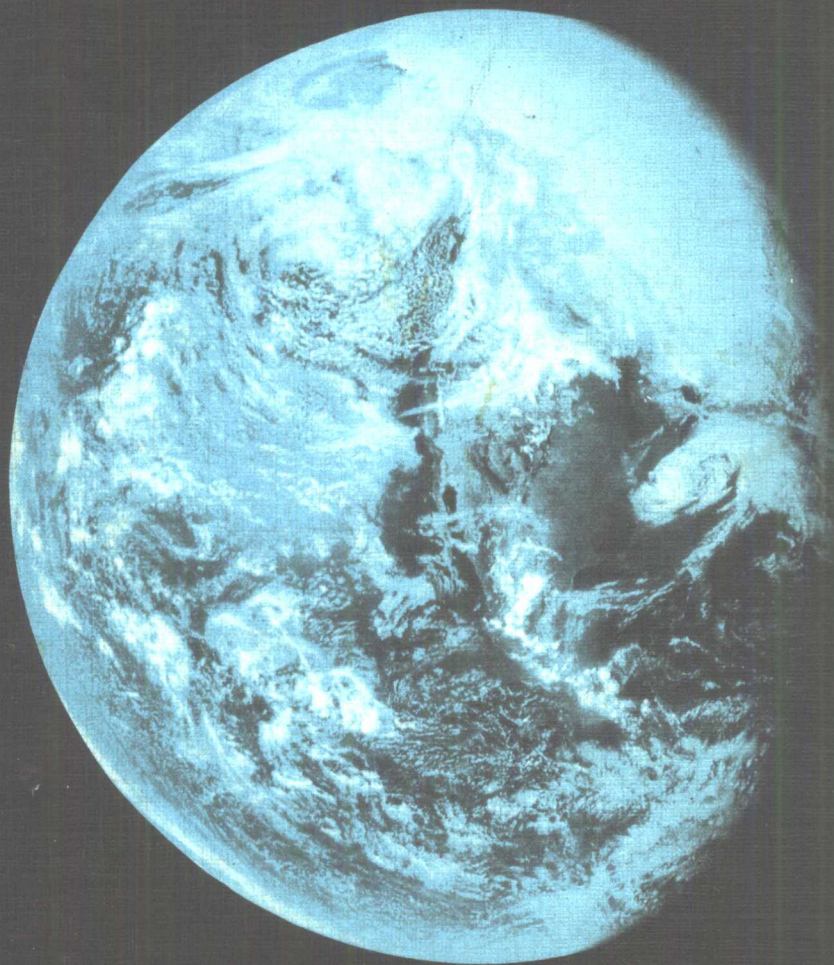


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Atmospheric Physics



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Atmospheric Physics

This view of the Earth – extending from the Mediterranean Sea area to the Antarctica ice cap – was photographed by Apollo 17 crewmen during their journey toward the Moon. (NASA.

Preface

The extraordinary growth and development of atmospheric sciences during the last decades, and the concern for certain applied problems, such as those related to the environment, have prompted the introduction of college and university courses in this field. There is consequently a need for good textbooks.

A few appropriate books have appeared in the last few years, aimed at a variety of levels and having different orientations. Most of them are of rather limited scope; in particular, a number of them are restricted to the field of dynamics and its meteorological applications. There is still a need for an elementary, yet comprehensive, survey of the terrestrial atmosphere. This short volume attempts to fill that need.

This book is intended as a textbook that can be used for a university course at a second or third year level. It requires only elementary mathematics and such knowledge of physics as should be acquired in most first-year general physics courses. It may serve in two ways. A general review of the field is provided for students who work or plan to work in other fields (such as geophysics, geography, environmental sciences, space research), but are interested in acquiring general information; at the same time, it may serve as a general and elementary introduction for students who will later specialize in some area of atmospheric science. The book is quite comprehensive, as a perusal of the table of contents will indicate; for instance, chapters on chemistry and electricity – usually absent in this type of book – have been included. Indeed, it tries to introduce most of the basic concepts and facts about the atmosphere that do not require any previous specialization. The variety and organization of the included topics are such that a lecturer can always choose to exclude specific subjects described, without losing continuity. Lists of questions and problems have been added to each chapter; these, even if elementary in nature, should help the reader to acquire some insight into the various subjects.

In summarizing from different sources, we owed much to such excellent elementary texts as those by Dobson and by Goody and Walker, as also to monographs written at a higher level. A short bibliography with some brief comments has been included; we hope that it may provide useful orientation toward further reading.

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Table of Constants

Fundamental Physical Constants

Gas constant	$R = 8.314 \text{ J/mol.K}$
Avogadro's number	$N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$
Boltzmann's constant	$k = 1.38 \times 10^{-23} \text{ J/K}$
Planck's constant	$h = 6.63 \times 10^{-34} \text{ J.s}$
Velocity of light in vacuum	$c = 3.00 \times 10^8 \text{ m/s}$
Elementary charge	$e = 1.60 \times 10^{-19} \text{ C}$
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ Nm}^2/\text{kg}^2$

Earth

Standard acceleration of gravity	$g_0 = 9.81 \text{ m/s}^2$
Solar constant	$S = 2.0 \text{ cal/cm}^2.\text{min} \simeq 1400 \text{ W/m}^2$
Earth's mean radius	$R = 6.37 \times 10^6 \text{ m}$
Earth's surface area	$5.1 \times 10^{14} \text{ m}^2$
Mean Earth–Sun distance	$1.49 \times 10^8 \text{ km}$
Mean Earth–Moon distance	$3.80 \times 10^5 \text{ km}$
Angular velocity of rotation	$\Omega = 7.29 \times 10^{-5} \text{ s}^{-1}$

Atmosphere

Standard atmospheric pressure	$1 \text{ atm} = 1.01325 \times 10^5 \text{ Pa}$
Total mass of atmospheric air	$5.3 \times 10^{18} \text{ kg}$
equivalent to	$4.1 \times 10^{18} \text{ m}^3 \text{ at STP (M} = 28.964 \text{ g/mol)}$
Average molecular weight of atmospheric air, up to 100 km altitude	$M = 28.964 \text{ (g/mol)}$
Dry adiabatic temperature lapse rate	$\beta_d = 9.76 \text{ K/km}$

Atomic and Molecular Weights*

H	: 1.01	C	: 12.01
He	: 4.00	N	: 14.00
Ne	: 20.18	O	: 16.00
Ar	: 39.95	S	: 32.06

* These constants enter the formulas as conversion factors with units of mass per mole. E.g. $M_{\text{H}_2\text{O}} = 18.0 \text{ g/mol} = 0.018 \text{ kg/mol}$.

Air	: see above	SO ₂	: 64.06
H ₂ O	: 18.02	H ₂ S	: 34.08
NaCl	: 58.44	NH ₃	: 17.02
CO ₂	: 44.01		

Thermodynamic

Heat capacity of air, at constant pressure	$C_p = 29.1 \text{ J/mol.K} = 1005 \text{ J/kg.K}$
Heat capacity of air, at constant volume	$C_v = 20.8 \text{ J/mol.K} = 718 \text{ J/kg.K}$
Heat capacity of water	$C_w = 76 \text{ J/mol.K} = 4218 \text{ J/kg.K}$
Latent heat of melting (water) (0°C)	$L_f = 6.01 \times 10^3 \text{ J/mol}$
Latent heat of vaporization (water) (0°C)	$L_v = 4.50 \times 10^4 \text{ J/mol}$
Latent heat of sublimation (water) (0°C)	$L_s = 5.10 \times 10^4 \text{ J/mol}$
Saturation water vapour pressures:	
At 0°C :	6.11 mb
At other temperatures:	See Figure II, 1

Others

Density of water	10^3 kg/m^3
Density of dry air at 0°C and 1 atm (STP)	1.29 kg/m^3
Surface tension of water: 0°C	$\sigma = 0.0756 \text{ N/m}$
20°C	$\sigma = 0.0727 \text{ N/m}$
Viscosity of air (0°C)	$\eta = 1.71 \times 10^{-5} \text{ N}\cdot\text{s/m}^2$
Permittivity of free space	$\epsilon_0 = 8.854 \times 10^{-12} \text{ F/m}$
Permeability of free space	$\mu_0 = 4\pi \times 10^{-7} \text{ H/m}$
Stefan–Boltzmann constant	$\sigma = 56.7 \text{ nW/m}^2 \text{ K}^4$
Mass of the electron	$9.11 \times 10^{-31} \text{ kg}$

Units

The International System (SI) is used in general. This implies MKS mechanical units (based on the fundamental units metre, kilogram and second for length, mass and time, respectively), Kelvin (K) for absolute temperature, Ampere (A) for electric current, and mole (mol) as a chemical unit of mass.

Other units used are summarized below.

Temperature:

Degrees Celsius ($^{\circ}\text{C}$), defined by $t = T - 273.15$, where t is the temperature in $^{\circ}\text{C}$ and T is the absolute temperature in K.

Pressure:

Atmosphere (atm). $1 \text{ atm} = 1.013\,25 \times 10^5 \text{ Pa}$, where $\text{Pa} = \text{Pascal} = \text{N/m}^2$ ($\text{N} = \text{Newton}$) is the SI unit.

Millibar (mb). $1 \text{ mb} = 100 \text{ Pa}$.

Energy:

Calorie (cal). $1 \text{ cal} = 4.184 \text{ J}$, where J (Joule) is the SI unit.

Electron-volt (eV). $1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$.

(If the energy is referred to one mole, 1 eV corresponds to 96.3 kJ/mol).

The SI system uses prefixes to indicate a multiplying factor. Some names, symbols and corresponding factors are given in the following table:

tera (T) : $\times 10^{12}$	milli (m) : $\times 10^{-3}$
giga (G) : $\times 10^9$	micro (μ) : $\times 10^{-6}$
mega (M) : $\times 10^6$	nano (n) : $\times 10^{-9}$
kilo (k) : $\times 10^3$	pico (p) : $\times 10^{-12}$

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I. General Description of the Atmosphere

1. Regions and Extension of the Atmosphere

The atmosphere is a gaseous envelope surrounding the Earth, held by gravity, having its maximum density just above the solid surface and becoming gradually thinner with distance from the ground, until it finally becomes indistinguishable from the interplanetary gas.

There is, therefore, no defined upper limit or 'top' of the atmosphere. As we go away from the surface of the Earth, different regions can be defined, with widely different properties, being the seats of a great variety of physical and chemical phenomena. If we want to understand the atmosphere, our first concern will be to introduce some sort of classification that will help to consider separately all these phenomena. Let us consider the pictorial representation of Figure 1.

First of all, let us observe that, apart from the first kilometre, the scale used is a logarithmic one, so that the upper regions are in fact much thicker, in comparison with the lower ones, than suggested by the picture.

There is a scale of pressures at the right side. The pressure, at each level, is given by the weight of all the air above it, per unit area of surface, and this weight is given by

$$\int_z^\infty g \rho \, dz$$

where ρ = density, g = acceleration of gravity, z = height (mass times acceleration of gravity, integrated above the level z). The value of g varies only slowly with height. Therefore, the pressure can be taken as roughly proportional to $\int_z^\infty \rho \, dz$, i.e. to the total mass above that level z . We can see, by comparing the pressure scale with the height scale at the left, that:

90% of the mass is contained within the first ~ 20 km (top at 100 mb level)

99.9% of the mass is contained within the first ~ 50 km (top at 1 mb level)

At 100 km, the pressure has dropped to about 10^{-3} mb, i.e. only a fraction of the order of 10^{-6} (one millionth) of the atmospheric mass will be above that level. And only a fraction 10^{-13} above 1000 km. These distances are to be compared with the Earth radius, ~ 6370 km. It is clear that from the point of view of its mass, the atmospheric envelope, although of diffuse limits, is a very thin sheath around the planet.

2. Homosphere and Heterosphere. Scale Height

The 'thickness' of the atmosphere can be characterized by a parameter called the *scale height*, which we shall now define. We can consider the atmosphere essentially as a fluid

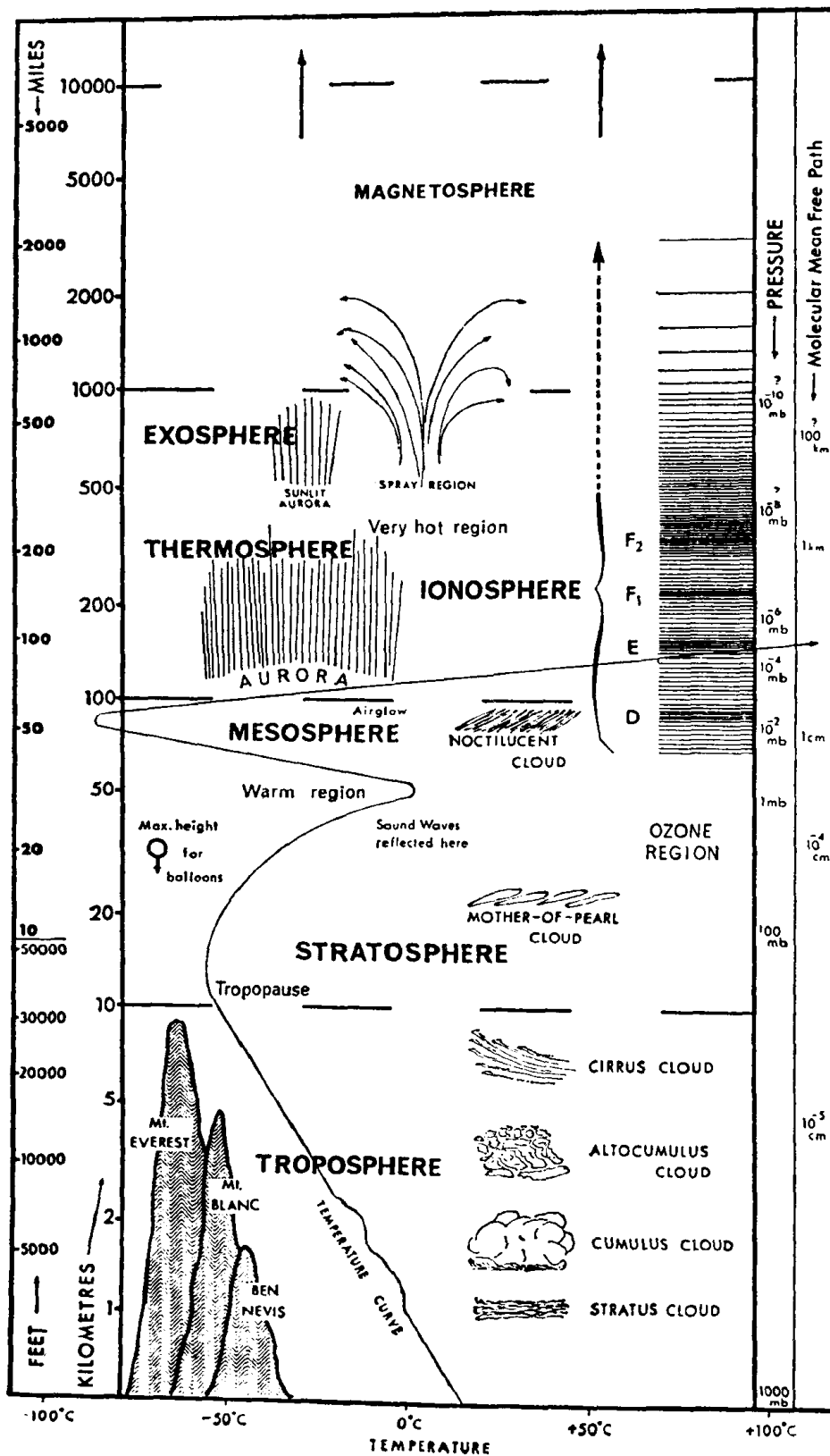


Fig. I-1. *The atmosphere.* Pictorial representation showing the main features of the terrestrial atmosphere. The explanation of this figure is developed in Ch. I.

in hydrostatic equilibrium. This means that for every infinitesimal layer of unit cross section we shall have the following relation (cf. Figure 2):

$$\begin{aligned} \text{upward force due to pressure gradient} &= \text{weight} \\ -dp &= g \cdot \rho \cdot dz \end{aligned} \tag{1}$$

This relation (1) (where p = pressure) is called the *hydrostatic equation*.

We observe now that air, at the temperatures and pressures of the atmosphere, behaves like a mixture of ideal gases, within at most a few percent of error. For lower and lower pressures, the behaviour approaches more and more that of an ideal gas. For each component we shall then have

$$p_i V = n_i R T \tag{2}$$

where p_i = partial pressure of component i ; V = volume; n_i = number of moles of component i ; R = universal gas constant; T = absolute temperature.

And for the mixture

$$\begin{aligned} p &= \Sigma p_i && \text{(Dalton's law)} \\ pV &= nRT \end{aligned} \tag{3}$$

where p = total pressure and n = total number of moles. An average molecular weight is defined as $M = m/n = (\Sigma n_i M_i)/n$ where m = mass and M_i = molecular weight of component i .

Equation (3) can also be written

$$p = \frac{RT}{M} \rho \tag{4}$$

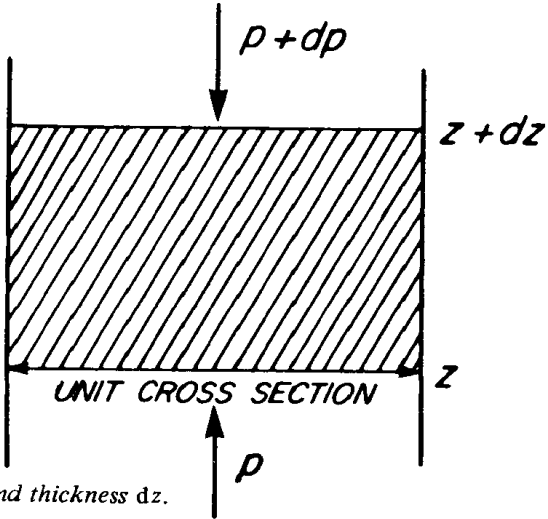


Fig. I-2. *Layer of air column of unit cross section and thickness dz .*

Eliminating ρ between (1) and (4), we can express the hydrostatic equation as

$$d \ln p = -\frac{gM}{RT} dz \quad (5)$$

which can be integrated to

$$p = p_0 \exp \left(-\int_0^z \frac{gM}{RT} dz \right) = p_0 \exp \left(-\int_0^z \frac{dz}{H} \right) \quad (6)$$

where we have defined the parameter $H = RT/gM$, which we call the (*local*) *scale height* of the atmosphere. As we shall see, M can be considered as a constant up to 100 km; g depends on z , but it varies only about 3% for every 100 km. H therefore varies roughly proportionally to T up to 100 km. For $T = 273$ K, we obtain ($g = 9.8$ m/s²; $M = 28.96$)

$$H = 8 \text{ km} \quad (7)$$

So, if the temperature was uniform, (6) could be written

$$p = p_0 \cdot e^{-z/H} \quad (8)$$

and H would indicate the height at which the pressure has decreased by a factor $e^{-1} = 0.37$, i.e. the height within which about $\frac{2}{3}$ of the atmosphere mass would be contained. Actually, as T varies with height, so does H ; but up to 100 km, only within the range of 5 to 9 km.

So far, we have assumed that the atmospheric air is a mixture of gases of constant composition, perfectly mixed, so that M is a constant in Equation (6). But this is not the situation throughout the whole atmosphere. Let us consider the problem more closely. If we have a mixture of gases in the gravitational field and wait for the equilibrium distribution, the Statistical Mechanics predicts that there will be a separate distribution for each kind of molecules; i.e. each gas will obey its own equation:

$$p_i = p_{0i} \exp \left(-\int_0^z \frac{dz}{H_i} \right) \quad (9)$$

according to its own value of M . This leads to a predominance of the heavier molecules in the lower levels, and of the lighter molecules in the higher levels. To understand this clearly, let us imagine, for simplicity, that g and T are constant, so that H varies only through the value of M , and let us consider a mixture of only two gases.

$$\text{gas 1, } H_1 = \frac{RT}{gM_1} \quad , \quad p_1 = p_{0_1} e^{-z/H_1}$$

$$\text{gas 2, } H_2 = \frac{RT}{gM_2} \quad , \quad p_2 = p_{0_2} e^{-z/H_2}$$

$$M_1 > M_2 \quad H_1 < H_2$$

Let us also imagine that gas 1 is predominant at the surface. Then the two distributions, i.e. the distributions of the two partial pressures p_1 and p_2 , will be such as is shown in Figure 3. Because of the different values of H in the exponent in Equation (9), the two curves intersect at a certain level, above which the lighter gas 2 becomes predominant.

The reason we did not consider this in the previous argument is that this type of equi-