Radiative Transfer and Climate I

Reading: GPC Ch3

Outline:

• Radiation and minority constituents of the atmosphere

•Solar radiation and terrestrial radiation

•Planck's law

•Stefan-Boltzmann's law

•Frequency selective absorption and emission by atm. gases

•Quantization

Radiation and minority constituents of the atmosphere

The atmosphere is relatively transparent to solar radiation, while it efficiently absorbs and emits thermal IR radiation.
The absorption of IR by the atmosphere is accomplished by molecules that comprise a small fraction of the atmospheric mass.

The dependence of climate on the abundance of these minority constituents makes the climate sensitive to natural and human-induced changes in atmospheric composition. Relatively small changes in composition can affect the flow of energy through the climate system and thereby produce surprisingly large climate changes.
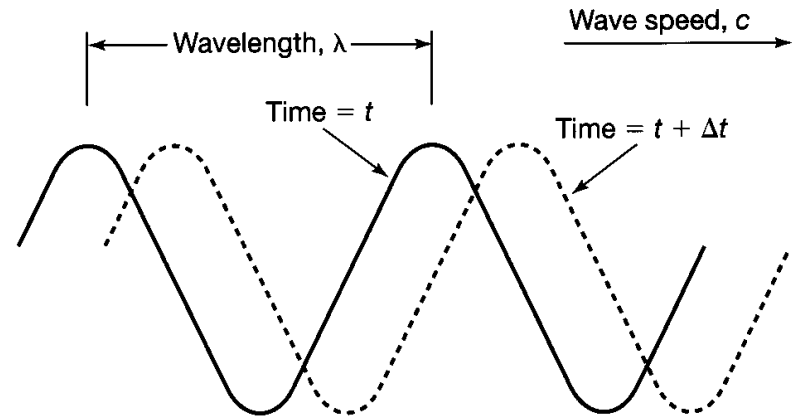
To understand how climate depends on atmospheric composition it is necessary to consider the physical processes through which the e.m. radiation interacts with gases and particles.

Electromagnetic radiation

Speed : $c=3\times10^8$ m/s
Speed, frequency(ν) and
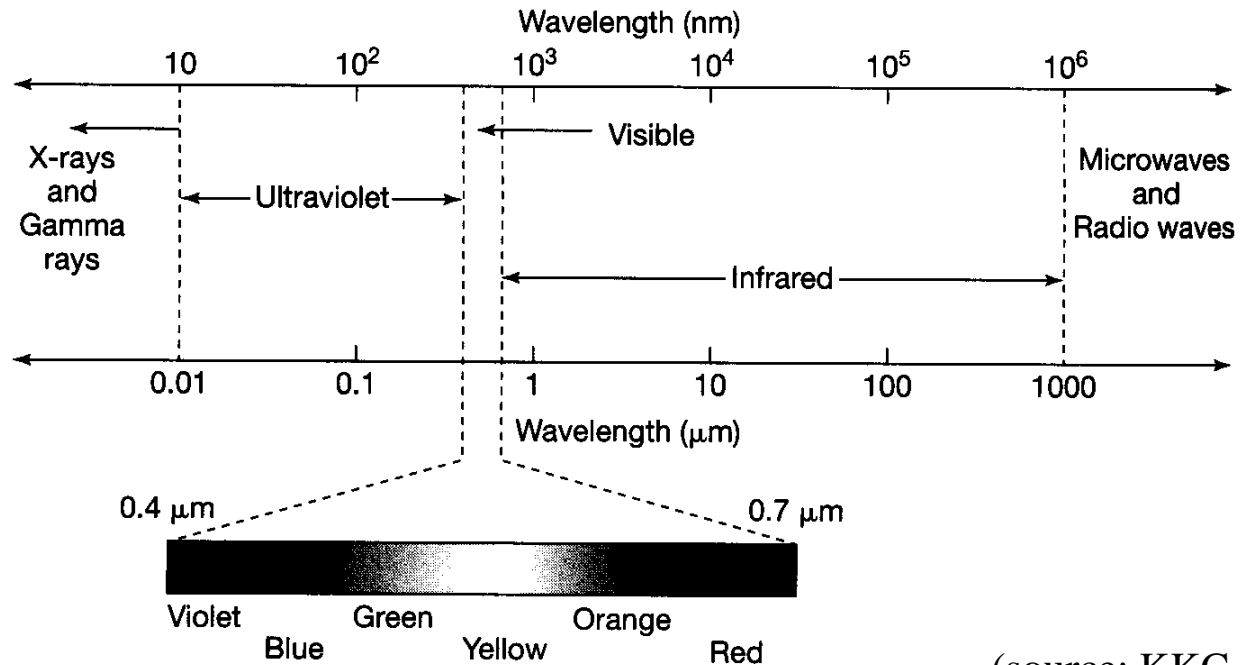wavelength(λ) related by:

$$c = \nu \, \lambda$$

Energy of a photon depends on frequency

$$E_\nu = h \, \nu \qquad h=6.625\times10^{-34}Js; \text{ Planck's constant}$$

Radiation can be *transmitted, scattered, or absorbed* by objects

Wavelength (nm)

10   10^2 10^3 10^4 10^5 10^6

X-rays and Gamma rays

Ultraviolet

Visible

Infrared

Microwaves and Radio waves

0.01   0.1   1   10   100   1000

Wavelength (μm)

0.4 μm   0.7 μm

Violet   Green   Orange

Blue   Yellow   Red

(source: KKC Ch3)

Sun: 150nm to 6 μm   (1nm=10^{-9}m; μm=10^{-6}m)

UV (~1%), visible and near infrared (~99%)

***Earth***: 4-200 μm - thermal infrared

Planck's law of blackbody radiation

Intensity of radiation with freq ν emitted by blackbody of temp T

$$B_v(T) = \frac{2\hbar v^3}{c*^2} \frac{1}{\left(e^{\hbar v/kT} - 1\right)} \tag{3.7}$$

ere $\hbar = 6.625 \times 10^{-34}$ J s (Planck's constant), $k = 1.37 \times 10^{-23}$ J K^{-1} (Boltz-
ann's constant), $c* = 3 \times 10^8$ m s^{-1} (speed of light), ν is the frequency of radiation
s^{-1}, T is the temperature in kelvins.

Units: Watts per unit area per unit frequency

Note: since c = λυ, B can also be written as
a function of wavelength
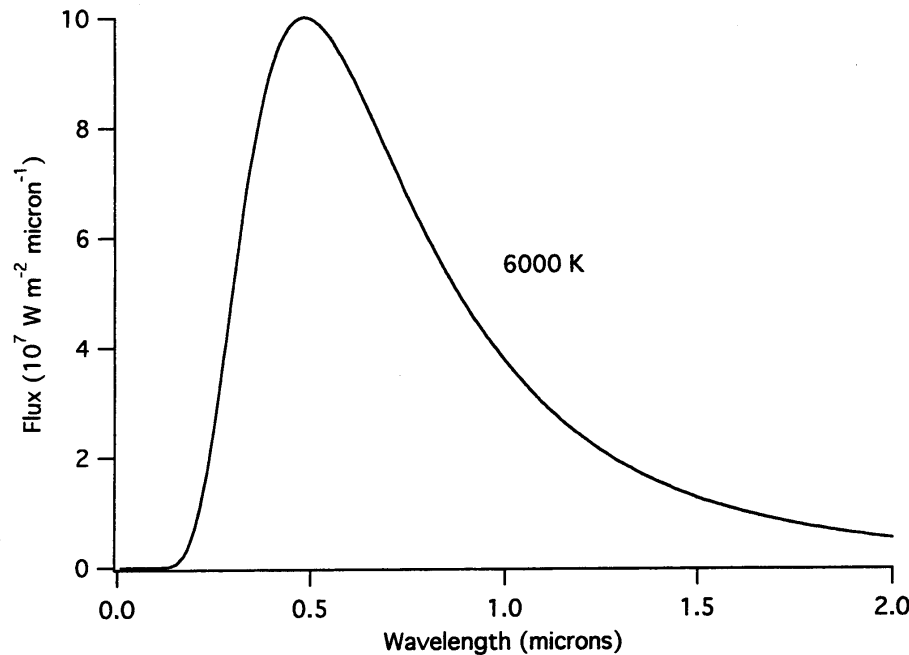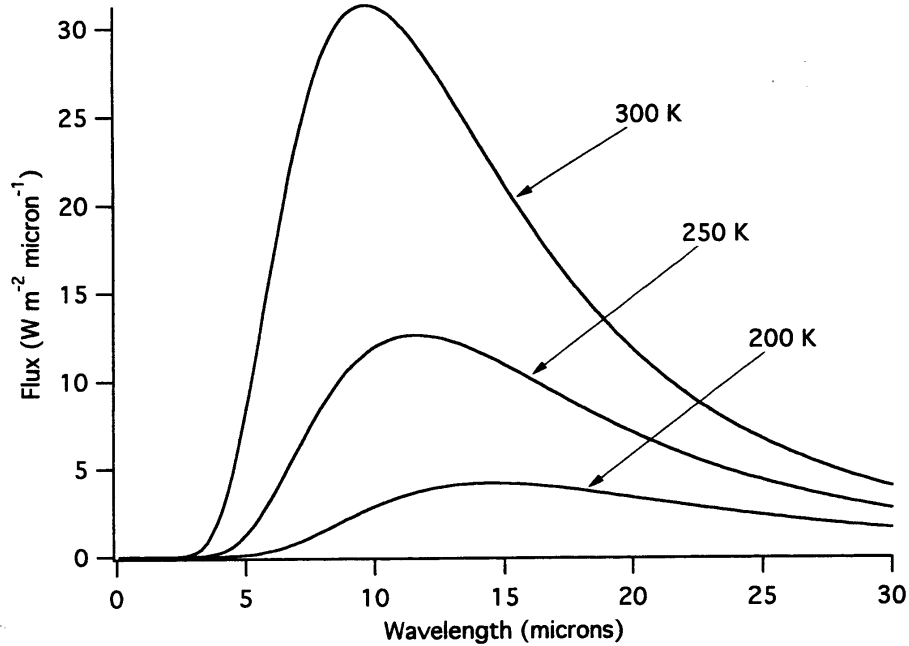
A property of Planck's law is that the wavelength of maximum emission is inversely proportional to the temperature (known as ***Wien displacement law***):

$$\lambda_{max} \cong 2898 / T$$

(T in K, wavelength in μm)

It means that the solar radiation (shortwave, or SW) and terrestrial radiation (longwave, or LW) occupy different intervals in the spectrum - it justifies separate treatment of SW and LW.
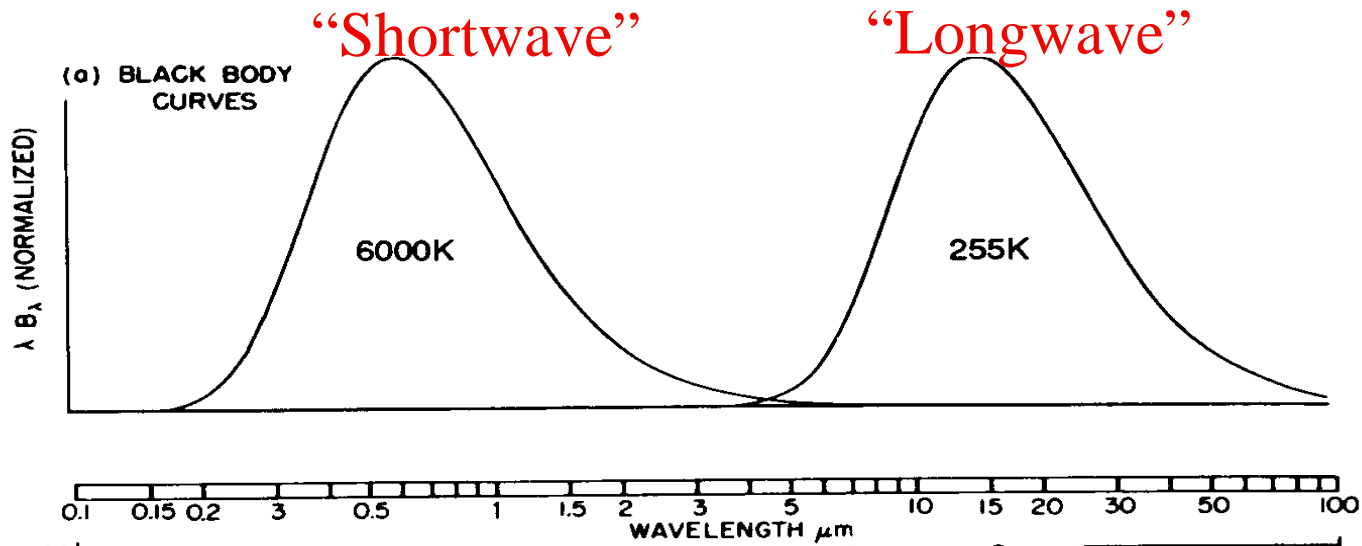
The Stefan-Boltzmann law is just the **flux density** computed from Planck's law, assuming that blackbody radiation is isotropic (independent of angle). The energy flux (in the S-B law) is proportional to to the area under the Planck curve.

Area under curve
$\propto \sigma T^4$

Planck function

(c)
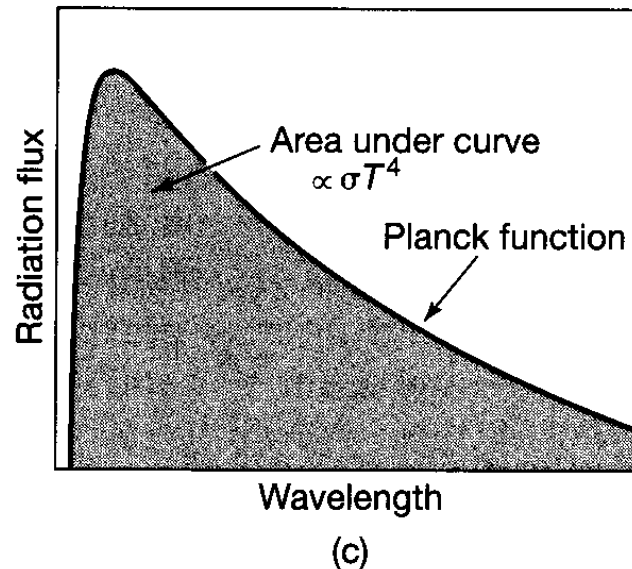
Source: KKC

Emission from black surface

a) Surface emits with intensity independent of direction.
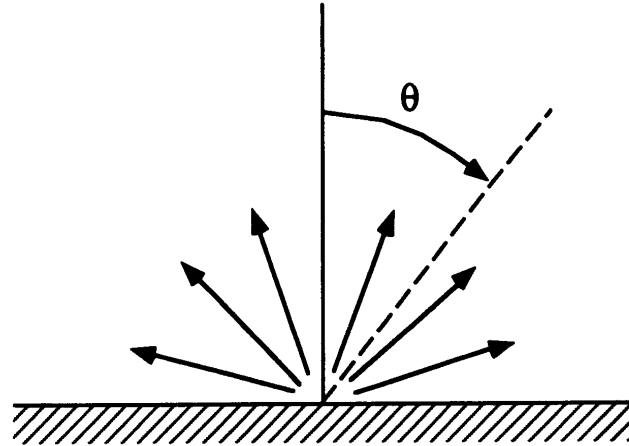
Energy flux perpendicular to surface, per unit frequency,

$$F_\nu = \int_{2\pi} B_\nu \cos\theta \, d\Omega = \int_0^{2\pi} \int_0^{\pi/2} B_\nu \cos\theta \sin\theta \, d\varphi \, d\theta$$
$$= \pi B_\nu$$

Integrate over all frequencies,

$$F = \int_0^\infty F_\nu dv = \int_0^\infty \pi B_\nu dv = \int_0^\infty \pi \frac{2h\nu^3}{c^3} \frac{1}{\exp(h\nu/kT)-1} dv$$
$$= \sigma T^4.$$

The Stefan-Boltzmann constant σ is given in terms of fundamental physical constants by

$$\sigma = \frac{2\pi^5 k^4}{15 c^2 h^3}.$$

When a beam of radiation encounters an object such a molecule, an aerosol particle or a solid surface, we can have:
• **perfect transmission** - the radiation passes the object unchanged
• **pure scattering** – the rad. changes direction without a ch. in energy
• **absorption** – the energy of the radiation is transferred to the object.
The probability that a photon will be scattered, absorbed or transmitted depends on frequency and on the physical properties of the object.
Pure water droplets in clouds scatter visible radiation very effectively, with relatively little absorption taking place.
Water vapor and CO_2 are very effective absorbers of thermal IR radiation at certain frequencies.
Matter can also add to the intensity of a beam, by emitting radiation in the direction of the beam.
Emission of radiation by matter depends, as we have seen, on the substance's physical properties and temperature (emissivity-blackbody radiation).

Quantization

In deriving his law, Planck found it necessary to postulate that the energy levels of an atomic or molecular oscillator are limited to a discrete set of values.

A transition from one energy level to another corresponds to a release

or capture of a packet of energy hν, accomplished by emitting or absorbing a photon of frequency ν.

A photon is emitted in some finite amount of time and then travels through space until it is absorbed. If it approaches an air molecule or a solid particle and is absorbed by it, its energy can appear as ***increased internal energy of a molecule or atom***, or as ***heat***.

For an atom or a molecule, the total energy corresponds to various ***modes of energy storage***: *translational* (not quantized, see T), *rotational, vibrational, electronic.*

A molecule can absorb a photon only if the energy of the photon corresponds to the difference between the energies of two allowable states of the molecule.

Each mode of energy storage corresponds to a range of (discrete) energies, with electronic transitions corresponding to the largest energy differences and rotational transitions corresponding to the smallest.

Allowable transitions determine the frequency of the photons that will be absorbed and emitted. If no transition corresponds to $h\nu$, then the photon will pass through the atmosphere without being absorbed.

A single "allowed" ν is an **absorption line.**

The collection of such absorption lines in a particular frequency band is called an **absorption band**.

Modes of energy storage and radiation wavelengths

•*Translational energy* (continuous) – at terrestrial temperatures, generally small compared to vibrational energy, but is important in spectral broadening (see later)

•*Rotational energy* (discrete) - corresponds to wavelengths shorter that *1cm*. Requires a dipole moment

•*Vibrational energy* (discrete) - corresponds to wavelengths less than *20 micrometers (IR)*

•*Photodissociation* - photon breaks the bond that hold together atoms in a molecule, wavelengths less than *1micrometer.* E.g. Ozone dissociation and the 200-300nm band (UV)

•*Electronic excitation* (discrete) - corresponds to energy wavelengths *< 1 micrometer*. Electrons are excited to the outer shell of the atom

•*Photoionization* - atom loses electron; wavelengths less than *100nm*

Terrestrial radiation (4-200 μm): rotational and vibrational modes are generally the most important for troposphere

CO_2 vibration-rotation mode important at 15μm (LW)

Water vapor has a important vibration-rotation mode near 6.3 μm, and densely spaced rotational bands in excess of 12 μm. The region between the two is called the *water vapor window*, as it is relatively transparent to LW

Molecule	Arrangement	Permanent Dipole Moment
N_2	N — N	No
O_2	O — O	No
CO	C — O	Yes
CO_2	O — C — O	No
N_2O	N — N — O	Yes
H_2O	H—O—H	Yes
O_3	O—O—O	Yes
CH_4	H—C—H (with H above and below)	No

Diatomic Structures

N_2, O_2, CO

Triatomic Structures

ν_1 Symmetric | ν_2 Bending | ν_3 Antisymmetric
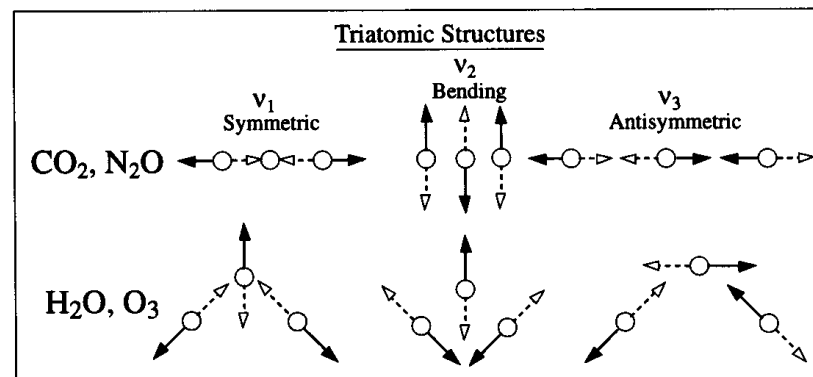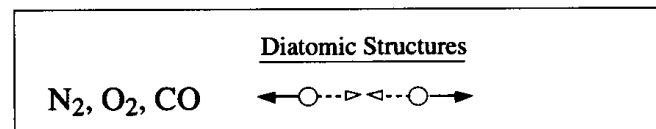
CO_2, N_2O

H_2O, O_3

Fig. 3.3 Schematic diagrams showing the vibrational modes of diatomic and triatomic molecules. [From McCartney (1983). Reprinted with permission from Wiley and Sons, Inc.]

Solar radiation (0.15-6 μm)

H_2O and CO_2 (and to a lesser extent also other atmospheric gases, such as O_2 and O_3) have some significant vibration-rotation absorption bands in **near IR** wavelengths (0.8-5 μm), that account for most of the absorption of solar radiation by air molecules in the troposphere.

Visible wavelengths (0.3-0.8 μm) are too energetic to be absorbed and not energetic enough for photodissociating atmospheric gases, and are therefore virtually free of gaseous absorption features.

The **UV** solar rad. (less than 0.3 μm) is absorbed in the upper atmosphere by O_3 and O_2 (and N_2). O_2 is photodissociated by wavelengths less than 0.2 μm. O_3 is more loosely bonded than O_2 and can be dissociated by 0.2-0.3 μm (stratosphere).
Most of UV solar radiation thus does not reach the surface.
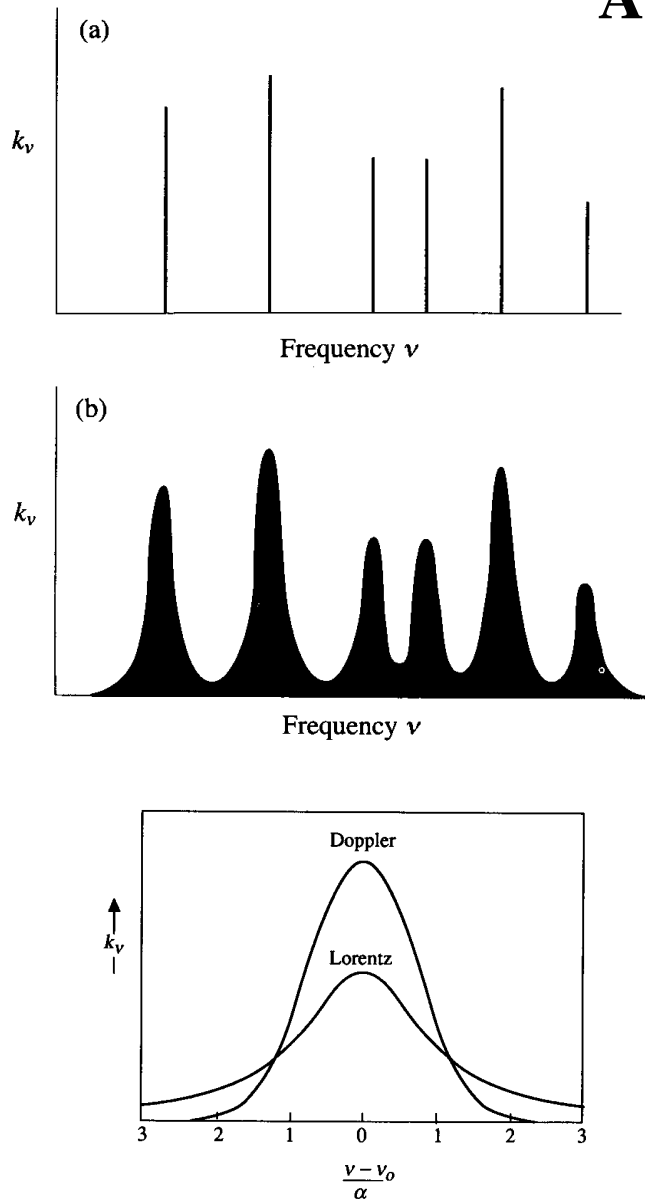
Absorption lines and line broadening

Fig. 3.6 Line shapes produced by pressure (Lorentz line shape) and Doppler broadening for the same line width (α) and intensity at some central frequency v_o. [From Goody and Yung (1989). Reprinted with permission from Oxford University Press.]

Pressure (collision) broadening
Broadening due to collision between atoms/molecules - most important in the troposphere where air is dense

Doppler broadening
Due to motion of atoms/molecules relative to a photon. Important where air is thin (high altitudes)

Natural broadening
Due to quantum mechanical effects (transition lifetimes, uncertainty principle)

Important points:

- N_2 and O_2 (which make up most of the atmosphere) do not produce dipole moments even when vibrating - so there are no rotational-vibrational modes at small energies corresponding to LW. So, the molecules important for LW radiative transfer on Earth are the trace constituents (water vapor, carbon dioxide, ozone).
- Apart from the 8-12μm range, the atmosphere is opaque to terrestrial LW. Important lines are: water vapor 6.3 μm, ozone 9.6 μm, carbon dioxide 15 μm
- The atmosphere is almost transparent to SW. Exceptions are the UV radiation (<0.2 μm) that are absorbed by photodissociation and ionization of N_2 and O_2 in the upper atmosphere, and 0.2-0.3 μm that is absorbed by ozone in the stratosphere

Selective absorption and emission by atmospheric gases   (source: P&O fig 4.2)