Concept: Atmosphere

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Keywords: Standard atmosphere, troposphere, stratosphere, lapse rate

1. Definition

The NASA Thesaurus [1] defines atmosphere as the mixture of gases surrounding the Earth, or filling the habitable volume of a spacecraft. The term is also used as a measure of pressure, meaning the pressure exerted by a column of mercury 760 mm high at 1 G (9.8 m/s2), equal to 101,329 Pascals. Here we are discussing the concept defined first, but generalized to atmospheres surrounding any celestial body.

2. Earth's Atmosphere

Earth's mean radius is approximately 6,371 kilometers. This is approximately 3982 miles. It is slightly larger (6378km) at the equator and slightly smaller (6357km) at the poles. Thus the circumference at the equator is roughly 25000 miles. Above the surface, there is about 0.9 x 105 meters of gaseous atmosphere. That's about 270,000 feet, or 51 miles. We do not consider ourselves to have reached outer space until we're about 100 miles up, but there is very little air above 51 miles. Because of gravity, the air above presses down on the air below. So as you come down towards the surface, the pressure gets higher. At the surface, the air pressure (due to the 270,000 feet of air above) is enough to support a column of mercury (Hg), 760 millimeters (mm) high. For a given base area, this column of mercury weighs about the same as a column of air only 10,608 meters high, if the density of the air in this column were the same as that at the surface. So this means that most of the air is actually within the bottom layers of the atmosphere. In fact, 80 percent of the air is contained below 60,000 feet. While strong steady winds such as the Jet Stream are encountered as high as 45,000 feet, most of the fluctuations in winds occur in the lower levels of the atmosphere, where exchange of heat and moisture with the surface occurs. The upper atmosphere provides excellent protection from objects falling from space, which are burned up in the heat generated when fast-moving objects encounter air, and from harmful high-energy radiation which is mostly absorbed by collision with molecules. Refraction and scattering of the different wavelengths of light in the solar spectrum by molecules and dust particles, causes the blue sky and the spectacular colors of sunrise and sunset.

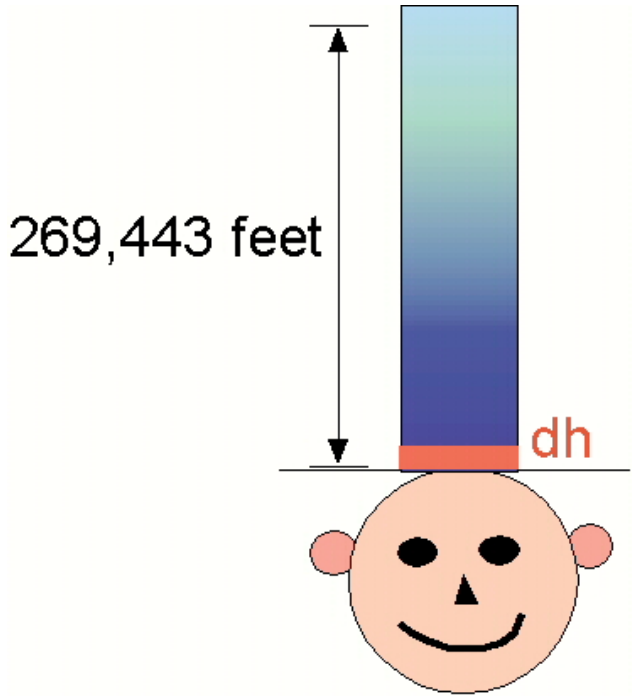

Figure 1: Why we feel pressure

2.1. Hydrostatic Equation

Although people at one time believed that the atmosphere was like a jungle with huge, transparent monsters waiting to eat pilots who flew too high, it is better compared to an ocean. While there are some non-uniformities due to weather (and maybe due to pollution), the overall, average characteristics of the atmosphere are surprisingly simple to calculate using physics and chemistry, and a little bit of calculus. At a given height h above the surface, let's say that pressure is p Newtons per square meter (N/m2, or Pascals), and density is ? kilograms per cubic meter (kg/m3). The acceleration due to gravity is g meters per meters-per-second (m2/s). If you go up by a tiny distance dh, the pressure decreases by a tiny amount dp.

$$dp = -\rho(gdh) \tag{1}$$

2.2. Perfect Gas Law

The Perfect Gas Law is a relation between pressure, density, temperature and composition of a gas.

The "perfection" refers to the fact that nothing inconvenient happens over the range of the variables that we consider, like the composition of the gas changing, etc. This is a good assumption at least over a range of several hundred degrees Kelvin of temperature, or a change of a few factors of 10 in pressure about any given "state". It is not adequate when we consider the huge changes that occur to the air as it is slammed by, say, the nose of a spacecraft re-entering the atmosphere at Mach 35 (35 times the speed of sound, typical speed of a re-entering Apollo space capsule), or even a hypersonic missile going at Mach 8. So let's not worry about those now, and safely assume that the gas is "perfect". Then, the quantity R is a constant which depends only on the composition (i.e., the average molecular weight) of the gas, i.e., air. The molecular weight of air is easy to calculate, knowing that it is generally composed of 20% diatomic oxygen (O2; molecular weight MW =32), 79% diatomic nitrogen (N2; MW =28), and 1% argon (MW =44). Thus the average (or "mean") molecular weight of air is (0.2*32 + 0.79*28 +0.01*44) = 28.96 The Universal Gas Constant is 8314 in SI units. Thus the gas constant for air is R = 8314/28.96 = 287.04

2.3. Stratosphere

Differentiating the perfect gas law,

$$\frac{dp}{p} = -\frac{g}{RT}dh \tag{2}$$

Integrating between two altitudes h1 and h2, in an isothermal region, i.e., in the stratosphere where temperature is constant,

$$ln\left(\frac{p_2}{p_1}\right) = -\frac{g\left(h_2 - h_1\right)}{RT} \tag{3}$$

or

$$\frac{p_2}{p_1} = \frac{\rho_2}{\rho_1} = \exp\left(\frac{-g}{RT}\left(h_2 - h_1\right)\right) \tag{4}$$

To see why the density and pressure behave the same way, write the Perfect Gas law for the two altitudes h1 and h2, and divide one by the other. This holds in the Stratosphere, the region between 11,000 meters and 25,000 meters.

2.4. Troposphere

In gradient regions, where T changes as altitude changes, we will assume that this variation is linear, i.e.,

$$T_2 = T_1 + a\left(h_2 - h_1\right) \tag{5}$$

In the Troposphere (the region below 11,000m), the constant a, which is called the temperature lapse rate is approximately -0.0065 deg. K per meter. thus, for a standard sea-level temperature of 288.12 Kelvin, the temperature in the troposphere is given by T= 288.12 - 0.0065*h, where h is in meters. In this region, the pressure and density variations can be found as follows:

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{-\frac{g}{aR}} \tag{6}$$

and

$$\frac{\rho_2}{\rho_1} = \left(\frac{T_2}{T_1}\right)^{\left[-\frac{g}{aR}-1\right]} \tag{7}$$

2.5. Sea-Level Standard Conditions

We all know that atmospheric conditions change from place to place, season to season, day to day and even more frequently. If we had one set of standard conditions, we could use those to do the calculations of how an aircraft flies, and then modify those calculations for the specific atmospheric conditions encountered at a given time. Thus the International Standard Atmosphere has been developed. In this, the Sea-level Standard conditions are as follows:

Temperature = 288.12 Kelvin,

Pressure = 101,300 N/m2.

Using these, the density is: 1.225Kg/m3.

The variations with altitude as given according to the formulae developed above. Now, on a given day, at a given point, let's say we measure a certain pressure (because the pressure happens to be what we can measure). We can express this as "so-many meters, Pressure Altitude", meaning: "if this pressure were in the Standard Atmosphere, I would be at this altitude".

Similarly, we can express Density Altitude and Temperature Altitude.

Altitude, meters	Temperature, K	Density, kg/m^3	Pressure, N/m^2	Viscosity, Nsec/m^2
0	288.15	1.225	101,327	0.00001789
11,000 (end of troposphere)	216.50	0.363925	22,633	0.00001421
25,000 (end of stratosphere)	221.65	0.03946	2511.18	0.00001448
47,000 (end of linear temp. increase)	270.65	0.00142	110.916	0.00001703
60,000	245.45	0.00028	20.3156	0.00001575
71,000	214.65	0.00006	3.95698	0.00001410

2.6. Regions of the Atmosphere

Below 500meters, we are in the Atmospheric Boundary Layer. The winds in the atmosphere get obstructed by hills, buildings, and by the friction of moving over the ground, and hence slow down, and also become turbulent, in this region. This is where we see most of the gusts, tornadoes, rain, snow, etc. Above this, and below 11,000 meters, is the Troposphere. Most of the "weather" occurs in this region, through some thunderstorms rise as high as 18,000 meters. From about 11,000 meters to 25,000 meters is the Stratosphere, where the temperature is constant at a cold 216.7 Kelvins. From 25,000 meters to about 47,000 meters, the temperature rises again, linearly, reaching 282.66K by 47,000 meters. Above that, the temperature is again assumed to remain quite constant.

3. Advanced

Planetary atmospheres are believed to exist in a balance between the kinetic energy of molecules in random thermal motion, and gravitational potential energy. Thus, weak gravitational fields cannot sustain a stable atmosphere on celestial bodies above some threshold temperature. Venus, Mars, Earth, and several of the moons of Jupiter (Titan and Europa for instance) have atmospheres. The gas giant planets Jupiter, Saturn, Uranus and Neptune certainly can be considered to have exterior atmospheres, with the surface arbitrarily defined at some density level. Mercury does not appear to have an atmosphere because of the very high surface temperature and intense solar radiation and particle streams energizing and accelerating away any gas in the planets vicinity. Enceladus, a moon of Saturn, exhibits some gas in its vicinity, but this is believed to be a streaming exchange between vented jets from the surface, capture by Saturns gravity, and capture by Enceladus gravity.

4. Supersets

Thermodynamics

5. Subsets

Troposphere, stratosphere, mesosphere, exosphere, ionosphere, tropopause, weather, temperature lapse rate

6. Other fields

hydrostatics, climatology, metrology

7. Calculators/Applets

"Atmosphere Calculator" from Professor Ilan Kroo's Web Page at Stanford University, based on the 1976 Standard Atmosphere, upto 71000 meters. http://aero.stanford.edu/StdAtm.html

ICAO Atmosphere Calculator http://www.aviation.ch/tools-atmosphere.asp

NewByte Atmospheric Calculator http://www.newbyte.co.il/calc.html NASA Atmosmodeler Simulator http://www.grc.nasa.gov/WWW/K-12/airplane/atmosi.html

8. Notes

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9. Byline

Narayanan Komerath

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[1] NASA Thesaurus, Washington, DC: National Aeronautics and Space Administration.

[2] Martian Atmosphere Model, NASA Glenn Research Center. http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmre.html

[3] Anon., What does a private pilot need to know about aviation weather? Free-online-private-pilot-ground-school.com

[4] International Civil Aviation Organization, Manual of the ICAO Standard Atmosphere (extended to 80 kilometers (262 500 feet)), Doc 7488-CD, Third Edition, 1993, ISBN 92-9194-004-6.