Chapter Two

The Neutral Atmosphere

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Vertical structure

1. The static atmosphere is described by the four properties, pressure (P), density (ρ), temperature (T) and composition.
2. Between them these properties determine much of the atmosphere's behavior. They are not independent, being related by the <u>*universal gas law*</u> which may be written in various forms. For our purposes the form

   $$P = nkT$$

   Where n is the number of molecules per unit volume, concentration or the *number density.*
3. The regions of the neutral atmosphere are named according to the variations with height of the temperature, the composition, and the state of mixing.
4. Figure 1 illustrates the most commonly used terms. <u>*The primary classification is according to the temperature gradient.*</u>

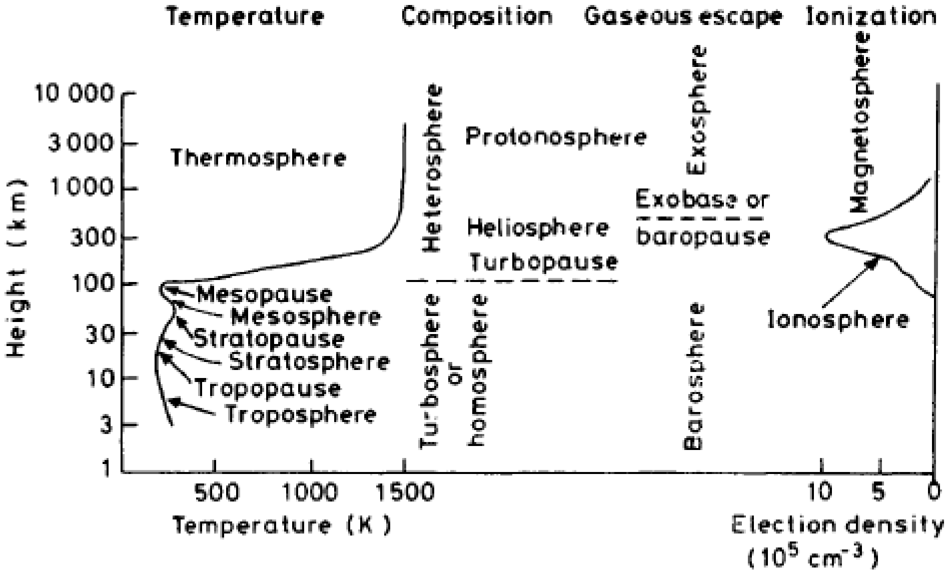


Figure (1) Nomenclature of the upper atmosphere based on temperature, composition, mixing and ionization.

5. Thus the *troposphere*, in which the temperature falls off at 10 K/km or less, is bounded by the *tropopause* at a height of 10-12 km.
6. The *stratosphere* above was originally thought to be isothermal, but in fact is a region where the temperature increases with height. A maximum, due to heating by ultra-violet absorption in ozone, appears at about 50 km and this is the *stratopause.*
7. The temperature again decreases with height in the *mesosphere* (or *middle atmosphere)* to a minimum at the *mesopause* at 80-85 km. With a temperature around 180 K this is the coldest part of the atmosphere.

8. Above the mesopause, heating by solar ultra-violet radiation ensures that the temperature gradient remains positive, and this is the *thermosphere.* The thermospheric temperature eventually becomes almost constant at a value that varies with time but is generally over 1000 K. This is the hottest part of the atmosphere.
9. The lower part of the atmosphere is well mixed, with a composition much like that at sea level except for minor components. This is the *turbosphere* or *homosphere.*
10. In the upper region, essentially the thermosphere, mixing is inhibited by the positive temperature gradient, and here, in the *heterosphere,* the various components may separate under gravity and so the composition varies with altitude.
11. The boundary between the two regions, which occurs at about 100 km, is the *turbopause.*
12. Above the turbopause the gases can separate by gaseous diffusion more rapidly than they are mixed by turbulence - compare the relative magnitudes of the coefficients of molecular diffusion and eddy diffusion in Figure 2.

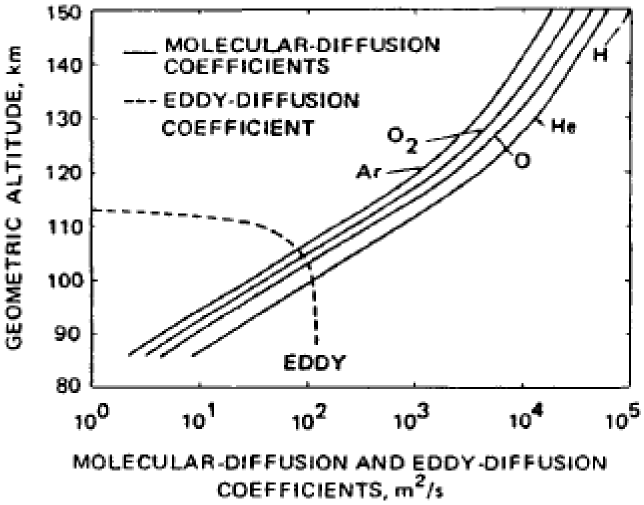


Figure (2) Comparison of coefficient for molecular and eddy diffusion.

13. Within the heterosphere, the dominant gas is helium or hydrogen, and these are the *heliosphere* and the *protonosphere* respectively.
14. From the higher levels, above about 600 km, individual atoms can escape from the Earth's gravitational attraction; this region is called the *exosphere.*

Hydrostatic equilibrium

1. This height variation is described by the *hydrostatic equation,* sometimes called the *barometric equation,* which is given as:

$$P = P_o \exp(-h/H)$$

where P_o is the pressure at height h_o, and if both H and T are constant with height,

$$n = n_o \exp(-h/H)$$

where n_0 is the number density at h_0.

2. In the terrestrial atmosphere the scale height increases with height from about 5 km at height 80 km to 70-80 km at 500 km, as the mean molecular mass decreases and the temperature increases.
3. It is often convenient to write

$$\frac{P}{P_0} = \exp\left(-\frac{(h-h_0)}{H}\right) = e^{-z},$$

where $P = P_o$ at the height $h = h_O$, and z is the *reduced height* defined by

$$z = (h-h_o)/H$$

Where the scale height of the atmosphere is given by:

$$H = \frac{RT}{M_a g}$$

4. Whatever the height distribution of the atmospheric gas, its pressure P_o at height h_0 is just the weight of gas above h_0 in a column of unit cross-section. Hence

$$P_o = N_T\, mg = n_o k T_o$$

where N_T is the total number of molecules in the column above h_0, and n_0 and T_o are the concentration and the temperature at h_0. Therefore

$$N_T = n_o k T_o / mg = n_0 H_0,$$

H_o being the scale height at h_0.

5. The total mass of the atmosphere above unit area of the Earth's surface is equal to the surface pressure divided by g.
6. Within the homosphere, where the atmosphere is well mixed, the mean molecular mass is used to determine the scale height and the height variation of pressure.
7. In the heterosphere, the partial pressure of each constituent is determined by the molecular mass of that species. Each species takes up an individual distribution and the total pressure is the sum of the partial pressures in accordance with Dalton's law.

The exosphere

Definition

1. In deriving the hydrostatic equation we treated the atmospheric gas as a compressible fluid* whose temperature, pressure and density are related by the gas law. This is only valid if there are sufficient collisions between the gas molecules for a Maxwellian velocity distribution to be established.
2. With increasing height the pressure and the collision frequency decrease. At this level and above (600 km) we have to regard the atmosphere in a different way, not as a single fluid but as an assembly of individual molecules or atoms, each following

its own trajectory in the Earth's gravitational field. This is the region called the *exosphere*.

3. Since more of the faster molecules will be lost and the velocity distribution will be altered thereby. Naturally, the lighter gases, helium and hydrogen, are affected most (high velocity). This brings us to the question of the escape of gas from a planetary atmosphere.

*A compressible fluid is one in which the fluid density changes when it is subjected to high pressure-gradients. For gasses, changes in density are accompanied by changes in temperature, and this complicates considerably the analysis of compressible flow.

Gaseous escape

1. **1.** Neglecting collisions, a particle of mass m and vertical velocity v_z will escape from the gravitational field if $mv_z^2/2 > mgr$, g being the gravitational acceleration and r the distance of the particle from the center of the planet; i.e.
2. **2.** if the particle's kinetic energy exceeds its gravitational potential energy, the escape velocity is given by

$$v_z^2 = 2gr$$

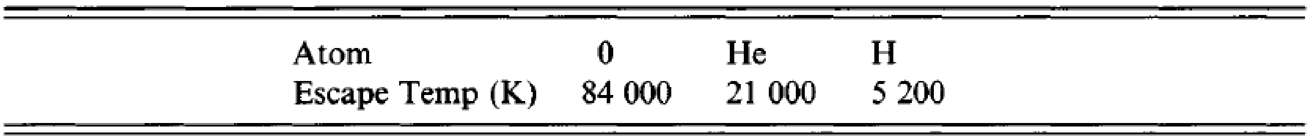
At the Earth's surface the escape velocity is 11.2 km/s.

3. **3.** By kinetic theory, the r.m.s. thermal speed of gas molecules depends on their mass and temperature, and for speeds in one direction, i.e. vertical:

$$\frac{mv_z^2}{2} = \frac{3kT}{2}$$

Thus, corresponding to an escape velocity there can be defined an *escape temperature*, having the values given in Table 4.1 for common atmospheric gases.

Table (1) Escape Temperature



Atom	0	He	H
Escape Temp (K)	84 000	21 000	5 200

Heat balance and vertical temperature profile

1. The atmosphere's temperature profile results from the balance between sources of heat, loss processes and transport mechanisms.
2. The total picture is complicated, but the main points are as follows.

Heat production and loss

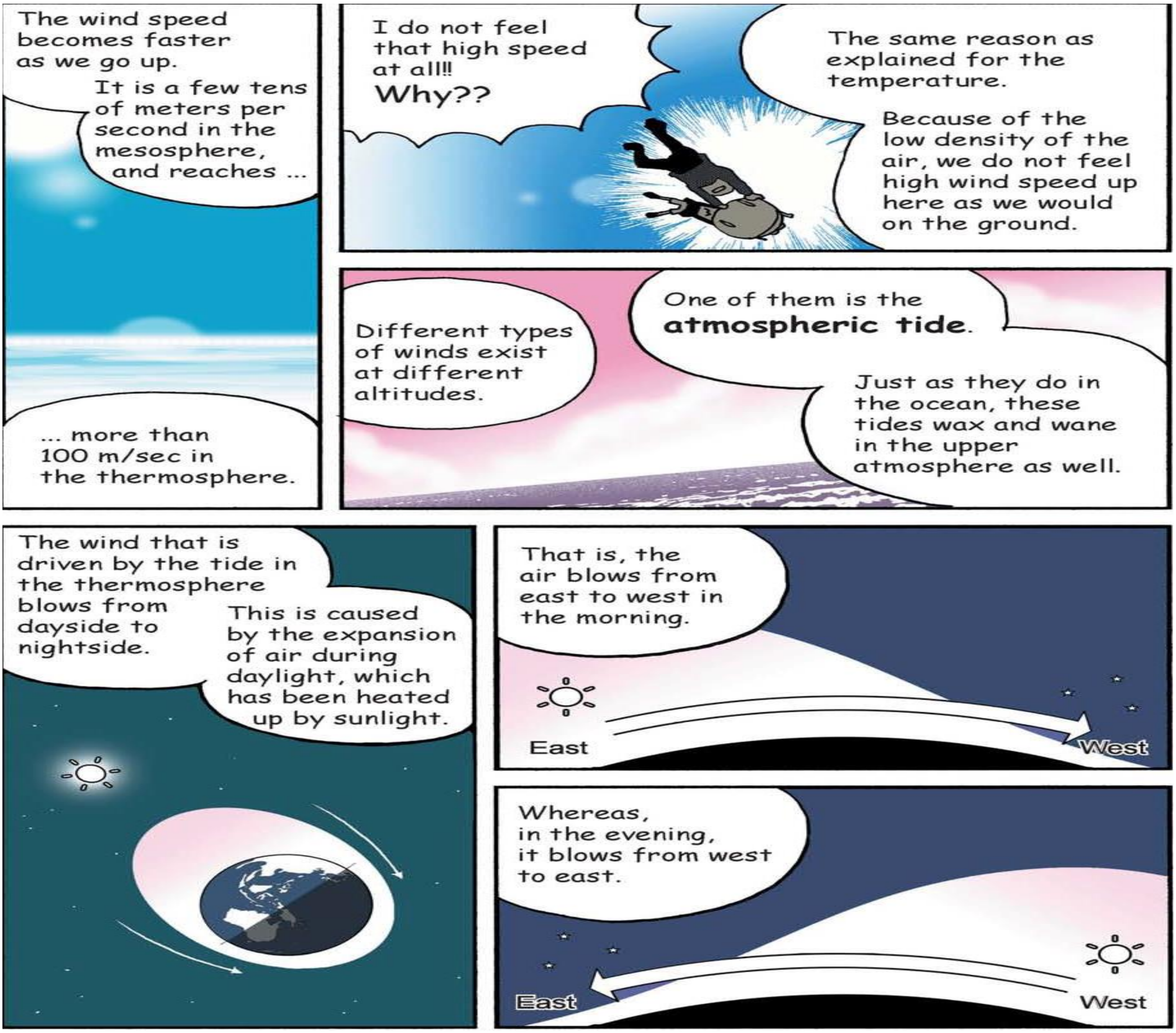
1. The troposphere is heated by convection from the hot ground, but in the upper atmosphere there are four sources of heat:

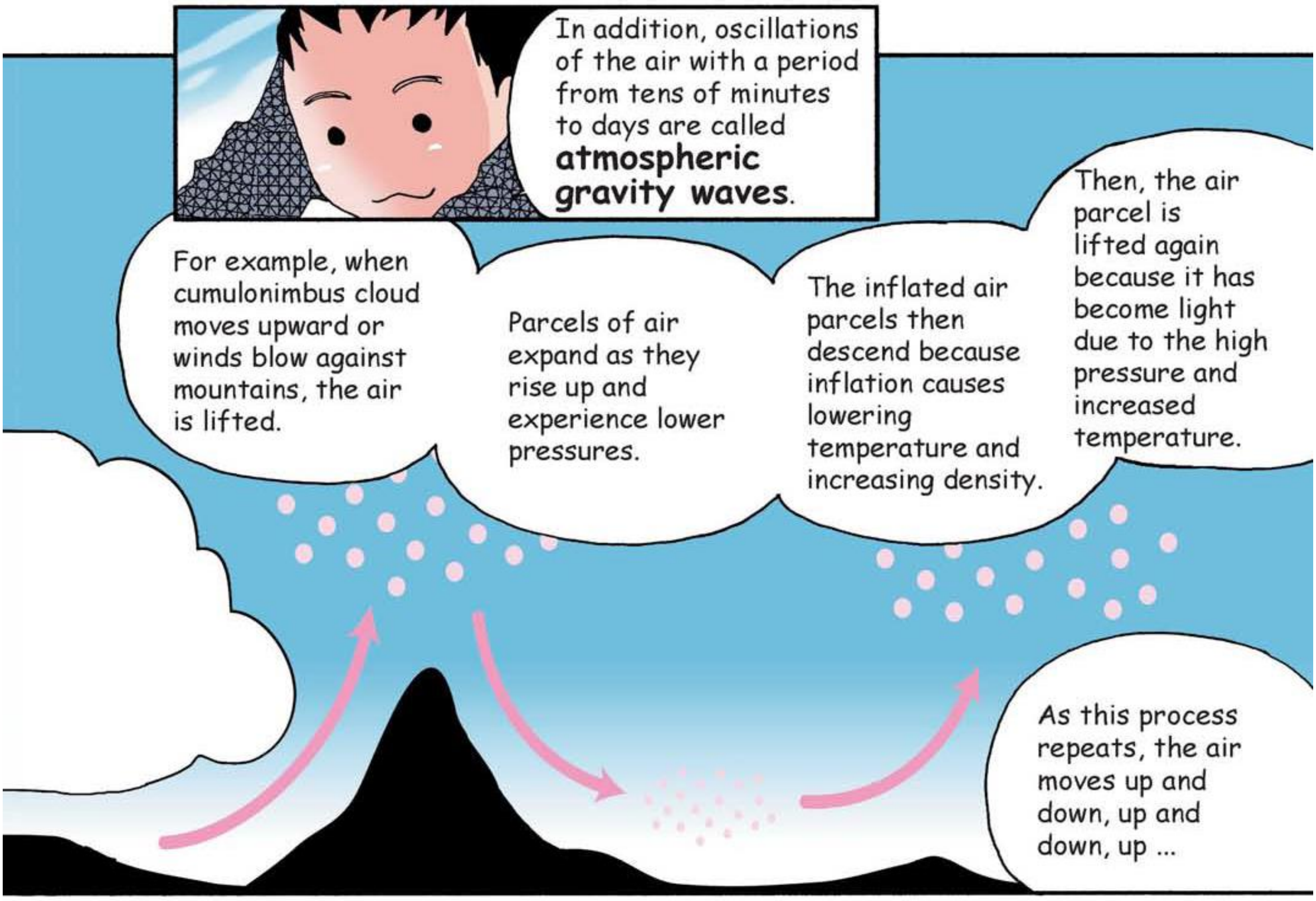
a. Absorption of solar ultra-violet and X-ray radiation, causing photodissociation, ionization and consequent reactions that liberate heat.

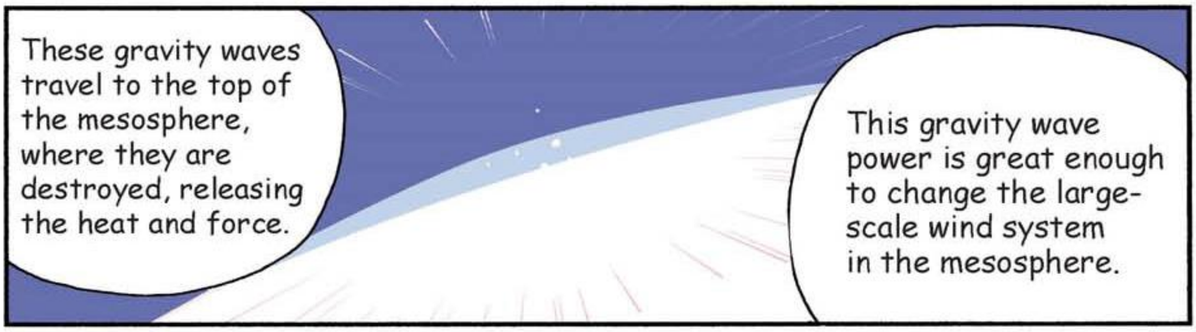
b. Energetic charged particles entering the upper atmosphere from the magnetosphere.

c. Joule heating by ionospheric electric currents. Under the action of an electric field, charged particles drift relative to one another and relative to neutral particles. Collisions between species limit the drift velocities and convert some of the drift energy into thermal energy

d. Dissipation of tidal motions[*] and gravity waves[**] by turbulence and molecular viscosity.







2. The contribution from dissipated motions is uncertain in magnitude but is estimated at about 0.7 mW/m^2 from gravity waves and about the same again from tides

3. Source (a) provides much more than this. Most radiation of wavelength less than 180 nm is absorbed by N_2, O_2 and O. Some energy is re-radiated, but about half, on average, goes into local heating.
4. Basically, this heating occurs because a photon absorbed to dissociate or ionize a molecule or an atom generally has more energy than that needed for the reaction, *and the excess appears as kinetic energy of the reaction products.*
5. The temperature maximum at the stratopause is due to the absorption of 200-300 nm radiation by ozone (O_3) over the height range 20 to 50 km. Some 18 W/m^2 is absorbed in the ozone layer.
6. Molecular oxygen (O_2), which is relatively abundant up to 95 km, absorbs radiation between 102.7 and 175 nm, much of this energy being used to dissociate O_2 to atomic oxygen (O). This contribution amounts to some 30 mW/m^2.
7. Radiation of wavelengths shorter than 102.7 nm, which is the ionization limit for O_2, is absorbed to ionize the major atmospheric gases O_2, O, and N_2 over the approximate height range 95-250 km, and this is what heats the thermosphere. The amount absorbed is only about 3 mW/m^2 at solar minimum (more at solar maximum), but a small heat input may raise the temperature considerably at great height because the air density is small.
8. At high latitude, heating associated with the aurora-items (b) and (c)-is important during storms. Joule heating by electric currents is greatest at 115-130 km. Auroral electrons heat the atmosphere mainly between 100 and 130 km.
9. The principal mechanism of heat loss from the upper atmosphere is radiation, particularly in the infra-red.

Heat transport

1. The third significant factor in the heat balance of the upper atmosphere is the movement of heat from one level to another by transport processes. Conduction, convection and radiation all come into play:

a. ***Radiation*** is the most efficient process at the lowest levels. The atmosphere is in radiative equilibrium between 30 and 90 km.
b. ***Molecular conduction*** is more efficient in the thermosphere (above 150 km); here the thermal conductivity is large because of the low pressure and the presence of free electrons. At the base of the thermosphere heat is conducted down towards the mesosphere.
c. ***Eddy diffusion***, or convection is more efficient than conduction below the turbopause. Thus, below about 100 km eddy diffusion carries heat from the thermosphere into the mesosphere. This is a major loss of heat from the thermosphere but a minor source for the mesosphere.

d. ***Chemical transport*** of heat occurs when an ionized or dissociated species is created in one place and recombines in another. The mesosphere is heated in part by the recombination of atomic oxygen created at a higher level.

2. The balance between these various processes produces an atmosphere with two hot regions, one at the stratopause and one in the thermosphere.

Composition

1. The upper atmosphere is composed of various major and minor species.
2. The former are the familiar oxygen and nitrogen in molecular or atomic forms, or helium and hydrogen at the greater heights.
3. The minor constituents may be present as no more than mere traces, but they can exert an influence far beyond their numbers. They include ozone, oxides of nitrogen, alkali metals, carbon dioxide, and water.

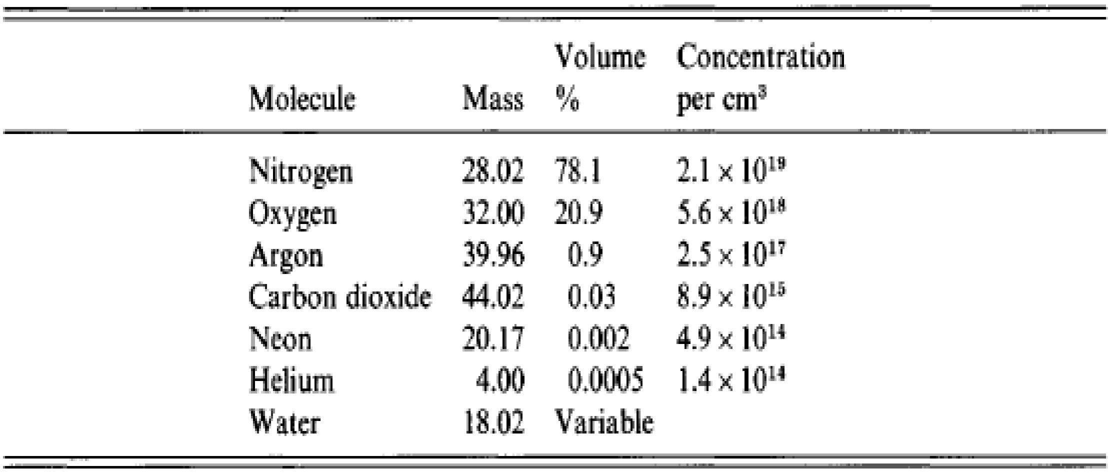
Major species

1. The turbulence of the atmosphere results in an almost constant proportion of major species up to 100 km, essentially the mixture as at ground-level called 'air' (Table 2).
2. Molecular oxygen is dissociated to atomic oxygen by ultra-violet radiation between 102.7 and 175.9 nm:

   $$O_2 + h\nu \rightarrow O + O,$$

   where hν is a quantum of radiation. One of the atomic oxygen atoms is in an excited state. An increasing amount of O appears above 90 km and the atomic and molecular forms are present in equal concentrations at 125 km; above that the atomic form increasingly dominates.
3. Nitrogen, however, is not directly dissociated to the atomic form in the atmosphere, though it does appear as a product of other reactions.
4. Above the turbopause, where mixing is less important than diffusion, each component takes an individual scale height depending on its atomic or molecular mass ($H = kT/mg$).
5. Because the scale heights of the common gases vary over a wide range ($H = 1$, $He = 4$, $O = 16$, $N_2 = 28$, $O_2 = 32$) the relative composition of the thermosphere is a marked function of height, the lighter gases becoming progressively more abundant as illustrated in Figure 5.
6. Atomic oxygen dominates at several hundred kilometers. Above that is the heliosphere where helium is the most abundant, and eventually hydrogen becomes the major species in the protonosphere.

Table (2) Composition of the atmosphere at ground level



Molecule	Mass	Volume %	Concentration per cm^3
Nitrogen	28.02	78.1	2.1×10^{19}
Oxygen	32.00	20.9	5.6×10^{18}
Argon	39.96	0.9	2.5×10^{17}
Carbon dioxide	44.02	0.03	8.9×10^{15}
Neon	20.17	0.002	4.9×10^{14}
Helium	4.00	0.0005	1.4×10^{14}
Water	18.02	Variable	

7. Because the scale height also depends on the temperature, so do the details of the composition, as may be seen from Figure 6. Note that the protonosphere starts much higher in a hot exosphere, and the heliosphere may be absent from a cool one.

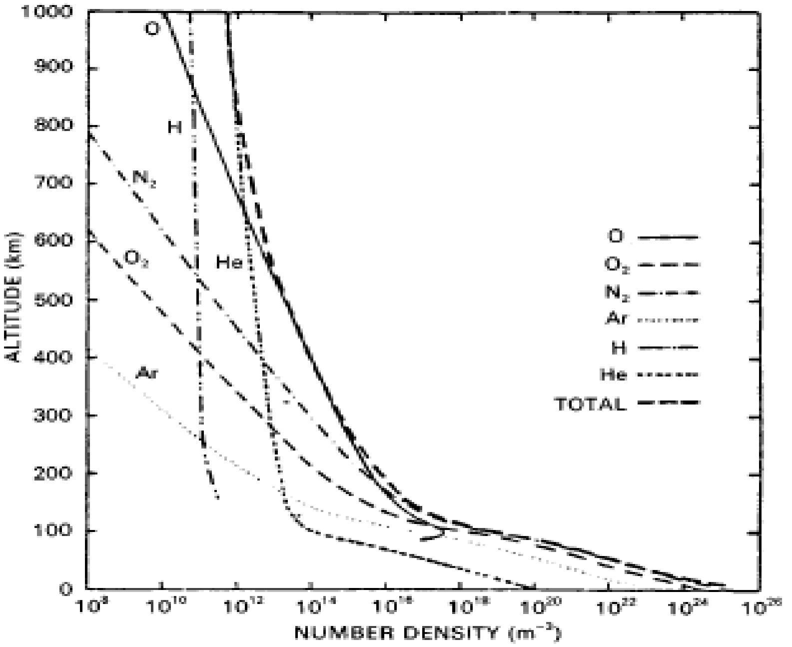


Figure (5) Atmospheric composition to 1000 Km for a typical temperature profile

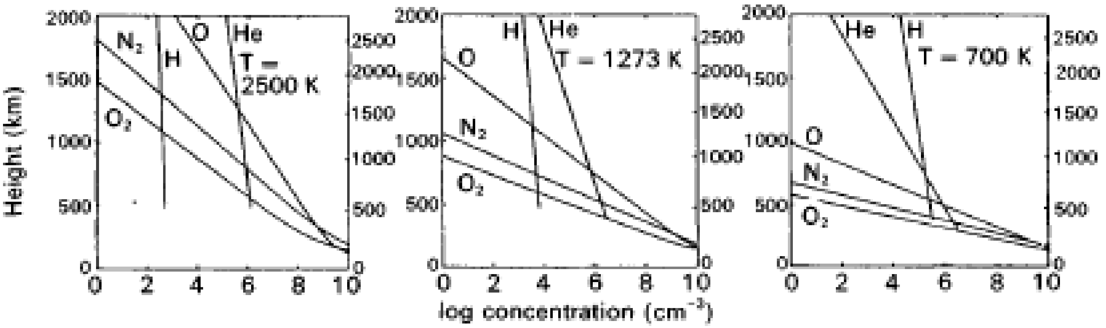


Figure (6) Effect of temperature on exospheric. Geopotential heights are given on the left of the diagram, geometric heights on the right.

5. Two of the important species of the upper atmosphere, helium and hydrogen, are, at most, minor species of the troposphere.
6. Helium is produced by radioactive decay in the Earth's crust, and it diffuses up through the atmosphere, eventually to escape into space.
7. Atomic hydrogen also flows constantly up through the atmosphere but its source is the dissociation of water vapor near the turbopause.

Water vapor

1. The height distribution of water is indicated in Figure 7. Water does not have the same dominating influence in the upper atmosphere as in the troposphere.
2. It is important nevertheless, first as a source of hydrogen, and second because it causes ions to be hydrated* below the mesopause.

*The formation of a solution involves the interaction of solute with solvent molecules. Many different liquids can be used as solvents for liquid solutions, and water is the most commonly used solvent. When water is used as the solvent, the dissolving process is called hydration.

Nitric oxide

1. The minor constituent, nitric oxide (NO), is significant for its contribution to the production of the lower ionosphere.
2. Measurements of the nitric oxide distribution show large variations, but usually there is a minimum at 85-90 km (Figure 8). The depth of the minimum is greater in summer than in winter and varies with latitude (Figure 9).
3. The lower, stratospheric, source of nitric oxide is the oxidation of nitrous oxide (N_2O) by excited atomic oxygen.
4. The upper source peaks in the thermosphere, at 150-160 km. The main thermospheric sources involve neutral or ionized atomic nitrogen, for example

   $$N^* + O_2 \rightarrow NO + O$$

   Where (*) indicates an excited state.
5. The concentration of nitric oxide therefore varies with time of day, latitude and season. It is three to four times greater at high latitude than at middle latitude, and more variable. The production rate increases during particle precipitation events.
6. The gas diffuses down (from thermosphere) to the mesosphere by molecular and then by eddy diffusion. The diffusion is weaker in the summer, and then the loss by photodissociation,

   $$NO + h\,\nu \rightarrow N + O$$

   And by recombination,

   $$NO + N \rightarrow N_2 + O$$

Aided also by the effect of the low mesopause temperature, are sufficient to create the minimum.

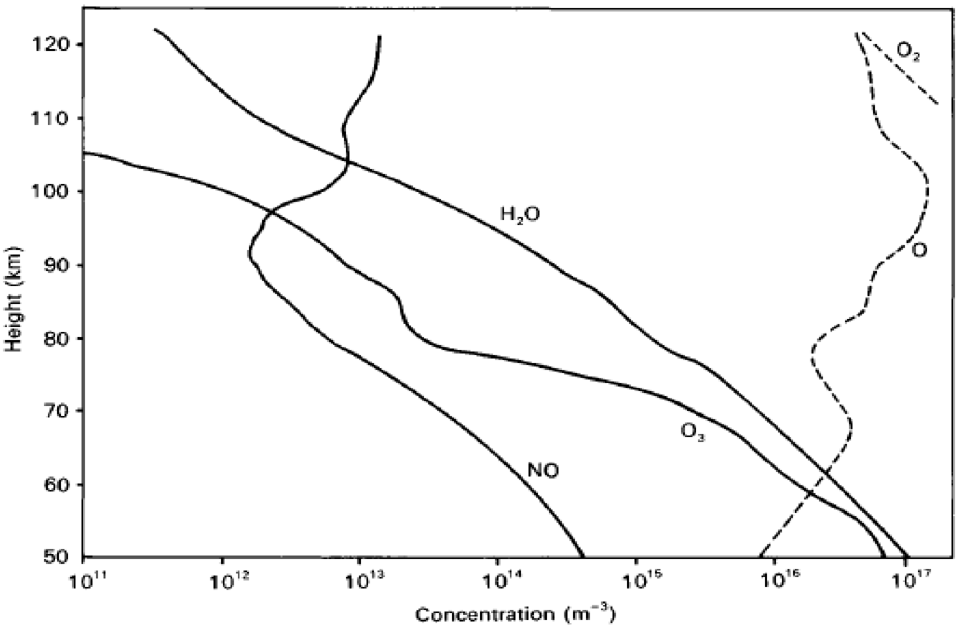


Figure (8) Calculated distributions of important minor constituents for noon at 45º latitude. O_2 and O are shown for comparison.

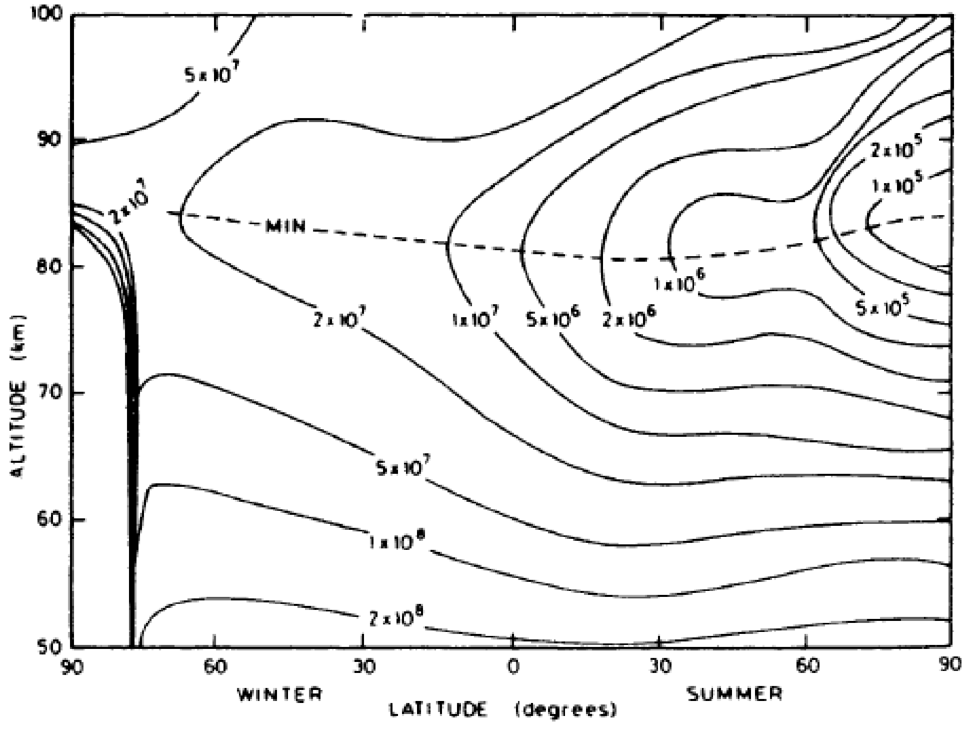


Figure (9) Height and latitude distribution of nitric oxide in the middle atmosphere, in unit of cm^{-3}.

Ozone

1. Relatively low in the atmosphere, between 15 and 35 km, ozone is produced by the reaction

$$O+O_2+M \rightarrow O_3+M$$

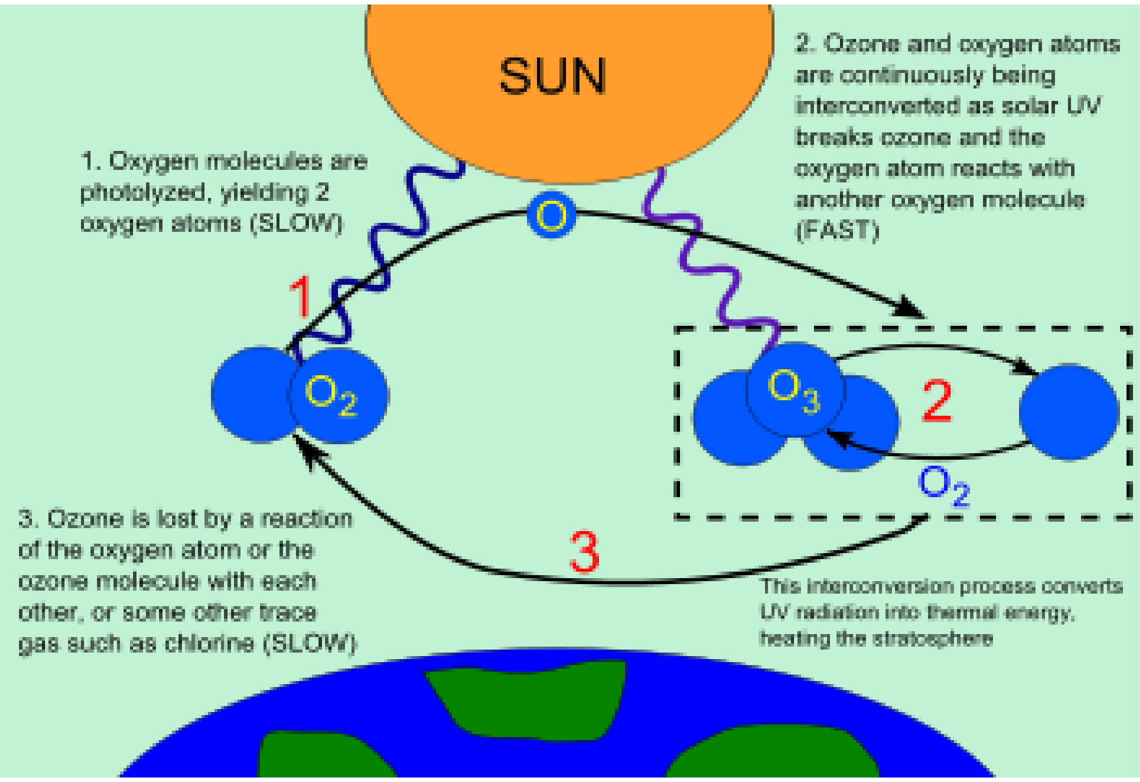
This is a *three-body reaction,* in which the third body, M, serves to carry away excess energy.

2. Such a reaction needs a relatively high pressure because its rate depends on the probability that three particles come together at the same time.
3. The atomic oxygen required is produced by the dissociation of O_2, though at this lower altitude the effective radiation is in the 200-240 nm band.
4. Once formed, the ozone may be dissociated again by radiation over a wide range of wavelengths, but particularly in the band 210-310 nm,

$$O_3 + h\nu \rightarrow O_2 + O$$

or destroyed by the reaction

$$O_3 + O \rightarrow O_2 + O_2$$



5. Only a small concentration of ozone remains on balance, amounting to less than 10 parts per million of the total gas concentration. The *ozonosphere* peaks near 20 km.
6. Ozone's importance to the atmosphere is that its strong absorption of UV provides a powerful heat source for the stratosphere. It also has a biological importance because the radiation that it absorbs would be harmful to life were it to reach the Earth's surface at sufficient intensity.
7. The amount of ozone in the atmosphere varies with the latitude and the season.
8. These changes have been attributed to the action of atomic halogens, mainly chlorine (Cl^*):

$$\begin{array}{c} Cl + O_3 \rightarrow ClO + O_2 \\ ClO + O \rightarrow Cl + O_2 \\ \hline O_3 + O \rightarrow 2O_2 \end{array}.$$

9. The second stage can involve NO instead of O, but in either case the net result is to remove ozone.
10. The chlorine atom is regenerated and so acts merely as a catalyst[*].
11. The chlorine atoms are believed to originate in chlorofluorocarbon compounds such as CFC13 and CF2C12, of which several thousand tons are released into the atmosphere each year and which are known to have long lifetimes (e.g. 75-150 years)
12. Figure 10 illustrates the so called *ozone hole* as observed from an Antarctic base.

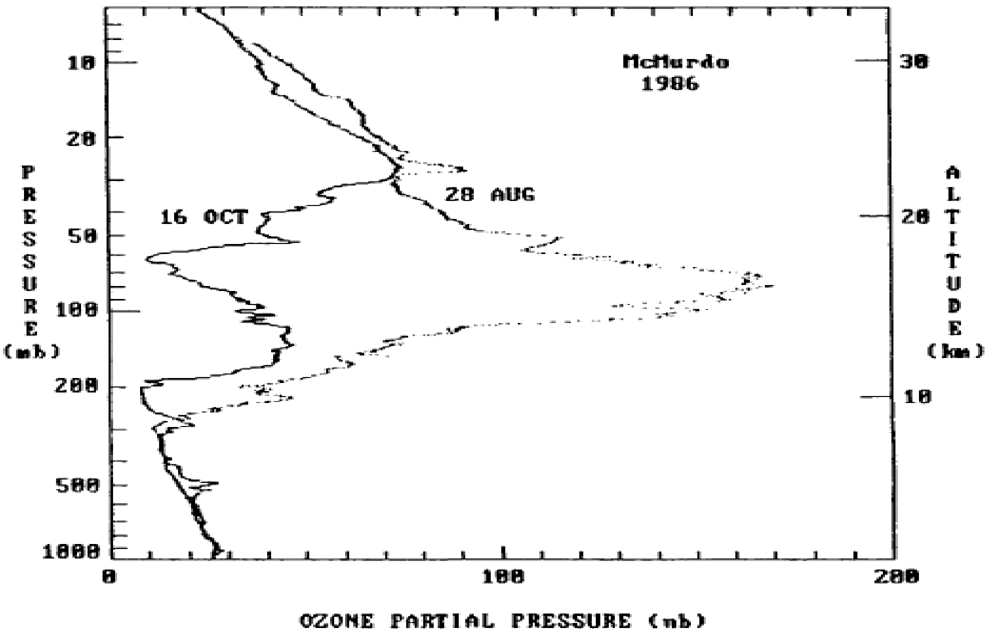


Figure (10) the dreaded ozone hole: Observations of the vertical profile of ozone over McMurdo stations, Antarctica, on 28 August 1986 and 16 October 1986

12. Ozone also reacts with nitric oxide:

$$\begin{array}{c} O_3 + NO \rightarrow O_2 + NO_2 \\ \underline{O + NO_2 \rightarrow O_2 + NO} \\ O_3 + O \rightarrow 2O_2 \end{array}$$

The net result, in the presence of atomic oxygen, is again a catalytic conversion of Ozone back to molecular oxygen. Thus, the ozone concentration is also affected by the natural production of nitric oxide as discussed above.

Ultraviolet light

1. Although the concentration of the ozone in the ozone layer is very small, it is vitally important to life because it absorbs biologically harmful ultraviolet (UV) radiation coming from the sun.
2. Extremely short or vacuum UV (10–100 nm) is screened out by nitrogen.

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[*] Catalysis is the increase in the rate of a chemical reaction due to the participation of an additional substance called a catalyst. With a catalyst, reactions occur faster and require less activation energy.

3. UV radiation capable of penetrating nitrogen is divided into three categories, based on its wavelength; these are referred to as UV-A (400–315 nm), UV-B (315–280 nm), and UV-C (280–100 nm).
4. UV-C, which is very harmful to all living things, is entirely screened out by a combination of dioxygen (< 200 nm) and ozone (> about 200 nm) by around 35 kilometers altitude.
5. UV-B radiation can be harmful to the skin and is the main cause of sunburn; excessive exposure can also cause cataracts, immune system suppression, and genetic damage, resulting in problems such as skin cancer.
6. The ozone layer (which absorbs from about 200 nm to 310 nm with a maximal absorption at about 250 nm) is very effective at screening out UV-B; for radiation with a wavelength of 290 nm, the intensity at the top of the atmosphere is 350 million times stronger than at the Earth's surface.
7. Nevertheless, some UV-B, particularly at its longest wavelengths, reaches the surface, and is important for the skin's production of vitamin D.
8. Ozone is transparent to most UV-A, so most of this longer-wavelength UV radiation reaches the surface, and it constitutes most of the UV reaching the Earth. This type of UV radiation is significantly less harmful to DNA, although it may still potentially cause physical damage, premature aging of the skin, indirect genetic damage, and skin cancer.

Metals

1. Metallic atoms are introduced to the atmosphere in meteors, whose flux over the whole Earth amounts to 44 metric tonnes per day.
2. In the ionized state, metals such as sodium, calcium, iron and magnesium are significant in the aeronomy of the lower ionosphere.

Home Works

1. What are the main classifications for the neutral atmosphere? Explain in details?
2. Find a new derivation of the hydrostatic equation?
3. If it is assumed that $T = T_0 - \beta z$, where T_0 is the temperature at the surface of the earth and β denotes a constant lapse rate of temperature with height. Find the relation of the hydrostatic equation?
4. Determine the total mass of the atmosphere above the Earth's surface?
5. Define 1. Geopotential height. *2.* Dalton's law. 3. Exosphere 4. Escape velocity 5. Eddy diffusion. 6. Chemical transport. 7. Three-body reaction
6. Find the escape velocity and the temperature energy for both helium and oxygen if the escape temperature are 21000 and 84000 respectively?
7. States the heat production processes in the atmosphere and explain one of it?
8. What are the effects of the solar activity on the height distribution of density and temperature?
9. What fraction of sea-level air density is at the top of Mountain Everest? (Assume *H* = 8 km and height of Mt. Everest is 9 km.)
10. What are the main reactions responsible for losses of Ozone?
11. Estimate the total number of molecules in the earth's surface over Iraq? (N_T)
12. What are the main sources and losses processes of Nitric oxide NO in the atmosphere, with all reactions?
13. Complete the following table and draw the results

n/n_o	M_A (gm/mole)	n/n_o	T K°
	1 H		500
	4 He		750
	16 O		1000
	28 N_2		1500
	32 O_2		2000
T =500 k° constant		M_A=16	