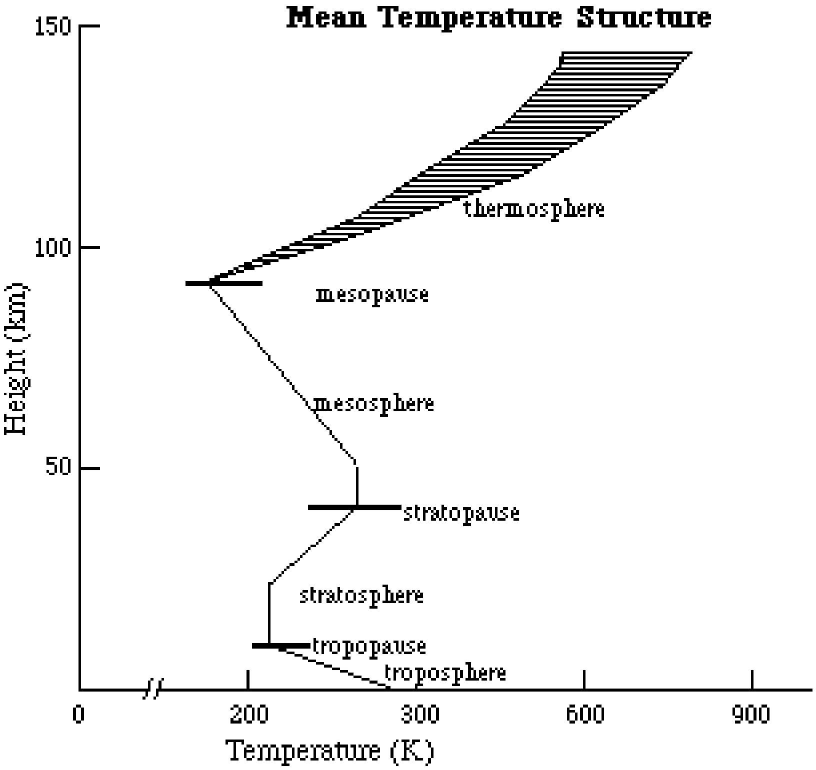
1.8 Vertical temperature structure.

Mean vertical temperature structure is displayed in MS, Figs. 1.2 and 1.3. The schematic diagram below illustrates this structure and atmospheric layer nomenclature based on vertical temperature gradients.



Note that temperature varies by only about ±20% below about 100km so that scale height H also varies by only about ±20%. Note also that temperature in the thermosphere is extremely variable as a result of diurnal, seasonal, solar cycle, and solar activity variations that affect absorption of energy in the thermosphere.

1.9. Vertical composition structure.

Below about 100km the major permanent gases (those with long lifetimes) are uniformly mixed by turbulence on all scales. Above 100km, the molar fractions of the most abundant gases vary with height because of two factors (MS, Fig. 1.3):

- Ultraviolet solar radiation (wavelengths less than about 0.175nm) rapidly dissociates molecular oxygen to atomic oxygen.

- Molecular diffusion becomes dominant over turbulent mixing.

When molecular diffusion dominates, under equilibrium conditions (steady state, no sources and sinks of constituents), each gas follows its individual scale height:

$$\boxed{\frac{\partial \ln p}{\partial z} = -\frac{1}{H_i} \quad , \qquad\qquad H_i = \frac{R^* T}{M_i g}} \; . \tag{1.33}$$

This equilibrium distribution is called diffusive equilibrium. In diffusive equilibrium, heavy gases that have small scale heights and lighter gases that have large scale heights separate from each other with the lighter gases rising to the top like cream from milk. Because of the dissociation of molecular oxygen, atomic oxygen becomes dominant over both molecular oxygen and nitrogen at sufficiently high levels in the thermosphere. At even greater heights, helium and even hydrogen can become the dominant gas.

Why do diffusive separation and approximate diffusive equilibrium occur above 100km?

Fundamentally this is because, at sufficiently high altitudes and low gas densities, molecular mean free path becomes so large that, in a given interval of time, molecules travel much farther by molecular diffusion than by turbulent mixing. The term "turbulent mixing" in this context refers to mixing by fluid motions on all scales up to planetary scale. From kinetic theory (or dimensional analysis), mean-free-path λ_f is

$$\lambda_f \approx \frac{1}{\cancel{n}\sigma} \tag{1.34}$$

where $\sigma =$ average collision cross-section $\approx 2\text{x}10^{-22}\,\text{m}^2$. Molecular collision time (mean time between collisions) is

$$t_c \approx \frac{\lambda_f}{\overline{v_m}} \approx \left(\cancel{n}\sigma\overline{v_m}\right)^{-1}$$

where $\overline{v_m}$ is the mean molecular thermal velocity

$$\overline{v_m} = \left(\frac{2kT}{\cancel{m}}\right)^{1/2} .$$

The molecular diffusion coefficient is the product of the mean free path and the mean speed

$$D_m \approx \overline{v_m}\lambda_f \approx \frac{\overline{v_m}}{\cancel{n}\sigma} . \tag{1.35}$$

Let $\overline{w}$ and L_z represent characteristic vertical eddy fluid speed and vertical length scales. Then, if the ratio

$$\frac{\overline{w}L_z}{D_m} \approx \frac{\overline{w}L_z}{\overline{v_m}\lambda_f} \approx \frac{\overline{w}L_z \mathcal{N}\sigma}{\overline{v_m}} > 1,$$

the rate of vertical mixing of constituents exceeds the rate of vertical diffusion by molecular motions. Notice that $\overline{w}L_z$ has the dimensions of a diffusion coefficient, but since turbulent mixing usually does not act like diffusion, we do not identify this with a "turbulent eddy diffusion coefficient". It simply provides a convenient way to compare effects of turbulence with those of molecular diffusion. Up to about 90km, this ratio is very large and turbulent mixing dominates. However, because of the exponential decrease with altitude of $\mathcal{N}$ and the corresponding increase of λ_f, above 120km, this ratio is very small. The transition between turbulent mixing and molecular diffusion occurs between 100 and 110km, and is called the homopause. Below the homopause, permanent gases are well-mixed. Above, diffusive flux of each species (i)

$$F_{d_i} \approx -D_{mi}\left(\frac{\partial \ln p_i}{\partial z} + \frac{1}{H_i}\right) \tag{1.36}$$

is the dominant mode of transport. In the absence of powerful sources and sinks or of flux of species across an upper boundary of the atmosphere, (1.36) reduces to the approximate equation for diffusive equilibrium, (1.33).

The region above the homopause in which major species tend to be in diffusive equilibrium is called the heterosphere. The region below is called the homosphere.

1.8 Ionosphere, exobase, exosphere, escape.

Because incident solar ultraviolet radiation with wavelengths short enough to ionize air molecules (wavelengths < 120nm) is absorbed in the thermosphere, with only a small fraction penetrating to the upper mesosphere, ionized regions are formed primarily in the thermosphere with only very weak ionization below, as in the following table.

Height range	Nomenclature	Electron density	Diurnality
60-90km	D-Region	10^6-10^8 m^{-3}	daytime only
90-120km	E-Region	10^{10}-$10^{11}m^{-3}$	mostly daytime
120-400km	F-region	10^{11}-$10^{12}m^{-3}$	day & night

These layers are responsible for reflection and absorption of radio signals. Their properties vary with season and state of the sun, as well as diurnally.

Above the level z_c at which

$$\boxed{\int_{z_c}^{\infty} \tilde{n}(z_c)dz \approx H(z_c)\tilde{n}(z_c) > \frac{1}{\sigma}}, \qquad (1.37)$$

atoms can escape without collision, provided their upward speed exceeds the escape velocity v_e obtained by equating particle kinetic and gravitational potential energies:

$$\frac{1}{2}\tilde{m}v_e = \int_{a_c}^{\infty} g(r)dr = \int_{a_c}^{\infty} \tilde{m}g_0\left(\frac{a_c}{r}\right)^2 dr$$

(where a_c is planetary radius at level z_c). Thus

$$v_e = \sqrt{2g_0a} \approx 11\mathrm{kms}^{-1} . \qquad (1.38)$$

The level defined by (1.37),

$$\boxed{\sigma H(z_c)\tilde{n}(z_c) \approx 1} \qquad (1.39)$$

above which sufficiently energetic atoms can escape is called the exobase. In the region above the exobase, which typically occurs around 4-500km, collisions are infrequent, and molecules are essentially executing free orbital motion in elliptic or hyperbolic (escaping) orbits. This region is called the exosphere. The fastest atoms in the high-energy tail of the velocity distribution (approximately the classical Maxwell-Boltzmann distribution) can escape from the exosphere because of their thermal energy (hence, by the process of thermal evaporation, also called Jeans escape; see MS Fig. 1.6 and eq. 1.23). For Earth, the rate of escape by this mechanism is normally very slow except for hydrogen and deuterium. However, atoms and molecules can be excited to higher energies than those of the high energy tail of the Maxwell-Boltzmann velocity distribution by impact with energetic charged particles, by chemical reactions including those that exchange charge between ions or between ions and neutrals, and by other mechanisms that may contribute much more to escape than thermal evaporation.