Course Notes

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Measuring Temperature

Simply stated, temperature is the measure of the internal heat energy of a substance. Adding or subtracting heat changes temperature and the degree of change is dependent on the molecular make-up of the substance. For example, for the same heat input, a land surface gets hotter than a water surface. The effect becomes obvious when comparing temperatures over bitumen and grassy verges on a hot day. Such contrasting surface temperatures have significant impact on the development of weather systems.

Changes in air temperature affect air density and hence aircraft performance.

Temperature scales are based on two internationally agreed fixed points: the freezing point and the boiling point. The ice point or freezing point is the temperature at which pure ice melts under a pressure of one standard atmosphere. The boiling point is the temperature at which pure water boils at a pressure of one standard atmosphere.

Common temperature scales are the Celsius scale on which the ice point is 0°C and the boiling point 100°C, and the Fahrenheit scale on which the ice point is 32°F and the boiling point 212°F.

In scientific literature reference is sometimes made to the Kelvin temperature scale. On this scale, the ice point is at 273.16 Kelvin. As the divisions of the Kelvin scale are the same as the Celsius scale, conversion is achieved by subtracting 273 from the Kelvin temperature, i.e. 280 Kelvin is 7°C.

Surface Air Temperature

For meteorological purposes, surface air temperature is the temperature of the air measured at approximately 1.25 m above the ground. It is usually measured in a shelter that protects the thermometer from radiation from the sun, sky, earth and any surrounding objects, and at the same time allows free ventilation of the shelter with outside air. Common shelters are the louvered screen type called a Stevenson screen. Nowadays, electronic temperature probes inside the screen measure the temperature, with manually read liquid-in-glass measurements becoming less common, particular for use in aviation weather service products.

Upper Air Temperature

Temperatures are also measured in the free air at various heights above the surface. These are referred to as upper air temperatures and are referenced by altitude in feet or pressure levels in hectopascal, i.e. the 18 500 feet or 500 hPa temperature.

The Variation of Temperature

Diurnal Variation of Surface Temperature

The change in surface temperature from day to night is referred to as the diurnal variation. During the 24 hour day/night cycle temperature changes are less pronounced over the sea than over the land. The diurnal variation in sea-surface temperature is usually less than 1°C, and the air temperature near the water surface is usually similar.

On the other hand, in desert regions in the interior of continents, surface air temperatures may vary by 26°C from day to night. In Figure 3.1, a typical inland diurnal change of temperature is depicted ranging between A and B. Near the coast, however, the diurnal variation of temperature depends on the direction of the wind, being largest if the wind is off the land and small if it is from the sea. Local land and sea breezes also tend to reduce the range of temperature variations near the coast.

The diurnal variation of surface air temperature tends to be greatest if calm conditions prevail. If it is windy, mixing of the air occurs through a deeper layer. Mixing within the atmosphere enables the gain of heat by day and the loss by night to be shared by more molecules of the atmospheric gases. As a result, the diurnal range of temperature is reduced during windy conditions.

Cloudiness also reduces the diurnal range of temperature. During the daytime clouds reflect radiation back to space while at night they act like a blanket keeping the air near the earth's surface warmer. Diurnal variation of surface air temperatures is therefore relatively small during cloudy conditions.

The type of surface (open fields, forests, deserts and oceans) and the ability of the underlying material to conduct heat to or from the atmosphere affects the diurnal range of air temperature in the lower layers. However, the nature of the neighbouring terrain is also important, because the temperature at a particular place may be affected by the flow of warm or cold air from adjacent areas.

Temperature Variation in the Vertical within the Troposphere

As already mentioned previously, the temperature decreases with altitude in the troposphere at about 2°C per 1000 feet (6.5°C per kilometre). This means if the temperature at sea level is 15°C, on average it will decrease to a value of -15°C at 15 000 feet (i.e. a fall of 30°C).

The rate of change of temperature with altitude is called the temperature lapse rate. Although the typical lapse rate (Figure 3.1 line E to D) is for decreasing temperature with height there are many variations. Actual lapse rates, particularly near the earth's surface, vary markedly from the average.

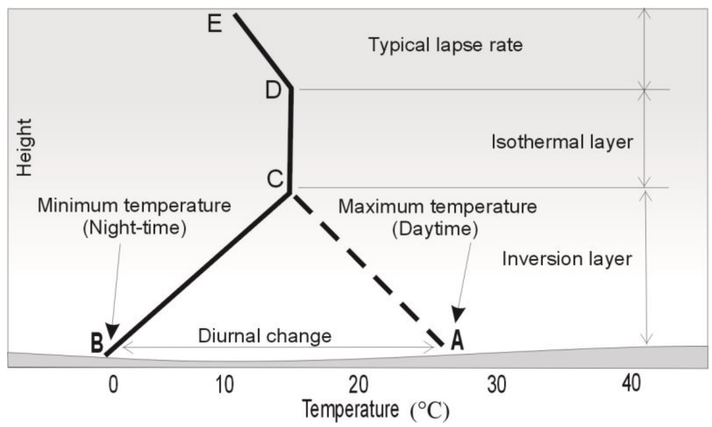

Figure 3.1: Surface and vertical variations in temperature.

Thin layers of air in contact with the ground, if heated by conduction and radiation from very hot surfaces will have lapse rates far exceeding the average. For example, a temperature of 44°C at 1.25 m above a runway surface temperature of 81°C has been observed at Melbourne Airport. In such conditions the lapse rate would be extreme within a few centimetres of the ground. However, because air is a poor conductor of heat, extreme lapse rates are not sustained to any depth. Similarly, shallow layers of air in contact with very cold surfaces may have extreme reversed lapse rates (temperature warms with height).

Inversions

When temperatures increase with altitude an inversion is said to occur across the affected layer, i.e. the normal change of temperature in the troposphere has been inverted or reversed (Figure 3.1 line B to C).

Inversions limit vertical development of cloud and trap pollutants resulting in reduced visibility. They also constrain or trap air within confined boundaries and therefore are often associated with turbulence and wind shear.

The troposphere, where the vast majority of weather develops, is contained by the tropopause inversion as illustrated previously in Figure 1.1.

Isothermal layers

When temperatures do not change with altitude (the temperature lapse rate is zero) the affected layer is said to be isothermal, i.e. the temperature remains the same for some vertical distance as illustrated by the line between D and C in Figure 3.1.

Air Density

Air density is a major factor in aerodynamic performance and engine efficiency. Increases in air temperature, humidity or altitude are coupled to decreases in air density.

Low air density decreases aircraft performance in a number of ways:

- the lifting force of an airplane's wings or helicopter's rotor decreases;
- the power produced by the engine decreases;
- the thrust of a propeller, rotor or jet engine decreases.

All three reduce climb rates and can drastically reduce maximum take-off weight. Also, all other factors being equal, lower air densities require longer take-off and landing distances for fixed wing aircraft.

The Density of Dry Air

The density of dry air having a pressure of 1013.25 hPa at 15°C is 1.225 kg per cubic metre.

For dry air the density is related to pressure and temperature by the fundamental gas equation: $D = P/RT$, where:

D is the density, P is the pressure, T is the absolute temperature, and R is a constant.

The equation shows that, for a fixed temperature:

- The density of dry air will increase as pressure increases (as air is compressed it occupies a smaller volume);
- With constant pressure, density will decrease as temperature increases. To retain the same pressure the air must occupy a larger volume.

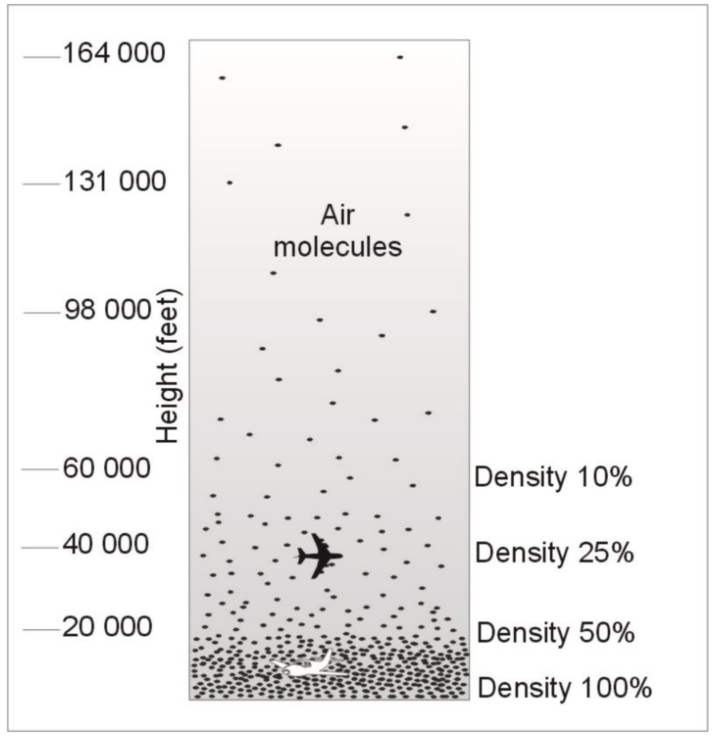

Figure 3.2: The rapid decrease in density with height.

The Density of Moist Air

Water vapour is a less dense gas than dry air, so the combination of water vapour and dry air (called 'moist air') is slightly less dense than dry air at the same pressure and temperature. The density difference is only noticeable in very moist air in the lower layers of the atmosphere in the tropics. The difference can be as much as one to two per cent.

The Variation of Air Density with Height

The density of air at 18,500 feet is about half the surface value. It then drops to about one quarter at 40,000 feet, and about one tenth at 60,000 feet as depicted in Figure 3.2.

Atmospheric Pressure

Atmospheric pressure is a measure of the total weight of the atmosphere above the point of measurement.

Surface pressures normally range between 1040 hPa and 970 hPa. However, extreme values of 1084 hPa and 870 hPa have been recorded. The variations of pressure are closely related to the generation of wind and changes in the weather. The intimate relationship between pressure and height is utilised by the pressure altimeter for determining the height of aircraft.

Variation of pressure with altitude

The rate of pressure decrease with altitude is not linear (as shown in Figure 3.3). Near mean sea level, the pressure decreases by one hectopascal for a rise of about 30 feet. At about 16 000 feet the same pressure decrease is equivalent to a rise of approximately 50 feet. Only approximate figures can be given because of the impact of temperature variations.

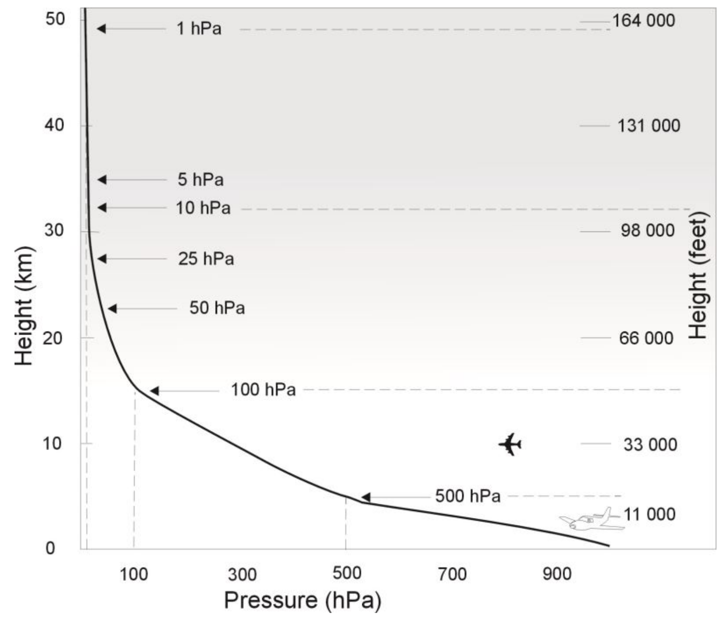

Figure 3.3: The variation of pressure with altitude in the standard atmosphere.

Adjustment of recorded pressure to standard levels

To compare station level pressure (SLP) at different elevations, it is necessary to reduce the recorded pressure to mean sea level (MSL) pressure.

Reduction to MSL pressure is done by adding the weight of the ISA column of air, between the recording station and sea level, to the measured pressure. Because the temperature and density chosen for the column are based on the imaginary ISA, inland mean sea level pressures are hypothetical. However the computed values give satisfactory results for most regions.

Pressures from numerous stations, adjusted to MSL pressure, are used for the production of weather charts. The weather charts comprise smooth curved lines of mean sea level pressure called isobars (lines of equal atmospheric pressure). Isobars depict weather systems such as highs and lows.

Variations of surface pressure

Atmospheric pressure at a given locality varies continually. The variations may be irregular or regular.

Irregular variations are primarily associated with the development, decay and passage of pressure systems. Sometimes purely local effects can force irregular pressure changes. An example of such an effect is a low-pressure trough in the lee of terrain. The air movement up and over the terrain causes a pressure reduction on the lee side. Thunderstorms and temperature variations can also cause pressure changes.

Regular oscillations have a period of about twelve hours generated by the alternate heating and cooling of the earth's atmosphere by the sun. This produces a rhythmic expansion and contraction of the atmosphere. Pressure maxima occur around 1000 and 2200 local mean time, with minima at about 0400 and 1600. The changes are not perfectly symmetrical and vary considerably with locality.

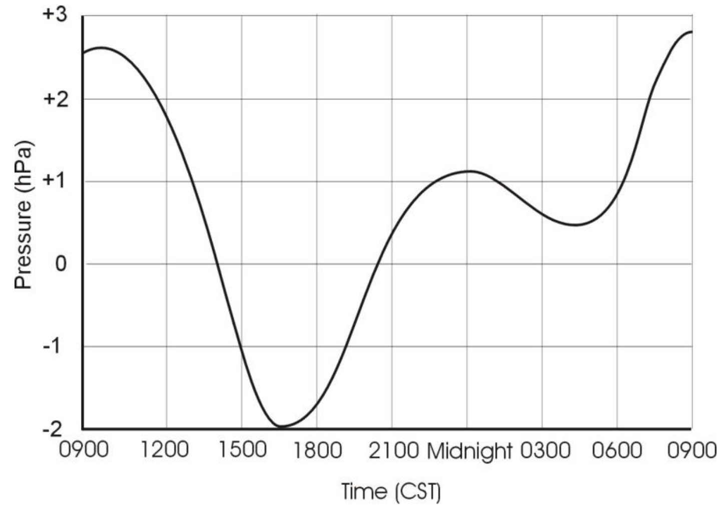

Figure 3.4: Regular pressure variations for Darwin during September, with a period of about twelve hours.

In the tropics, the diurnal variation of pressure is more evident than in higher latitudes. Figure 3.4 illustrates the diurnal pressure variations (about 5 hPa) for a typical September day at Darwin, Australia.

Pressure gradient

The rate of change of pressure between locations is termed the pressure gradient. Isobar spacing on weather maps reflects the pressure gradient. Isobars close together are indicative of strong-pressure gradients and strong wind. Conversely, isobars far apart are indicative of weak-pressure gradients and light wind.

A synoptic chart is depicted in Figure 3.5 showing tightly spaced isobars around a low-pressure system near Perth. This is indicative of a strong-pressure gradient and strong winds. Well separated isobars around a high pressure system centred near Adelaide are indicative of a weak-pressure gradient and light winds.

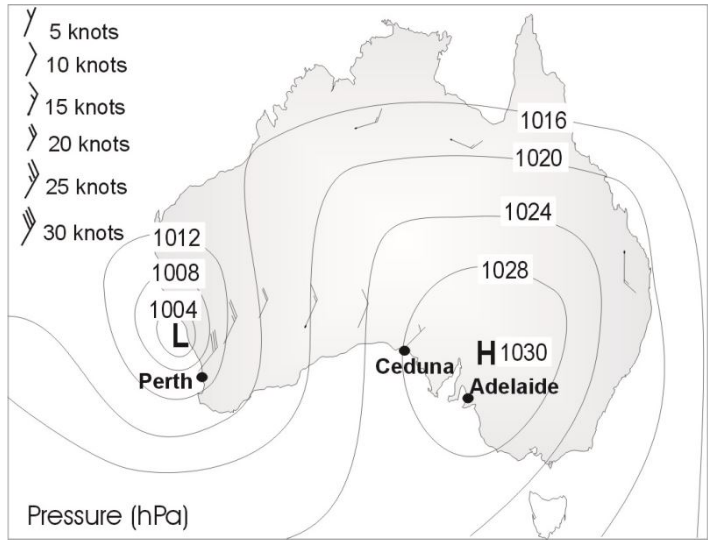

Figure 3.5: Isobar spacing and wind speed.

Altimetry

A clear definition of the following terms (illustrated in Figure 3.6) in relation to aviation is necessary:

- *Height* is the vertical distance above a specified datum, usually ground level;
- *Elevation* is the vertical distance above mean sea level (MSL) of a point on the earth's surface;
- *Altitude* is the vertical distance above MSL.

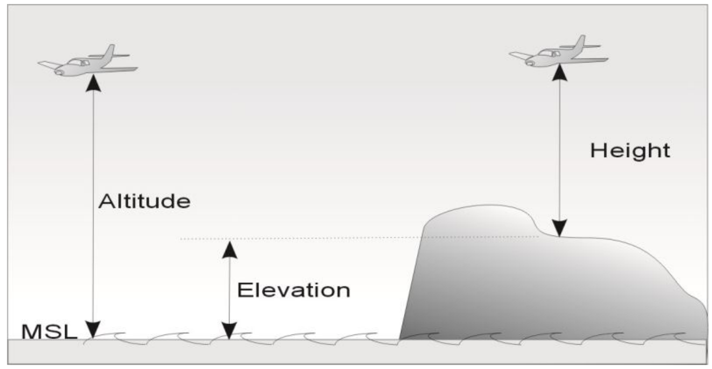

Figure 3.6: Altitude, elevation and height.

Altimeter settings

An aircraft's altimeter uses a similar operating principle to an aneroid barometer. On an altimeter, the pilot will set a known pressure in the barometric subscale (for a particular datum), and the pointers will indicate the height above that datum.

The following pressure settings are used:

QNH

The QNH pressure setting is the mean sea level pressure for a location or area that has been calculated assuming ISA conditions. This is the altimeter pressure setting that aircraft in Australia use when operating up to and including 10,000 feet. This is the pressure value given in all meteorological forecasts and observations and in the Automatic Terminal Information Service (ATIS).

An altimeter set to QNH while an aircraft is on the ground will indicate the height of the aicraft above sea level, or in other words, the aerodrome's elevation. When an accurate local QNH is available at an aerodrome, the pilot is required to perform a check of the accuracy of the altimeter prior to departure by comparing the known aerodrome elevation with that displayed on the altimeter.

In flight the QNH will indicate the aircraft's altitude, ie. the height above mean sea level.

1013 hPa

Figure 3.7: Altimeter.

1013 hPa is the mean sea level pressure in the ISA. An altimeter with this pressure setting will indicate the aircraft height above the 1013 hPa level. This is known as pressure altitude. The 1013 pressure setting is sometimes referred to as QNE.

In Australia, pilots of aircraft passing through 10,000 ft on climb change the altimeter setting from the QNH to 1013 hPa. Pressure altitudes above 10,000 feet are generally quoted in hundreds of feet and called flight levels. For example, the pressure altitude of 12,500 feet is FL125 (read as flight level one two five); 41,000 feet is FL410 (read as flight level four one zero).

QFE

QFE is the station level pressure, or more simply the pressure at ground level.

An altimeter set to QFE will read zero when the aircraft is on the runway. In flight, the QFE setting will indicate the approximate height of the aircraft above the aerodrome. QFE is generally not used in Australia, although a pilot may choose to set QFE for local operations such as when performing low-level aerobatics or crop dusting.

More about altimetry

As stated above, to obtain the correct altitude, an accurate QNH must be entered or dialled on the barometric subscale on the altimeter. An error of 1hPa entered on the subscale will result with a 30 foot error in the height indicated on the altimeter.

If the pilot of an inbound aircraft incorrectly sets a QNH is 1031hPa when in fact it is actually 1013hPa, the altimeter would over-read by 540 feet; that is, the pilot would think the aircraft was 540 feet higher than it actually is. If the aircraft is operating close to terrain without visual reference to the surrounds, the consequences could be disastrous.

Accurate pressure information is vital for the safety of aircraft operations.

Pressure Altitude & Density Altitude

Aircraft manufacturers use the ISA sea-level Pressure and Temperature (1013.25 hPa and 15°C) as a baseline for determining aircraft performance parameters such as take-off and landing distance requirements, climb and cruise profiles, and power settings.

But what happens when the ambient conditions vary from the ISA?

Pilots must have a way of determining how an aircraft will perform over a wide range of atmospheric conditions. Changes in pressure and temperature will change the number of air molecules available for a power-plant to produce power, for a propeller to produce thrust, and for a wing to produce lift. Under extreme circumstances the air may not be dense enough for an aircraft to become airborne with the runway distance available, or alternatively once airborne, it may not be able to achieve the required climb gradient to clear nearby obstacles, particularly in the event of the loss of an engine of an mutli-engine aircraft.

Pressure Altitude

Pressure altitude within the atmosphere is the altitude in the International Standard Atmosphere with the same pressure as the part of the atmosphere in question. Calculating the pressure altitude is one of the steps a pilot takes to determine expected aircraft performance when the sea-level pressure varies from the ISA.

For every 1 hPa variation in the ambient pressure from 1013 hPa, a 30 foot change occurs to the pressure altitude. A simple formula can be used:

Pressure Altitude = Elevation + (1013 - QNH) x 30

Example:

Aerodrome elevation is 550 ft, and the mean sea-level pressure (QNH) is 998 hPa.

Pressure Altitude = 550 + (1013 - 998) x 30

= 550 + 15 x 30

= 550 + 450

= 1000 ft

What does this mean? - For departure at this aerodrome, the pilot will use a pressure altitude of 1000 ft in the take-off/climb-out performance calculations.

Note that for a QNH greater than 1013 hPa, the pressure altitude will be a lower value than the elevation (or altitude) in question.

Density Altitude

The variation in temperature from ISA has a much greater effect near sea-level than pressure variations in terms of aircraft performance. The density altitude calculation accounts for this.

Density altitude is the pressure altitude corrected for temperature deviation from the ISA. It is computed from the pressure altitude and the outside air temperature. A high density altitude value equates to low air density, and a low density altitude value equates to high air density.

An approximate method for calculating density altitude is to add 120 feet to the pressure altitude for each degree Celsius that the actual temperature is above the ISA standard for that level.

The following formula can be used:

Density Altitude = Pressure Altitude + (ISA Temp Deviation x 120)

Using the Pressure Altitude example above, we will now consider the effect of temperature for the aircraft departure.

Aerodrome elevation is 550 ft, and the mean sea-level pressure (QNH) is 998 hPa - Calculated Pressure Altitude is 1000 ft. The temperature at the aerodrome is 31°C

At a Pressure Altitude of 1000 ft, the ISA Temperature is 13°C (ISA temperature at sea-level of 15°C and a lapse rate of 2°C per 1000 ft)

If the actual temperature is 31°C then the ISA Temperature deviation is 31 - 13 = 18°C.

Plug this into our formula:

Density Altitude = Pressure Altitude + (ISA Temp Deviation x 120)

= 1000 + (18 x 120)

= 1000 + 2160

= 3160 ft.

What does this mean? - For departure at this aerodrome, the pilot will use a density altitude of 3160 ft in the take-off/climb-out performance calculations. Another way of thinking about it is the aircraft will *perform* as though it is at an altitude of 3160 ft rather than the aerodrome elevation of 550 ft.

Note that if the ISA temperature deviation is a negative value (that is, the actual temperature is colder than the ISA temperature for that pressure altitude), then the density altitude will be a lower value than pressure altitude.

High density altitudes are a particular problem in Australia during summer. Some extreme values for Australian aerodromes are shown in Table 3.3. An aircraft leaving Alice Springs when the temperature is 43°C and the station level pressure is 941.4 hPa will effectively be taking off at an aerodrome 3579 feet higher than indicated by standard ISA pressure values and performance will thus be lower than indicated by ISA standards. In comparison an aircraft leaving Canberra on the -8°C day will have higher performance than indicated by ISA conditions.

Accurate pressure and temperature measurements are vital for accurate aircraft performance calculations.

Aerodrome	Temp (C°)	Station level pressure (hPa)	Density altitude (ft)	Elevation of aerodrome (ft)	Pressure altitude of aerodrome (ft)	Aircraft performance
Kalgoorlie	43	963.4	4900	1247	1389	lower
Broken Hill	46	972.9	4800	1000	1120	lower
Canberra	43	941.7	5500	1850	2012	lower
Canberra	- 8	963.4	- 1100	1850	1389	higher
Alice Springs	43	941.4	5600	1901	2021	lower
Alice Springs	- 2	956.6	- 100	1901	1583	higher
Cloncurry	46	980.4	4500	633	909	lower

Table 3.1: Some extreme values of observed density altitude in Australia.

Review Questions

1. What is the term given to a layer of the atmosphere where an increase in height corresponds to an increase in air temperature?

   ➞ Answer

2. What is the term given to a layer of the atmosphere where the temperature remains constant with an increase in height?

   ➞ Answer

3. What is the approximate pressure lapse rate near mean sea level?

   ➞ Answer

4. What is the density of dry air at sea level in the international standard atmosphere?

   ➞ Answer

5. Above what datum will the pointers of an altimeter indicate with the altimeter subscale set to QNH?

   ➞ Answer

6. For the same temperature and pressure, which is less dense – very dry air or very moist air?

   ➞ Answer

7. What is the relationship between a decrease in air density and aircraft take-off performance?

   ➞ Answer

8. Find the Pressure Altitude and Density Altitude for the following:

   - Aerodrome Elevation: 200 ft
   - QNH: 1003 hPa
   - Temperature: 26°C

   ➞ Answer