Lecture 5

Composition and structure of the atmosphere.

1. Structure and composition of the Earth's atmosphere

2. Properties of atmospheric gases

Required reading:

S: 1.3-1.5

Suggested reading:

Liou 3.1

https://scied.ucar.edu/shortcontent/earths-atmosphere

1. Structure and composition of the Earth's atmosphere.

Temperature

Temperature lapse rate is the rate at which temperature decreases with increasing altitude:

$$\Gamma = -(T_2 - T_1) / (z_2 - z_1) = -\Delta T/\Delta z \qquad [3.1]$$

where T is temperature and the height z.

For a parcel of dry air under adiabatic conditions it can be shown that

$$dT/dz = -g/c_p \qquad [3.2]$$

where c_p is the heat capacity at constant pressure per unit mass of air and $c_p = c_v + R/m_a$ and m_a is the molecular weight of dry air. The quantities g/c_p is a constant for dry air equal to **9.76 C per km**. This constant is called **dry adiabatic lapse rate**.

Pressure

- ✓ The law of hydrostatic balance states that the pressure at any height in the atmosphere is equal to the total weight of the gas above that level.

***The hydrostatic equation*:** $$dP(z) / dz = -\rho(z)\, g \qquad [3.3]$$

where $\rho(z)$ is the mass density of air at height z, and **g** = 9.81 m/s is the acceleration of gravity.

- Integrating the hydrostatic equation at constant temperature as a function of z gives

$$P = P_0 \exp(-z/H) \qquad [3.4]$$

where $\boldsymbol{H}$ is **the scale height:** $\boldsymbol{H = k_B\, T / mg}$; and $\boldsymbol{m}$ is the average mass of air molecule ($\boldsymbol{m}$ = 4.8096x10^{-26} kg/air molecule).

Example: T = 290 K, gives $\boldsymbol{H}$ = 8500 m ; T = 210 K, gives $\boldsymbol{H}$ = 6000 m

Standard atmospheric models used in radiative transfer modeling: each model includes profiles of T, P, and concentration of main gases.

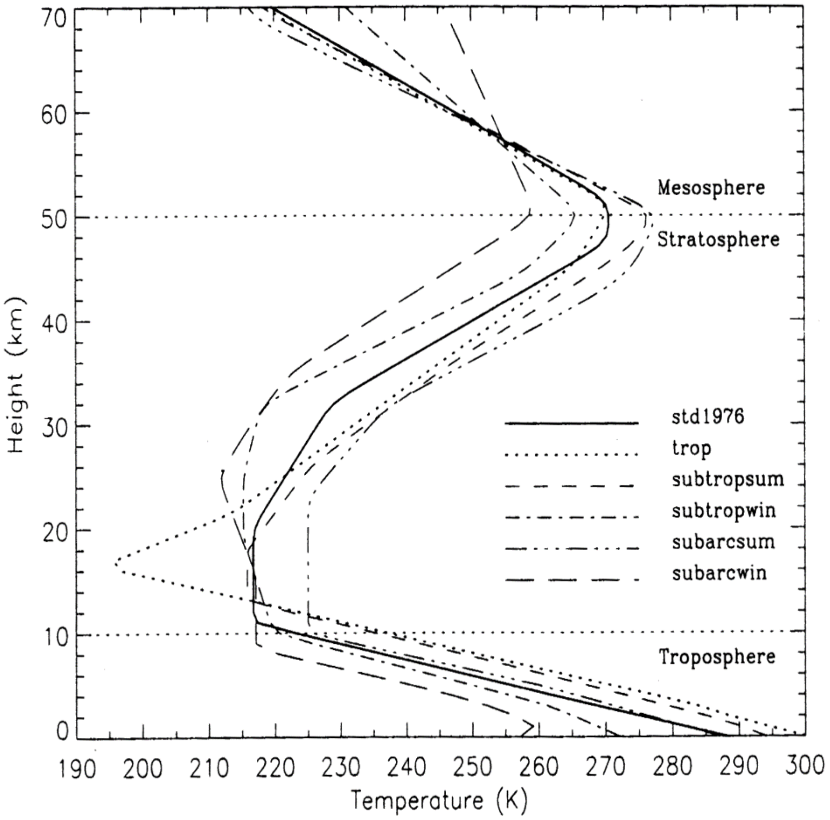

Figure 3.1 Temperature profiles of the standard atmospheric models which are often used in radiative transfer calculations to represent different climatic zones. “Standard U.S. 1976 atmosphere” is representative of the global mean atmospheric conditions; “Tropical atmosphere” is for latitudes < 30^0; “Subtropical atmosphere” is for latitudes between 30^0 and 45^0; “Subarctic atmosphere” is for latitudes between 45^0 and 60^0; and “Arctic atmosphere” is for latitudes > 60^0.

Composition (gases)

Table 3.1 Three most abundant gases in planetary atmospheres (Yung and DeMore, 1999). *Mixing ratios are given in parentheses. All compositions refer to the surface or 1 bar for the giant planets*.

Jupiter	H_2 (0.93)	He (0.07)	CH_4 ($3.0x10^{-3}$)
Saturn	H_2 (0.96)	He (0.03)	CH_4 ($4.5x10^{-3}$)
Uranus	H_2 (0.82)	He (0.15)	CH_4 (1 –2 $x10^{-2}$)
Neptune	H_2 (0.80)	He (0.19)	CH_4 ($2.0x10^{-3}$)
Titan	N_2 (0.95-0.97)	CH_4 ($3.0x10^{-2}$)	H_2 ($2.0x10^{-3}$)
Triton	N_2 (0.99)	CH_4 ($2.0x10^{-2}$)	CO (<0.01)
Pluto	N_2 (?)	CH_4 (?)	CO (?)
Io	SO_2 (0.98)	SO (0.05)	O (0.01)
Mars	CO_2 (0.95)	N_2 ($2.7x10^{-2}$)	Ar ($1.6x10^{-2}$)
Venus	CO_2 (0.96)	N_2 ($3.5x10^{-2}$)	SO_2 ($1.5x10^{-4}$)
Earth	**N_2 (0.78)**	**O_2 (0.21)**	**Ar ($9.3x10^{-3}$)**

Table 3.2 The gaseous composition of the Earth's atmosphere

Gases	% by volume	Comments
Constant gases		
Nitrogen, N_2	78.08%	Photochemical dissociation high in the ionosphere; mixed at lower levels
Oxygen, O_2	20.95%	Photochemical dissociation above 95 km; mixed at lower levels
Argon, Ar	0.93%	Mixed up to 110 km
Neon, Ne	0.0018%	Mixed in most of the middle atmosphere
Helium, He	0.0005%	
Krypton, Kr	0.00011%	
Xenon, Xe	0.000009%	
Variable gases		
Water vapor, H_2O	4.0% (maximum, in the tropics) 0.00001%(minimum, at the South Pole)	Highly variable; photodissociates above 80 km dissociation

Carbon dioxide, CO_2	0.0365% (increasing ~0.4% per year)	Slightly variable; mixed up to 100 km; photodissociates above
Methane, CH_4	~0.00018% (increases due to agriculture)	Mixed in troposphere; dissociates in mesosphere
Hydrogen, H_2	~0.00006%	Variable photochemical product; decreases slightly with height in the middle atmosphere
Nitrous oxide, N_2O	~0.00003%	Slightly variable at surface; dissociates in stratosphere and mesosphere
Carbon monoxide, CO	~0.000009%	Variable
Ozone, O_3	~0.000001% - 0.0004%	Highly variable; photochemical origin
Fluorocarbon 12, CF_2Cl_2	~0.00000005%	Mixed in troposphere; dissociates in stratosphere

✓ Variations of temperature, pressure and density are much larger in vertical directions than in horizontal. This strong vertical variations result in the atmosphere being **stratified** in layers that have small horizontal variability compare to the variations in the vertical. Therefore, a plane-parallel model of the atmosphere is often used in modeling the propagation of radiation through the atmosphere.

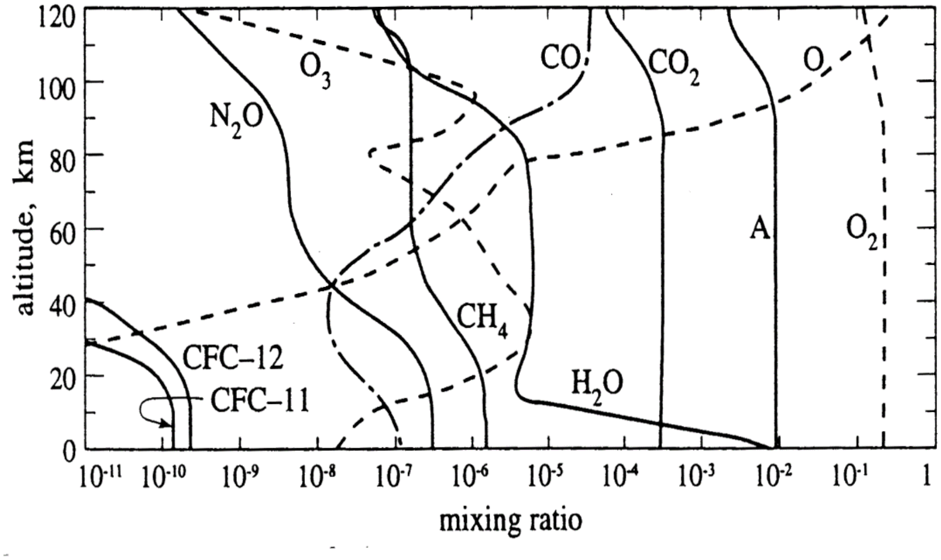

Figure 3.2 Representative vertical profiles of mixing ratios of some gases in the Earth's atmosphere.

<u>The amount of the gas may be expressed in several ways:</u>

i) **Molecular number density = molecular number concentration = molecules per unit volume of air;**

ii) **Density = molecular mass concentration = mass of gas molecules per unit volume of air;**

iii) **Mixing ratios:**

Volume mixing ratio is the number of gas molecules in a given volume to the total number of all gases in that volume (when multiplied by 10^6, in ppmv (parts per million by volume))

Mass mixing ratio is the mass of gas molecules in a given volume to the total mass of all gases in that volume (when multiplied by 10^6, in ppmm (parts per million by mass))

NOTE: Commonly used mixing fraction: one part per million 1 **ppm** (1×10^{-6});
one part per billion 1 **ppb** (1×10^{-9}); one part per trillion 1 **ppt** (1×10^{-12}).

iv) **Mole fraction** is the ratio of the number of moles of a given component in a mixture to the total number of moles in the mixture.

NOTE: Mole fraction is equivalent to the volume fraction.

NOTE: The equation of state can be written in several forms:

using molar concentration of a gas, $c = \mu/v$: $\mathbf{P = c\,T\,R}$

using number concentration of a gas, $N = c\,N_A$: $\mathbf{P = N\,T\,R/N_A}$ or $\mathbf{P = N\,T\,k_B}$

using mass concentration of a gas, $q = c\,m_g$: $\mathbf{P = q\,T\,R/m_g}$

Avogadro's number: $N_A = 6.02212 \times 10^{23}$ molecules/mole