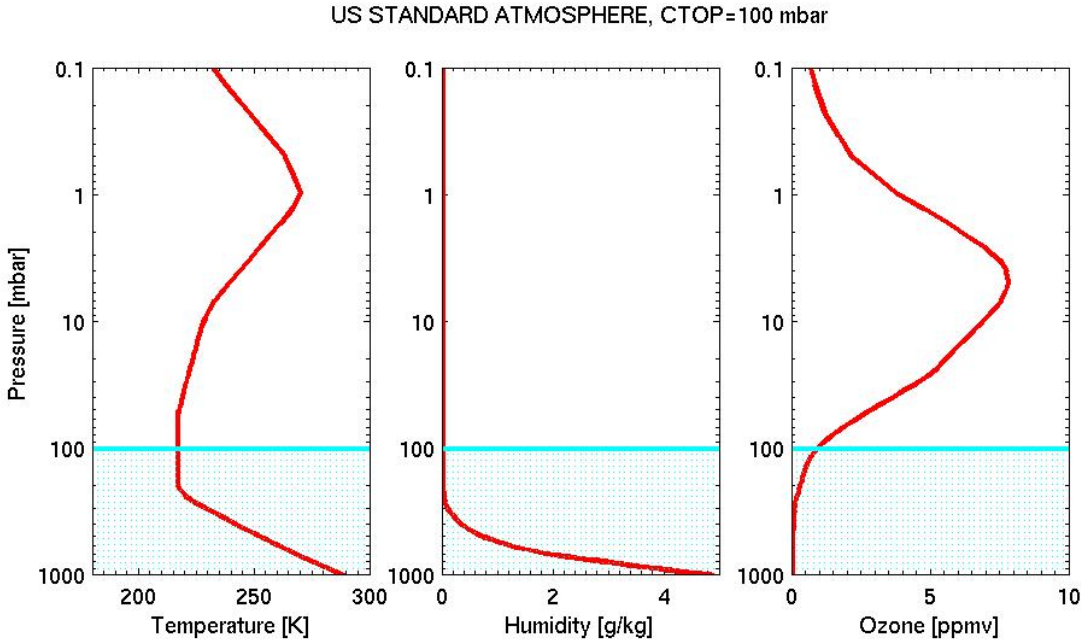
- T at cloudtop at ~220 K
- essentially no moisture above cloud
- Every layer above cloud is warmer than cloudtop

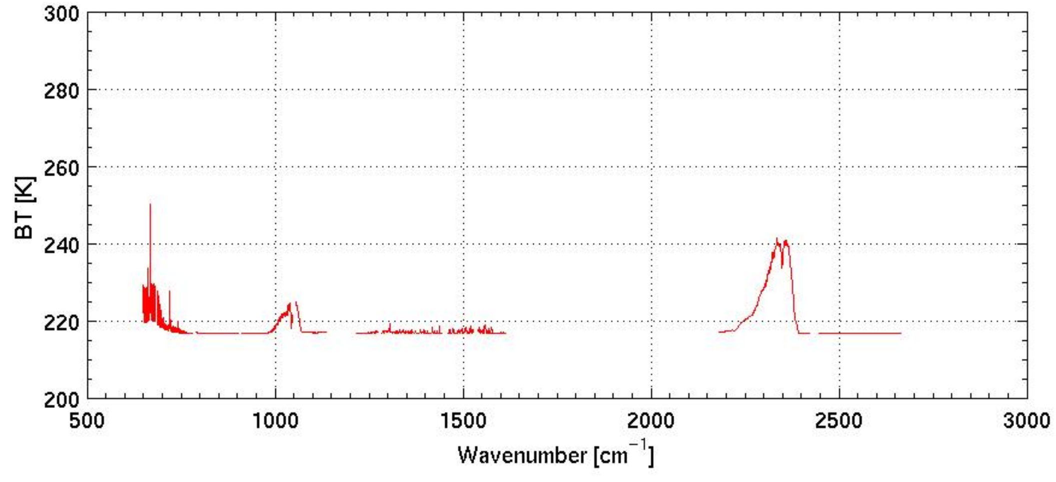


Opaque Cloud Simulation – Cloudtop at 100 mbar

Opaque Cloud at 100 mbar:

- same results as for 200 mbar since there is no change in T between 100 and 200 mbar
- T at cloudtop at ~220 K
- no moisture above cloud
- Every layer above cloud is warmer than cloudtop





Radiance received by Satellite

RTE (no scattering) in LTE

$$R_\nu = \tau_{s\nu} \cdot \varepsilon_{s\nu} \cdot B_\nu(T_S)$$ ← Upwelling IR radiation from surface

$$+ \int_{p_s}^{0} B_\nu(T(p))\, d\tau_\nu(p)$$ ← Upwelling IR radiation from atm. layers

$$- \tau_{s\nu} \cdot r_{s\nu} \cdot \int_{p_s}^{0} B_\nu(T(p))\, d\tau_\nu^*(p)$$ ← Reflected downwelling IR radiation

$$+ R_\nu^{sun} \cdot \cos(\theta) \cdot \tau_{s\nu}^{sun}(p_s) \cdot r_\nu^{sun}$$ ← Reflected solar radiation

R…radiance, υ…wavenumber, *s*…surface, *p*…pressure, *sun*…solar,

T…temperature, *B*…Planck function, ε …emissivity,

τ…level to space transmittance, θ...local solar zenith angle

r…reflectivity, with $r = (1-\varepsilon)/\pi$,

τ^*…level to surface (downwelling) transmittance [$\tau^* = \tau_\upsilon^2(p_s)/\tau_\upsilon(p)$]