Chapter 2
The Atmosphere

No one has ever collided with the sky.
Anon.

Abstract The atmosphere is the medium through which all terrestrial aircraft travel. Thus, it is vital that any discussion of airworthiness begins with a discussion of the properties of the atmosphere, and how, in calculation and testing, we characterise the medium. The core components of the atmosphere, its different layers and how they are characterised are described. The International Standard Atmosphere (ISA)—its standard definitions and reference latitudes, and how ISA influences and informs airworthiness practice are also described. An integral part of airworthiness is human survivability in the airborne environment and as the final part of this chapter, how atmospheric conditions (pressure, oxygen content and temperature) affect human survivability are discussed.

2.1 General Principles of the Atmosphere

The atmosphere is the sphere of gas that surrounds the Earth, it is made up of the gas mixture which we call air. Air itself is primarily a nitrogen/oxygen mix, with a lot of small components, made up as shown in Table 2.1.

In practice this is not quite right, since there is often a proportion of water vapour also present in the air (typically somewhere in the range 0–4 %), however this tends not to be considered for airworthiness purposes (except when considering the chemical effects of that moisture, such as corrosion or mass gain).

At all aircraft operating altitudes, it is safe to assume that this mix remains consistent. Therefore, virtually all human endeavours, including the building and operation of flying machines, takes place in an essentially diatomic gas mixture of 78 % Nitrogen, 21 % Oxygen, and about 1 % of "other" mixed gasses which tend not to affect gas properties much.

Airworthiness involves vehicles which travel through this atmosphere. At the same time, most aerial vehicles are also operated by human beings who in particular rely upon the 21 % oxygen fraction to continue to function efficiently (or at-all!). So, an understanding of the gas mix called "air" is very important.

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Table 2.1 Atmospheric consistuents

Gas	Percentage (molar fraction)
Nitrogen	78.09
Oxygen	20.95
Argon	0.93
Carbon dioxide	0.03
Neon	1.8×10^{-3}
Helium	5.24×10^{-4}
Krypton	1×10^{-4}
Hydrogen	5×10^{-5}
Xenon	8×10^{-6}
Ozone	1×10^{-6}
Radon	6×10^{-13}

Intuitively and correctly, one would expect the pressure (and thus density) of air to reduce as one travels from the surface of the earth upwards towards space, since as one climbs, the size (and thus weight) of the column of air above one will reduce—and in practice this is what happens. Figure 2.1 below shows how atmospheric pressure typically changes with altitude[1].

Having established that pressure changes, it is reasonable to assume that temperature and density will also change, and they do. Temperature in particular changes in an interesting manner, acting in layers as shown in Fig. 2.1 (Fig. 2.2).

And clearly, alter temperature and pressure and the density changes also, as shown in Fig. 2.3.

In fact we consider, based primarily upon temperature variation, that the aeronautically usable atmosphere exists in three layers:

From the surface to a nominal 11,000 m (or 36,069 ft) there is the *troposphere*, in which temperature and pressure decrease. The top of the troposphere is called the tropopause.

From about 11,000 m to about 20,000 m (or 65,617 ft) we enter the lower *stratosphere*, in which pressure continues to reduce, but temperature remains constant at a nominal value of 216.7 K (−56.5°). The top of this layer is called the lower stratopause.

Above 20,000 m and up to 32,000 m (104,987 ft) we enter the *middle stratosphere*. Again, pressure continues to decrease, but now the temperature increases. This terminates at the middle stratopause.

There are further layers above this—the upper stratosphere and then the mesosphere, these are mentioned later, but in practice we will only consider behaviour up to the top of the lower stratosphere, at about 65,617 ft when temperature ceases to be constant—since virtually all aeronautical endeavours take place below this.

[1] *A note on terminology: Conventionally, "height" implies a distance above the ground or a predetermined point on it (such as a building or runway), whilst "altitude" implies a distance above mean sea level. We may also refer to pressure altitude or density altitude, each of which becomes important at different times.*

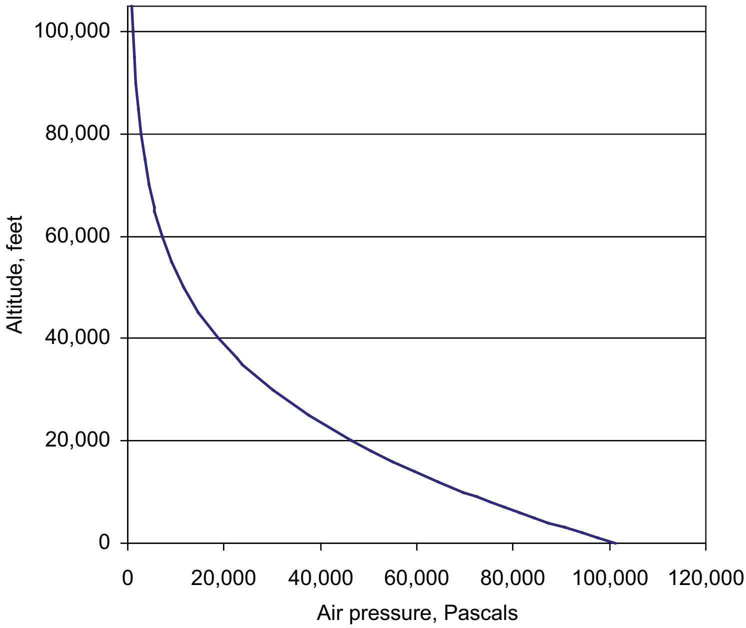

Fig. 2.1 Typical change in air pressure with altitude

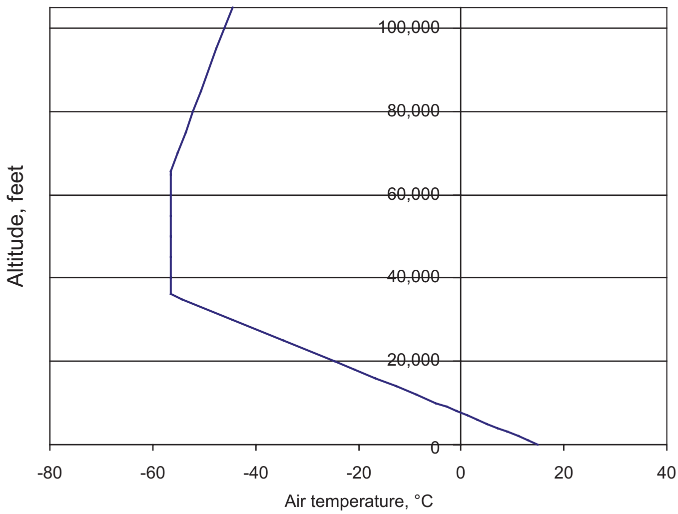

Fig. 2.2 Typical temperate climate temperature variation with altitude

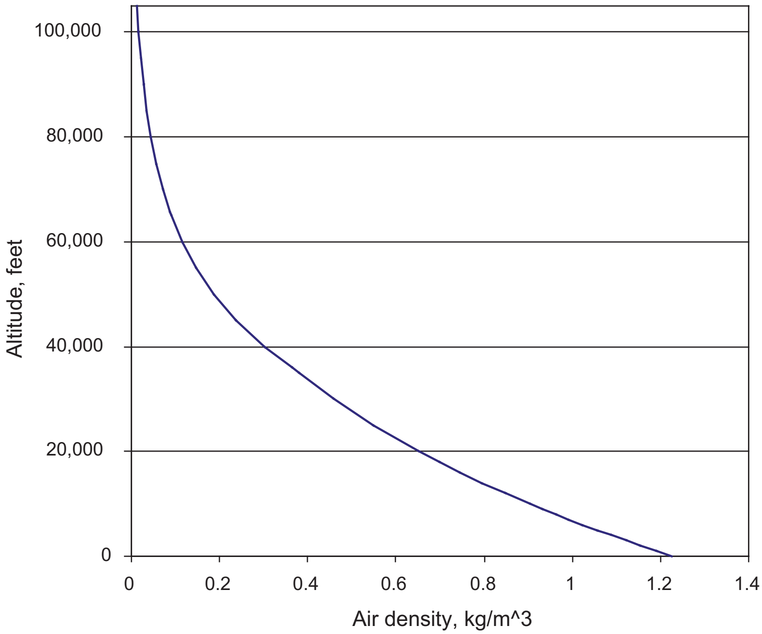

Fig. 2.3 Typical temperate condition variation in air density with altitude

2.2 The International (or US) Standard Atmosphere

Whilst the generalised characteristics of the earth's atmosphere have been well understood since the mid nineteenth century, in the post-WW2 expansion of civil aviation, it became important for several reasons that the world all used a common atmosphere model (although several, national standard atmosphere models had existed since the 1920s). There were many good reasons for this, for example ensuring a common standard in structural calculations, and ensuring that all commercial air-traffic is using altimeters calibrated to a common scale.

In 1952, NACA—the (US) National Advisory Council for Aeronautics, a predecessor organisation to NASA, published a set of tables and data for what was referred to as the "ICAO Standard Atmosphere" showing data to 65,800 ft (20,056 m)—the limit of reliably explored atmosphere at that time; it was based upon atmospheric data at about a latitude of 40°. This was accepted worldwide, although more commonly known as the "US Standard Atmosphere".

As atmospheric data was revised, this atmosphere model was revised by NACA and later NASA in 1958, 1962, 1966 and most recently 1976—whilst no change occurred to the low level model, much work was done to expand the model upwards. The 1976 US Standard Atmosphere was (as with previous NACA and NASA generated atmosphere models) adopted by ICAO and accepted as a worldwide

Table 2.2 ISA layers from the 1976 model

Level	Name	Lower altitude (km)	Upper altitude (km)	Upper altitude (ft)
1	Troposphere	0	11	36,089
2	Lower stratosphere	11	20	65,618
3	Middle stratosphere	20	32	104,987
4	Upper stratosphere	32	47	154,199
5	Upper stratosphere	47	51	167,323
6	Mesosphere	51	71	232,940

standard—a status it retains today, although it is more commonly referred to nowadays as the "International Standard Atmosphere" or "ISA".

ISA is published for several latitudes—15°, 30°, 45°, 60° and 75°, however unless stated otherwise (and for virtually all airworthiness work) published values correspond to 45° latitude—a nominal temperate condition representing (approximately) average conditions for central Europe, northern US states, southern Russia, or the southern parts of south America and New Zealand.

This book will content itself with consideration of the models for the troposphere and lower to middle stratospheres; higher altitudes are of only very specialist interest and very rarely even will any airworthiness engineer have concerns beyond the lower stratopause).

The model and threshold values shown in Table 2.2 above adequately model the standard atmosphere for any altitude below the first stratopause at 20 km. Fuller derivations exist in other textbooks, but for completeness the actual formulae by which the temperate (45°) ISA is defined are shown below.

2.2.1 Troposphere

Geopotential altitude range: 0–36,089 ft (0–11,000 m)
Temperature, T:

$$T = T_0(1 - h/145542\text{ ft}),$$

or

$$T = T_0(1 - h/44329\text{ m}),$$

where $T_0 = 288.15\text{K}$. Density is defined as:

$$\rho = \rho_0(1 - h/145442\text{ ft})^{4.255876},$$

or

$$\rho = \rho_0(1 - h/44329\text{ m})^{4.255876},$$

where $\rho_0 = 1.225$ kg/m^2. Pressure is defined as:

$$P = P_0(1 - h/145442\text{ ft})^{5.255876},$$

$$P = P_0(1 - h/44329\text{ m})^{5.255876},$$

where $P_0 = 101{,}325\text{ Pa} (= \text{N}/\text{m}^2)$.

2.2.2 Lower Stratosphere

Geopotential altitude range: 36,089–65,617 ft (11,000–20,000 m)

Temperature, $\text{T} = 216.65\text{ K} (-56.5\,°\text{C})$.

$\rho = \rho_0(0.297076)e^{((36089-h)/20806)}$ where altitude is given in feet.

$\rho = \rho_0(0.297076)e^{((10999-h)/6341.4)}$ where altitude is given in metres.

$P = P_0(0.223361)e^{((36089-h)/20806)}$ where altitude is given in feet.

$P = P_0(0.223361)e^{((10999-h)/6341.4)}$ where altitude is given in metres.

2.2.3 Middle Stratosphere

Geopotential altitude range: 65,617–104,987 ft (20,000–32,000 m)

$T = T_0(0.682457 + h/945374)$, where altitude is given in feet.

$T = T_0(0.682457 + h/288136)$, where altitude is given in metres.

$\rho = \rho_0(0.978261 + h/659515)^{-35.16319}$ where altitude is given in feet.

$\rho = \rho_0(0.978261 + h/201010)^{-35.16319)}$ where altitude is given in metres.

$P = P_0(0.988626 + h/652600)^{-34.16319}$ where altitude is given in feet.

$P = P_0(0.988626 + h/198903)^{-34.16319)}$ where altitude is given in metres.

The pilot, design, performance or airworthiness engineer will find that these relationships underpin a great deal of aeronautical work—indeed atmospheric conditions are commonly referred to by a temperature plus/minus ISA. However it is important to remember whilst doing so that this is only a standardised set of values, and that it is extremely rare to actually experience a close approximation to ISA conditions. It is also worth noting that the tropopause in particular is not a theoretical level—it is better to think of it as the surface of an ocean, complete with waves (termed "folds") and storms, and where the chemistry of the atmosphere is dependent upon what crosses that surface. Much on-going study of climatology is build upon a still building understanding of the way in which various chemicals (particularly those referred to as "greenhouse gasses" cross the tropopause).

It is also common and useful to define altitude in terms of a single ISA related parameter; hence it is common to find altitude referred to as "Standard Pressure Altitude" (sHp) or "Standard Density Altitude" (sHd). Occasionally it is also convenient to think in terms of "Standard Temperature Altitude" (sHT) [the author has on one occasion used an aeroplane's OAT—Outside Air Temperature gauge successfully as a crude altimeter after the sole barometric altimeter had failed], however this is only ever of use if remaining constantly below the tropopause, and away from any temperature inversion (this is a common atmospheric feature where for a short period of a climb temperature increases whilst still relatively low—usually at a few thousand feet, but often higher).

A note on terminology: Atmospheric parameters are often expressed by three non-dimensional terms, representing relative temperature, pressure and density respectively. These are given as $\theta = T/T_0$, $\delta = P/P_0$ and $\sigma = \rho/\rho_0$. In each case the "0" subscript describes the standard sea-level condition. For the temperate ISA, these are 15 °C (288.15 K), 1013.25 hPa, 1.225 kg/m^3.

2.3 Which Altitude Matters?

There are effectively four types of altitude then that we have discussed. These are:

1. Pressure
2. Density
3. Geopotential
4. Temperature

Each has a role within airworthiness practice and aircraft operations, and whilst these will be discussed in greater depth later, it's useful to understand now what matters when:

Pressure Altitude is used for altitude reference in most flying, usually by reference to a pressure altimeter. It is also the critical parameter when determining the ability of the human body to absorb oxygen. Pressurised aircraft cabins will normally be set to an equivalent pressure altitude, which will be a design parameter.

Temperature Altitude is of primary interest in aircraft operations in comparison to the dewpoint (where cloud tends to start forming) and the freezing level (when ice starts to form, and thus around which airframe icing becomes most critical). In theory it could also be used as a crude operational measure of altitude within the tropopause, but it seldom is.

Density Altitude is the fundamental parameter when determining aircraft performance; it is also necessary when converting between Equivalent and True Airspeeds, and thus is essential to both cruise performance determination, and instrument calibration.

Geopotential Altitude, with additional knowledge of terrain elevation, provides height, and thus terrain clearance—it also provides a baseline for calculation of the other three altitudes. Historically, geopotential altitude was an essentially theoretical value, and precise terrain clearance was determined by other means—either by calculation, or use of a radio altimeter (RadAlt) system; however, modern navigation systems will now use a combination of GPS determined geopotential altitude and a terrain and obstacle database to provide this information. Increasingly also satellite[2] based approach procedures, known as GNSS, or Global Navigation Satellite System—pioneered in the USA but now spreading around the world, are using satellite position and altitude data: at present pressure altitude is still used for altitude reference in these procedures, but this may change in the future officially, and has already changed in some informal practices, particularly in general aviation.

Debates occasionally occur about the possible replacement of pressure altitude with geopotential altitude (provided by GPS) for routine air navigation. This appears unlikely to happy for the foreseeable future, but there may be value in this for some applications in the longer term.

2.4 Variation in the Tropopause

Whilst ISA (based upon 45° latitude) assumes that the tropopause exists at a uniform 36,089 ft/11,000 m, in practice it varies a great deal with latitude and with local conditions. Typically the polar tropopause is much lower and warmer than the tropical tropopause, and the summer tropopause is higher than the winter tropopause. Table 2.3 indicates typical tropopause characteristics at different latitudes (expecting however higher altitudes in local summer, and lower altitudes in local winter).

Table 2.3 Typical tropopause characteristics

	Typical altitude	Typical temperature
Polar tropopause	25,000 ft/7620 m	−45 °C
Temperate tropopause	40,000 ft/12,190 m	−55 °C
Tropical tropopause	55,000/16,760 m	−75 °C

[2] GPS is the most commonly use GNSS reference system, but the Russian GLONASS and European Galileo systems are also, at-least in theory, available. Combined GPS/GLONASS receivers are becoming increasingly common and have advantages of duplication, reliability, acquisition time, and usability at very high latitudes—the GPS constellation can become unreliable beyond 80° latitude—depending upon constellation configuration at the time.

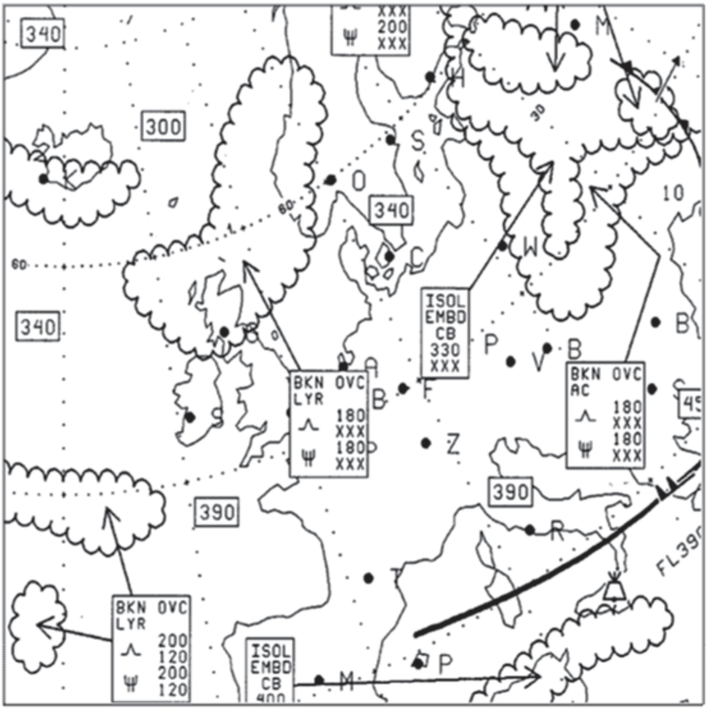

Fig. 2.4 Section of significant weather chart over northern Europe

Weather charts designed for use by aircraft flying high altitude or long distance will often show the altitude of the tropopause at different locations, and possibly its temperature. For example, Fig. 2.4, which is an excerpt from a "Sigmet" or significant weather chart for northern Europe shows that in the area of the Atlantic to the north of Britain, the tropopause is at 30,000 ft (300) whilst over warmer northern Italy it is at 39,000 ft (390); clearly there is a great deal more information portrayed on that chart, for which the reader is referred to any of a large number of excellent and readily available texts on meteorology, particularly those published for Air Transport Pilots Licence (ATPL) training.

2.5 The Effects of Atmospheric Conditions Upon Human Survivability

Most airworthiness calculations involve consideration only of the aircraft and not of its occupant(s). However, a brief mention is made here of human beings—who are generally the operators and occupants of any aircraft (or at least those aircraft for which airworthiness is the greatest concern).

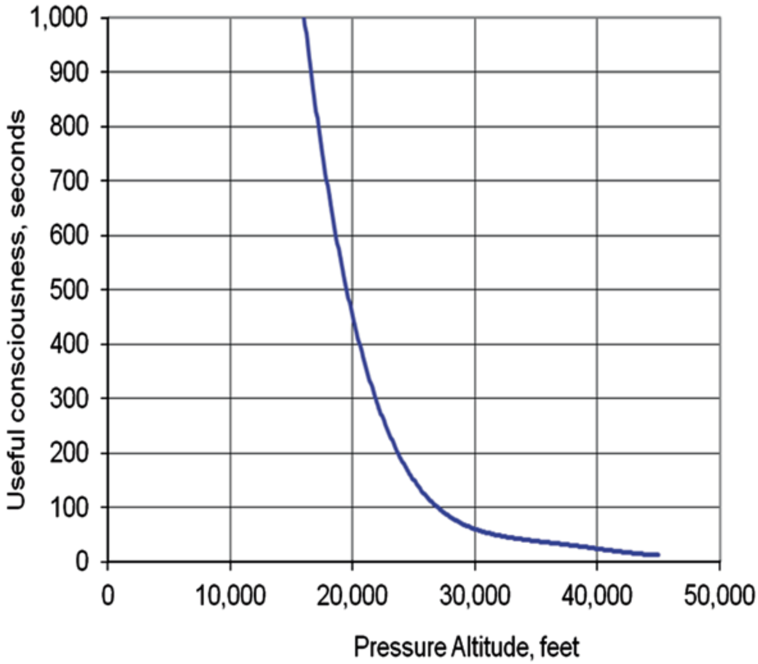

Fig. 2.5 Typical adult useful consciousness time at various altitudes

The human body relies upon two things primarily in its environment for short-term survival; those are an acceptable temperature, and an acceptable partial pressure of oxygen—the nitrogen component of the atmosphere, so far as the aviator is concerned, is of sole use as a provider of air density, and not of life support.

2.5.1 Pressure and Oxygen Supply

Whilst it is not safe to assume that every human body will behave identically—for example a 20 year old non-smoking athlete should certainly have far better tolerance to low oxygen levels than a 60 year old sedentary smoker, there is a clear relationship—the lower the partial pressure of oxygen, the poorer the performance of the human body. Figure 2.5 is representative of the time that it is accepted an average adult can expect at various pressure altitudes to remain usefully conscious—that is before they pass out or at-least become incapable of performing any rational task.

It can be seen that below about 15,000 ft, it is likely that an average pilot or passenger should remain usefully conscious for a prolonged flight. Above this however, they will start to enter a state known as *hypoxia*, or oxygen starvation. It is unsurprising then that it is illegal in most countries to fly for prolonged periods above a certain pressure altitude without the use of supplementary oxygen—in Europe this is 10,000 ft, whilst in the USA it is 12,000 ft, (the variation reflecting only slight differences in local interpretation of aeromedical evidence).

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