AOSC 621
Physics and Chemistry of the Atmosphere II: Radiative Transfer

LESSON 1

- **AOSC 621 - PHYSICS AND CHEMISTRY OF THE ATMOSPHERE II**
- Texts: *Radiative Transfer in the Atmosphere and Ocean,* Gary E. Thomas and Knut Stamnes, Cambridge University Press
- *Chemistry of Atmospheres,* Richard P. Wayne, Oxford University Press
- Lecturer: Professor Zhanqing Li, Room 4013, ESSIC , CSS 2441
- M-Square
- Phone 301-405-6699
- E-mail zli@atmos.umd.edu
- Lessons Tuesday 9.00 am to 10.15 am
- Thursday 9.00 am to 10.15 am
- Office hours No set office hours will be posted. Students may come by my office at any time.
- If you wish to make a formal appointment - send me an e-mail, or call me ahead.

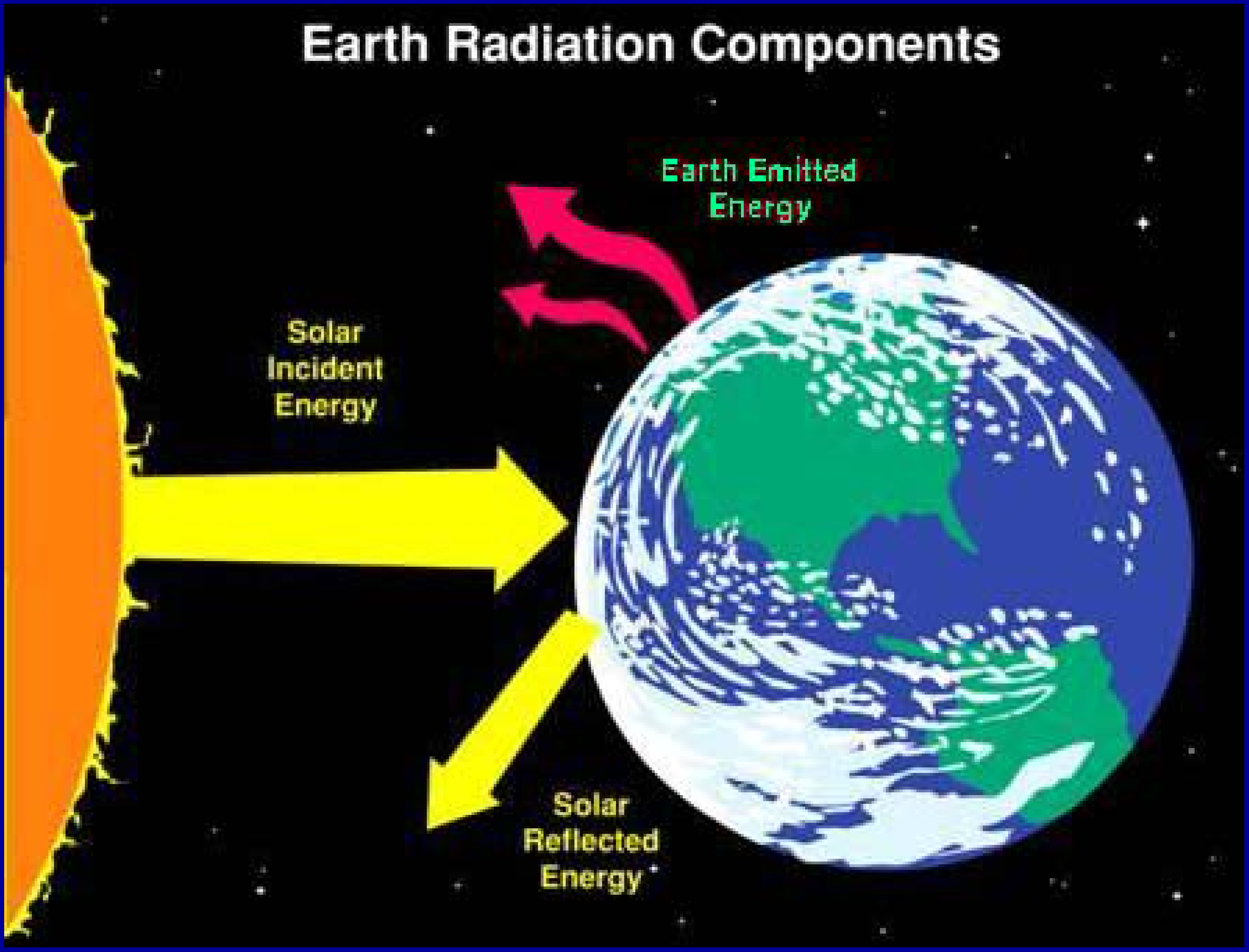
- The textbooks listed above cover most of the material given in this course.. However, some contents may be extracted from other books. PowerPoint presentations will be prepared for each class, these will contain any material not covered by either book. .The .ppt files will be distributed after each class.
- In addition to the homework, projects will be assigned. There will be two exams, a mid-term exam and a final exam. 60% of the final grade will be based on these two exams, 20% on the project, and the remaining 20% on the homework assignments. Mid exam: March 15

Purpose

- The purpose of this course is twofold:
- (1) To examine how solar radiation is transferred through the atmosphere, absorbed by the Earth, and re-emitted by the Earth and atmosphere.
- (2) To examine how this radiation drives the dynamics and chemistry of the atmosphere.

Earth's (long-term) energy balance

solar incident=solar reflected + Earth emitted



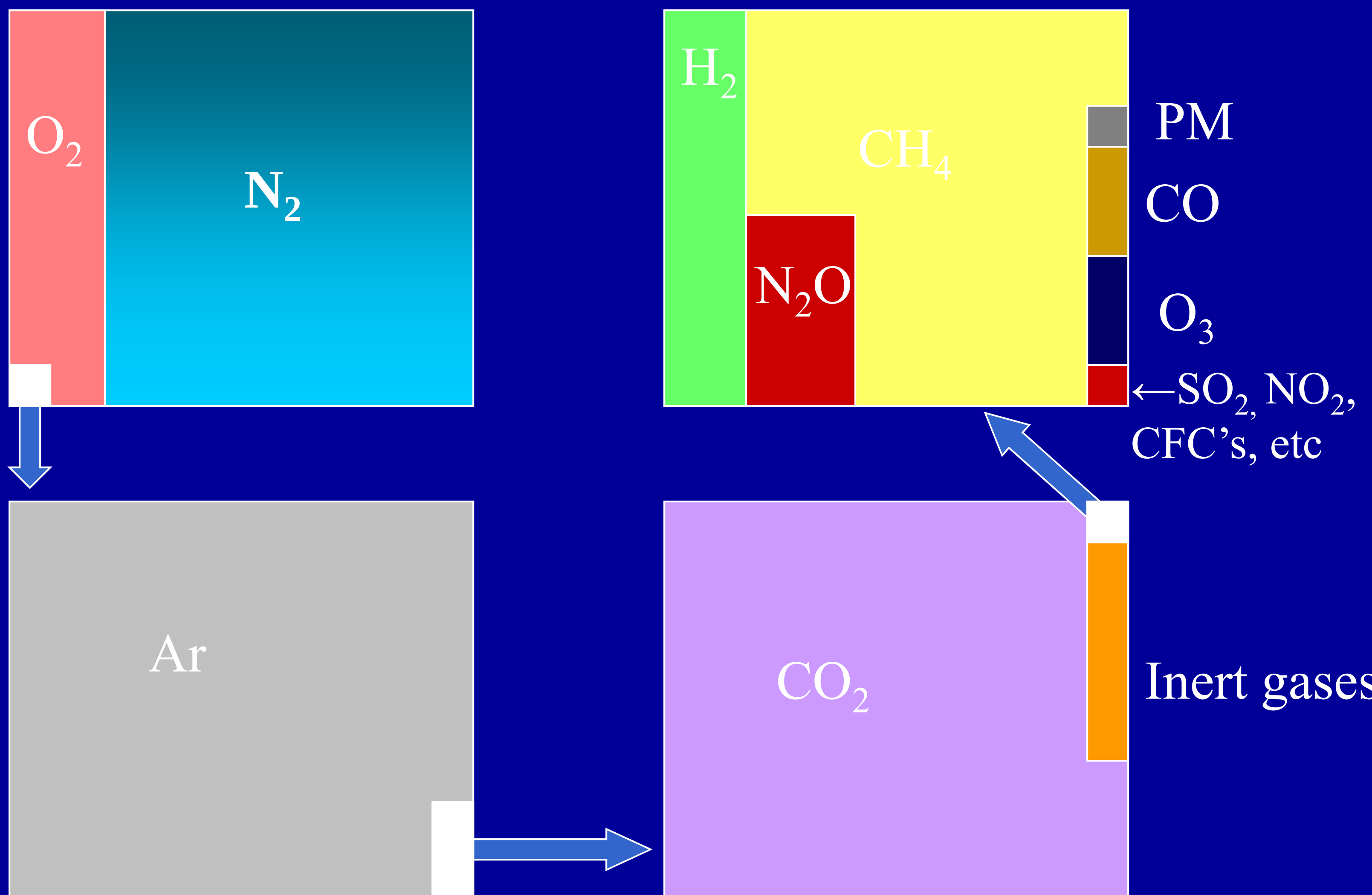
Atmospheric composition

Table 1.1 The composition of the atmosphere[a]

Permanent constituents		Variable constituents	
Constituent	**% by volume**	**Constituent**	**% by volume**
Nitrogen (N_2)	78.084	Water vapor (H_2O)	0–4
Oxygen (O_2)	20.948	Ozone (O_3)	$0\text{–}12 \times 10^{-4}$
Argon (Ar)	0.934	Sulfur dioxide (SO_2)[b]	0.001×10^{-4}
Carbon dioxide (CO_2)	0.034	Nitrogen dioxide (NO_2)[b]	0.001×10^{-4}
Neon (Ne)	18.18×10^{-4}	Ammonia (NH_3)[b]	0.004×10^{-4}
Helium (He)	5.24×10^{-4}	Nitric oxide (NO)[b]	0.0005×10^{-4}
Krypton (Ke)	1.14×10^{-4}	Hydrogen sulfide (H_2S)[b]	0.00005×10^{-4}
Xenon (Xe)	0.089×10^{-4}	Nitric acid vapor (HNO_3)	Trace
Hydrogen (H_2)	0.5×10^{-4}	Chlorofluorocarbons $CFCl_3$, CF_2Cl_2, CH_3CCl_3, CCl_4, etc.	Trace
Methane (CH_4)	1.7×10^{-4}		
Nitrous oxide (N_2O)[b]	0.3×10^{-4}		
Carbon monoxide (CO)[b]	0.08×10^{-4}		

[a] After the U.S. Standard Atmosphere (1976) with modifications.
[b] Concentration near the earth's surface.

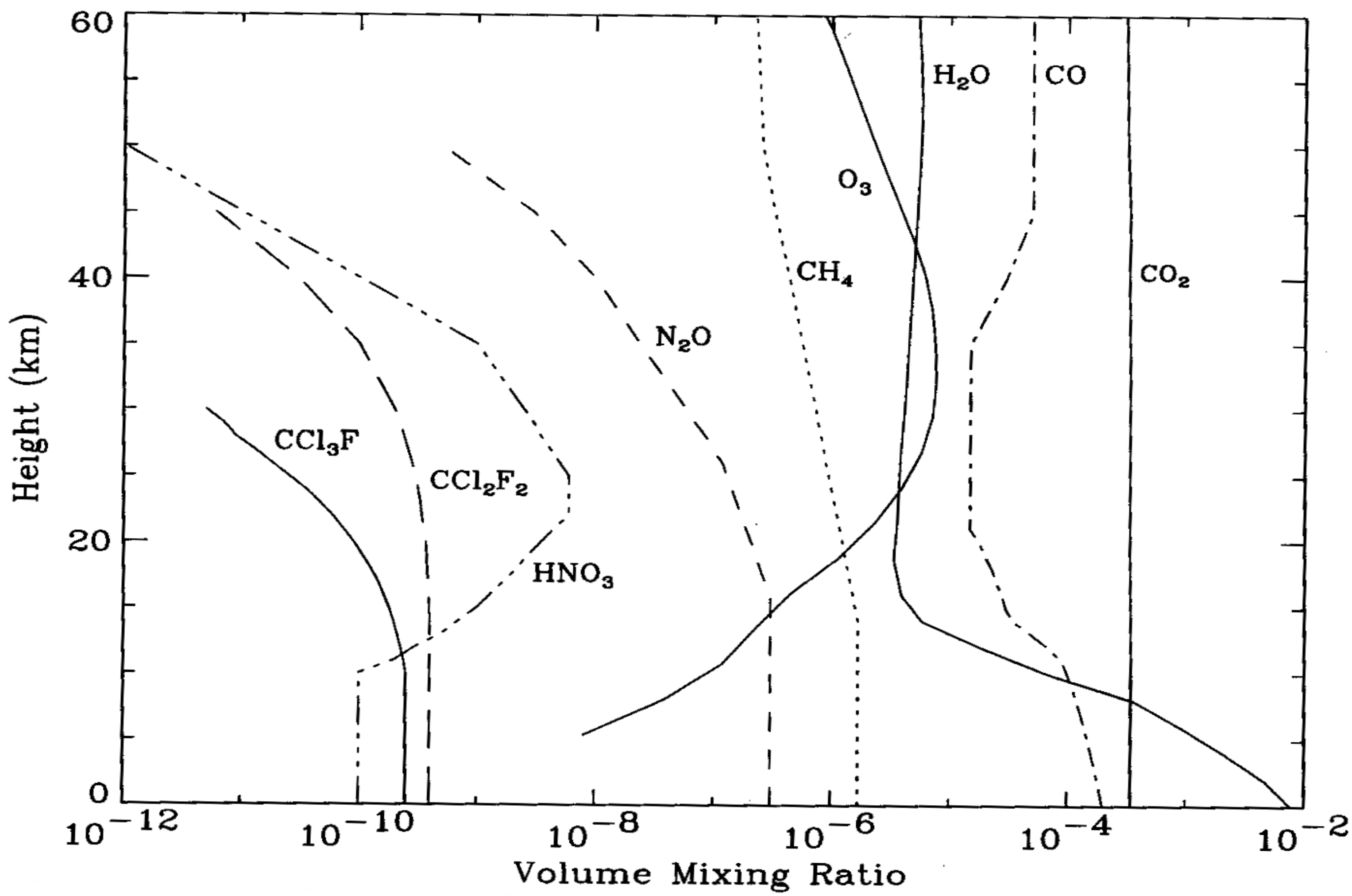
Composition of the Earth's Troposphere



Height profiles for minor species

- Species:
  Chlorofluorocarbons, CCl_3F and CCL_2F_2
  Nitrous oxide, N_2O
  Methane, CH_4
  Nitric acid, HNO_3
  Carbon monoxide, CO
  Carbon dioxide, CO_2.
- Note that the CO_2 line is vertical. This signifies that CO_2 is well mixed in the atmosphere and has no significant chemical loss or production
- The lines for the chlorofluorocarbons and nitrous oxide are vertical in the troposphere (well mixed) but suffer chemical loss in the stratosphere.

Height profiles for minor species



HYDROSTATIC EQUATION

$$dp = -g\rho dz. \tag{1.1}$$

For planetary atmospheres of moderate and low density, and specifically the Earth's atmosphere, the equation of state is closely approximated by the *ideal gas law*,

$$\rho = \frac{\bar{M}p}{RT} = \bar{M}n, \tag{1.2}$$

where $\bar{M}$ is the *mean molecular mass*, R is the *gas constant per mole*, and n is the total *concentration* of molecules (number of molecules per unit volume). More detailed descriptions of each of the above quantities are given below. Substituting Eq. 1.2 into Eq. 1.1, we find

$$\frac{dp}{p} = -\frac{dz}{H}, \quad \text{where } H \equiv \frac{RT}{\bar{M}g}. \tag{1.3}$$

Where H is called the atmospheric scale height

HYDROSTATIC EQUATION-2

Three forms of the hydrostatic equation

$$p(z) = p(z_0) \exp\left[-\int_{z_0}^{z} dz'/H(z')\right], \tag{1.4a}$$

$$n(z) = n(z_0)\frac{T(z_0)}{T(z)} \exp\left[-\int_{z_0}^{z} dz'/H(z')\right], \tag{1.4b}$$

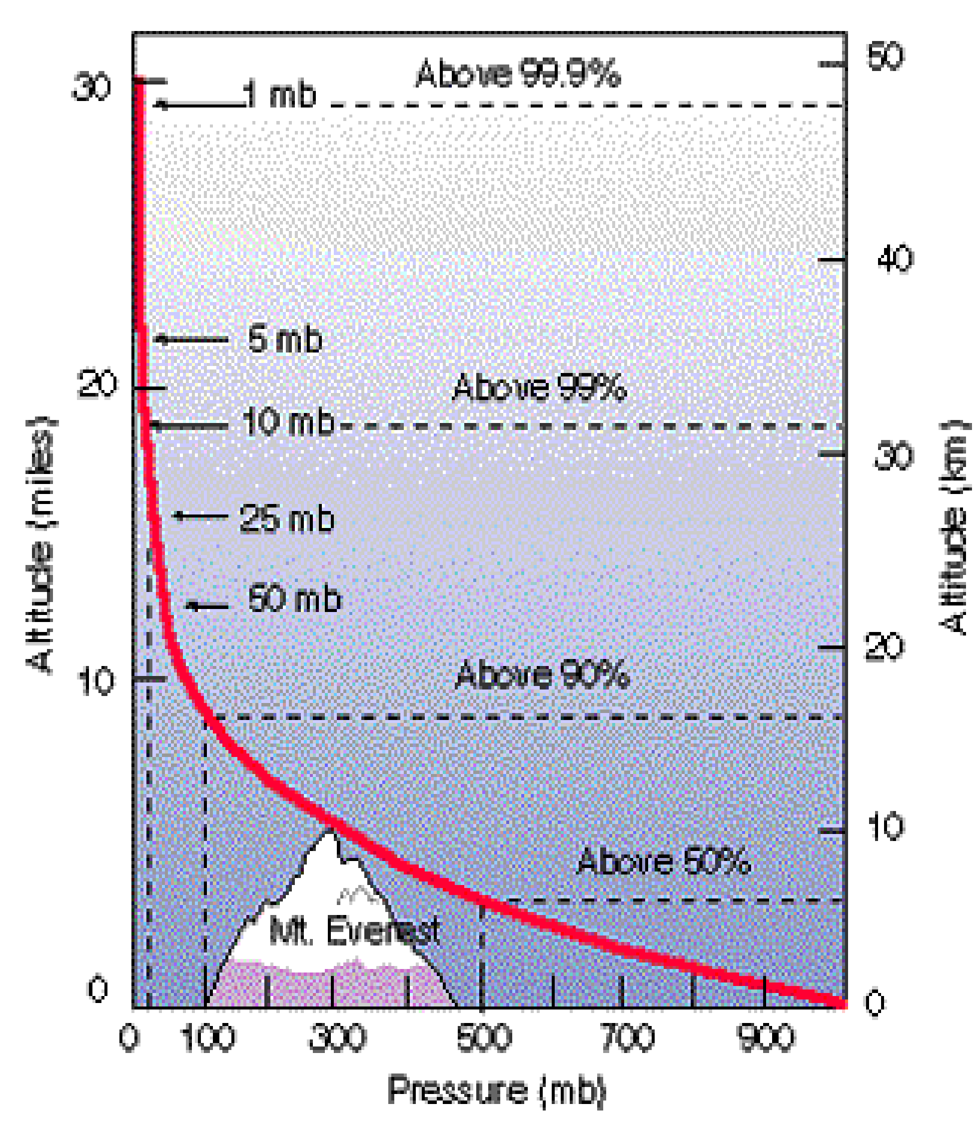
$$\rho(z) = \rho(z_0)\frac{T(z_0)}{T(z)} \exp\left[-\int_{z_0}^{z} dz'/H(z')\right]. \tag{1.4c}$$

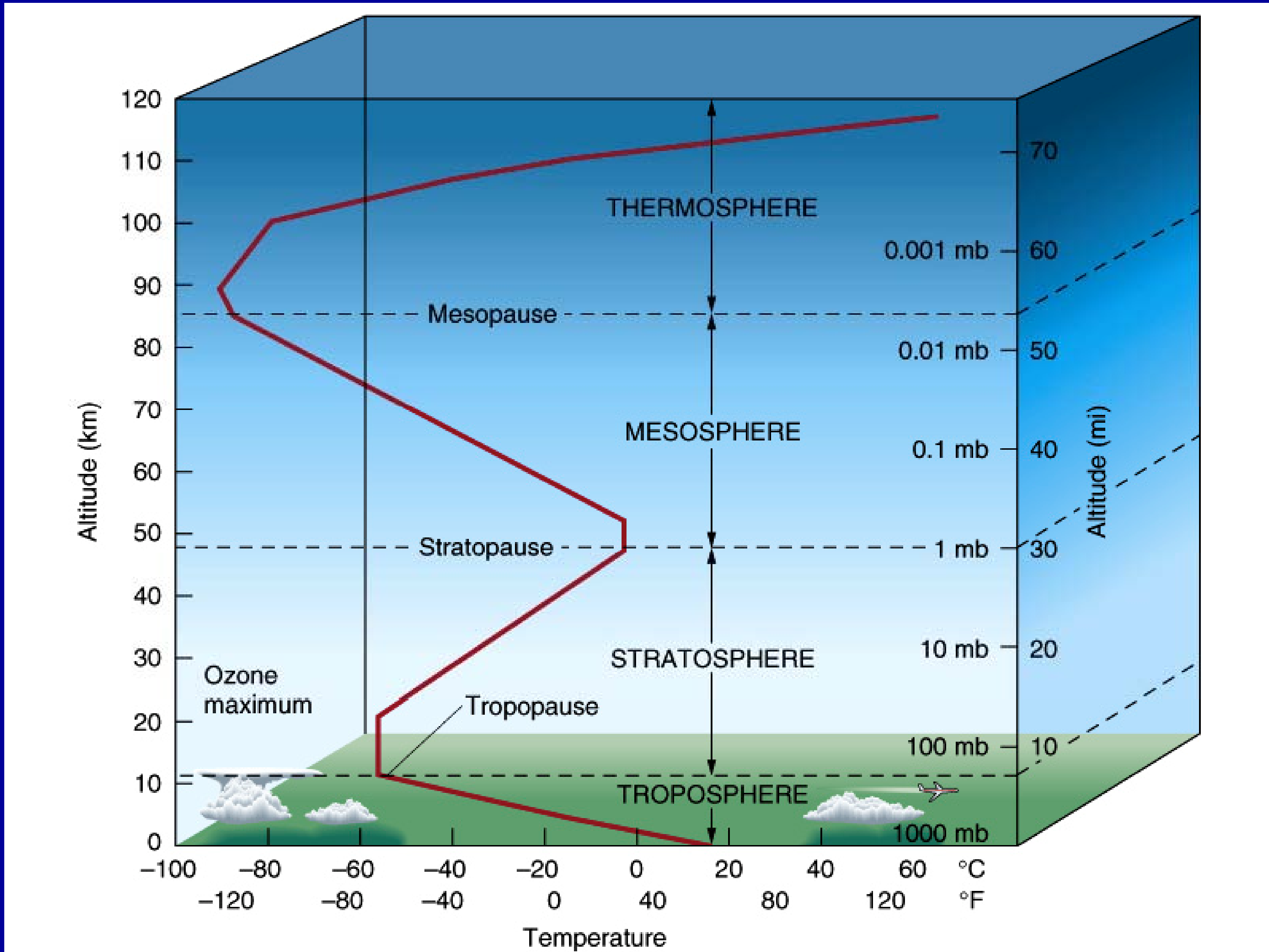
Pressure and Atmospheric Mass

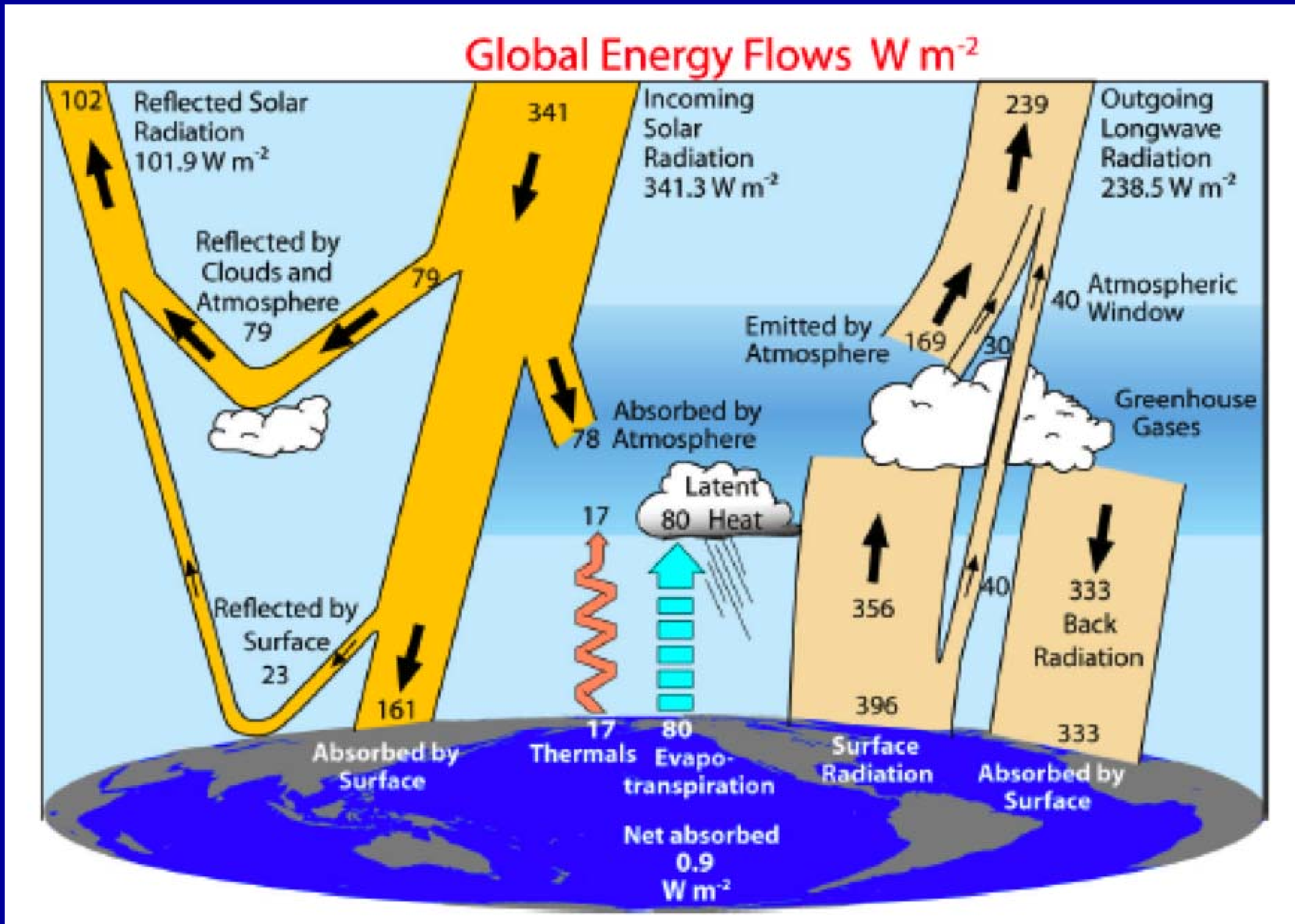
- The hydrostatic relationship tells us that the pressure decreases exponentially with height.

- A hydrostatically balanced atmosphere does not mean that there is no vertical motion. There still can be vertical motion (topographically forced vertical motion). , but no acceleration or deceleration.

- But a non-hydrostatic balance atmosphere column would have severe up/down draft (gravity waves) => typically in thunderstorm (very short time over a small area)




120
110
100
90
80
70
60
50
40
30
20
10
0
Altitude (km)
THERMOSPHERE
Mesopause
MESOSPHERE
Stratopause
STRATOSPHERE
Ozone
maximum
Tropopause
TROPOSPHERE
0.001 mb
0.01 mb
0.1 mb
1 mb
10 mb
100 mb
1000 mb
70
60
50
40
30
20
10
Altitude (mi)
–100 –80 –60 –40 –20 0 20 40 60 °C
–120 –80 –40 0 40 80 120 °F
Temperature



Trenberth et al., 2009, BAMS

❑Radiation

⌧ Primary Energy transfer mechanisms in the atmosphere and oceans

- ❑ Phase Change (ice <=> water <=> water vapor)
- ❑ Vertical convection (including turbulent heat and momentum fluxes at the (land and ocean) surface.
- ❑ Meridional mass circulation driven by equator-pole heating contrast.
- ❑ West-east mass circulation driven by west-east thermal and mechanic contrasts (land-ocean, sea surface temperature variation, and orography).

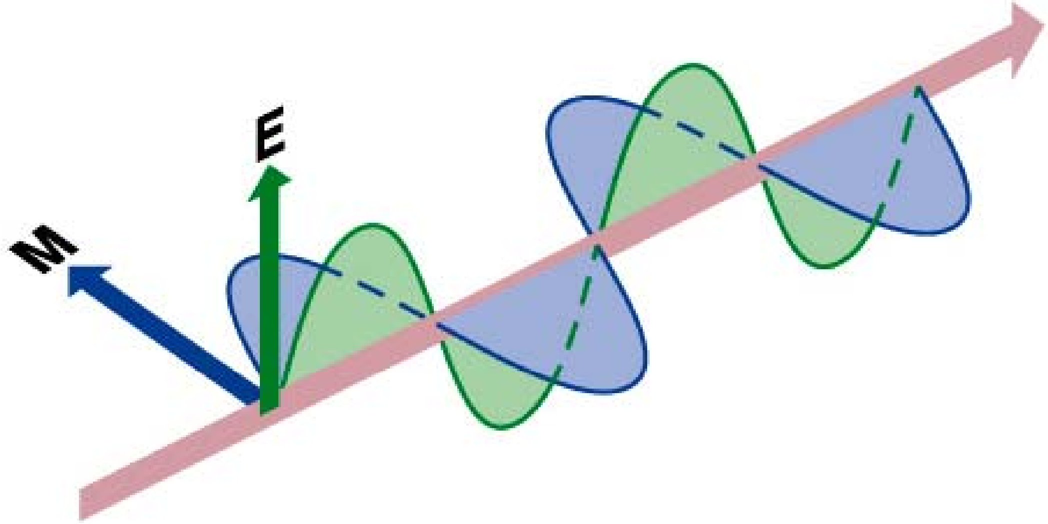
Radiation - quantity and quality

- To describe electromagnetic radiation, we need to provide information about the amount of energy transferred (quantity), and the type, or quality, of the energy.

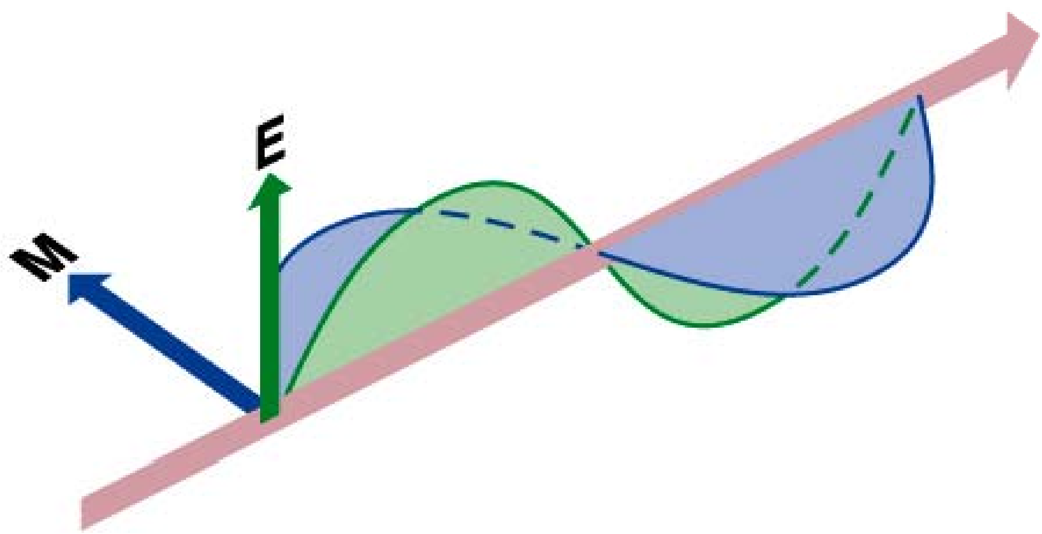
- In the case of radiation, quantity is associated with the height of the wave, or its amplitude. Everything else being equal, the amount of energy carried is directly proportional to wave amplitude.

- The quality, or "type," of radiation is related to another property of the wave, the distance between wave crests (wavelength).

- The radiation emitted by an object obey some fundamental physical laws => the amount of radiation (quantity) emitted and its wavelength (quality) is related.



(a)

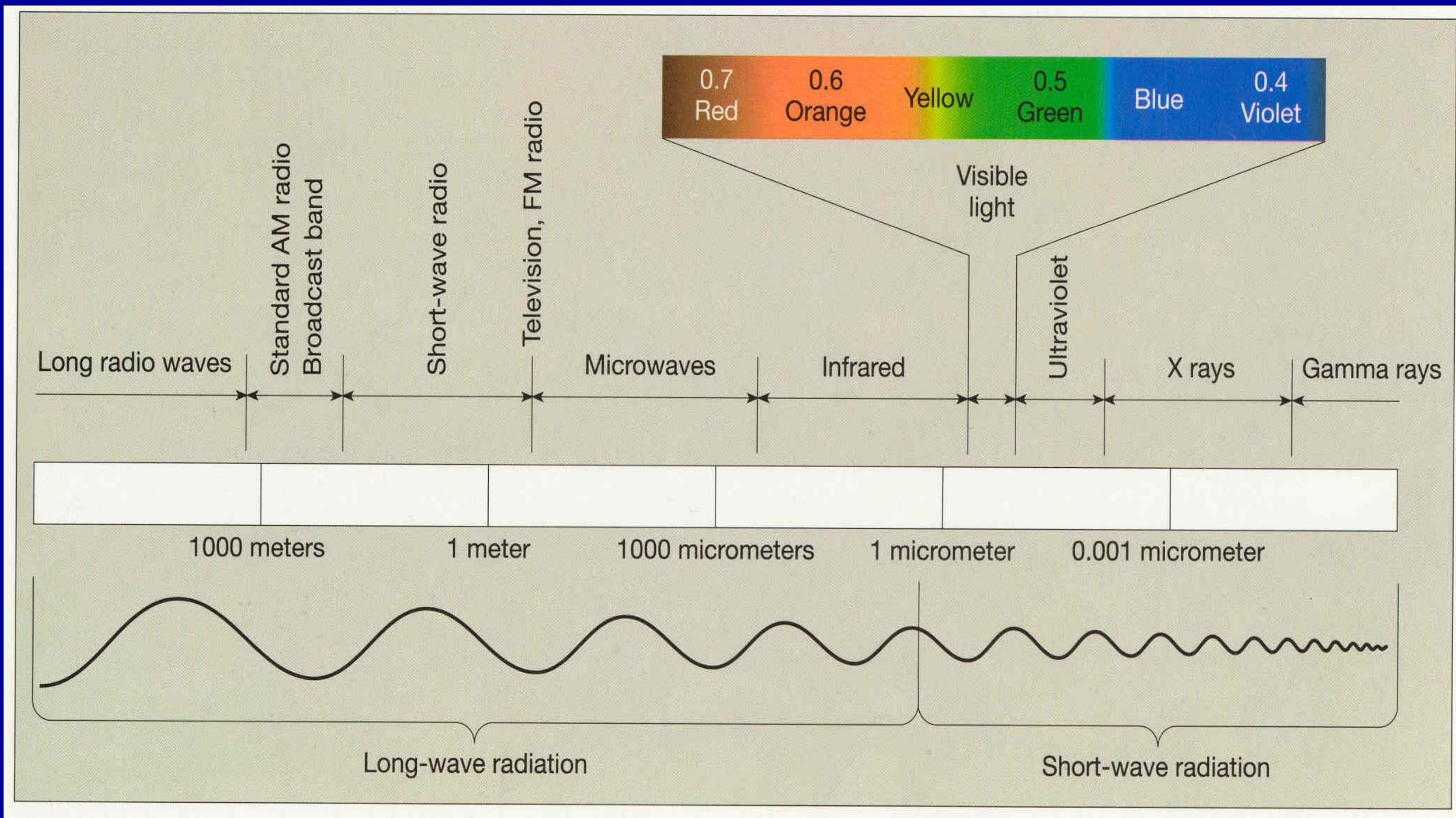


(b)

Electromagnetic Radiation

- By analogy a stream of particles can be considered as a wave.
- The chemistry of the atmosphere is dominated by radicals derived from the dissociation of atmospheric species.
- It is much easier to picture this dissociation as the interaction of a photon with a molecule than as an interaction of a wave with the molecular field.
- Dissociation requires a threshold of energy, i.e. a certain frequency. Only photons with an energy (frequency) above this threshold will cause dissociation.

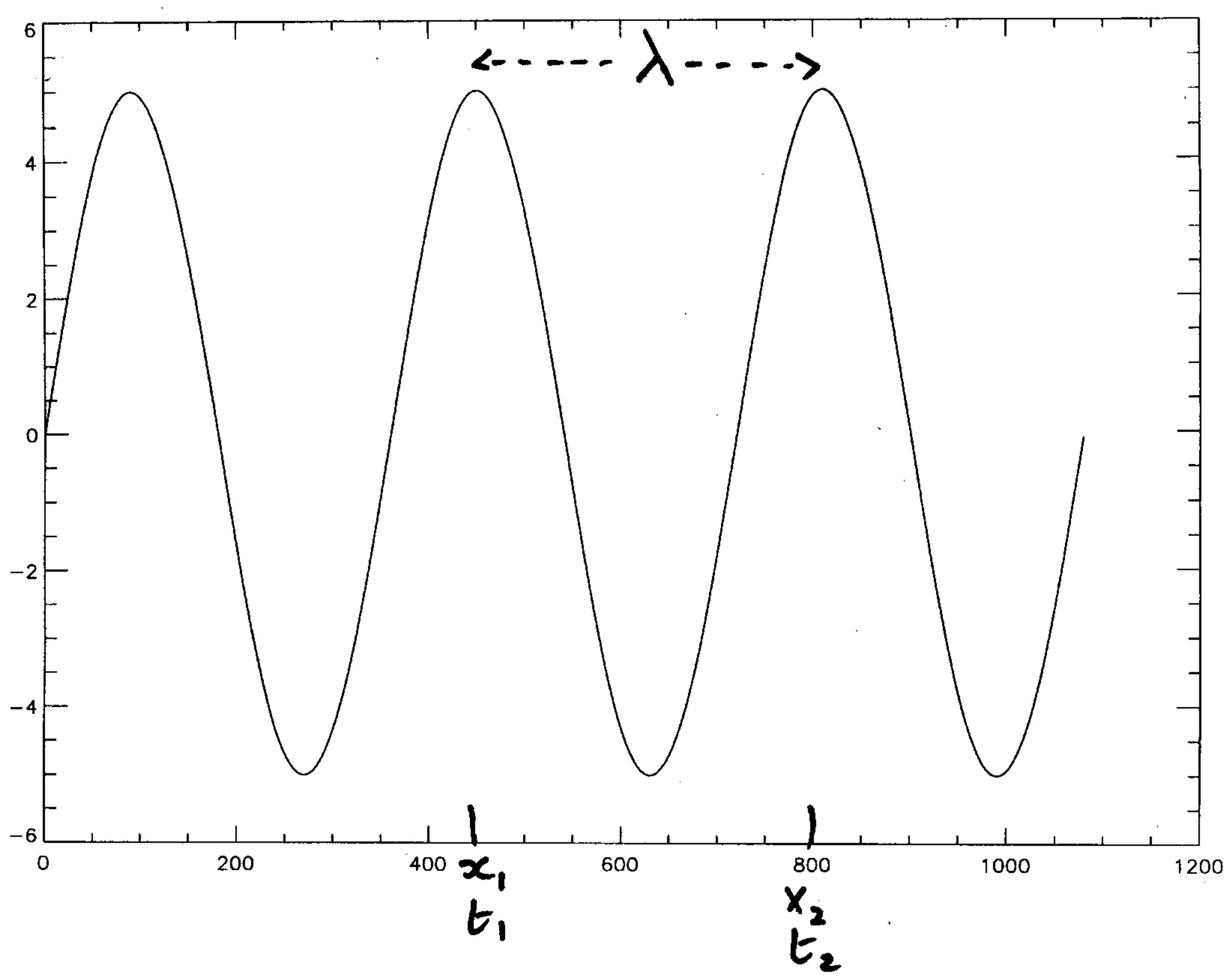
Electromagnetic spectrum



Electromagnetic spectrum

- Most of the energy that drives the dynamics comes from a narrow band of frequencies known as the visible spectrum - heats the ground
- Most the the energy that drives the chemistry pf the atmosphere comes from the ultraviolet part of the spectrum - high energy photons.
- Most of the energy that heats the atmosphere is thermal radiation from the ground

Schematic of a wave



WAVELENGTH

- **DISTANCE BETWEEN SUCCESSIVE PEAKS**
- **GIVEN THE SYMBOL λ**
- **MANY UNITS USED :**
- **(A) MICRON, 10^{-6} METERS**
- **(B) NANOMETER, 10^{-9} METERS**
- **(C) ANGSTROM, 10^{-10} METERS**

FREQUENCY

Defined as the number of maxima that pass an observer per second

Given the symbol ν

$$c = \lambda\nu$$

Wave number is also used. It is the reciprocal of the wavelength

In the textbook it is given the symbol $\overline{\nu}$

Caution - the use of ν and $\overline{\nu}$ are reversed in many textbooks

VELOCITY

- **WAVE VELOCITY IS DEFINED AS THE DISTANCE A PEAK MOVES IN ONE SECOND.**
- **IN VACUO THE WAVE VELOCITY OF AN ELECTROMAGNETIC WAVE IS 2.997925×10^8 METERS PER SECOND**
- **THE WAVE VELOCITY IS GIVEN THE SYMBOL c.**

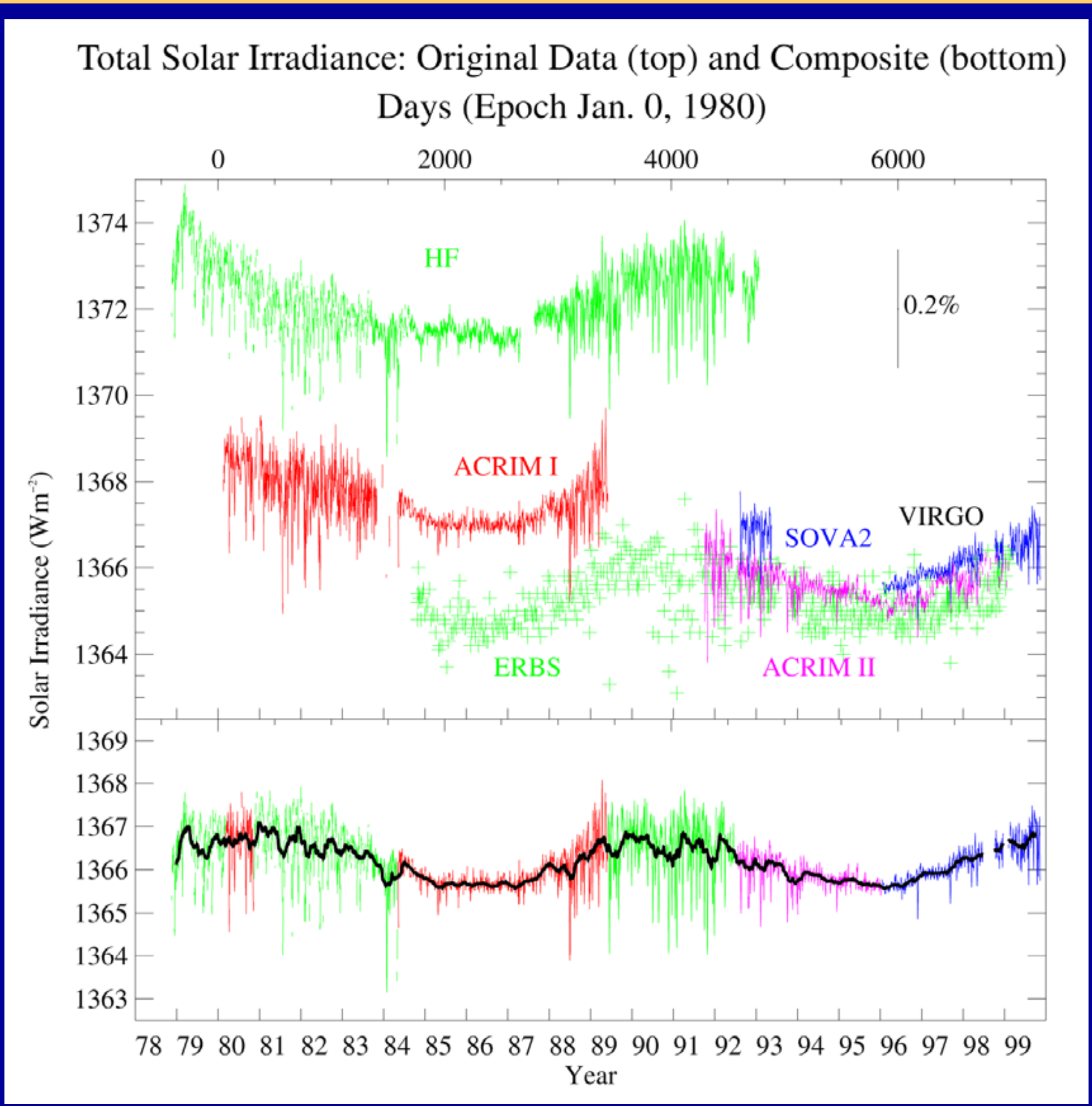
SOLAR ENERGY

- Solar constant – energy from the sun that falls on unit surface normal to the line from the sun, per unit time, at the outside of the atmosphere at the mean solar distance

$$S = 1.368 \text{ Kw per meter}^2$$

- S is integrated over all wavelengths
- S varies with the sunspot cycle

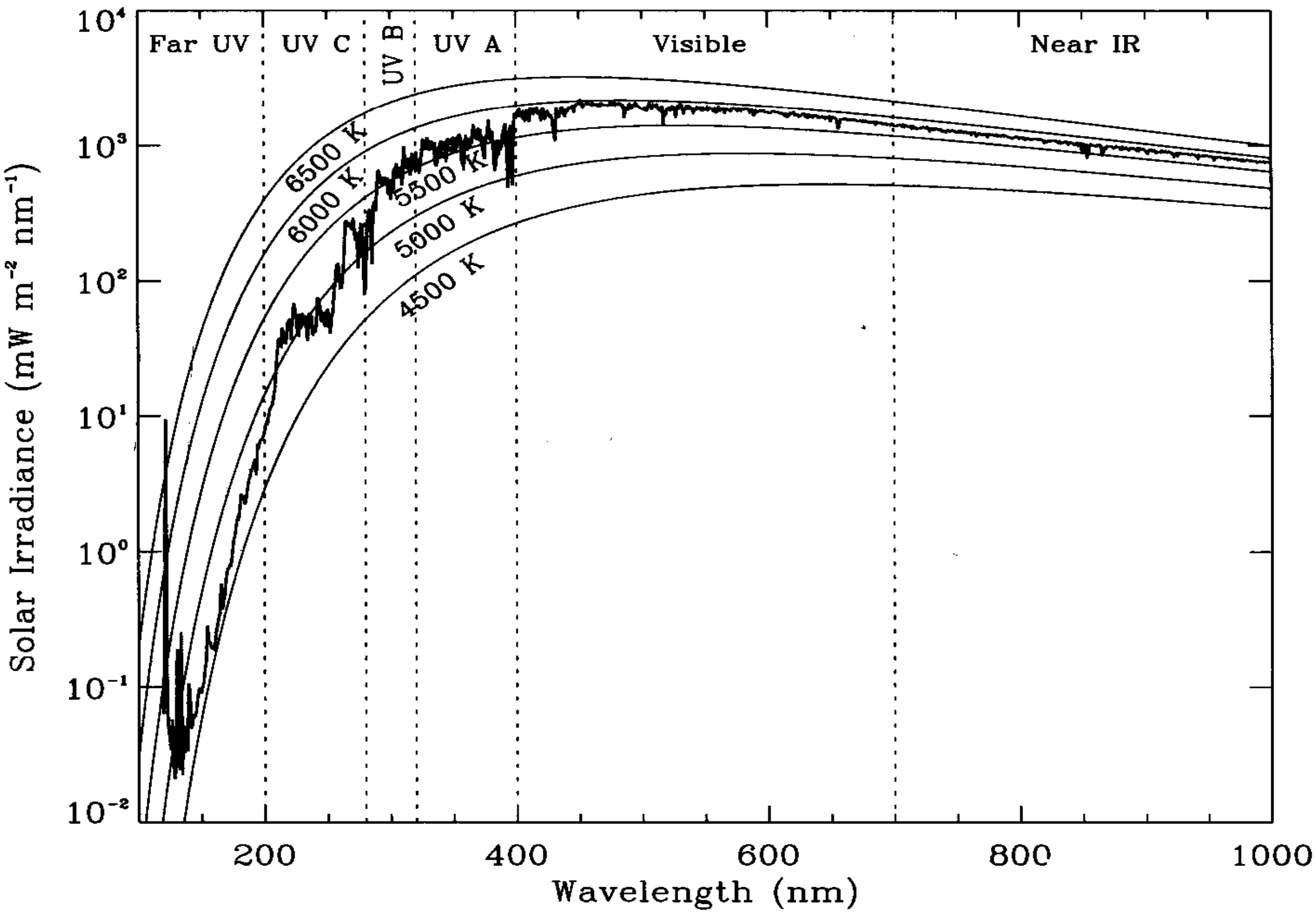
Measurements of total solar irradiance 1979-2000



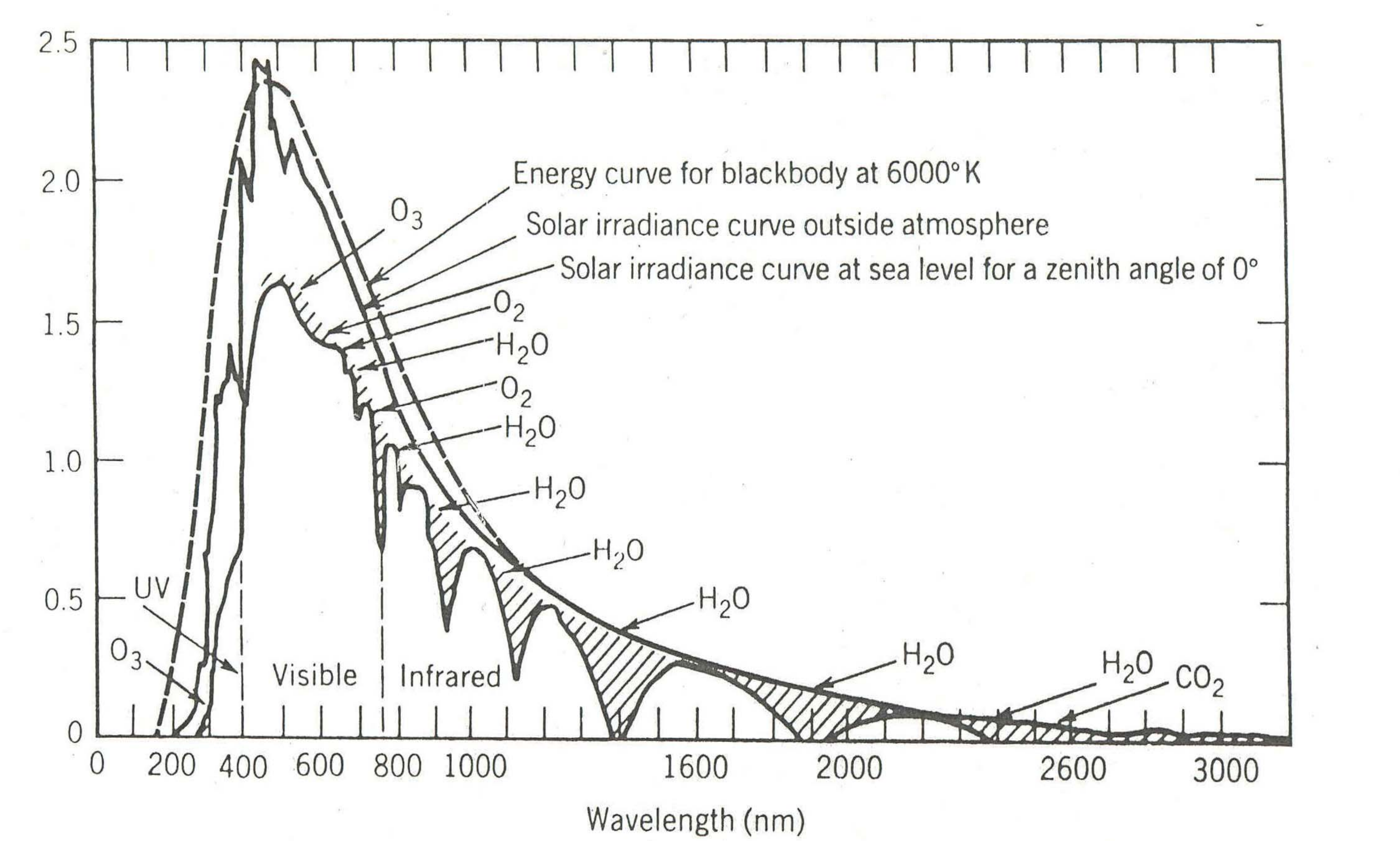
SOLAR SPECTRUM

- A blackbody curve for a temperature of 6000K matches the observed solar spectrum.
- The difference between the 6000K spectrum below about 400 nm is due to absorption in the photosphere.
- The structures shown below 400 nm are known as Fraunhoffer lines

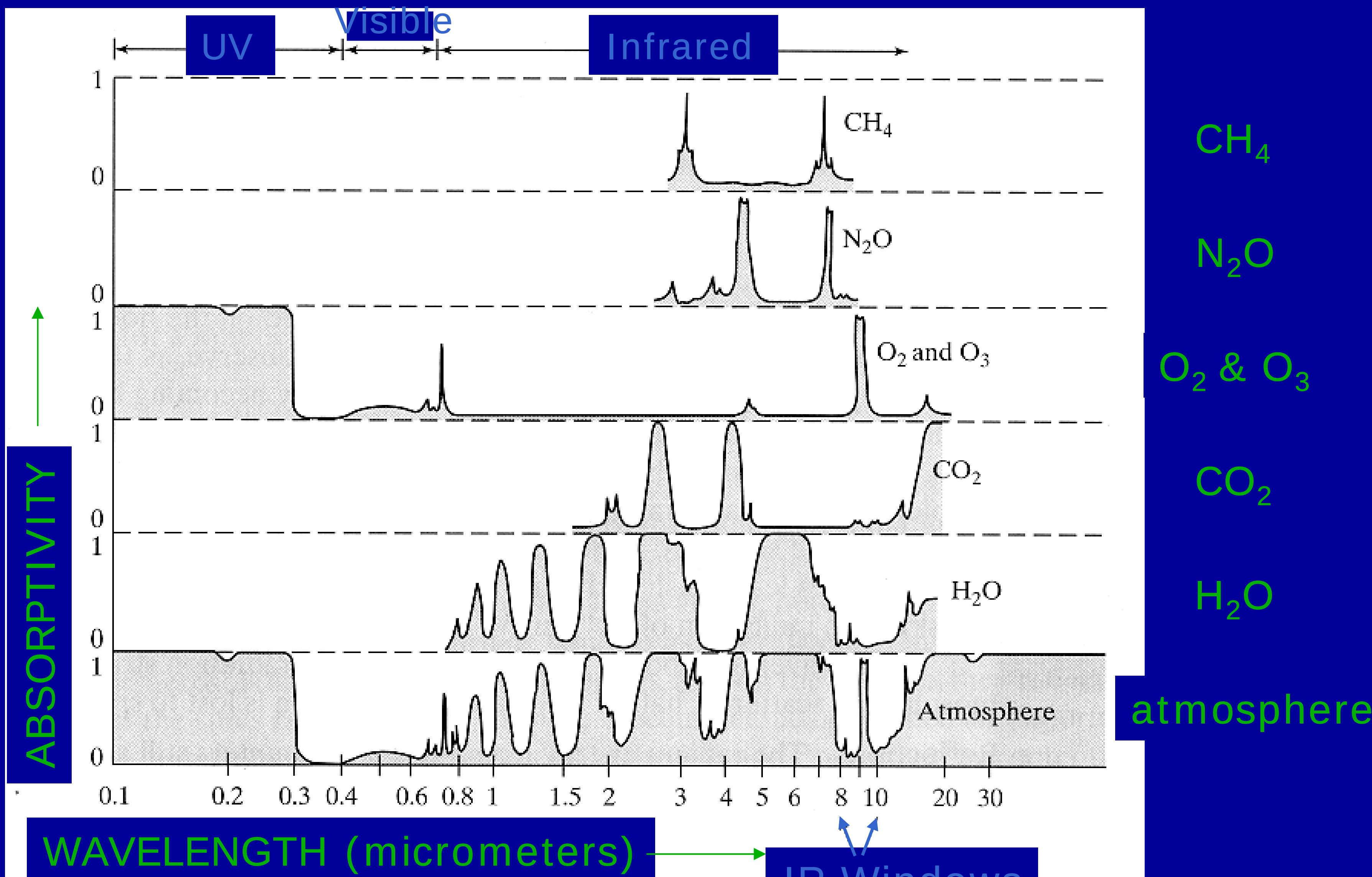
SOLAR SPECTRUM



UV-VISIBLE SOLAR SPECTRUM OBSERVED FROM THE GROUND



Absorption spectra of atmospheric gases

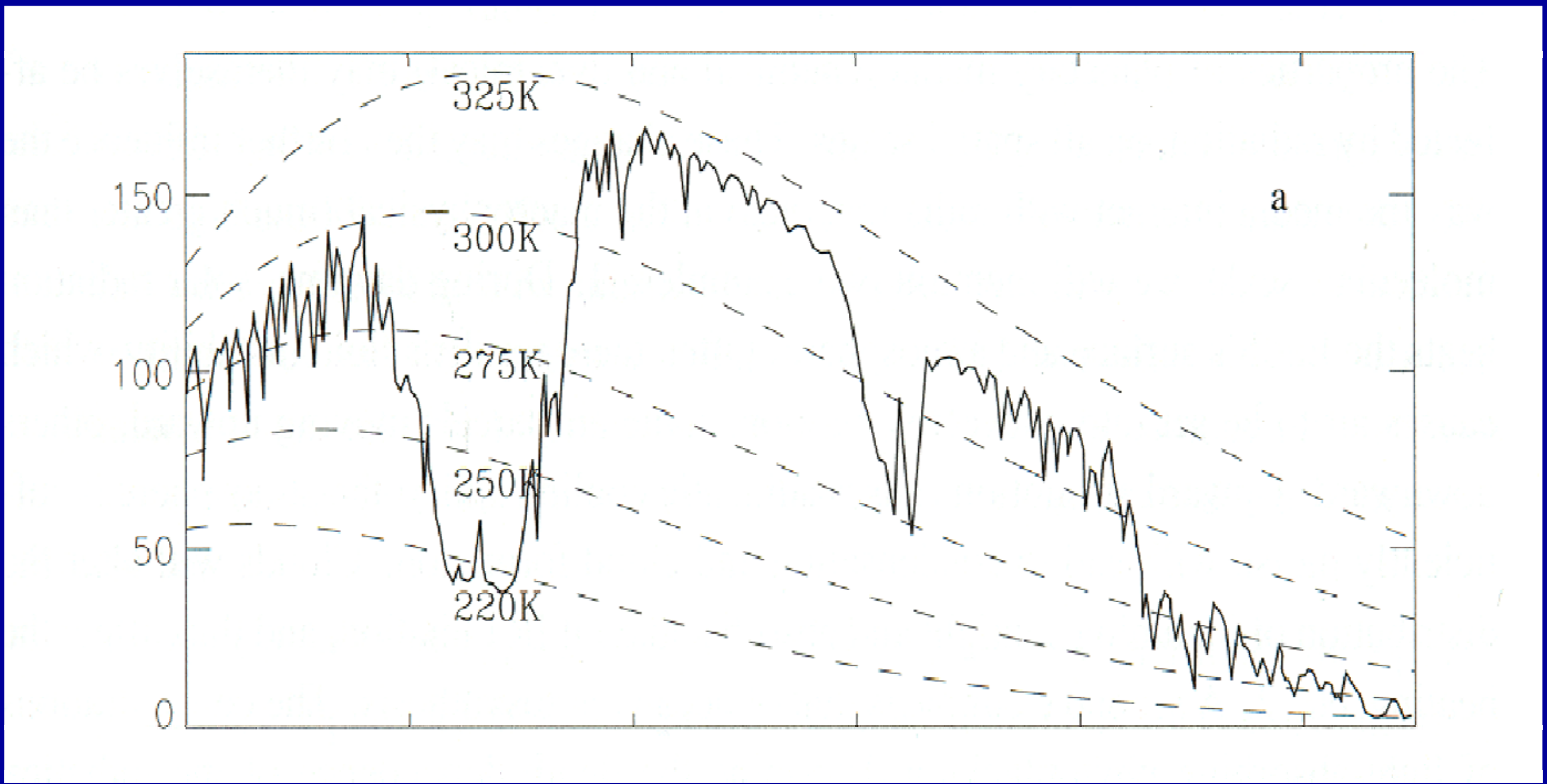


H_2O dominates >15 μm

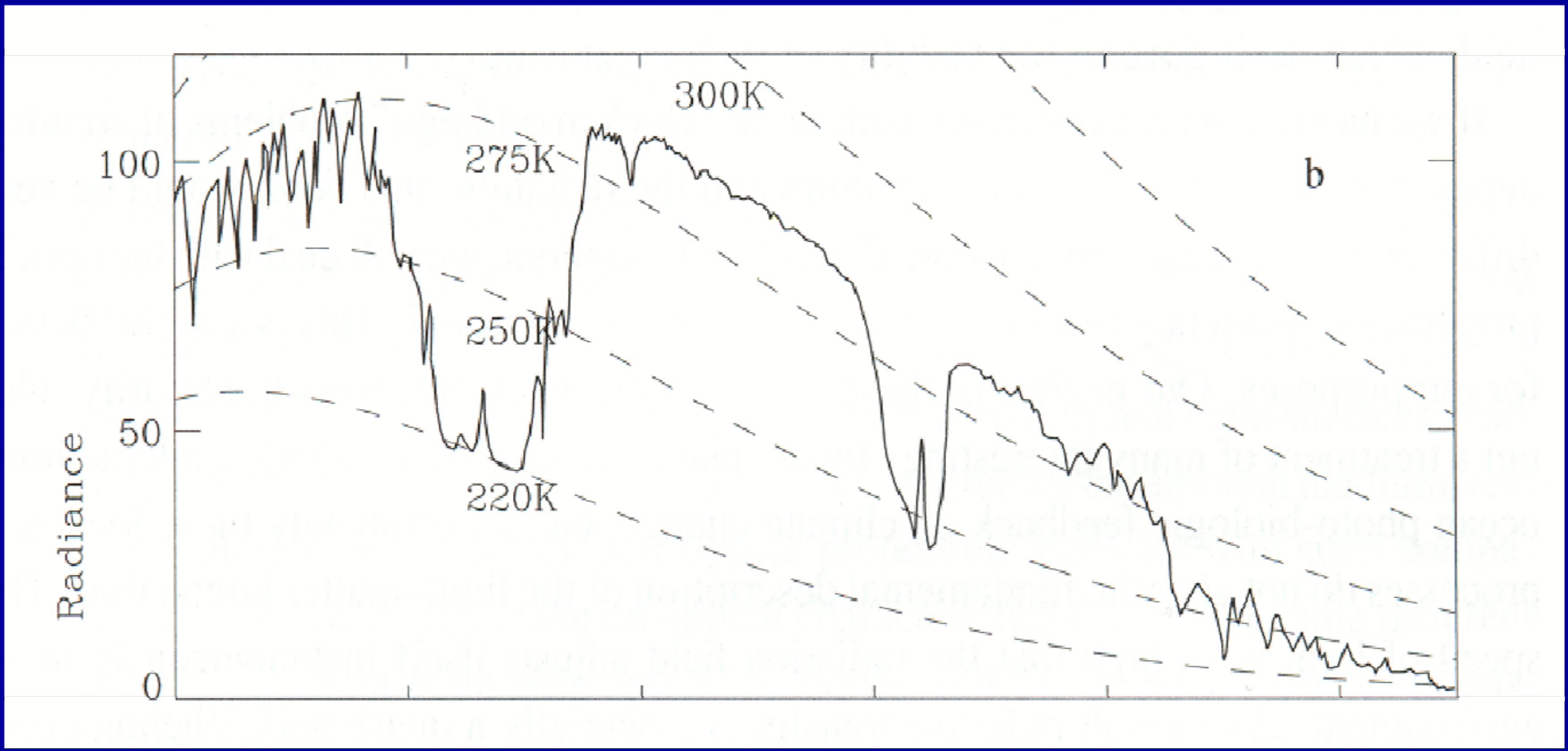
UV-VISIBLE SOLAR SPECTRUM OBSERVED FROM THE GROUND

- Slide shows the absorption of the solar radiation by the atmosphere.
- Major absorbers are molecular oxygen (O_2), ozone (O_3), water vapor (H_2O) and carbon dioxide (CO_2).
- The wavelength is in nm. 1000nm is equal to one micron.

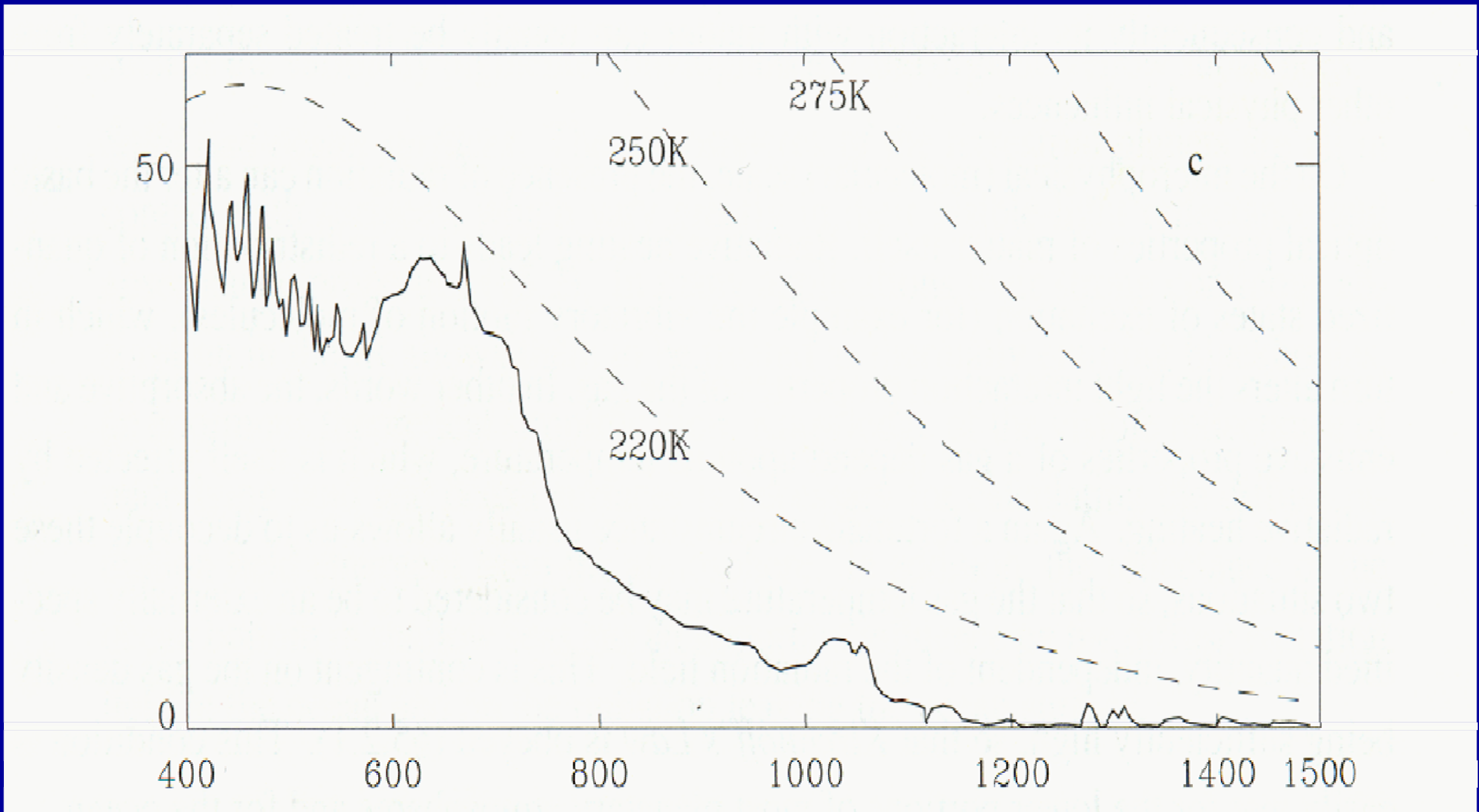
INFRARED FLUX FROM EARTH
SAHARA



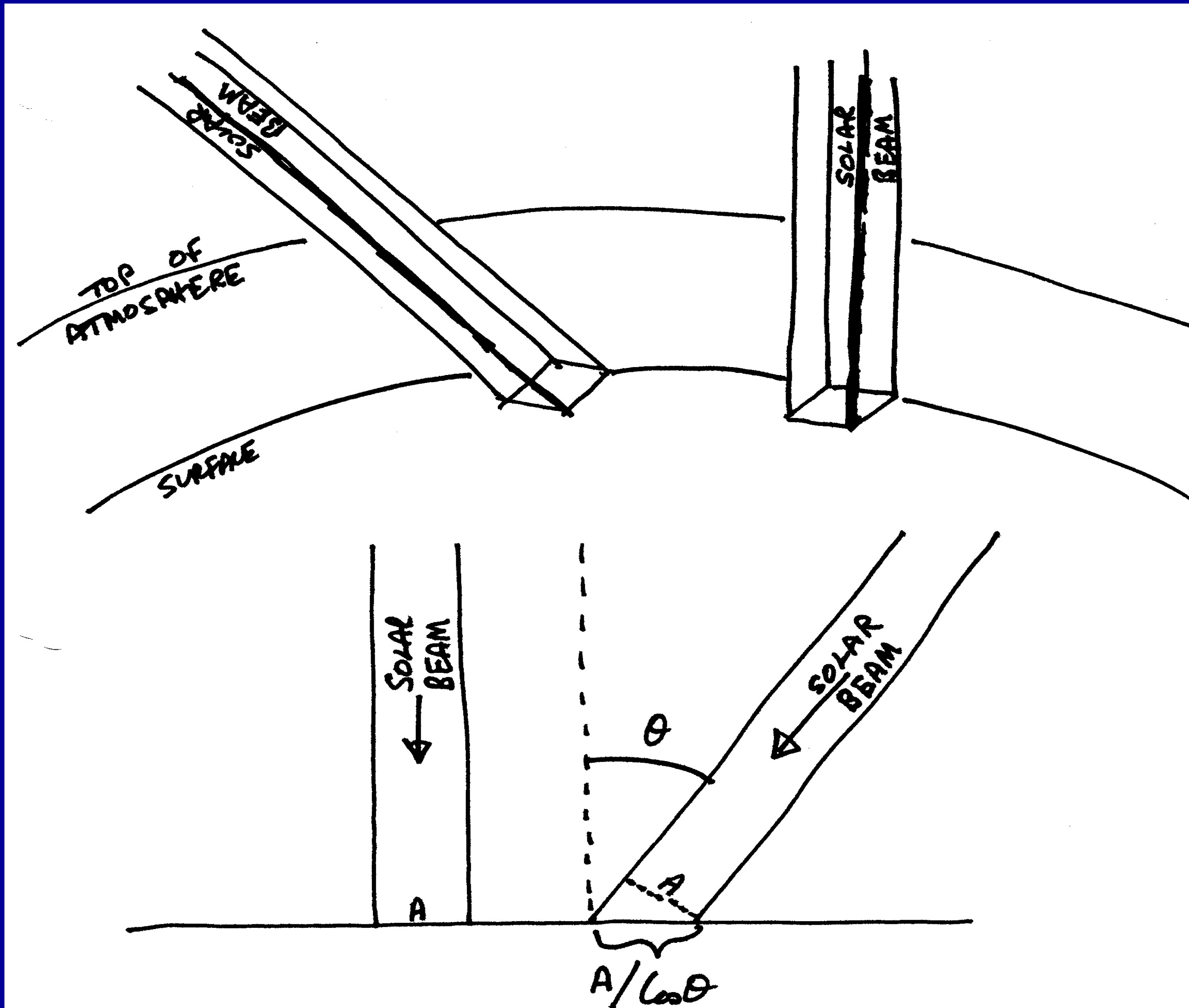
INFRARED FROM EARTH MEDITERRANEAN



INFRARED FROM EARTH ANTARCTIC



SOLAR GEOMETRY



EFFECTIVE AREA

- If the solar zenith angle (SZA) of the sun is θ, then the effective area is given by

  $$1/\cos\theta.$$

- Hence the energy on unit area at the surface is S divided by the effective area, i.e. $S.\cos\theta$.
- College Park is at a latitude of 39 degrees
- At summer solstice the SZA is 17 degrees, and at the winter solstice 61 degrees
- The ratio of the effective areas is 1.97, i.e. twice as much energy per unit area is incident on College Park at summer solstice than at winter solstice.

Optical line-of-sight paths

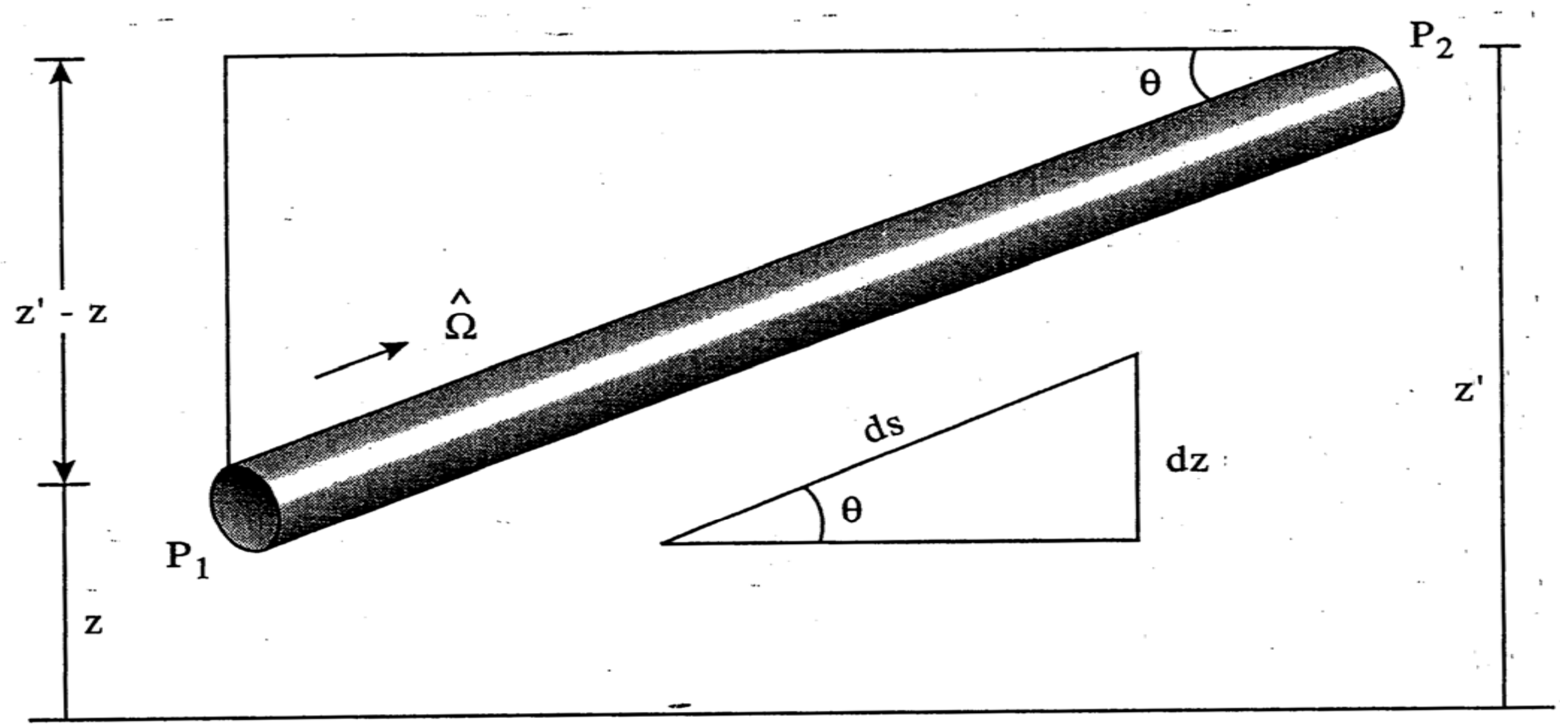


Figure 1.5 Geometry of the slant-column number. The right-circular cylinder of unit geometrical cross section contains $\mathcal{N}$ molecules (number per m^2).

Note that the angle defined here is the polar angle

Slant column mass

$$\mathcal{M}_i(1,2) = \int_1^2 ds\rho_i(s) \approx \rho_i(z_0) \int_1^2 dse^{-[z_2(s)-z_1(s)]/H_i}. \tag{1.7}$$

Referring to Fig. 1.5, we transform from the variable ds to dz; $ds = dz \sec\theta$, where θ is the polar angle ($0 \leq \theta < \pi/2$) made by the vector $\hat{\Omega}$ with the vertical, $\cos\theta = |\hat{z} \cdot \hat{\Omega}|$. $\hat{z}$ is a unit vector in the positive z direction. Integration of the above equation yields

$$\begin{aligned}\mathcal{M}_i(1,2) &= \rho_i(z_0) H_i \sec\theta \left(e^{-z_1/H_i} - e^{-z_2/H_i}\right) \\ &= [\rho_i(z_1) - \rho_i(z_2)] H_i \sec\theta.\end{aligned} \tag{1.8}$$