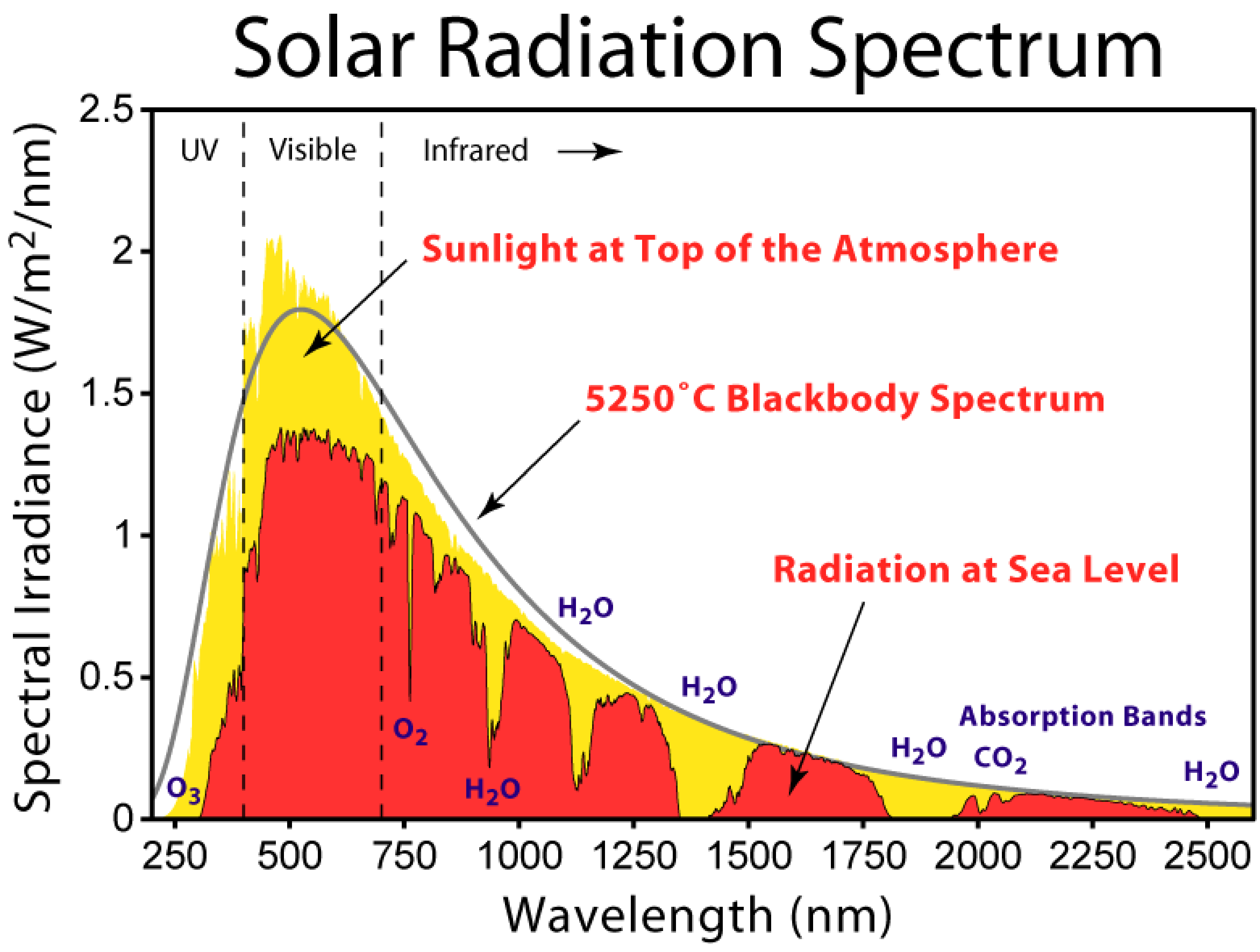
Thermal Infrared Radiation and Carbon Dioxide in the Atmosphere

Bill Satzer

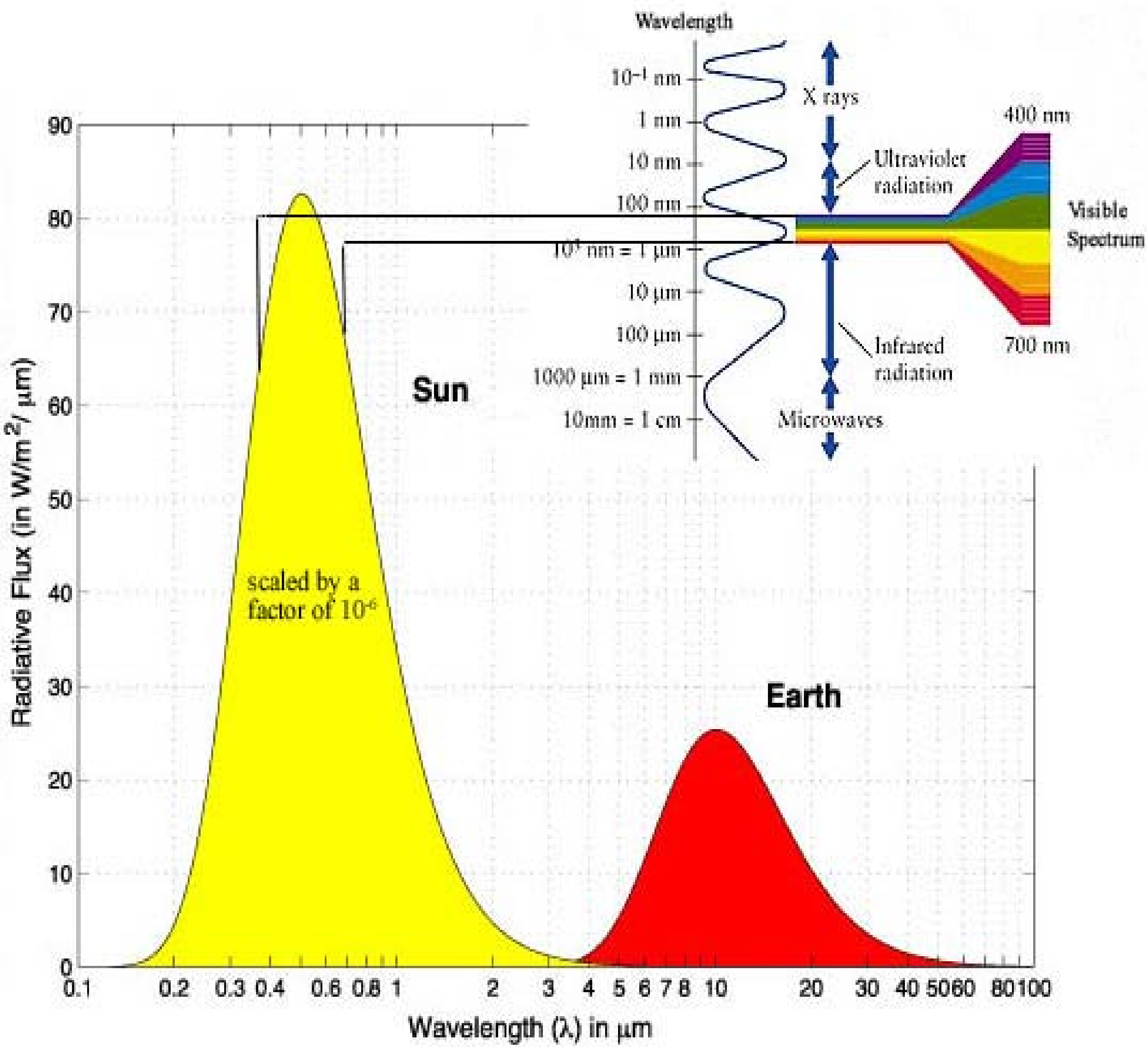
3M Company

Outline

- Radiation spectra – incoming and outgoing
- Physical setting – characteristics of the atmosphere
- CO_2 interaction with infrared
- Basic model and some results



Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250˚C Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500


Wavelength
10⁻¹ nm
1 nm
10 nm
100 nm
10³ nm = 1 μm
10 μm
100 μm
1000 μm = 1 mm
10mm = 1 cm
X rays
Ultraviolet radiation
Infrared radiation
Microwaves
400 nm
700 nm
Visible Spectrum
Sun
scaled by a factor of 10⁻⁶
Earth
Radiative Flux (in W/m²/ μm)
Wavelength (λ) in μm
0
10
20
30
40
50
60
70
80
90
0.1
0.2
0.3
0.4
0.6
0.8
1
2
3
4
5
6
7
8
10
20
30
40
50
60
80
100

Earth's emitted spectrum

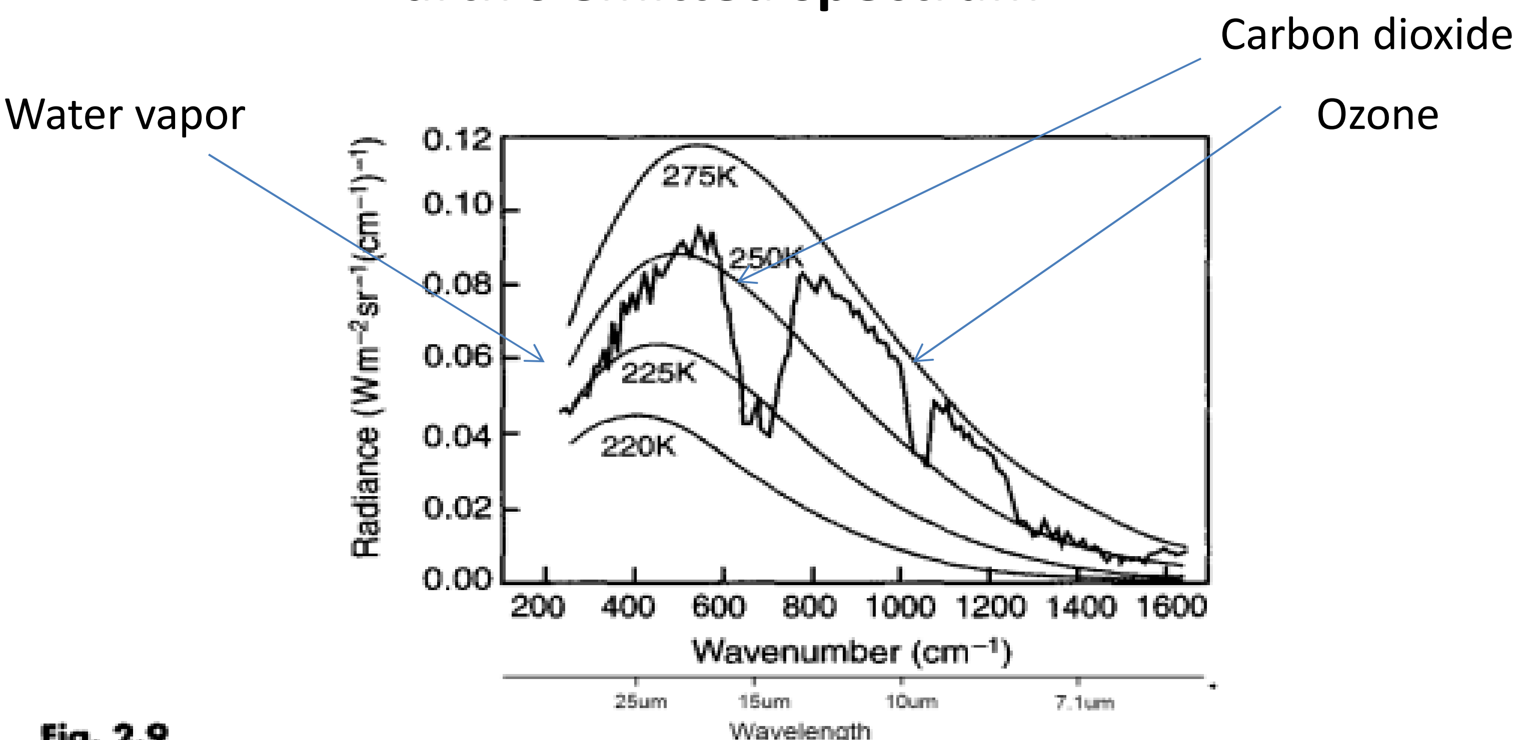


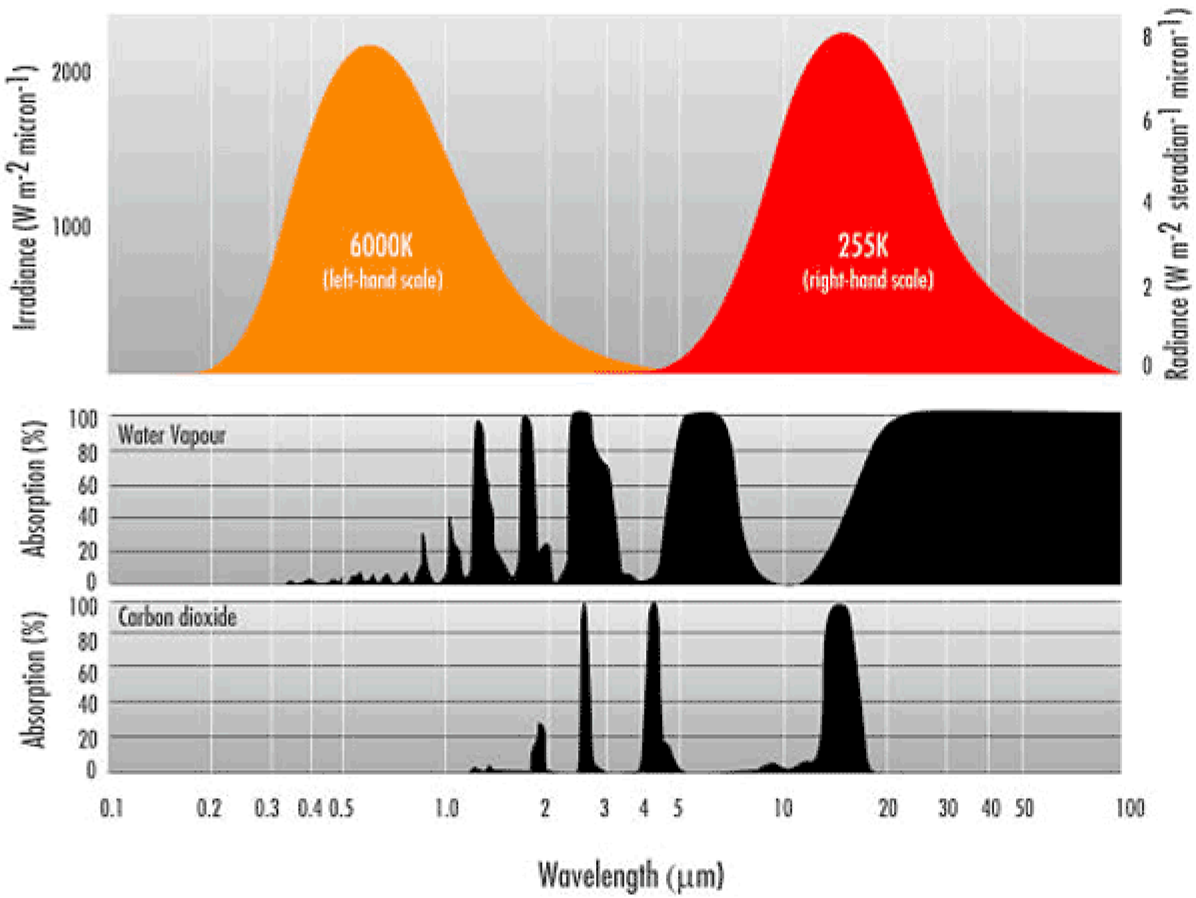
Fig. 2.9

The spectrum of the infrared energy emitted by the Earth.[32] The various features are the absorption/emission bands of atmospheric gases, especially water vapour, ozone, and carbon dioxide (Fig. 2.5). The area under the Earth's spectrum, when averaged over latitude, longitude, and time, and integrated over wavelength, is about the same as the area obtained by integrating the Planck function (represented at four different temperatures by the smooth curves) for a temperature of 255K. At this temperature, the thermal infrared emission from the Earth just balances the incoming solar radiative energy at shorter UV, visible, and near-infrared wavelengths.

Atmospheric composition

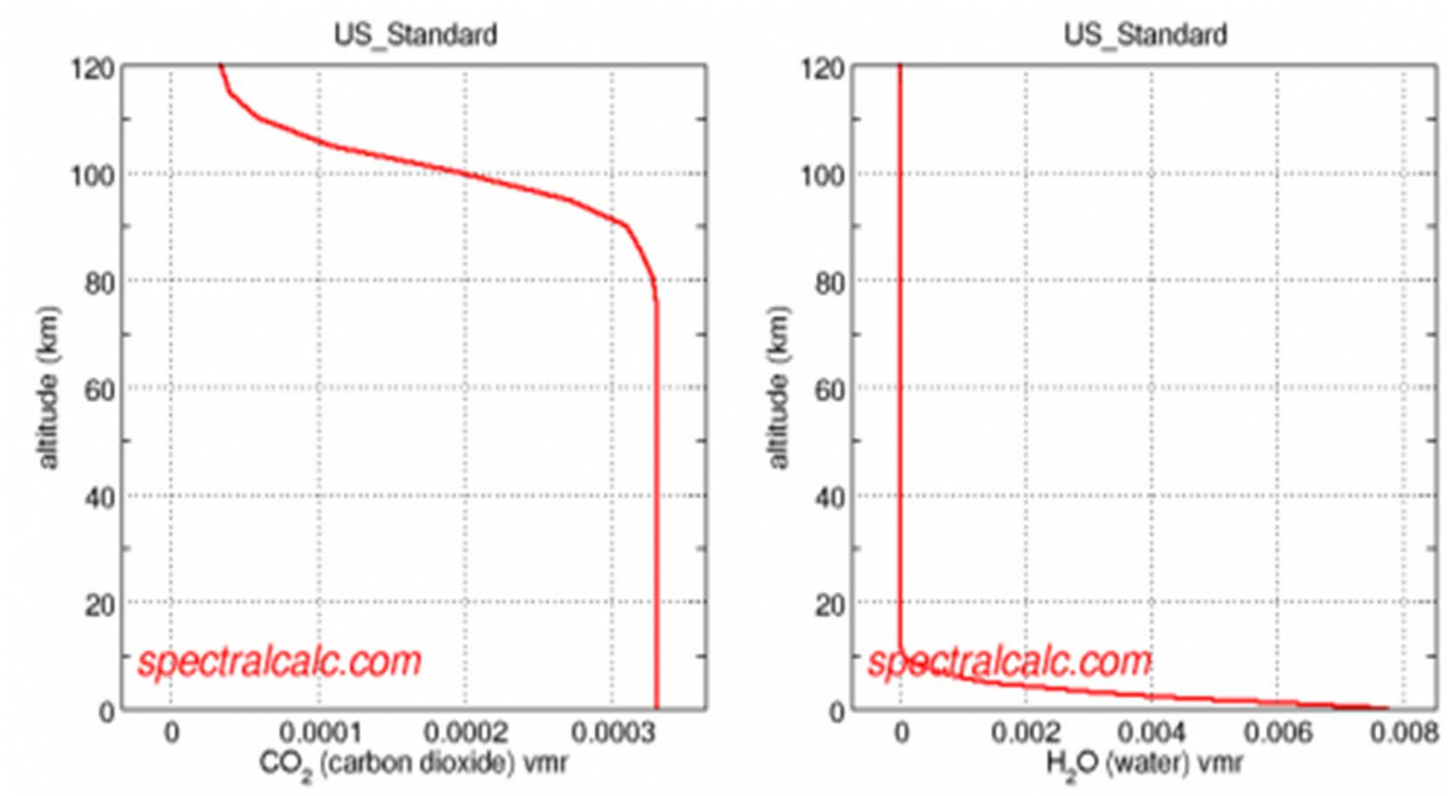
(parts per million by volume)

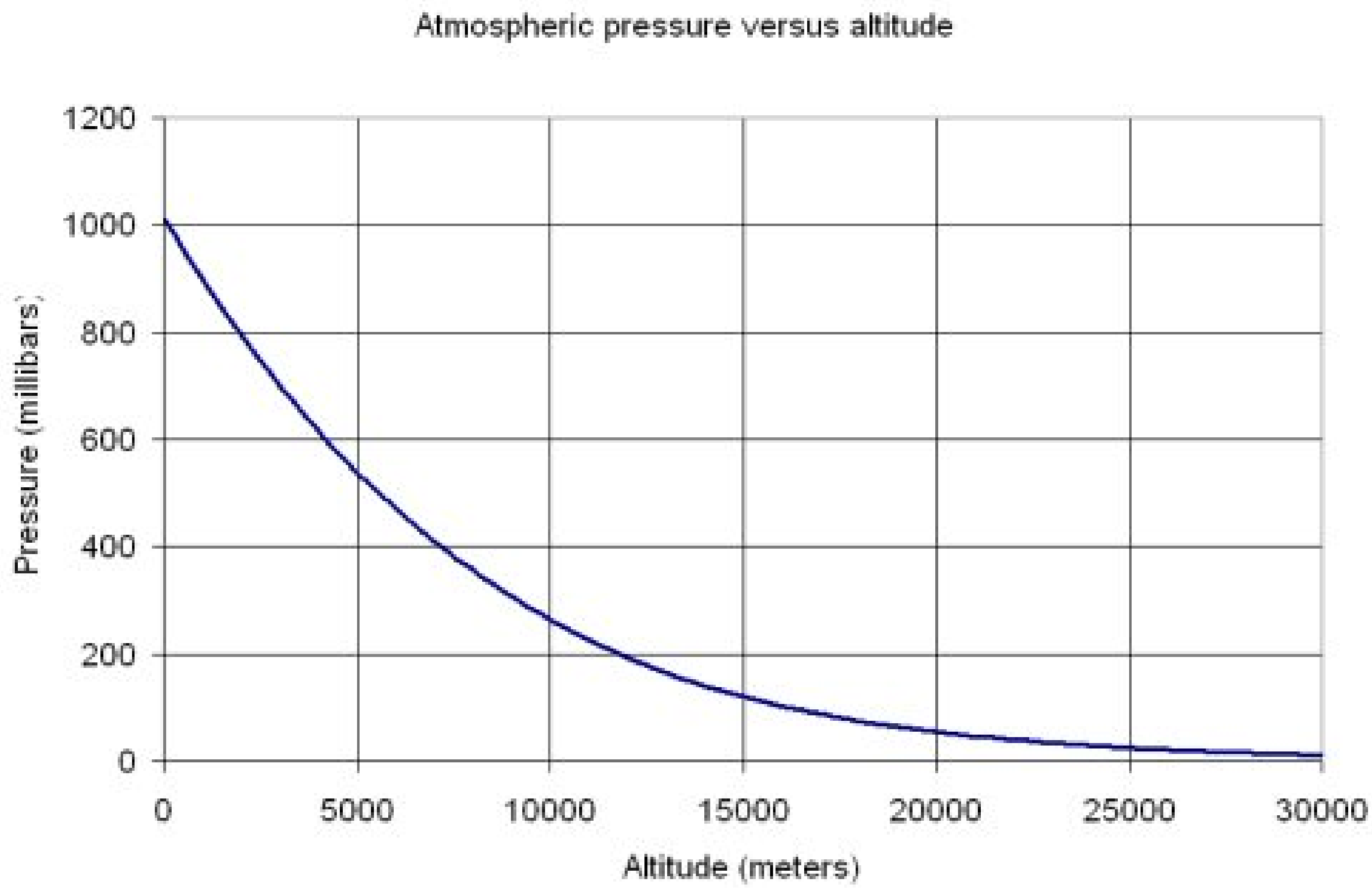
• Nitrogen (N_2)	780,840
• Oxygen (O_2)	209,460
• Argon (Ar)	9340
• Carbon dioxide (CO_2)	394
• Methane (CH_4)	1.79
• Ozone (O_3)	0.00 – 0.07
• Water vapor	4000 (average over full atmosphere)



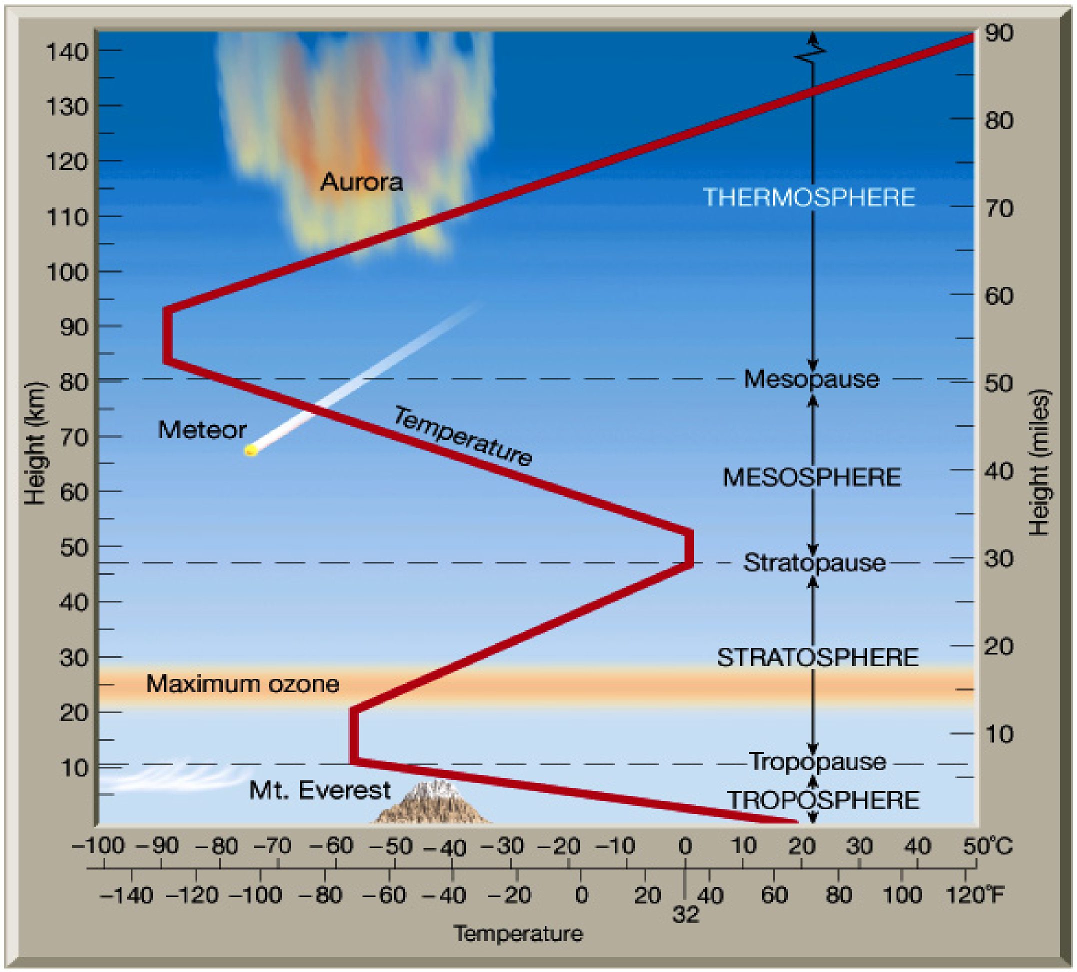
Irradiance (W m-2 micron-1)
2000
1000
6000K
(left-hand scale)
255K
(right-hand scale)
8
6
4
2
0
Radiance (W m-2 steradian-1 micron-1)
Water Vapour
Absorption (%)
100
80
60
40
20
0
Carbon dioxide
Absorption (%)
100
80
60
40
20
0
0.1
0.2
0.3
0.4
0.5
1.0
2
3
4
5
10
20
30
40
50
100
Wavelength (µm)

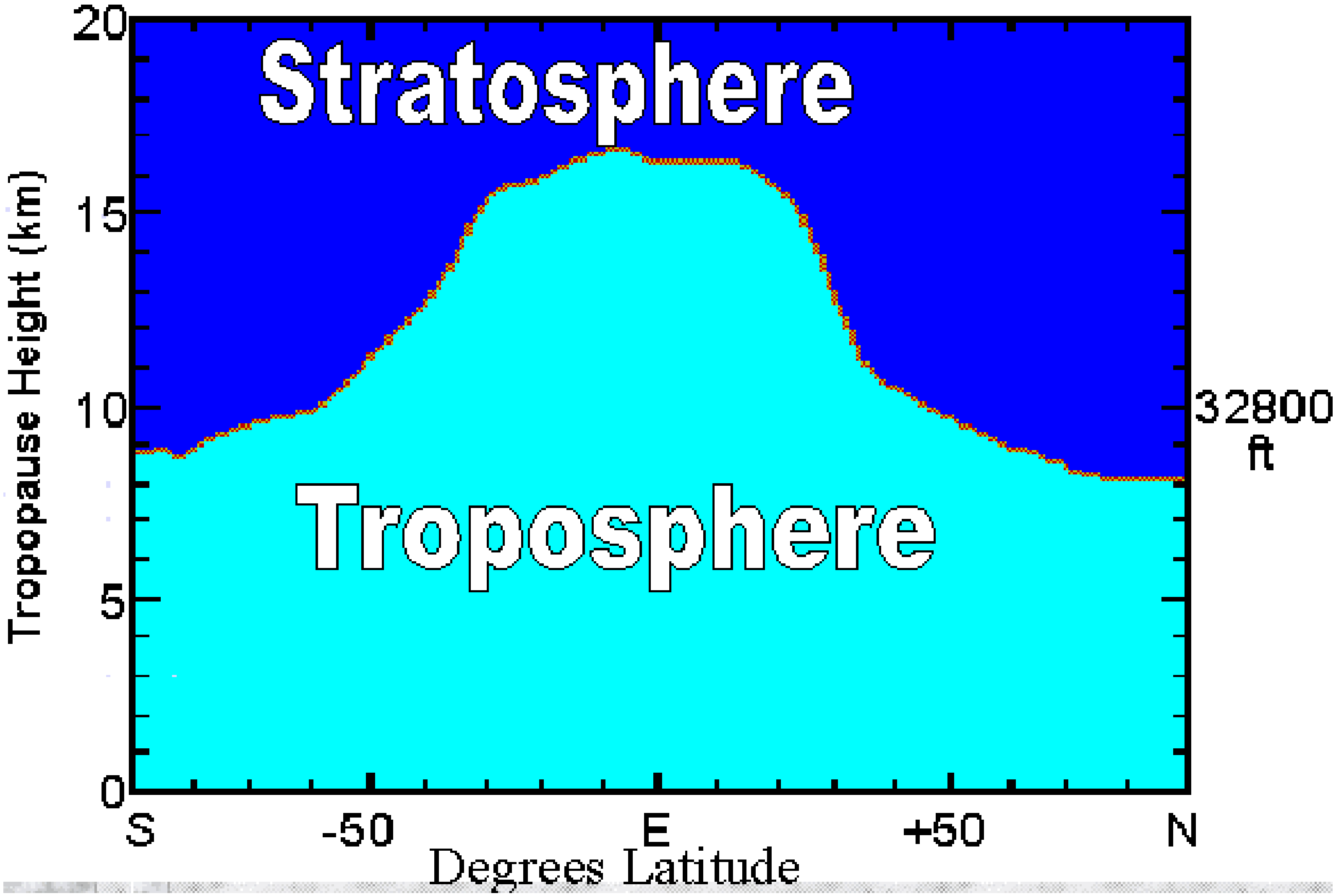
Carbon dioxide and water vapor: concentration as a function of height in the atmosphere




Atmospheric pressure versus altitude
1200
1000
800
600
400
200
0
Pressure (millibars)
0
5000
10000
15000
20000
25000
30000
Altitude (meters)

Temperature vs. altitude in earth's atmosphere




Stratosphere
Troposphere
Tropopause Height (km)
20
15
10
5
0
32800
ft
S
-50
E
+50
N
Degrees Latitude

Effect of an atmospheric gas on long wave radiation from the earth's surface depends on:

- Amount of the gas by volume;
- Amount of long wave energy radiated; and
- Amount of energy the gas can absorb at a given wavelength.

Receptivity of gas molecules to infrared radiation

• Molecules can absorb and emit energy only at certain wavelengths.

• The typical infrared wavelength of interest is about 400 times the size of a carbon dioxide molecule. Interaction is via electric field with molecule's electric charge distribution.

• Excited molecular states have very long lifetimes compared to excited electron states – from milliseconds to tenths of seconds.

• Mean time between collisions with another molecule is roughly 0.1 microseconds – so, many collisions and efficient energy transfer.

• Very little scattering occurs.

Downward long wave radiation spectrum (measured at the earth's surface)

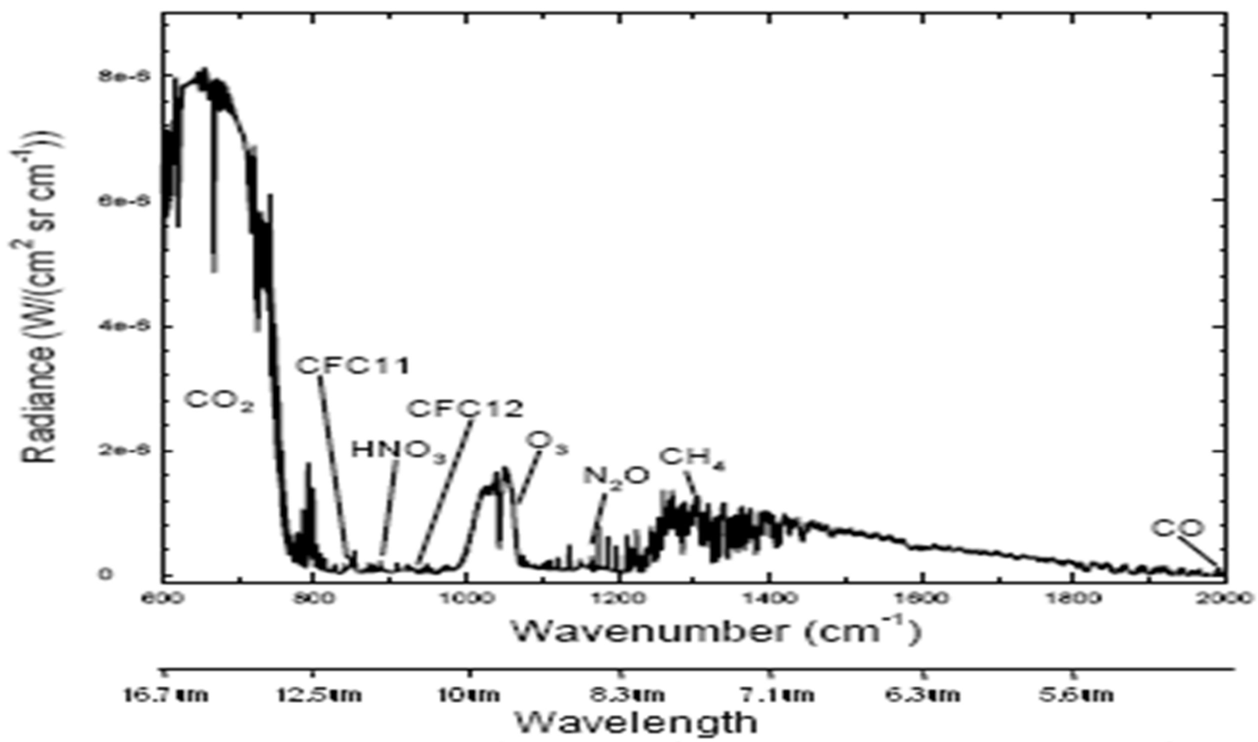
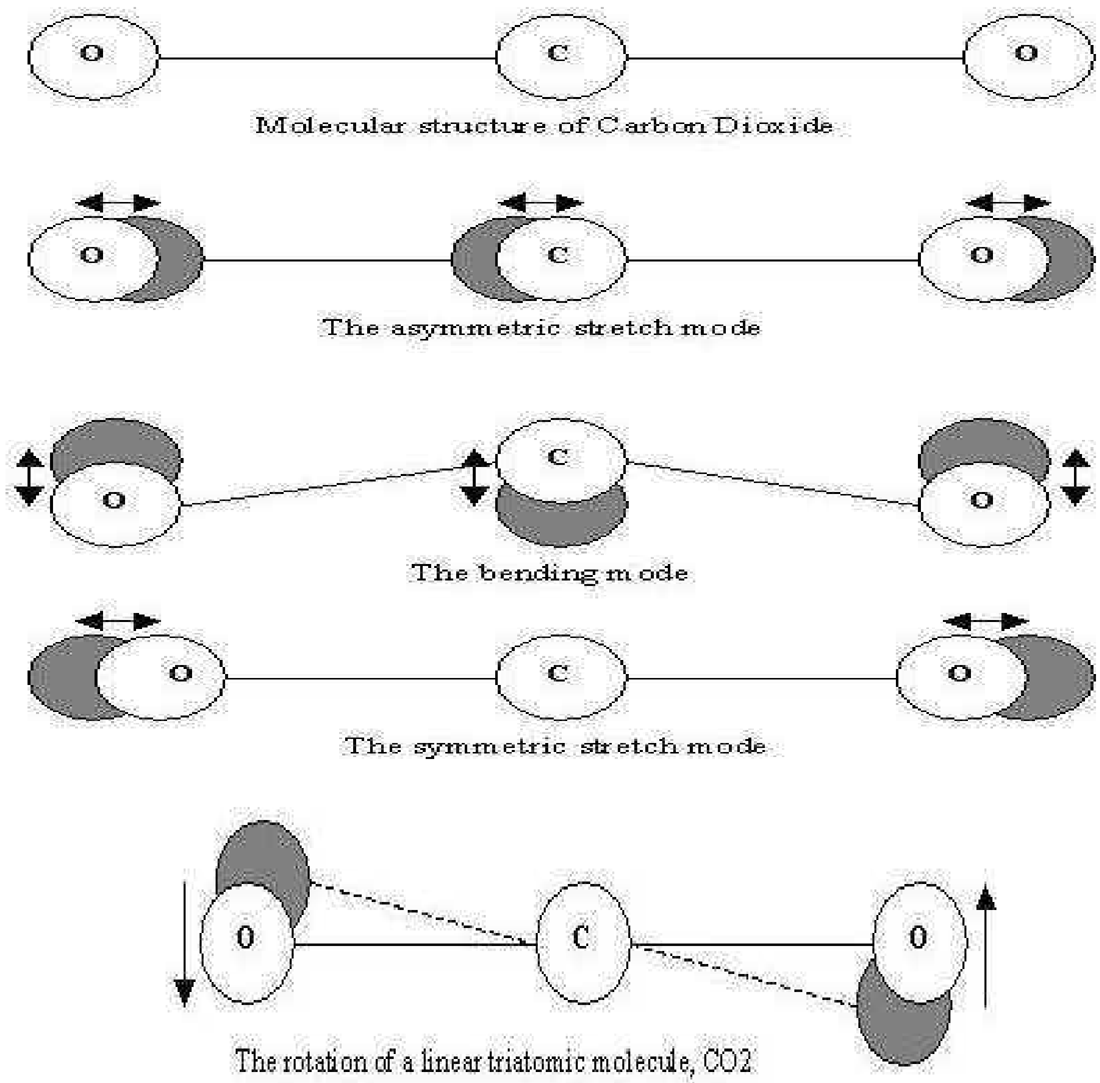


Figure 1. A spectrum of the greenhouse radiation at the surface measured for February, 1996, showing the contributions of several greenhouse gases.

Which gases are the important absorbers?

- N_2 and O_2 **are not** – they are essentially transparent to IR.
- H_2O
- CO_2
- CH_4

Good absorbers of IR are gases with molecules having easily excited bending, vibration or rotation modes.



Bending, stretching and rotating modes for CO_2 molecule

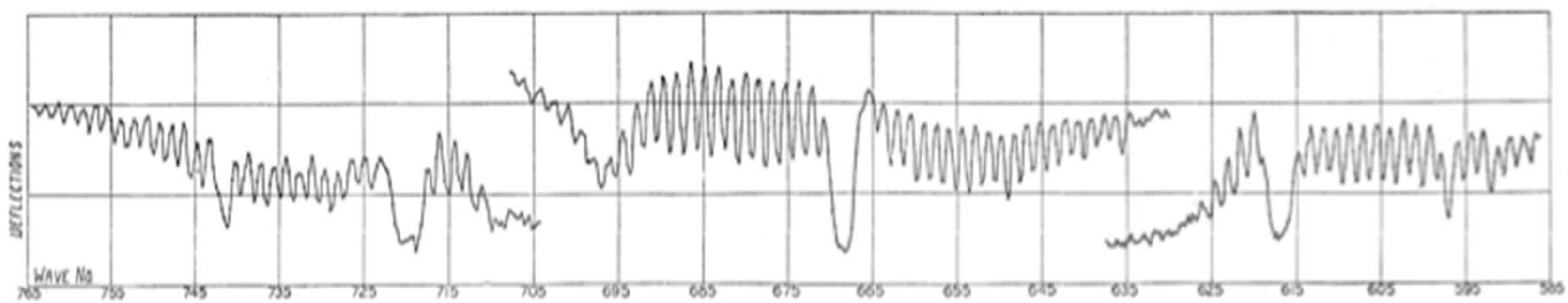


Fig. 2. Fine structure of the 15μ band.

Fine structure of carbon dioxide absorption spectrum near 15 micron wavelength

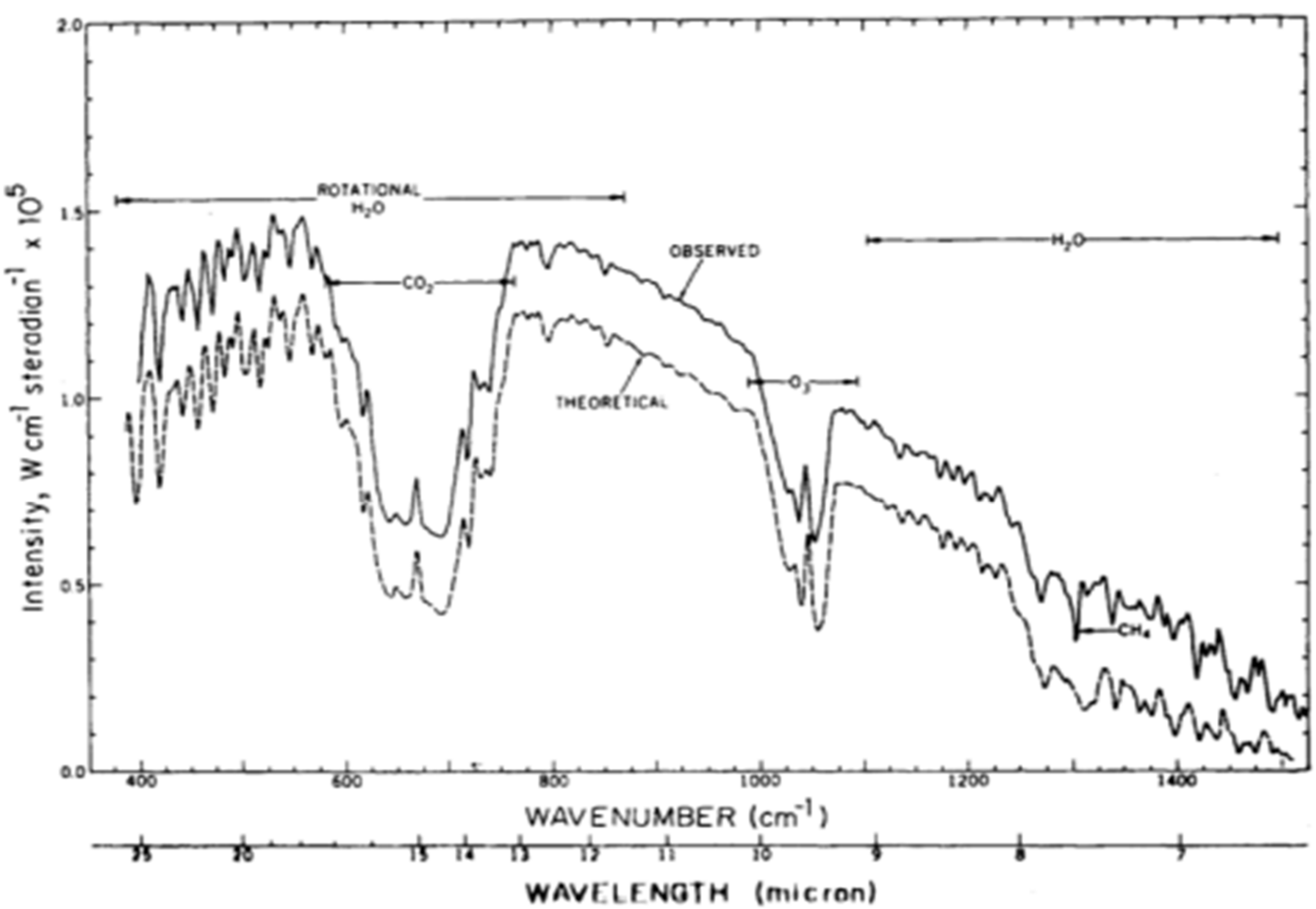


Fig 6.1. Observed and theoretical spectra for clear skies over the Gulf of Mexico, April 23, 1969. The observed spectrum is displaced upward by 0.2×10^{-5} W cm^{-2} steradian^{-1} wavenumber^{-1}.

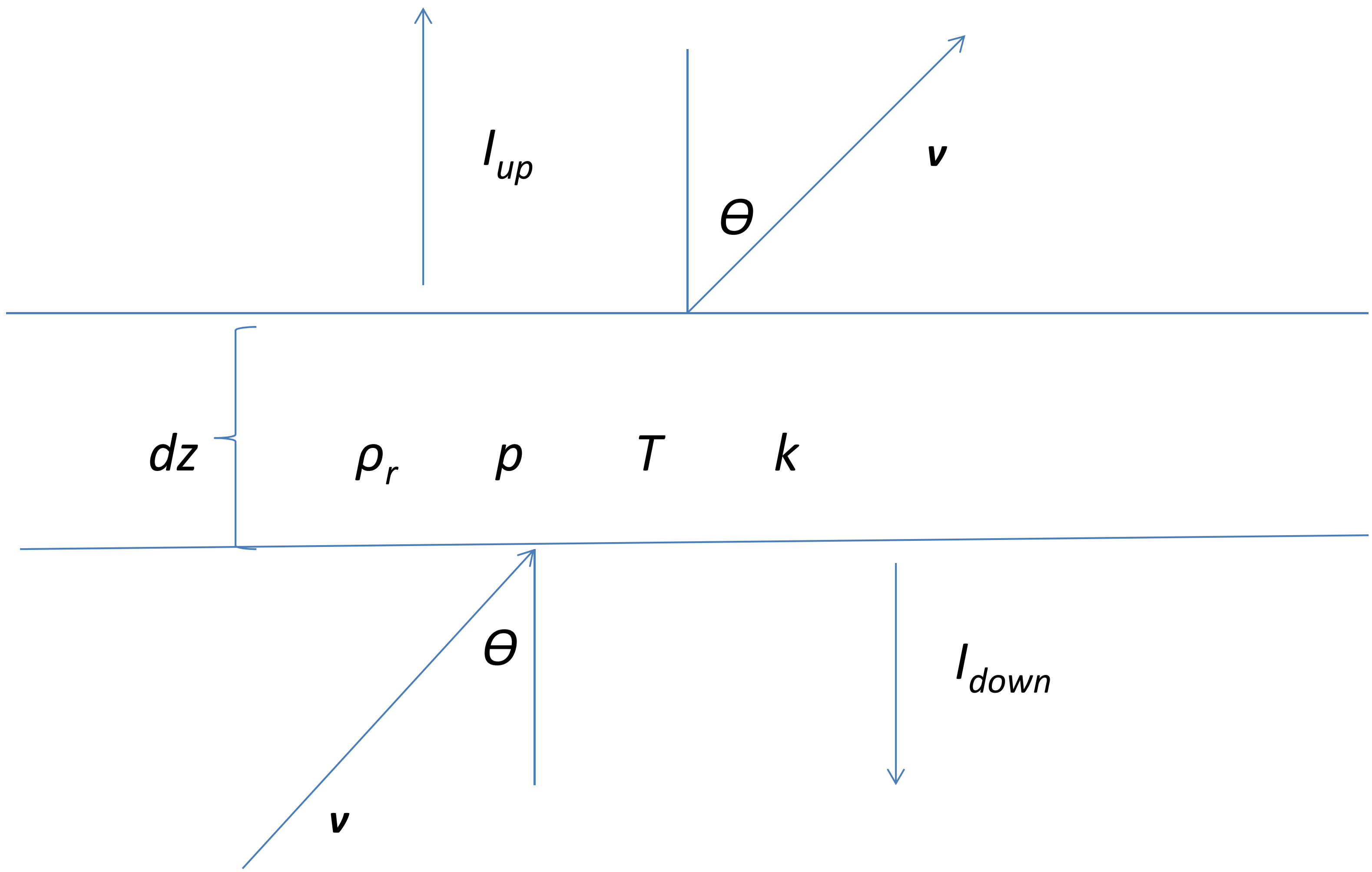
Schwarzschild equations for radiative transfer

In an infinitesimal layer in local thermodynamic equilibrium , for a fixed frequency and angle of incidence:

$$dI_{up} = -kI_{up}\,\rho_r \sec\theta\, dz \;+\; kI_b\,\rho_r \sec\theta\, dz$$

$$dI_{down} = kI_{down}\,\rho_r \sec\theta\, dz \;-\; kI_b\,\rho_r \sec\theta\, dz$$

where I is radiative flux, $k = k(z, p, T, v)$ is the absorption coefficient, ρ_r is the density of the radiating gas, $I_b = I_b(T)$ is blackbody radiation flux from Planck's law, z is altitude, p is pressure, T is temperature, and v is frequency.



I_{up}
θ
v
dz
ρ_r
p
T
k
θ
I_{down}
v

It's convenient to introduce a transmission function.

First take u to be the *mass of the radiating gas per unit area*:

$$u = \int_z^{\infty} \rho_r \, dz$$

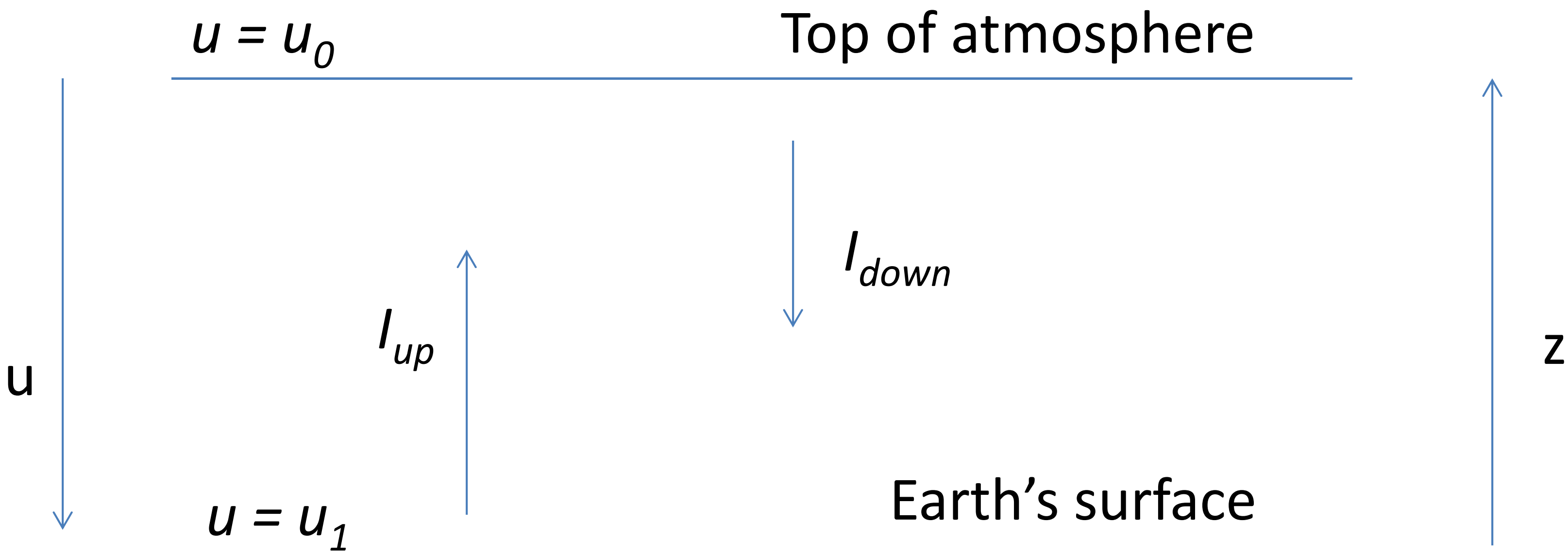
Note: u = 0 at the top of the atmosphere, and increases as z decreases.

Then the transmission function is defined as:

$$\tau(u_0, u_1) = exp\,[-sec\theta \int_{u_0}^{u_1} k\, du]$$

for $u_0 < u_1$.

τ takes values in [0, 1].



$u = u_0$
Top of atmosphere
I_{down}
I_{up}
u
z
$u = u_1$
Earth's surface

Rewriting the Schwarzschild equations in terms of u:

$$dI_{up} = \quad kI_{up} \sec\theta \, du \; - \; kI_b \sec\theta \, du$$

$$dI_{down} = -kI_{down} \sec\theta \, du \; + \; kI_b \sec\theta \, du$$

Then the general solution is :

$$I_{up}(u) = I_{up}(u_1)\,\tau(u, u_1) + \sec\theta \int_{u}^{u_1} k(w) I_b(w)\,\tau(u,w)\,dw$$

$$I_{down}(u) = I_{down}(u_0)\,\tau(u_0, u) + \sec\theta \int_{u_0}^{u} k(w) I_b(w)\,\tau(w,u)\,dw$$

u_0 is the value at the upper boundary, taken to be the top of the atmosphere.
u_1 is the value at the lower boundary, usually taken to be the earth's surface.

Also $I_{down}(u_0) = 0$ because there is essentially no downward infrared flux from the top of the atmosphere. Furthermore, $I_{up}(u_1)$ is the blackbody radiation from the surface of the earth.

$= I_b(u_1)$

Integrating these general solutions by parts, and applying boundary conditions, we eliminate explicit dependence on absorption coefficient:

$$I_{up}(u) = I_b(u) + \int_u^{u_1} \tau(u,w) \frac{dI_{b\,(w)}}{dw}\, dw$$

$$I_{down}(u) = I_b(u) - I_b(0)\,\tau(0,u) - \int_0^u \tau(w,u) \frac{dI_{b\,(w)}}{dw}\, dw$$

Some special cases:

I. High transmission. Low absorption ($\tau \rightarrow 1$).

$$I_{up}(u) = I_b(u_1)$$

$$I_{down}(u) = 0$$

II. Low transmission, high absorption ($\tau \rightarrow 0$).

$$I_{up}(u) = I_b(u)$$

$$I_{down}(u) = I_b(u)$$

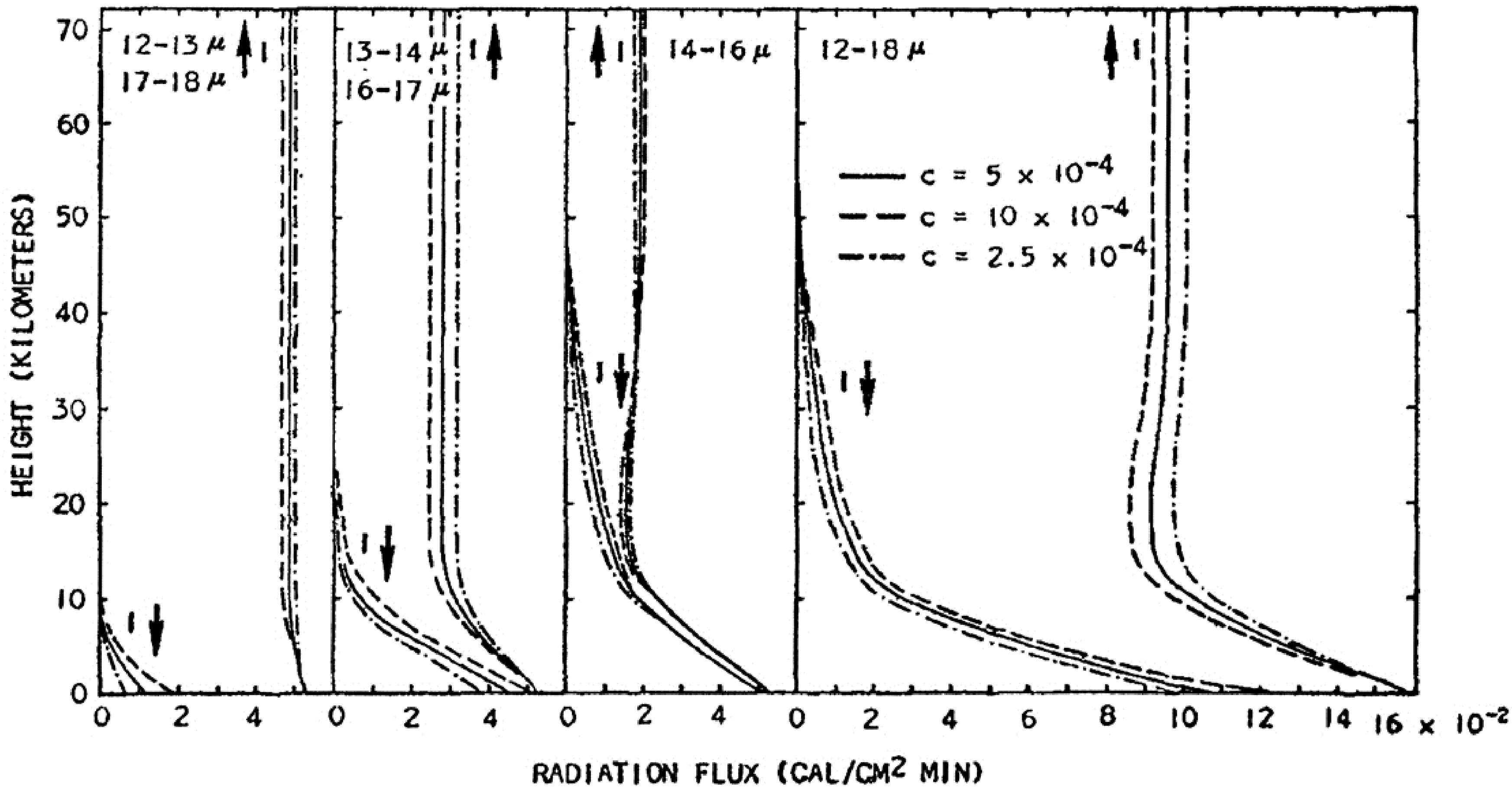


FIG. 8. The upward and downward radiation flux as a function of height for the combined frequency intervals from 12–13 and 17–18μ, from 13–14 and 16–17μ, from 14–16μ, and for the entire interval from 12–18μ. Curves are given for the following carbon dioxide concentrations: $c=5\times10^{-4}$ (0.033% by volume); $c=10\times10^{-4}$ (0.066% by volume); $c=2.5\times10^{-4}$ (0.0165% by volume). The temperature curve D (Fig. 7) was used for these calculations.

Radiation flux computation (Gilbert Plass)

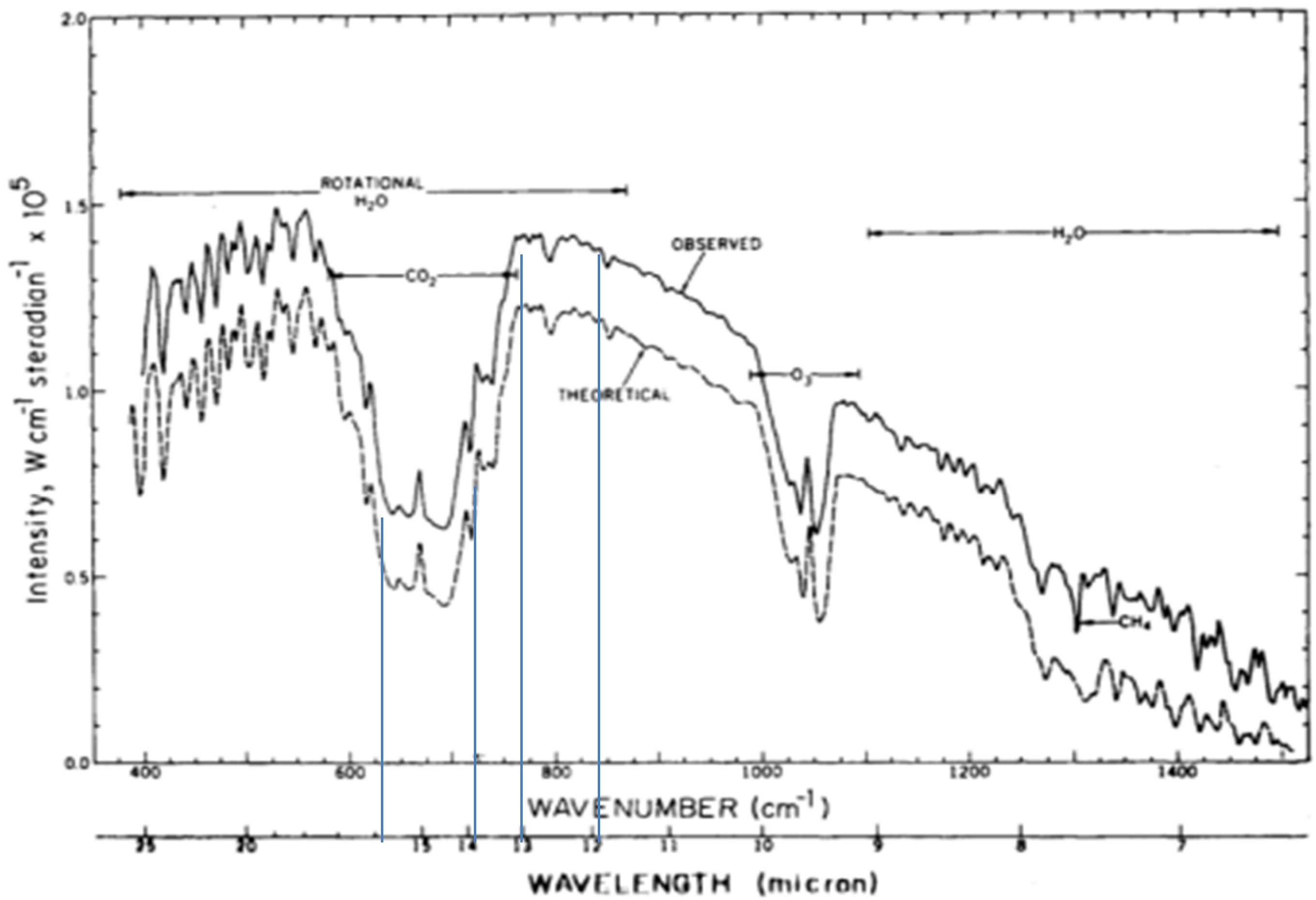


Fig 6.1. Observed and theoretical spectra for clear skies over the Gulf of Mexico, April 23, 1969. The observed spectrum is displaced upward by 0.2 x 10^{-5} W cm^{-2} steradian^{-1} wavenumber^{-1}

Conclusions and Caveats

- Carbon dioxide is a potent absorber of infrared radiation, especially near 15 microns.

- We've only considered radiative transfer, but convection and other energy transport mechanisms operate, especially in the troposphere

- We've considered CO_2 , but water vapor is also a significant atmospheric absorber.

SCIENCE IN REVIEW
By WALDEMAR KAEMPFFERT
New York Times (1857-Current file); Oct 28, 1956; ProQuest Historical Newspapers The New York Times (1851 - 2003)
pg. 191

SCIENCE IN REVIEW

Warmer Climate on the Earth May Be Due To More Carbon Dioxide in the Air

By WALDEMAR KAEMPFFERT

The general warming of the climate that has occurred in the last sixty years has been variously explained. Among the explanations are fluctuations in the amount of energy received from the sun, changes in the amount of volcanic dust in the atmosphere and variations in the average elevation of the continents.

According to a theory which was held half a century ago, variation in the atmosphere's carbon dioxide starches) causes a large loss of carbon dioxide, but the balance is restored by processes of respiration and decay of plants and animals.

Despite nature's way of maintaining the balance of gases the amount of carbon dioxide in the atmosphere is being artificially increased as we burn coal, oil and wood for industrial purposes. This was first pointed out by Dr. G. S. Callendar about seven years ago. Dr. Plass develops the implications.

from the New York Times – October 28, 1956

Even if our coal and oil reserves will be used up in 1,000 years, seventeen times the present amount of carbon dioxide in the atmosphere must be reckoned with. The introduction of nuclear energy will not make much difference. Coal and oil are still plentiful and cheap in many parts of the world, and there is every reason to believe that both will be consumed by industry so long as it pays to do so.

Last paragraph of the NYT story

References

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